Exploring the $U(1)_{L_\mu - L_\tau}$ Solution to the Muon's Anomalous Magnetic Moment Using Future Experimental Probes

Based on: arXiv: `2104.03297`

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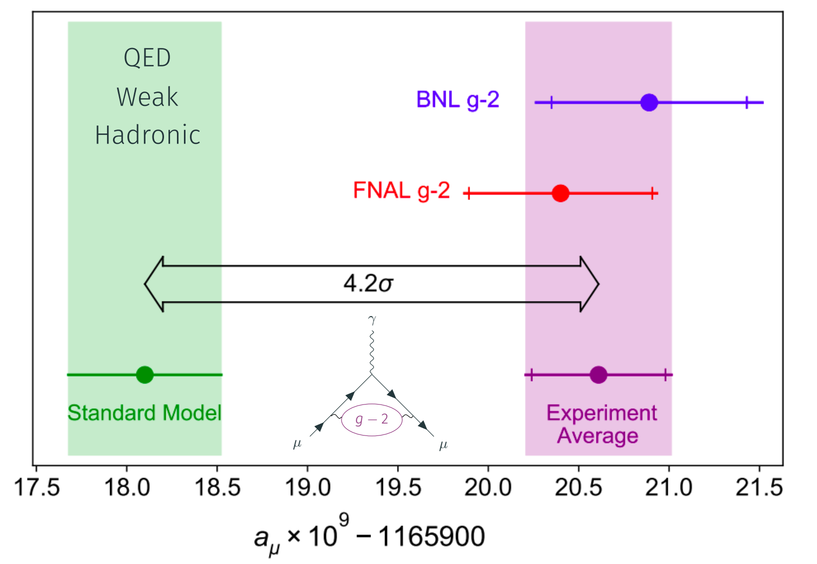


Adapted from: [B. Abi et al. arXiv: `2104.03281`]

... And There was (Hidden) Light!

Adding a generic $U(1)_X$ extension to the SM gives us:

Kinetic mixing

$$\mathcal{L}_{\mathrm{BSM}} \ni -\frac{\epsilon_X}{2\cos\theta_W} B_{\alpha\beta} X^{\alpha\beta} - g_X j^X_\alpha X^\alpha - \frac{M_X^2}{2} X_\alpha X^\alpha$$

Gauge coupling

- Simple $U(1)_{L_\mu}$ can explain Δa_μ :

Coupling to second gen.

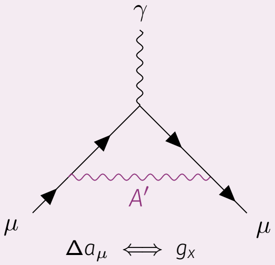
Anomaly cancellation

$$j^\mu_\alpha \ni \boxed{\bar{L}_2 \gamma_\alpha L_2} + \boxed{\sum_\psi Q_\psi \bar{\psi} \gamma_\alpha \psi}$$

- But so can $U(1)_{L_\mu - L_\tau}$, **with no anomalies**:

$$j^{\mu-\tau}_\alpha \ni \bar{L}_2 \gamma_\alpha L_2 - \boxed{\bar{L}_3 \gamma_\alpha L_3}$$

Coupling to third gen.



A Bet on Elegance

Suppose $(g-2)_\mu$ is real and $U(1)_{L_\mu - L_\tau}$ is responsible for it.

Can we:

1. Experimentally observe $U(1)_{L_\mu - L_\tau}$ signatures?
2. Distinguish $U(1)_{L_\mu - L_\tau}$ signatures from $U(1)_{L_\mu}$ signatures?

