Theoretical Overview

Gordan Krnjaic

Discovering the new physics of g-2 with fixed target muon facilities at Fermilab 6/22/21

Overview

Current Status of a_μ

Model Survey

Dark Matter Connection

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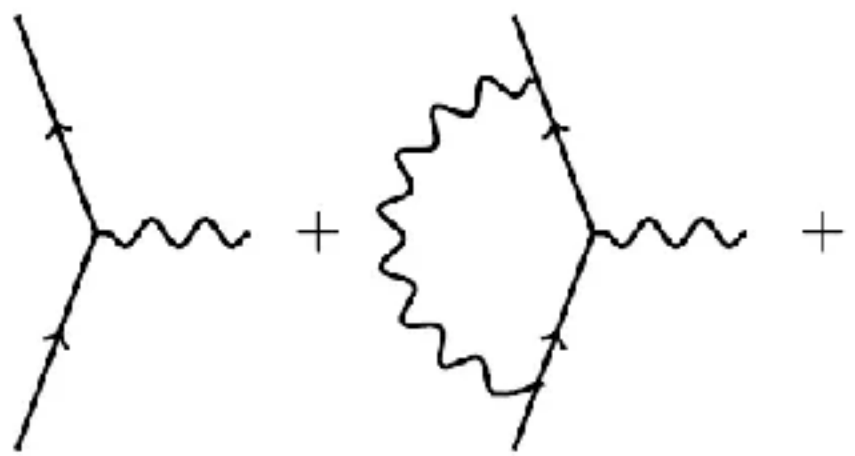
Muon Anomalous Magnetic Moment

Lepton dipole moment $\vec{\mu}_\ell = \pm g_\ell \frac{e}{2m_\ell}\vec{S}$ $a \equiv \frac{g-2}{2}$

Tree level QED prediction: $a = 0$

Quantum loop corrections: $a \neq 0$



$$\cdots \rightarrow g = 2 + \frac{\alpha}{2\pi} + \cdots$$

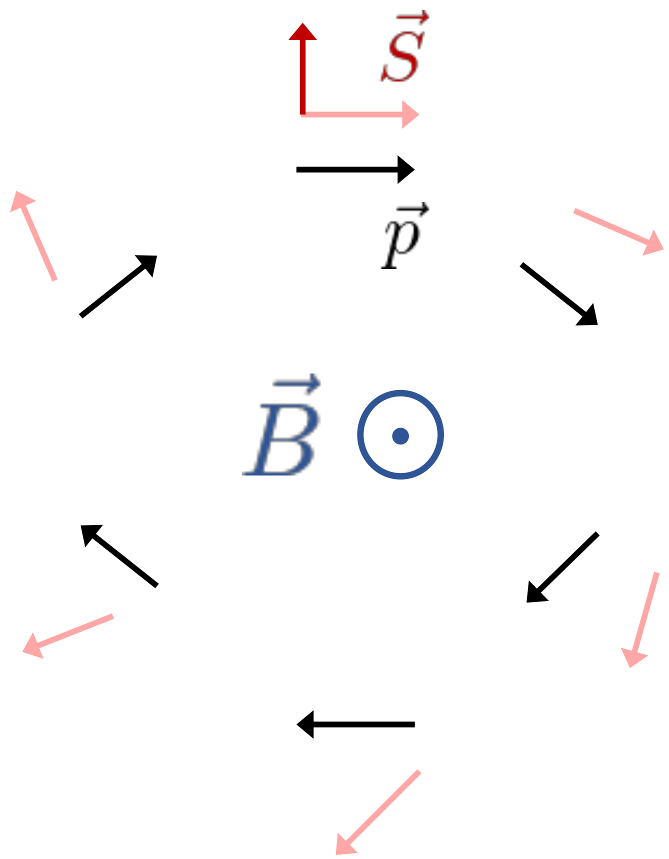
Sensitive to all known ***and unknown*** particles coupled to leptons

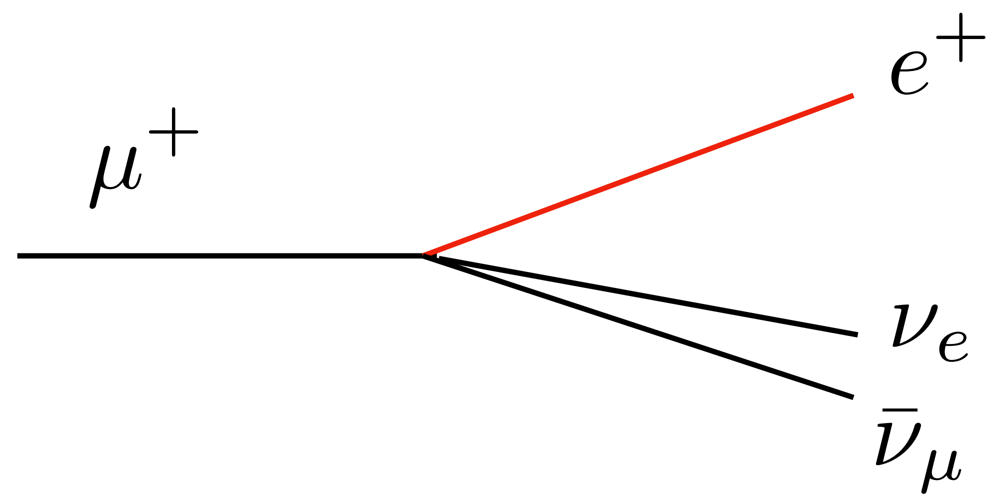
For electrons agrees SM to ~ 12 decimals, best prediction in history

Spin precession in a uniform B field

$$\omega_a = a_\mu \frac{eB}{2m_\mu}$$

Lab Frame





$$\frac{d\Gamma}{dE} = A\left[1 - B(\vec{s}\cdot\vec{p})\right] \qquad \vec{s}\cdot\vec{p} \propto \cos\omega_a t$$

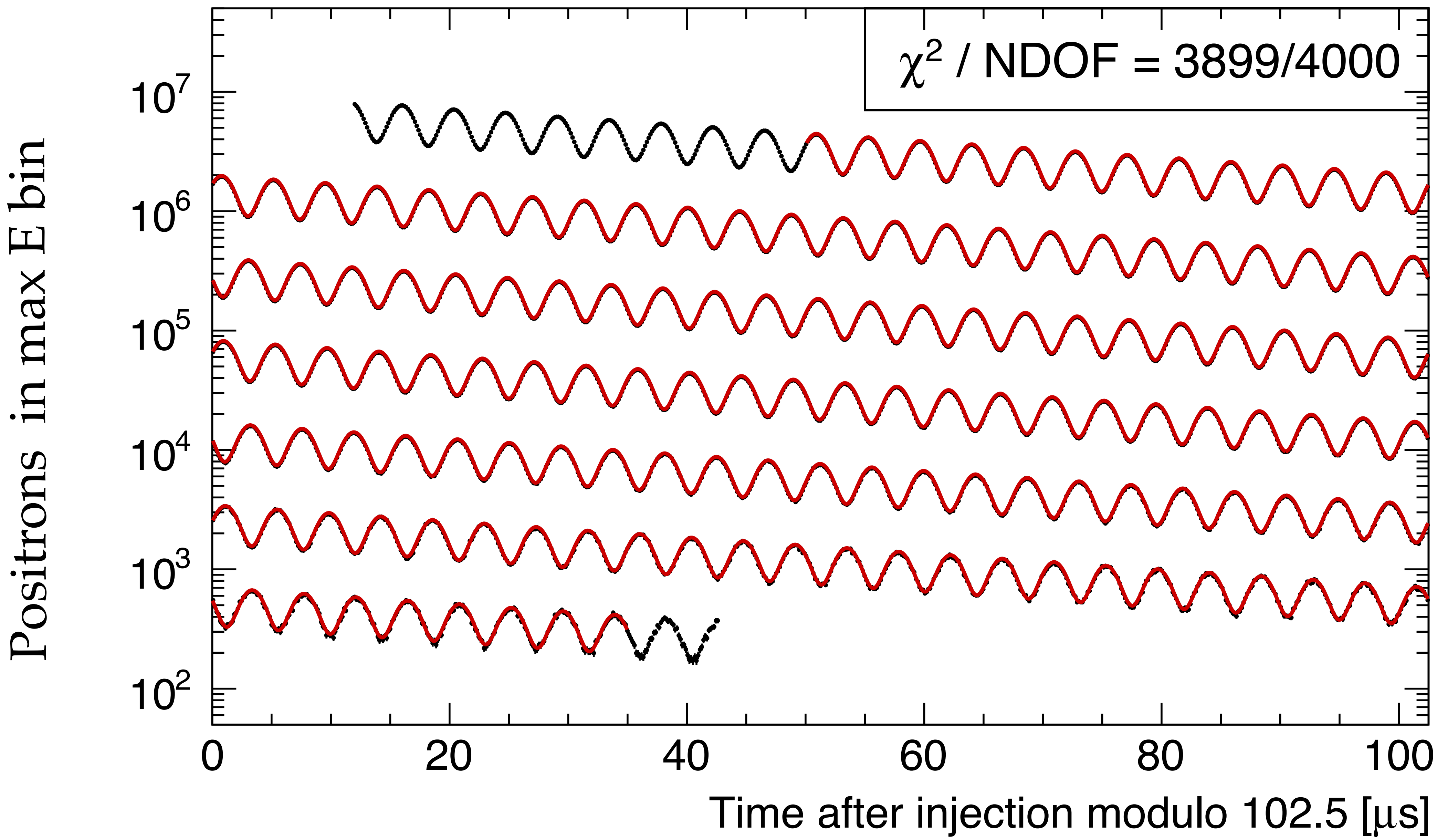
Upon $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ decay e^+ emitted preferentially along $\vec{S}$

