BSM: Bounds based on muonic hydrogen, muonic deuterium and muonic helium

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Type of new physics interaction considered here

In general, for a massive force mediator of integer spin s,

$$V_{\mathrm{NP}}(r) = (-1)^{s+1}\frac{g_l g_N}{4\pi}\,\frac{1}{r}\,e^{-m_{X_0} r}$$

Type of new physics interaction considered here

Using light atoms spectroscopic data in searching for such an interaction: E.g.,

Jaekel and Roy [PRD **82**, 125020 (2010)]

Karshenboim [PRL **104**, 220406 (2010)]

Brax and Burrage [PRD **83**, 035020 (2011)]

Delaunay et al [PRD **96**, 115002 (2017)] ←

Jones et al [PRRes **2**, 013244 (2020)]

Frugiuele and Peset [JHEP **05**, 002 (2022)] ←

Delaunay et al [PRL **130**, 121801 (2023)] ←

Potvliege et al [PRA **108**, 052825 (2023)]

Potvliege [NJP **27**, 045002 (2025)]

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$$1 \text{ eV} \leq m_{X_0} \leq 1 \text{ MeV}$$

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$$g_l = g_e \text{ or } g_\mu$$

$$g_\mu / g_e = 1? \qquad g_\mu / g_e = m_\mu / m_e?$$

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$$g_N = g_p,\ g_d,\ g_h \text{ or } g_\alpha$$

$$g_n = g_d - g_p = g_\alpha - g_h$$

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In general, for a massive force mediator of integer spin s,

$$V_{\rm NP}(r) = (-1)^{s+1} \frac{g_l g_N}{4\pi} \frac{1}{r} e^{-m_{X_0} r}$$

Our aim: Set upper bounds on $g_e g_p$ and $g_e g_n$.

NP shifts

In general, for a massive force mediator of integer spin s,

$$V_{\rm NP}(r) = (-1)^{s+1}\frac{g_l g_N}{4\pi}\,\frac{1}{r}\,e^{-m_{X_0} r}$$

Energy shift: $\delta E^{\rm NP}_{nl} = \langle\, n, l\,|\, V_{\rm NP}\,|\, n, l\,\rangle$

NP shifts

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$$V_{\mathrm{NP}}(r) = (-1)^{s+1} \frac{g_l g_N}{4\pi} \frac{1}{r} e^{-m_{X_0} r}$$

Energy shift: $\delta E_{nl}^{\mathrm{NP}} = \langle n, l \,|\, V_{\mathrm{NP}} \,|\, n, l \rangle$

Shift of the transition frequency: $\nu_{ba}^{\mathrm{NP}} = (\delta E_{n_b l_b}^{\mathrm{NP}} - \delta E_{n_a l_a}^{\mathrm{NP}})/h$

Chi-squared fitting to the standard model

How compatible is experiment with theory, assuming a NP interaction?

$$\nu^{\mathrm{SM}}_{b_i a_i}(\mathcal{R}, r_p, r_d) \doteq \nu^{\mathrm{exp}}_{b_i a_i} - \nu^{\mathrm{NP}}_{b_i a_i}, \quad i = 1, 2, 3, \ldots$$

$\mathcal{R}$: the Rydberg constant

r_p : proton charge radius

r_d : deuteron charge radius

Chi-squared fitting to the standard model

Two possible approaches:

1. Use all the available data

- Single species only (e.g., eH)
- Combine eH, eD, r_p(μH) and r_d(μD)
- Combine eH, eD, r_p(μH), r_d(μD), g-factors, molecular systems, …

[Delaunay et al (2023)]

2. Use selected transitions only

- E.g., the isotope shift of the 1s – 2s interval + r_p(μH) and r_d(μD) or Lamb shift only, …

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Chi-squared fitting to the standard model

1. Use all the available data

Pros: Use a number of independent measurements; broad range of transitions

Cons: Discrepancies in the data tend to make the bounds more stringent for no good reasons; need to magnify the experimental errors; large number of degrees of freedom may hide trends

Chi-squared fitting to the standard model

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Pros: Use a number of independent measurements; broad range of transitions

Cons: Discrepancies in the data tend to make the bounds more stringent for no good reasons; need to magnify the experimental errors; large number of degrees of freedom may hide trends

2. Use selected transitions only

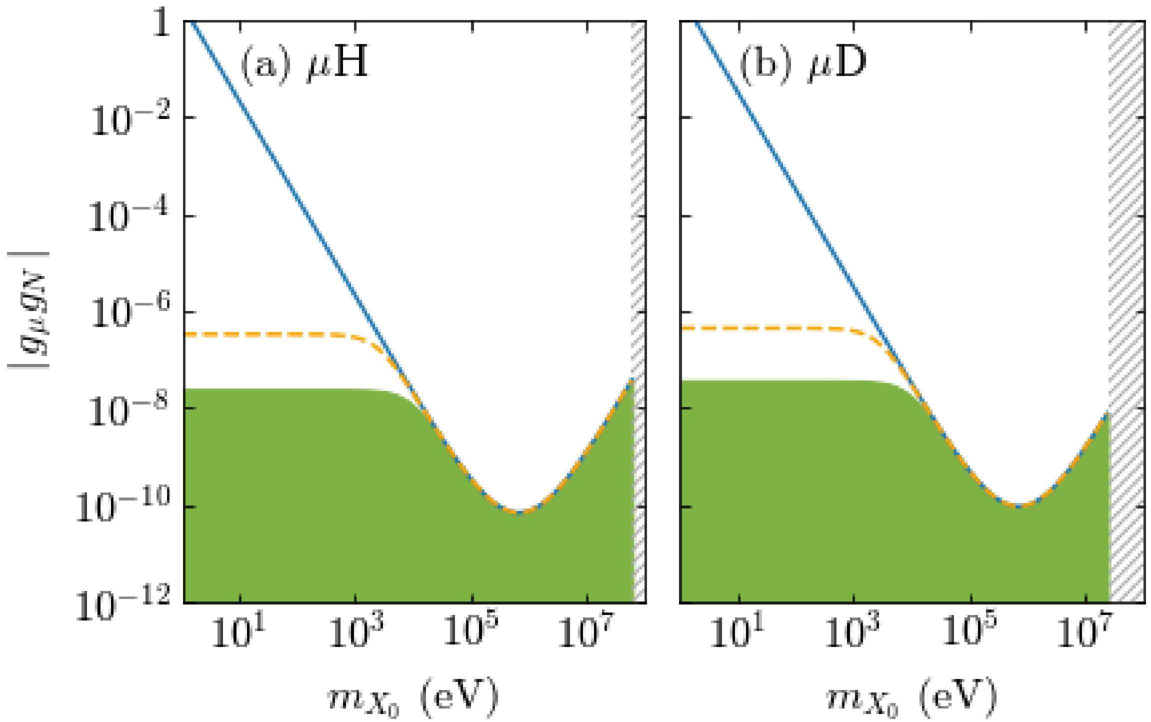
Pros: Reduces discrepancies, focuses on the most precise data

