Muon g-2 from confined millicharged particles

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Outline

- Introduction
- Muon g-2 from millicharged particles (mCPs)
- Detection of mCPs
- Astro-cosmo bounds and confinement
- Summary

Introduction

Some basics

- Magnetic moment for spin-1/2 particle $\vec{\mu}_m = g\, Q\, \mu_0\, \frac{\vec{\sigma}}{2}$ $\mu_0 = e/2m$

anomalous magnetic moment (AMM) $a_\ell \equiv \frac{g_\ell - 2}{2}$

- AMM: can be calculated unambiguously in a given theory and compared with experiments

- Muon AMM: one of the most precisely measured & theoretically best investigated quantities in particle physics

- Muon AMM: sensitive to BSM

  e.g. if BSM scale $m_\chi \gtrsim m_\mu$ $\Delta a_\mu \sim (m_\mu/m_\chi)^2$

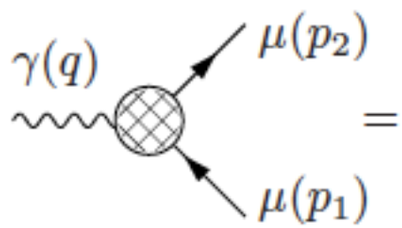
  $(m_e/m_\mu)^2 = 2.34 \times 10^{-5}$

- muon AMM: 40000 times more sensitive than electron AMM

Introduction

- EFT for AMM: $\delta\mathcal{L}_{\rm eff}^{\rm AMM} = -\frac{\delta g}{2}\frac{e}{4m}\left\{\bar\psi_L(x)\,\sigma^{\mu\nu}F_{\mu\nu}(x)\,\psi_R(x) + \bar\psi_R(x)\,\sigma^{\mu\nu}F_{\mu\nu}(x)\,\psi_L(x)\right\}$

In perturbation theory (QED)



$$= (-\mathrm{i}e)\,\bar u(p_2)\left[\gamma^\mu F_{\rm E}(q^2) + \mathrm{i}\frac{\sigma^{\mu\nu}q_\nu}{2m_\mu}F_{\rm M}(q^2)\right]u(p_1)$$

$q^2 = (p_2 - p_1)^2 \to 0.$

a_μ

$$a_\mu^{\rm QED} = A_1 + A_2(m_\mu/m_e) + A_2(m_\mu/m_\tau) + A_3(m_\mu/m_e, m_\mu/m_\tau)$$

universal mass-dependent

$$A_1 = A_1^{(2)}\left(\frac{\alpha}{\pi}\right) + A_1^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + A_1^{(6)}\left(\frac{\alpha}{\pi}\right)^3 + A_1^{(8)}\left(\frac{\alpha}{\pi}\right)^4 + A_1^{(10)}\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$

$$A_2 = A_2^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + A_2^{(6)}\left(\frac{\alpha}{\pi}\right)^3 + A_2^{(8)}\left(\frac{\alpha}{\pi}\right)^4 + A_2^{(10)}\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$

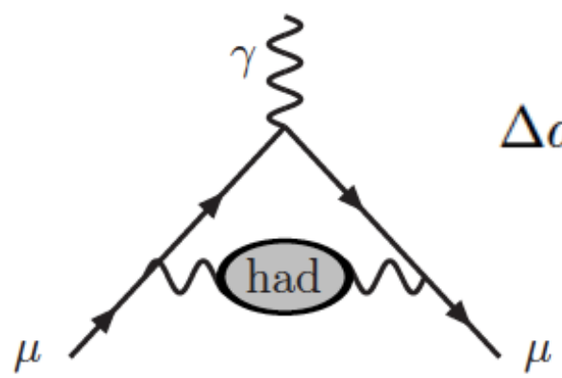
$$A_3 = A_3^{(6)}\left(\frac{\alpha}{\pi}\right)^3 + A_3^{(8)}\left(\frac{\alpha}{\pi}\right)^4 + A_3^{(10)}\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$