Asymmetry in e^+ energy distribution measures ω_a

Graphic: Ryan Janish

Spin precession in a uniform B field

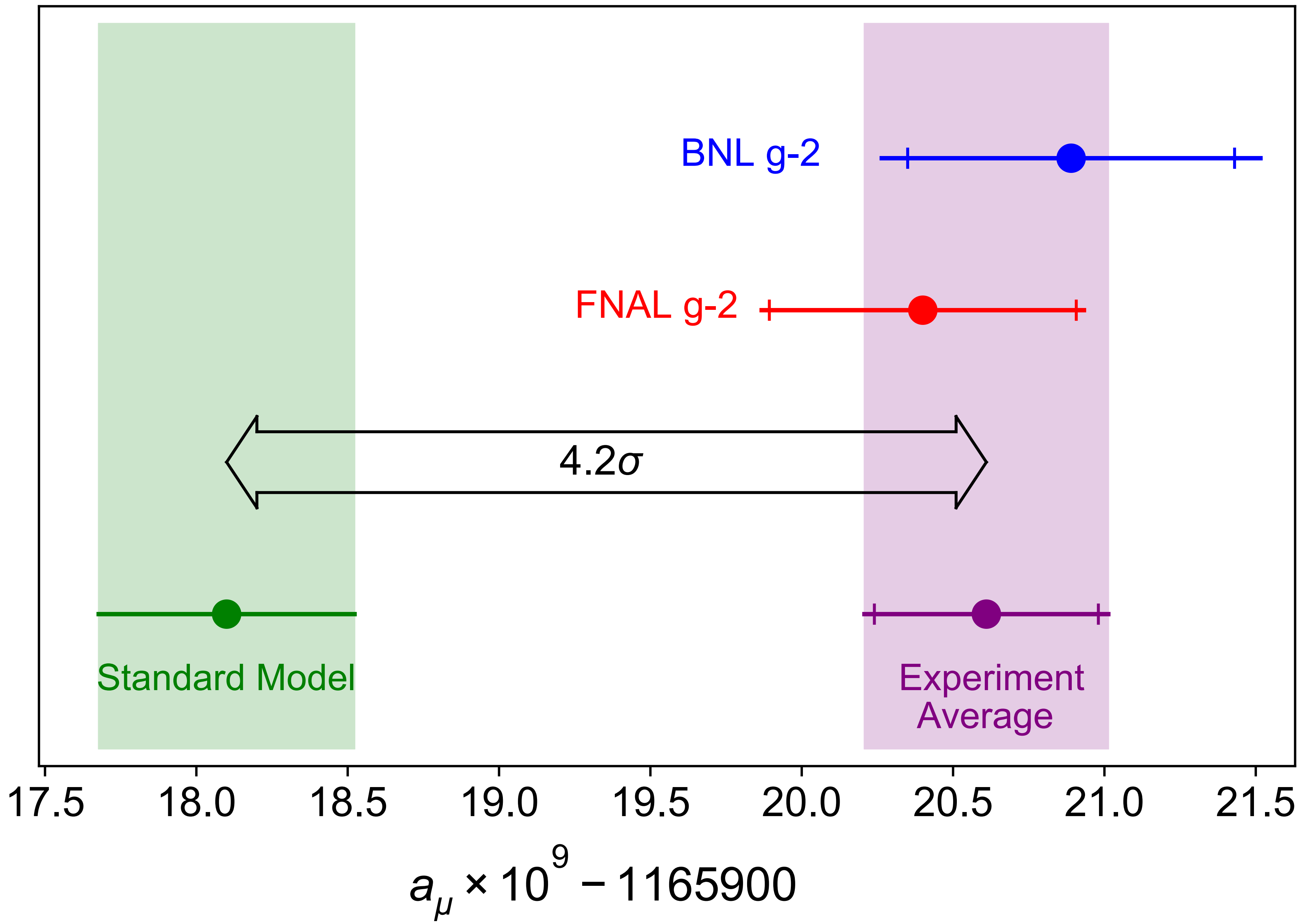
$$\omega_a = a_\mu \frac{eB}{2m_\mu}$$

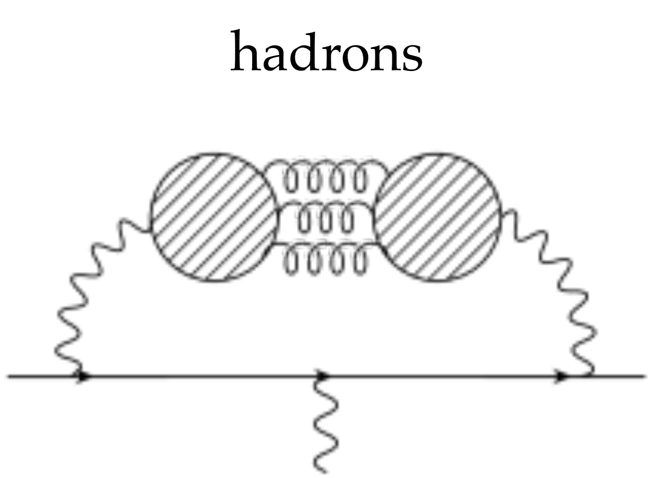


$$N_e(t) \propto e^{-t/\tau_\mu} \left(1 + B' \cos \omega_a t\right)$$

g-2 collaboration 2104.03247

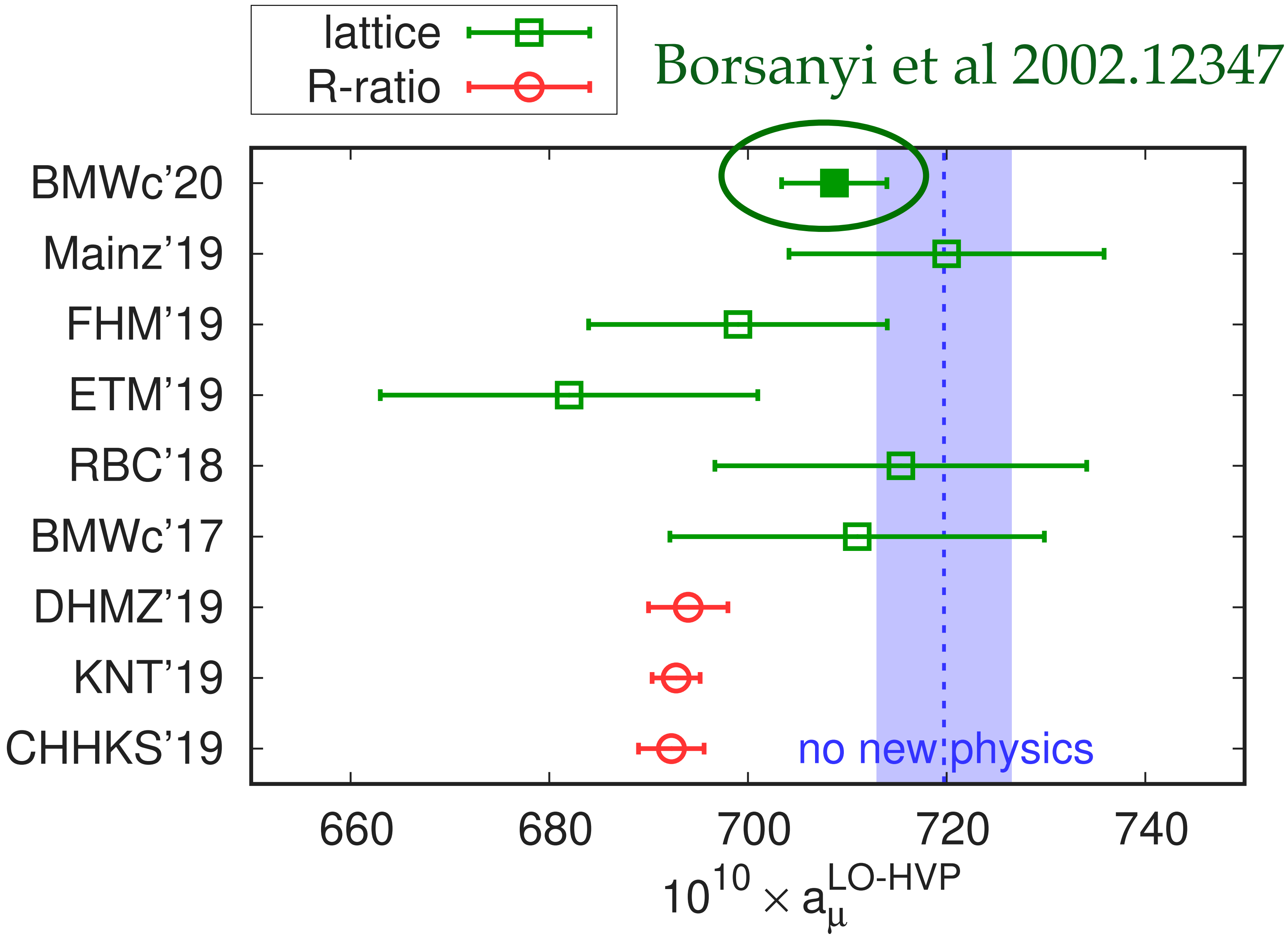
Theory vs. Experiment





Theory uncertainty driven by non-perturbative QCD corrections

Comparing SM Theory Calculations

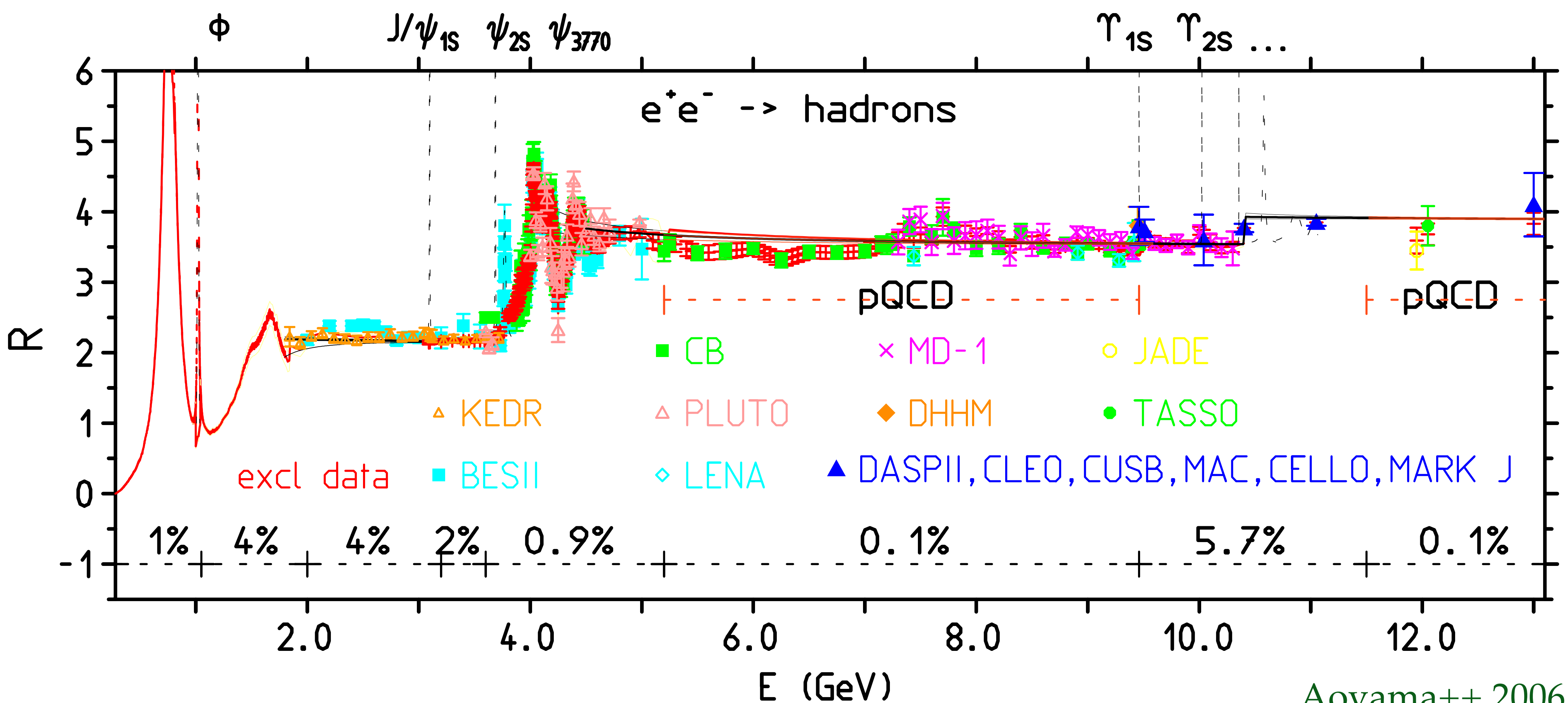


Recent lattice BMWc result in tension with data driven R-ratio method

… but it's closer to experiment

R-Ratio Calculations

Hadronic contributions can be extracted from $e^+e^- \to \text{hadrons}$ data



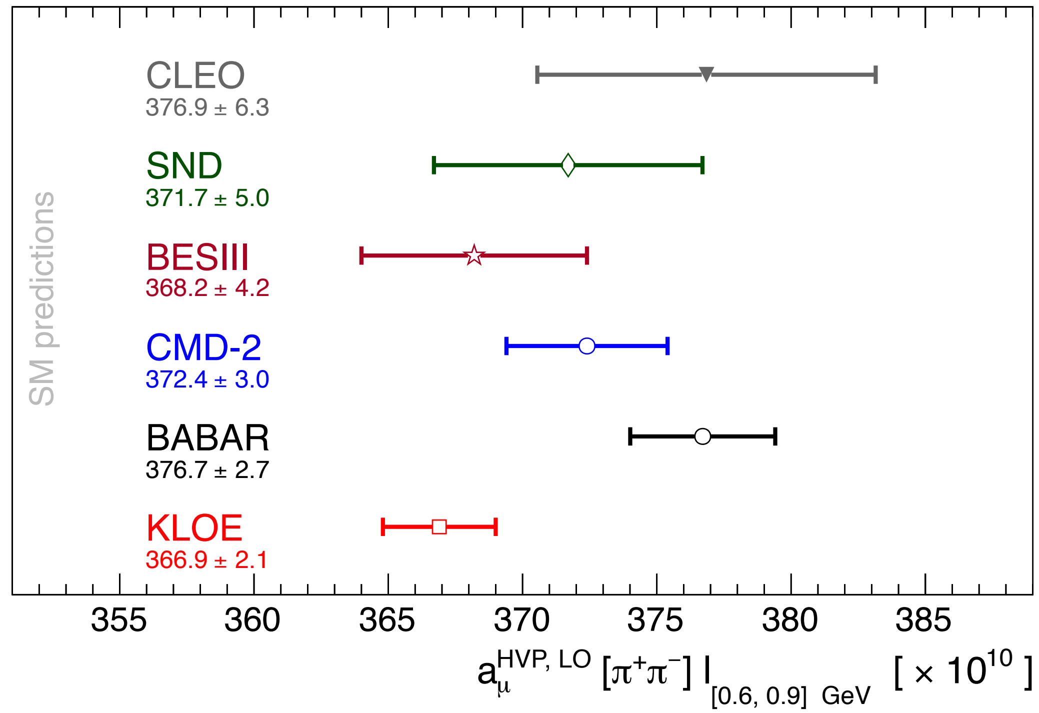
Aoyama++ 2006.04822

$$a_\mu^{\text{HVP, LO}} = \frac{\alpha^2}{3\pi^2}\int_{M_\pi^2}^{\infty}\frac{K(s)}{s}R(s)\,ds$$