$U(1)_{L_\mu - L_\tau}$	$U(1)_{L_\mu}$
• Couples to (μ, ν_μ) and (τ, ν_τ)	• Couples to (μ, ν_μ) only
• $\varepsilon_X \simeq -g_X/70$	• $\varepsilon_X \in (-g_X/10, -g_X/100)$

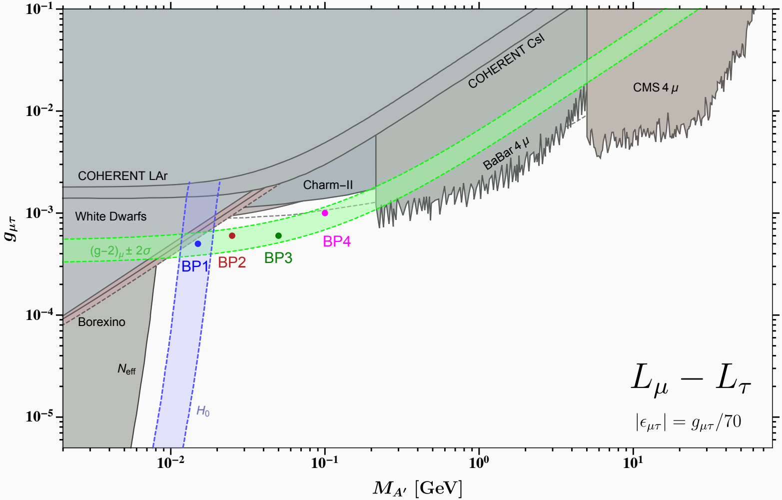
The Outline

1. Muon Beams: The Coupling Capturers

2. Spallation: The Mixing Managers

3. Direct Dectection: The Tau Tester

Where to Look?



[DA DC AC PF. arXiv: 2104.03297, D. Amaral et al. arXiv: 2006.11225]

The Fitting Game

1. Generate 'data' from our four $U(1)_{L_\mu - L_\tau}$ BPs for given experiment.
2. Pretend we don't know the underlying model.
3. Perform a $(g_x, M_{A'})$-fit assuming the model is:
    a $U(1)_{L_\mu - L_\tau}$
    b $U(1)_{L_\mu}$
4. Hope we can retrieve the BP *with* model discrimination.

Muon Beams: The Coupling Capturers

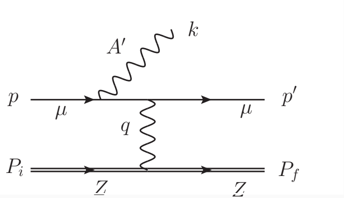
How it Works: Energy Convervation

The Invisible A' in the Muon Beam

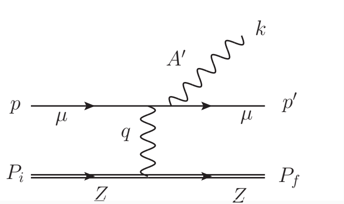
1. Muons sent hurtling towards a target
2. Kinetic mixing with SM photon $\implies$ Bremsstrahlung production
3. A' decays. This can happen via two channels:

$$A' \to \mu\bar{\mu} \qquad\qquad A' \to \nu_\mu\bar{\nu}_\mu$$

   Within $(g-2)_\mu$ solution, $M_{A'} < 2m_\mu$, so have **only** invisible decay
4. Missing energy signature gives us spectrum for A' events



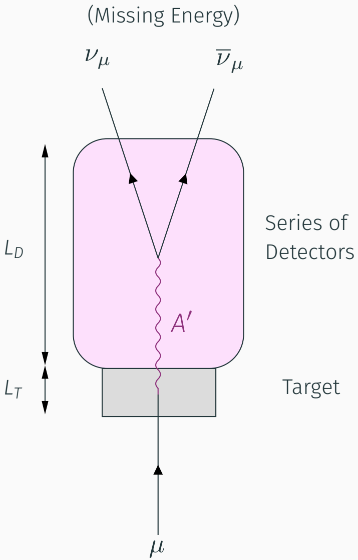
Brems. from initial muon state



Brems. from final muon state

NA64μ at CERN

- Extension of its e^- cousin
- Detects missing energy through series of calorimeters
- Characterised by:
  - Lead target material
  - No. Muons on target (MOT)
  - Target length
  - Detector length



Data Generation: How Many A' Events?

