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The 23rd International Workshop on Neutrinos from Accelerators

Overview of physics results with coherent elastic neutrino-nucleus scattering data

INFN CAGLIARI

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In collaboration with

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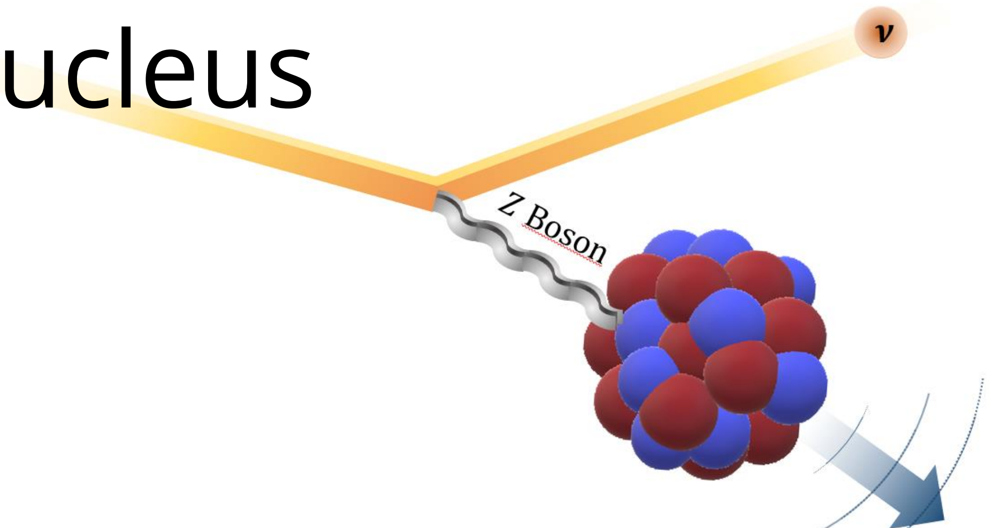
Coherent elastic neutrino nucleus scattering (aka CEνNS)

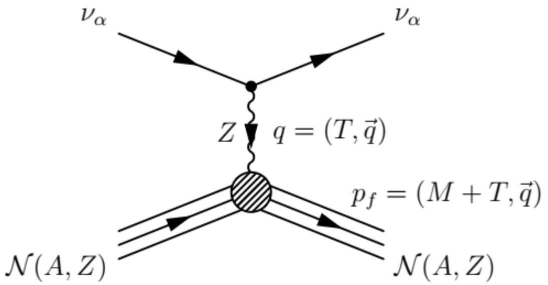


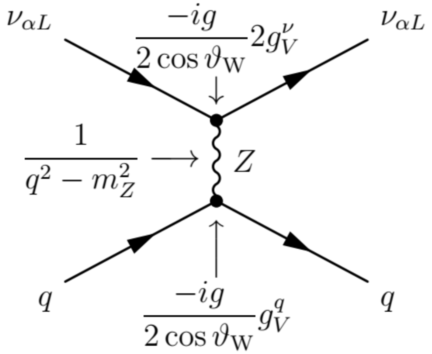
- A pure weak neutral current process

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

- Weak charge of the nucleus

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





In 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!

- The form factor takes into account the finite size of nucleus.

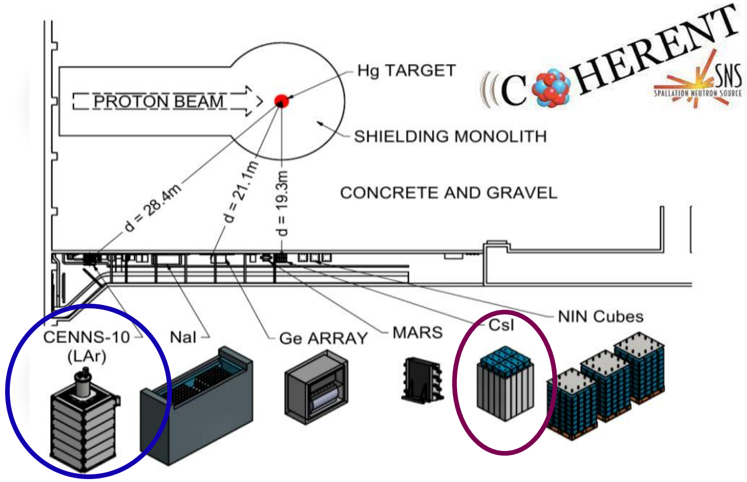
$$g_V^{p,\text{tree}} = \frac{1}{2} - 2\sin^2(\vartheta_W) \cong 0.0229$$

$$g_V^{n,\text{tree}} = -\frac{1}{2}$$

The coupling to proton depends on the weak mixing angle!

CEνNS players so far

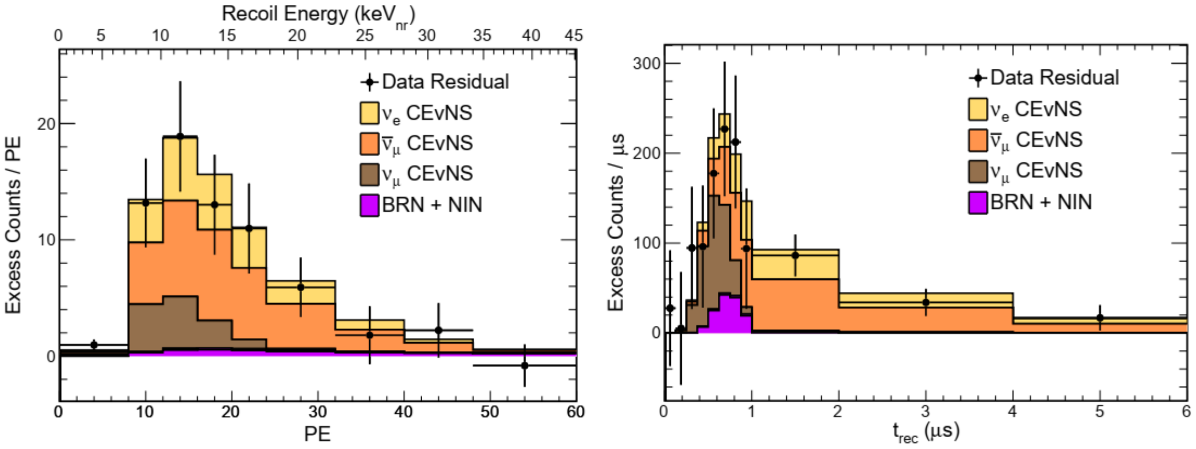
See S. Hedges's talk for details



COHERENT CsI

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

+ Updated in arXiv:2110.07730v1

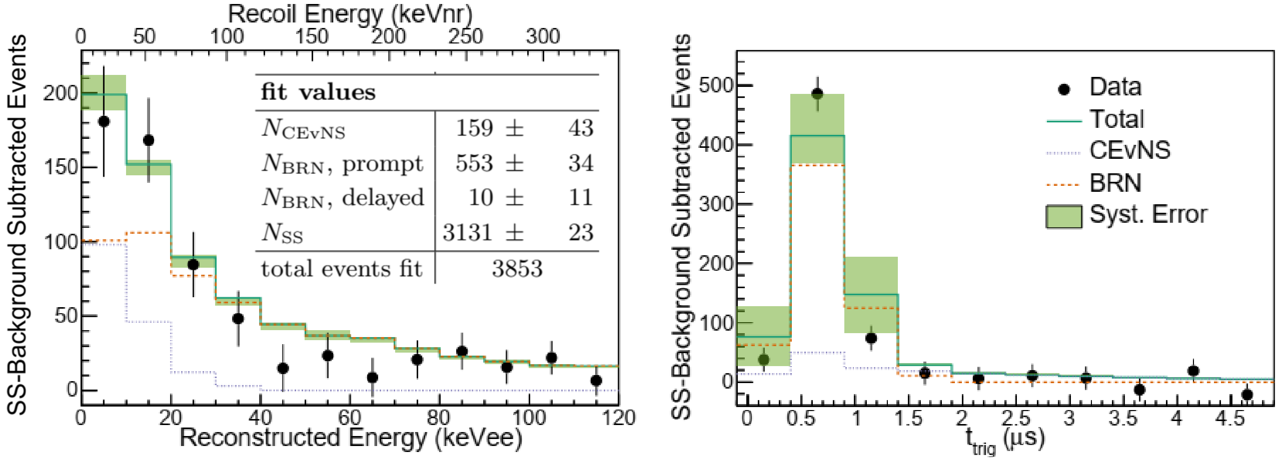


	Prior Prediction	Best-Fit Total
Steady-state background	1286 ± 27	1273 ± 24
BRN	18.4 ± 4.6	17.3 ± 4.5
NIN	5.6 ± 2.0	5.5 ± 2.0
CEvNS	–	306 ± 20

Table I. A summary of prior prediction and best-fit event rates and statistical uncertainties for CEvNS and each background type. The standard-model expectation for CEvNS is 341 ± 11 ± 42.

COHERENT Ar

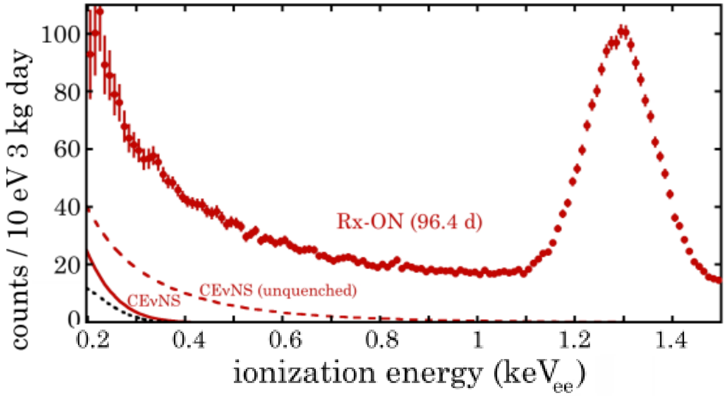
Akimov et al., COHERENT Coll. PRL 126, 01002 (2021)

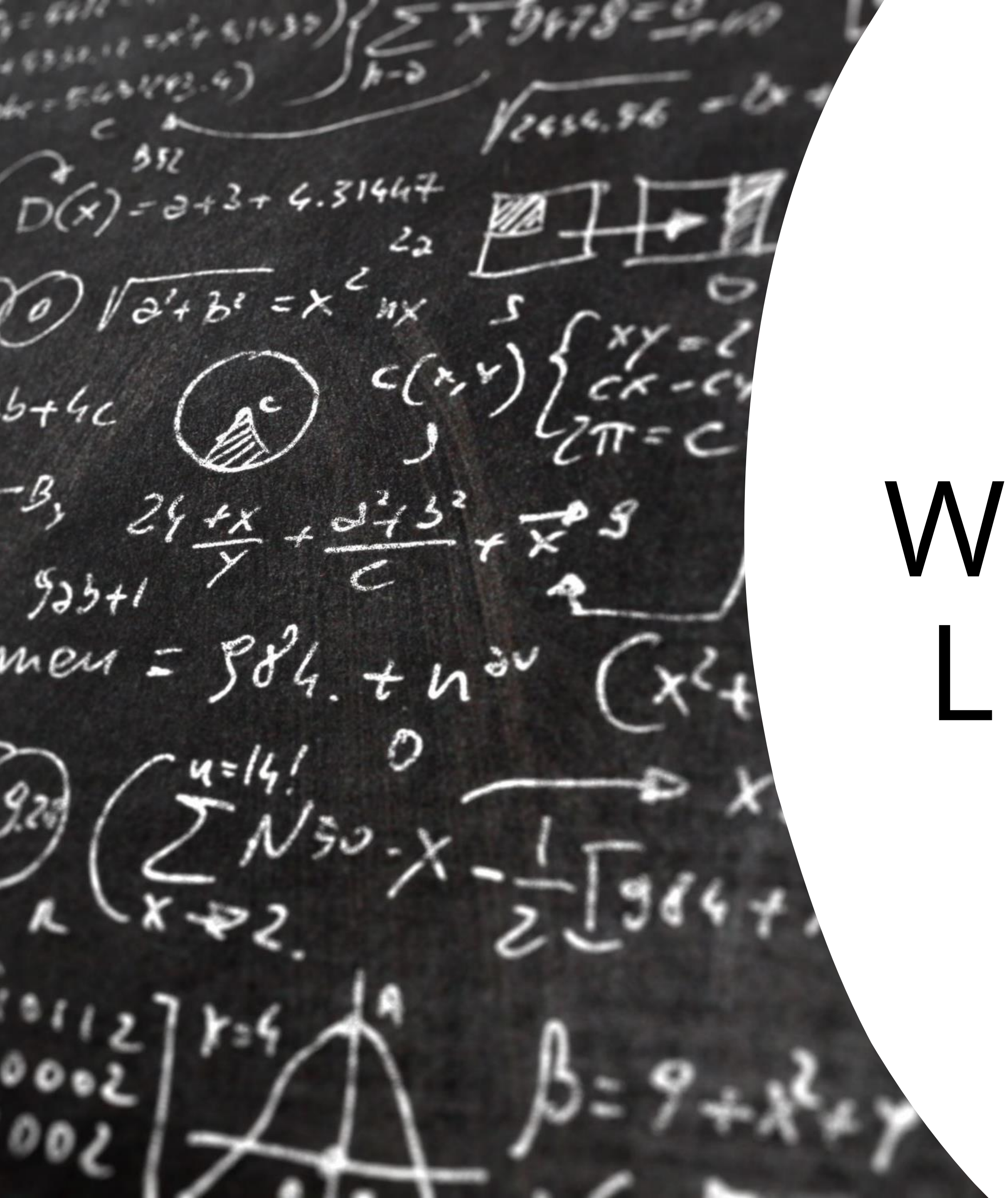


fit values		
N_{CEvNS}	159 ±	43
N_{BRN}, prompt	553 ±	34
N_{BRN}, delayed	10 ±	11
N_{SS}	3131 ±	23
total events fit	3853	

2022 New player: Dresden-II

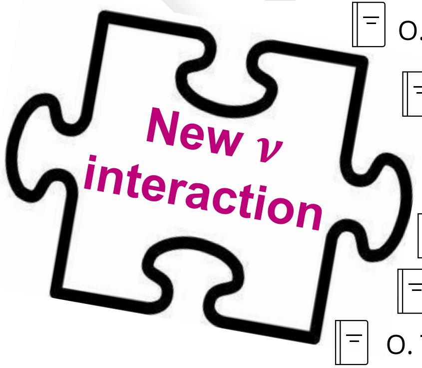
+ 3 kg ultra-low noise germanium detector.
A strong preference for the presence of CEνNS is found.





WHAT CAN WE LEARN FROM CEνNS?

What can we 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
- O. Tomalak et al. *JHEP* 02 (2021) 097, arXiv:2011.05960

- M. Cadeddu et al., PRD 102, 015030 (2020), arXiv:2005.01645
- O. G. Miranda et al., JHEP 05 (2020) 130, arXiv:2003.12050
- A. N. Khan et al., PRD 100 (2019) 11, 113003, arXiv:2003.12050
- O. G. Miranda et al., JHEP 07 (2019) 103, arXiv: 1905.03750
- J. Liao et al., arXiv: 2202.10622

SM vector proton coupling

Proton Form Factor: very well-known

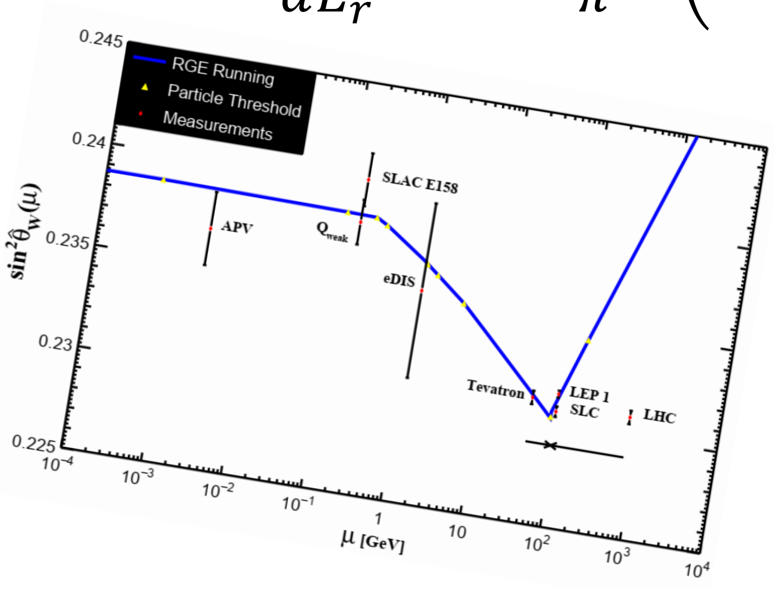
SM vector neutron coupling

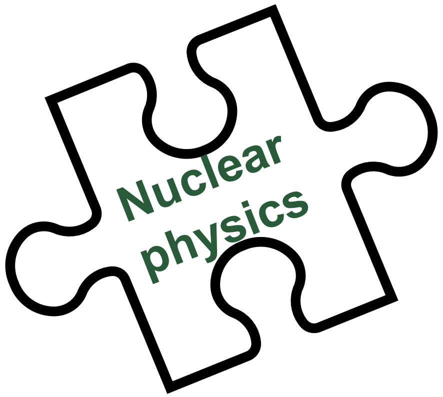
$$\frac{d\sigma(E_\nu,E_r)}{dE_r} \cong \frac{G_F^2 M}{\pi}\left(1-\frac{M E_r}{2E_\nu^2}\right)\left[g_V^p\left(\sin^2(\vartheta_W)\right) Z\, F_Z(|\vec{q}|^2) + g_V^n\, N\, F_N(|\vec{q}|^2)\right]^2 + \text{add. terms}$$

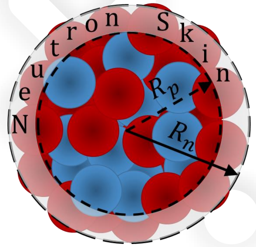
Weak mixing angle

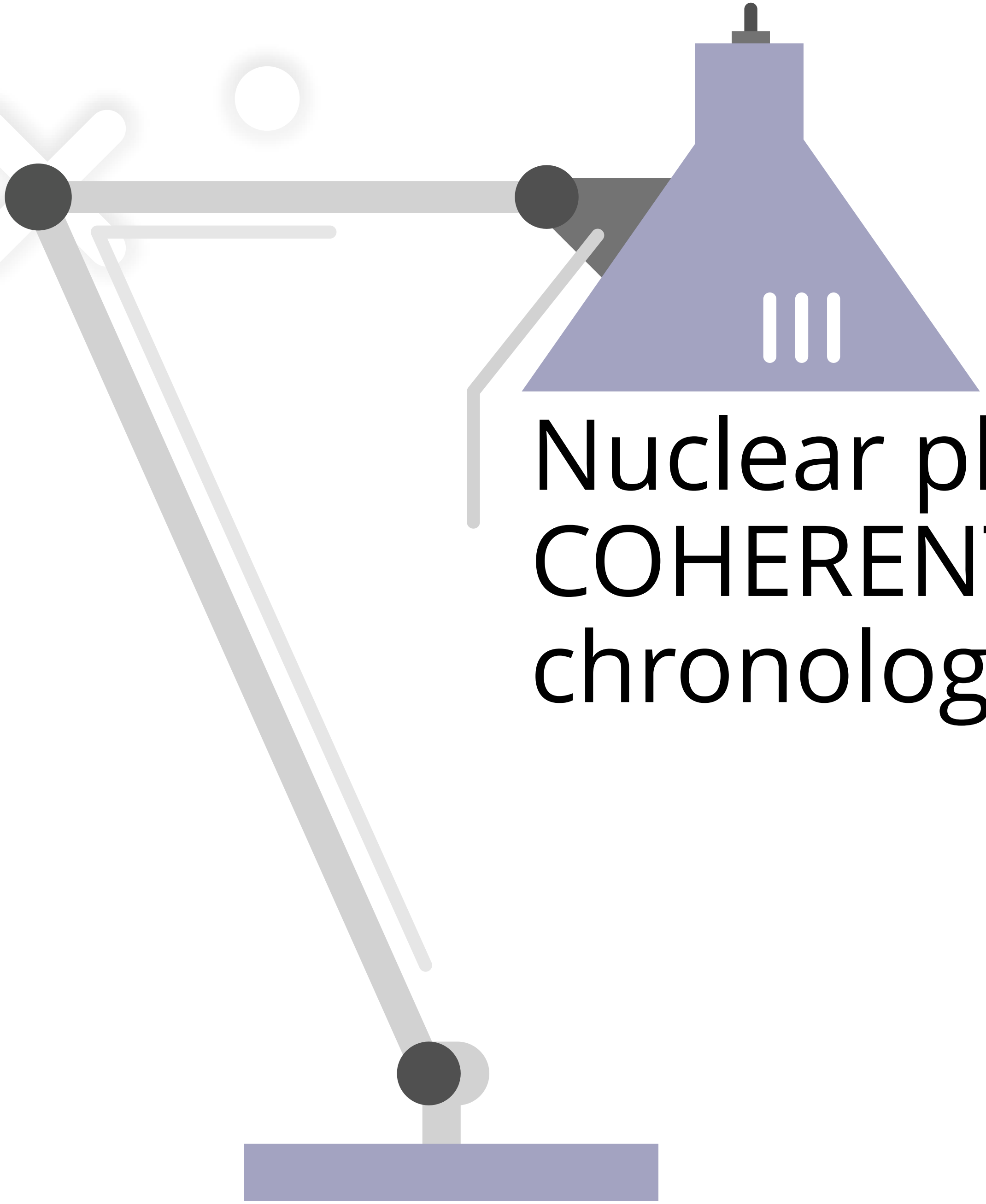
Neutron Form Factor

- N. Van Dessel et al., arXiv:2007.03658

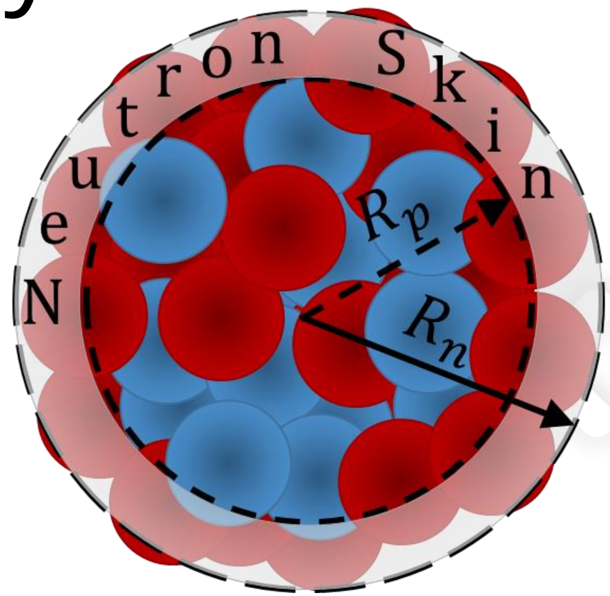








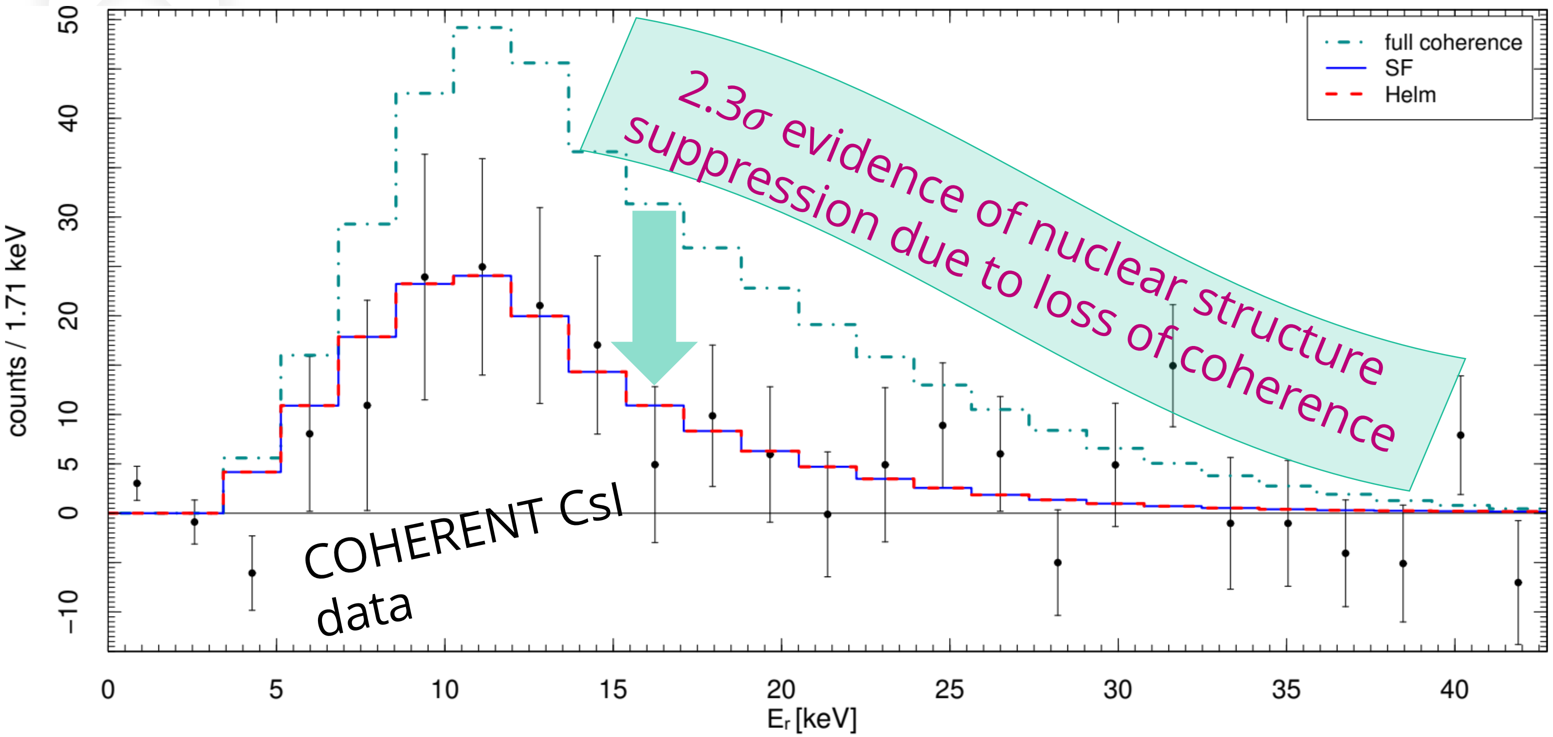
Nuclear physics with COHERENT(CsI) data… a chronological summary



First average CsI neutron radius measurements (2018)

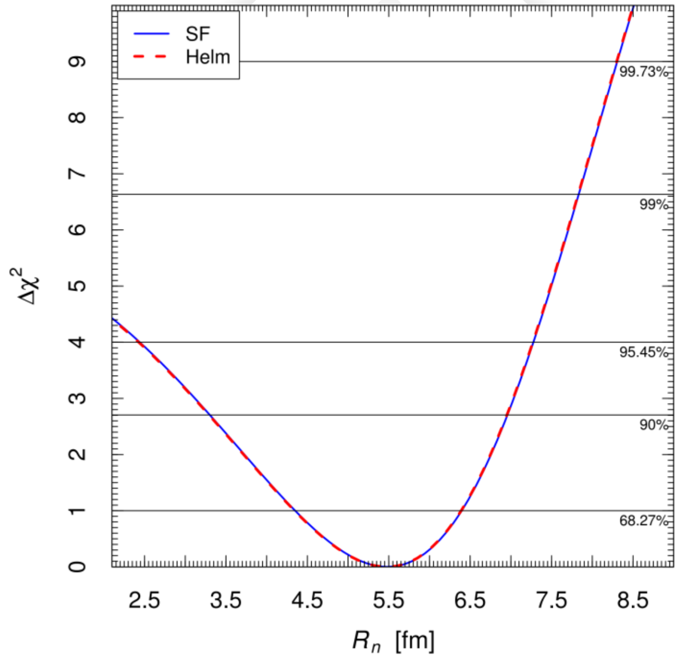
+ Using the first CsI dataset from D. Akimov et al. **Science** 357.6356 (2017)

M. Cadeddu, C. Giunti, Y.F. Li, Y.Y. Zhang, PRL 120 072501, (2018), arXiv:1710.02730



2.3σ evidence of nuclear structure suppression due to loss of coherence

COHERENT CsI data



- We first compared the data with the predictions in the case of full coherence, i.e. all nuclear form factors equal to unity: the corresponding histogram does not fit the data.
- We fitted the COHERENT data in order to get information on the value of the neutron rms radius R_n, which is determined by the minimization of the χ^2 using the symmetrized Fermi (t=2.3 fm) and Helm form factors (s=0.9 fm).

$$R_n^{CsI} = 5.5^{+0.9}_{-1.1}\ \text{fm}$$

✓ Only energy information used
x No energy resolution
x No time information
x Small dataset and big syst. uncer.