Cons: Relies on the accuracy of a small number of measurements

Sensitivity of the muonic species on NP

Values of $g_\mu g_p$ or $g_\mu g_d$ for which the NP shift of the $2s_{1/2}$ - $2p_{3/2}$ interval in μH or μD is less than 5% of the respective experimental error

Dirac wave functions for the Uehling potential and the nucleus charge distribution



[PRA **108**, 052825 (2023)]

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See also Jaeckel and Roy (2010), Frugiuele and Peset (2022), Peset (this meeting)

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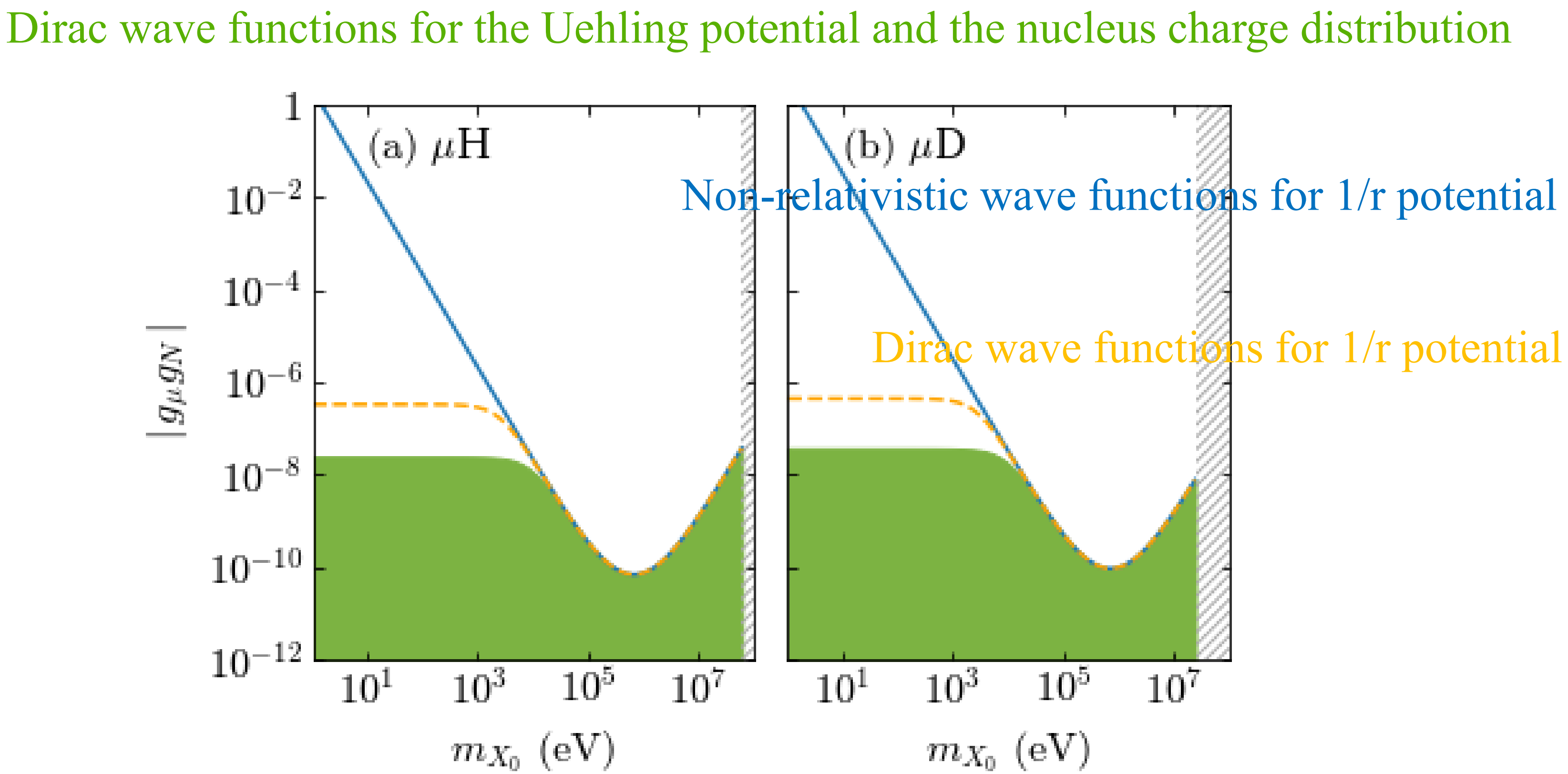
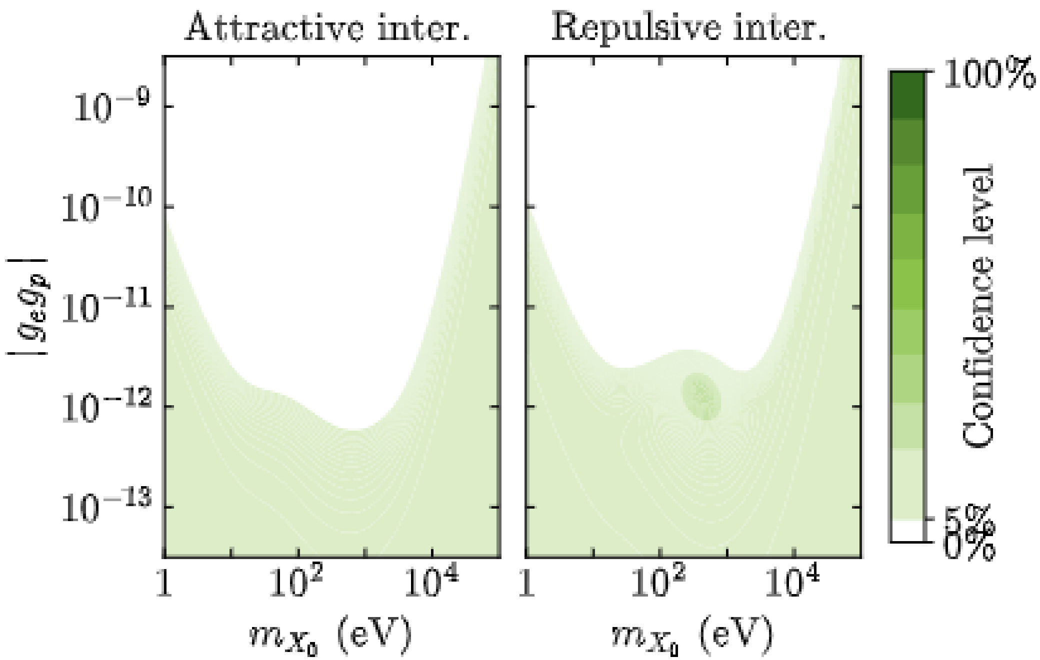


