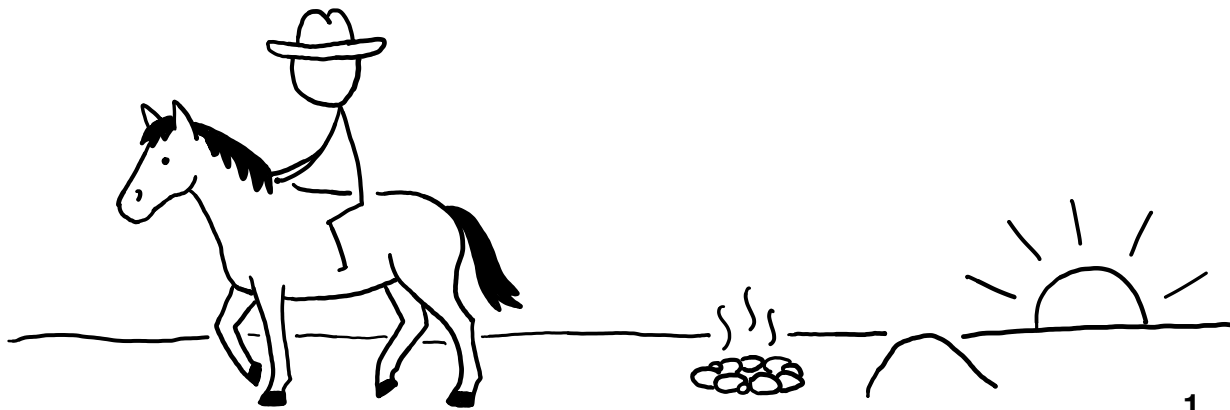


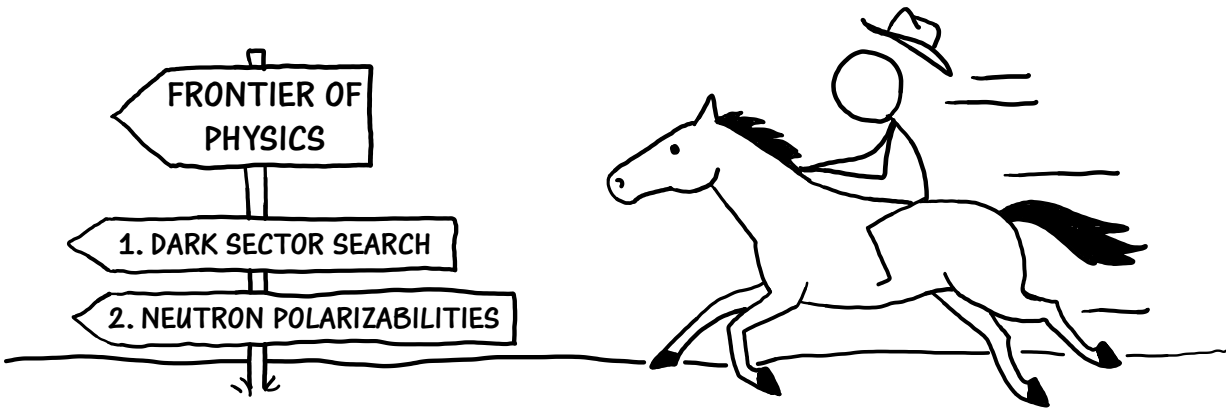
Joint **neutron polarizability** extraction and **dark sector search** using deuteron photodisintegration

Cornelis J.G. Mommers, 2025-10-30

Phys.Rev.D 109 (2024) 9, 095010

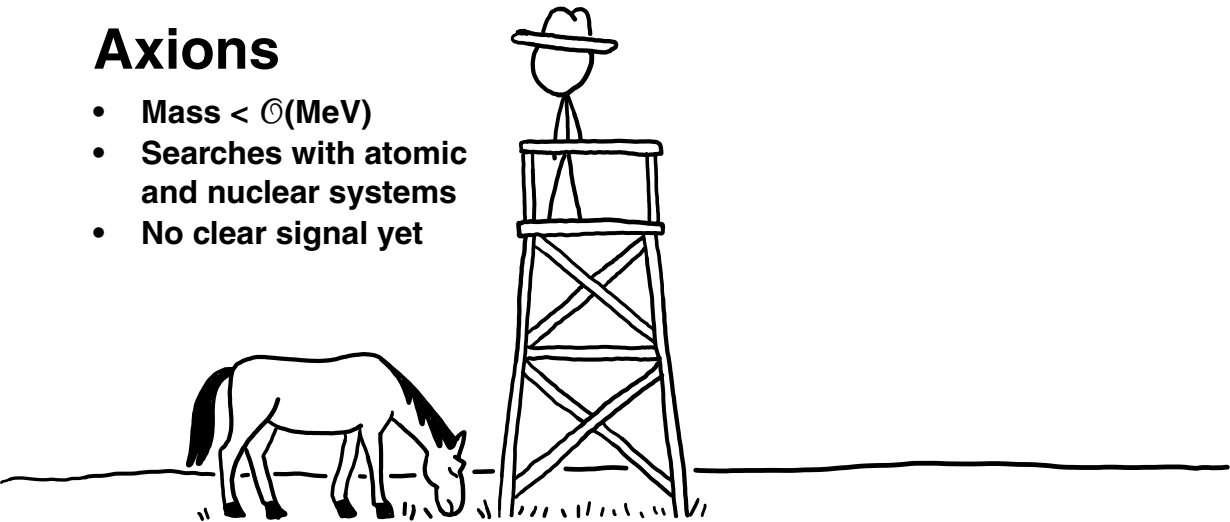


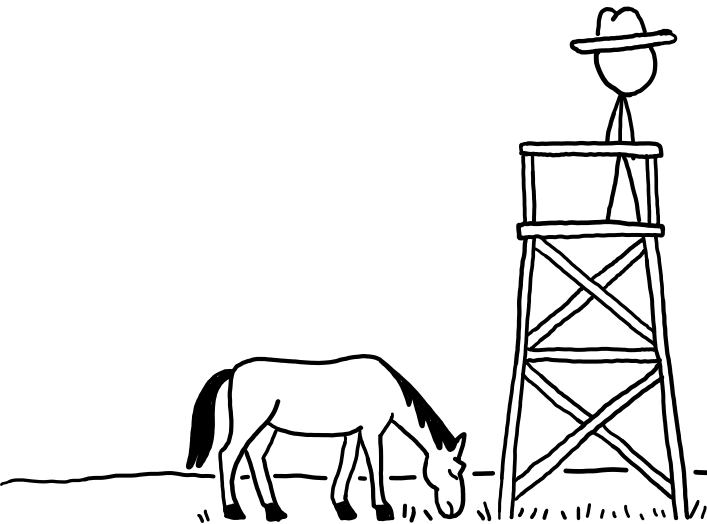




Axions

- Mass $< \mathcal{O}(\text{MeV})$
- Searches with atomic and nuclear systems
- No clear signal yet





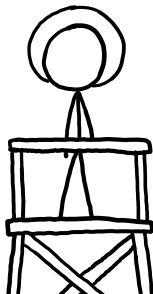
WIMPS

- Mass $> \mathcal{O}(\text{GeV})$
- Searches with high-energy colliders
- No clear signal yet