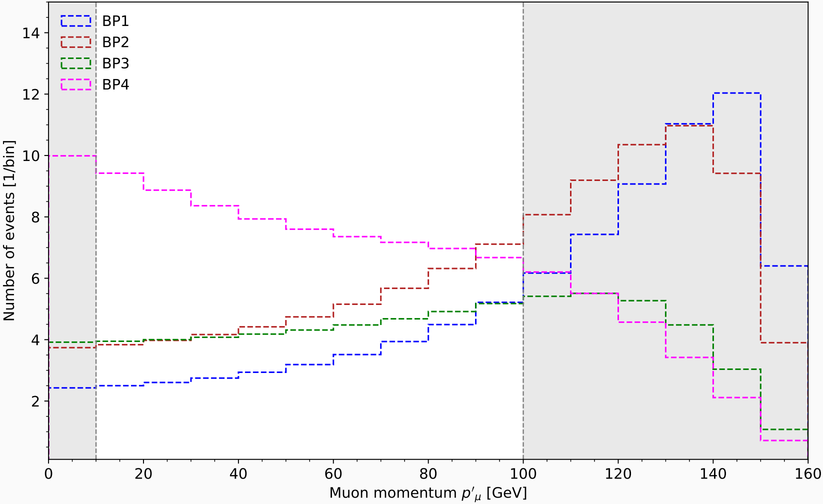
$$N_{A'}(g_X, M_{A'}) = \mathrm{MOT}\, n_{\mathrm{targ}} L_T \underbrace{\int_{x_i}^{x_{i+1}}}_{\substack{\uparrow \\ \text{Binning}}} \overbrace{\frac{\mathrm{d}\sigma_{2\to3}}{\mathrm{d}x}}^{\substack{\text{Important:} \\ A' \text{ production}}}(g_X, M_{A'})\, \underbrace{\mathrm{BR}_{A'\to\mathrm{inv}}}_{=1}\, \mathrm{d}x$$

We meet the A' in the brems. production cross section:

$$\frac{\mathrm{d}\sigma_{2\to3}}{\mathrm{d}x} \propto \overset{\substack{\text{Oh no!} \\ \downarrow}}{g_X^2}\, \underbrace{f(M_{A'})}_{\text{Complicated fn.}}$$

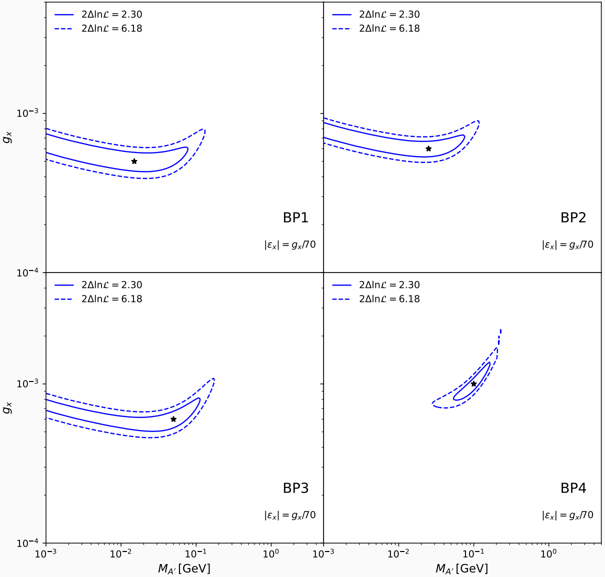
Cross section is only sensitive to g_X! Could be either g_μ or $g_{\mu\tau}$

This means we can play *The Fitting Game*, but we have no way to distinguish a $U(1)_{L_\mu - L_\tau}$ from a $U(1)_{L_\mu}$.