$$R(s) \propto \sigma(e^+e^- \to \text{hardons})$$

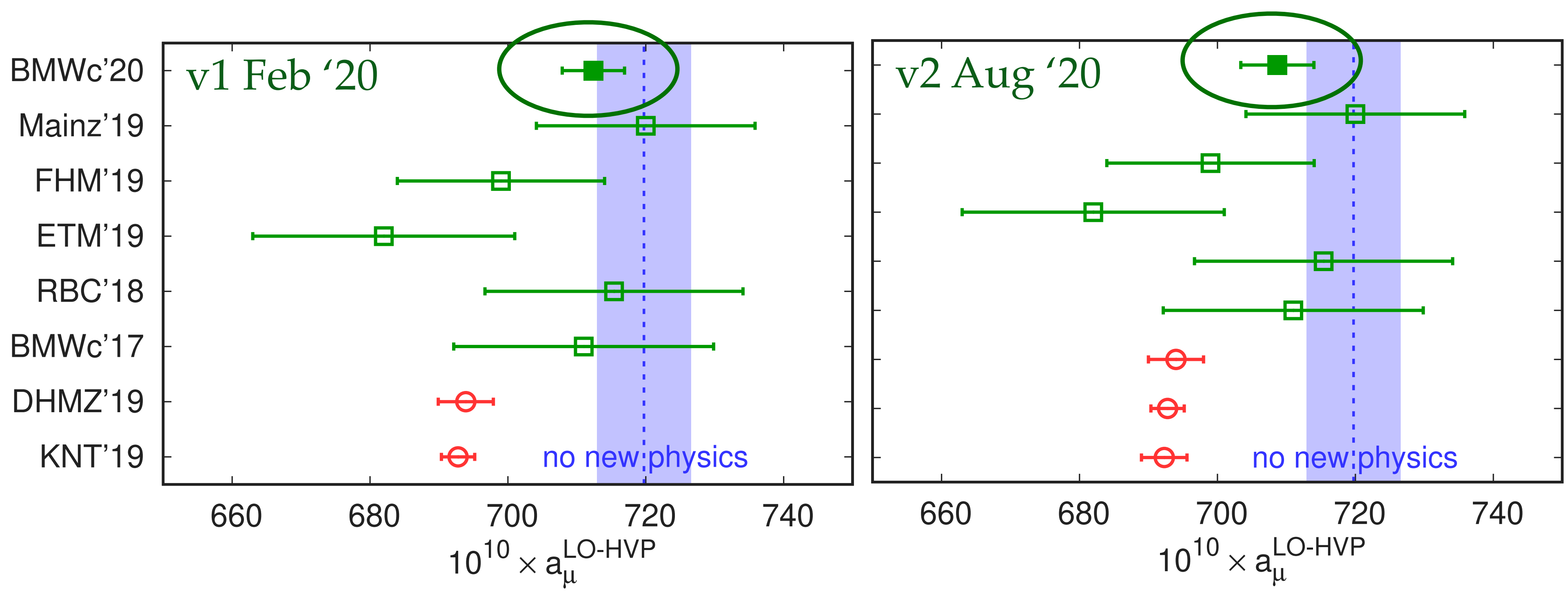
R-Ratio Possible issue of internal consistency across full data set?

Aoyama++ 2006.04822



Borsanyi++ 2002.12347

Lattice



Possible issue of extrapolating to continuum limit?

BMW also makes electroweak fit worse and in tension with $e^+e^- \to \pi\pi$

What should we believe?

1) Issue with with R-ratio calculations?

Possible, but nothing obvious (maybe tension in data?)

2) Issue with lattice calculations?

Also possible, need confirmation from other groups

3) R-ratio correct, but unknown experimental systematic?

After new data, this is extremely unlikely

This is the main new thing we have learned

4) New BSM particles contributing to loops?

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What's the highest BSM scale?

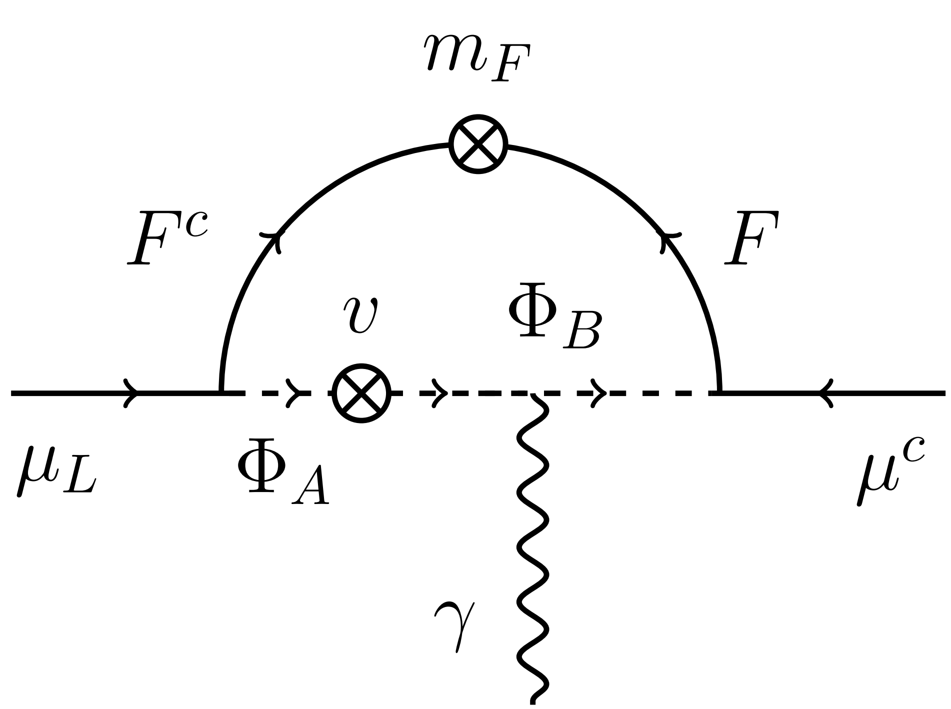
$$\mathcal{L}_{\rm eff} = C_{\rm eff}\,\frac{v}{M^2}(\mu_L \sigma^{\nu\rho}\mu^c)F_{\nu\rho} + \text{h.c.}$$

Contributing to g-2 requires EWSB insertion and chiral flip

What's the highest BSM scale?

$$\mathcal{L}_{\text{eff}} = C_{\text{eff}} \frac{v}{M^2} (\mu_L \sigma^{\nu\rho} \mu^c) F_{\nu\rho} + \text{h.c.}$$

Contributing to g-2 requires EWSB insertion and chiral flip
If both arise from BSM vertices, highest scale **~ few 10s TeV**



Nightmare Heavy BSM
Muon-philic~50 TeV
with $O(1)$ couplings

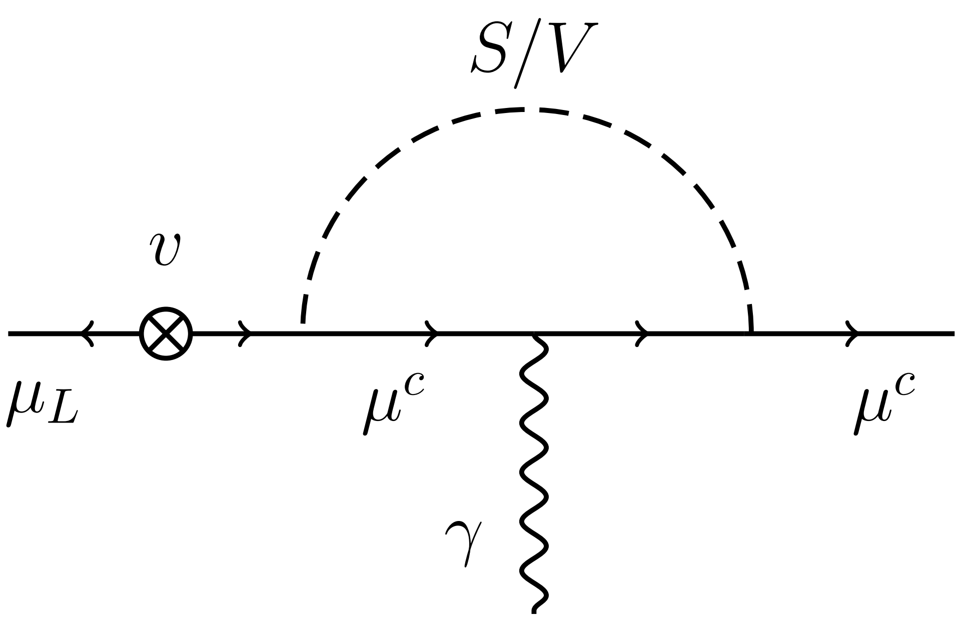
Requires future *muon* collider to test "nightmare" scenario

Capdevilla, Curtin, Kahn, GK 2006.16277

What about light (< GeV) new physics?

$$\mathcal{L}_{\text{eff}} = C_{\text{eff}} \frac{v}{M^2} (\mu_L \sigma^{\nu\rho} \mu^c) F_{\nu\rho} + \text{h.c.}$$

Chiral flip and EWSB on muon line



Simpler BSM Landscape

Must be scalar (S) or vector (V)

Must be SM gauge singlet

Must be > MeV (cosmology)

$$\Delta a_\mu^V = \frac{g_V^2}{4\pi^2} \int_0^1 dz \frac{m_\mu^2 z (1-z)^2}{m_\mu^2 (1-z)^2 + m_V^2\, z} \simeq 1.3 \times 10^{-10} \left(\frac{g_V}{10^{-4}}\right)^2 \quad (m_V \ll m_\mu)$$

Pospelov 0811.1030

Options For Light BSM?

1) Mix S/V with existing SM particles

2) Couple S/V to heavy states that mix with the muon

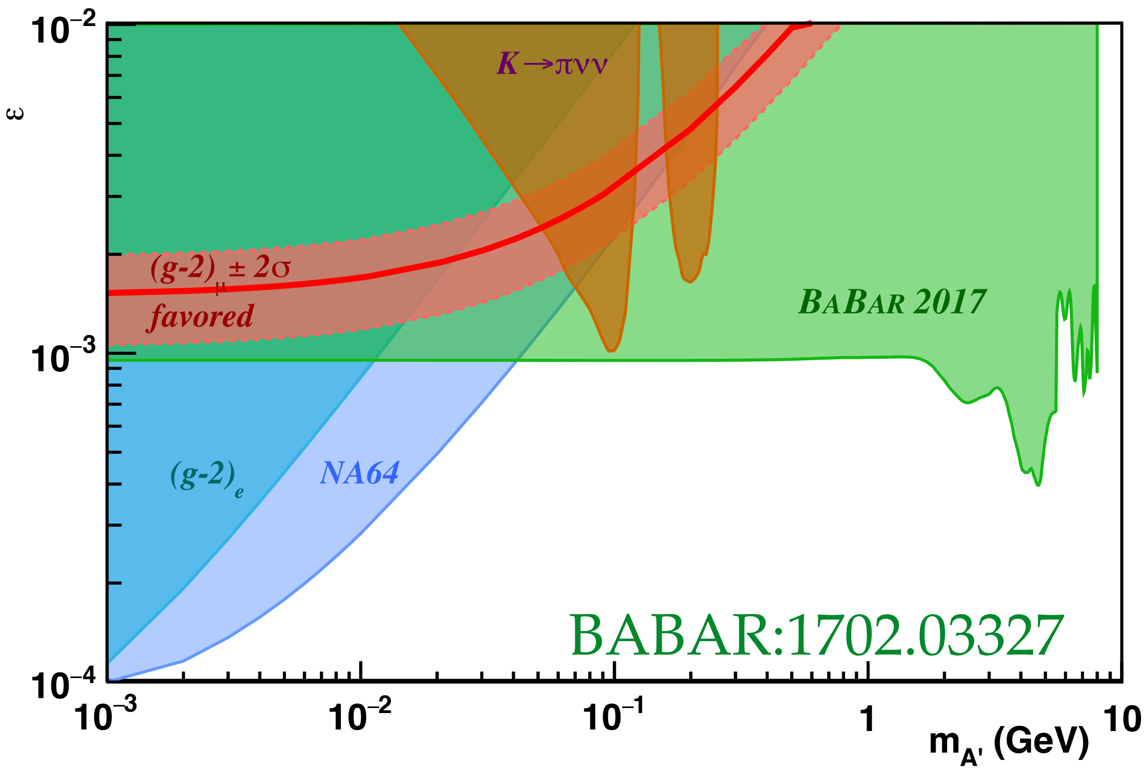
3) V is the gauge boson of a new U(1) SM extension

Options For Light BSM?