Light dark



matter

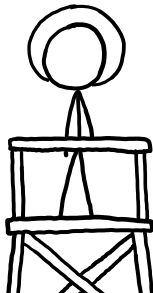


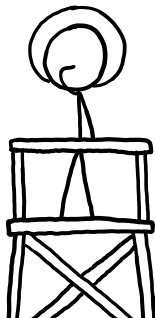
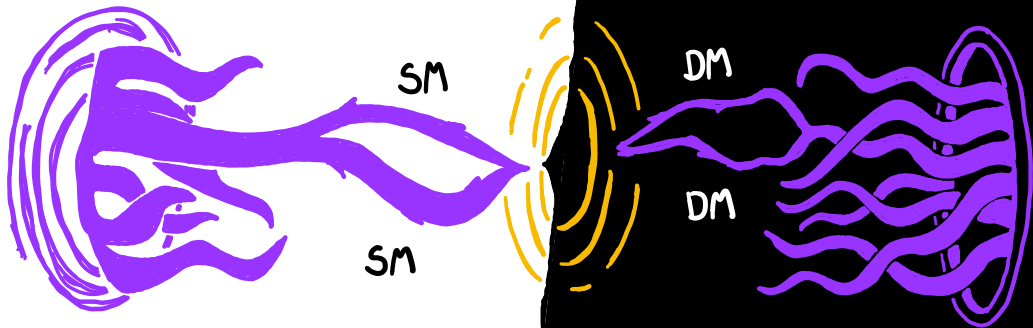
Light dark



matter

- Increasing interest
- Exists dark sector (uncharged under SM gauge symmetries)
- 'Portal' to dark sector via mediator particle (boson)

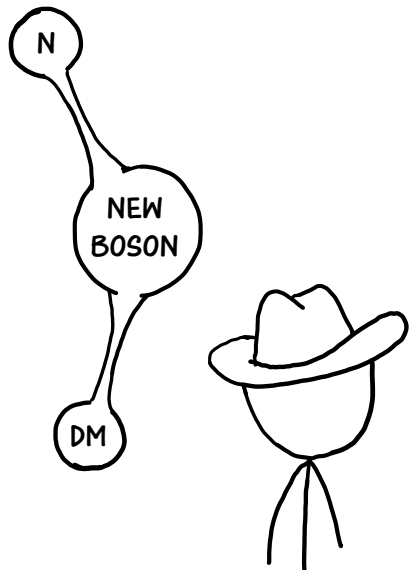




Light dark matter

- Mediator mass $\sim \mathcal{O}(\text{MeV})$ for correct relic density
- Small mass $\sim$ small coupling
- Searches with low-energy, high-intensity experiments
- Dark photon, dark Higgs, etc.

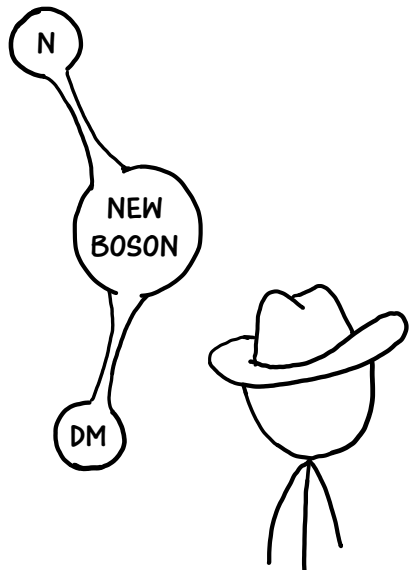
Exclusion limits



- Suppose mediator couples u and d quarks to dark sector
- Implies coupling mediator to proton and neutron,

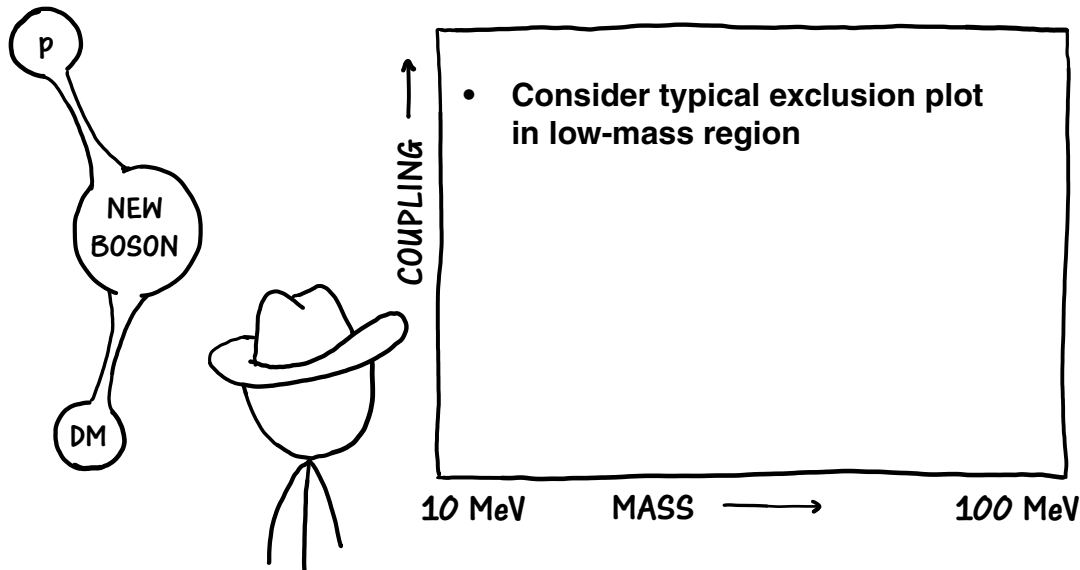
$$\begin{aligned}\mathcal{L}_S &= g_S \bar{N} N X, & \mathcal{L}_P &= g_P \bar{N} i \gamma_5 N X, \\ \mathcal{L}_V &= g_V \bar{N} \gamma_\mu N X^\mu, & \mathcal{L}_A &= g_A \bar{N} \gamma_\mu \gamma_5 N X^\mu.\end{aligned}$$

Exclusion limits

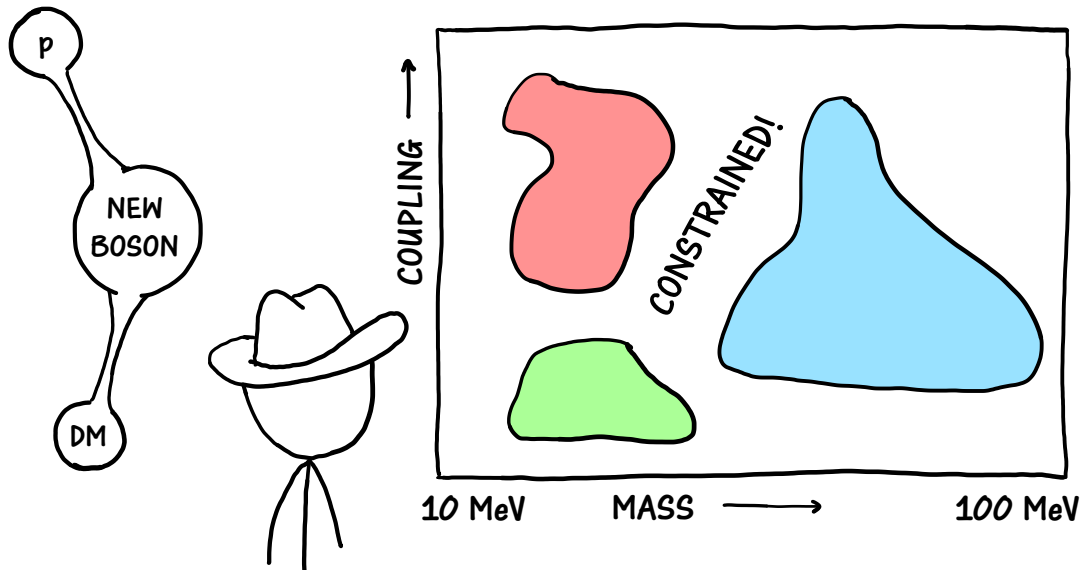


- Suppose mediator couples u and d quarks to dark sector
- Implies coupling mediator to proton and neutron.
- Proton coupling need not be equal to neutron coupling (flavor dependent, e.g., X17)
- $g^N \rightarrow g^p, g^n$ with $g^p \neq g^n$