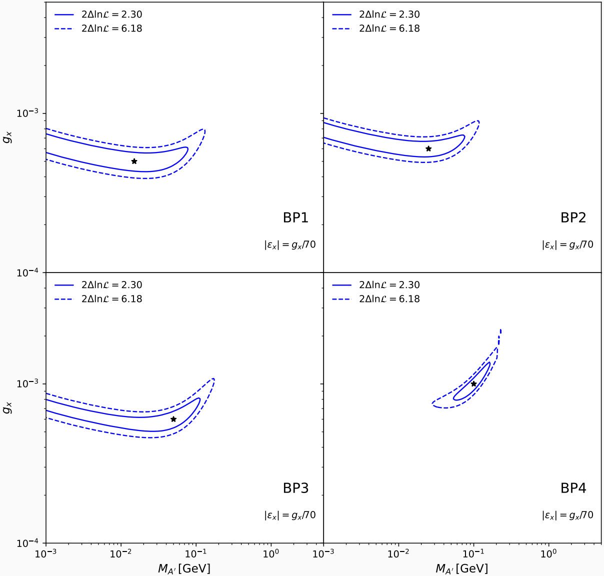
[DA DC AC PF. arXiv: 2104.03297]

The Fitting Game: NA64μ and $U(1)_{L_\mu - L_\tau}$



[DA DC AC PF. arXiv: 2104.03297]

The Fitting Game: NA64μ and $U(1)_{L_\mu}$



[DA DC AC PF. arXiv: 2104.03297]

NA64μ: The Key Points

- NA64μ gives us the g_x puzzle piece (to good extent)

- NA64μ has some sensitivity to $M_{A'}$ (better for higher masses)

- But we have no way to discriminate between $U(1)_{L_\mu - L_\tau}$ and more generic $U(1)_{L_\mu}$...

  If only we had sensitivity to the kinetic mixing...

Spallation: The Mixing Managers

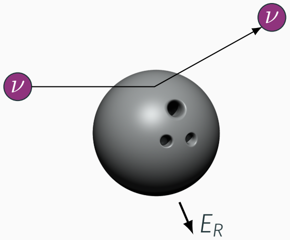
How it Works: Coherent Elastic Neutrino-Nucleus Scattering

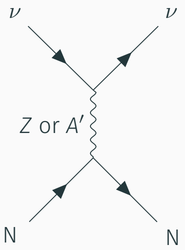
CEνNS with Spallation

1. Spallation: Protons collide with a target to produce π^+
2. π^+ decays, allowing for two neutrino production channels:

$$\pi^+ \rightarrow \mu^+ \nu_\mu \qquad\qquad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

3. Neutrinos coherently scatter off nuclei, which recoil at energy E_R
4. Distribution of events in E_R tells us about CEνNS physics!





A Spallation Smorgasbord

Experiment	Mass [ton]	E_{th} [keV$_{\mathrm{nr}}$]	NPOT [10^{23}/yr]	r	L [m]	σ_{sys}
CENNS610	0.61	~ 20	1.5	0.08	28.4	8.5%
ESS10	0.01	0.1	2.8	0.3	20	5%
CCM	7	10	0.177	0.0425	20	5%
ESS	1	20	2.8	0.3	20	5%

Data Generation: How Much CEνNS?

$$N\left(g_x \varepsilon_x, M_{A'}\right) = \varepsilon\, n_T \overbrace{\sum_{\nu_\alpha}}^{\substack{\text{Flavour sum} \\ \text{(only } \nu_e \text{ and } \nu_\mu\text{!)}}} \underbrace{\int_{E_{\text{th}}}}_{\text{Binning}} \int_{E_\nu^{\text{min}}}^{E_\nu^{\text{max}}} \epsilon\left(E_R\right) \underbrace{\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E_\nu}}_{\substack{\text{Experimental} \\ \nu_\alpha \text{ flux}}} \overbrace{\frac{\mathrm{d}\sigma_{\nu_\alpha N}}{\mathrm{d}E_R}}^{\substack{\text{Important} \\ \text{Scattering Physics}}} \mathrm{d}E_\nu \mathrm{d}E_R$$