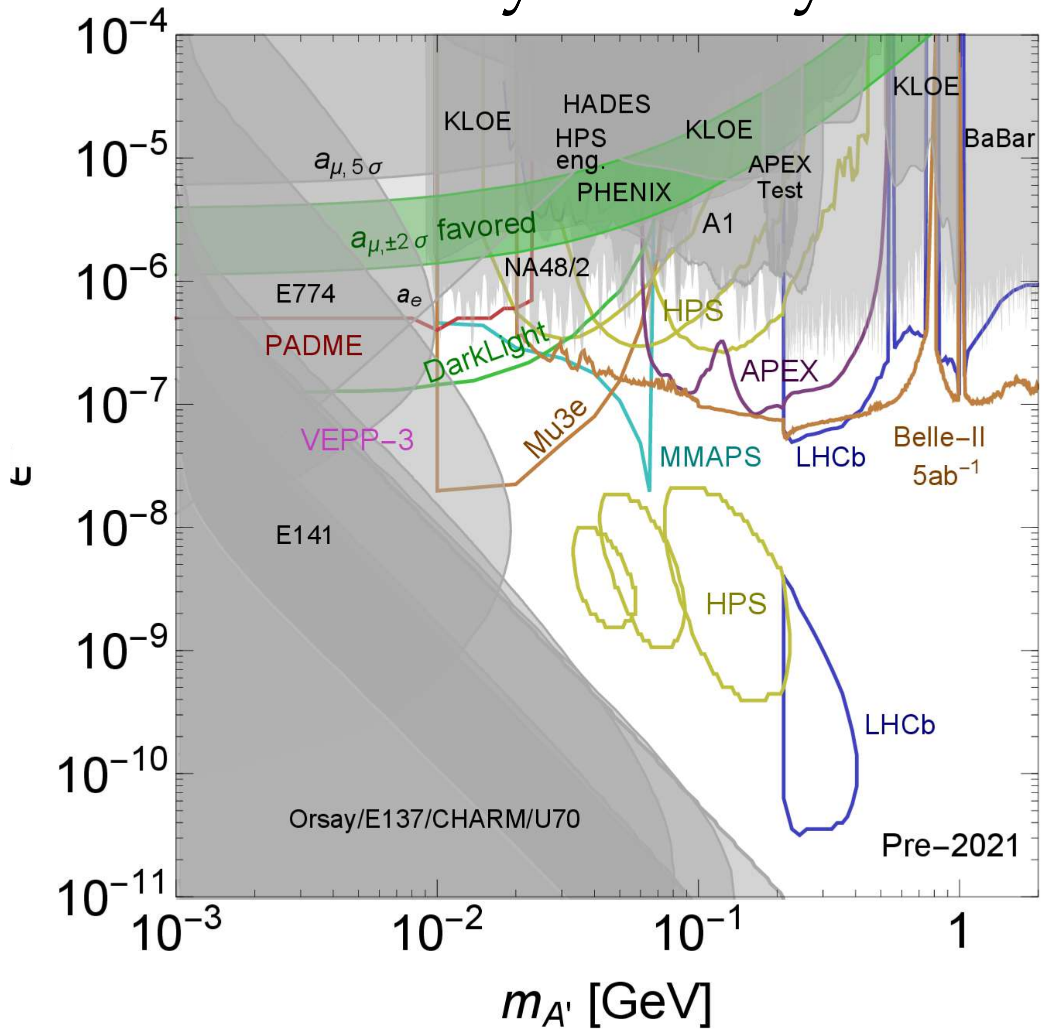
1) Mix S/V with existing SM particles

Kinetically mixed dark photon *A′* ruled out $\mathcal{L}_{\rm int} = \epsilon e A'_\mu J^\mu_{\rm EM}$

Decays invisibly



Decays visibly



See Mohlabeng for semi-visible decays 1809.07768

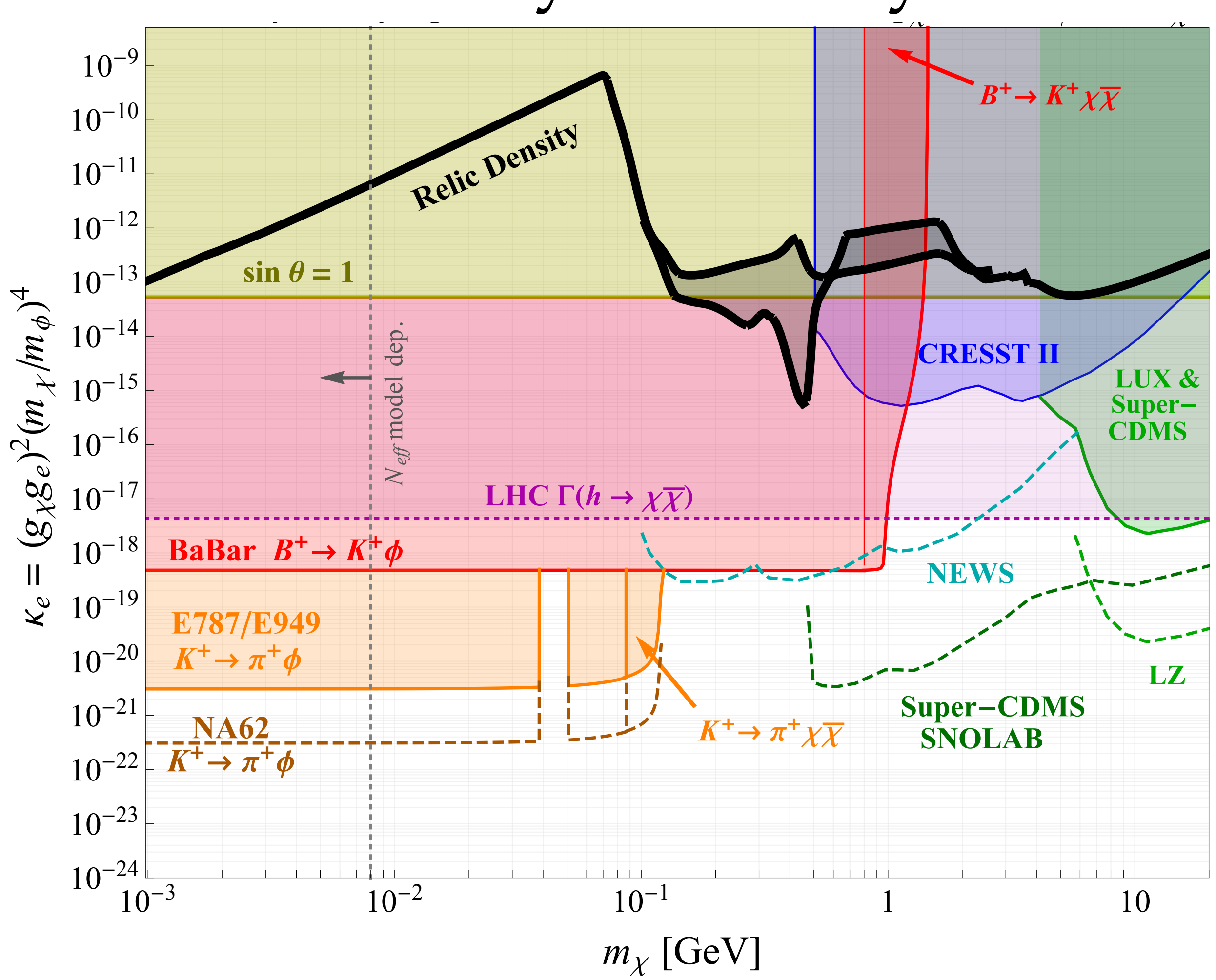
1707.04591

Options For Light BSM?

1) Mix S/V with existing SM particles

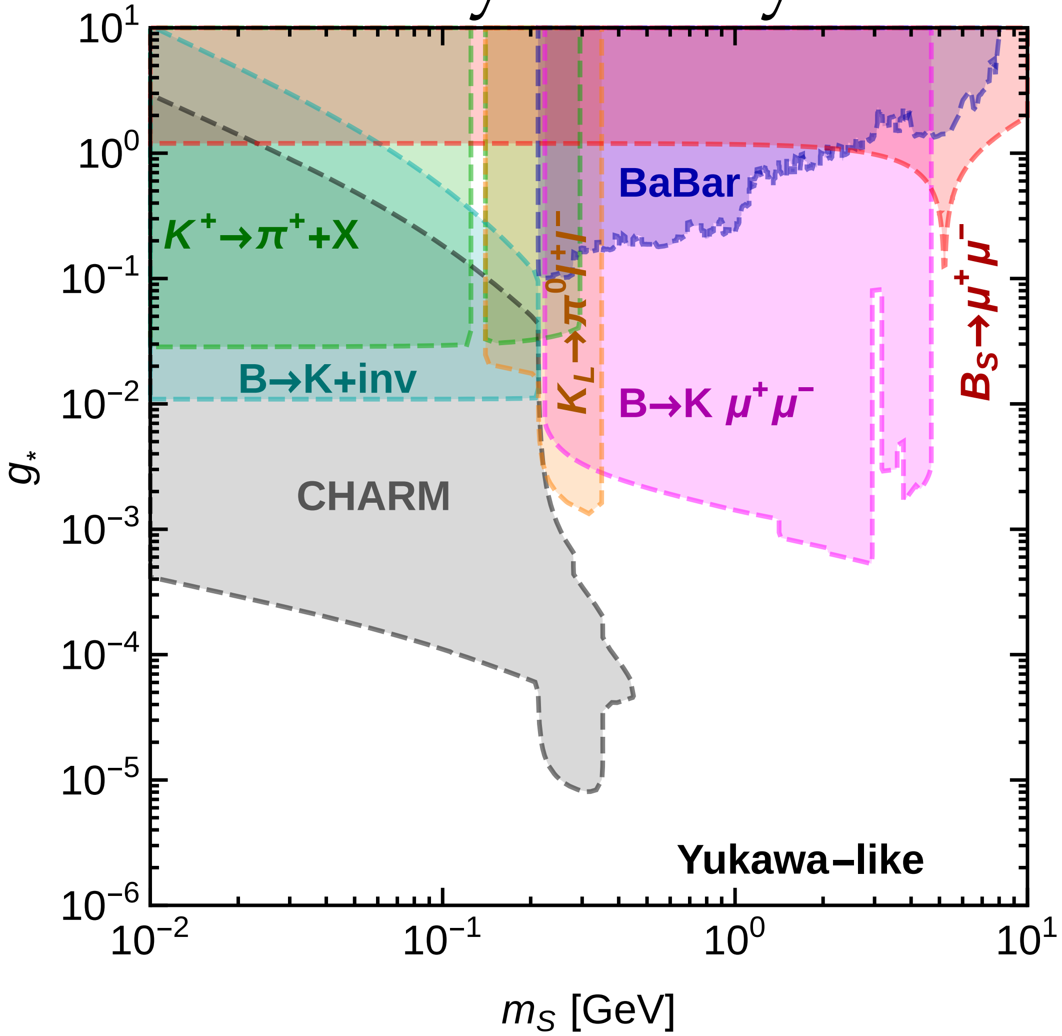
Higgs mixed scalar ϕ ruled out $\qquad \mathcal{L}_{\rm int} = \sin\theta\, \phi\, \frac{m_f}{v} \bar{f} f$