Improvements with the latest CsI dataset

+ New quenching factor

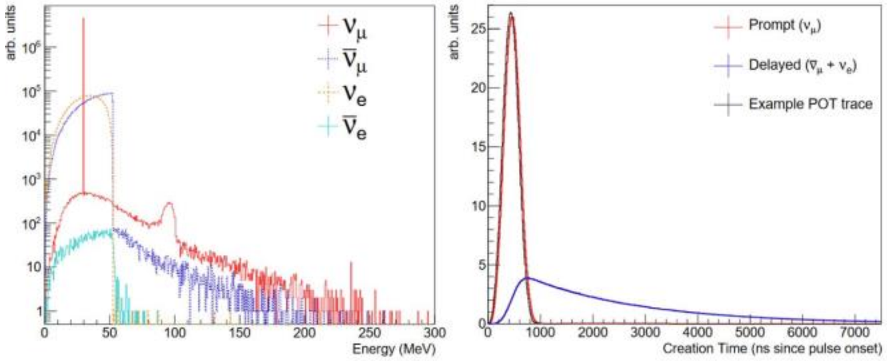
$$E_{ee} = f(E_{nr}) = aE_{nr} + bE_{nr}^2 + cE_{nr}^3 + dE_{nr}^4.$$

a=0.05546, b=4.307, c= -111.7, d=840.4

Akimov et al. (COHERENT Coll), arXiv:2111.02477

+ 2D fit, arrival time information included

$$N_{ij}^{\text{CE}\nu\text{NS}} = (N_i^{\text{CE}\nu\text{NS}})_{\nu_\mu} P_j^{(\nu_\mu)} + (N_i^{\text{CE}\nu\text{NS}})_{\nu_e,\bar{\nu}_\mu} P_j^{(\nu_e,\bar{\nu}_\mu)}$$



+ Doubled the statistics and reduced syst. uncertainties

$$\sigma_{\text{CE}\nu\text{NS}} = 13\%, \sigma_{\text{BRN}} = 0.9\%,$$
$$\text{and } \sigma_{\text{SS}} = 3\%$$

➢ Theoretical number of CEvNS events

$$N_i^{\text{CE}\nu\text{NS}} = N(\text{CsI}) \int_{T_{\text{nr}}^i}^{T_{\text{nr}}^{i+1}} dT_{\text{nr}}\, A(T_{\text{nr}}) \int_0^{T'^{\text{max}}_{\text{nr}}} dT'_{\text{nr}}\, R(T_{\text{nr}}, T'_{\text{nr}}) \int_{E_{\text{min}}(T'_{\text{nr}})}^{E_{\text{max}}} dE \times \sum_{\nu=\nu_e,\nu_\mu,\bar{\nu}_\mu} \frac{dN_\nu}{dE}(E) \frac{d\sigma_{\nu\text{-CsI}}}{dT'_{\text{nr}}}(E, T'_{\text{nr}}),$$

➢ With the inclusion of energy resolution

$$R(N_{\text{PE}}, N'_{\text{PE}}) = \frac{[a_R(1+b_R)]^{1+b_R}}{\Gamma(1+b_R)} N_{\text{PE}}^{b_R}\, e^{-a_R(1+b_R)N_{\text{PE}}}$$

✓ Analysis with a Gaussian least-square function

$$\chi^2_{\text{C}} = \sum_{i=2}^{9} \sum_{j=1}^{11} \left(\frac{N_{ij}^{\text{exp}} - \sum_{z=1}^{3} (1+\eta_z) N_{ij}^z}{\sigma_{ij}} \right)^2 + \sum_{z=1}^{3} \left(\frac{\eta_z}{\sigma_z} \right)^2,$$

Cadeddu et al., PRC 104, 065502, arXiv:2102.06153

Analysis updated in this talk using a Poissonian least-square function after the COHERENT data release!

The CsI neutron skin (updated in 2022)

$R_n^{CsI} = 5.4 \pm 0.4$ fm

~7% precision

Average proton rms radius for CsI

$R_p^{CsI} \approx 4.78$ fm

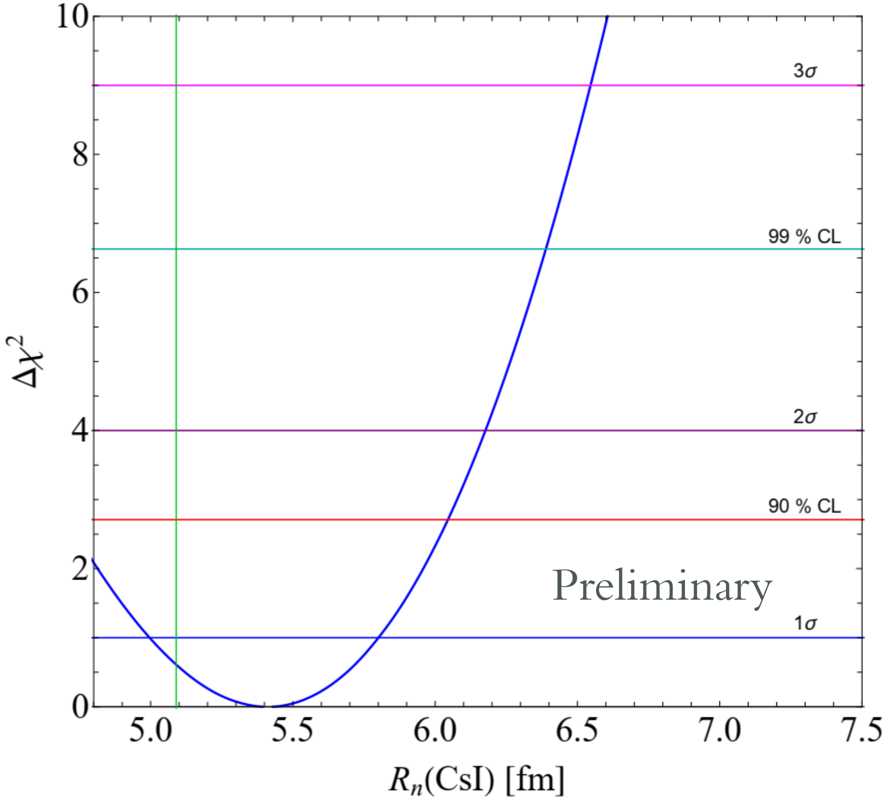
G. Fricke et al., At. Data Nucl. Data Tables **60**, 177 (1995).

$\Delta R_{np}^{CsI} \equiv R_n^{CsI} - R_p^{CsI} =$
0.6 ± 0.4 fm

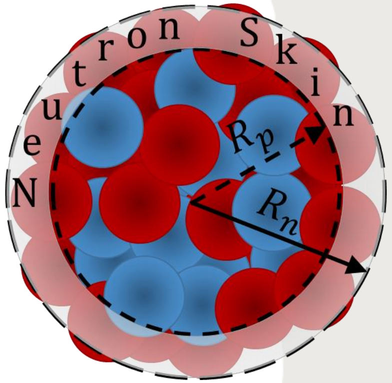
Cadeddu et al., PRC 104, 065502 arXiv:2102.06153
Updated in this talk!

Cadeddu et al., PRD 101, 033004 (2020), arXiv:1908.06045

Half of the uncertainty with respect to the previous analysis



To obtain this value we fix the weak mixing angle to the SM value, can we do more?

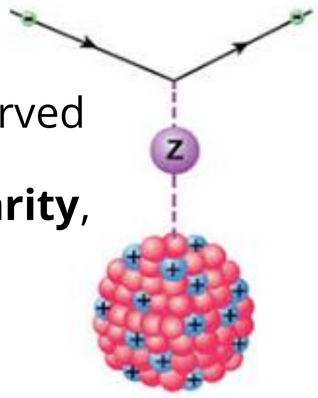


Use another electroweak process that measures the weak charge of Cs in order to break this degeneracy

Atomic Parity Violation in cesium APV(Cs)

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

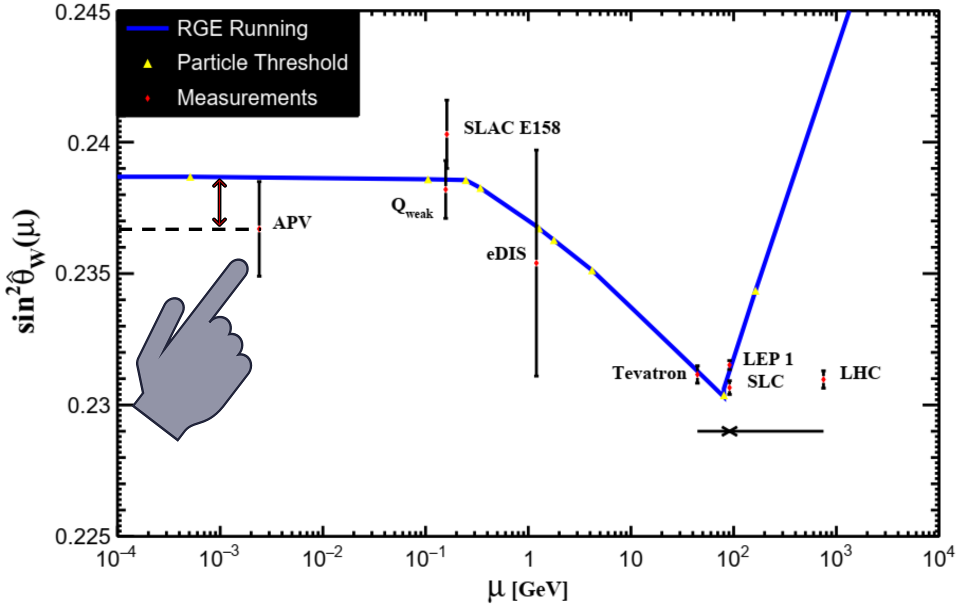
- Parity violation in an atomic system can be observed as an **electric dipole transition amplitude between two atomic states with the same parity**, such as the $6S$ and $7S$ states in cesium.

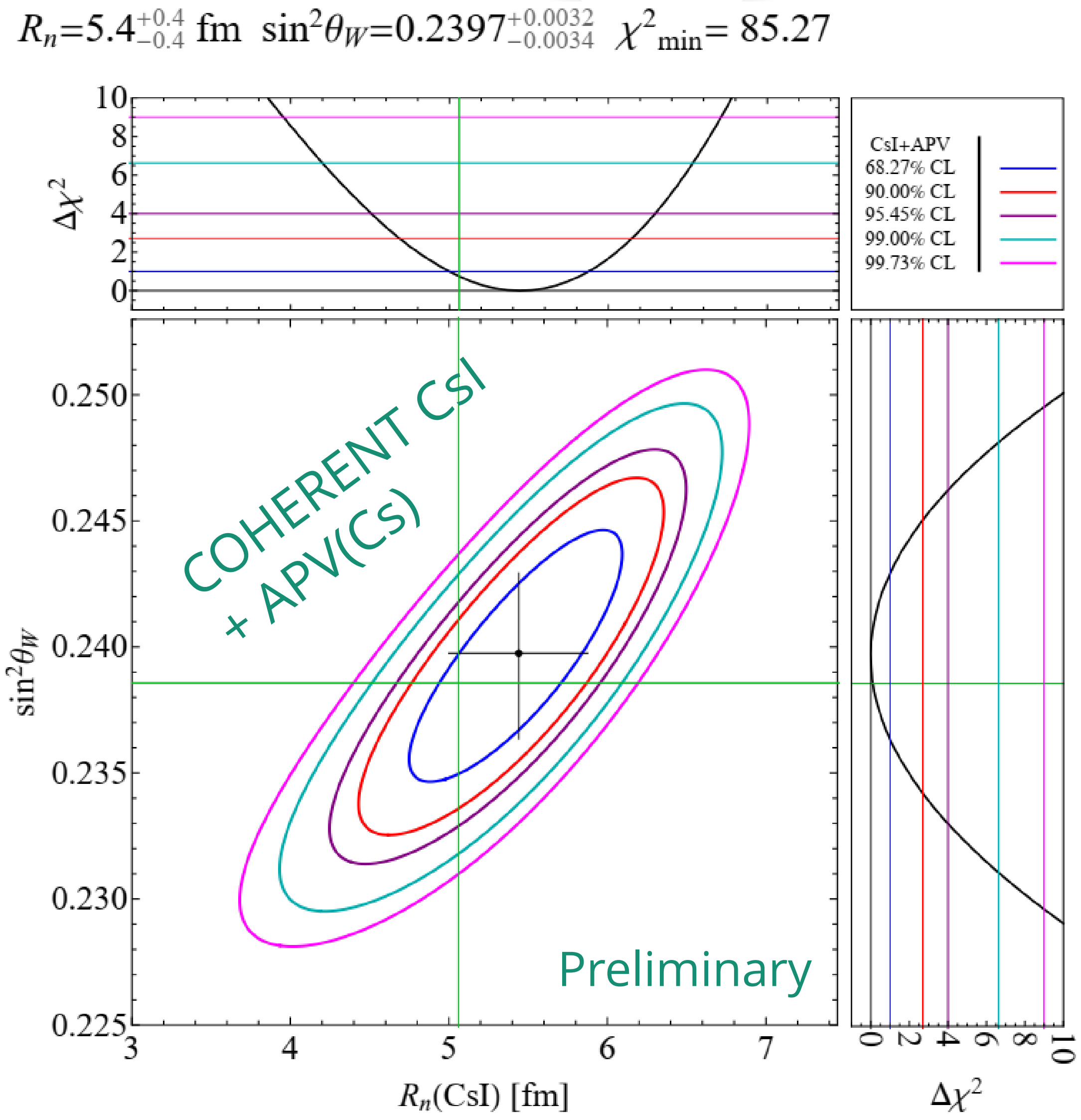


$$Q_W^{SM} \approx Z\left(1 - 4\sin^2\theta_W^{SM}\right) - N$$

Historically APV(Cs) has been used to derive the lowest determination of $\sin^2\theta_W$ **but fixing R_n^{Cs} to theoretical nuclear models**

P.A. Zyla et al. (PDG 2021)





COHERENT CsI + APV(Cs)

Preliminary

Cadeddu et al., PRC 104, 065502 arXiv:2102.06153 Updated in this talk!

Dresden-II result

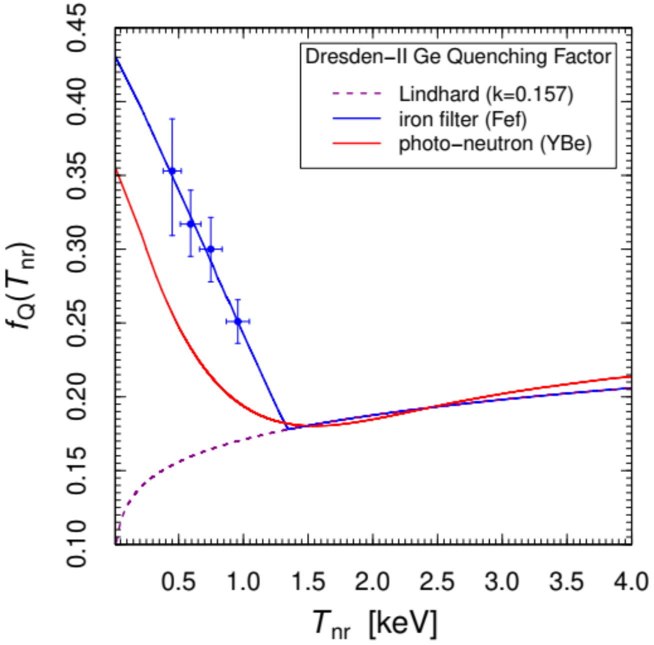
- 3 kg ultra-low noise germanium detector 10 m away from a reactor
- the background comes from the elastic scattering of epithermal neutrons and the electron capture in ^{71}Ge.
- The Quenching Factor describes the suppression of the ionization yield produced by a nuclear recoil compared to an electron recoil.

Electron-equivalent energy:

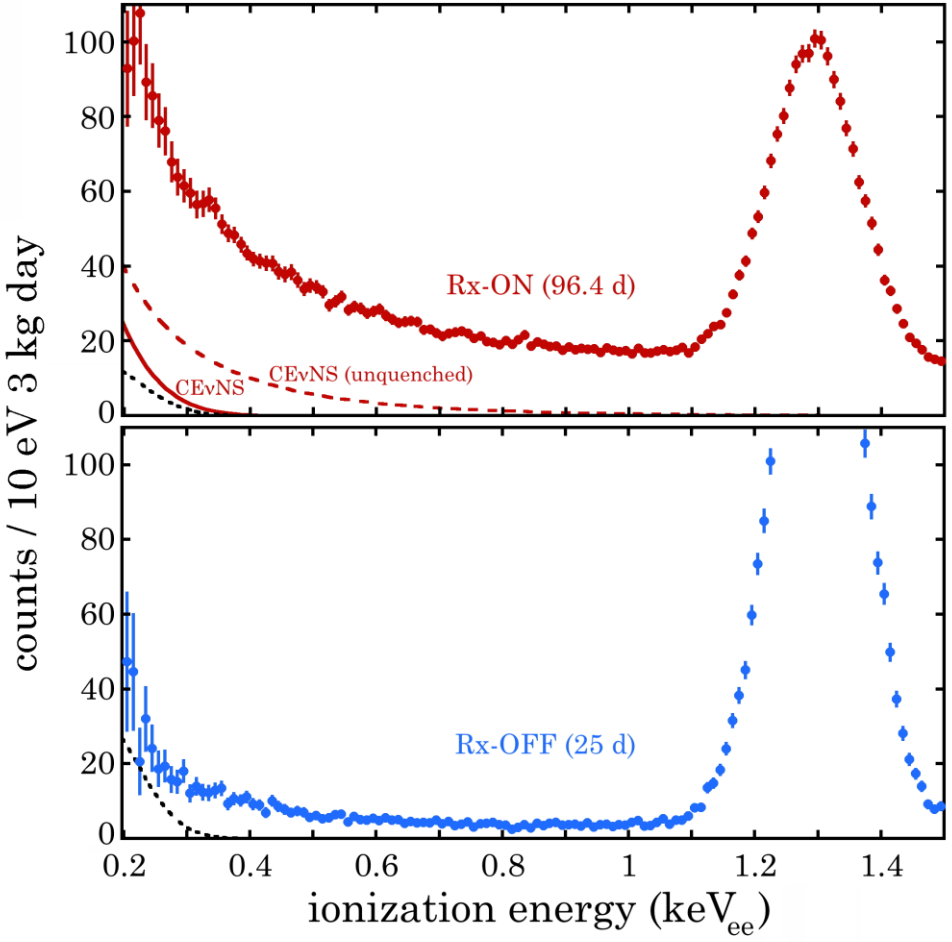
$$T_e = f_Q(T_{nr})\, T_{nr}$$

➢ Dresden-II Ge quenching factor models

- Fef: iron filtered neutron beam
- YBe: photo-neutron source



Colaresi et al. arXiv:2202.09672v1



- Ultra-low energy threshold

$$\boxed{0.2 < T_e < 1.5\ \text{keV}_{ee}}$$

➢ This feature makes reactor neutrinos very sensitive to possible ν electromagnetic properties (millicharge, magnetic moment) since the related cross section goes like 1/T

Neutrino electromagnetic properties

For ν the electric charge is zero and there are no electromagnetic interactions at tree level. However, such interactions can arise at the quantum level from loop diagrams at higher order of the perturbative expansion of the interaction.

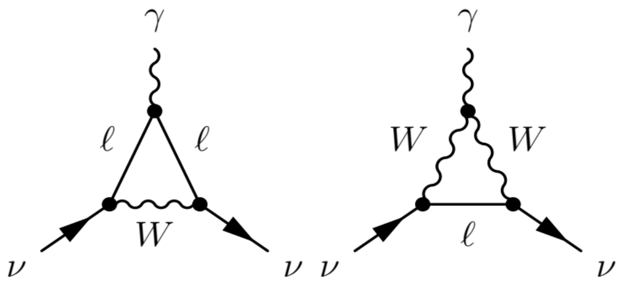
- In the SM the ν charge radius is

$$\langle r^2_{\nu_\ell}\rangle_{SM} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m_\ell^2}{m_W^2}\right)\right]$$

$$\langle r^2_{\nu_e}\rangle_{SM} = -8.2\times10^{-33}\ \mathrm{cm}^2$$

$$\left\langle r^2_{\nu_\mu}\right\rangle_{SM} = -4.8\times10^{-33}\ \mathrm{cm}^2$$

$$\langle r^2_{\nu_\tau}\rangle_{SM} = -3.0\times10^{-33}\ \mathrm{cm}^2$$



- The charge radius contributes as a correction to the neutrino-proton coupling

- In the minimally extended SM the ν magnetic moment

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

- In CEνNS $$\frac{d\sigma_{\nu_\alpha\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E_\nu^2}\right)\left[g_V^n N F_N(|\vec{q}|) + g_V^p Z F_Z(|\vec{q}|)\right]^2 + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)Z^2F_Z^2(|\vec{q}|)\frac{\mu_{\nu_\alpha}^2}{\mu_B^2}$$

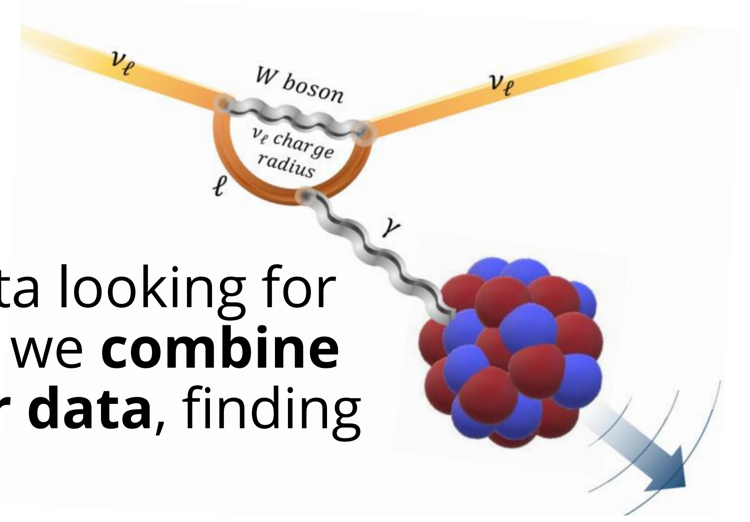
- Neutrino-electron scattering in the SM is negligible

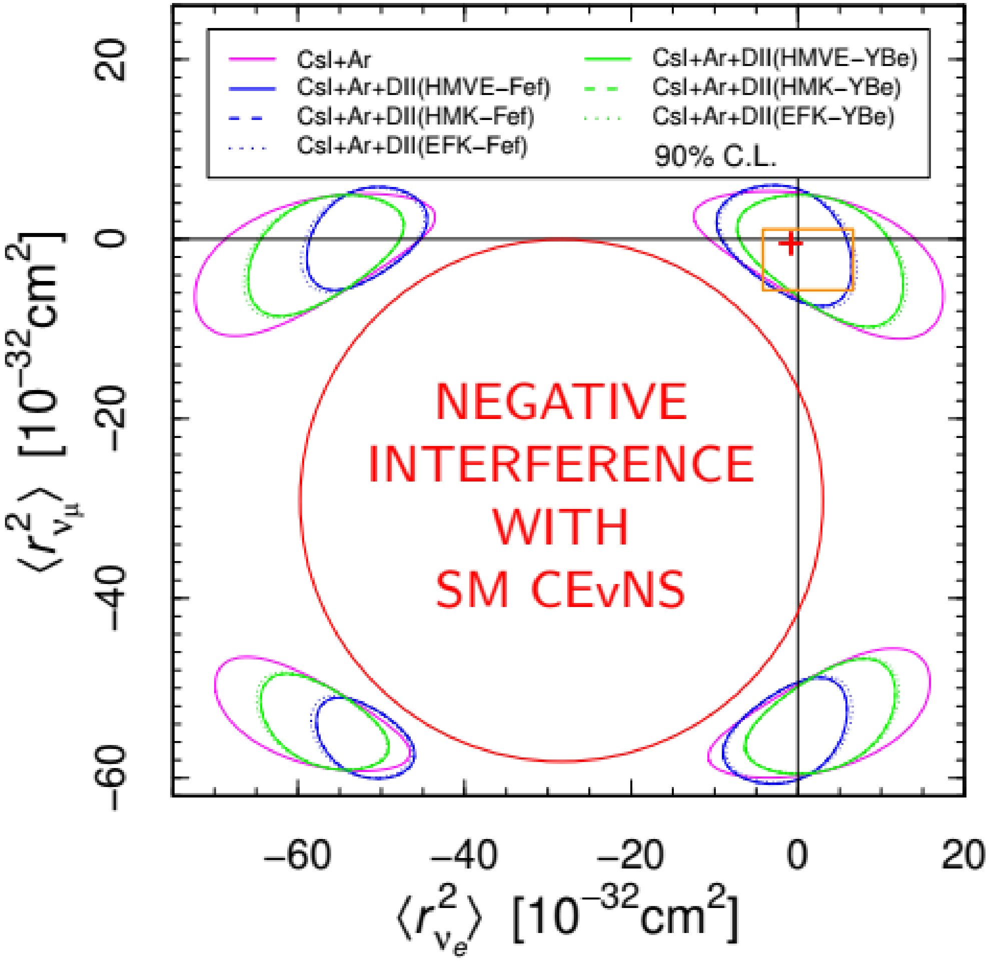
$$\frac{d\sigma^{\mathrm{ES}}_{\nu_\alpha-\mathcal{A}}}{dT_e}(E, T_e) = Z_{\mathrm{eff}}^{\mathcal{A}}(T_e)\frac{G_F^2 m_e}{2\pi}\left[(g_V^{\nu_\alpha}+g_A^{\nu_\alpha})^2 + (g_V^{\nu_\alpha}-g_A^{\nu_\alpha})^2\left(1-\frac{T_e}{E}\right)^2 - ((g_V^{\nu_\alpha})^2-(g_A^{\nu_\alpha})^2)\frac{m_e T_e}{E^2}\right]$$

- ► Significant neutrino magnetic moment contribution for small T_e:

$$\frac{d\sigma^{\mathrm{ES,\ MM}}_{\nu_\alpha\text{-}\mathcal{A}}}{dT_e}(E, T_e) = Z_{\mathrm{eff}}^{\mathcal{A}}(T_e)\frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E}\right)\left|\frac{\mu_{\nu_\alpha}}{\mu_B}\right|^2$$

Neutrino charge radius limits





+ We fitted the **Dresden-II** data looking for neutrino EM properties and we **combine with COHERENT CsI and Ar data**, finding very interesting results.

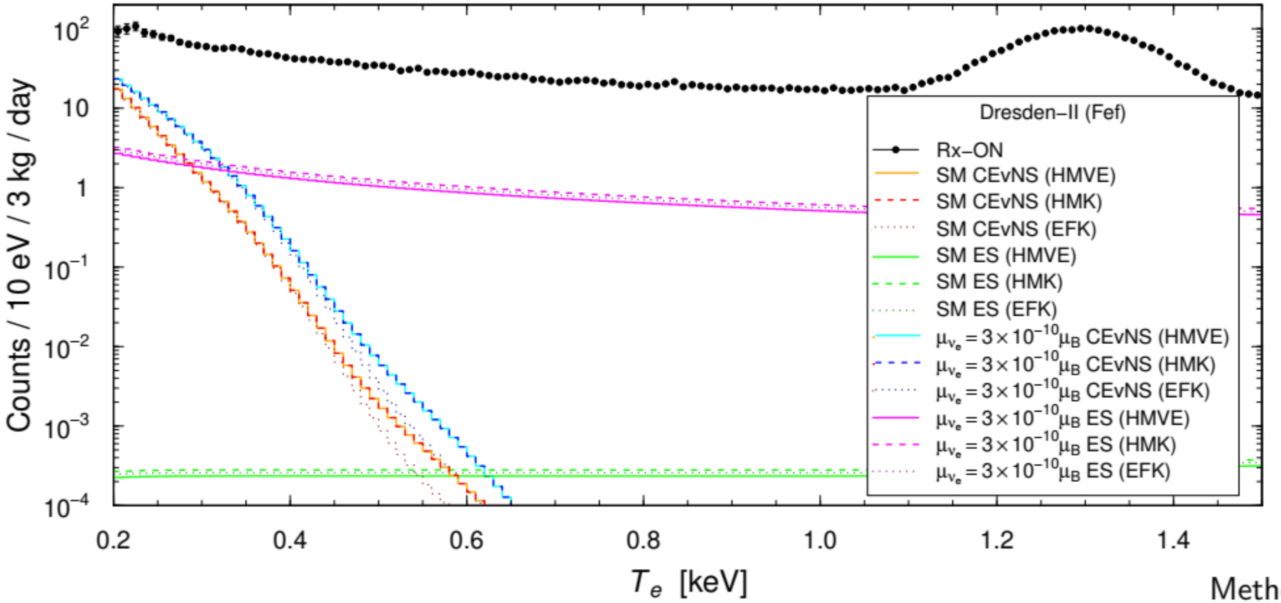
Method	Experiment	Limit $[10^{-32}\ \text{cm}^2]$	C.L.	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3$	90%	1992
	TEXONO	$-4.2 < \langle r^2_{\nu_e}\rangle < 6.6^a$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 < \langle r^2_{\nu_e}\rangle < 10.88^a$	90%	1992
	LSND	$-5.94 < \langle r^2_{\nu_e}\rangle < 8.28^a$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 < \langle r^2_{\nu_\mu}\rangle < 1.1^{a,b}$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2^a$	90%	1994
CEvNS [arXiv:2205.09484]	COHERENT + Dresden-II	$-7.1 < \langle r^2_{\nu_e}\rangle < 11.2$ $-8.1 < \langle r^2_{\nu_\mu}\rangle < 4.3$	90%	2022

[a] Corrected by a factor of two due to a different convention.
[b] Corrected in Hirsch, Nardi, Restrepo, hep-ph/0210137.