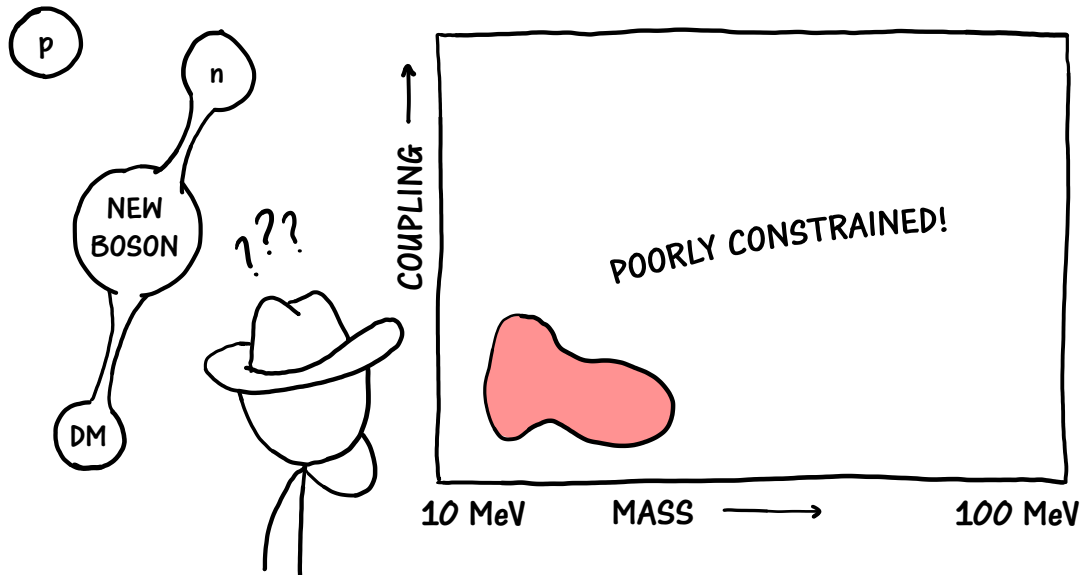
Exclusion limits (proton)



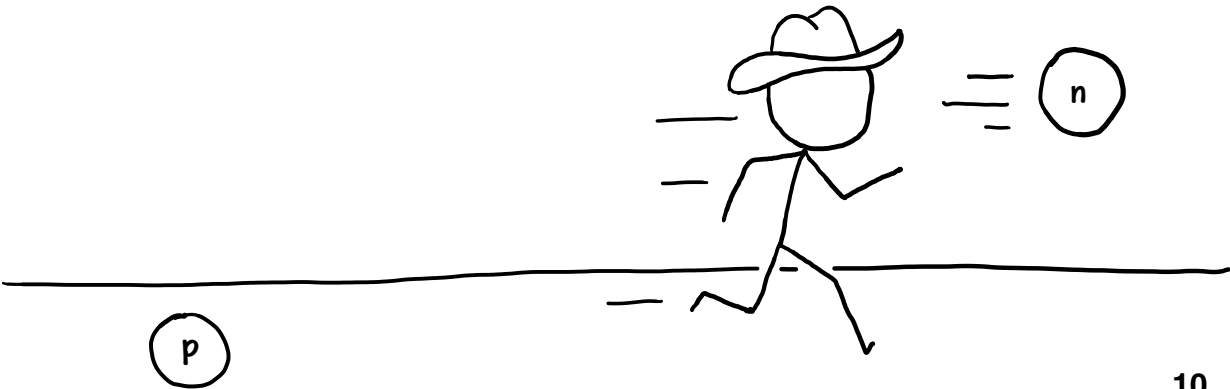
Exclusion limits (proton)



Exclusion limits (neutron)

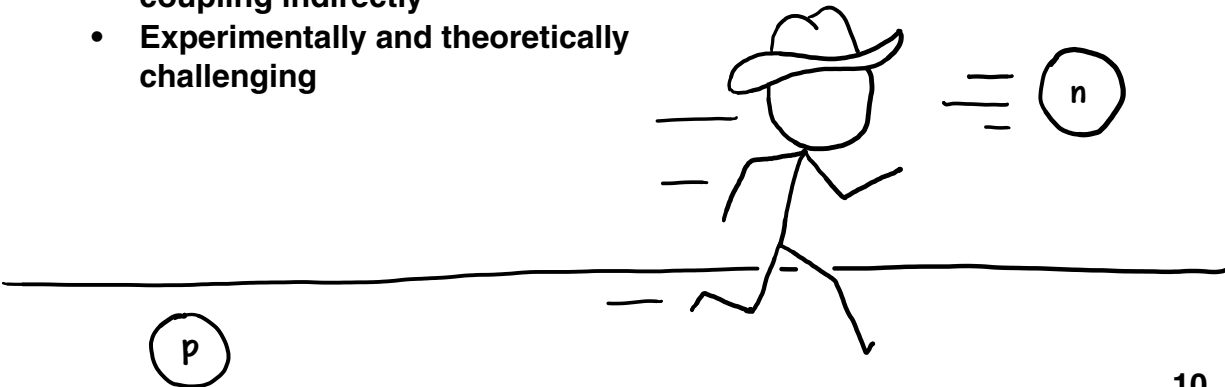


Why neutron coupling ill constrained?

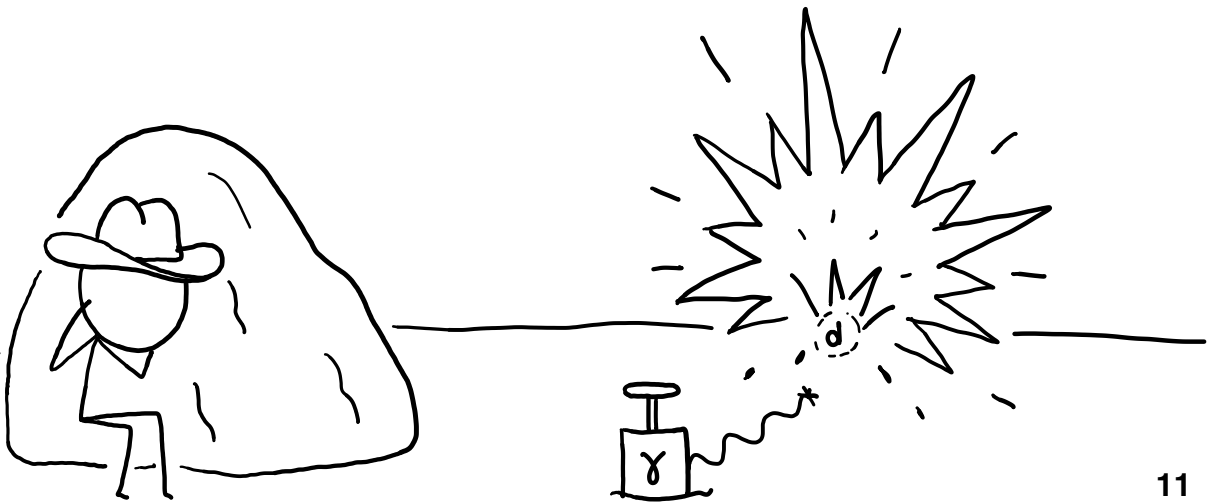


Why neutron coupling is constrained?