Decays invisibly



GK 1512.04119

Decays visibly



SHiP collab 1504.04855

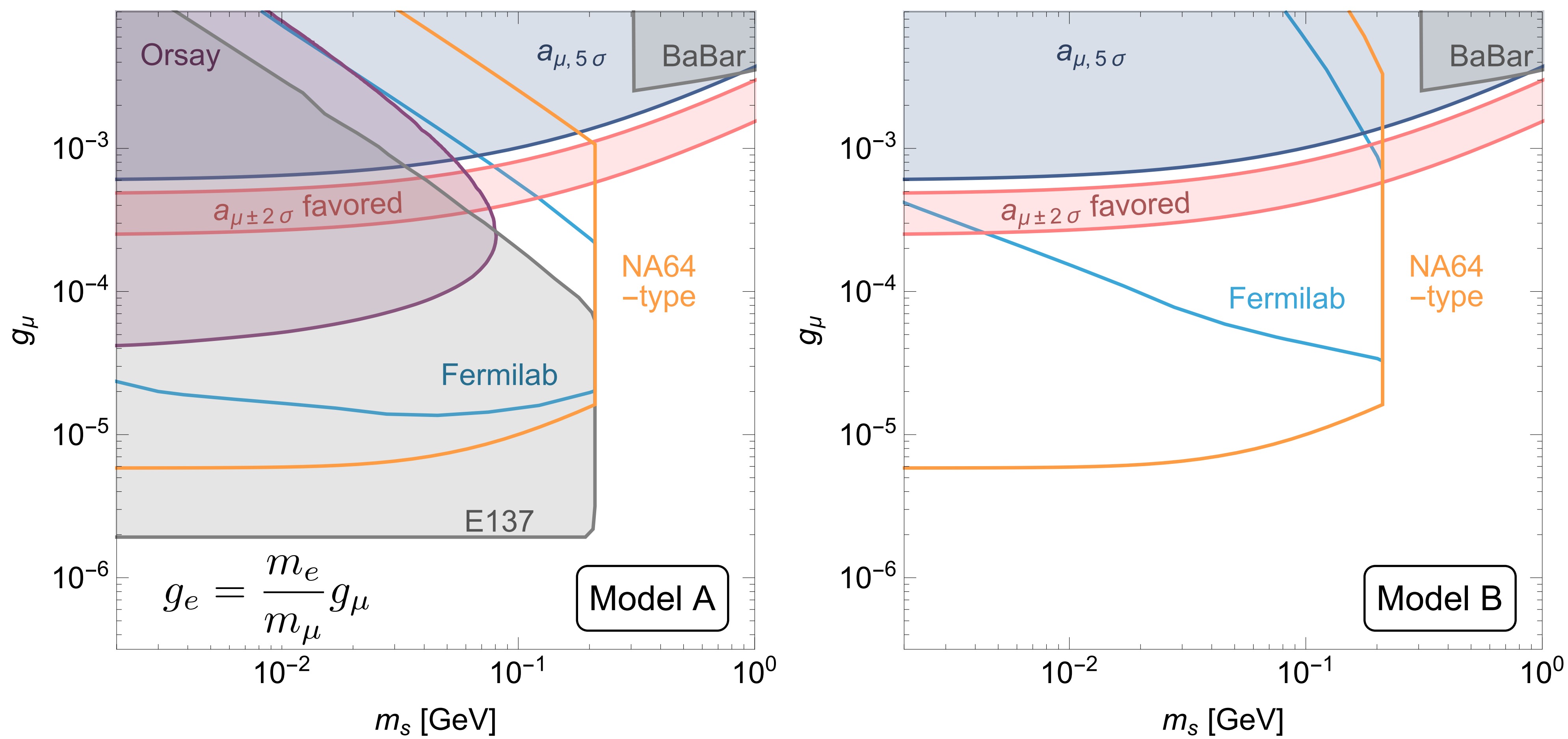
Options For Light BSM?

2) Couple S/V to heavy states that mix with the muon

$$\mathcal{L} \supset -\frac{1}{2} m_S^2 - \left(y_\mu H^\dagger L \mu^c + \frac{c_s}{M} S H^\dagger L \mu^c \right) \rightarrow \mathcal{L}_{\rm eff} = g_\mu S \mu \mu^c$$

$S \rightarrow e^+ e^-$ decay allowed

$S \rightarrow \gamma\gamma$ via muon loop



Both viable below ~ 200 MeV

Chen, Pospelov, Zhong, 1701.07437
Batell, Freitas, Ismail, McKeen 1712.10022

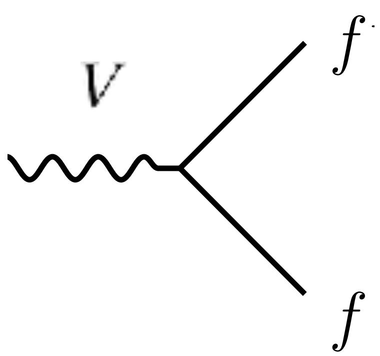
See Yiming Zhong and Brian Batell's talks

Options For Light BSM?

3) V is the gauge boson of a new U(1) SM extension

SM particles now carry a new gauge quantum number

$$\mathcal{L} \supset g V_\mu J^\mu_{\rm SM} \quad , \quad J^\mu_{\rm SM} \equiv \sum_f Q_f \bar{f} \gamma^\mu f$$



Only anomaly free possibilities:

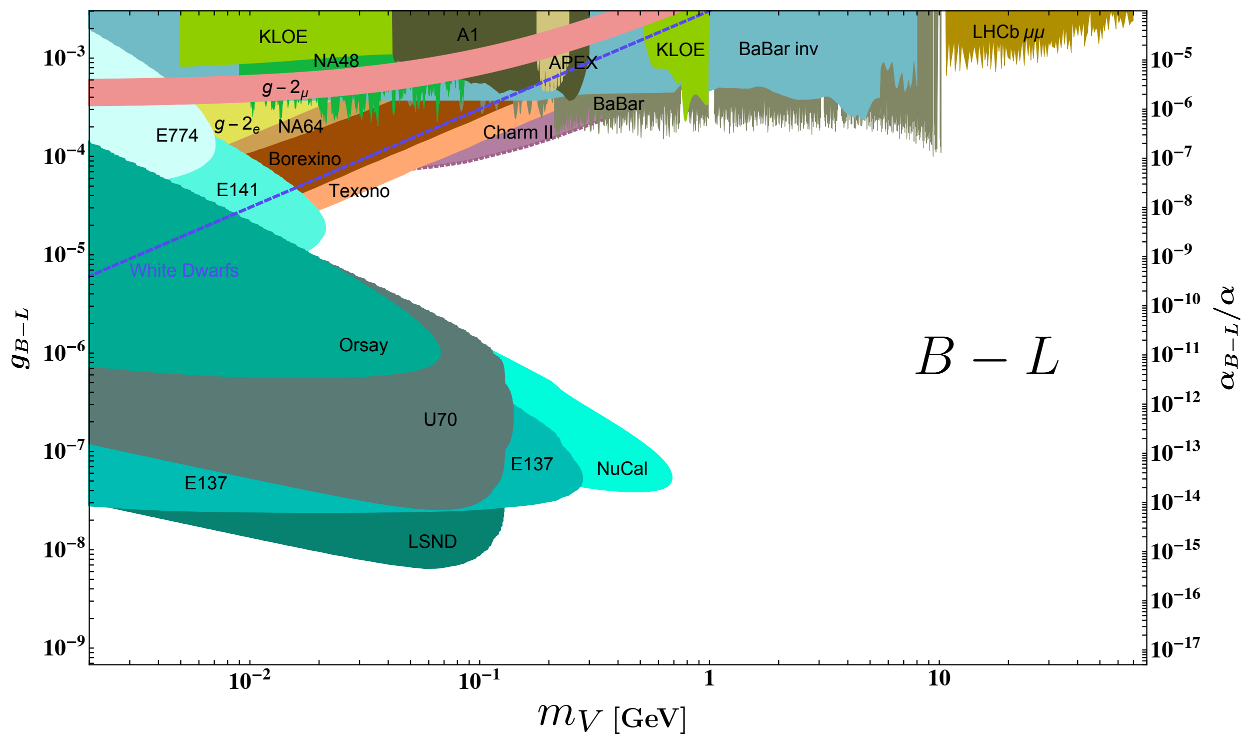
$$U(1)_{B-L} \ , \ U(1)_{L_i - L_j} \ , \ U(1)_{B-3L_i}$$

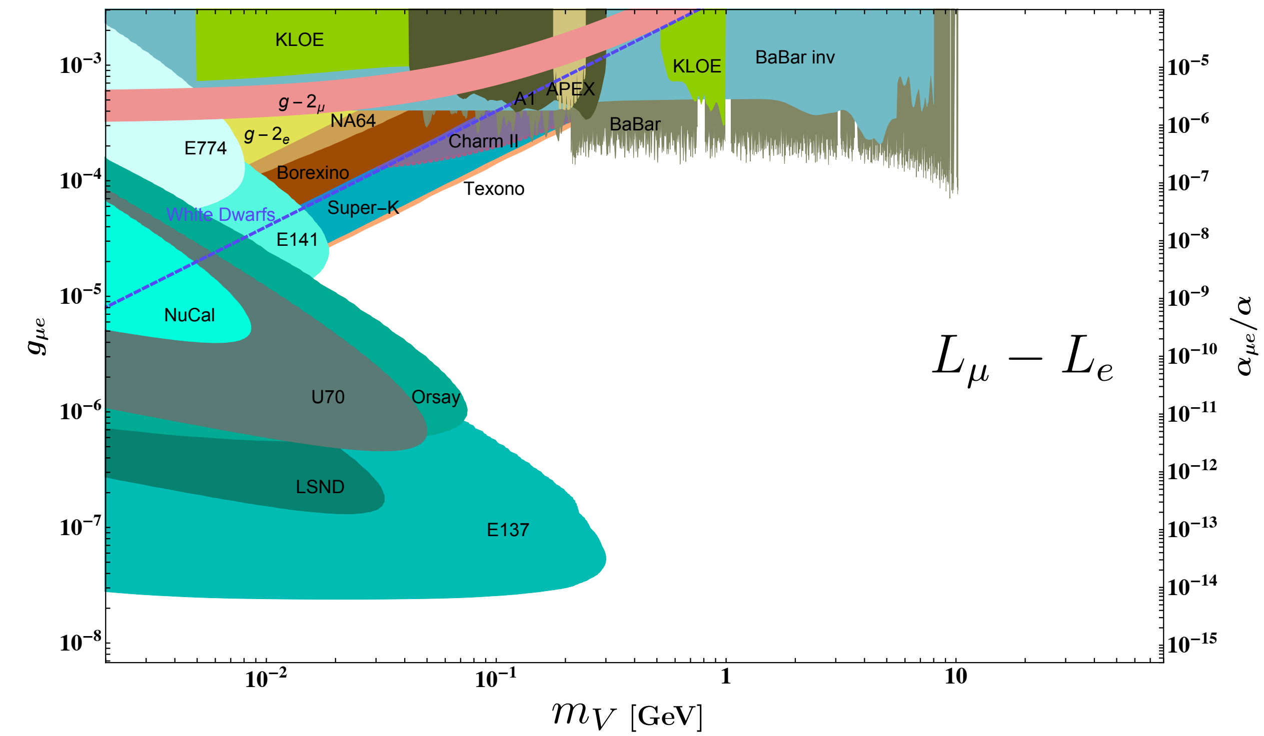
Qualitatively similar, but some differences in bounds

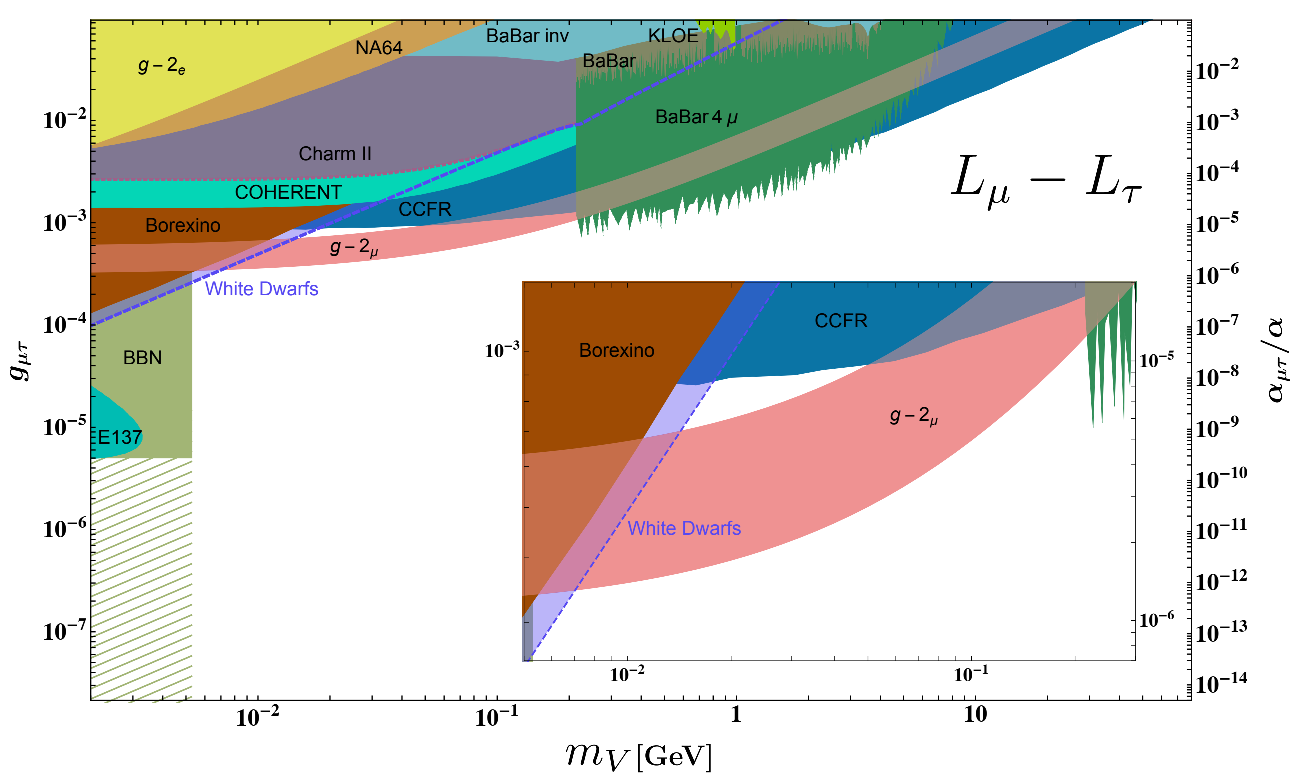
Two parameter family of models: $\{g, m_V\}$

Options For Light BSM?