M. Atzori Corona et al, arXiv:2205.09484

Most stringent upper limit on the electron neutrino charge radius when using the Fef quenching factor for germanium data

Neutrino magnetic moment limits



- SM ES are practically negligible
- The ES with magnetic moment are not negligible.
- Moreover ES is sensitive to the low energy antineutrino reactor flux:

▶ **HMVE**: Huber-Mueller (2011)
+ Vogel-Engel (1989) ($E_\nu < 2$ MeV)
▶ **HMK**: Huber-Mueller
+ Kopeikin (2012) ($E_\nu < 2$ MeV)
▶ **EFK**: Estienne-Fallot (2019)
+ Kopeikin (2012) ($E_\nu < 0.44$ MeV)

Limits on ν magnetic moment @ 90% CL

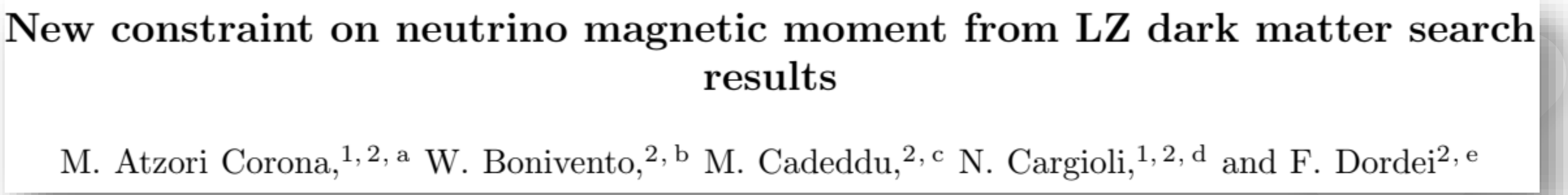
$$
\begin{aligned}
|\mu_{\nu_e}| &< 2.13 \times 10^{-10}\,\mu_B \quad \mathrm{Dresden-II}\,(\mathrm{CE}\nu\mathrm{NS}+\mathrm{ES}),\\
|\mu_{\nu_\mu}| &< 18 \times 10^{-10}\,\mu_B \quad \mathrm{CsI}\,(\mathrm{CE}\nu\mathrm{NS}+\mathrm{ES})+\mathrm{Ar}\,(\mathrm{CE}\nu\mathrm{NS}),
\end{aligned}
$$

Using the Fef quenching factor for germanium data

M. Atzori Corona et al, arXiv:2205.09484

These limits are still less stringent than the bounds obtained in other reactor and accelerator neutrino experiments, but the strategy looks promising.

Method	Experiment	Limit [μ_B]	CL	Year
Reactor ES ($\bar{\nu}_e\, e^-$)	Krasnoyarsk	$\lvert\mu_{\nu_e}\rvert < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\lvert\mu_{\nu_e}\rvert < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\lvert\mu_{\nu_e}\rvert < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\lvert\mu_{\nu_e}\rvert < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\lvert\mu_{\nu_e}\rvert < 2.9 \times 10^{-11}$	90%	2012
Reactor CEvNS+ES	Dresden-II [Coloma et al, arXiv:2202.10829] [Atzori Corona et al, arXiv:2205.09484]	$\lvert\mu_{\nu_e}\rvert < 3.3 \times 10^{-10}$	90%	2022
Accelerator ES ($\nu_\mu\, e^-$)	BNL-E734	$\lvert\mu_{\nu_\mu}\rvert < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\lvert\mu_{\nu_\mu}\rvert < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\lvert\mu_{\nu_\mu}\rvert < 6.8 \times 10^{-10}$	90%	2001
Accelerator CEvNS+ES	COHERENT [Coloma et al, arXiv:2202.10829] [Atzori Corona et al, arXiv:2205.09484]	$\lvert\mu_{\nu_\mu}\rvert < 2 \times 10^{-9}$	90%	2022

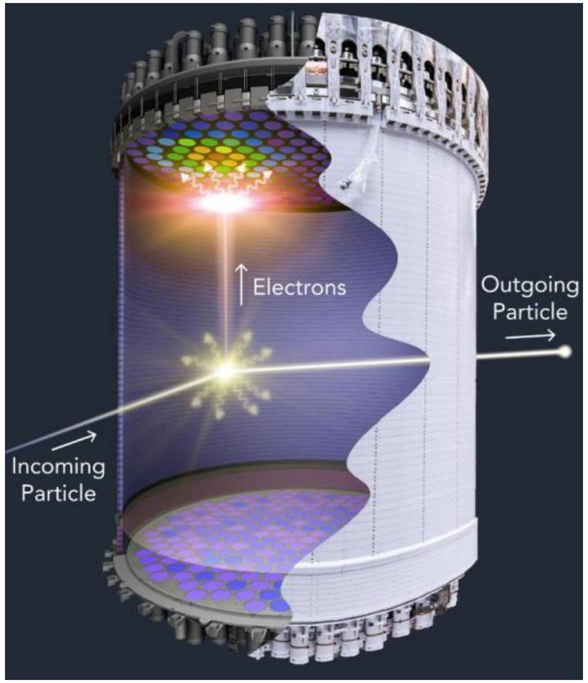


New constraint on neutrino magnetic moment from LZ dark matter search results

M. Atzori Corona,[1,2,a] W. Bonivento,[2,b] M. Cadeddu,[2,c] N. Cargioli,[1,2,d] and F. Dordei[2,e]

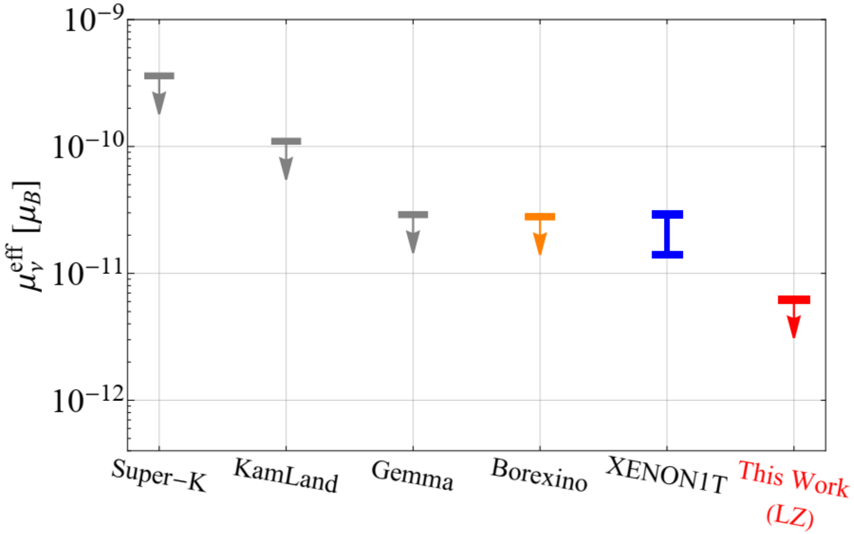
J. Aalbers et al., First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment (2022), arXiv:2207.03764

- LZ @the Sanford Underground Research Facility in South Dakota.
- Dual-phase TPC filled with about 10 t of LXe, of which 7 (5.5) t of the active (fiducial) region.

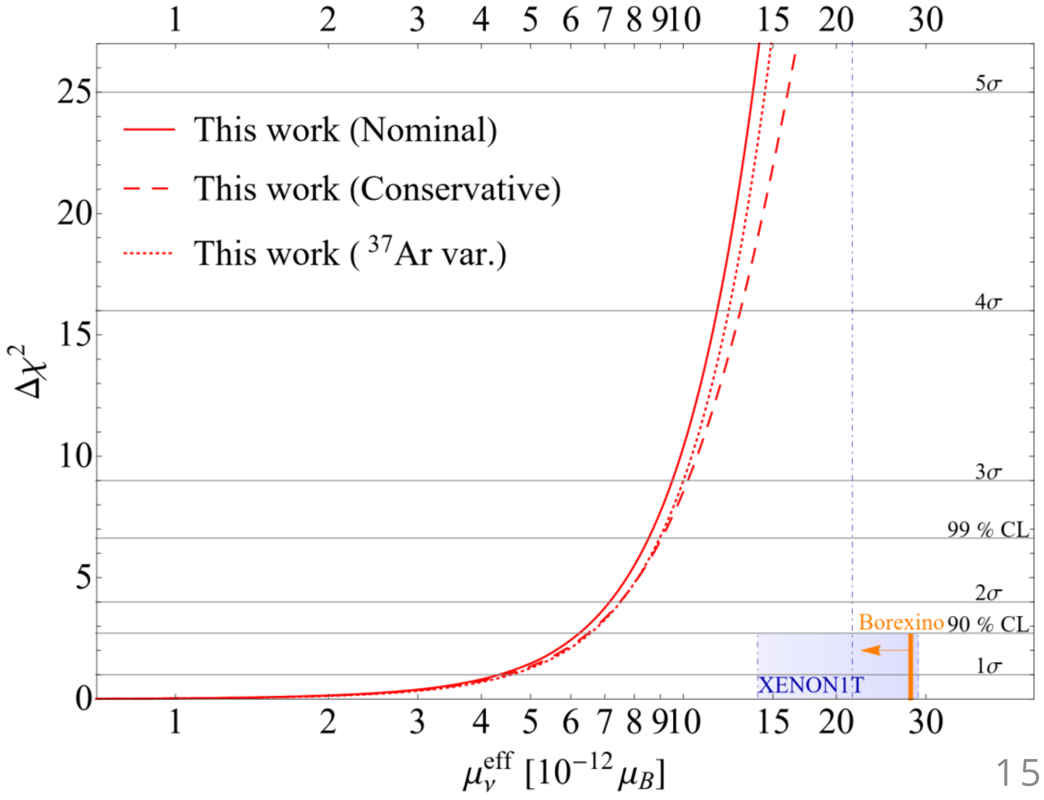


- The new LZ data allows us to set the **most stringent limit on the ν magnetic moment**
- It supersedes the previous best limit set by Borexino by almost a factor of 5
- It rejects by more than 5σ the hint of a possible ν magnetic moment found by the XENON1T Collaboration

M. Atzori Corona et al. arXiv:2207.05036v2 (2022)

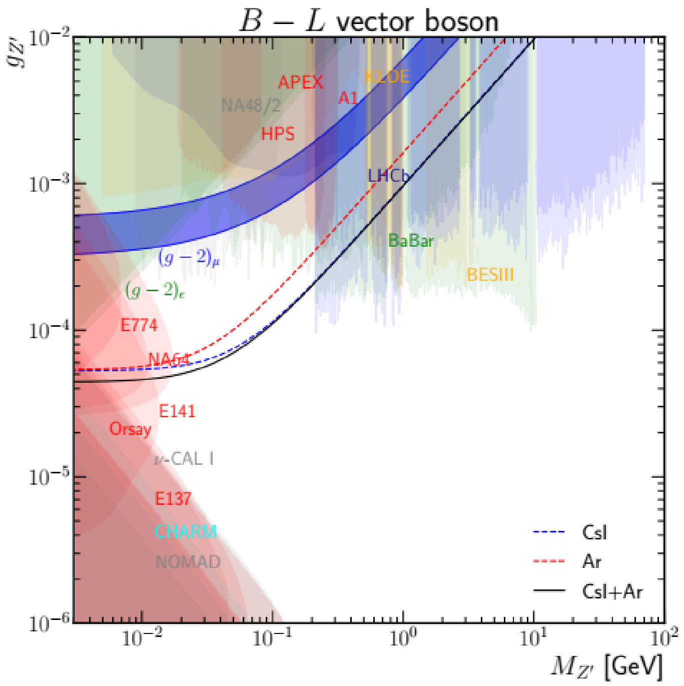


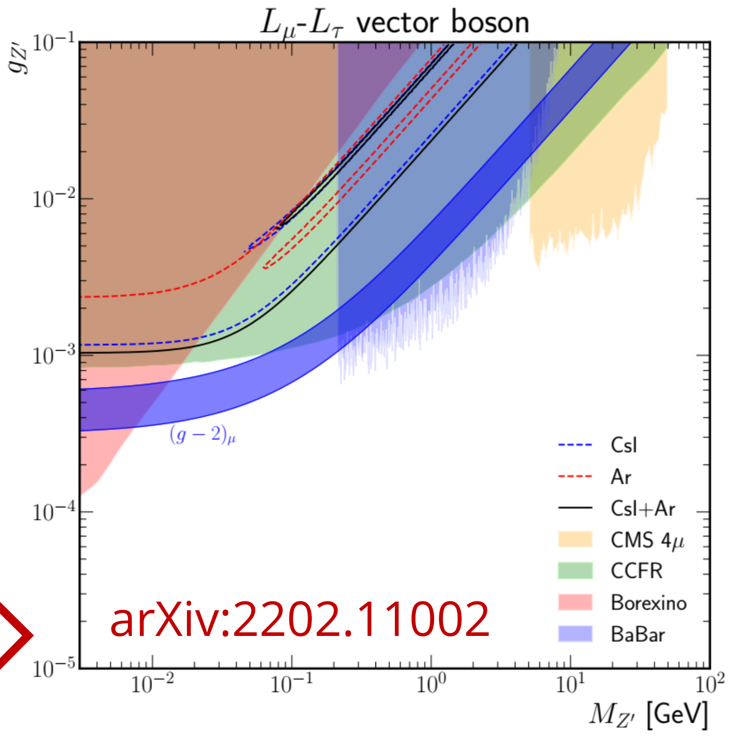
$\mu_\nu^{\rm eff} < 6.2 \times 10^{-12} \mu_B$ @ 90% CL $\quad \chi^2_{\rm min} = 106.2$

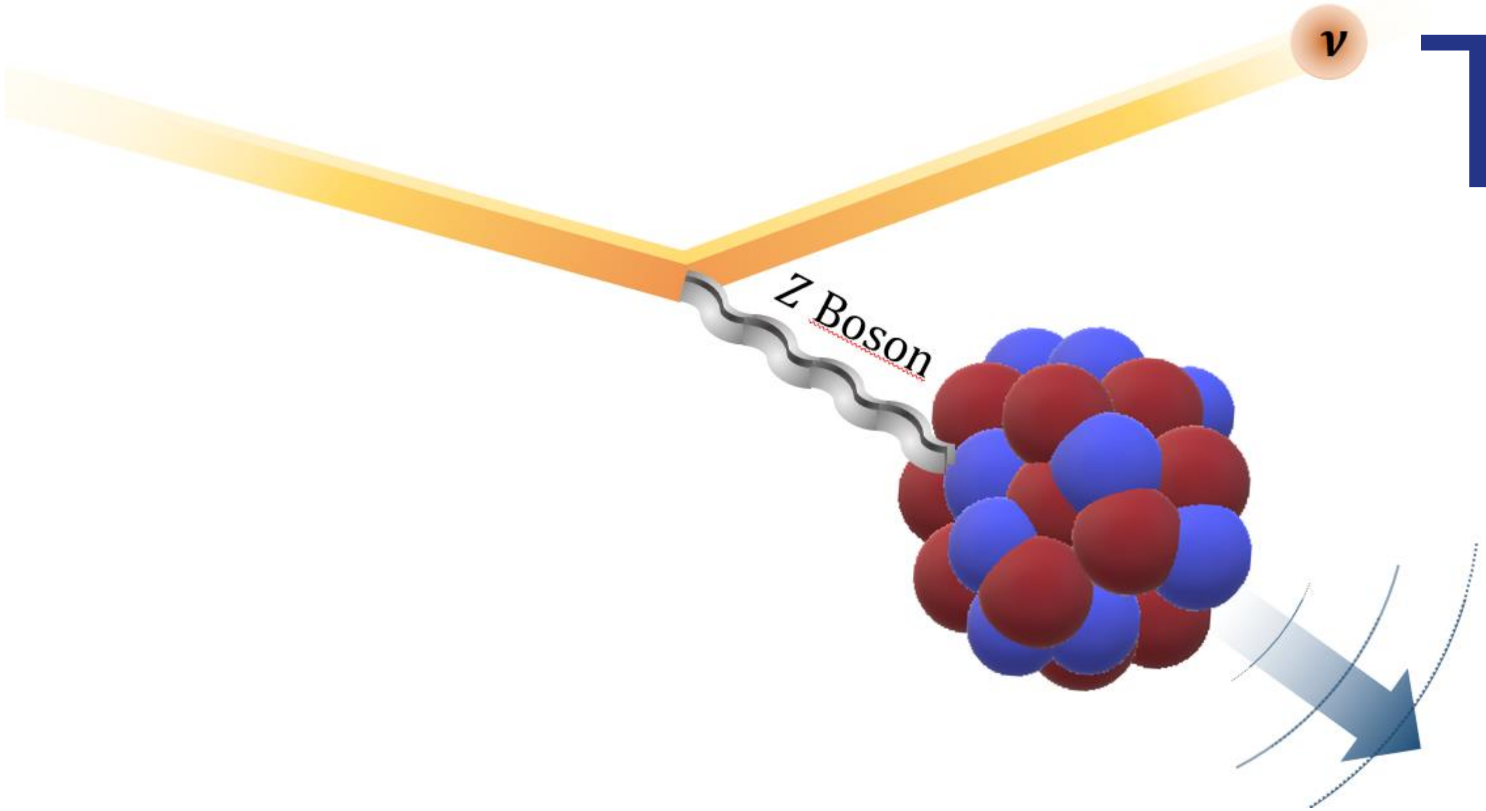


Conclusions

- CEνNS is a powerful tool for measuring the neutron form factor and in turn the neutron radius, even if not explicitly designed for this purpose.
- The weak-mixing angle-neutron radius degeneracy is always present in weak processes on nuclei.
- To break this degeneracy one can combine different EW measurements like APV(Cs): Complementarity is the key!
- CEνNS and ES data are very useful to constraint possible neutrino electromagnetic properties.
- CEνNS also great in exploring light mediator models (take a look at M. Atzori Corona et al. arXiv:2202.11002)







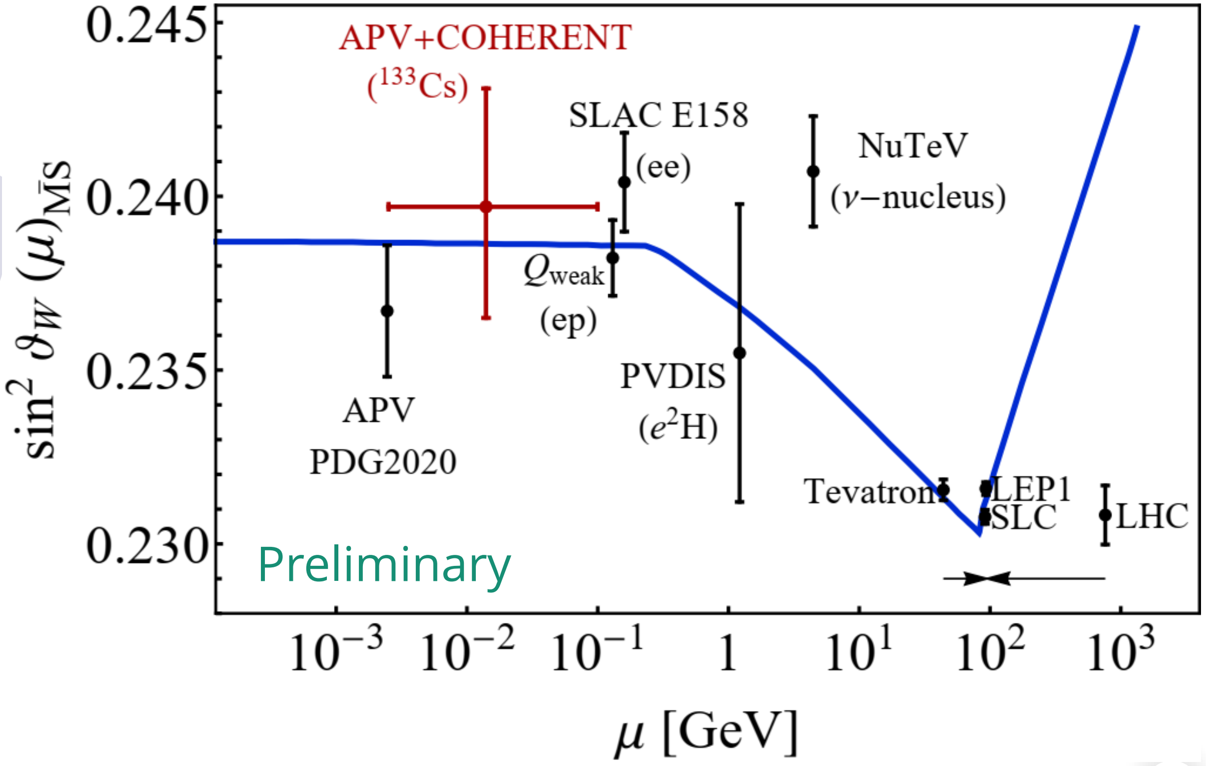
Thanks for your attention

BACKUP

Advantage: extract both R_n and $\sin^2\theta_W$ from data

We keep almost the same uncertainty as the original APV(Cs) for $\sin^2\theta_W$ but not assuming a neutron skin value for Cs which instead is driven by CEνNS

No assumptions on ΔR_{np}^{Cs} are made. The skin is taken directly from CEνNS experimental data



Cadeddu et al., PRC 104, 065502
arXiv:2102.06153 Updated in this talk!

Heavy vs light NSI

$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_{\rm F} \sum_{\alpha,\beta=e,\mu,\tau} (\overline{\nu_{\alpha L}}\gamma^{\rho} \nu_{\beta L}) \sum_{f=u,d} \varepsilon_{\alpha\beta}^{fV}(\bar{f} \gamma_{\rho} f)$$

$$\frac{d\sigma_{\nu_\alpha\text{-}\mathcal{N}}}{dT}(E,T) = \frac{G_{\rm F}^2 M}{\pi}\left(1-\frac{MT}{2E^2}\right)Q_\alpha^2,$$

$$Q_\alpha^2 = [(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV})ZF_Z(|\vec{q}|^2) + (g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})NF_N(|\vec{q}|^2)]^2 + \sum_{\beta\neq\alpha}|(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV})ZF_Z(|\vec{q}|^2) + (\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})NF_N(|\vec{q}|^2)|^2,$$

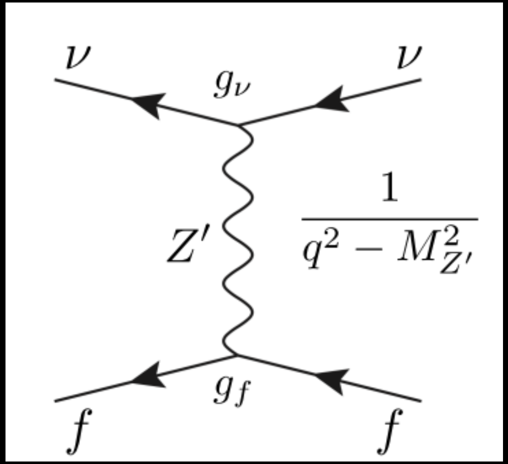
«Heavy» mediator

$$q^2 \ll M_{Z'}$$

Effective four fermion interaction Lagrangian. The parameters ε describe the size of NSI relative to standard neutral-current weak interactions.

«Above ~ 1 GeV»

$$\epsilon_{\ell\ell}^{fV} = \frac{g_{Z'}^2\, Q'_\ell Q'_f}{\sqrt{2}G_F\,(|\vec{q}|^2 + M_{Z'}^2)}$$

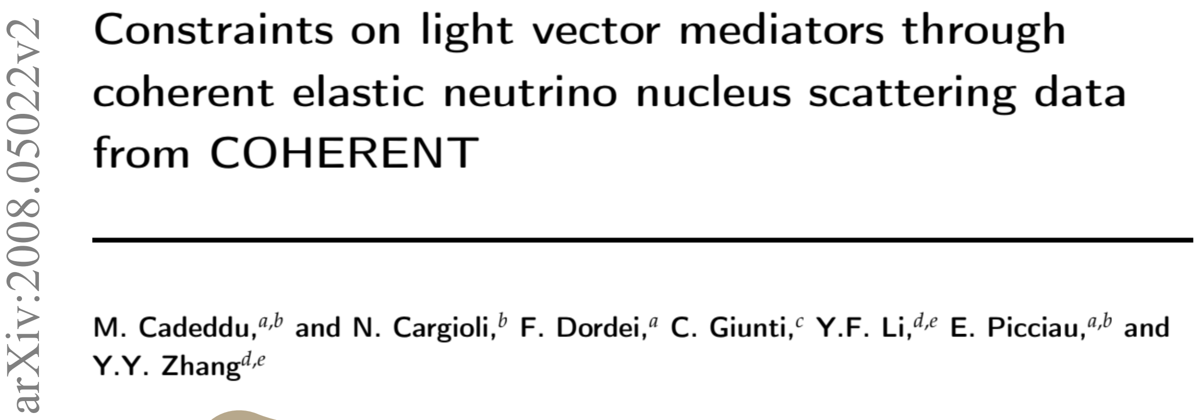


«Light» mediator

$$q^2 \gg M_{Z'}$$

One can assume the existence of U'(1) with an additional vector Z' or a scalar ϕ. One has also an explicit dependence on momentum transfer and Q charges.