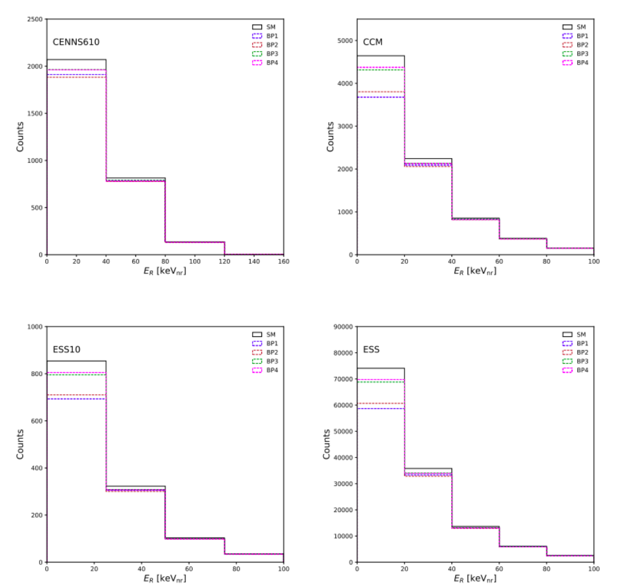
Our hidden photon makes an appearance in cross section:

$$\frac{\mathrm{d}\sigma_{\nu_\alpha N}}{\mathrm{d}E_R} \propto c_{\mathrm{SM}} + \big(\underbrace{g_x \varepsilon_x}_{\text{Product!}} \overbrace{Q'_{\nu_\alpha}}^{A' \text{ charge}}\big) \underbrace{c_{\mathrm{int}}(E_R, M_{A'})}_{>0} + \left(g_x \varepsilon_x Q'_{\nu_\alpha}\right)^2 c_{\mathrm{BSM}}(E_R, M_{A'})$$

$$Q'_{\nu_\alpha} = \begin{cases} 0 & \text{if } \alpha = e \\ +1 & \text{if } \alpha = \mu \\ -1 & \text{if } \alpha = \tau \end{cases}$$

We only get negative interference!

CEνNS Spectra

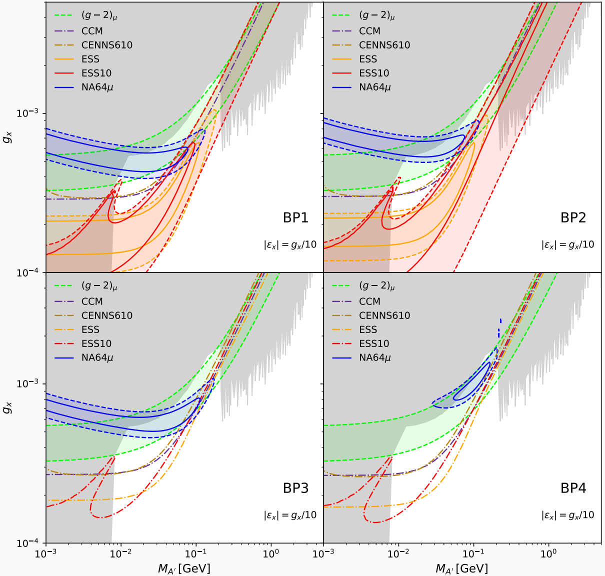


[DA DC AC PF. arXiv: 2104.03297]

The Fitting Game: Spallation Experiments

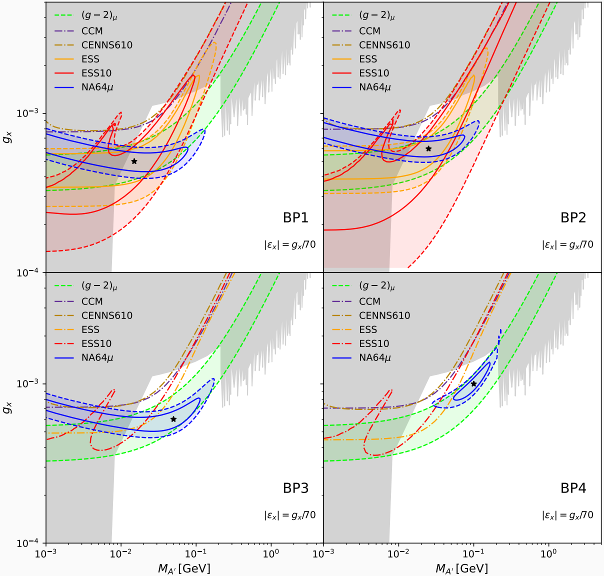
- We now have sensitivity to ε_X
- What happens when we assume the wrong value of ε_X in $U(1)_{L_\mu}$?
  - Say, $\varepsilon_X = -g_X/10$ instead of underlying $\varepsilon_X = -g_X/70$?
- Expect g_X fit will be lower to compensate.
  - Remember, spallation only sensitive to the product $g_X \varepsilon_X$!
- **But NA64μ already has stakes on g_X. There's going to be tension.**