3) V is the gauge boson of a new U(1)



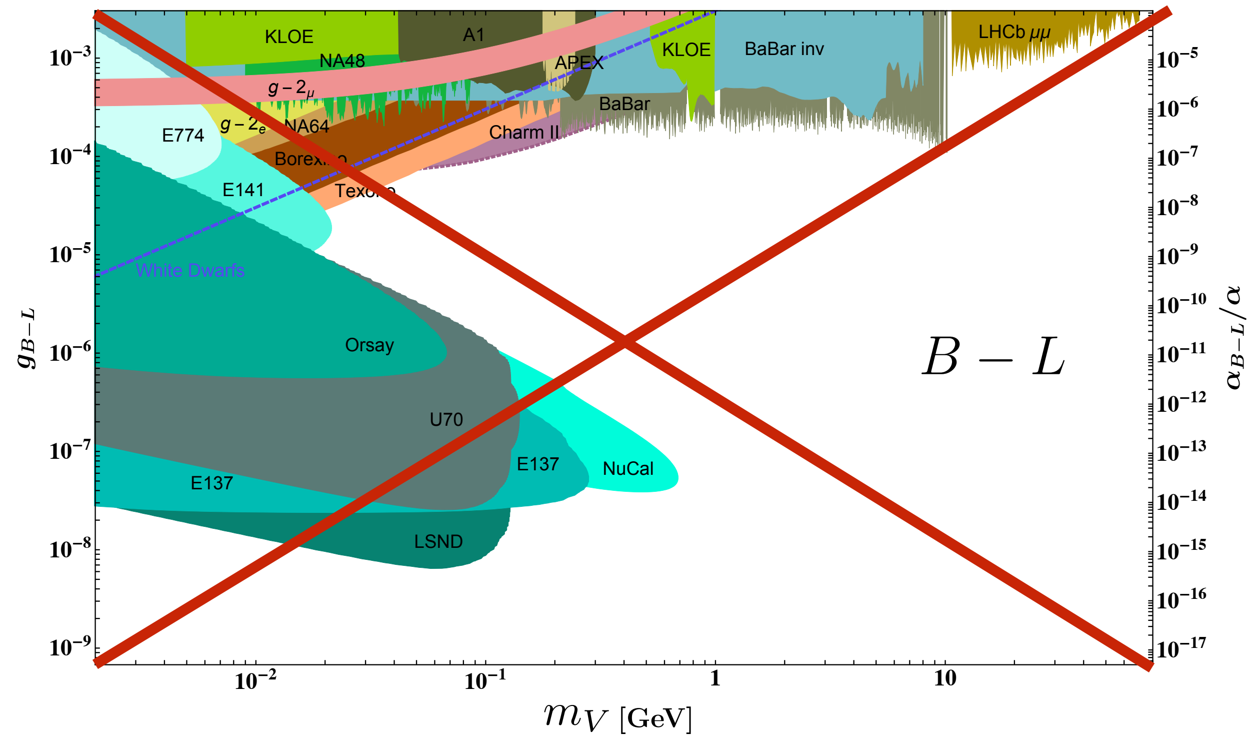


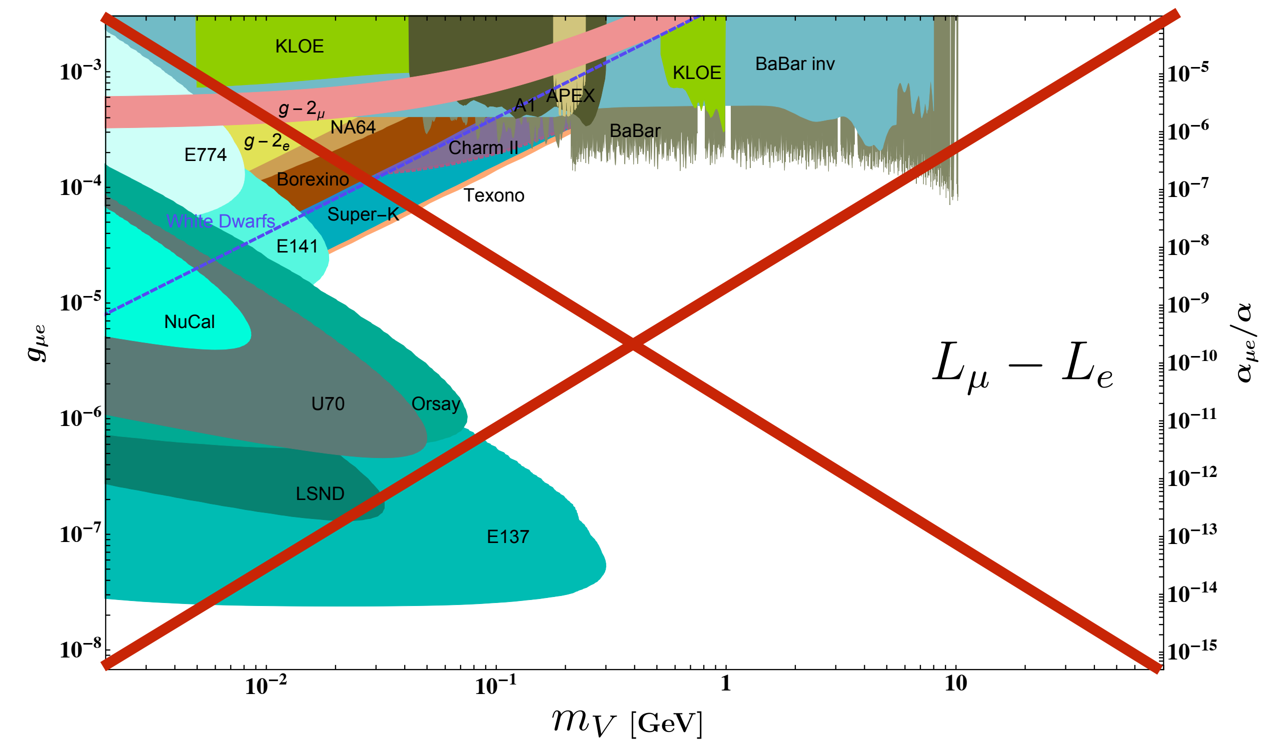


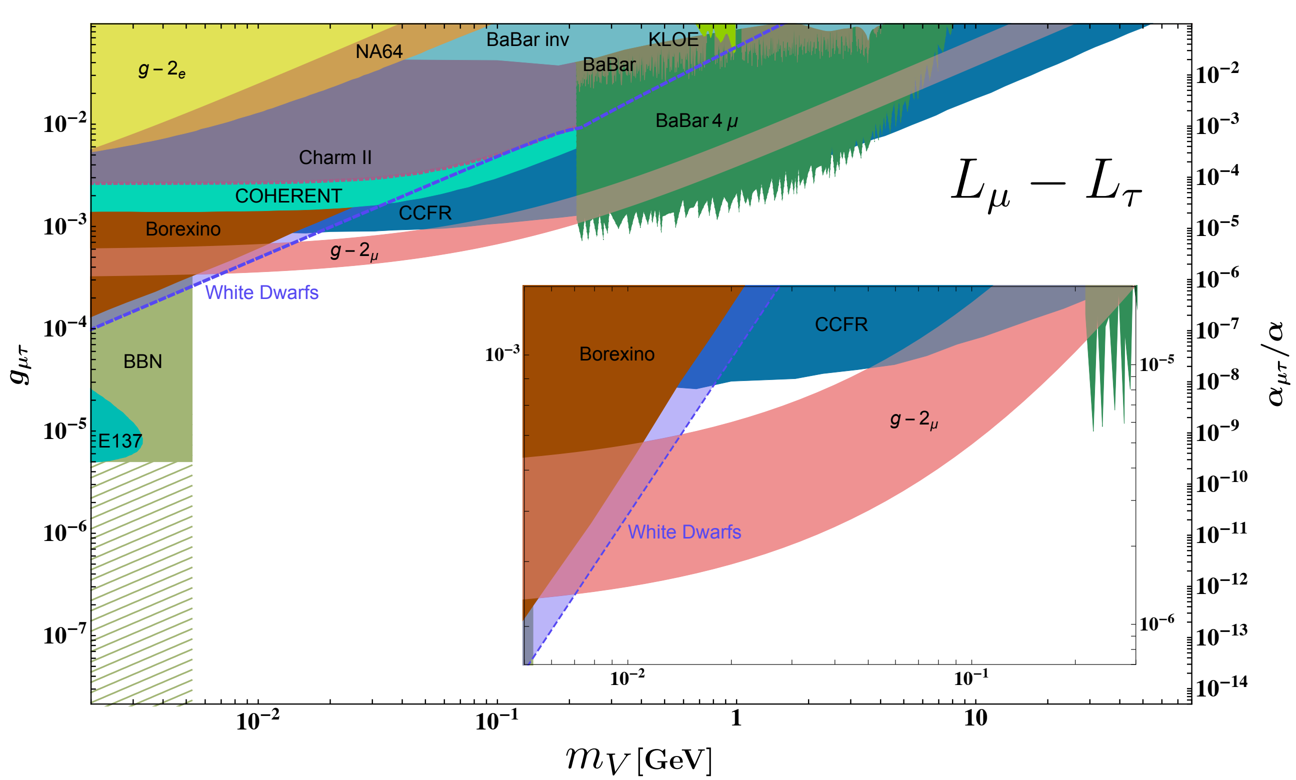
Bauer, Foldenauer, Jaeckel, 1803.05466

Options For Light BSM?

3) V is the gauge boson of a new U(1)







Only one possibility left

Viable between $\text{MeV} - 2m_\mu$

$<$ MeV spoils BBN

$> 2m_\mu$ decays to muons

Bauer, Foldenauer, Jaeckel, 1803.05466

Summary of what's left

Experimental bounds require muon-philic forces for < GeV singlets

Scalar model

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \sum_{\ell=e,\mu,\tau} g_\ell S\bar{\ell}\ell,$$

Generically need $g_{e,q} \ll g_\mu$

Some model dependence in decays

Need additional SM charged fields in UV

Vector model

$U(1)_{\mu-\tau}$

$$\mathcal{L} \supset \frac{m_V^2}{2} V_\alpha V^\alpha + g_V V_\alpha J^\alpha_{\mu-\tau}$$

$$J^\alpha_{\mu-\tau} \equiv \bar{\mu}\gamma^\alpha\mu + \bar{\nu}_\mu\gamma^\alpha P_L \nu_\mu - (\mu \to \tau)$$

For viable mass range < 200 MeV, V always decays invisibly

See Cristina Mantilla-Suarez's talk

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Q: Why haven't we discovered dark matter in the lab?

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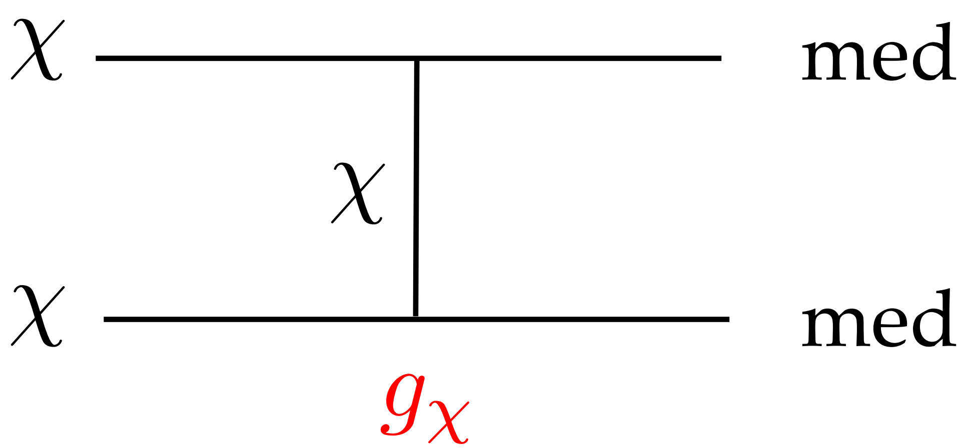
A: Maybe because it couples more to muons

The same bosons (S/V) for g-2 can also mediate DM annihilation during "freeze out" in early universe

Who’s heavier: mediator or DM?