«Above ~10 MeV»



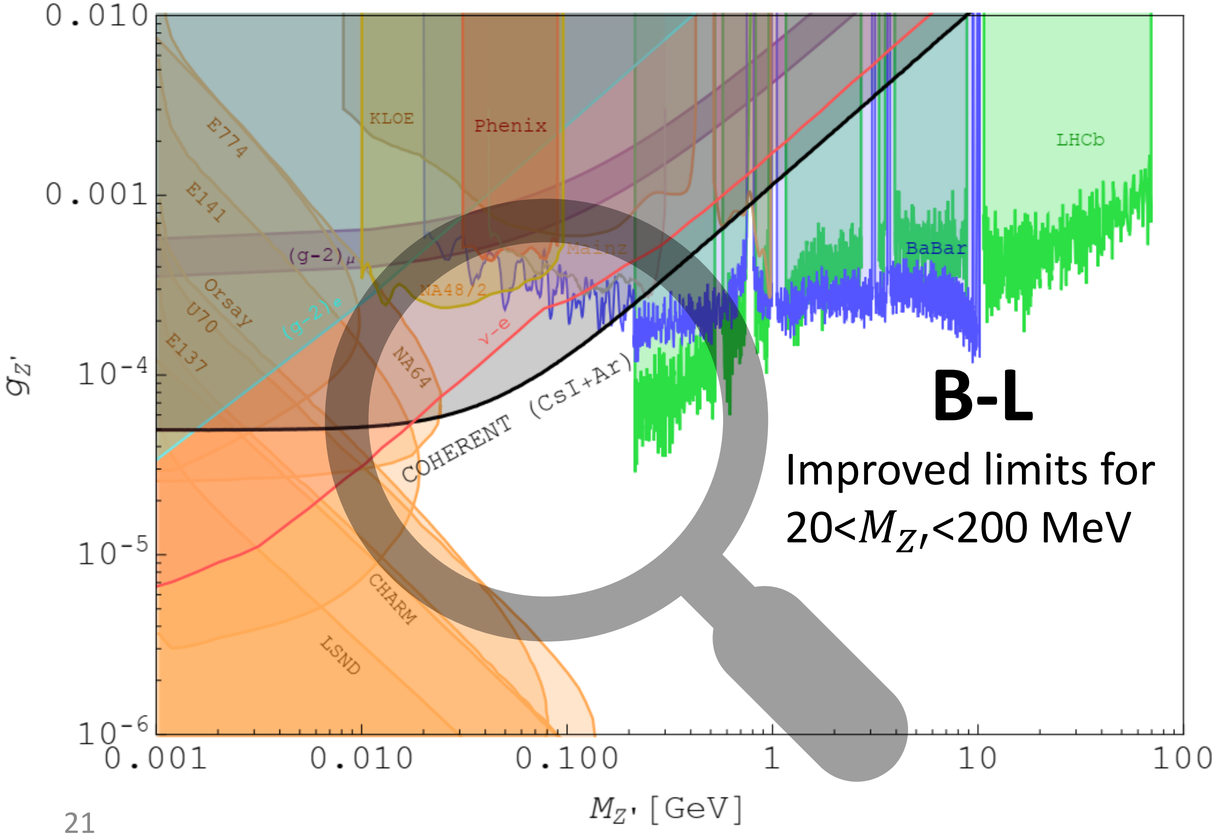
arXiv:2008.05022v2

Constraints on light vector mediators through coherent elastic neutrino nucleus scattering data from COHERENT

M. Cadeddu,[a,b] and N. Cargioli,[b] F. Dordei,[a] C. Giunti,[c] Y.F. Li,[d,e] E. Picciau,[a,b] and Y.Y. Zhang[d,e]

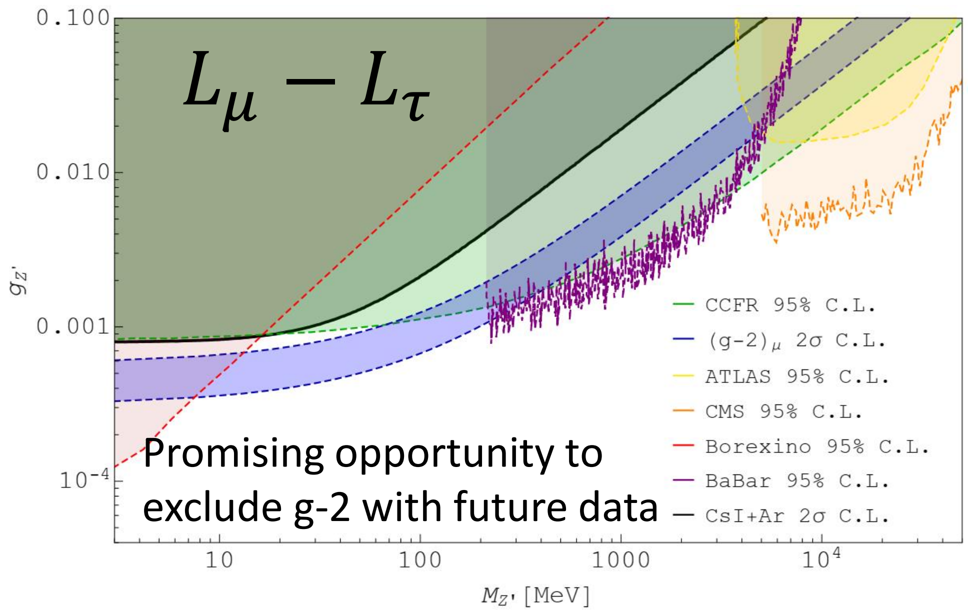
«light» mediator scenario

✓ Limits on three different light mediator models combining CsI and argon COHERENT data

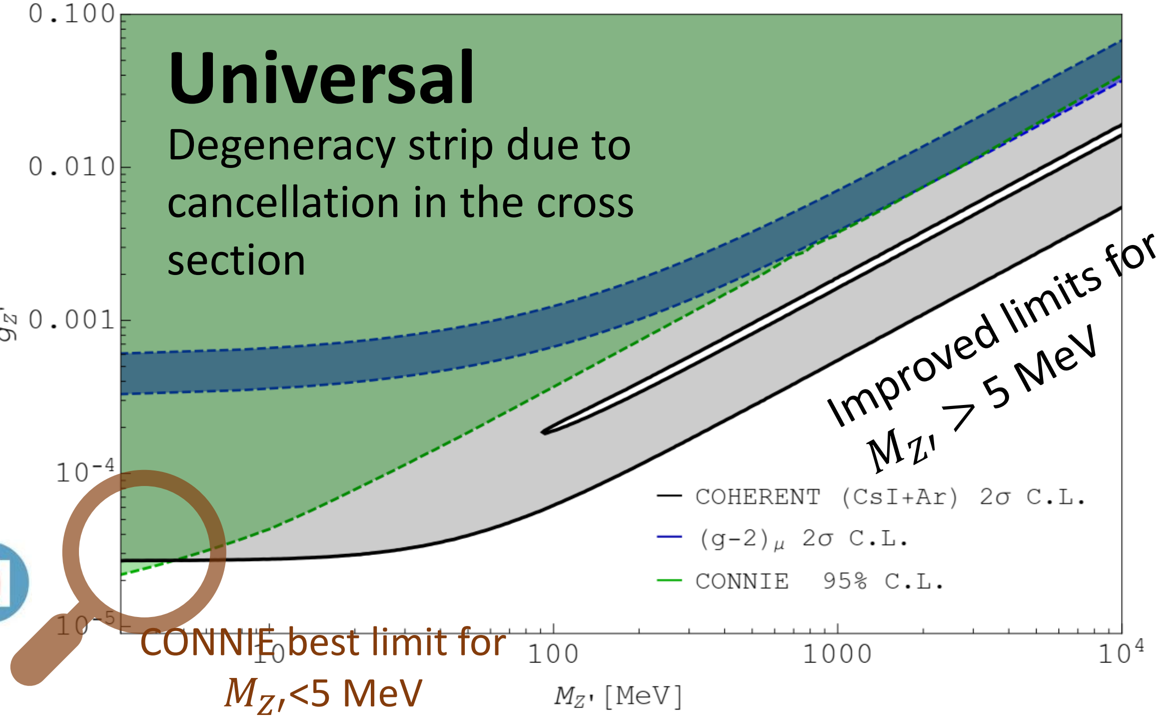


B-L

Improved limits for $20<M_{Z'}<200$ MeV



Promising opportunity to exclude g-2 with future data



Universal

Degeneracy strip due to cancellation in the cross section

Improved limits for $M_{Z'} > 5$ MeV

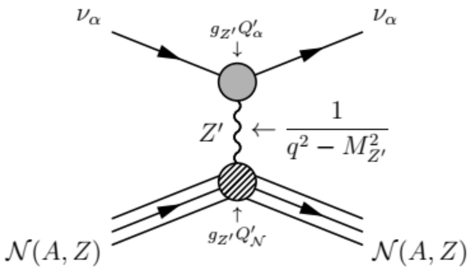
CONNIE best limit for $M_{Z'}$<5 MeV

Light mediators (update)

- Non-standard interactions mediated by a vector boson Z' with mass $M_{Z'} \lesssim 100$ GeV, associated with a new $U(1)'$ gauge symmetry.
- Generic lepton flavor conserving Lagrangian:

$$\mathcal{L}_{Z'}^{V} = -g_{Z'}\, Z'_{\mu} \left[\sum_{\alpha=e,\mu,\tau} Q'_{\alpha}\, \overline{\nu_{\alpha L}} \gamma^{\mu} \nu_{\alpha L} + \sum_{q=u,d} Q'_{q}\, \overline{q} \gamma^{\mu} q \right]$$

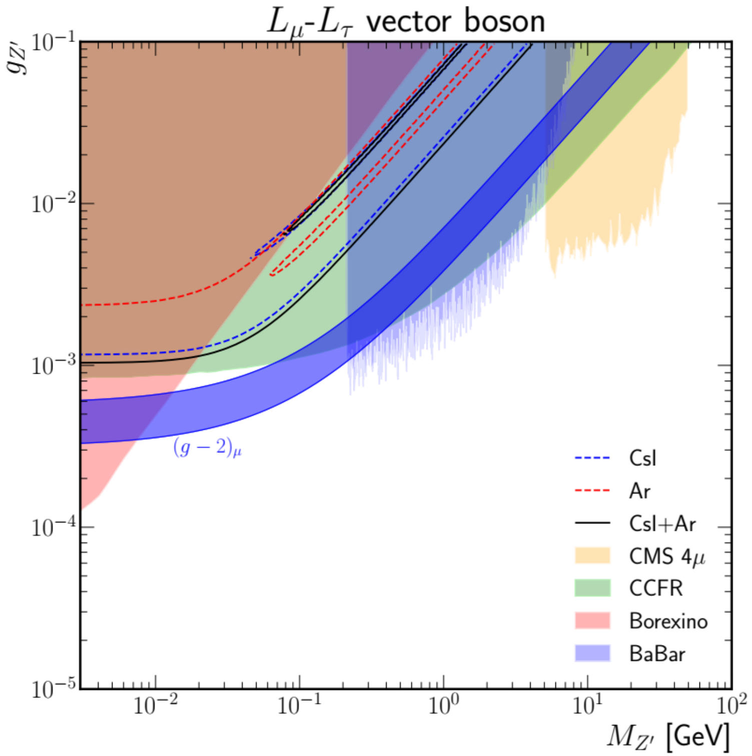
- CEvNS:



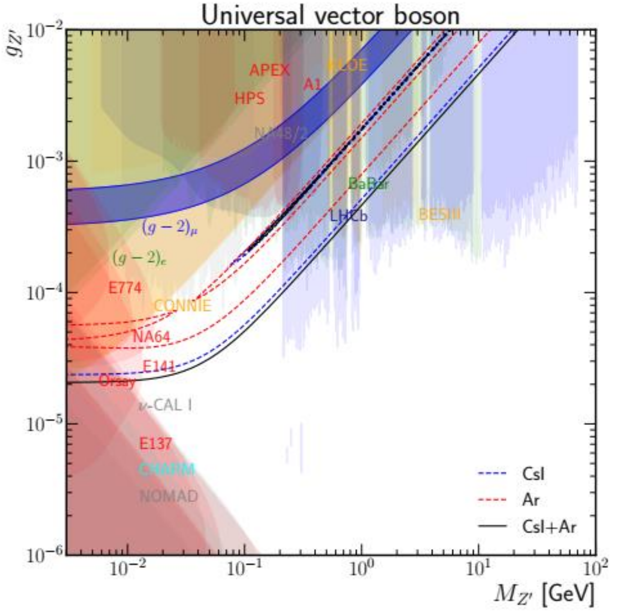
- Many models, that can be divided in
  - Anomaly-free models generated by appropriate combinations of

$$B,\ L_e,\ L_\mu,\ L_\tau$$

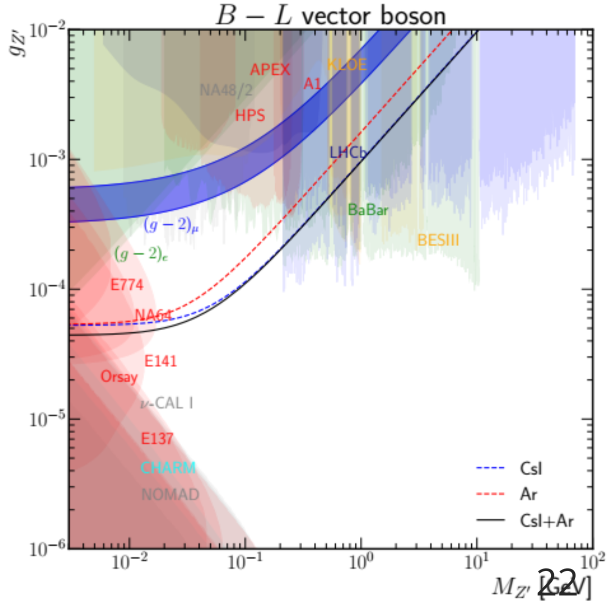
  - Anomalous models, assuming that the anomalies are canceled by the contributions of non-standard fermions an extended theory.


L_μ-L_τ vector boson

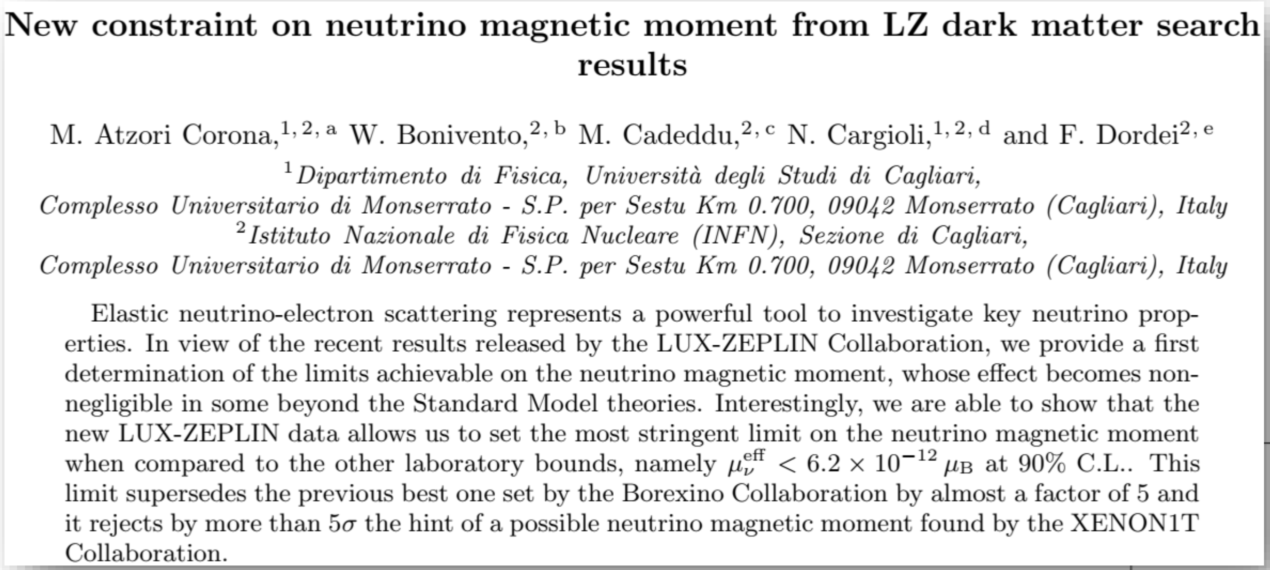
$$Q_W = Q_W^{\rm SM} + \frac{3g_{Z'}^2}{\sqrt{2}G_F}\left(\frac{ZF_Z(|\vec{q}|) + NF_N(|\vec{q}|)}{|\vec{q}|^2 + M_{Z'}^2}\right)$$


Universal vector boson

$$Q_W = Q_W^{\rm SM} - \frac{g_{Z'}^2}{\sqrt{2}G_F}\left(\frac{ZF_Z(|\vec{q}|) + NF_N(|\vec{q}|)}{|\vec{q}|^2 + M_{Z'}^2}\right)$$


$B-L$ vector boson

M. Atzori Corona et al. arXiv:2202.11002



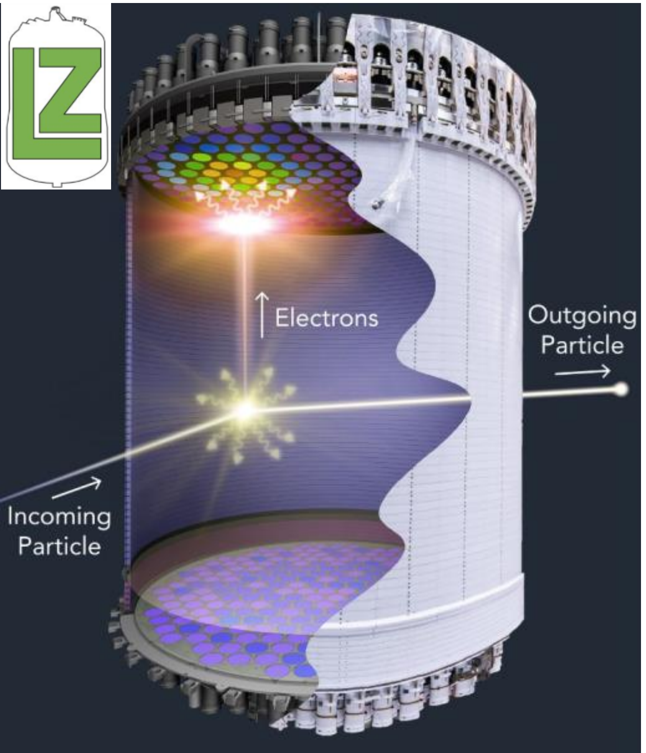
New constraint on neutrino magnetic moment from LZ dark matter search results

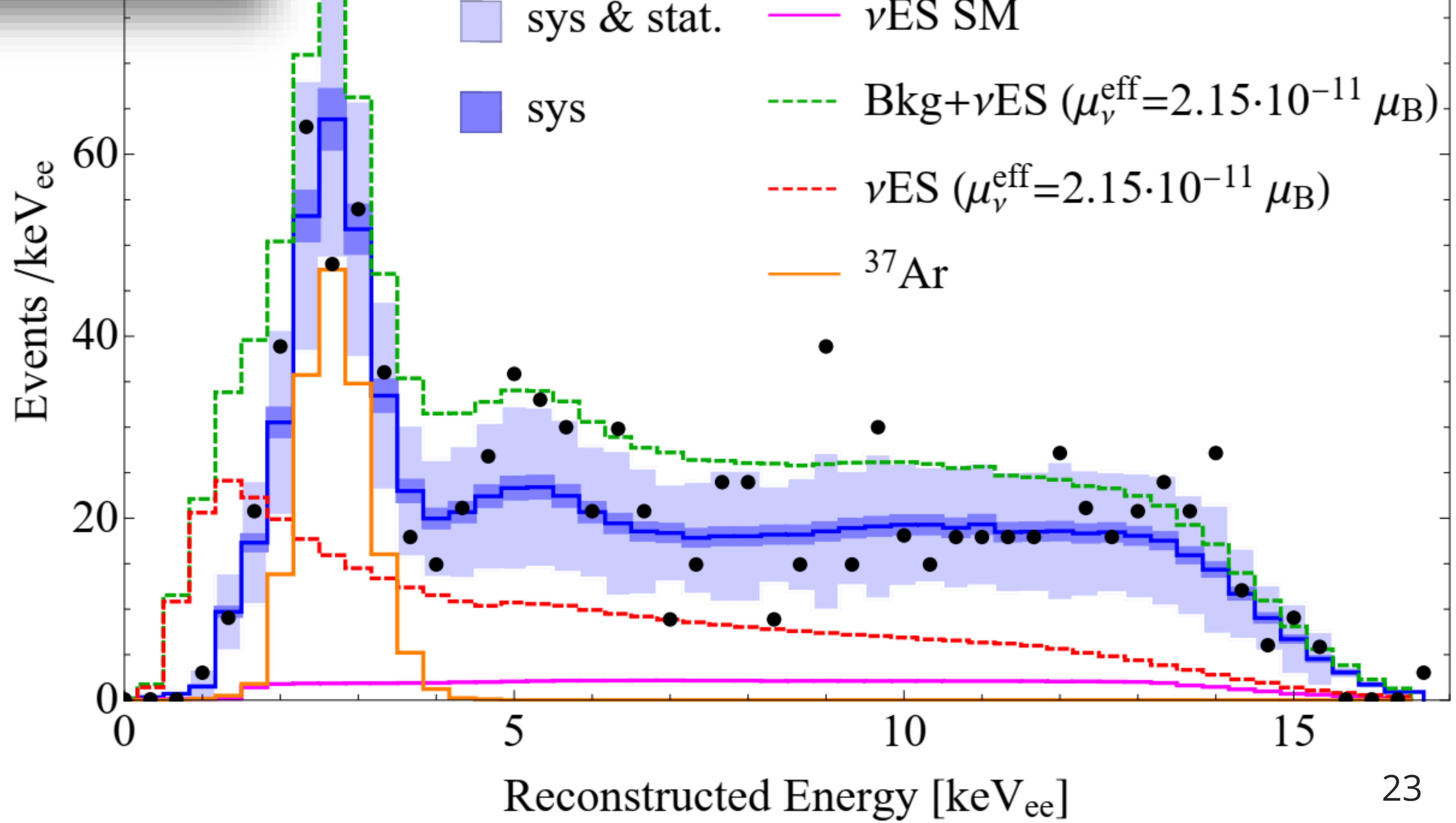
M. Atzori Corona,[1,2,a] W. Bonivento,[2,b] M. Cadeddu,[2,c] N. Cargioli,[1,2,d] and F. Dordei[2,e]

[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

Elastic neutrino-electron scattering represents a powerful tool to investigate key neutrino properties. In view of the recent results released by the LUX-ZEPLIN Collaboration, we provide a first determination of the limits achievable on the neutrino magnetic moment, whose effect becomes non-negligible in some beyond the Standard Model theories. Interestingly, we are able to show that the new LUX-ZEPLIN data allows us to set the most stringent limit on the neutrino magnetic moment when compared to the other laboratory bounds, namely $\mu_\nu^{\rm eff} < 6.2 \times 10^{-12}\,\mu_{\rm B}$ at 90% C.L.. This limit supersedes the previous best one set by the Borexino Collaboration by almost a factor of 5 and it rejects by more than 5σ the hint of a possible neutrino magnetic moment found by the XENON1T Collaboration.

arXiv:2207.05036v2





What can we learn from CEνNS?

Neutrino energy

Fermi constant

Mass of the nucleus

SM vector proton coupling

SM vector neutron coupling

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

Nuclear recoil energy

Weak mixing angle

Proton Form Factor

Neutron Form Factor

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

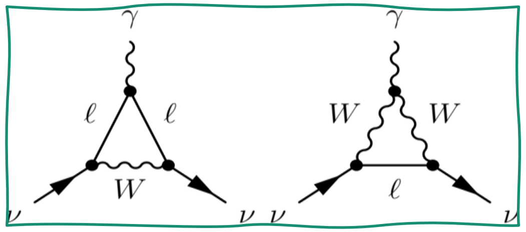
- Neutrino-nucleon tree-level couplings

$$g_V^p = \frac{1}{2} - 2\sin^2(\vartheta_W) \cong 0.0229$$

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

J. Erler and S. Su. *Prog. Part. Nucl. Phys.* 71 (2013). arXiv:1303.5522 & PDG2021

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



$$\underbrace{g_V^p(\nu_e) = 0.0382,\ g_V^p(\nu_\mu) = 0.0300}_{\text{Flavour dependence}} \text{ and } g_V^n = -0.5117$$

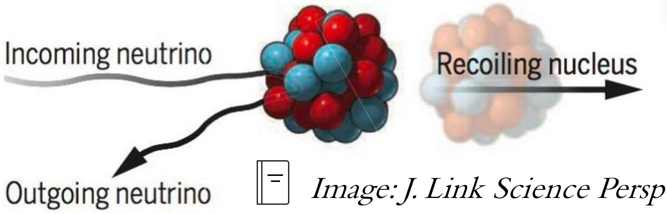
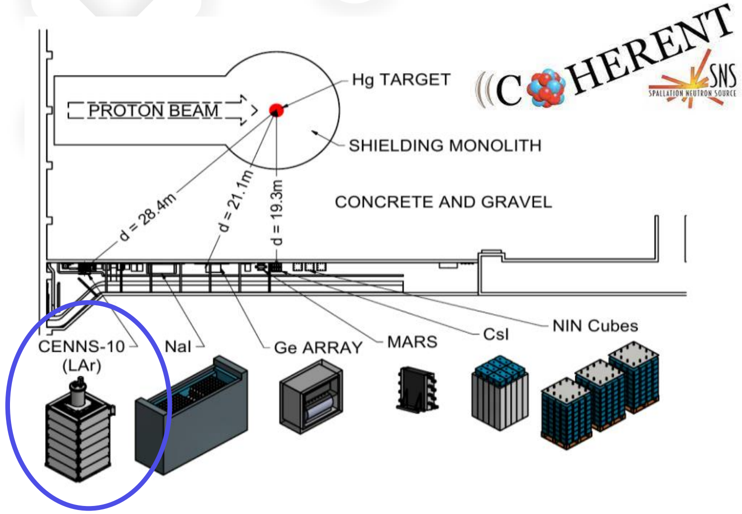


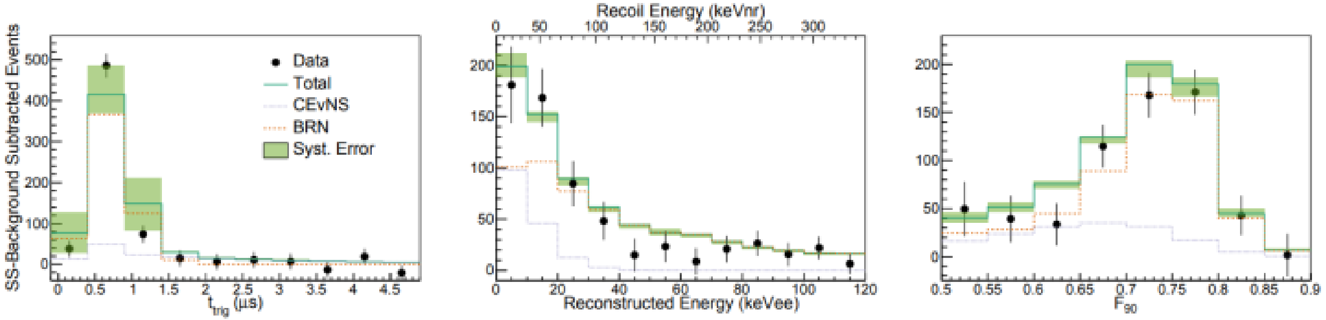
Image: J. Link Science Perspectives

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

Neutron nuclear radius in argon



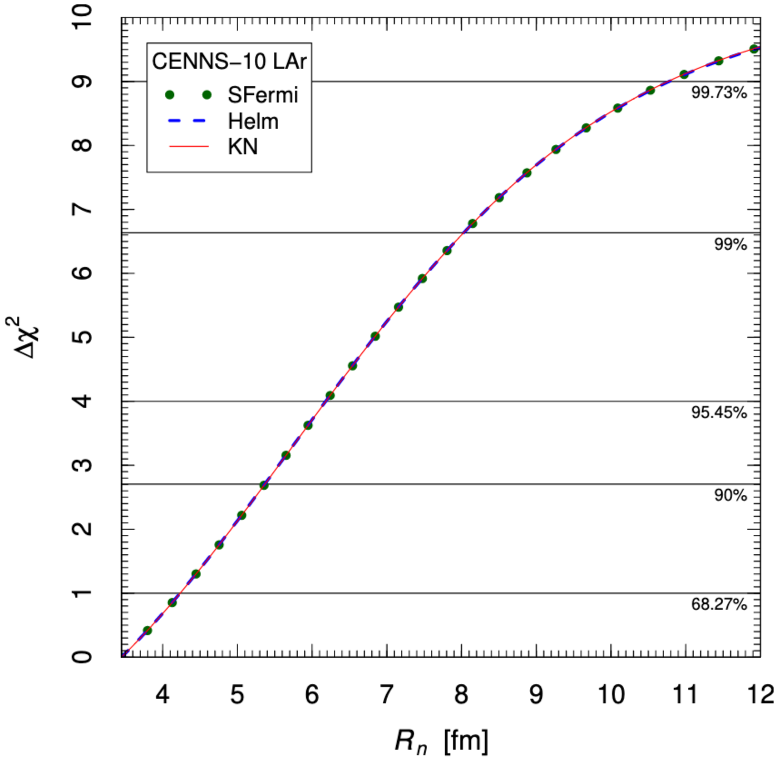
Combined fit in (time, energy, PSP) space suggest >3σ CEvNS detection significance



Dominant backgrounds:

1. ^{39}Ar beta decay
2. Beam related neutrons

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

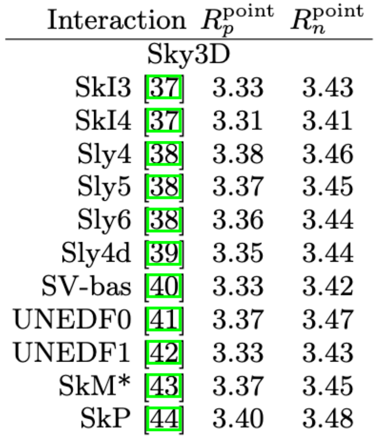


COHERENT Argon

$$R_n(^{40}\text{Ar}) < 4.2\ \text{fm}$$

Cadeddu et al., PRD 102, 015030 (2020)

Theoretical values

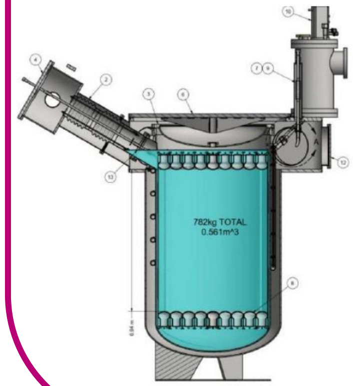


Interaction		R_p^{point}	R_n^{point}
Sky3D			
SkI3	[37]	3.33	3.43
SkI4	[37]	3.31	3.41
Sly4	[38]	3.38	3.46
Sly5	[38]	3.37	3.45
Sly6	[38]	3.36	3.44
Sly4d	[39]	3.35	3.44
SV-bas	[40]	3.33	3.42
UNEDF0	[41]	3.37	3.47
UNEDF1	[42]	3.33	3.43
SkM*	[43]	3.37	3.45
SkP	[44]	3.40	3.48

See also:
Payne et al.,
PRC 100, 061304 (2019)

See also:
Miranda et al.,
JHEP 05 (2020) 130

COHERENT future argon: “COH-Ar-750”
LAr based detector for precision CEνNS



- Single phase, scintillation only, 750 kg total (610 kg fiducial)
- 3000 CEνNS/year

The CsI neutron skin (in 2018)

$$R_n^{CsI} = 5.5_{-1.1}^{+0.9}\ \text{fm}$$

Proton rms radius for Cs and I

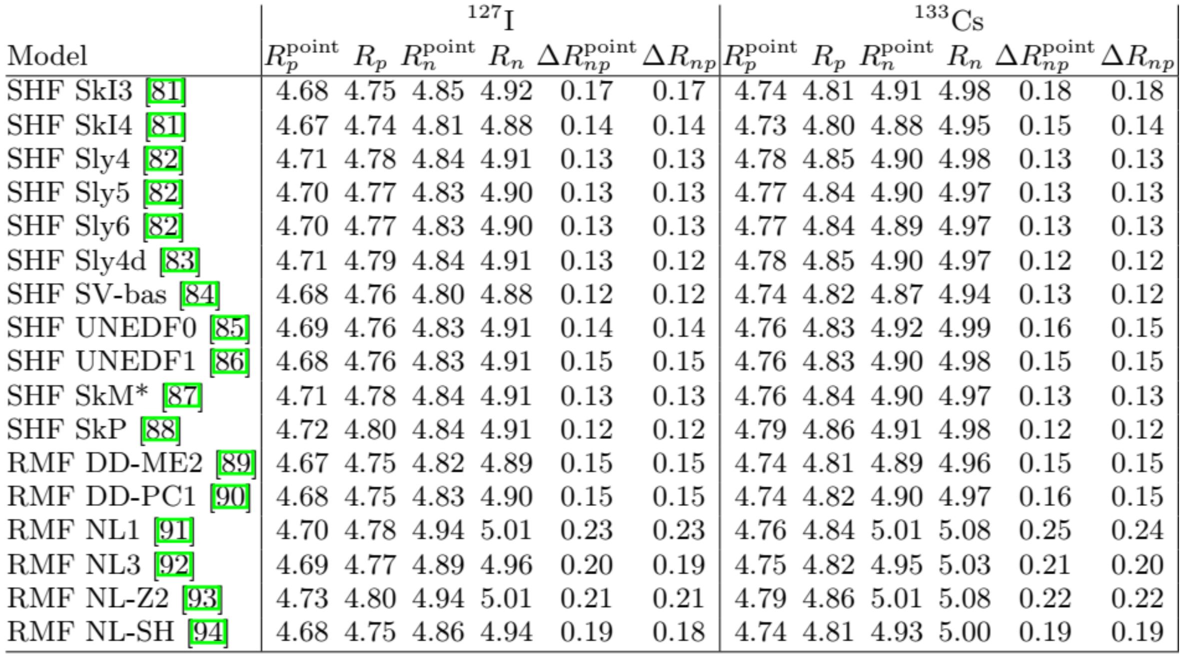
$R_p^{Cs} = 4.821(5)$ fm and
$R_p^{I} = 4.766(8)$ fm
are around 4.78 fm, with a difference of about 0.05 fm

G. Fricke et al., At. Data Nucl. Data Tables **60**, 177 (1995).

The neutron skin

$$\Delta R_{np}^{CsI} \equiv R_n - R_p \cong 0.7_{-1.1}^{+0.9}\ \text{fm}$$

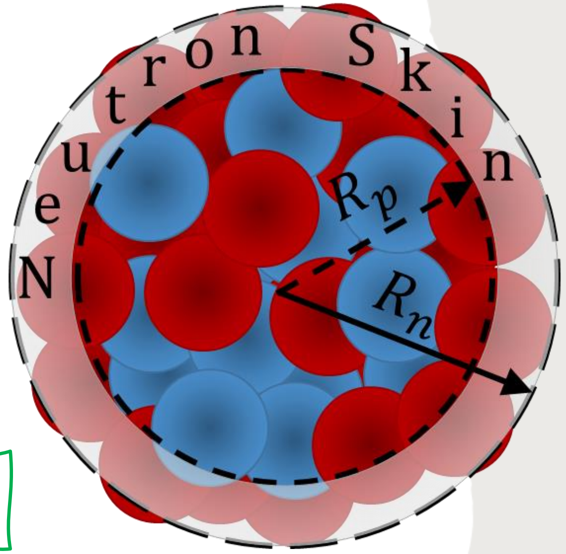
Theoretical values of the proton and neutron rms radii of Cs and I obtained with nuclear mean field models. The value was compatible with all the models...