The Fitting Game: Spallation and The Wrong Shoe ($\varepsilon_X = -g_X/10$)



[DA DC AC PF. arXiv: 2104.03297]

The Fitting Game: Spallation and The Shoe Fits! ($\varepsilon_X = -g_X/70$)

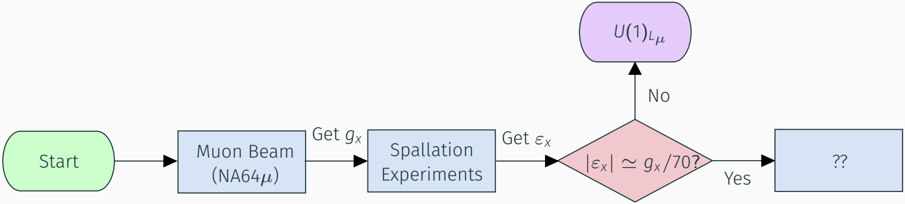


[DA DC AC PF. arXiv: 2104.03297]

Spallation: The Key Takeaways

- Spallation sources are sensitive to the product $g_x \varepsilon_x$
- In order to fit g_x, must assume a value for ε_x
- If we make the wrong assumption, have tension with a g_x-measurer (NA64μ)
- So NA64μ + Spallation gives us the ε_x puzzle piece

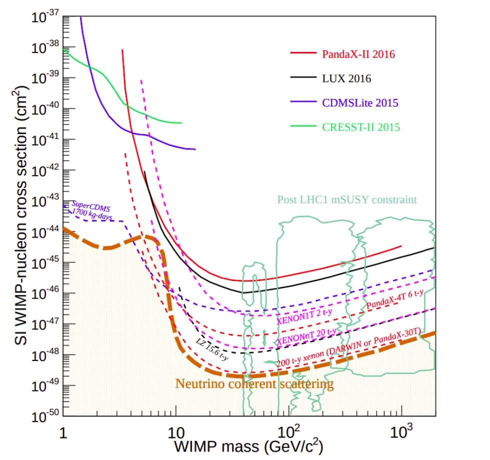
Two Possible Paths



Direct Dectection: The Tau Tester

How it Works: The Cosmic Punching Bag

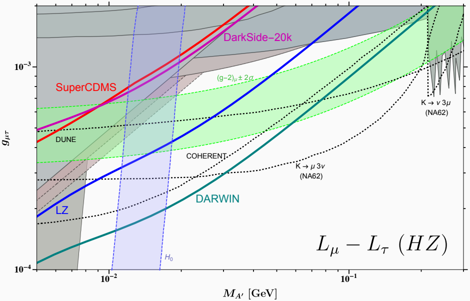
- Dark matter detectors by trade
- But branching out to **solar** ν's!
- Bad for DM detection (irreducible bkg)...
- But good for ν detection (irreducible signal)!



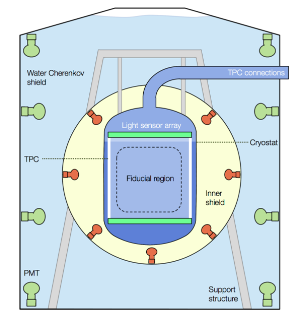
[Jianglai Liu, Xun Chen, and Xiangdong Ji. arXiv: 1709.00688]

DARWIN: Our Best Hope

- Previous work: Xe-based detectors best for $(g-2)_\mu$
- DARWIN biggest one proposed



[D. Amaral et al. arXiv: 2006.11225]



[J. Aalbers et al. arXiv: 1606.07001]