e.g. photon vacuum polarization (PVP)

focus

Introduction

- Apart from QED contribution, there are weak and hadronic contributions
- Lowest order hadronic contribution: hadronic vacuum polarization (HVP) at 2-loop



dominant contribution to total error of SM prediction

Δa_μ: from HVP

R-ratio $6931(40) \times 10^{-11}$

Lattice $7116(184) \times 10^{-11}$

- SM prediction $a_\mu^{\rm SM} = 116591810(43) \times 10^{-11}$
- Comp. w/ exp $\Delta a_\mu^{\rm FNAL+BNL} = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59) \times 10^{-11}$ ~ 4% of HPV
- If BSM modifies PVP and Δa_μ, its contribution could be of ~ O(0.01) of SM PVP

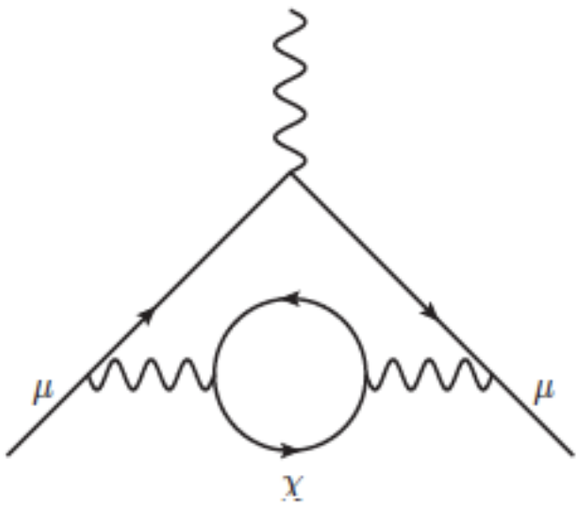
Introduction

- If BSM modifies PVP

A BSM particle must carry EM charge

not necessary to have hadronic contribution

e.g. with milli-electric charge,
behaving as missing energy



- A toy model: mCPs χ with a mass m_χ and a multiplicity factor N_χ

crucial for explaining muon g-2
while satisfying constraints

- Interaction: $\varepsilon\, e\, A_\mu \overline{\chi} \gamma^\mu \chi$