[PRA **108**, 052825 (2023)]

See also Jaeckel and Roy (2010), Frugiuele and Peset (2022), Peset (this meeting)

Bounds on $g_e g_p$ based on the spectroscopy of eH only (World data)



[PRA **108**, 052825 (2023)]

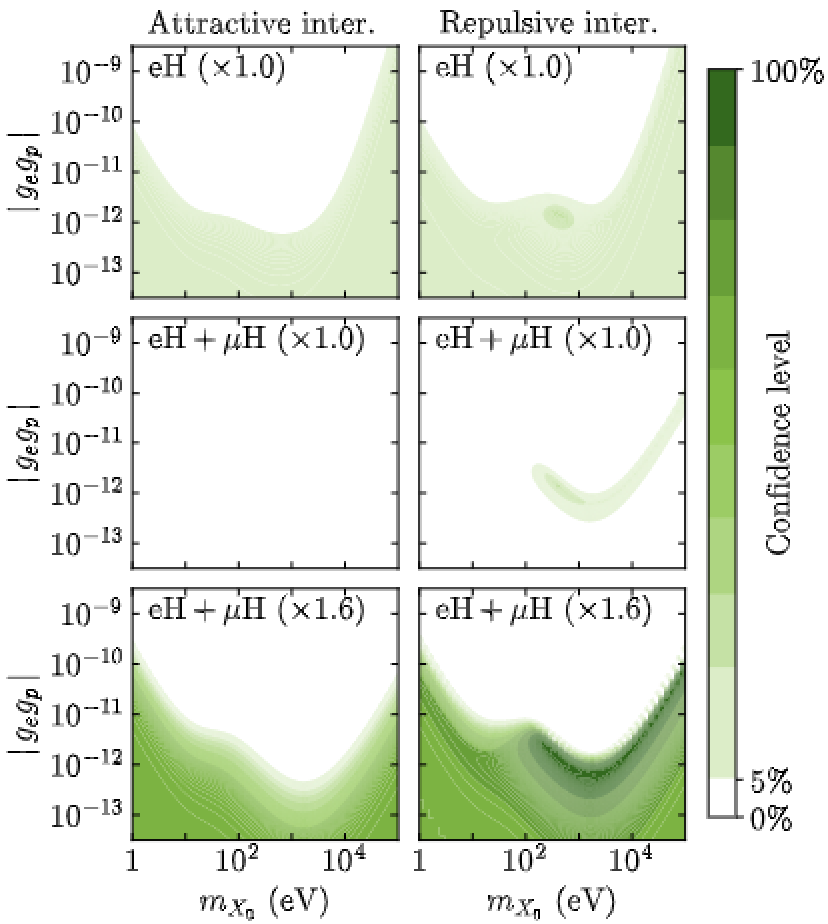
Bounds on gegp

Bounds on $g_e g_p$ based on eH only or on eH + μH ($g_\mu = g_e$)