- BIG exposure: $200\,\mathrm{ton}\cdot\mathrm{yr}$
- Light/charge signal can be used to tell if NR or ER
- High WIMP threshold ($E_{\mathrm{th}} \sim 5\,\mathrm{keV}$), but precedent for $E_{\mathrm{th}} \sim 1\,\mathrm{keV}$ (LUX)

Data Generation: ν_τ Appears

Same as for spallation but with some important differences:

Target dependent | ν_τ included! | Target dependent

$$N^T(g_x\varepsilon_x, M_{A'}) = \varepsilon\, n_T \sum_{\nu_\alpha} \int_{E_{\rm th}} \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} \epsilon(E_R)\, \overbrace{\frac{dN_{\nu_e}}{dE_\nu}}^{\text{Solar } \nu_e \text{ flux}}\, \underbrace{P(\nu_e \to \nu_\alpha)}_{\text{Osc. Prob.}}\, \frac{d\sigma_{\nu_\alpha T}}{dE_R}\, dE_\nu dE_R$$

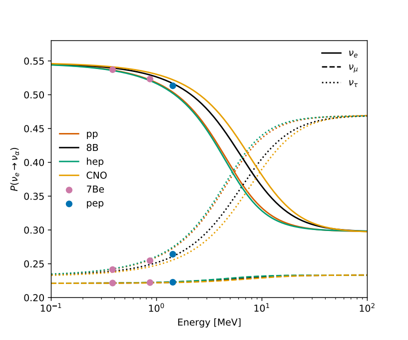
- ν_τ's mean **+ve interf.**

$$Q'_{\nu_\alpha} = \begin{cases} 0 & \text{if } \alpha = e \\ +1 & \text{if } \alpha = \mu \\ -1 & \text{if } \alpha = \tau \end{cases}$$

- More ν_τ's than ν_μ's too!

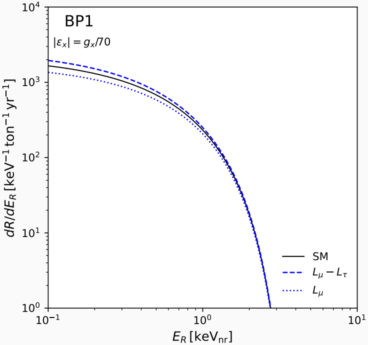
$$U(1)_{L_\mu - L_\tau} \implies \textbf{excess}$$

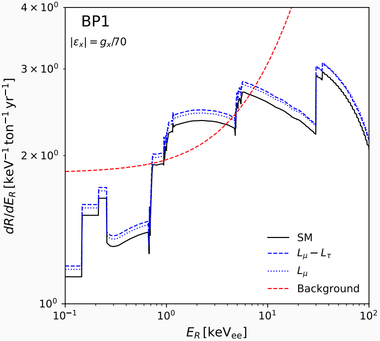
$$U(1)_{L_\mu} \implies \textbf{deficit}$$



[E. Reid prelim.]

The NR Killer: A Deficit vs. An Excess





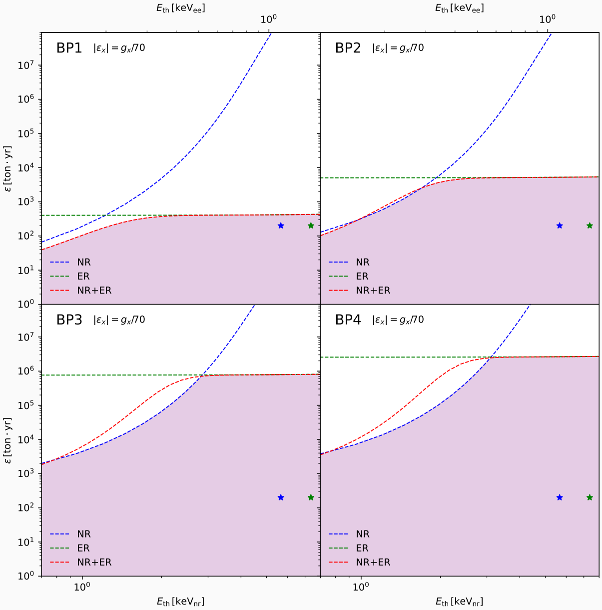
[DA DC AC PF. arXiv: 2104.03297]

NRs die off quickly and ERs drowning in background! Difficult...