	^{127}I						^{133}Cs					
Model	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

Theoretically

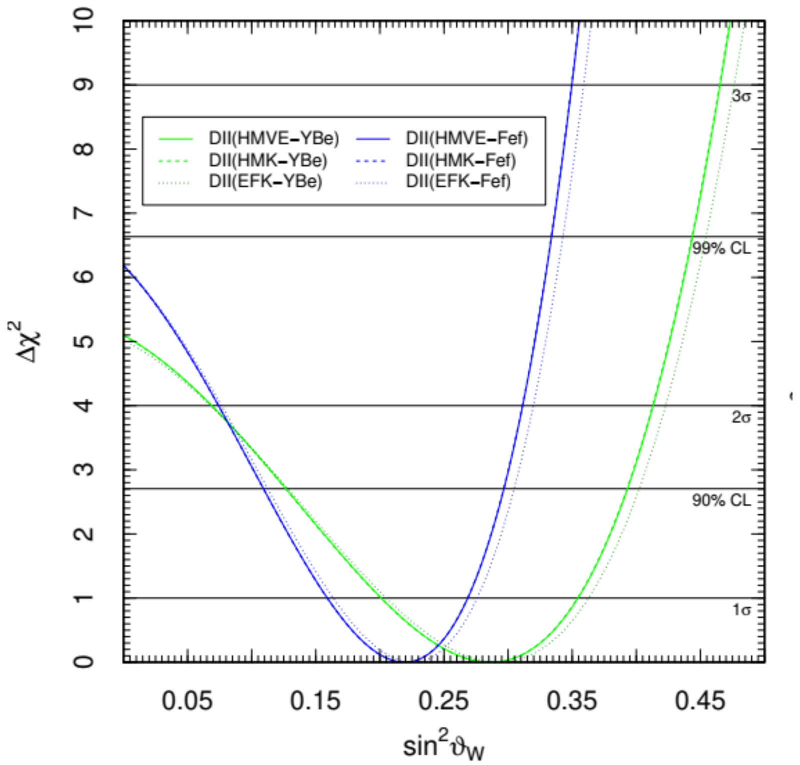
$$0.12 < \Delta R_{np}^{CsI} < 0.24\ \text{fm}$$



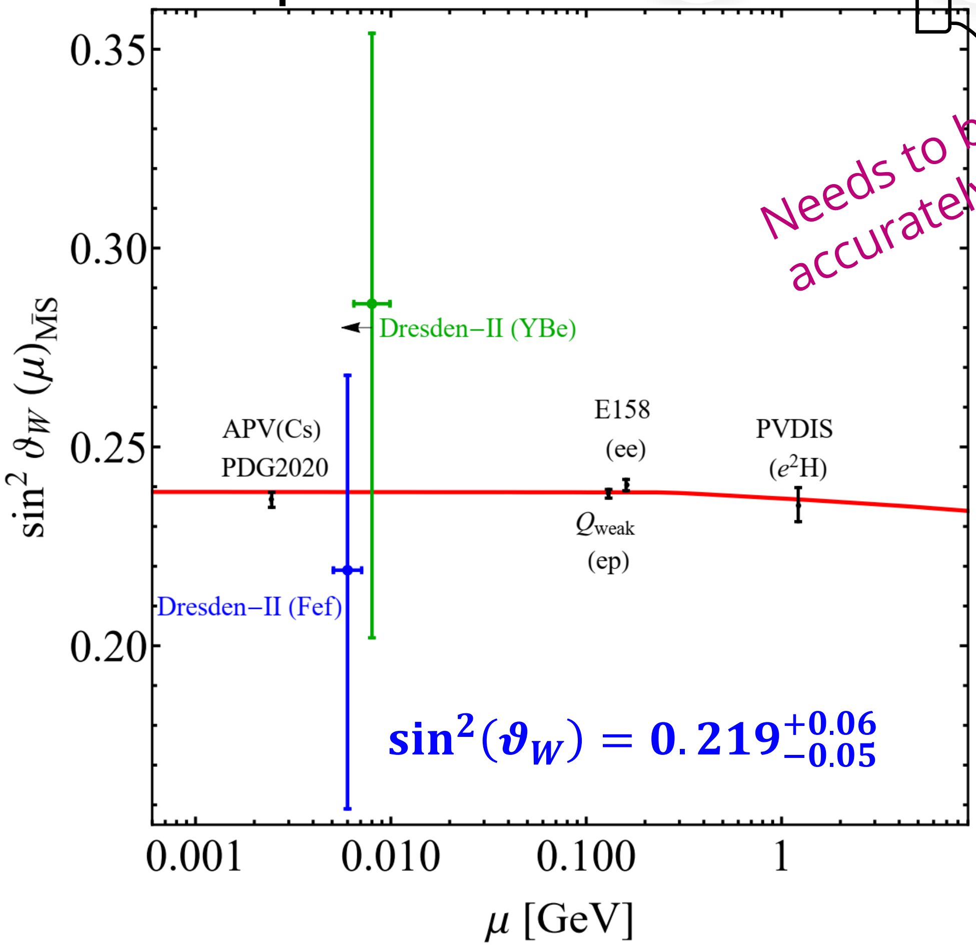
But this is not the end of the story...
In 2020 the COHERENT Collaboration released a new CsI dataset

Dresden-II weak mixing angle results

- +Insensitive to $R_n(\mathrm{Ge})$
- +Insensitive to the antineutrino flux parametrization



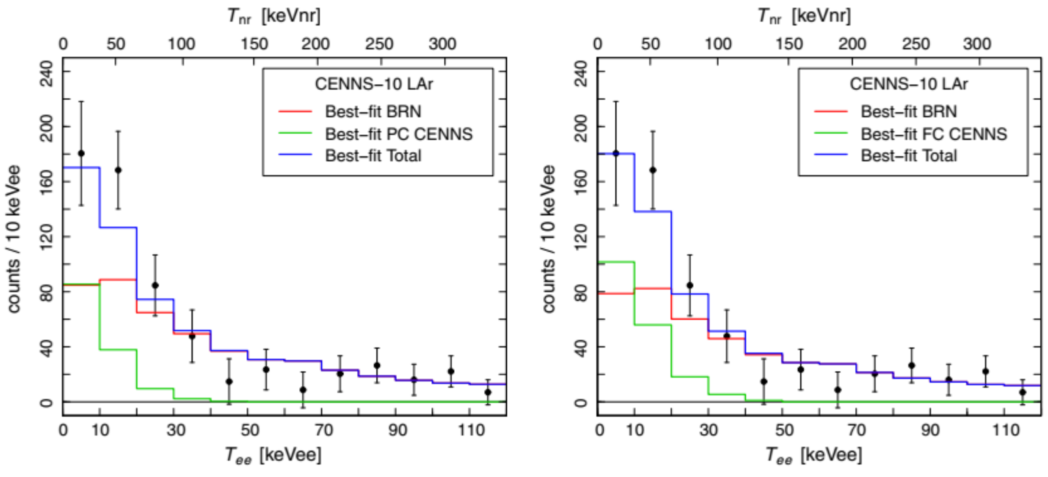
- +Very sensitive to the Ge quenching factor parametrization



$$\mathbf{\sin^2(\vartheta_W) = 0.219^{+0.06}_{-0.05}}$$

Needs to be measured accurately at low energies

$$\chi^2_{\mathrm{S}} = \sum_{i=1}^{12} \left(\frac{N_i^{\mathrm{exp}} - \eta_{\mathrm{CE}\nu\mathrm{NS}} N_i^{\mathrm{CE}\nu\mathrm{NS}} - \eta_{\mathrm{PBRN}} B_i^{\mathrm{PBRN}} - \eta_{\mathrm{LBRN}} B_i^{\mathrm{LBRN}}}{\sigma_i} \right)^2 + \left(\frac{\eta_{\mathrm{CE}\nu\mathrm{NS}} - 1}{\sigma_{\mathrm{CE}\nu\mathrm{NS}}} \right)^2 + \left(\frac{\eta_{\mathrm{PBRN}} - 1}{\sigma_{\mathrm{PBRN}}} \right)^2 + \left(\frac{\eta_{\mathrm{LBRN}} - 1}{\sigma_{\mathrm{LBRN}}} \right)^2,$$



(a)

(b)

Physics results from the first COHERENT observation of coherent elastic neutrino-nucleus scattering in argon and their combination with cesium-iodide data

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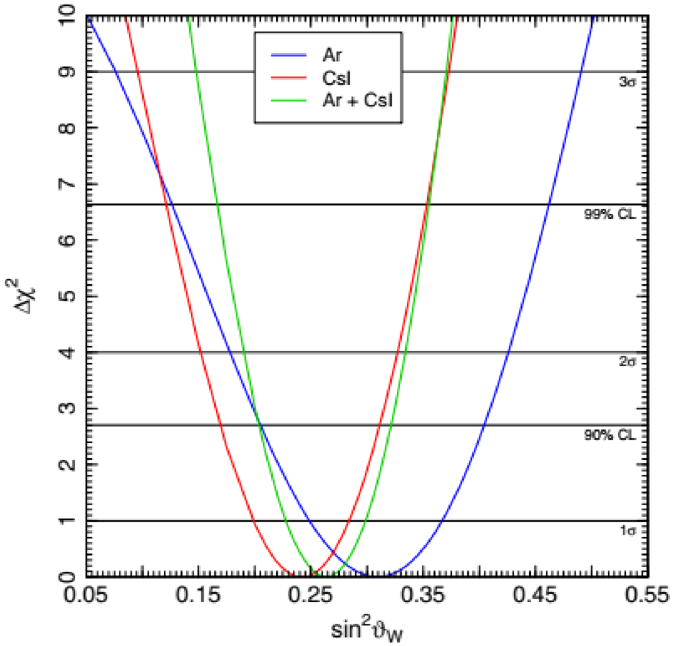
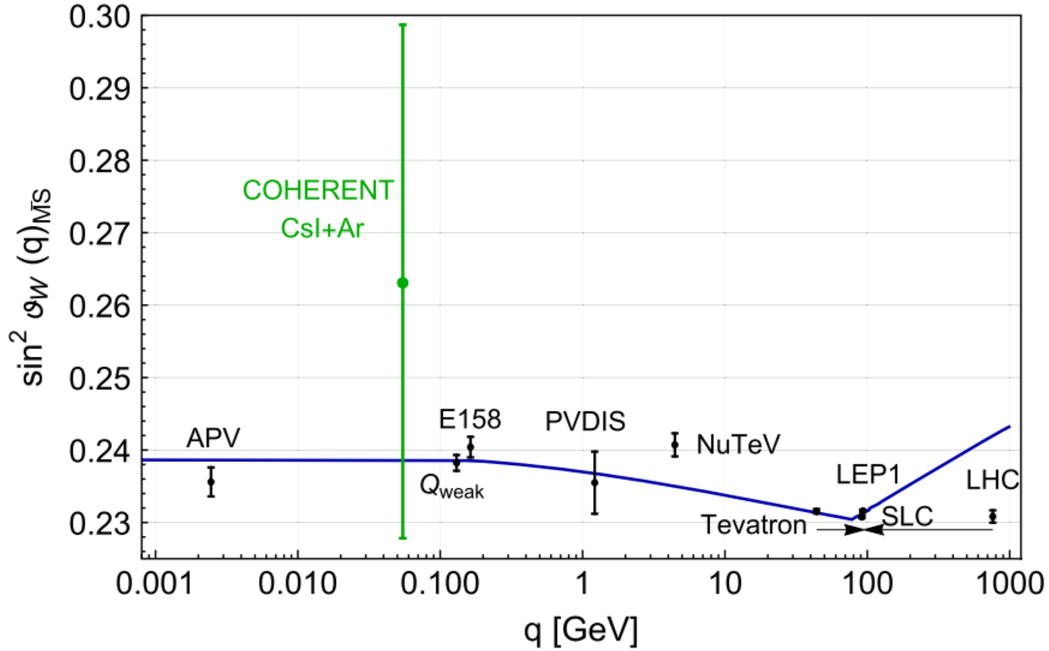
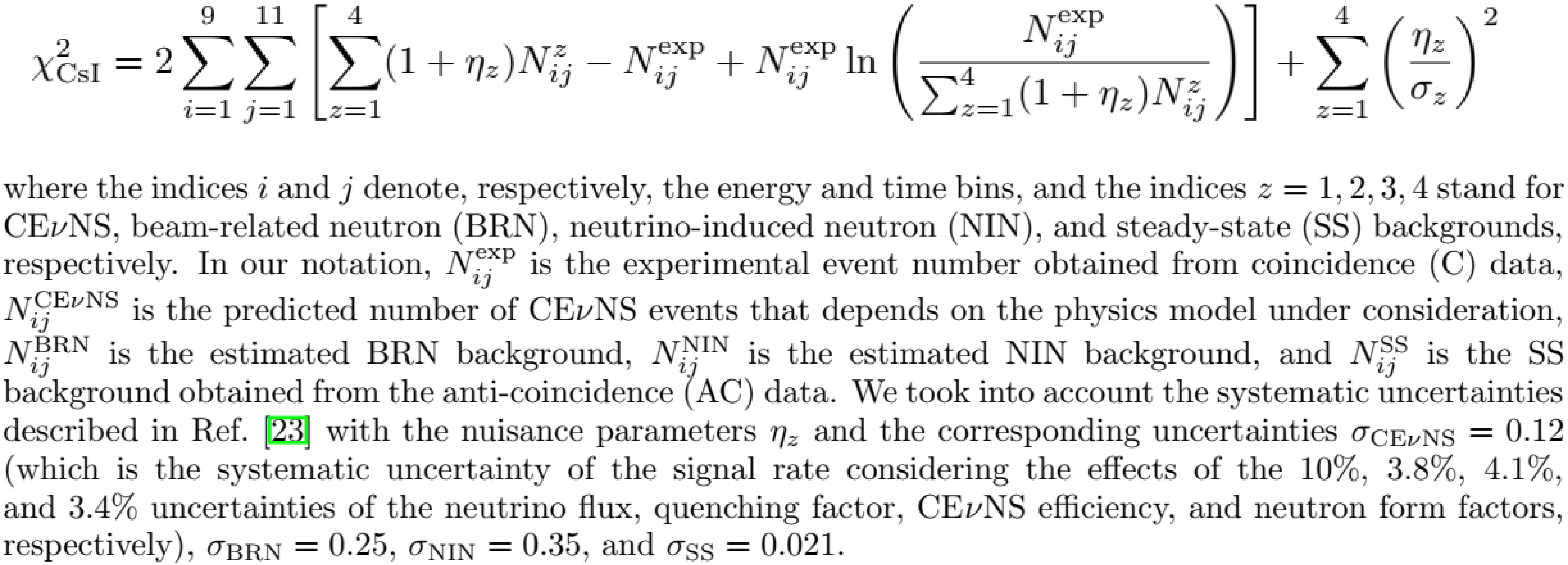




COHERENT CsI χ^2

- Poissonian least-square function:
  - Since in some energy-time bins the number of events is zero, we used the Poissonian least-squares function



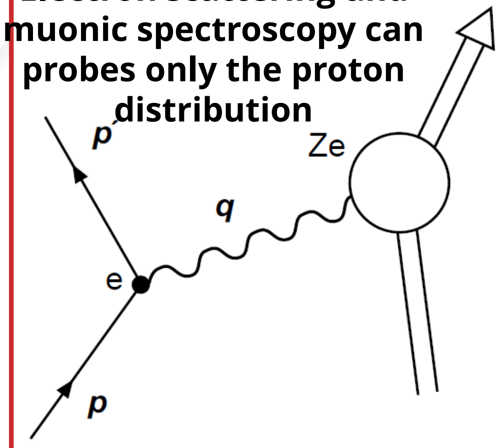
$$\chi^2_{\mathrm{CsI}} = 2\sum_{i=1}^{9}\sum_{j=1}^{11}\left[\sum_{z=1}^{4}(1+\eta_z)N_{ij}^{z} - N_{ij}^{\mathrm{exp}} + N_{ij}^{\mathrm{exp}}\ln\left(\frac{N_{ij}^{\mathrm{exp}}}{\sum_{z=1}^{4}(1+\eta_z)N_{ij}^{z}}\right)\right] + \sum_{z=1}^{4}\left(\frac{\eta_z}{\sigma_z}\right)^2$$

where the indices i and j denote, respectively, the energy and time bins, and the indices $z = 1, 2, 3, 4$ stand for CEνNS, beam-related neutron (BRN), neutrino-induced neutron (NIN), and steady-state (SS) backgrounds, respectively. In our notation, N_{ij}^{exp} is the experimental event number obtained from coincidence (C) data, $N_{ij}^{\mathrm{CE\nu NS}}$ is the predicted number of CEνNS events that depends on the physics model under consideration, N_{ij}^{BRN} is the estimated BRN background, N_{ij}^{NIN} is the estimated NIN background, and N_{ij}^{SS} is the SS background obtained from the anti-coincidence (AC) data. We took into account the systematic uncertainties described in Ref. [23] with the nuisance parameters η_z and the corresponding uncertainties $\sigma_{\mathrm{CE\nu NS}} = 0.12$ (which is the systematic uncertainty of the signal rate considering the effects of the 10%, 3.8%, 4.1%, and 3.4% uncertainties of the neutrino flux, quenching factor, CEνNS efficiency, and neutron form factors, respectively), $\sigma_{\mathrm{BRN}} = 0.25$, $\sigma_{\mathrm{NIN}} = 0.35$, and $\sigma_{\mathrm{SS}} = 0.021$.

The proton form factor

$$\frac{d\sigma_{\nu-CsI}}{dT} = \frac{G_F^2 M}{4\pi}\left(1-\frac{MT}{2E_\nu^2}\right)\left[N\, \boldsymbol{F_N(T,R_n)} - \varepsilon Z\, \boldsymbol{F_Z(T,R_p)}\right]^2$$

Electron scattering and muonic spectroscopy can probes only the proton distribution



The proton structures of $^{133}_{55}Cs$ $(N = 78)$ and $^{127}_{53}I$ $(N = 74)$ have been studied with muonic spectroscopy and the data were fitted with **two-parameter Fermi density distributions** of the form

$$\boxed{\rho_F(r) = \frac{\rho_0}{1 + e^{(r-c)/a}}}$$

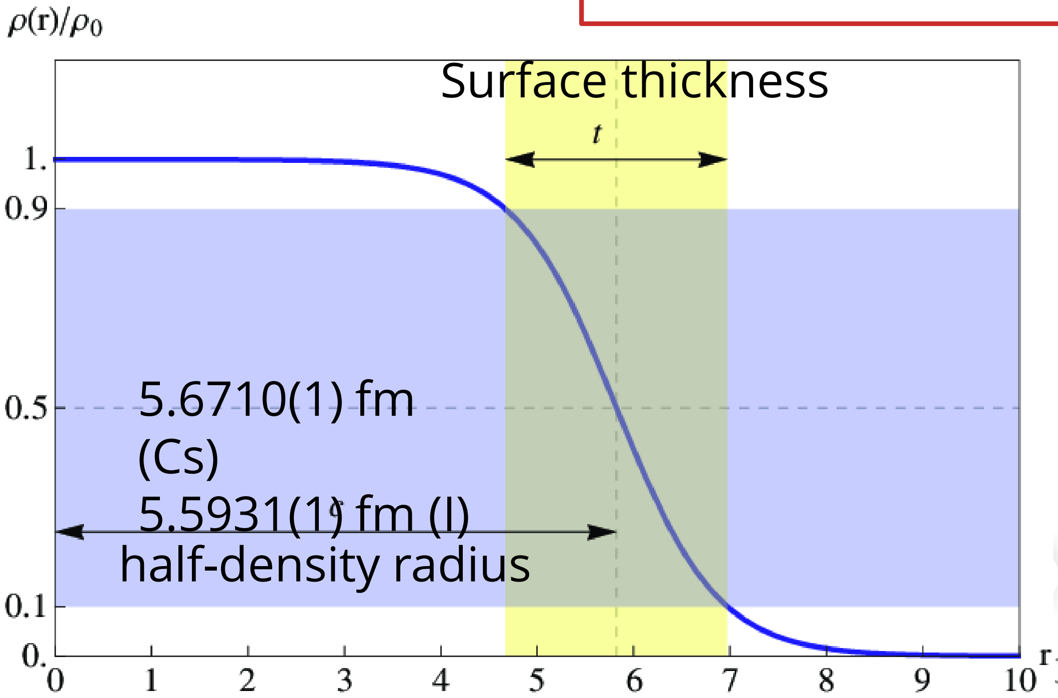
Where, the **half-density radius *c*** is related to the **rms radius** and the a parameter quantifies the **surface thickness** $t = 4\, a\, \ln 3$ (in the analysis fixed to 2.30 fm).

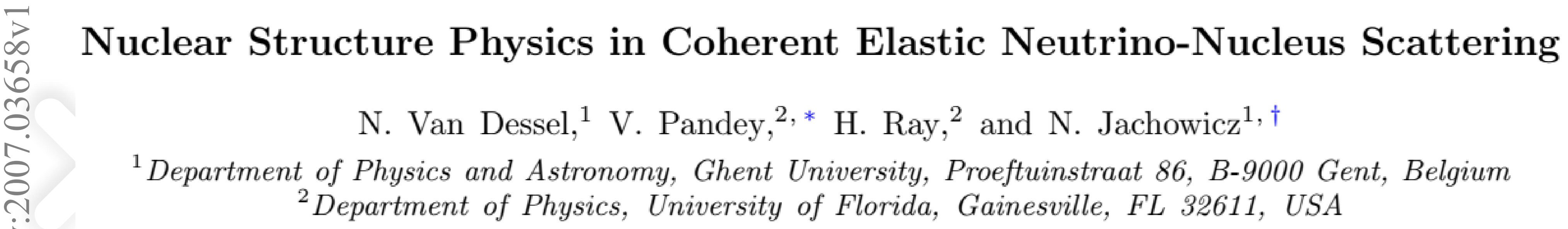
- Fitting the data they obtained

$R_p^{Cs} = 4.804$ fm (Caesium proton rms radius)

$R_p^{I} = 4.749$ fm (Iodine proton rms radius)

[G. Fricke et al., Atom. Data Nucl. Data Tabl. **60**, 177 (1995)]





Nuclear Structure Physics in Coherent Elastic Neutrino-Nucleus Scattering

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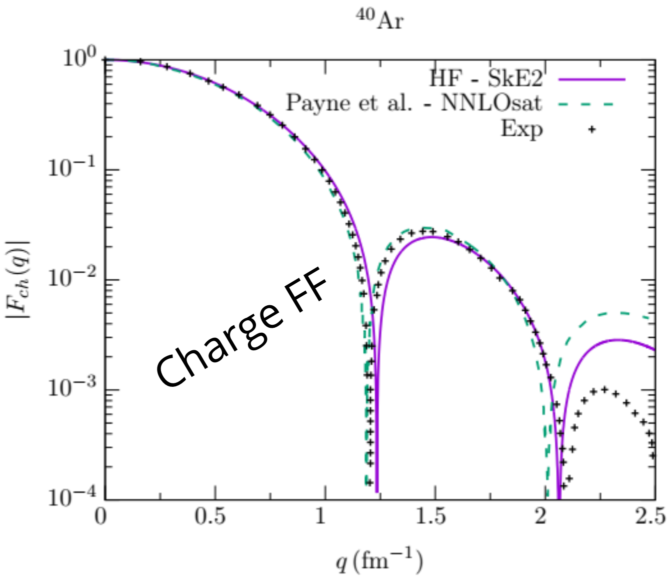
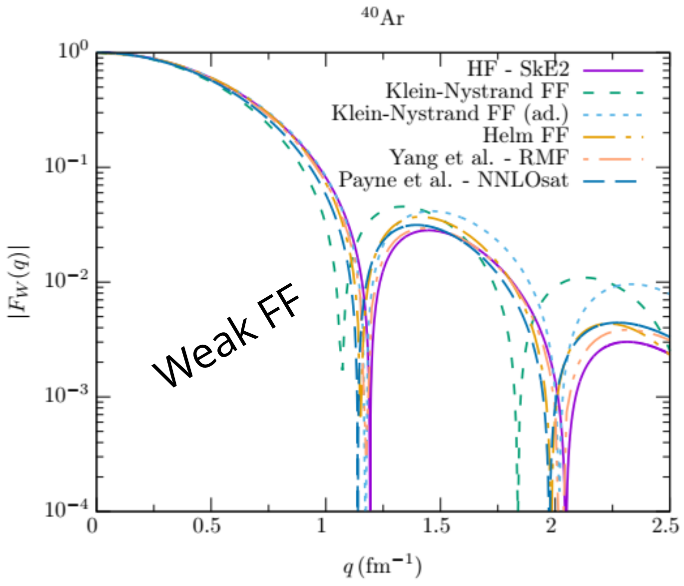
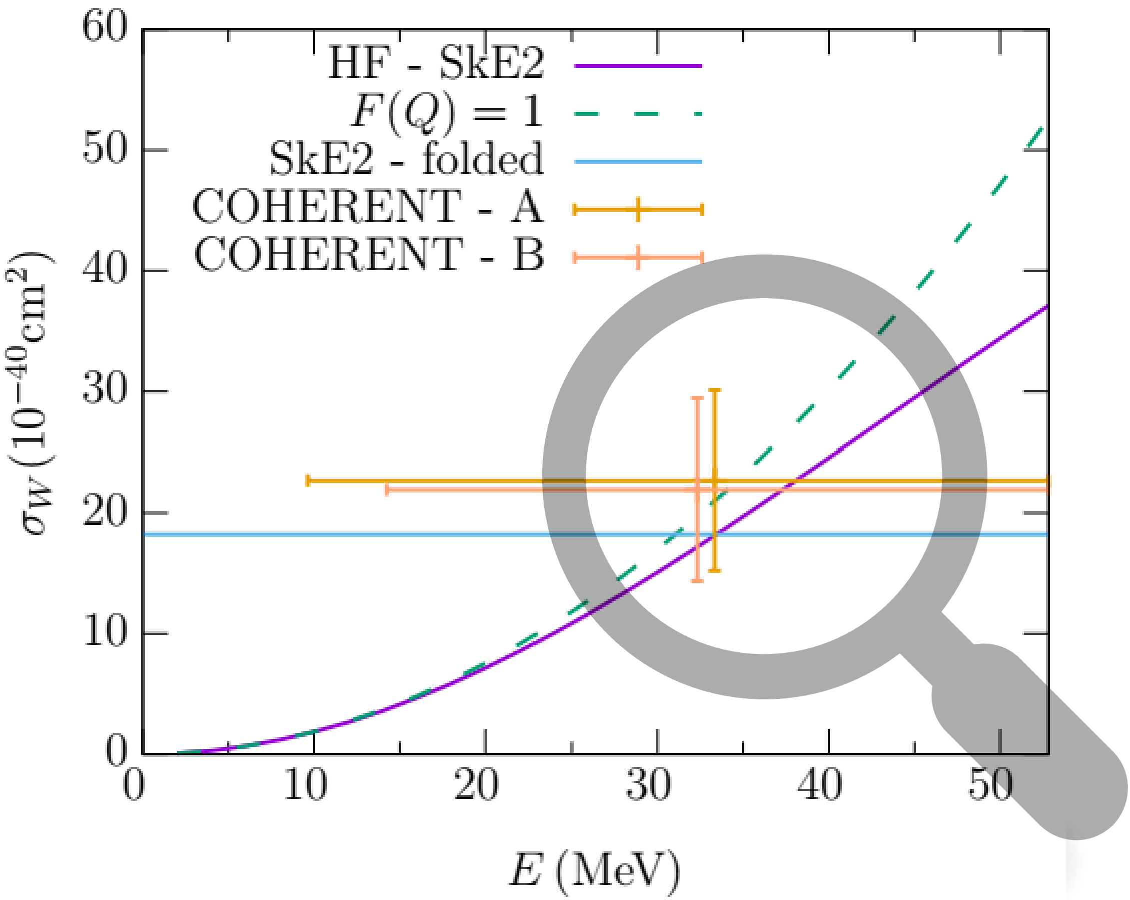
They perform **microscopic many-body nuclear structure physics calculations** of charge and weak nuclear form factors and CEνNS cross sections on different nuclei, including Ar.