Without μH →

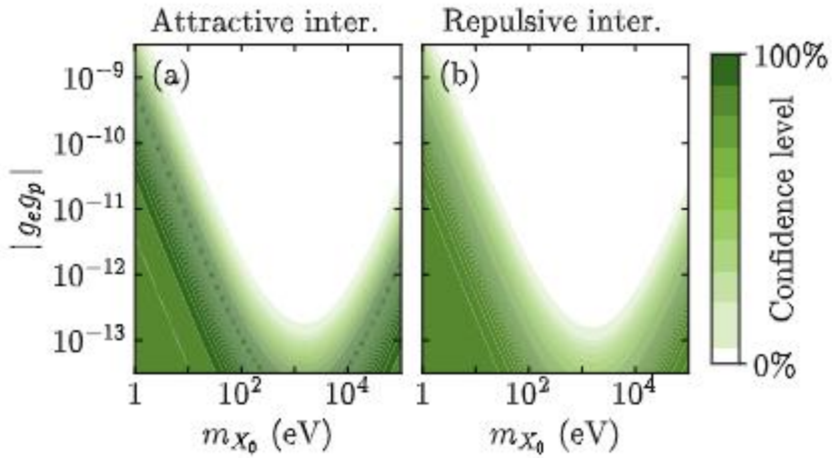
With μH →

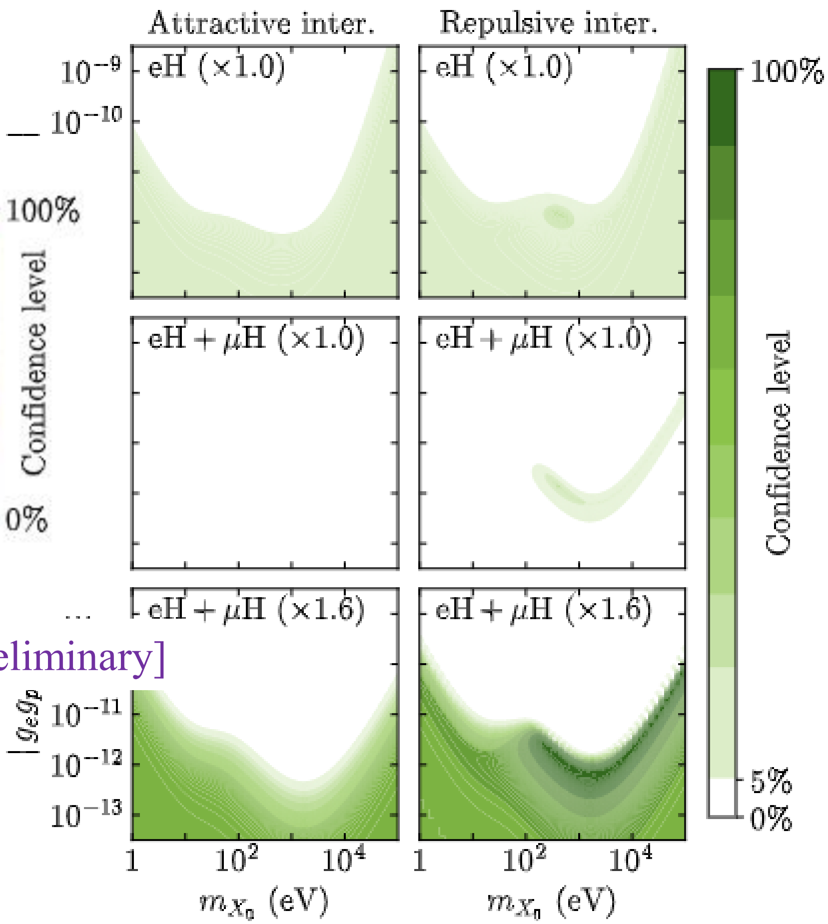
With μH, errors expanded by 60% →



[PRA **108**, 052825 (2023)]

Bounds on gegp





Only with μH, eH(1s-2s) and eH(2s-6p) [preliminary]

Overall bounds

Goal: 95% - bounds on $g_e g_p$ and $g_e g_n$ based on H and D spectroscopy which do not depend on particular choices of g_d/g_p or g_μ/g_e.

[NJP **27**, 045002 (2025)]

Overall bounds

Goal: 95% - bounds on $g_e g_p$ and $g_e g_n$ based on H and D spectroscopy which do not depend on particular choices of g_d/g_p or g_μ/g_e.

Method:

- Vary $g_e g_p$, g_d/g_p and g_μ/g_e and find the maximum values of $g_e g_p$ and $g_e g_n$ (with $g_n = g_d - g_p$) for which the theory fits the data.

[NJP **27**, 045002 (2025)]

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- The fit includes values of $r_p(\mu\text{H})$ and $r_d(\mu\text{D})$ rederived taking the NP interaction into account.

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- The fit includes values of $r_p(\mu\text{H})$ and $r_d(\mu\text{D})$ rederived taking the NP interaction into account.
- Additional constraint: The measured isotope shift of the 1s – 2s interval is consistent with the values of r_p and r_d obtained from the fit.

[NJP **27**, 045002 (2025)]

Overall bounds

Alternative method, entirely based on the isotope shift of the 1s – 2s, 2^3S – 2^1S or 2^3S – 2^3P intervals:

Find the largest value of $g_e g_n$ for which

$$r_d^2(\mathrm{eD}) - r_p^2(\mathrm{eH}) = r_d^2(\mu\mathrm{D}) - r_p^2(\mu\mathrm{H})$$

or

$$r_h^2(\mathrm{e}^3\mathrm{He}) - r_\alpha^2(\mathrm{e}^4\mathrm{He}) = r_h^2(\mu^3\mathrm{He}) - r_\alpha^2(\mu^4\mathrm{He})$$

within experimental and theoretical errors.

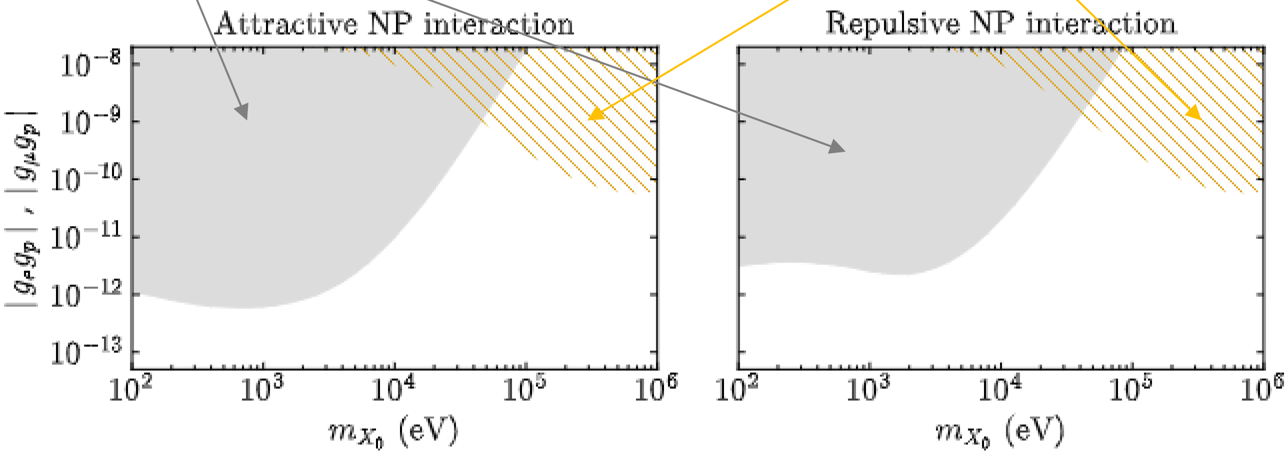
[NJP **27**, 045002 (2025)]

Results based on a global fit

Bounds on $g_e g_p$

Excluded by eH spectroscopy alone

Significant NP contribution to the muonic data

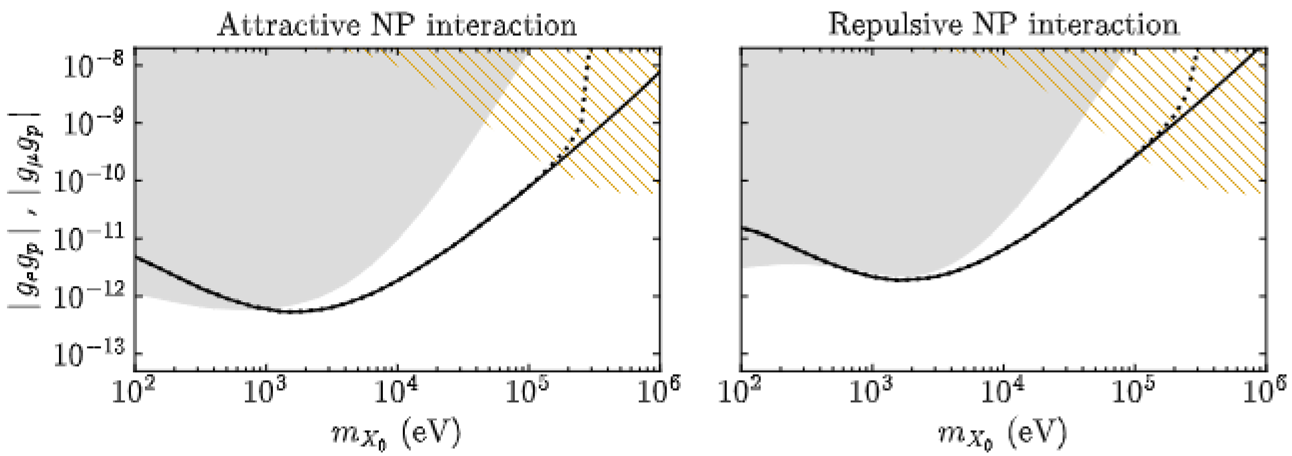


[NJP **27**, 045002 (2025)]