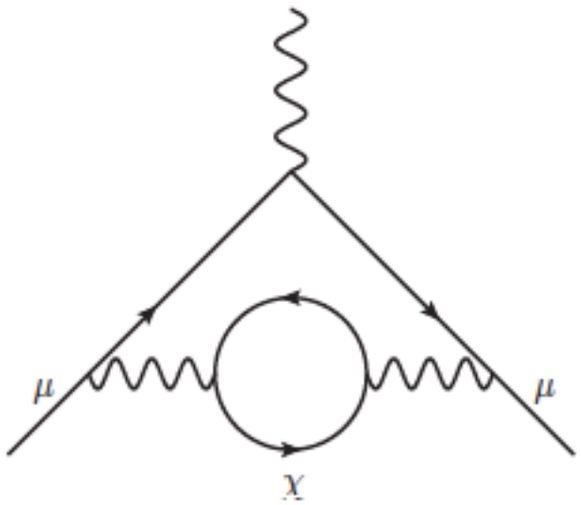
ε << 1

Muon g-2 from mCP

LO (2-loop VP) contribution from mCP

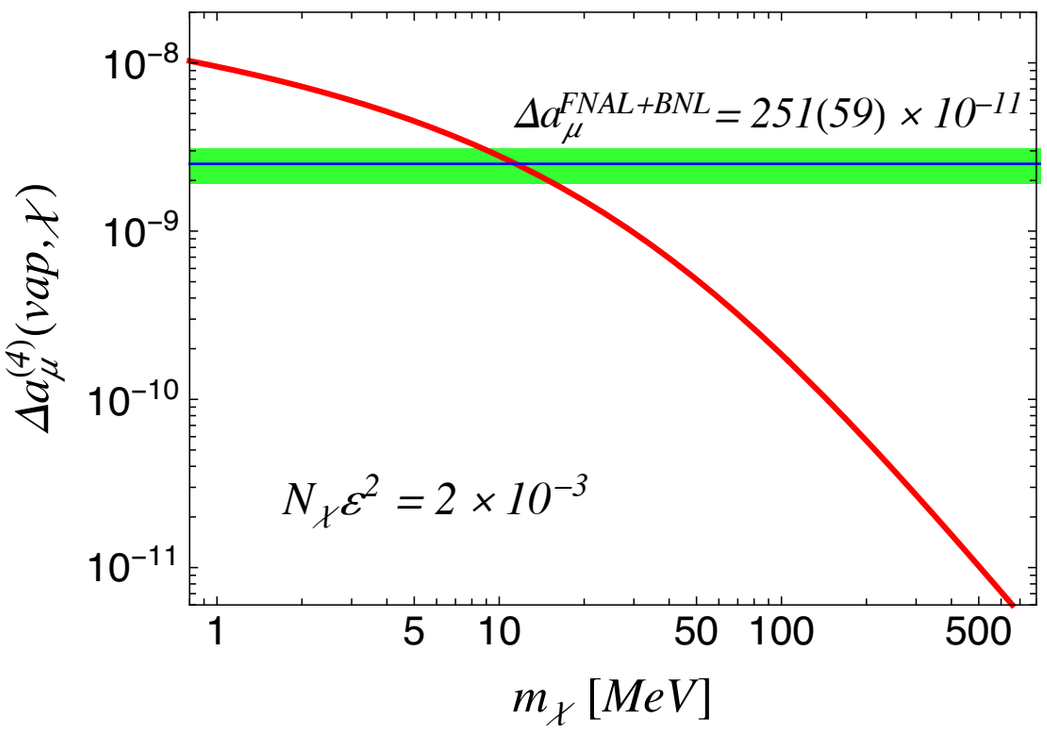
$$\Delta a_\mu^{(4)}(\mathrm{vap},\chi) \approx N_\chi \varepsilon^2 \left[-\frac{1}{3}\log\frac{m_\chi}{m_\mu} - \frac{25}{36} + \frac{\pi^2}{4}\frac{m_\chi}{m_\mu} + \left(3 + 4\log\frac{m_\chi}{m_\mu}\right)\left(\frac{m_\chi}{m_\mu}\right)^2 \right]\left(\frac{\alpha}{\pi}\right)^2$$

$$\to 251 \times 10^{-11} \cdot \left(\frac{N_\chi \varepsilon^2}{1.79 \times 10^{-3}}\right)(m_\chi = 10\ \mathrm{MeV})$$



$$N_\chi \varepsilon^2 \sim 10^{-3}$$

$$m_\chi \sim \mathcal{O}(10)\ \mathrm{MeV}$$



Muon g-2 from mCP

Constraint from electron g-2

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = -88(36) \times 10^{-14}$$

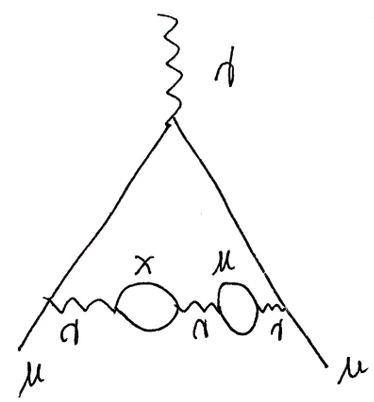
- MCP also contributes to electron g-2
- Deviation in electron g-2 has an opposite sign
- We require mCP contribution to electron g-2 smaller than the absolute value of the deviation
- This sets a lower bound on mCP mass
- $$m_\chi > 7 \text{ MeV}$$