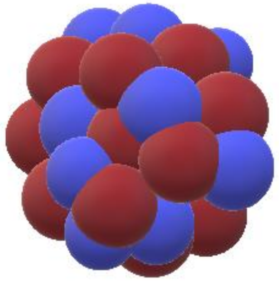




- ✓ After validating Ar charge form factor calculation, they make predictions for the Ar weak form factor.
- ➢ They calculate differential cross section and compare it with widely used phenomenological form factor predictions and recent measurements of the COHERENT collaboration. Future precise measurements of CEνNS will aid in constraining neutron densities.

See also C. G. Payne, et al Phys. Rev. C **100**, 061304 (2019)

THE NUCLEAR FORM FACTOR



- The nuclear form factor, F(q), is taken to be the **Fourier transform** of a spherically symmetric ground state **mass distribution (both proton and neutrons)** normalized so that **F(0) = 1**:

For a weak interaction like for CEvNS you deal with the **weak form factor**: the Fourier transform of the weak charge distribution (neutron + proton distribution weighted by the weak mixing angle)

$$\frac{d\sigma}{dE_r} \cong \frac{G_F^2\, m_N}{4\pi}\left(1-\frac{m_N E_r}{2E_\nu^2}\right)\; Q_w^2 \times |F_{weak}(E_r)|^2$$

Weak charge × weak form factor

$$\overbrace{\left[g_V^p Z F_Z(E_r, R_p) + g_V^n N F_N(E_r, R_n)\right]^2}$$

Proton + Neutron from factor

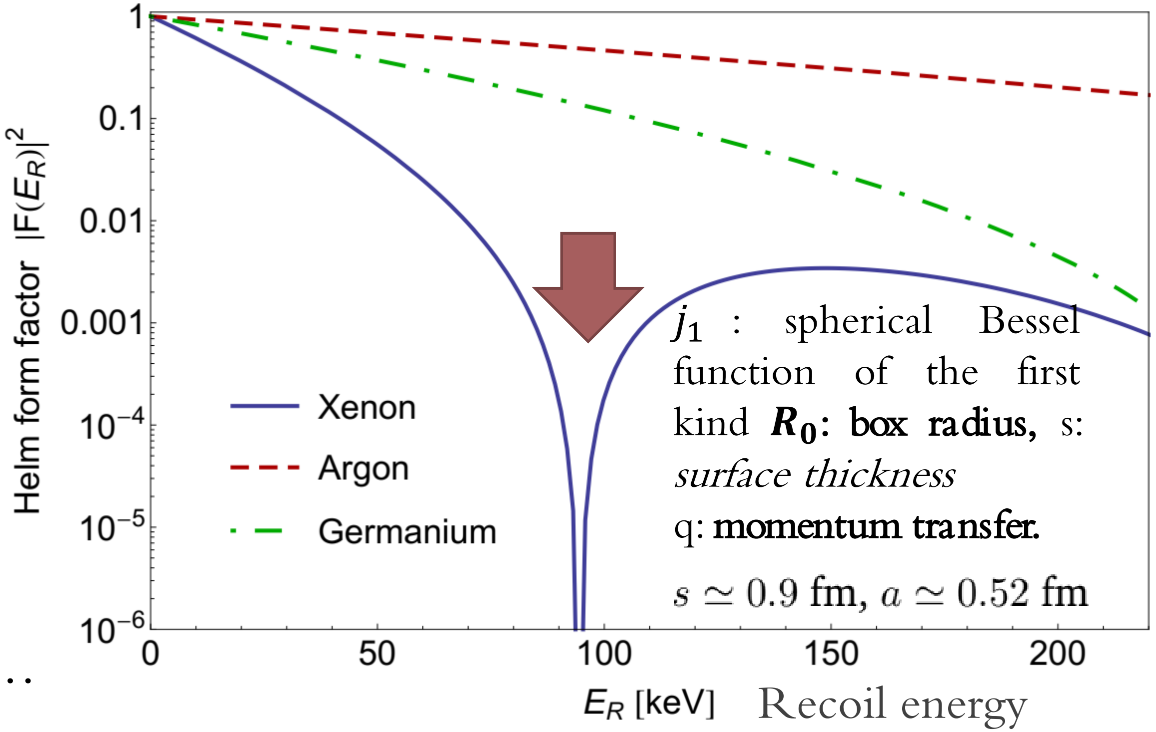
Extensively studied
Huge bibliography

Poorly known…

Helm R. Phys. Rev. **104**, 1466 (1956)

It is convenient to have an analytic expression like the **Helm form factor**

$$\boxed{F_N^{\text{Helm}}(q^2) = 3\,\frac{j_1(qR_0)}{qR_0}\, e^{-q^2 s^2/2}}$$

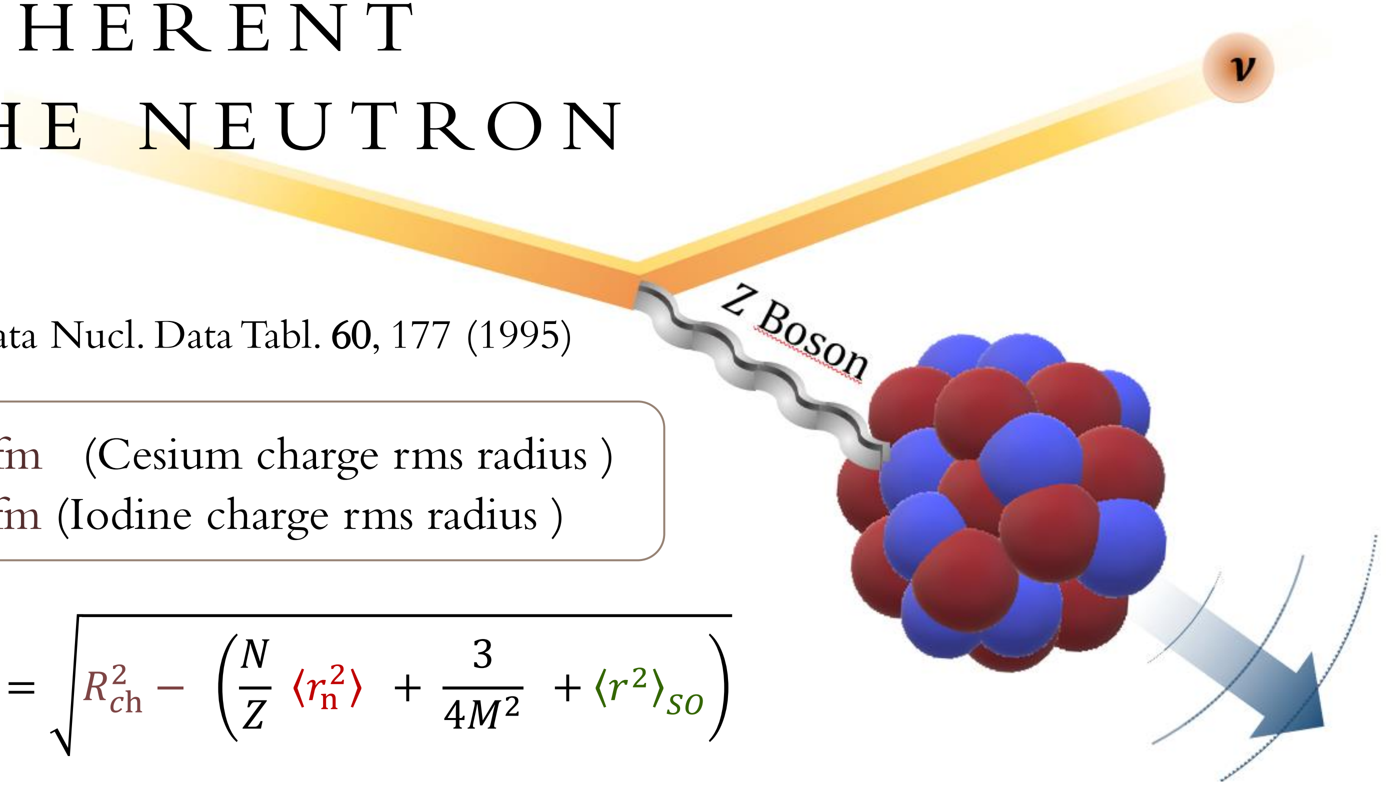


j_1 : spherical Bessel function of the first kind $\boldsymbol{R_0}$**: box radius,** s: *surface thickness*
q: **momentum transfer.**

$s \simeq 0.9$ fm, $a \simeq 0.52$ fm

Recoil energy

FITTING THE COHERENT CsI DATA FOR THE NEUTRON RADIUS



G. Fricke et al., Atom. Data Nucl. Data Tabl. **60**, 177 (1995)

✓ From muonic X-rays data we have

(For fixed $t = 2.3$ fm)

$R_{ch}^{Cs} = 4.804$ fm (Cesium charge rms radius)
$R_{ch}^{I} = 4.749$ fm (Iodine charge rms radius)

$$R_p^{\mathrm{rms}} = \sqrt{R_{\mathrm{ch}}^2 - \left(\frac{N}{Z}\langle r_{\mathrm{n}}^2\rangle + \frac{3}{4M^2} + \langle r^2\rangle_{SO}\right)}$$

$R_p^{Cs} = 4.821 \pm 0.005$ fm (Cesium rms proton radius)
$R_p^{I} = 4.766 \pm 0.008$ fm (Iodine rms-proton radius)

$$\frac{d\sigma}{dE_r} \cong \frac{G_F^2\, m_N}{4\pi}\left(1 - \frac{m_N E_r}{2E_\nu^2}\right)\left[g_V^p Z F_Z\left(E_r, R_p^{Cs/I}\right) + g_V^n N F_N(E_r, R_n^{CsI})\right]^2$$

R_n^{Cs} & R_n^{I} very well known so we fitted COHERENT CsI data looking for R_n^{CsI} …

FROM THE CHARGE TO THE PROTON RADIUS

One need to take into account finite size of both protons and neutrons plus other corrections

$$R_{ch}^2 = R_{\text{point}}^2 + \langle r_{\text{p}}^2 \rangle + \frac{N}{Z} \langle r_{\text{n}}^2 \rangle + \frac{3}{4M^2} + \langle r^2 \rangle_{SO}$$

Charge radius

Point-proton radius

Mean squared charge radius of a single proton

$\langle r_{\text{p}}^2 \rangle = 0.7071\ \text{fm}^2$

Mean squared charge radius of a single neutron

$\langle r_{\text{n}}^2 \rangle = -0.1161\ \text{fm}^2$

Relativistic Darwin-Foldy correction

$\sim 0.033\ \text{fm}^2$

Spin-orbit correction

$\sim 0.09\ \text{fm}^2$ for ^{48}Ca

$\sim 0.028\ \text{fm}^2$ for ^{208}Pb

G. Hagen et al. *Nature Physics* **12**, 186–190 (2016), Arxiv: 1509.07169

M. Cadeddu et al. PRD 102, 015030 (2020), Arxiv: 2005.01645

$$R_p^{\text{rms}} = \sqrt{R_{\text{point}}^2 + \langle r_{\text{p}}^2 \rangle} =$$

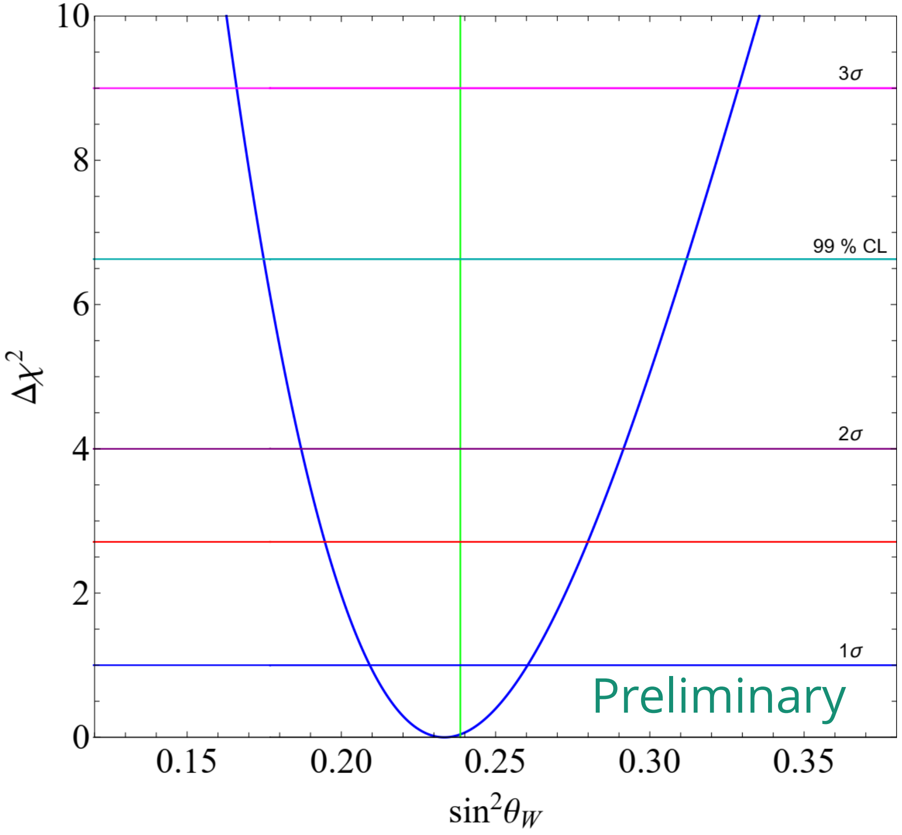
$$= \sqrt{R_{ch}^2 - \left(\frac{N}{Z} \langle r_{\text{n}}^2 \rangle + \frac{3}{4M^2} + \langle r^2 \rangle_{SO} \right)}$$

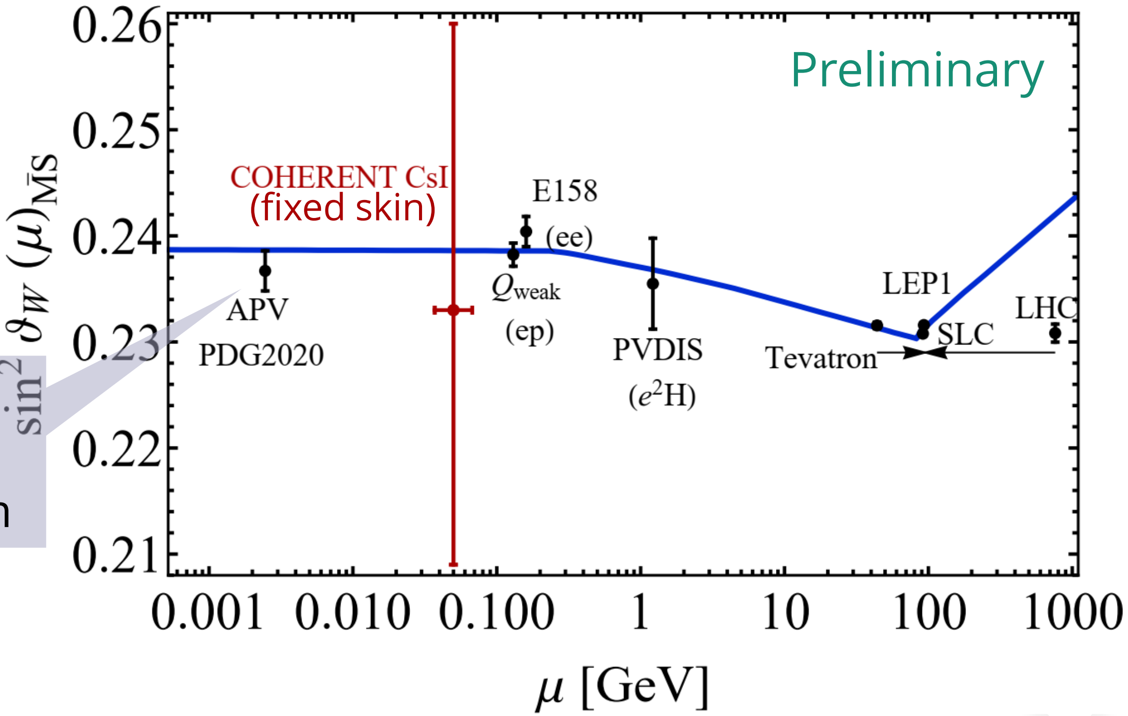
RMS proton distribution radius

COHERENT (CsI) @fixed skin

- CEνNS is sensitive to the neutron skin
- But less sensitive to the weak mixing angle

$\sin^2\theta_W = 0.233^{+0.027}_{-0.024}$

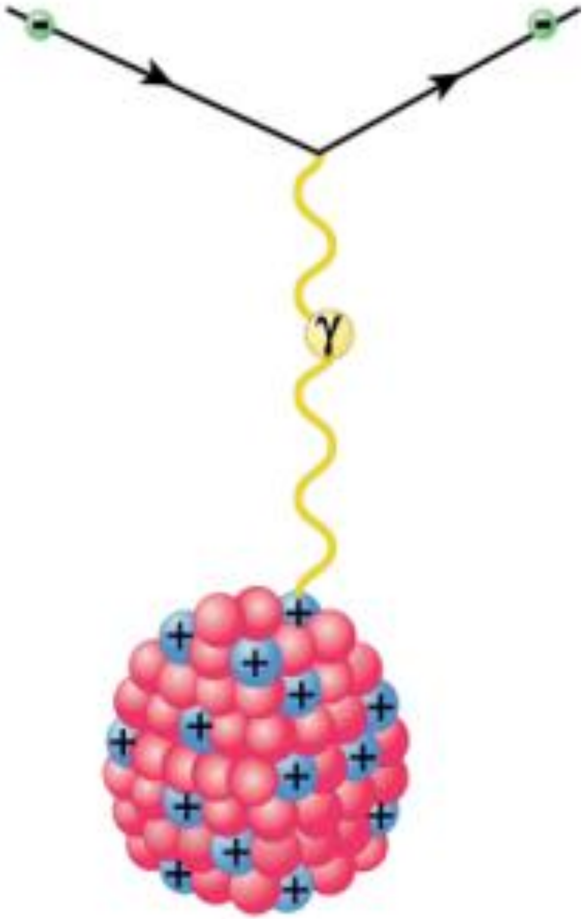


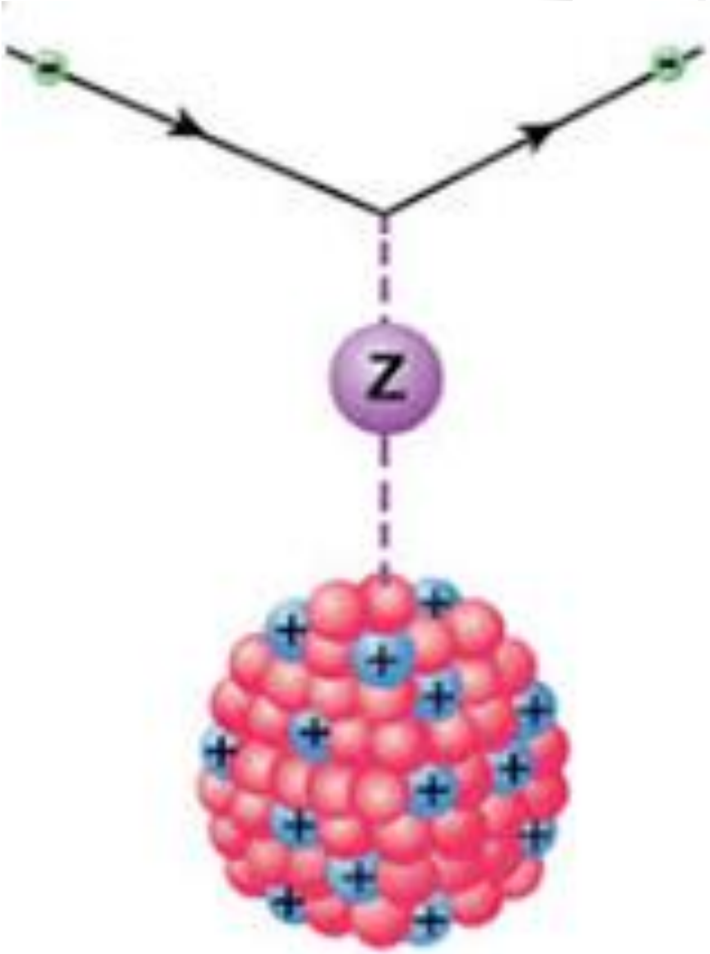


APV(Cs) PDG2020 corresponds to $\Delta R_{np}^{Cs}(\text{Extr.}) = 0.13$ fm

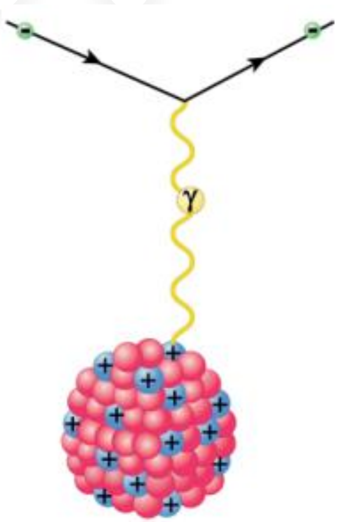
Extrapolated from antiprotonic atoms…

COHERENT+APV

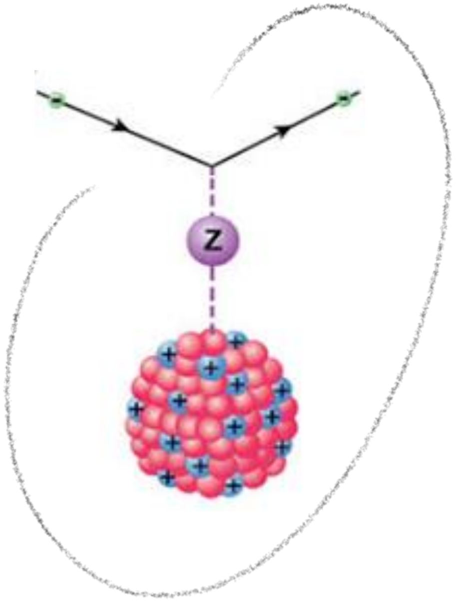




Atomic Parity Violation in cesium APV(Cs)



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.

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

\+ Parity violation in an atomic system can be observed as an **electric dipole transition amplitude between two atomic states with the same parity**, such as the $6S$ and $7S$ states in cesium.

- ➢ Indeed, a transition between two atomic states with same parity is forbidden by the parity selection rule and cannot happen with the exchange of a photon.
- ✓ However, 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).

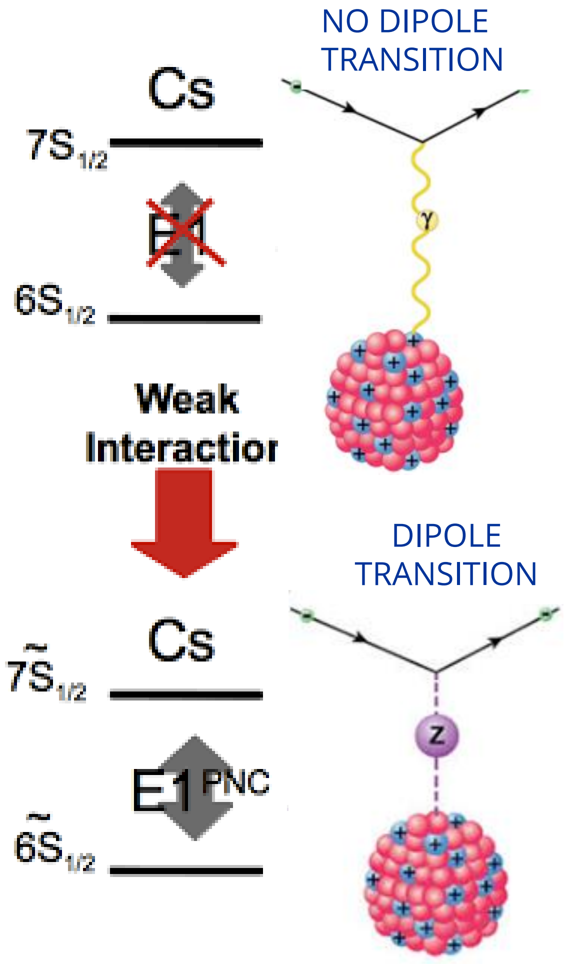
\+ The quantity that is measured is the usual **weak charge**

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

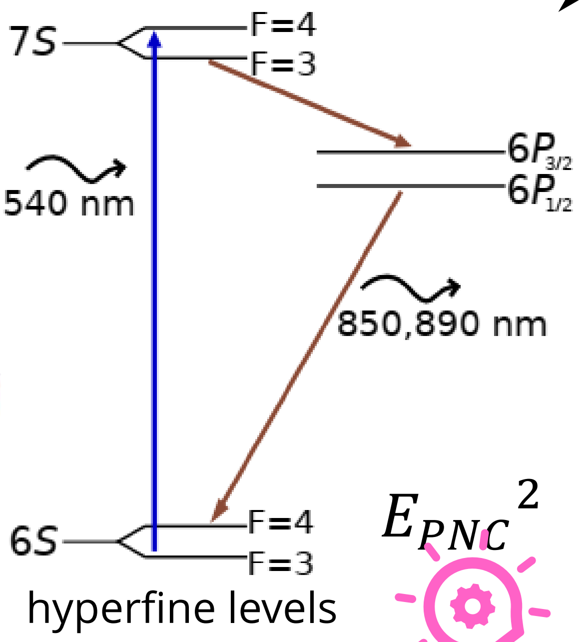
Atomic parity violation* on Cs

*also known as PNC (Parity nonconservation)

- In the absence of electric fields and weak neutral currents, **an electric dipole** (E1) transition between two atomic states with same parity (6*S* and 7*S* in Cs) is forbidden by the parity selection rule.
- However an electric dipole transition amplitude can be induced by a Z boson exchange between atomic electrons and nucleons → Atomic Parity Violation (APV)



- ➢ The weak NC interaction violates parity and mixes a small amount of the *P* state into the 6*S* and 7*S* states ($\sim 10^{-11}$), characterized by the quantity $\mathbf{Im}(\boldsymbol{E1_{PNC}})$, giving rise to a 7S → 6S transition.



hyperfine levels

- ➢ To obtain an observable that is at first order in this amplitude, an electric field **E** (that also mixes S & P) is applied. **E** gives rise to a "**Stark induced**" E1 transition amplitude, $\mathbf{A_E}$ that is typically 10^5 times larger than $\mathbf{A_{PNC}}$ and can **interfere** with it.

$$R_{7S\to 6S} = |A_E \pm A_{PNC}|^2 =$$

$$= \boldsymbol{E1_\beta}^2 \pm 2\boldsymbol{E1_\beta}\boldsymbol{E1_{PNC}} +$$

$$E_{PNC}{}^2$$

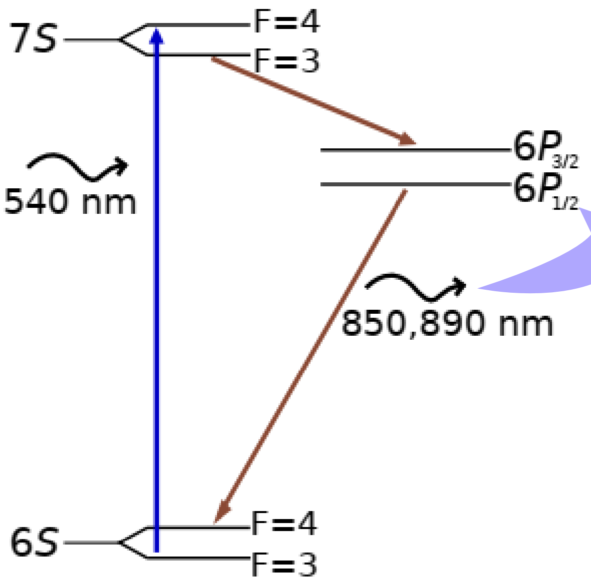
Because the interference term is linear in $\boldsymbol{E1_{PNC}}$ it can be large enough to be measured, but it must be distinguished from the large background contribution ($E1_\beta{}^2$).