Bounds on $g_e g_p$

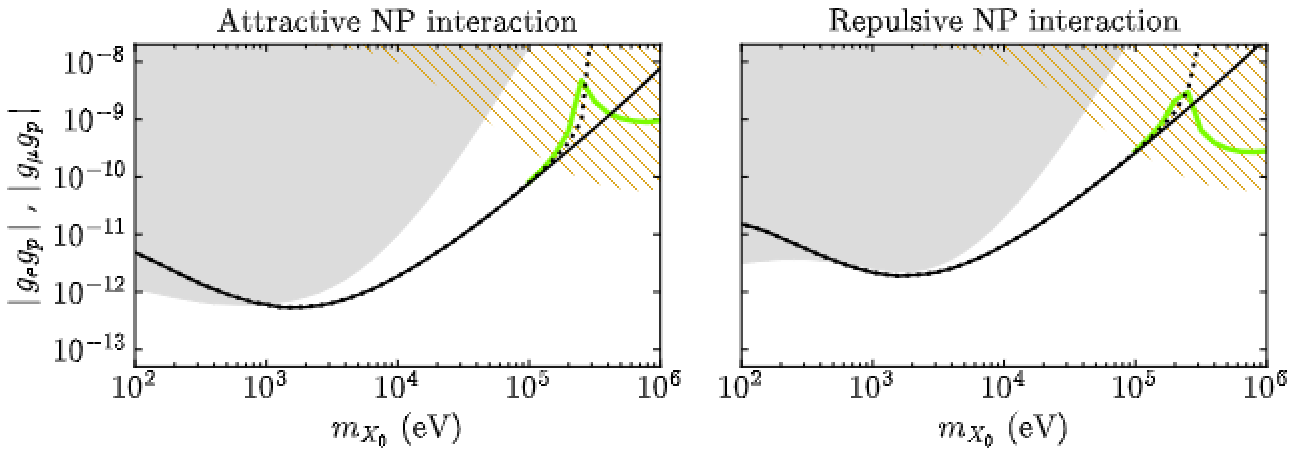
Solid curves: bounds based on eH, eD, μH and μD for g_μ = g_e

Dotted curves: bounds based on eH, eD, μH and μD for -g_e ≤ g_μ ≤ 100 g_e



[NJP **27**, 045002 (2025)]

Green curves: bounds based on eH, eD, μH and μD for g_μ = 207 g_e



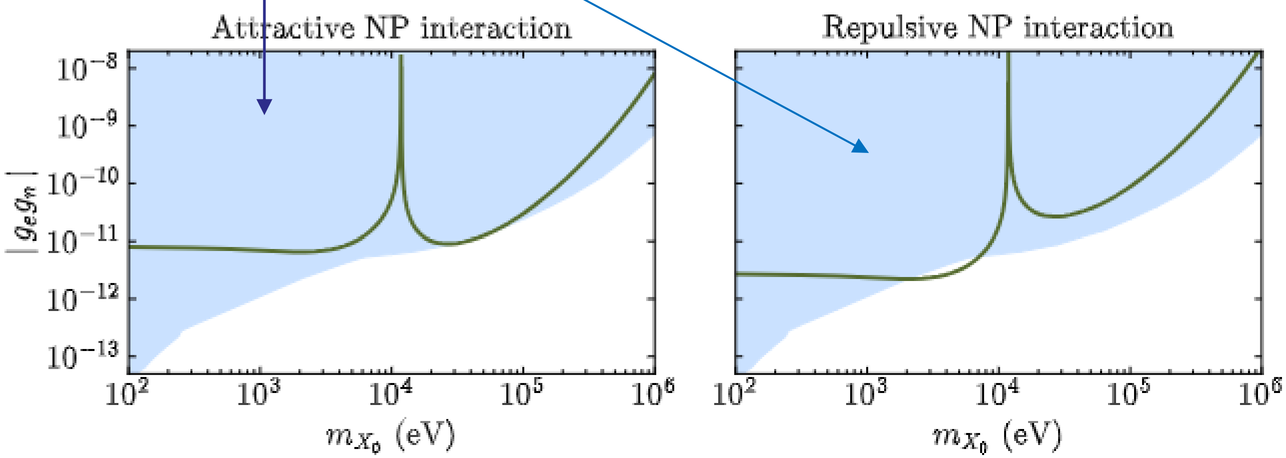
[NJP **27**, 045002 (2025)]

Bounds on $g_e g_n$

Excluded by neutron scattering data + anomalous magnetic moment of the electron

[Delaunay et al (2017)]

Bounds from Yb/Yb+ isotope shift [Hur et al (2022)]