Muon g-2 from mCP

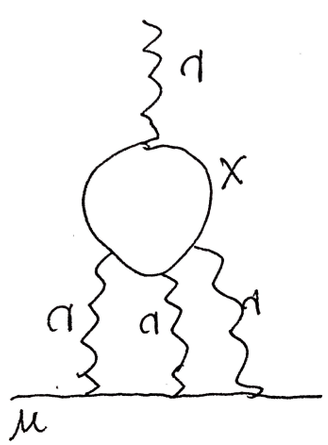
Other contributions to muon g-2 from mCP: higher orders, suppressed

- Mixed contribution from mCP and SM leptons to PVP: 3-loop

$(\alpha/\pi)^3$



- Light-by-light from a mCP loop: 3-loop

- 

extra $\varepsilon^2\alpha/\pi$ **compared to HVP**

Muon g-2 from mCP

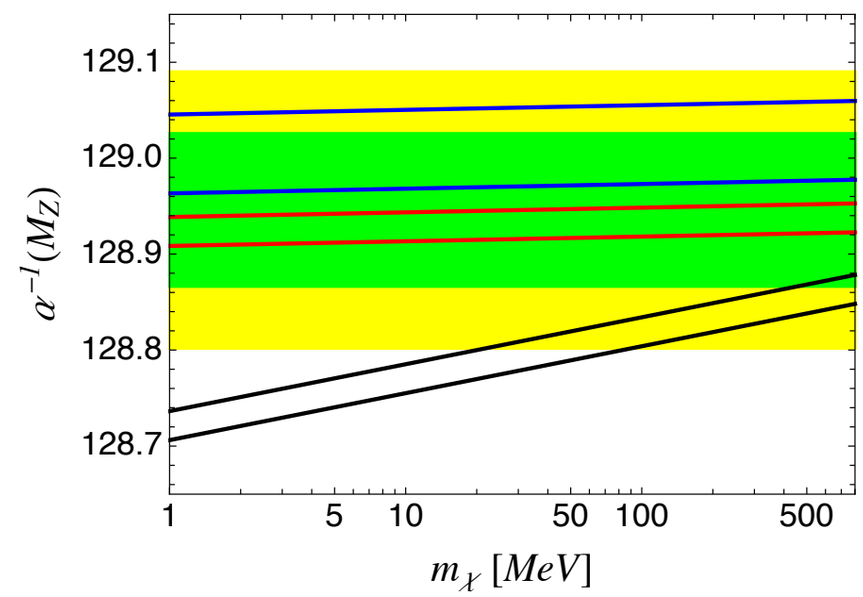
Constraints from electroweak precision observables

- MCP modifies running coupling of QED up to EW scale

$$\alpha^{-1}(M_Z^2) = \alpha^{-1}\Big[1 - \Delta\alpha_{\rm lep}(M_Z^2) - \Delta\alpha_{\rm had}^{(5)}(M_Z^2) - \Delta\alpha^{\rm top}(M_Z^2) - \Delta\alpha_\chi(M_Z^2)\Big] ,$$

$$\Delta\alpha_\chi(M_Z^2) = N_\chi \varepsilon^2 \times \Delta\alpha_{{\rm lep},\, l=\chi}(M_Z^2)$$

$$\Delta\alpha_{{\rm lep},\, l}(M_Z^2) = \frac{\alpha}{\pi}\left[-\frac{5}{9} + \frac{1}{3}\ln\frac{M_Z^2}{m_l^2} - 2\frac{m_l^2}{M_Z^2} + \mathcal{O}\left(\frac{m_l^4}{M_Z^4}\right)\right]$$