- In lab no free neutron target
- Unlike proton coupling, must infer neutron coupling indirectly
- Experimentally and theoretically challenging

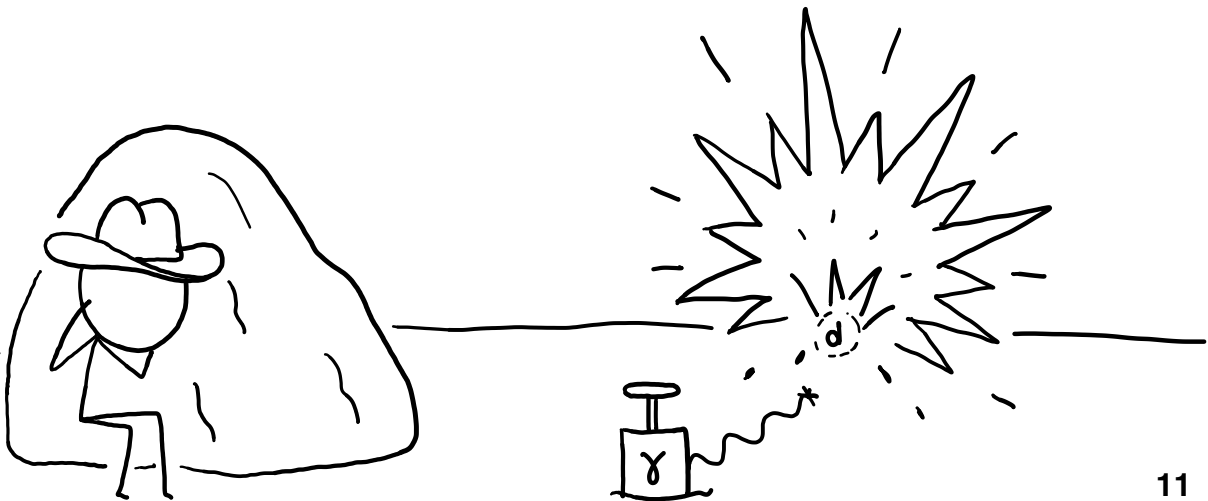


Solution: quasi-free neutrons



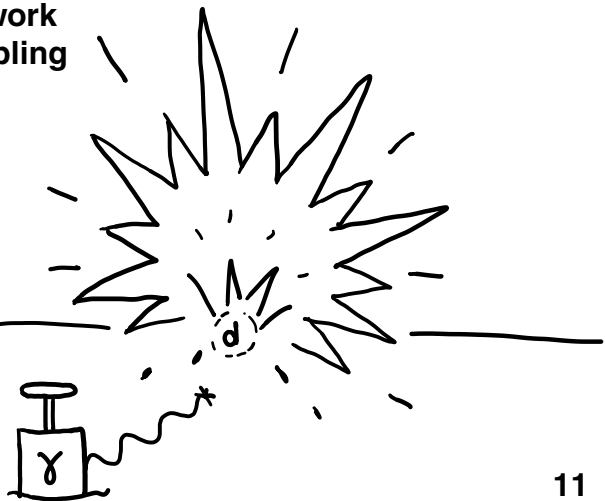
Solution: quasi-free neutrons

- Quasi-free = in bound system, but behave as if free

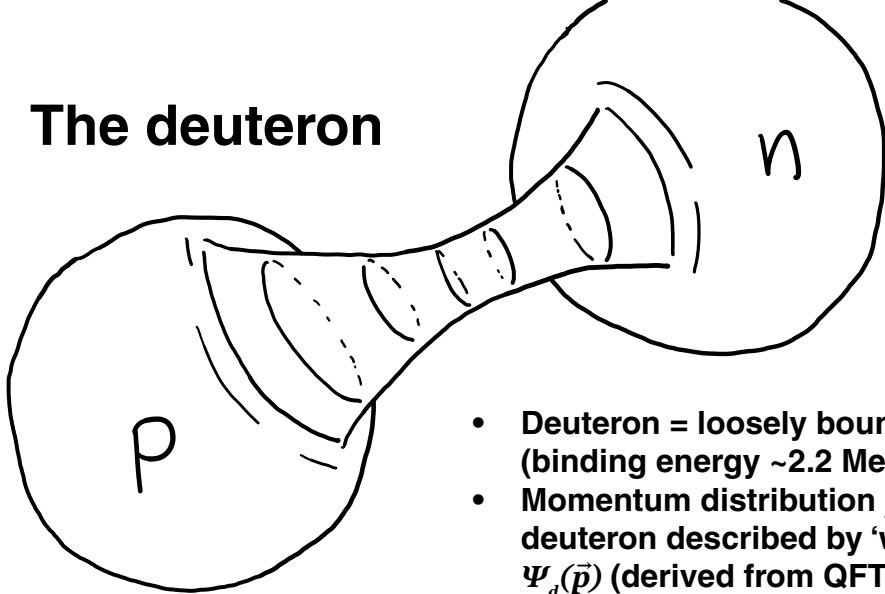


Solution: quasi-free neutrons

- Quasi-free = in bound system, but behave as if free
- 1st part of my PhD: set up framework to derive bounds on neutron coupling using $\gamma d \rightarrow e^+ e^- pn$

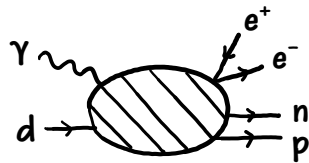


The deuteron



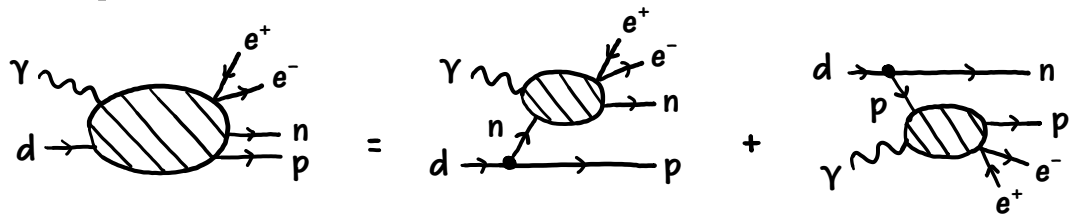
- Deuteron = loosely bound pn pair (binding energy ~ 2.2 MeV)
- Momentum distribution pn inside deuteron described by 'wave function' $\Psi_d(\vec{p})$ (derived from QFT)

Amplitudes to lowest order



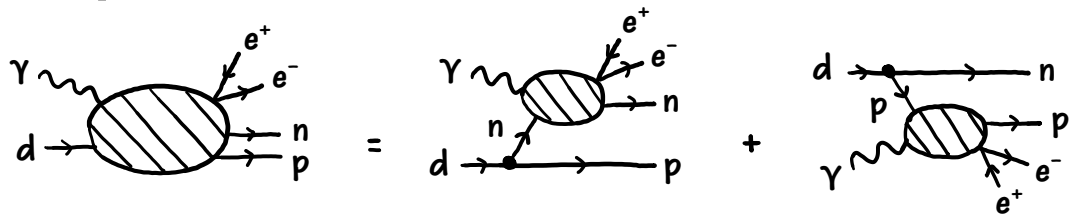
$\rightarrow M(d\gamma \rightarrow e^+ e^- pn)$

Amplitudes to lowest order



$$\rightarrow M(d\gamma \rightarrow e^+e^-pn) = M_0^{(p)}(d\gamma \rightarrow e^+e^-pn) + M_0^{(n)}(d\gamma \rightarrow e^+e^-pn)$$

Amplitudes to lowest order



$$\rightarrow M(d\gamma \rightarrow e^+e^-pn) = M_0^{(p)}(d\gamma \rightarrow e^+e^-pn) + M_0^{(n)}(d\gamma \rightarrow e^+e^-pn)$$

In d rest frame, $M_0^{(p)}(d\gamma \rightarrow e^+e^-pn) \sim \Psi_d(|p_p|)$

$M_0^{(n)}(d\gamma \rightarrow e^+e^-pn) \sim \Psi_d(|p_n|)$

Neutron quasi-free peak

In d rest frame,

$$M_0^{(p)}(d\gamma \rightarrow e^+e^-pn) \sim \Psi_d(|p_p|)$$

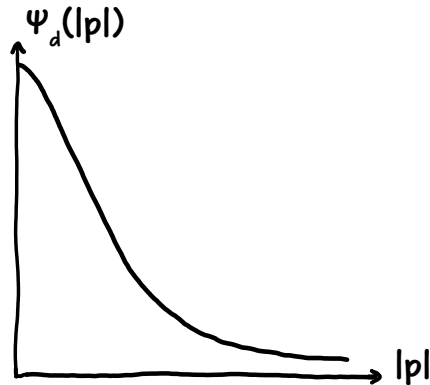
$$M_0^{(n)}(d\gamma \rightarrow e^+e^-pn) \sim \Psi_d(|p_n|)$$

Neutron quasi-free peak

In d rest frame,

$$M_0^{(p)}(d\gamma \rightarrow e^+e^-pn) \sim \Psi_d(|p_p|)$$

$$M_0^{(n)}(d\gamma \rightarrow e^+e^-pn) \sim \Psi_d(|p_n|)$$



Neutron quasi-free peak

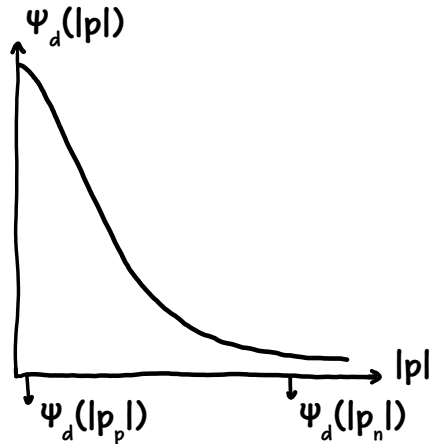
In d rest frame,

$$M_0^{(p)}(d\gamma \rightarrow e^+e^-pn) \sim \Psi_d(|p_p|)$$

$$M_0^{(n)}(d\gamma \rightarrow e^+e^-pn) \sim \Psi_d(|p_n|)$$

$$|p_p| \rightarrow 0$$

processes on neutron
enhanced!