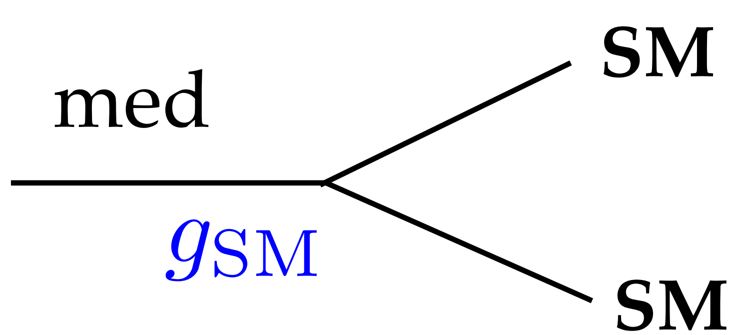
Secluded Annihilation

$m_\chi > m_{\rm med}$



No clear experimental target

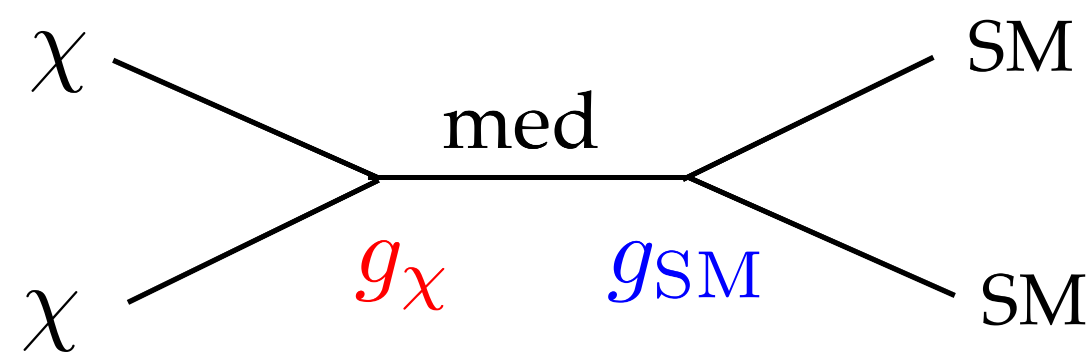
Abundance set by g_χ



Mediator decays **visibly**

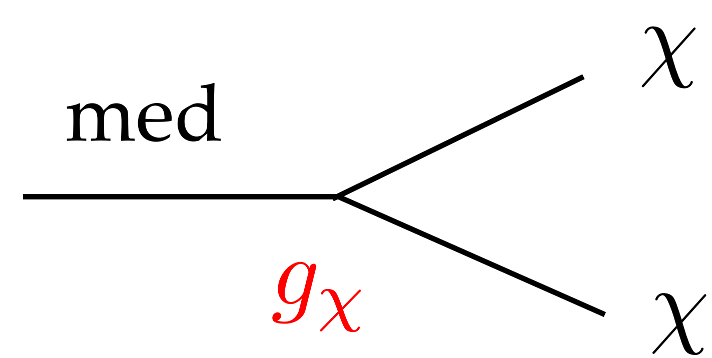
Direct Annihilation

$m_\chi < m_{\rm med}$



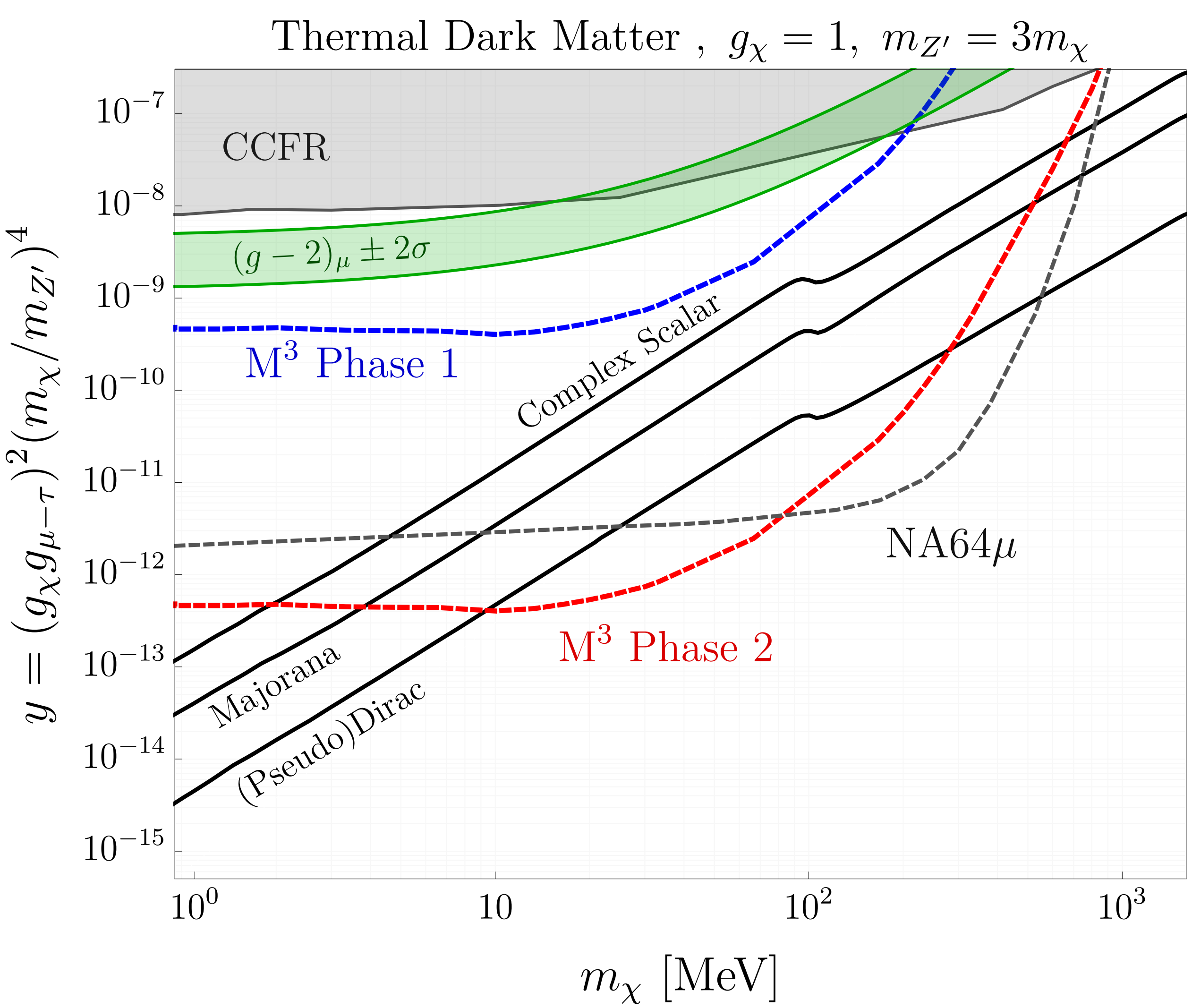
Predictive thermal targets

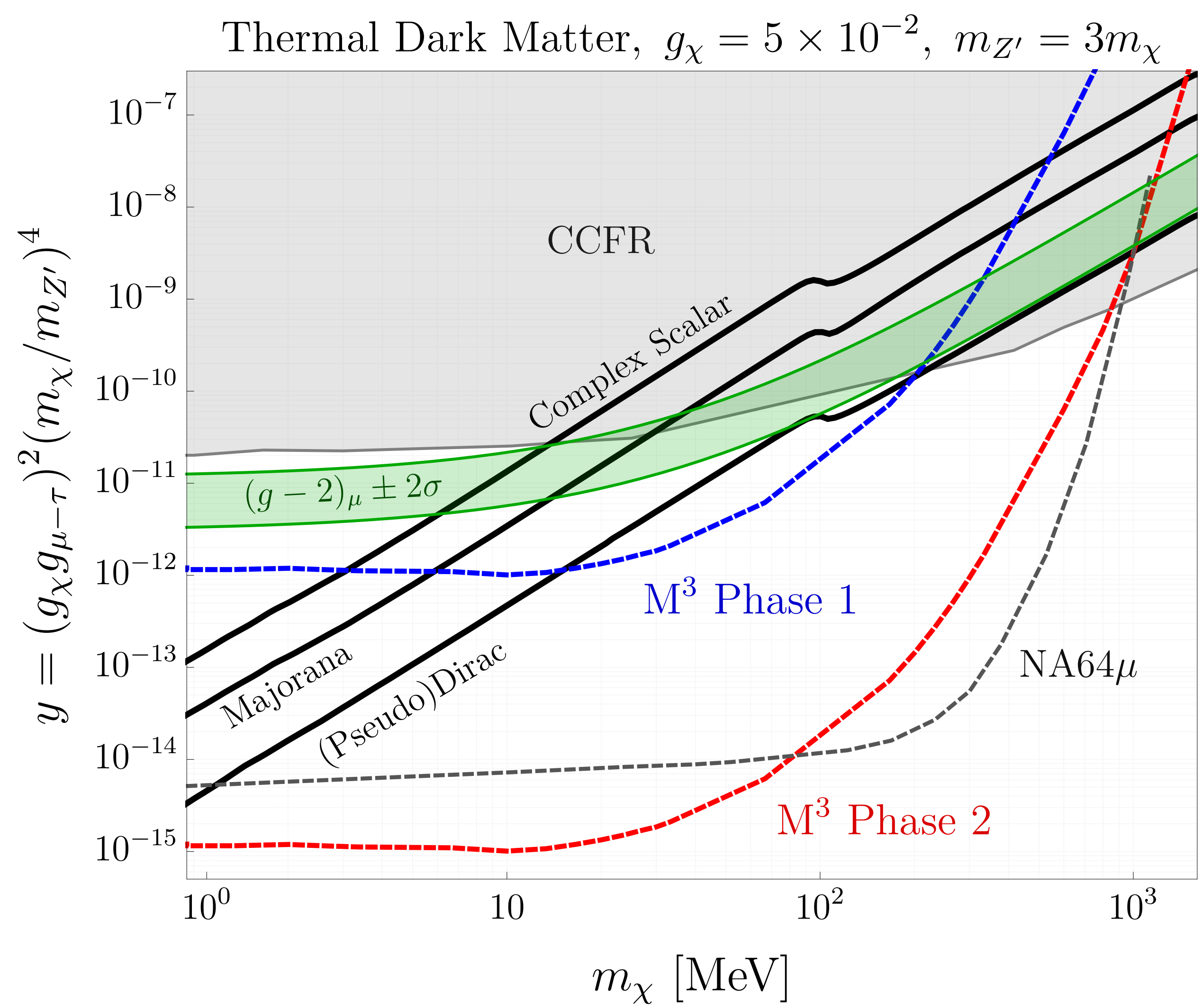
Abundance depends on $g_{\rm SM}$



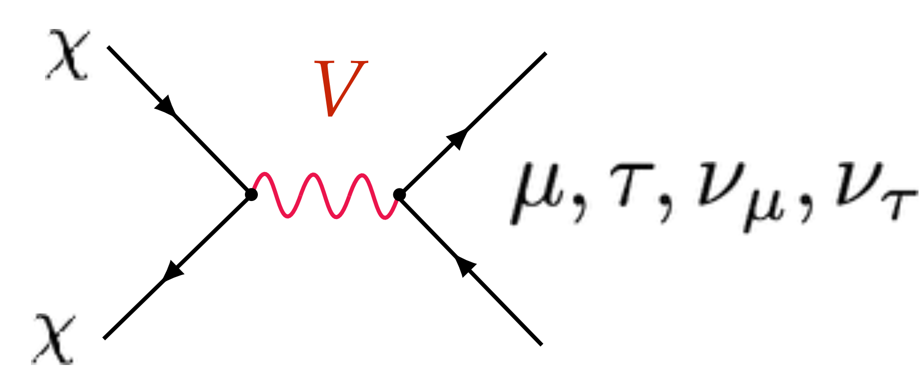
Mediator decays **invisibly***

Comprehensive Coverage





Gauged $L_\mu - L_\tau$ Interaction



Also resolve muon g-2 with light physics

Compatible parameter space for freeze-out

Phase 1,2: 1e10, 1e13 muons

See Cristina Mantilla-Suarez's talk

Concluding Remarks

Exciting time for g-2, new results soon!

Awaiting new SM lattice / R-ratio results
4.2 sigma anomaly probably not systematic error

If anomaly is due to light < GeV BSM physics

Must be muon-philic boson: S/V
Can decay either visibly or invisibly
Muon fixed targets can probe nearly all variations

See Cristina, Yiming, and Brian's talks

Same particles can couple to dark matter

Common parameter space for g-2 + freeze out
Same fixed target searches give this for free

Thanks!