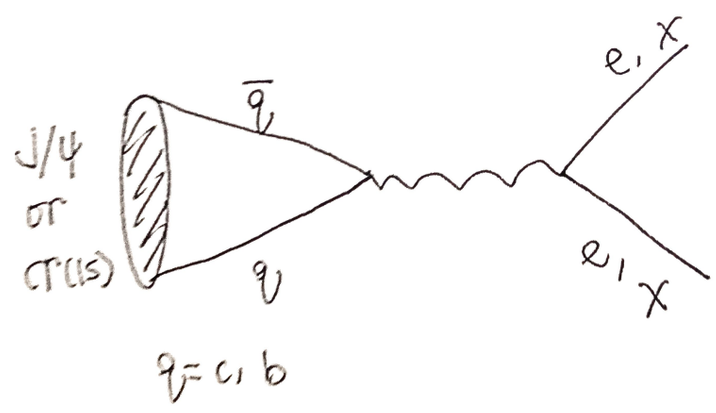
Yellow (green): 0.1% (0.05%) deviations from c.v. $\alpha^{-1}(M_Z^2)$
Black (red): $N_\chi\varepsilon^2 = 0.1(0.01)$
Blue: $N_\chi\varepsilon^2 = 0.01$ (different $\Delta\alpha_{had}(M_Z^2)$)

For $m_\chi \sim 10$ MeV and $N_\chi\varepsilon^2 \lesssim 10^{-2}$

mCP modification to fine structure const. at Z mass is well below 0.05%

Detection of mCP

- Indirect search: not detecting interaction-generated signal
- 1) Invisible decay of hadrons (JPC = 1- -) J/ψ $\Upsilon(1S)$



$$\mathrm{Br}\,(\Upsilon(1S) \to \text{invisible}) < 3.0 \times 10^{-4} \qquad \mathrm{Br}\,(\Upsilon(1S) \to e^+e^-) \approx (2.38 \pm 0.11)\%$$

$$N_\chi \varepsilon^2 = \frac{\mathrm{Br}\,(\Upsilon(1S) \to \text{invisible})}{\mathrm{Br}\,(\Upsilon(1S) \to e^+e^-)} < 1.3 \times 10^{-2} \qquad m_\chi \ll M_{\Upsilon(1S)}/2 \approx 4.7\ \mathrm{GeV}$$