Neutron quasi-free peak

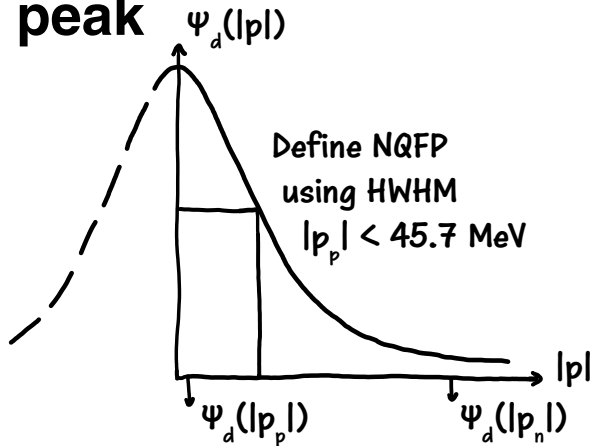
In d rest frame,

$$M_0^{(p)}(d\gamma \rightarrow e^+e^-pn) \sim \Psi_d(|p_p|)$$

$$M_0^{(n)}(d\gamma \rightarrow e^+e^-pn) \sim \Psi_d(|p_n|)$$

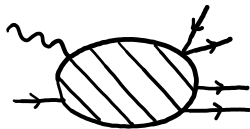
$$|p_p| \rightarrow 0$$

processes on neutron
enhanced!



The main idea

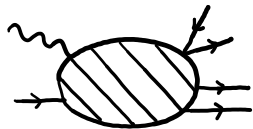
At NQFP $d\gamma \rightarrow e^+e^-pn$ 'proportional to' $n\gamma \rightarrow e^+e^-n$



Infer neutron observables using the deuteron!

The main idea

At NQFP $d\gamma \rightarrow e^+e^-pn$ 'proportional to' $n\gamma \rightarrow e^+e^-n$

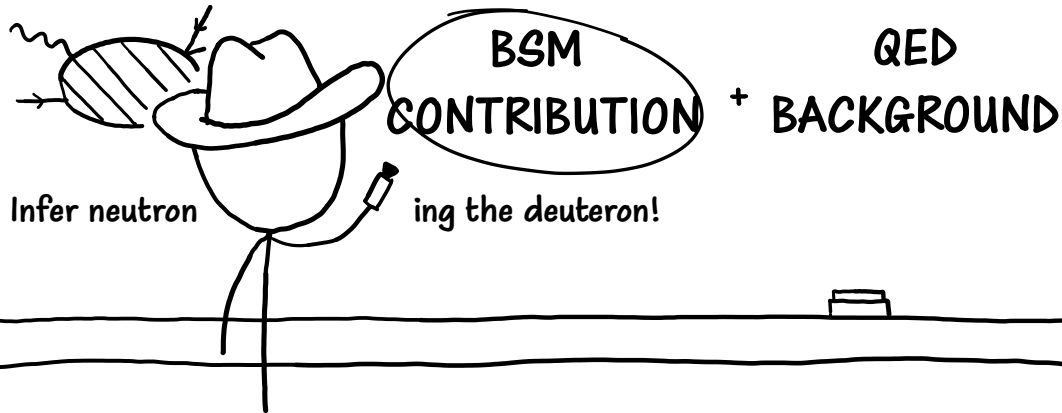


$$\text{BSM} = \text{CONTRIBUTION} + \text{QED BACKGROUND}$$

Infer neutron observables using the deuteron!

The main idea

At NQFP $d\gamma \rightarrow e^+e^-\bar{p}n$ 'proportional to' $n\gamma \rightarrow e^+e^-\bar{n}$

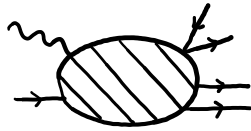


BSM

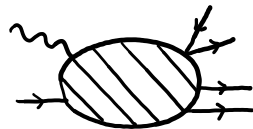
Assume:

1. new boson couples to n, p, e^+, e^-
2. width new boson $\ll 0.1$ MeV

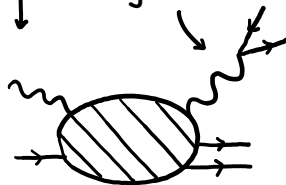
(original motivation: X17)



BSM



New boson detectable as
very narrow resonance



BSM

$d\gamma \rightarrow e^+e^-pn$ rather than $d\gamma \rightarrow \gamma pn$
to access all quantum numbers
(S, P, V, A)

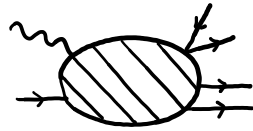
$f = n, p, e,$

$$\mathcal{L}_S = g_S \bar{f} f X,$$

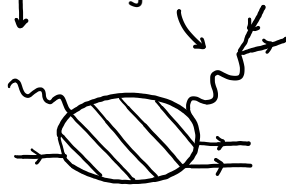
$$\mathcal{L}_P = g_P \bar{f} i \gamma_5 f X,$$

$$\mathcal{L}_V = g_V \bar{f} \gamma_\mu f X^\mu,$$

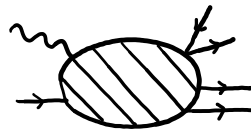
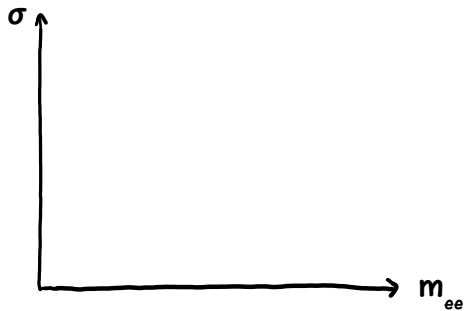
$$\mathcal{L}_A = g_A \bar{f} \gamma_\mu \gamma_5 f X^\mu.$$



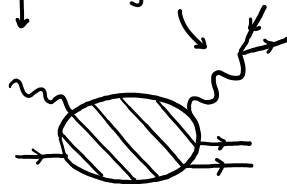
New boson detectable as
very narrow resonance



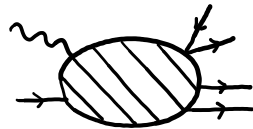
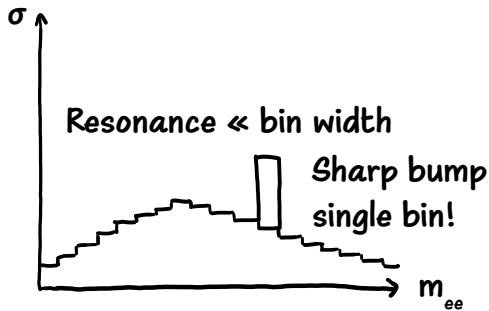
BSM



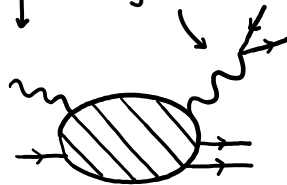
New boson detectable as
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BSM