Constraints: Big Bang Nucleosynthesis

V is in chemical equilibrium with SM in early universe

$$n_V \propto \begin{cases} T^3 & (T \gg m_V) \\ e^{-m/T} & (T \ll m_V) \end{cases}$$

When T < *m*, the V decays transfer entropy to SM particles
Must happen before neutrinos decouple from photons

$$m \gtrsim T_{\nu,\text{dec}} \approx 2\,\text{MeV}$$

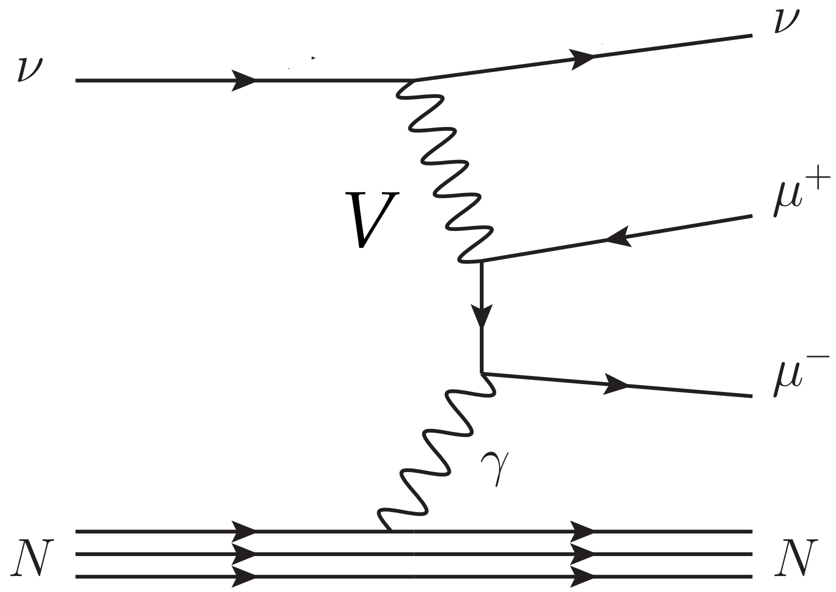
Otherwise V decays heat neutrinos not CMB $\rightarrow \Delta N_{\text{eff}} \gtrsim 0.5$

Spoils BBN element yields

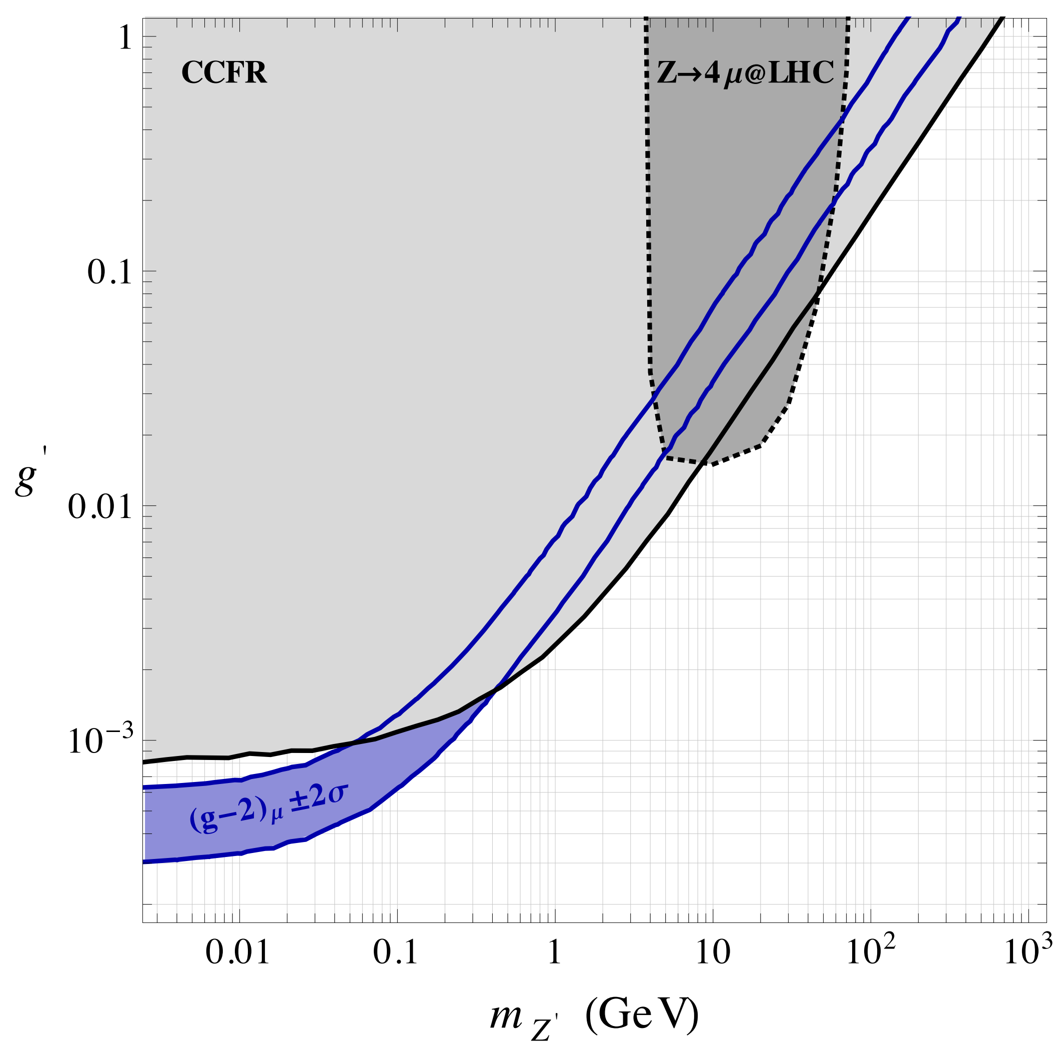
*mild contribution for *m*~ few MeV may reduce Hubble tension

Escudero, Hooper, GK, Pierre, 1902.02010

Constraints: Neutrino Tridents, CCFR + CHARM II



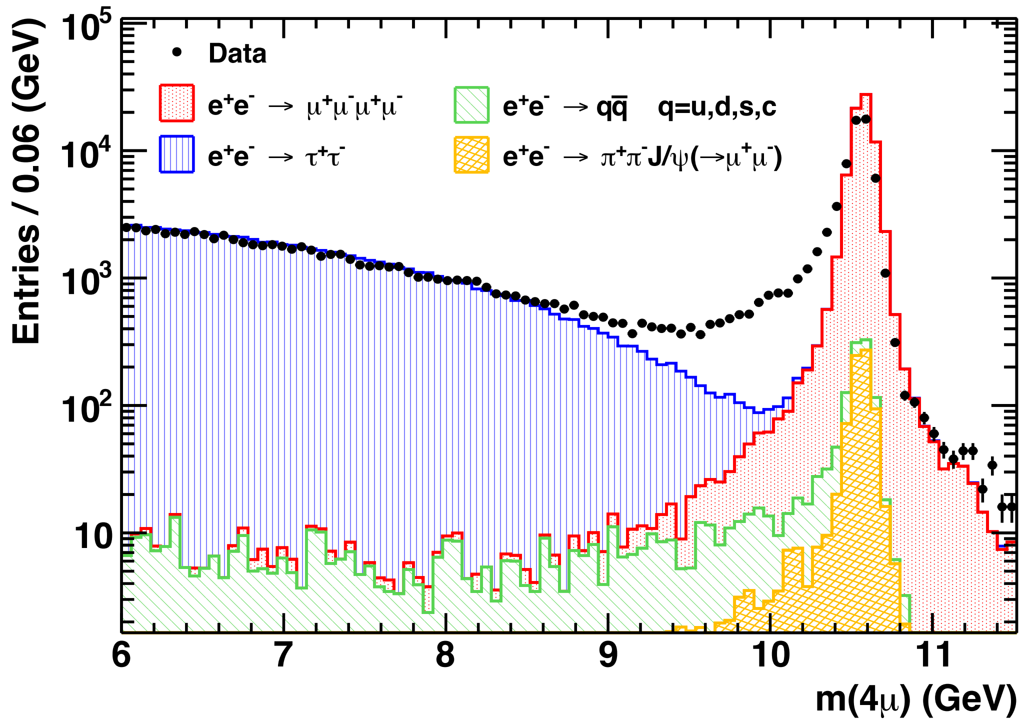
$$\frac{\sigma^{\mathrm{CCFR}}}{\sigma^{\mathrm{SM}}} = 0.82 \pm 0.28.$$

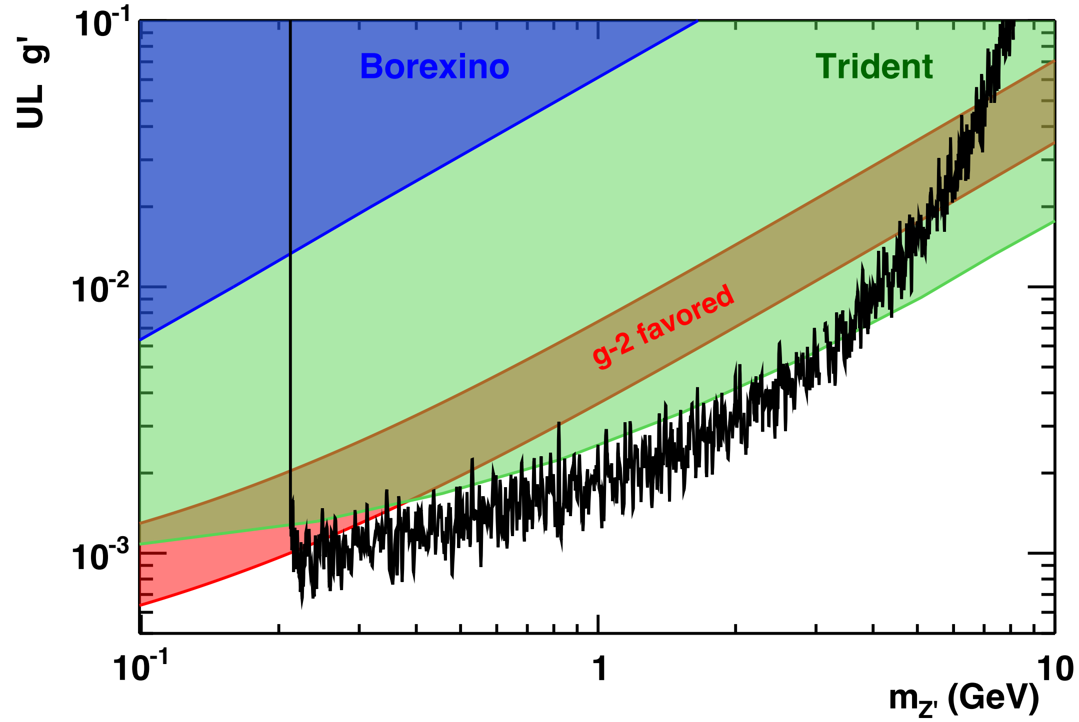


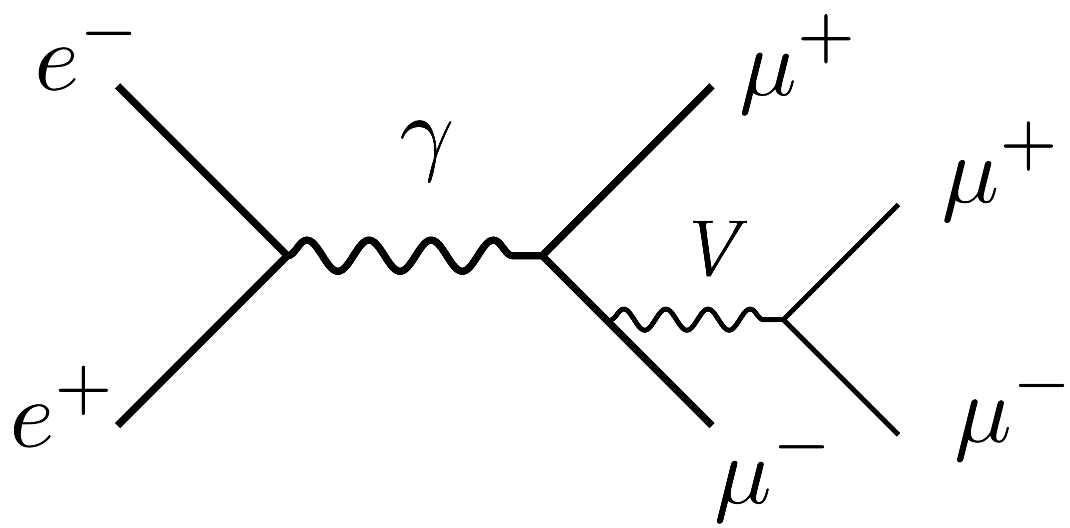
S. Mishra et al. (CCFR Collaboration), Phys.Rev.Lett. 66, 3117 (1991)

Altmanshoffer, Pospelov, Gori, Yavin 1406.2332

Constraints: BABAR Experiment







Search for 4 muon excess

Excludes g-2 for $m > 200$ MeV

BABAR Collaboration 1606.03501