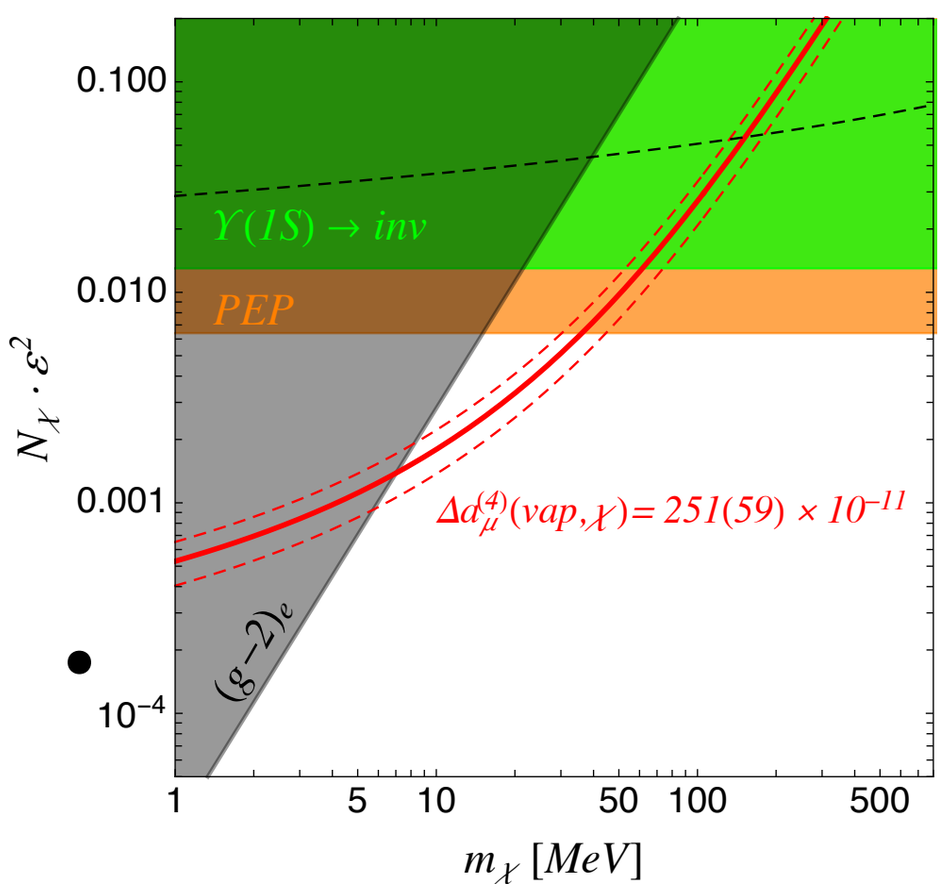
Similar bound from J/ψ

Detection of mCP

- 2) Mono-photon + missing E search at lepton collider

$$e^+e^- \to \gamma + \not{E}$$

$N_\chi \varepsilon^2 < 6.4 \times 10^{-3}$, (PEP) $m_\chi < 5$ GeV $N_{\text{signal}} \propto N_\chi \, \varepsilon^2$



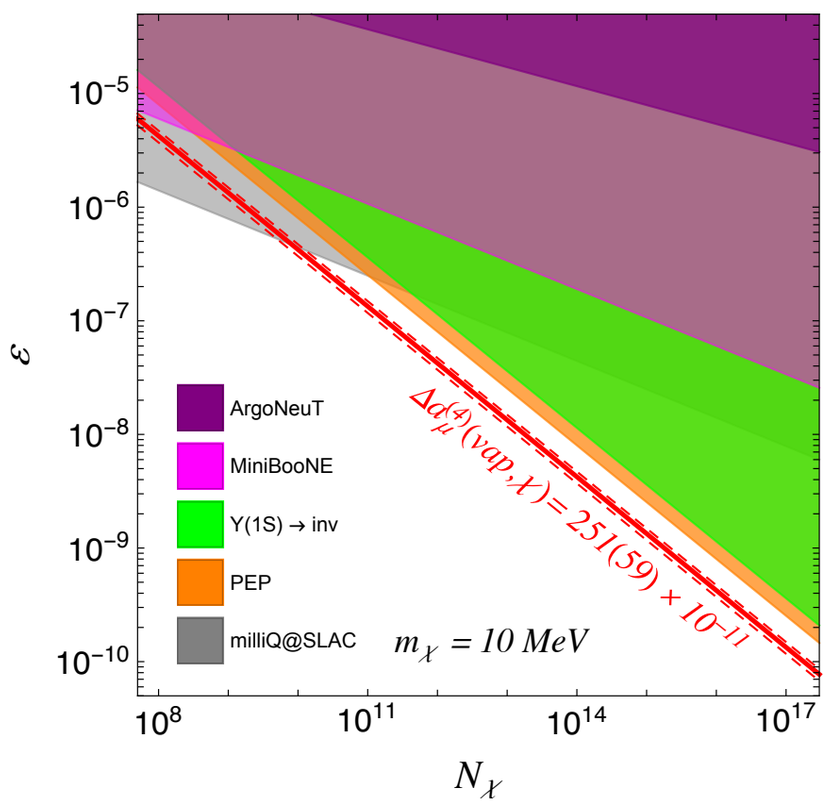
Preferred mCP mass range:
7~36 MeV

Detection of mCP

- Direct search: detecting mCP-electron/nucleon scattering generated signals

- Fixed target experiments $N_{\rm signal} \propto N_\chi \, \varepsilon^{2+2n_{\rm hit}}$

- Recasting to get our bounds $N_\chi \varepsilon^2 < N_\chi^{\frac{n_{\rm hit}}{1+n_{\rm hit}}} \, \varepsilon^2_{\rm max}(N_\chi = 1, m_\chi)$

- 

$N_\chi \gtrsim 10^{10}$

Enormously large!