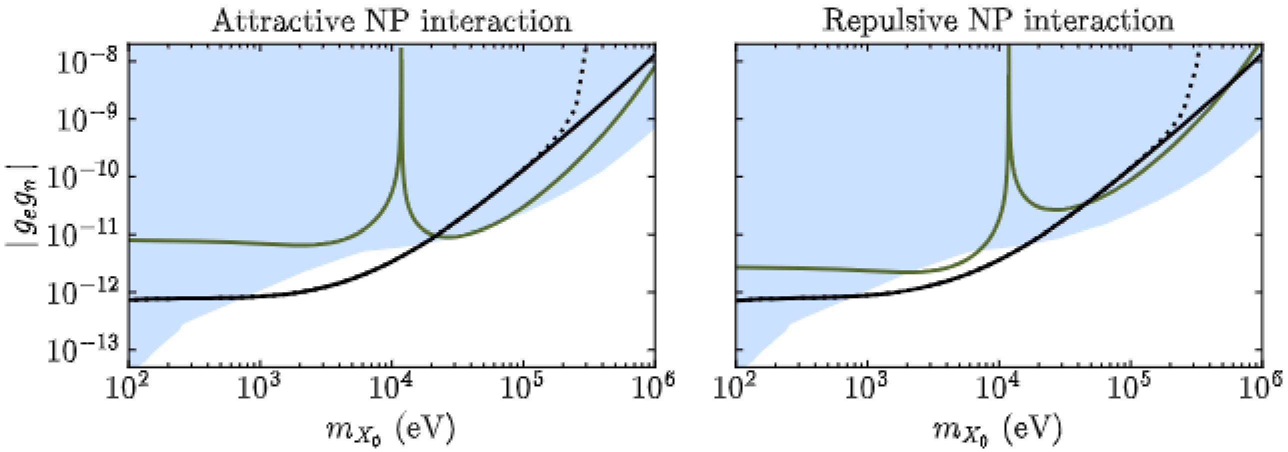


[NJP **27**, 045002 (2025)]

Bounds on $g_e g_n$

Solid curves: bounds based on eH, eD, μH and μD for $g_\mu = g_e$

Dotted curves: bounds based on eH, eD, μH and μD for $-g_e \leq g_\mu \leq 100\, g_e$



[NJP **27**, 045002 (2025)]

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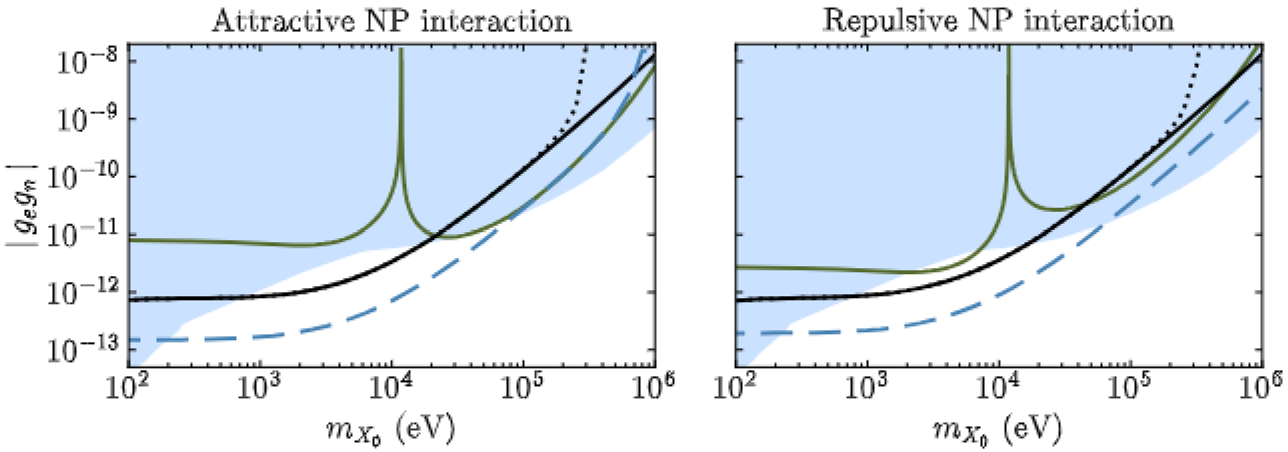
Long dashed curves: bounds based on the 1s-2s interval, μH and μD for gμ = ge



[NJP **27**, 045002 (2025)]

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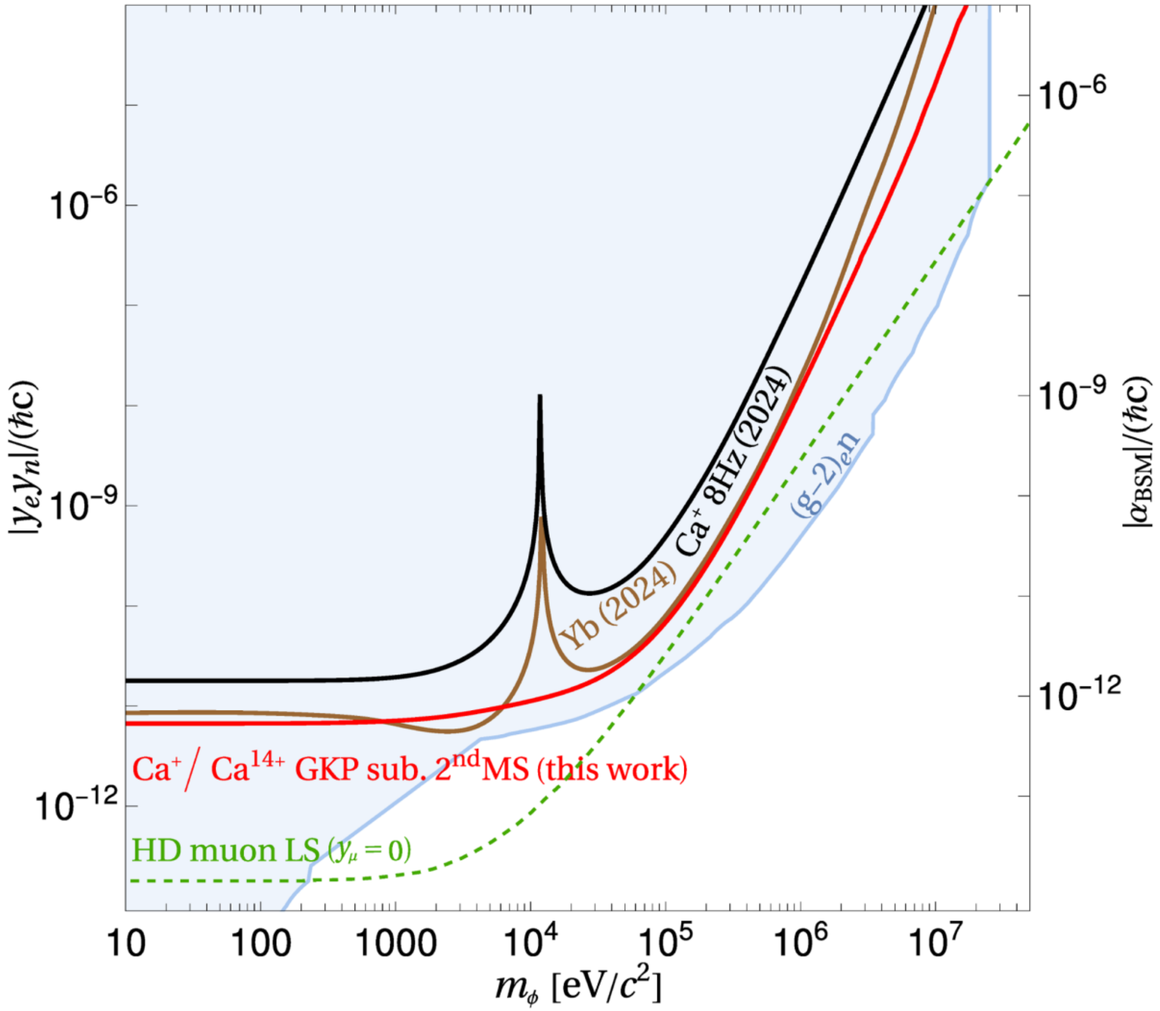
Comparison with KP results