The experimental technique

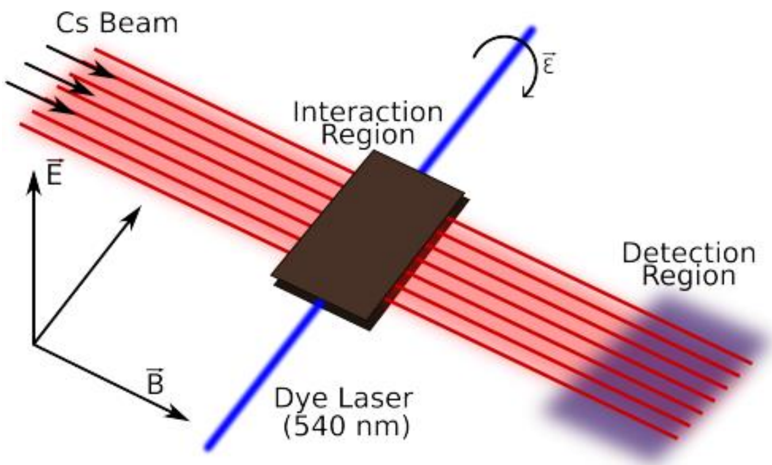
For there to be a nonzero interference term, **the experiment must have a “handedness”,** and if the handedness is reversed, the interference term will change sign, and can thereby be distinguished as a modulation in the transition rate

$$R_{7S\rightarrow 6S} = |A_E \pm A_{PNC}|^2 \simeq E1_\beta{}^2 \pm 2\boldsymbol{E1_\beta E1_{PNC}}$$

- **Stark-interference technique**: cesium atoms pass through a region of perpendicular electric, magnetic, and laser fields. The “handedness" of the experiment is changed by reversing the direction of all fields.



The transition rate is obtained by measuring the amount of 850- and 890-nm light emitted in the 6*P*-6*S* step of the 7*S*-6*S* decay sequence.



✓ The measurements culminated in 1997 when the Boulder group performed a measurement of A_{PNC}/A_E with an uncertainty of just 0.35%.

$$\mathrm{Im}\left(\frac{E_{PNC}}{\beta}\right) = -1.5935(56)\ \frac{\mathrm{mV}}{\mathrm{cm}}$$

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

The PV amplitude is in units of the equivalent electric field required to give the same mixing of S and Pstates as the PV interaction

[Roberts et al., Annu. Rev. Nucl. Part. Sci. 65, 63 (2015)]

State of the art of E_{PNC} and weak charge

[Dzuba V.A. et al. PRL 109, 203003 (2012)]

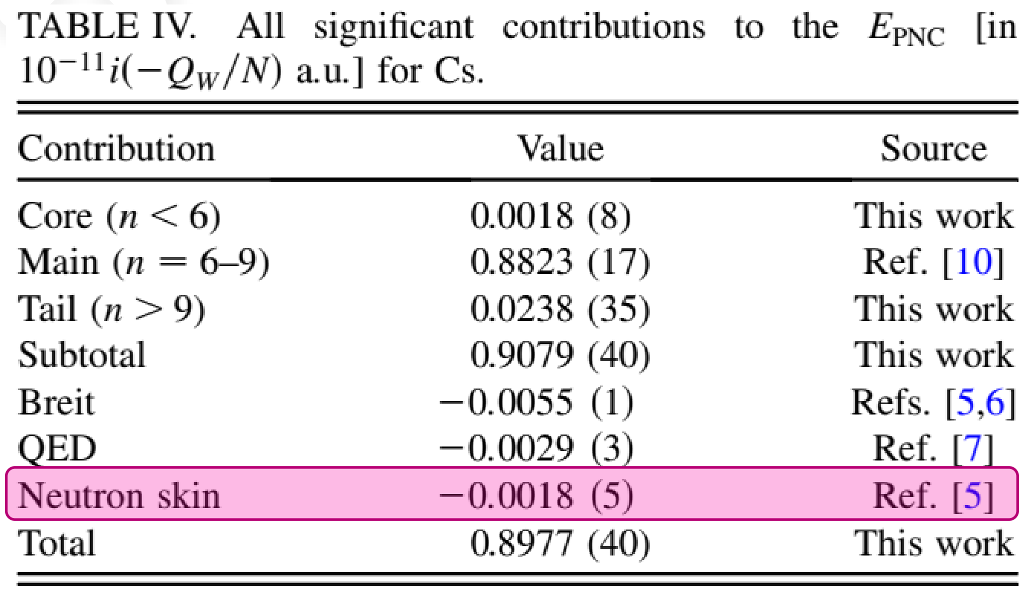


TABLE IV. All significant contributions to the E_{PNC} [in $10^{-11}i(-Q_W/N)$ a.u.] for Cs.

Contribution	Value	Source
Core ($n < 6$)	0.0018 (8)	This work
Main ($n = 6$–9)	0.8823 (17)	Ref. [10]
Tail ($n > 9$)	0.0238 (35)	This work
Subtotal	0.9079 (40)	This work
Breit	−0.0055 (1)	Refs. [5,6]
QED	−0.0029 (3)	Ref. [7]
Neutron skin	−0.0018 (5)	Ref. [5]
Total	0.8977 (40)	This work

$$E_{\text{PNC}} = 0.8977(40) \times 10^{-11} i(-Q_W/N)$$

$$Q_W^{\text{exp.}}\left({}^{133}_{55}Cs\right) = -72.58(29)_{\text{expt}}(32)_{\text{theory}}$$

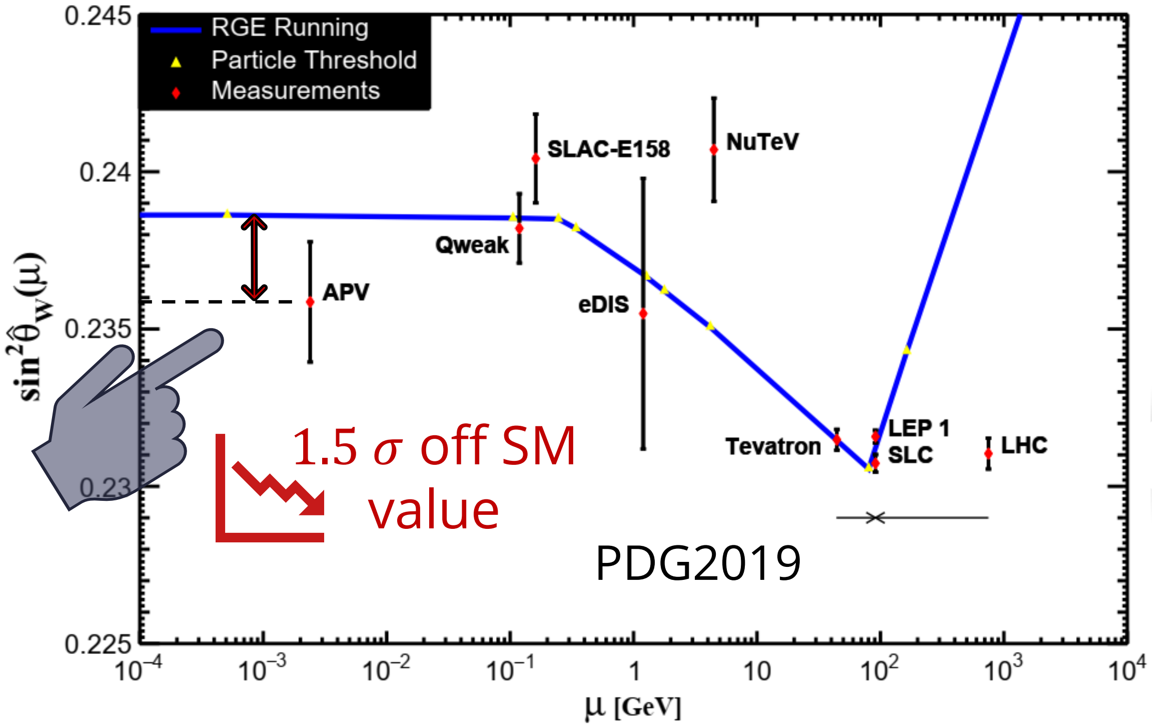
$$\mathbf{\sin^2\theta_W^{APV} = 0.2356(20)}$$

✓ Weak charge in the SM including radiative corrections

$$Q_W^{SM+\text{r.c.}} \equiv -2\left[Z\left(g_{AV}^{ep} + 0.00005\right) + N\left(g_{AV}^{en} + 0.00006\right)\right]\left(1 - \frac{\alpha}{2\pi}\right)$$

$$\approx Z\left(1 - 4\sin^2\theta_W^{SM}\right) - N \Rightarrow Q_W^{SM+r.c.}\left({}^{133}_{55}Cs\right) = -73.23(1)$$

SM prediction: $\sin^2\hat{\theta}_W(0) = 0.23857(5)$



1.5 σ off SM value

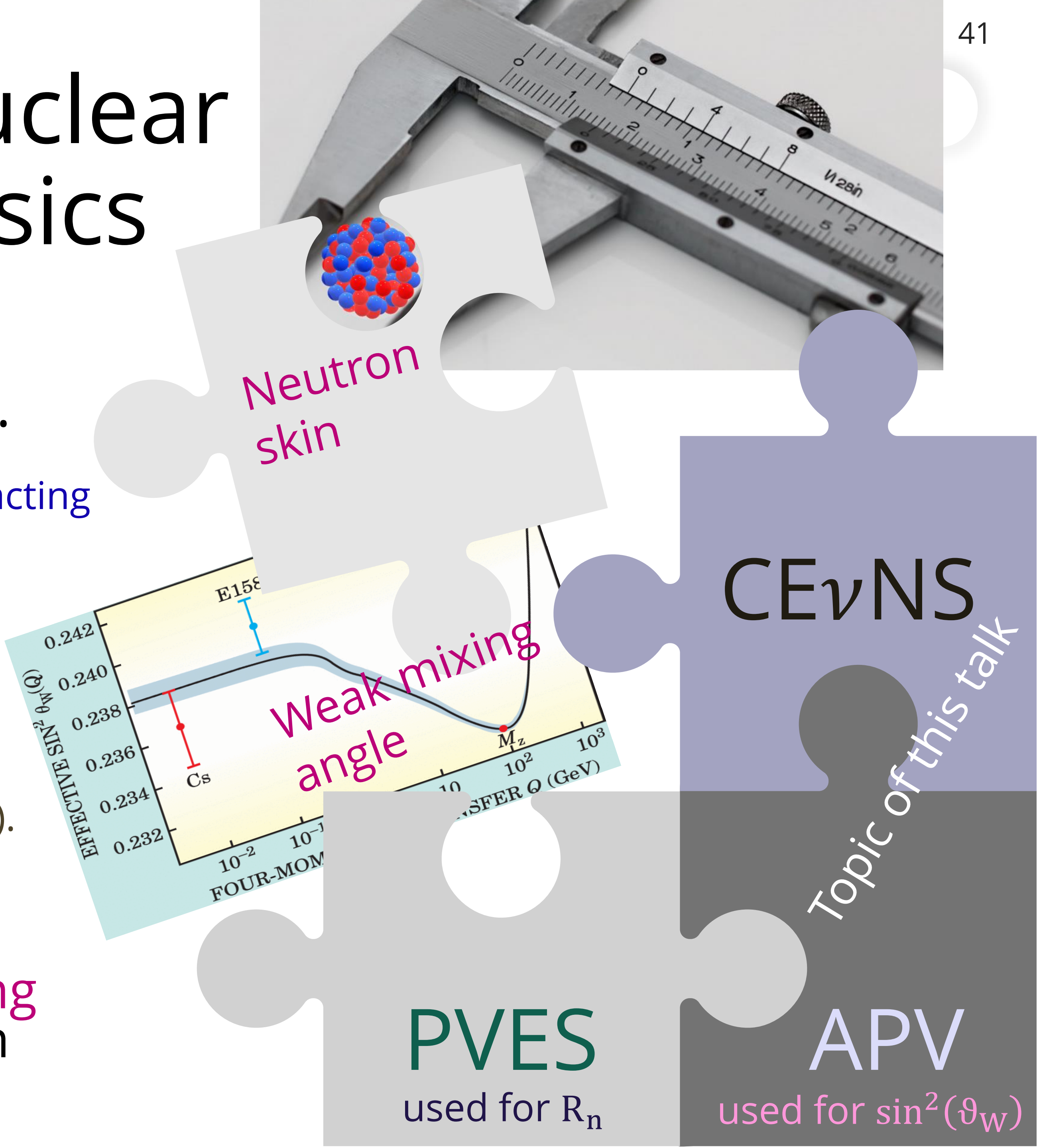
PDG2019

Interplay between nuclear and electroweak physics

- This feature is always present when dealing with electroweak processes.

- Atomic Parity Violation (APV): atomic electrons interacting with nuclei. Cs and Pb available.
- Parity Violation Electron Scattering (PVES): polarized electron scattering on nuclei. PREX(Pb), CREX(Ca), Qweak(Al), Qweak(p).
- Coherent elastic neutrino-nucleus scattering (CEνNS). Cesium-iodide (CsI), argon (Ar) and germanium (Ge) available.

- Can we gain information combining different EW processes together in order to break this degeneracy?



Neutron skin

Weak mixing angle

CEνNS

Topic of this talk

PVES

used for R_n

APV

used for $\sin^2(\vartheta_W)$

Extracting the weak charge from APV

$$Q_W = N\left(\frac{\mathrm{Im}\,E_{\mathrm{PNC}}}{\beta}\right)_{\mathrm{exp.}}\left(\frac{Q_W}{N\,\mathrm{Im}\,E_{\mathrm{PNC}}}\right)_{\mathrm{th.}}\beta_{\mathrm{exp.+th.}}$$

+ Experimental value of electric dipole transition amplitude between 6S and 7S states in Cs

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

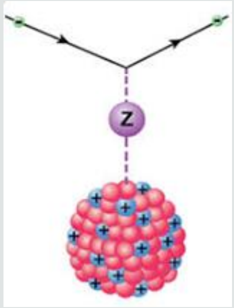
J. Guena, et al., PRA **71**, 042108 (2005)

PDG2020 average

$$\mathrm{Im}\left(\frac{E_{\mathrm{PNC}}}{\beta}\right) = -1.5924(55)\ \mathrm{mV/cm}$$

✓ Theoretical amplitude of the electric dipole transition

$$E_{\mathrm{PNC}} = \sum_n \left[\frac{\langle 6s|H_{\mathrm{PNC}}|np_{1/2}\rangle\langle np_{1/2}|\boldsymbol{d}|7s\rangle}{E_{6s}-E_{np_{1/2}}} + \frac{\langle 6s|\boldsymbol{d}|np_{1/2}\rangle\langle np_{1/2}|H_{\mathrm{PNC}}|7s\rangle}{E_{7s}-E_{np_{1/2}}}\right],$$



➢ where ***d*** is the electric dipole operator, and

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

S. G. Porsev et al. PRD 82, 036008 (2010)

B. K. Sahoo et al. PRD 103, L111303 (2021)

$$\mathrm{Im}\,E_{\mathrm{PNC}} = (0.8977 \pm 0.0040)\times 10^{-11}|e|\,a_B\,Q_W/N$$

Used by PDG2020 (V. Dzuba *et al.*, PRL 109, 203003 (2012)) but see also

nuclear Hamiltonian describing the **electron-nucleus weak interaction**

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

β: tensor transition polarizability

It characterizes the size of the Stark mixing induced electric dipole amplitude (external electric field)

Bennet & Wieman, PRL 82, 2484 (1999)

Dzuba & Flambaum, PRA 62 052101 (2000)

PDG2020 average

$\beta = 27.064\ (33)\ a_B^3$

Atomic Parity Violation for weak mixing angle measurements

- ✓ Weak charge in the SM including radiative corrections

Using SM prediction at low energy
$\sin^2\hat{\theta}_W(0) = 0.23857(5)$

$$Q_W^{SM+\text{r.c.}} \equiv -2\left[Z\left(g_{AV}^{ep}+0.00005\right)+N\left(g_{AV}^{en}+0.00006\right)\right]\left(1-\frac{\alpha}{2\pi}\right) \approx Z\left(1-\ 4\sin^2\theta_W^{SM}\right)-N$$

Theoretically

$$Q_W^{SM\ \text{th}}\left({}^{133}_{55}Cs\right) = -73.23(1)$$

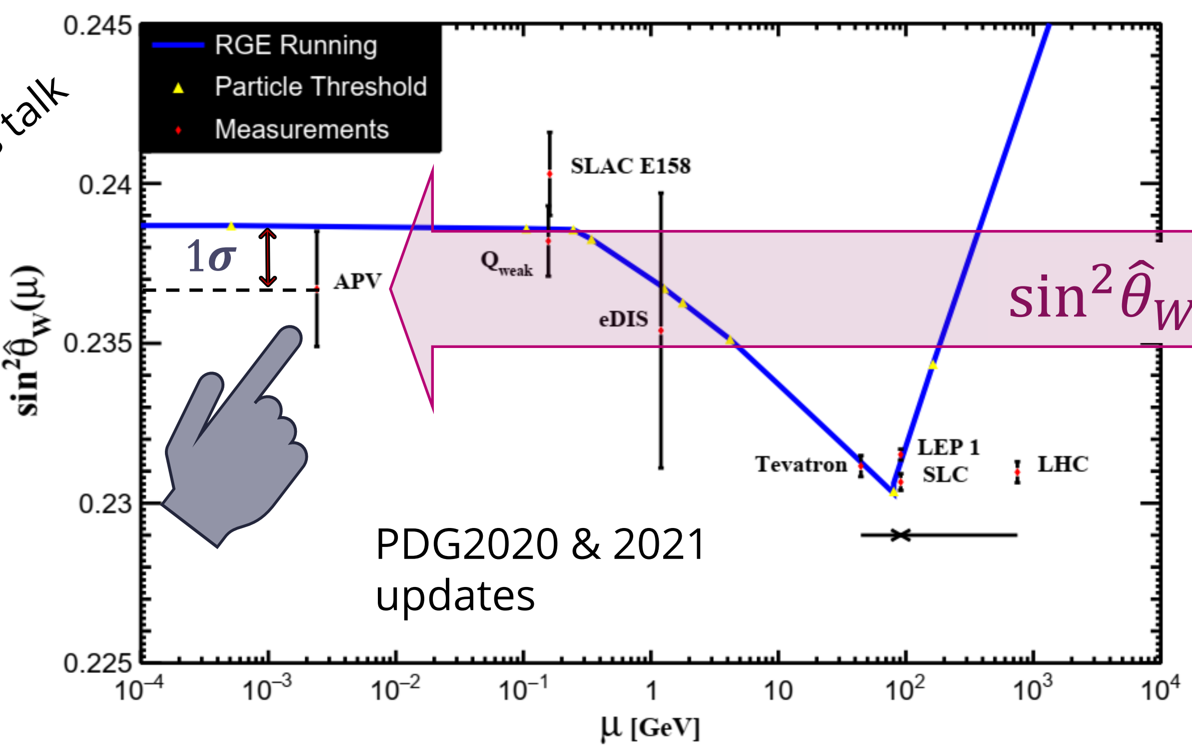
1σ difference

Experimentally

$$Q_W^{\text{exp.}}\left({}^{133}_{55}Cs\right) = -72.82(42)$$

$\sin^2\hat{\theta}_W(2.4\text{ MeV})$=0.2367±0.0018

See R. F. Hernandez's talk

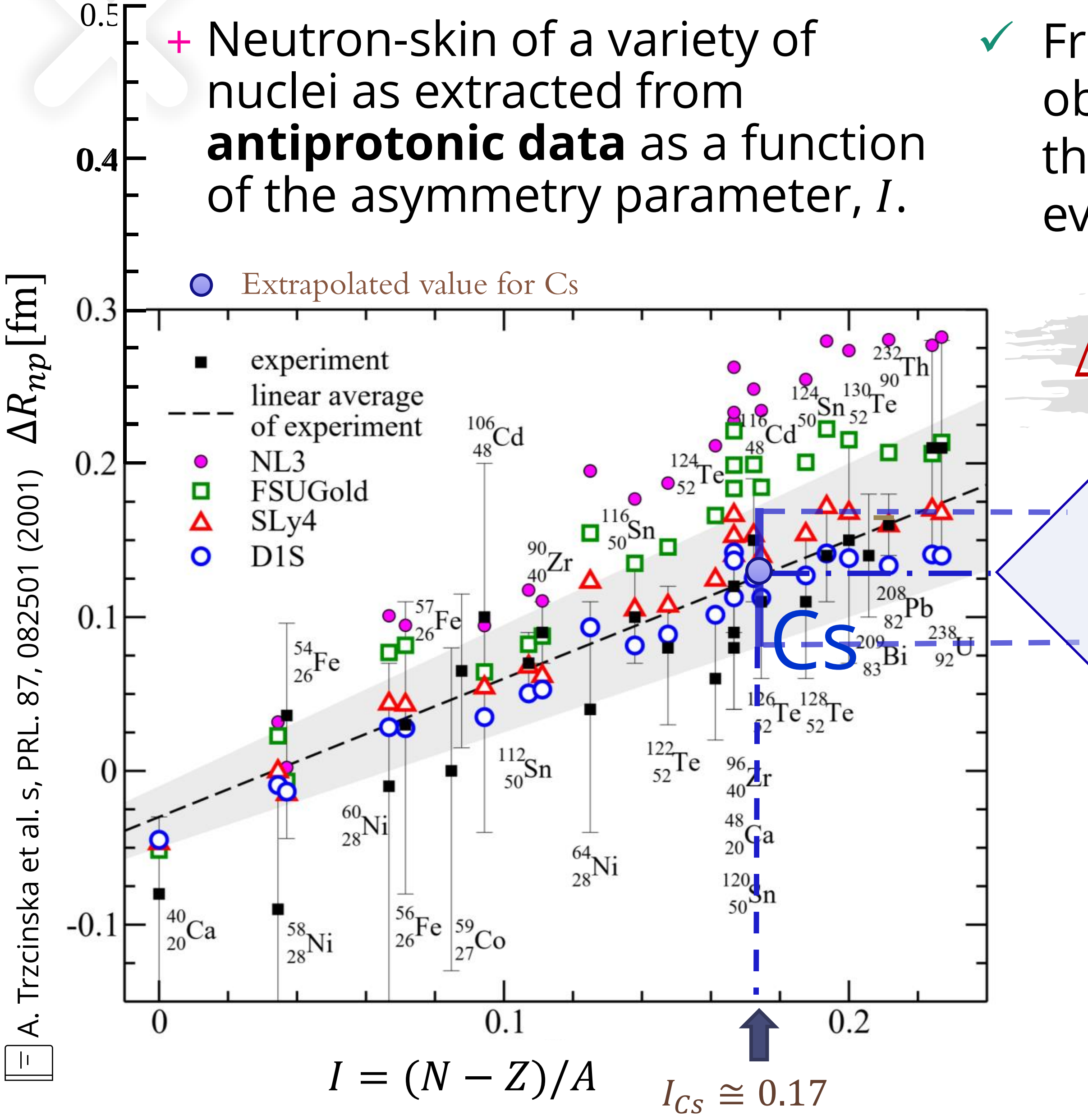


PDG2020 & 2021 updates

P.A. Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

But which Cs neutron skin correction is used?

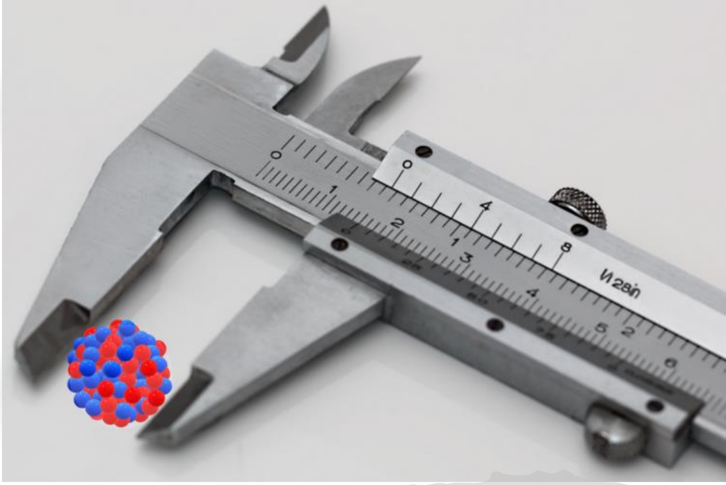
Extrapolated value of ΔR_{np}^{Cs}



A. Trzcinska et al. s, PRL. 87, 082501 (2001)

- + Neutron-skin of a variety of nuclei as extracted from **antiprotonic data** as a function of the asymmetry parameter, I.