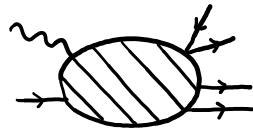
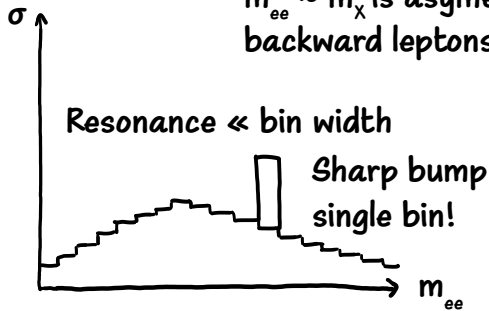


New boson detectable as
very narrow resonance

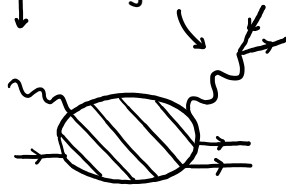


BSM

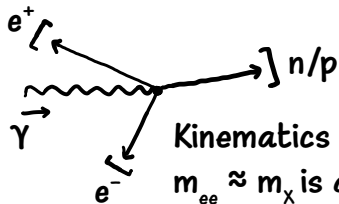
Kinematics s.t.
 $m_{ee} \approx m_\chi$ is asymmetric
backward leptons



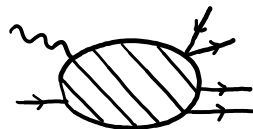
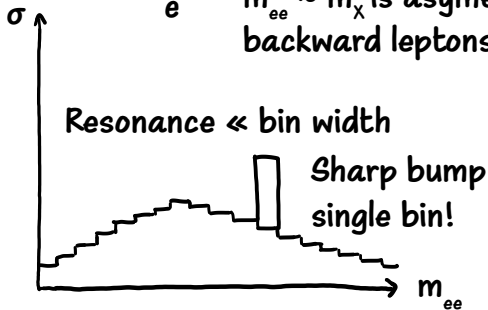
New boson detectable as
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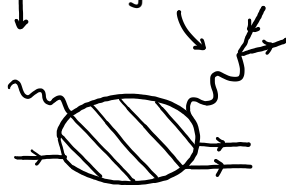
BSM



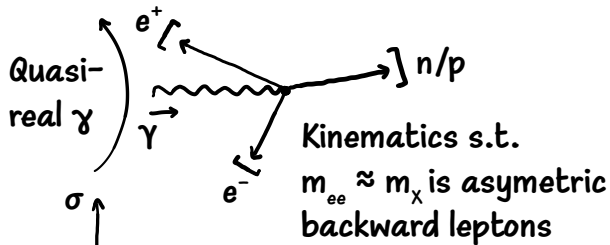
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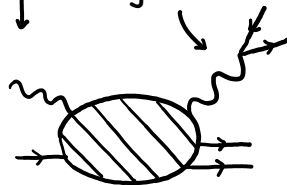
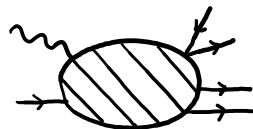
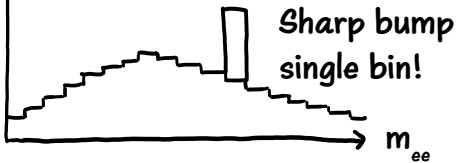
New boson detectable as
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BSM



Resonance $\ll$ bin width





MESA

- Mainz Energy-Recovering Superconducting Accelerator
- Low energy, high intensity electron beam
- Double-sided superconducting energy-recovery linac

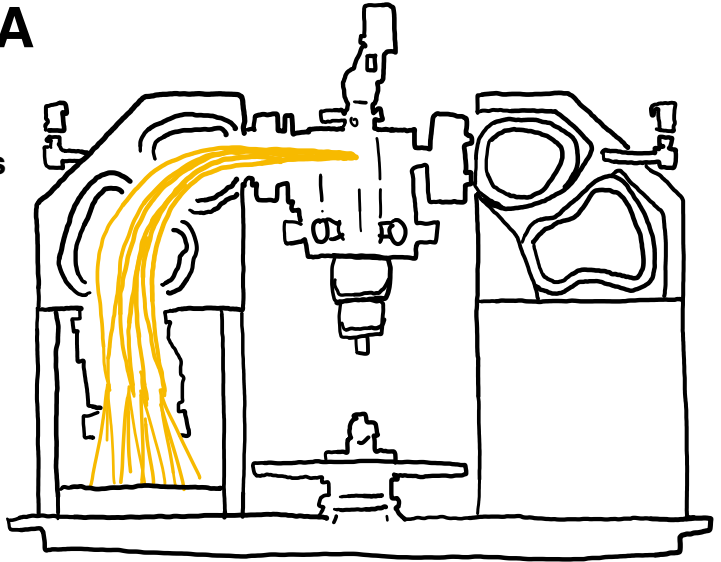


MESA

- Mainz Energy-Recovering Superconducting Accelerator
- Low energy, high intensity electron beam
- Double-sided superconducting energy-recovery linac
- Final stages of construction
- Beam energy ~ 105 MeV
- Luminosity $\sim 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

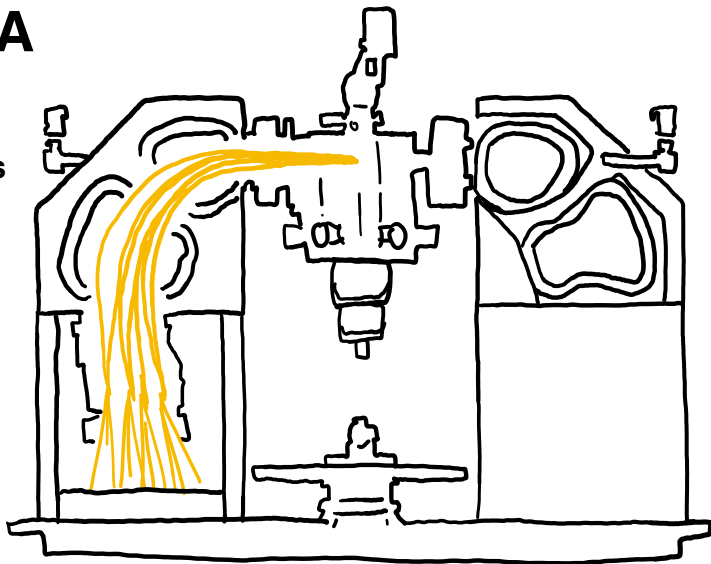
MAGIX@MESA

- Internal gas jet target, two high-resolution magnetic spectrometers + more



MAGIX@MESA

- Internal gas jet target, two high-resolution magnetic spectrometers + more
- Expected precision $\delta m_{ee} < 0.1 \text{ MeV}$ (very good!)



Results

Scalar, $\mathcal{L}_s = g_s \bar{N} N X$

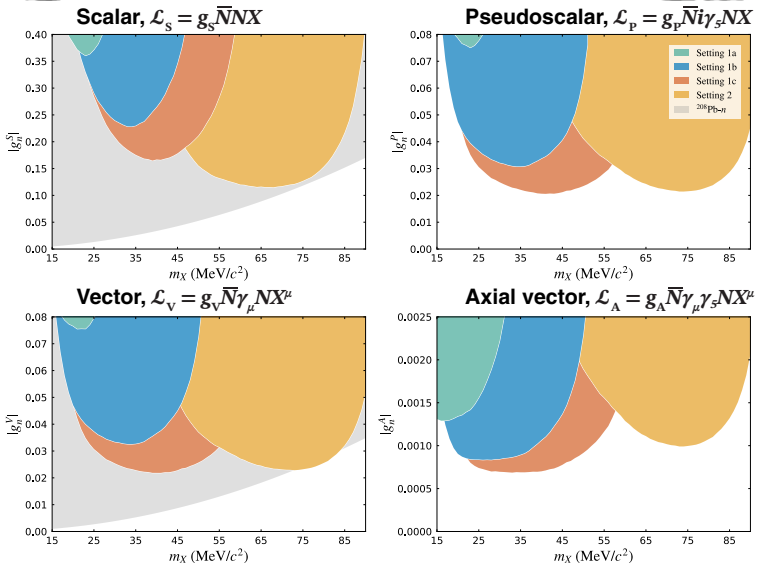
Pseudoscalar, $\mathcal{L}_p = g_p \bar{N} i \gamma_5 N X$