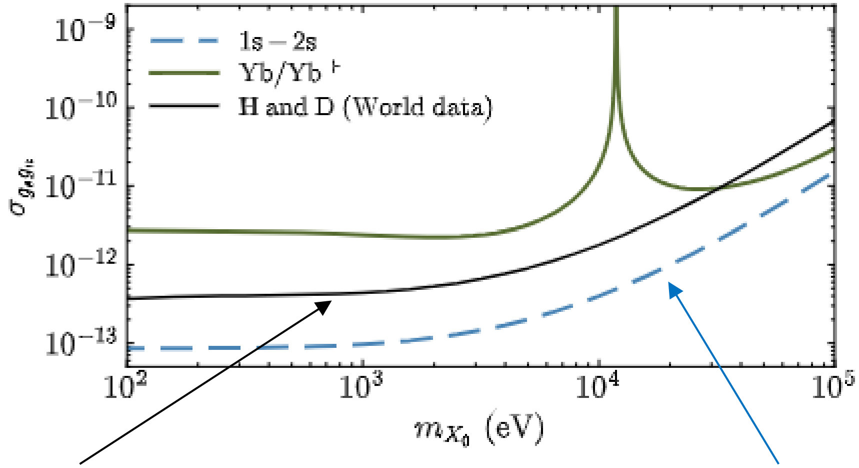


[Wilzewski et al, PRL **134**, 233002 (2025)]

Results based on isotope shifts

Sensitivity of the data to a non-zero gegn

$\sigma_{g_e g_n}$: a measure of how large should $g_e g_n$ be for the NP interaction to affect the data significantly



Global fit approach
(World data)

Isotope shift approach
(1s – 2s interval)
[Also Delaunay et al (2017)]

[NJP **27**, 045002 (2025)]

Sensitivity of the data to a non-zero gegn

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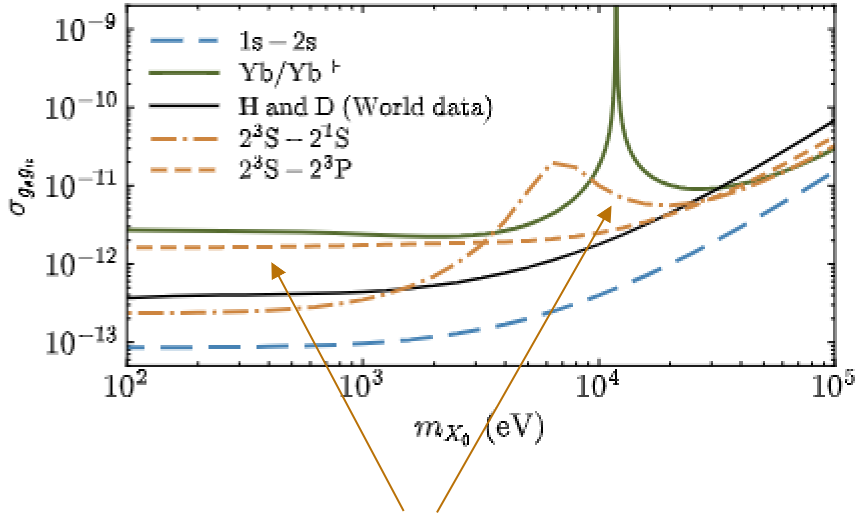
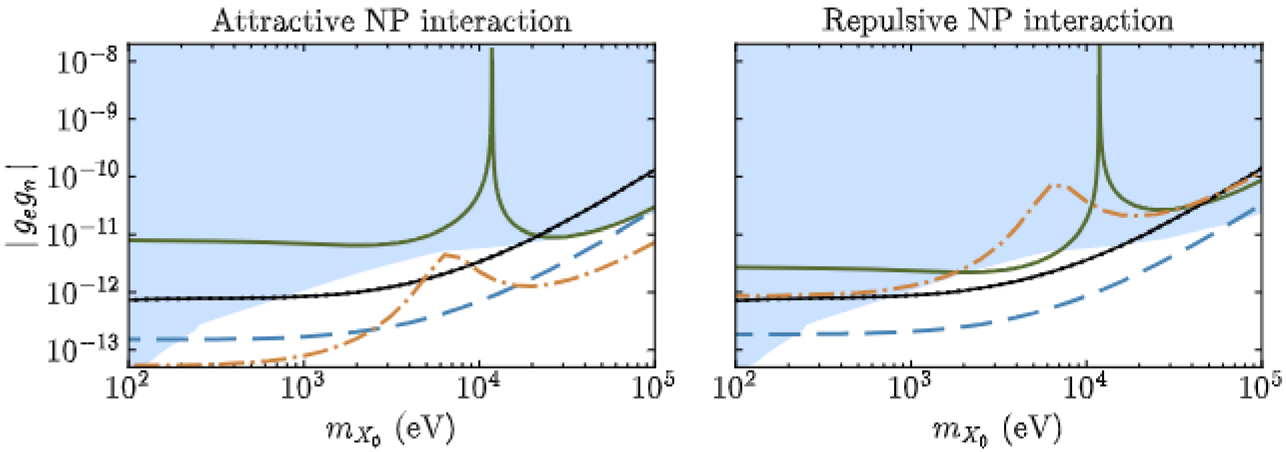


Isotope shift approach (2 ^{3}S – 2 ^{1}S or 2 ^{3}S – 2 ^{3}P interval of He)

[NJP **27**, 045002 (2025)]

Bounds on $g_e g_n$

Dash-dotted curves: bounds based on the isotope shift of the 2 ³S – 2 ¹S interval of He