But not end of the story

Astro-cosmo bounds

Constraints from Supernova (SN) 1987A

- Massive star collapses at the end of its life, emitting neutrinos and anti-neutrinos. Eventually massive star -> neutron star
- Neutrinos and anti-neutrinos carry away ~ 99% gravitational energy of the dying star
- SN 1987A: number of neutrinos detected @ Earth roughly agrees with theoretical exception
- @ SN core T ~ 30 MeV -> possible to produce mCPs ~ 10 MeV
- If mCP produced from SN core can fly away, it will reduce neutrino fluxes & neutrino signal duration -> constrained by neutrino observation

Astrophysical bounds

Constraints from Supernova (SN) 1987A

To be consistent with neutrino observation

- 1) If mCPs produced in the core fly away, the energy they carry must be small enough

$\varepsilon \lesssim 10^{-9}$ for a single species [Davidson, Hannestad & Raffelt, 00']

Recasting to our case:

$N_\chi \varepsilon^2 \lesssim 10^{-18}$ But muon g-2 requires $N_\chi \varepsilon^2 \sim 10^{-3}$

- 2) If mCPs produced in the core are trapped, their mean-free-path (or lifetime) must be shorter than the core size L ~ 1 km

$\varepsilon > 10^{-7}$ [Davidson, Hannestad & Raffelt, 00']

Ours: $N_\chi \gtrsim 10^{10}$ $N_\chi \varepsilon^2 \sim 10^{-3}$ $\Rightarrow 10^{-7} < \varepsilon \lesssim 10^{-6.5}$ Tiny range!

But $10^{-9} < \varepsilon < 10^{-5}$ is ruled out by [Chang, Essig & McDermott, 18']

Astrophysical bounds

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The simplest mCP model with large multiplicity is ruled out by SN bounds

Astrophysical bounds

- Apart from the SN constraints, the relic abundance of mCP in this simplest model is also a problem (overclosure), for the parameter range that can explain muon g-2.

- A remedy to cure all these problem: + hidden sectors with strong dynamics under which mCPs are charged + other necessary DOF

-

Hidden confined sector(s)

Hidden sectors

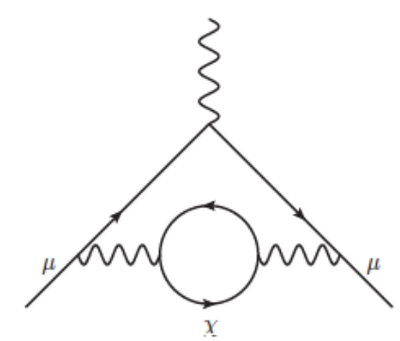
- Hidden gauge groups: $[SU(N_d)]^{N_{\rm ds}}$ $N_\chi = N_{\rm ds} \cdot N_d$. $N_d \gg 1$

  not have to be enormously large

- Each hidden sector contains 1 hidden gauge group and 1 mCP as fundamental under this group

- Confinement scale < mCP mass ~ O(10) MeV

  momentum in the loop ~ muon mass > confinement scale
  => mCP instead of hidden hadron in PVP



- Running coupling $\alpha_d(\mu) \approx 6\pi/(11N_d)(1/\ln(\mu/\Lambda_\chi))$. $N_d \gg 1$

  $\alpha_d(\mu) N_d$ ~ O(1) for $\mu \sim m_\chi > \Lambda_\chi$

Hidden confined sector(s)

Hidden hadrons

- Meson: $\chi\bar{\chi}$ form Upsilon Υ_χ (JPC = 1 - -)

  like QCD Upsilon in which b mass > QCD confinement scale

  no pion (only 1 flavor in each sector, no global sym. breaking, no goldstone)

- Baryon: N_d χ's form a baryon in each sector

  (and an antibaryon formed by anti mCPs)

Make baryon heavy s.t. they are non-relativistic in SN plasma $N_d \geq 10$

$$\text{Minimal choice: } N_\chi = N_d = 10$$

- Glueballs of various quantum numbers

  JPC = 0 + +, 0 - +, ...