What E_{th} and ε do we need to observe an overall 5σ excess over SM?

Note: For ERs, $|c_{\mathrm{int}}| \ll |c_{\mathrm{BSM}}| \implies$ Get an excess in both models

Discovering the Excess



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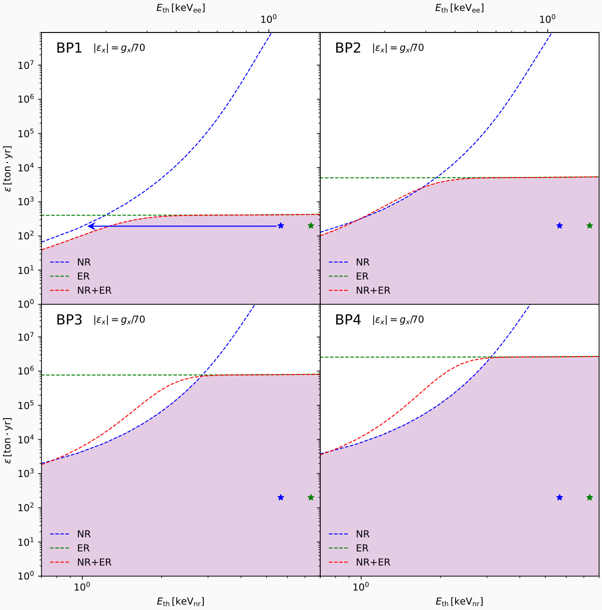
Discovering the Excess



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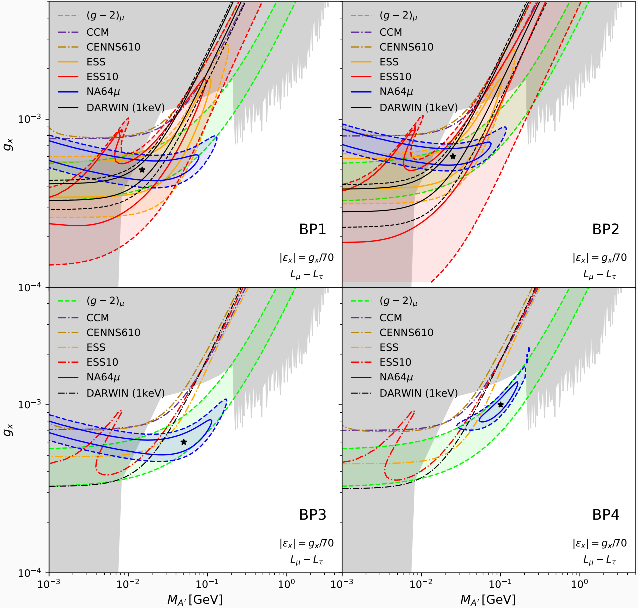
The Fitting Game: Putting it All Together...



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DM Direct Detection: The Key Takeaways

- DM direct detectors are also sensitive to the product $g_x \varepsilon_x$
- Direct detectors sensitive to ν_τ's
- DARWIN modified to $1\,\mathrm{keV}$ could discover $U(1)_{L_\mu - L_\tau}$ excess at 5σ
- Direct detectors would see excess in $U(1)_{L_\mu - L_\tau}$ and deficit in $U(1)_{L_\mu}$ for CEνNS
- DARWIN tells us what puzzle we're solving!

Conclusions and a Path to the Nobel Prize?

1. FNAL $(g-2)_\mu$ results hint at exciting new physics
   - $U(1)_{L_\mu - L_\tau}$ very elegant explanation, but difficult to disentangle from $U(1)_{L_\mu}$
2. Muon beam experiments could tightly constrain g_x
   - Spallation experiments could give us valuable information about ε_x
   - DD experiments could be model tie-breaker
3. **Together, form powerful probes of $U(1)_{L_\mu - L_\tau}$!**