Vector, $\mathcal{L}_v = g_v \bar{N} \gamma_\mu N X^\mu$

Axial vector, $\mathcal{L}_A = g_A \bar{N} \gamma_\mu \gamma_5 N X^\mu$

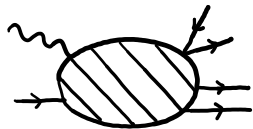
Results

- Projected exclusion limits
MAGIX@MESA
- $L = 7.2 \times 10^8 \text{ nb}^{-1}$
- $\delta m_{ee} = 0.1 \text{ MeV}$
- Competitive results
pseudoscalar
and axial
vector

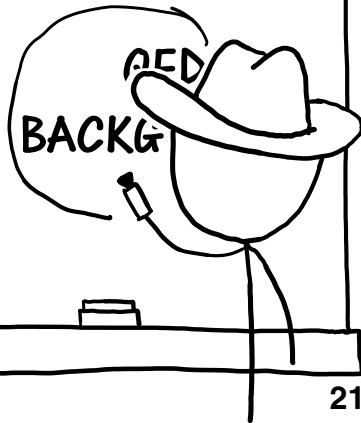


The main idea

At NQFP $d\gamma \rightarrow e^+e^-pn$ 'proportional to' $n\gamma \rightarrow e^+e^-n$



= BSM
CONTRIBUTION +

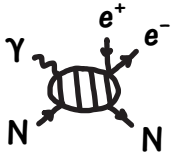


Infer neutron observables using the deuteron!

QED background

Consider $N\gamma \rightarrow e^+e^-N$ blob in more detail

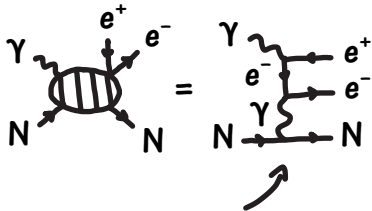
$E_\gamma \sim 100$ MeV, crossed diagrams not shown



QED background

Consider $N\gamma \rightarrow e^+e^-N$ blob in more detail

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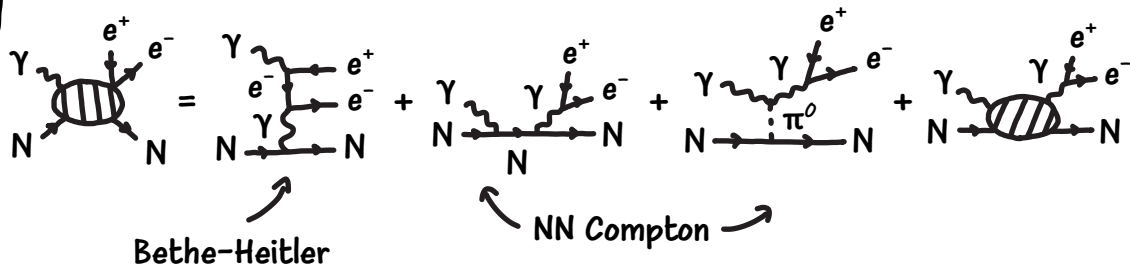


Bethe-Heitler

QED background

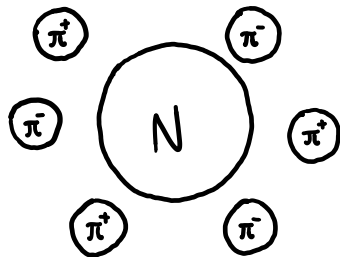
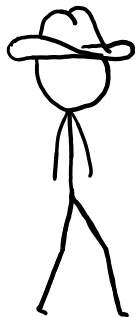
Consider $N\gamma \rightarrow e^+e^-N$ blob in more detail

$E_\gamma \sim 100$ MeV, crossed diagrams not shown



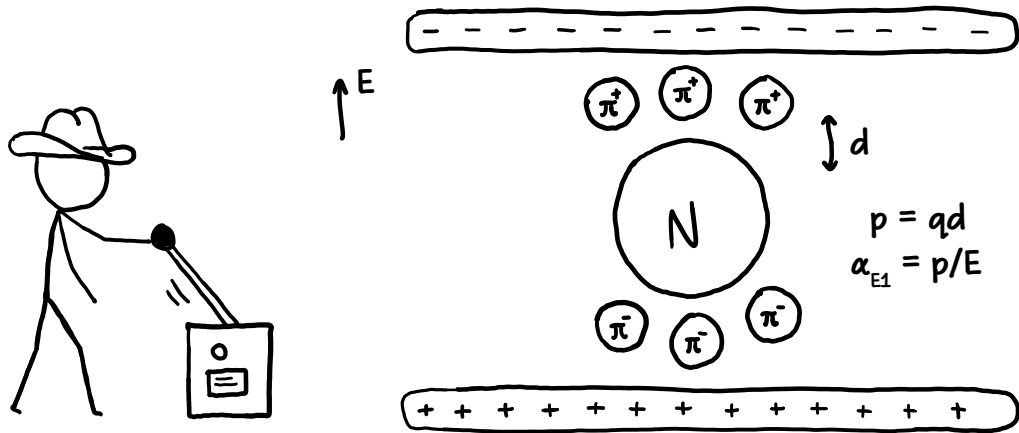
QED BG sensitive to polarizabilities

- QED background ~ Compton scattering ~ neutron polarizabilities
- Electric/magnetic polarizabilities quantify E/M moments induced in response to external E/M field

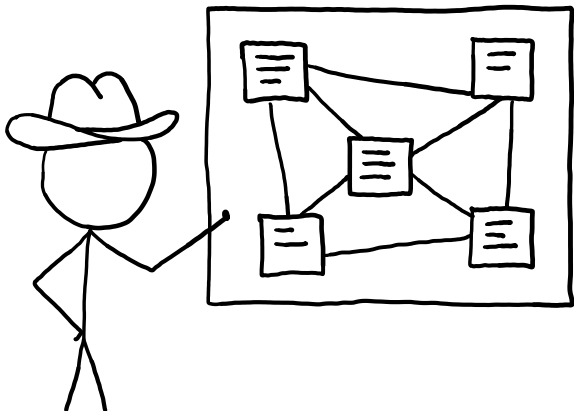


What are polarizabilities?

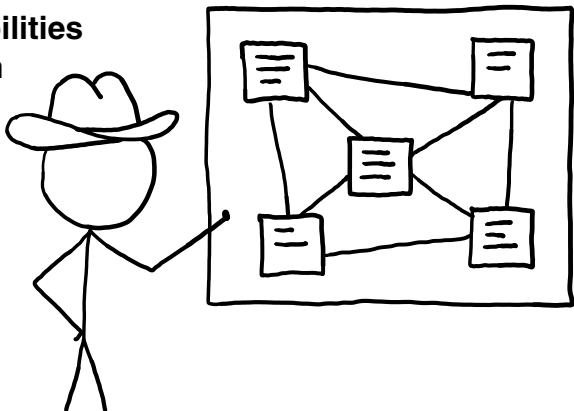
- Nucleon deforms along direction electric field
- Similar for magnetic polarizabilities



- Like couplings, proton polarizabilities ‘directly’ accessible, but neutron polarizabilities must be inferred



- Like couplings, proton polarizabilities ‘directly’ accessible, but neutron polarizabilities must be inferred
- Like mass, charge, etc., polarizabilities ‘fundamental’ quantity in nucleon structure, reappear in many calculations, large source theory uncertainty