- ✓ From this **linear fit** one obtains the relation for the neutron skin for every nuclei



$$\Delta R_{np}[\mathrm{fm}] = -(0.04 \pm 0.03) + (1.01 \pm 0.15)\frac{N-Z}{A}$$

For cesium it gives

$$\Delta R_{np}^{Cs}(\mathrm{extrap}) \cong 0.13 \pm 0.04 \text{ fm}$$

Extrapolated (not measured) value for cesium! ⚠

Antiprotonic data: radiochemical and the other based on x-ray data constraining the neutron distribution at the nuclear periphery

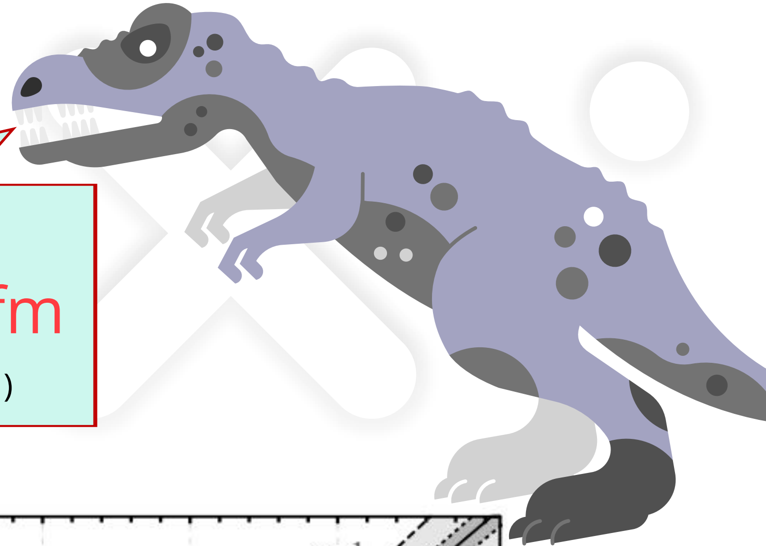
M. Thiel et al., Journal of Physics G, 46, 9 (2019), arXiv:1904.12269v1

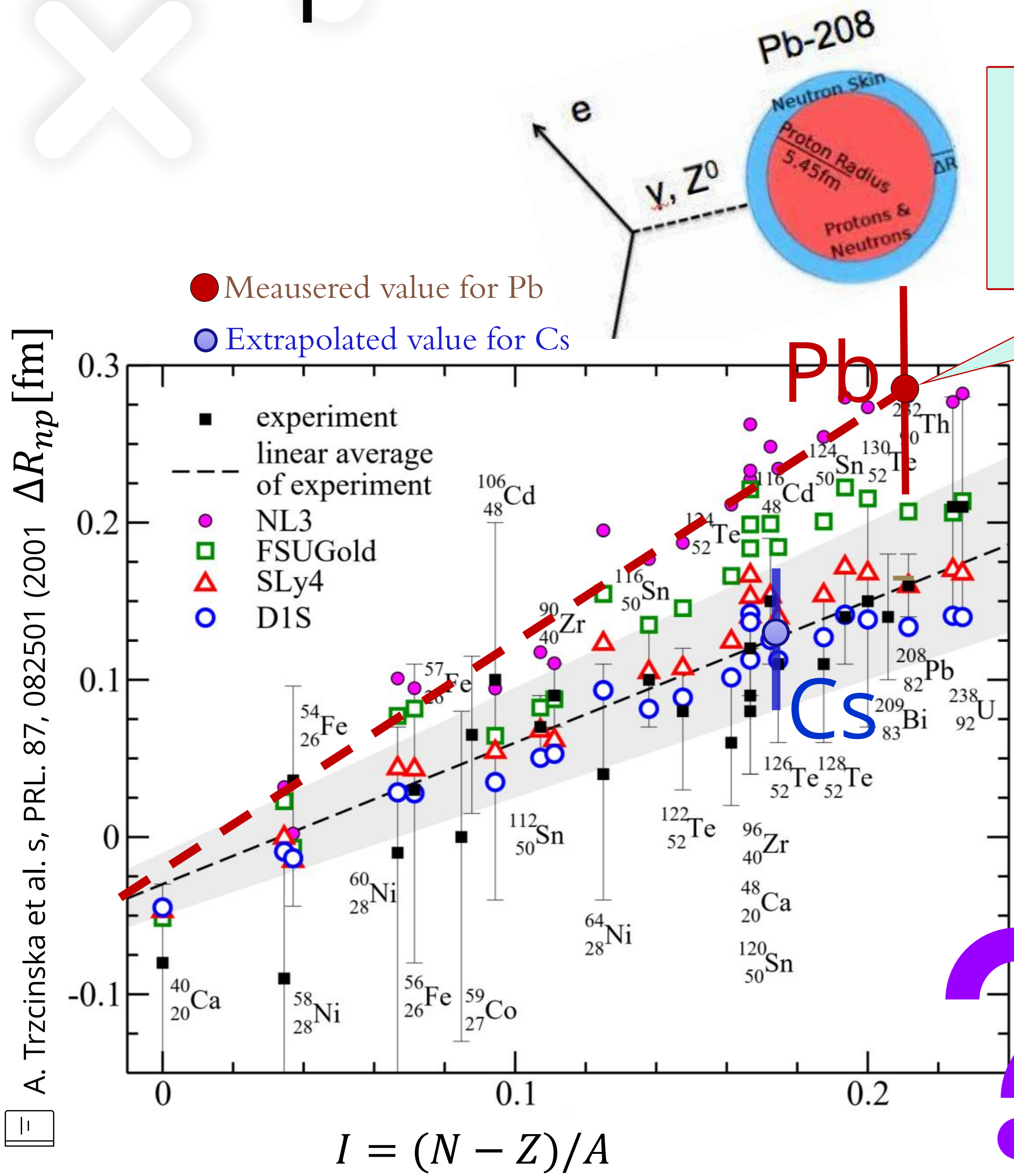
Extrapolated value of ΔR_{np}^{Cs}

PREX-I & PREX-II

$\Delta R_{np}^{Pb} = 0.283 \pm 0.071$ fm

D. Adhikari *et al.* PRL 126, 172502 (2021)

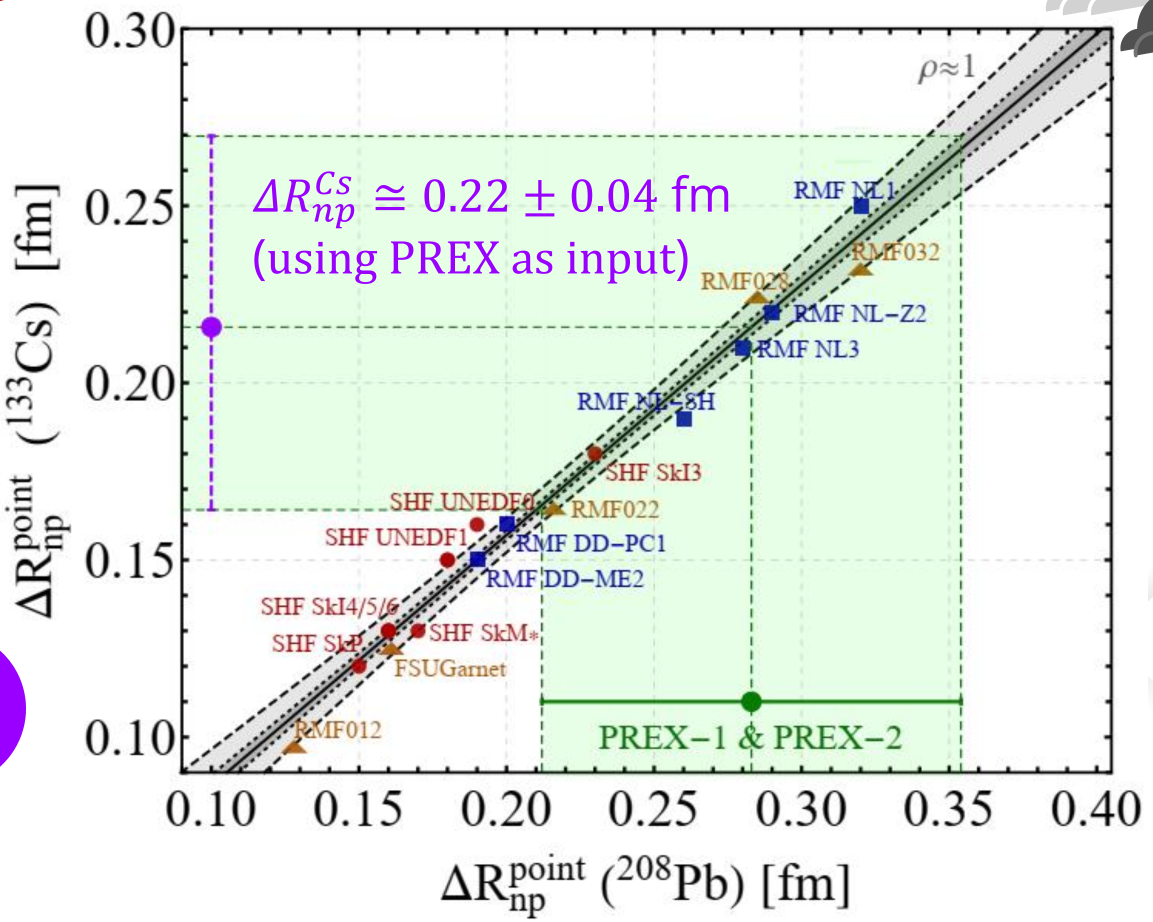




A. Trzcinska et al. s, PRL. 87, 082501 (2001

?

$\Delta R_{np}^{Cs} \cong 0.22 \pm 0.04$ fm (using PREX as input)

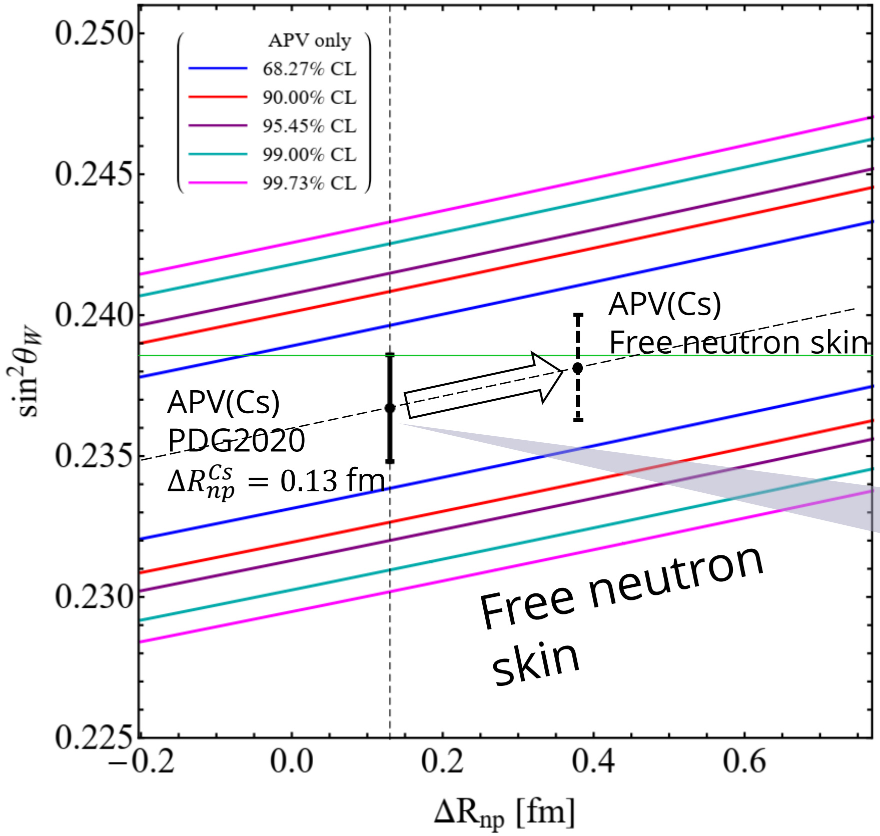


M. Cadeddu et al. PRD 104, L011701 (2021), arXiv:2104.03280

The dilemma

APV (Cs)

- Sensitive to the weak mixing angle
- Less sensitive to the neutron skin

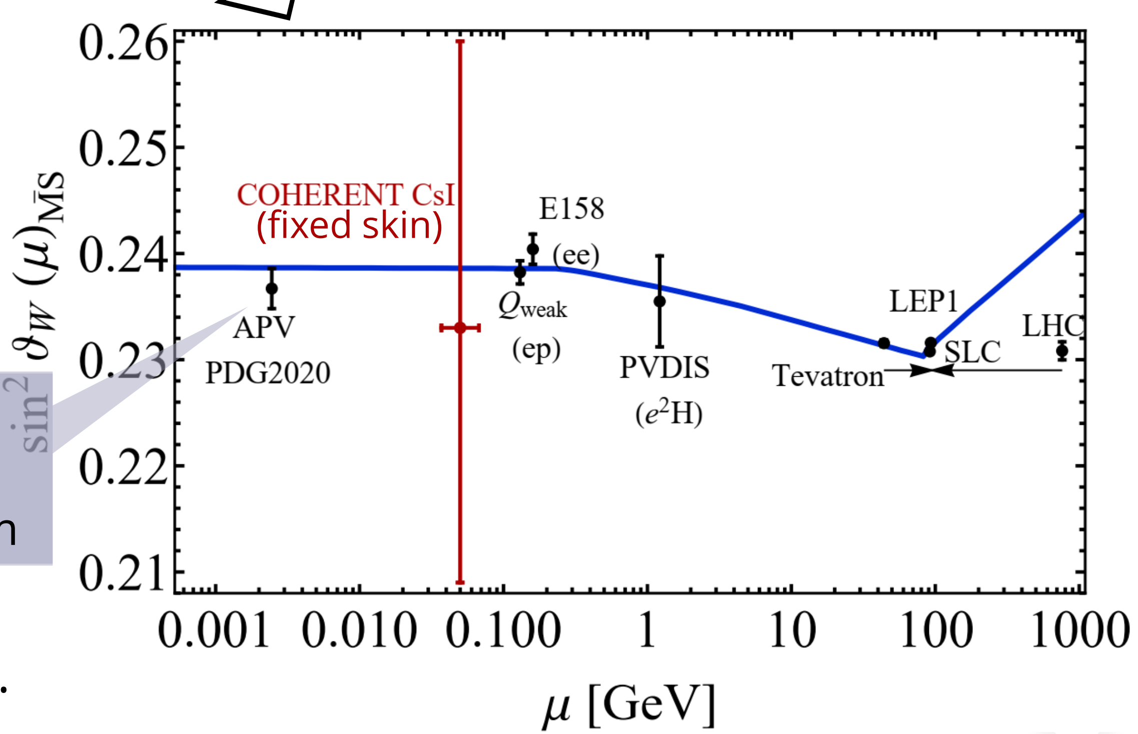


APV(Cs) PDG2020 corresponds to $\Delta R_{np}^{Cs}(\mathrm{Extr.}) = 0.13$ fm

Extrapolated from antiprotonic atoms…

COHERENT (CsI)

- CEνNS is sensitive to the neutron skin
- But less sensitive to the weak mixing angle



Combined COHERENT(CsI)+ APV(Cs) analysis

- ✓ Assuming to know the value of the weak mixing angle at low energy $\sin^2\hat{\theta}_W(0) = 0.23857(5)$

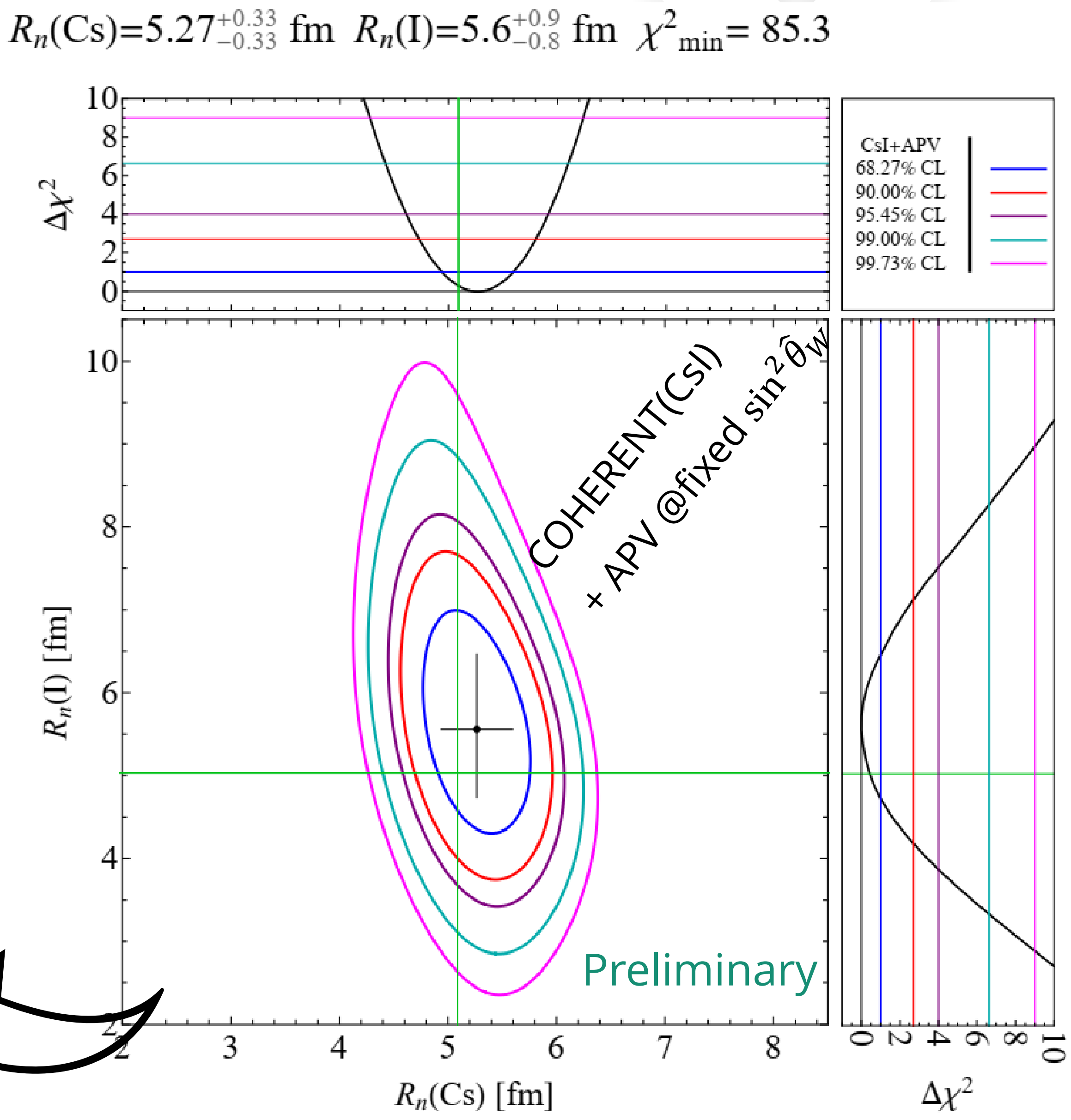
COHERENT χ^2 APV χ^2

$$\chi^2 = \chi^2_{\mathrm{C}} + \left(\frac{Q_W^{\mathrm{Cs\,ns}}(R_n) - Q_W^{\mathrm{th}}(\sin^2\vartheta_W)}{\sigma_{\mathrm{APV}}(R_n, \sin^2\vartheta_W)} \right)^2$$

$\Delta R_{np}(^{127}\mathrm{I})= R_n - R_p = 0.8^{+0.9}_{-0.8}$ fm

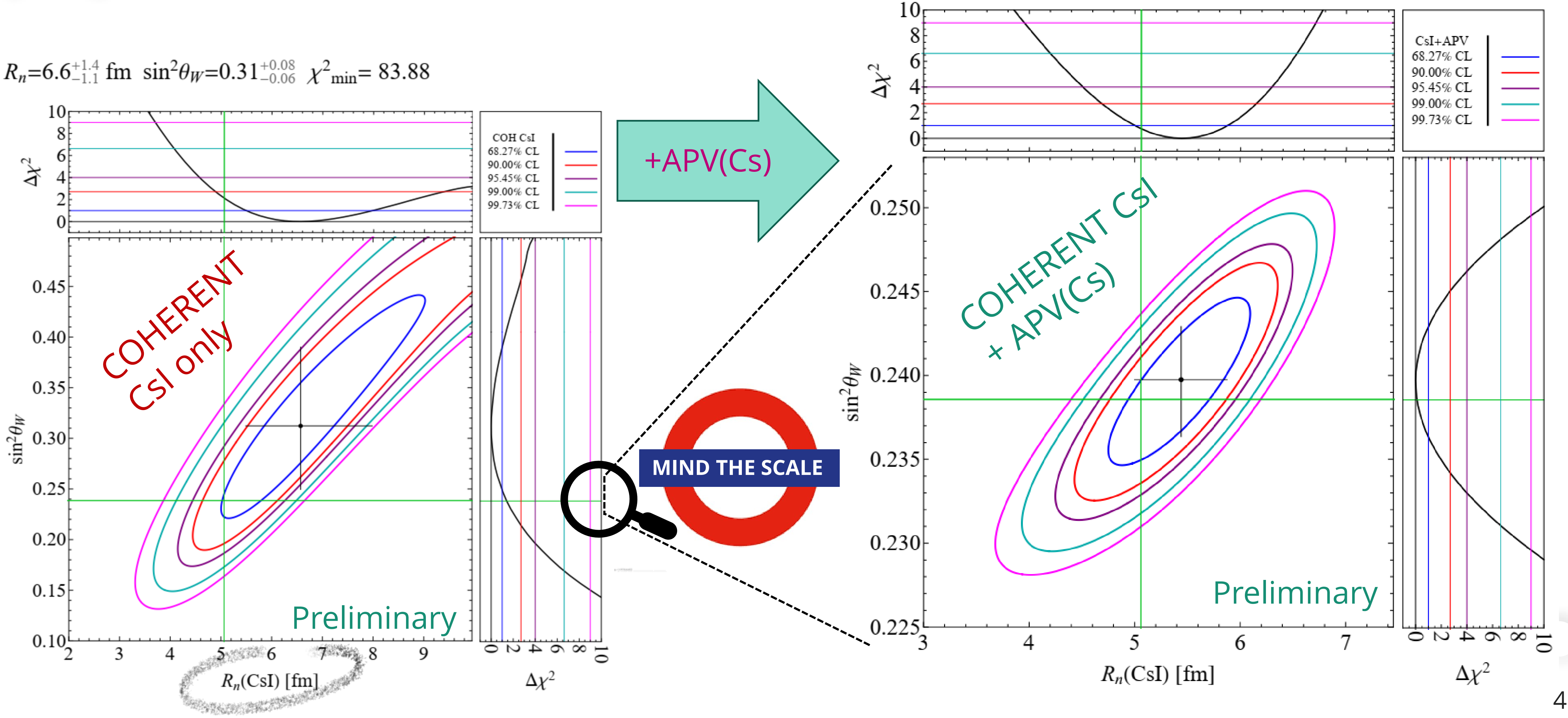
$\Delta R_{np}(^{133}\mathrm{Cs})= R_n - R_p = 0.45^{+0.33}_{-0.33}$ fm

Contribution of Cs and I disentangled!!



Cadeddu et al., PRC 104, 065502
arXiv:2102.06153 Updated in this talk!

Second advantage: extract both R_n(CsI) and $\sin^2\hat{\theta}_W$ from data



$R_n=6.6^{+1.4}_{-1.1}$ fm $\sin^2\theta_W=0.31^{+0.08}_{-0.06}$ $\chi^2_{\min}=83.88$

$R_n=5.4^{+0.4}_{-0.4}$ fm $\sin^2\theta_W=0.2397^{+0.0032}_{-0.0034}$ $\chi^2_{\min}=85.27$

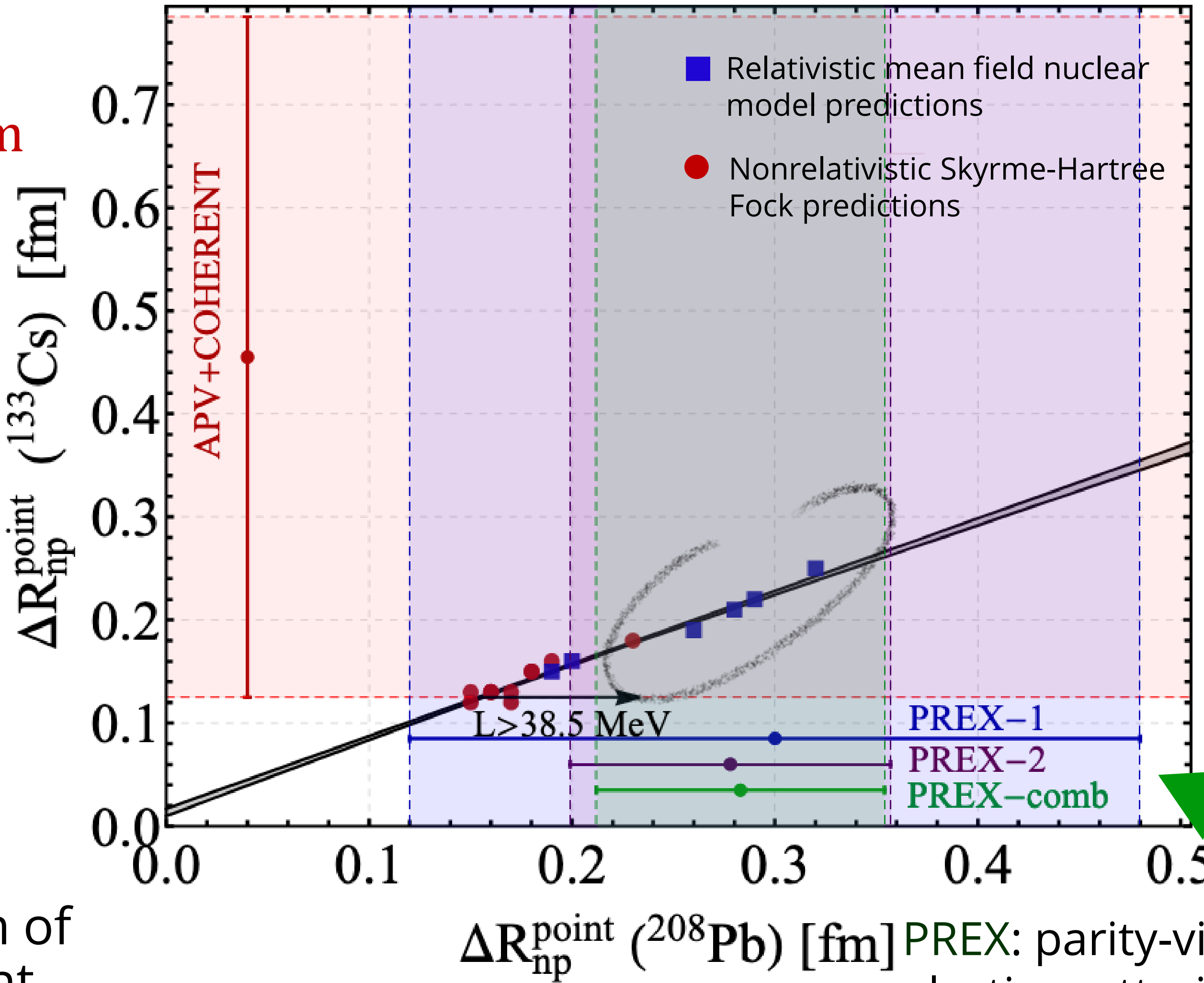
+APV(Cs)

MIND THE SCALE

COHERENT+APV compared to PREX

$\Delta R_{np}(^{133}\mathrm{Cs}) = 0.45^{+0.33}_{-0.33}$ fm

@fixed $\sin^2\hat{\theta}_W$



Cadeddu et al., PRC 104, 065502
arXiv:2102.06153

@fixed $\sin^2\hat{\theta}_W$

- Strong linear correlation between the neutron skin of Cs and Pb among different nuclear model predictions

PREX: parity-violating asymmetry in the elastic scattering of longitudinally polarized electrons on ^{208}Pb

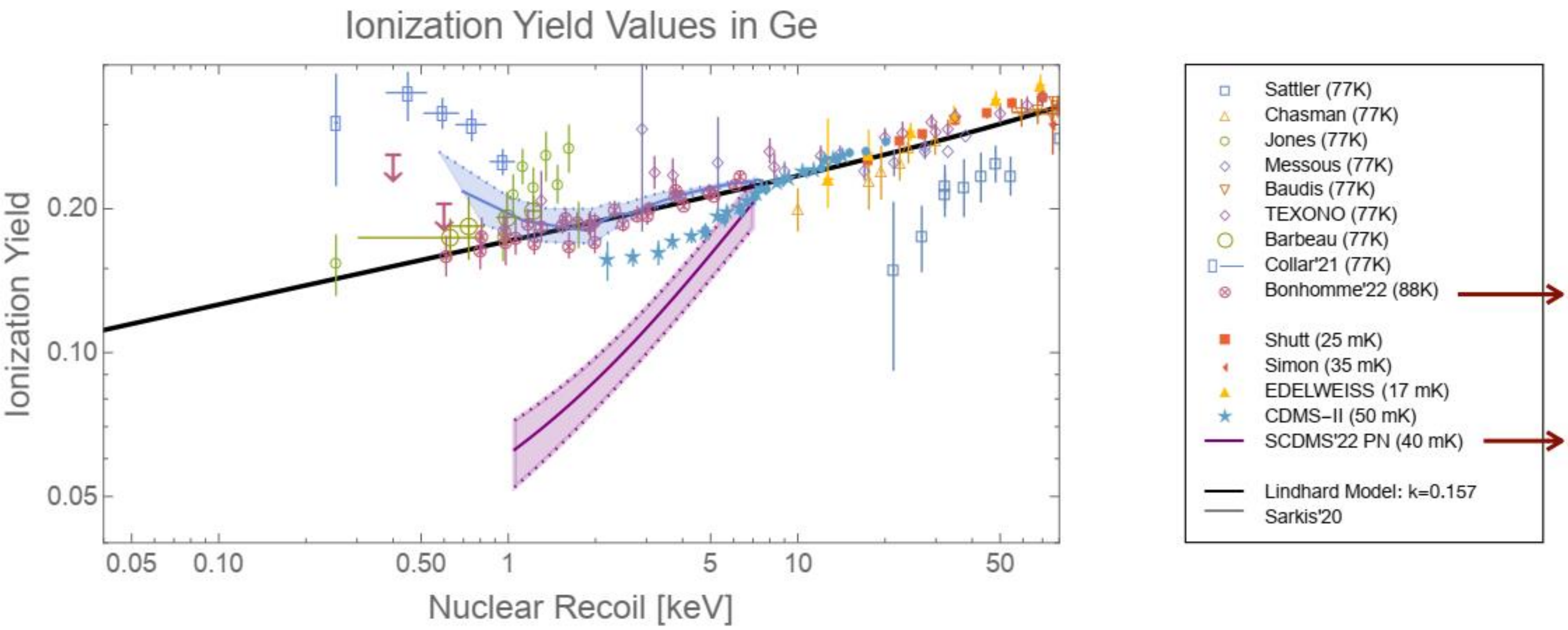
PREX, PRL 126, 172502 (2021)

$$A_{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2 |Q_W|}{4\sqrt{2}\pi\alpha Z} \frac{F_{\mathrm{W}}(Q^2)}{F_{\mathrm{ch}}(Q^2)}$$

+ Dresden-II quenching

Photo-neutron Ionization Yield in Context

- Multiple yield measurements in Ge are inconsistent with each other
- Variations in operating temperature, electric field and experiment specific parameters suggest a more nuanced yield response at low recoil energies
- Git repository being assembled to collect literature values of yield and operating conditions



arXiv:2202.03754

arXiv:2202.07043

Credits to T. Saab @ EXCESS Workhosp