[NJP **27**, 045002 (2025)]

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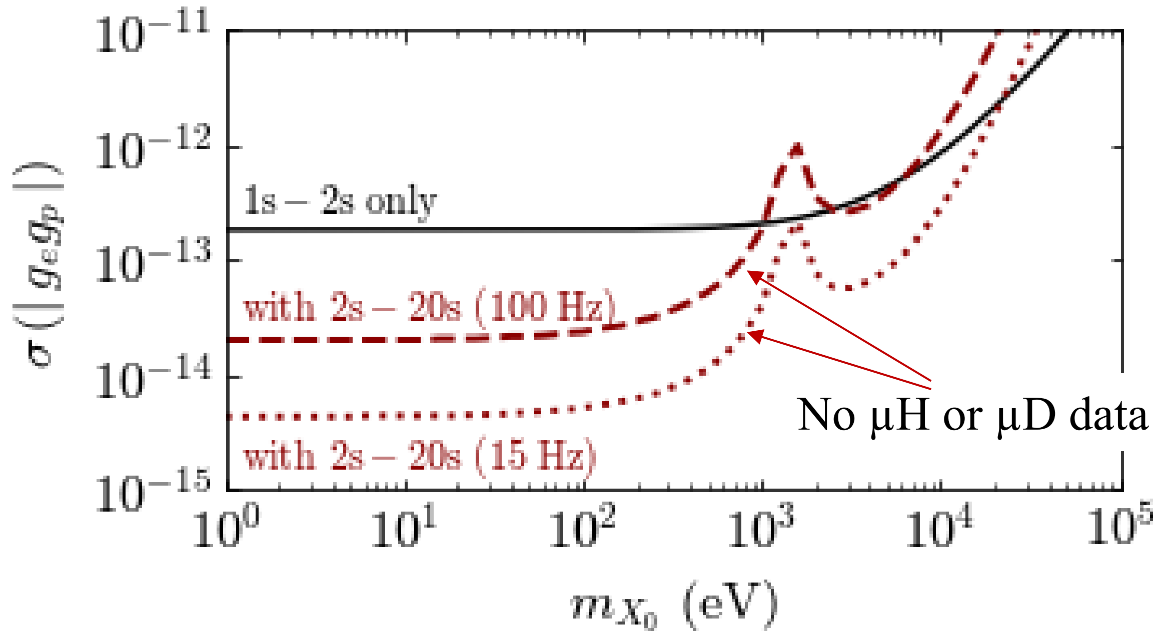
Reach of the isotope shift approach

Bounds based on the isotope shifts of two different transitions



Phys. Rev. A **108**, 032825 (2023), also Delaunay et al (2017)

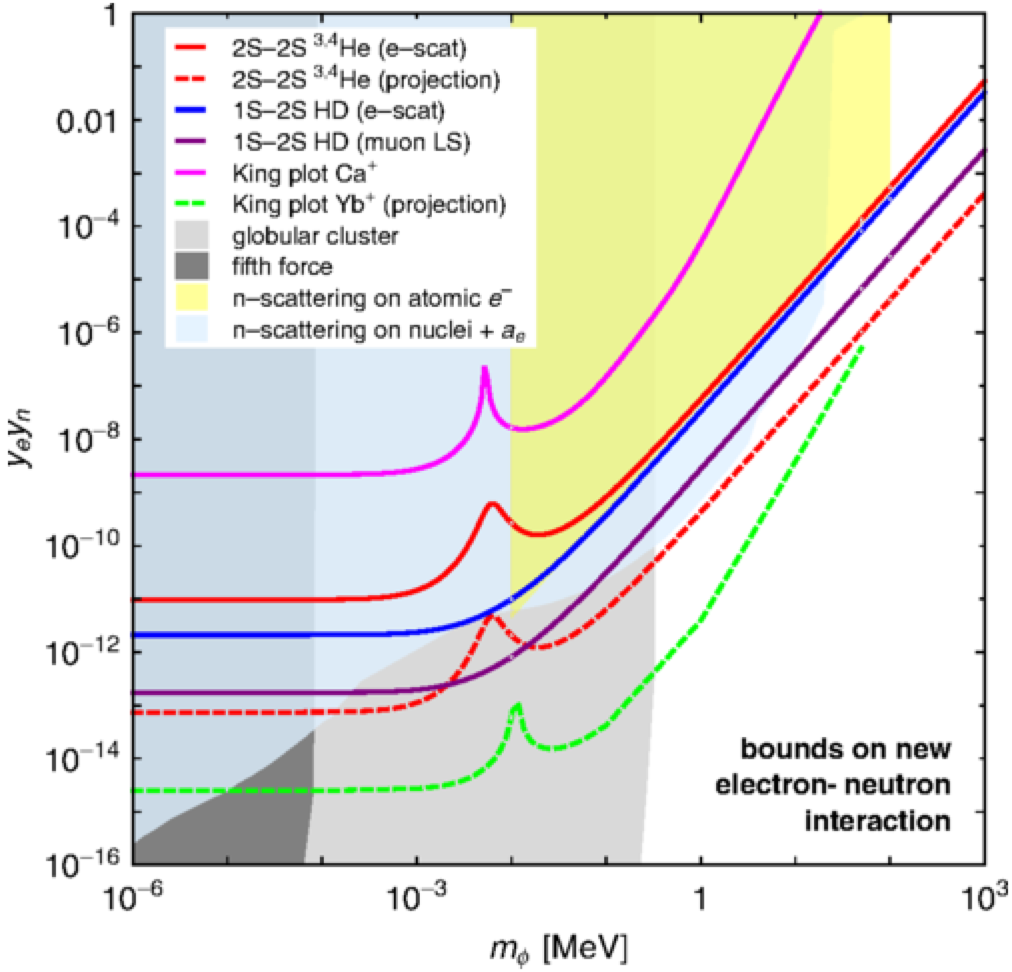
Conclusions

To conclude...

The μH, μD and μHe$^+$ data are unlikely to be significantly affected by a fifth force of the type considered here, assuming a carrier mass below 100 keV.

These muonic atom data much help strengthen the bounds on $g_e g_p$ and $g_e g_n$, particularly those based on isotope shift spectroscopy. The theoretical error on $r_d^2(\mu D) - r_p^2(\mu H)$ is currently the main limitation on the sensitivity of the latter approach.

Other calculations



From C Delaunay et al, Phys. Rev. D **96**, 115002 (2017)