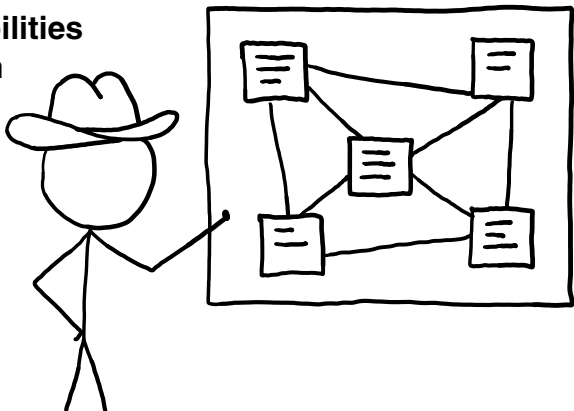


Theory uncertainty Lamb shift



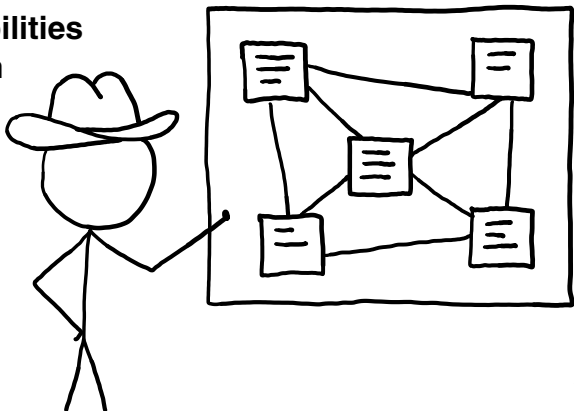
	$\Delta E_{\text{TPE}} \pm \delta_{\text{th}}(\Delta E_{\text{TPE}})$	Ref.	$\delta_{\text{exp}}(\Delta_{\text{LS}})$	Ref.
μH	$33 \mu\text{eV} \pm 2 \mu\text{eV}$	Antognini et al. (2013)	$2.3 \mu\text{eV}$	Antognini et al. (2013)
μd	$1710 \mu\text{eV} \pm 15 \mu\text{eV}$	Krauth et al. (2015)	$3.4 \mu\text{eV}$	Pohl et al. (2016)
$\mu^3\text{He}^+$	$15.30 \text{ meV} \pm 0.52 \text{ meV}$	Franke et al. (2017)	0.05 meV	Krauth et al. (2020)
$\mu^4\text{He}^+$	$9.34 \text{ meV} \pm 0.25 \text{ meV}$	Diepold et al. (2018)	0.05 meV	Krauth et al. (2020)
	THEORY		EXPERIMENT	

- Like couplings, proton polarizabilities ‘directly’ accessible, but neutron polarizabilities must be inferred
- Like mass, charge, etc., polarizabilities ‘fundamental’ quantity in nucleon structure, reappear in many calculations, large source theory uncertainty
- Turns out: (1st order) kinematic regions sensitive to BSM and neutron polarizabilities similar!

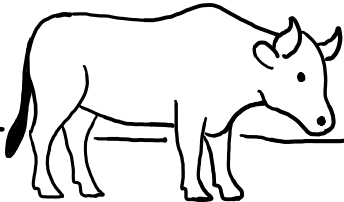
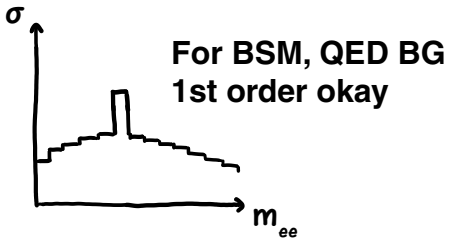


Joint neutron polarizability extraction and new physics search feasible?

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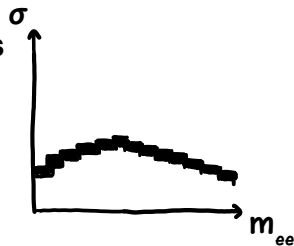
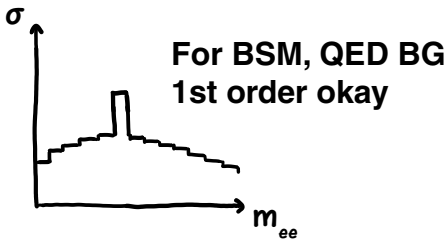


Complications

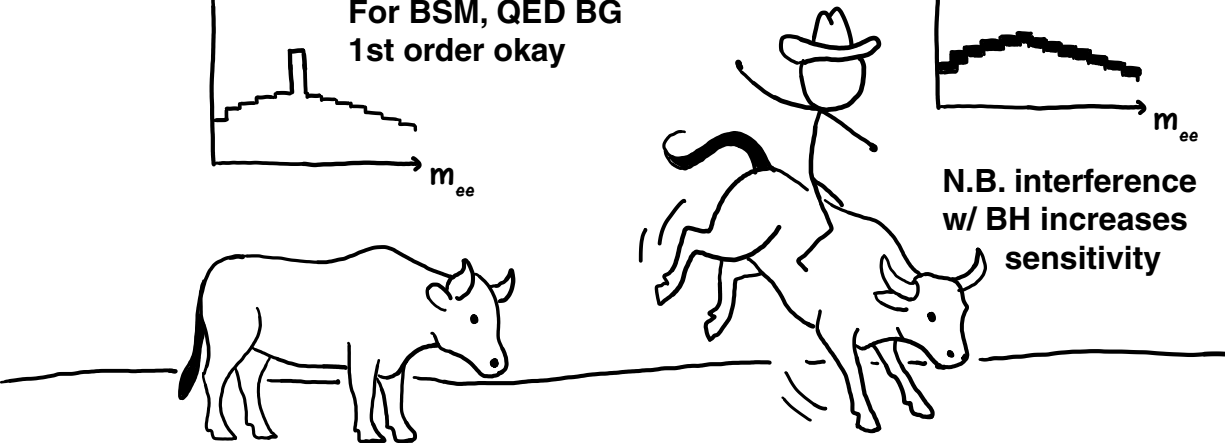


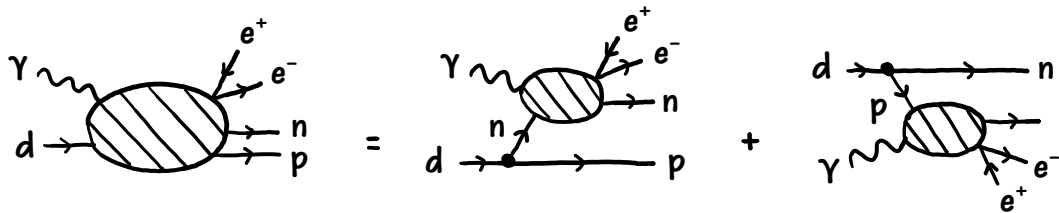
Complications

For polarizabilities,
need BG higher orders



N.B. interference
w/ BH increases
sensitivity





Higher-order terms

Currently
working on...

$$\begin{array}{c} n \\ \hline \text{[shaded box]} \\ \hline p \end{array} = \text{I} + \text{II} + \text{X} + \dots$$
$$= \text{[V]} + \text{[shaded box] [V]}$$

Rescattering bound system, must resum!
For now: (reduced) BS equation, CD-Bonn





Conclusion

- Increasing interest in new $\mathcal{O}(\text{MeV})$ boson
- At same time, need for better extraction neutron polarizabilities
- *Both* can be accessed using $\gamma d \rightarrow e^+ e^- pn$
- But, can both be extracted simultaneously?
- Keep your eyes peeled for an answer!



**Thank you for
your attention!**

**Joint neutron polarizability extraction and dark sector search using
deuteron photodisintegration**

Cornelis J.G. Mommers, 2025-10-30, Phys.Rev.D 109 (2024) 9, 095010



I am looking for postdocs!

1. in nucl-th, hep-th, hep-ph*
2. starting ~fall 2026

Know a position?

cmommers@uni-mainz.de

Cornelis Mommers, AG Vanderhaeghen

***e.g., few-body systems, Compton scattering, hadron spectroscopy, photo- and electroproduction & hadrons, etc., but very open to other possibilities!**