Hidden confined sector(s)

Upsilon decay channels

Visible

suppression

$$\Gamma(\Upsilon_\chi \to e^+e^-) = N_d \frac{16\pi\alpha^2\varepsilon^2}{3}\frac{|\psi_{\Upsilon_\chi}(0)|^2}{M^2_{\Upsilon_\chi}}$$

$M^2_{\Upsilon_\chi} \to 2m_\chi$

meson wavefunction

$$|\psi_{\Upsilon_\chi}(0)|^2 \sim (C_F\alpha_d\,\mu)^3 \;\; (\mu = m_\chi/2 \text{ as the reduced mass of the } \chi \text{ pair})$$

$$C_F = T_F(N_d^2-1)/N_d$$

Hidden dominant

$$\Gamma(\Upsilon_\chi \to g_d g_d g_d) = \frac{(N_d^2-4)(N_d^2-1)}{16N_d^2}\frac{1}{N_d}\frac{N_d}{3}\frac{64}{3}\left(\pi^2-9\right)\alpha_d^3(M_{\Upsilon_\chi})\frac{|\psi_{\Upsilon_\chi}(0)|^2}{M^2_{\Upsilon_\chi}}$$

$$\Gamma(\Upsilon_\chi \to \gamma g_d g_d) = \frac{12N_d}{N_d^2-4}\Gamma(\Upsilon_\chi \to g_d g_d g_d\,;\; \alpha_d^3 \to \alpha_d^2\alpha\varepsilon^2)$$

$$= \frac{16}{3}\frac{N_d^2-1}{N_d}\left(\pi^2-9\right)\alpha_d^2(M_{\Upsilon_\chi})\,\alpha\varepsilon^2\frac{|\psi_{\Upsilon_\chi}(0)|^2}{M^2_{\Upsilon_\chi}}$$

Gluons will form glueballs **JPC = 0 + +, 0 - +, …**

Hidden confined sector(s)

A few comments

- Upsilon and glueballs must satisfy the SN constraints: lifetime shorter than the core size L ~ 1 km to be trapped

- Glueballs eventually decay into photons or electrons unless new channels are opened

- Upsilon mixes with photon and should be constrained by dark photon (DP) search.

  Difficult! Those experiment detectors have similar sizes with SN core.
  The visible decay products (electrons and photons) will be detected!

  Will be fixed

- Constraints from fixed target neutrino experiments (e.g. milliQ & ArgoNeuT) can be removed

- Multiplicity does not need to be enormously

Hidden confined sector(s)

To satisfy both SN and DP search constraints

A simple solution: let Upsilon dominantly decay into neutrinos, eventually

How:
introduce two real singlet scalars of similar mass, coupling to mCP via Yukawa and neutrino via L-violating dim-6 operator, and an approximate discrete symmetry

to prevent (LH)^2 with large coefficient

$$S \to -S\ , \quad \chi_{L/R} \to \chi_{R/L}\ , \quad L \to iL\ , \quad e_R \to ie_R \quad H \to H$$

O(1)

tiny

$$-iy_s S\bar{\chi}\gamma_5\chi - m_\chi\bar{\chi}\chi - (y_l\bar{L}He_R + \text{h.c.}) + \frac{S(LH)^2}{\Lambda^2} \quad -\kappa_s y_s S\bar{\chi}\chi$$

Upsilon (JPC =1 - -)
can decay both to 2Si,
i = 1, 2, or S1 + S2

S mass << mCP mass

discrete sym-breaking

for 2nd lightest glueball (JPC = 0 -+) to decay to nu via S

tadpole of S —> <S> —> neutrino mass

$$m_\nu \sim \langle S\rangle \frac{v^2}{2\Lambda^2} \approx \frac{\kappa_s y_s}{16\pi^2}\frac{m_\chi^3}{m_s^2}\frac{v^2}{2\Lambda^2}$$ <~ 0.1 eV

Hidden confined sector(s)

Summary of decay channels

$$\Upsilon_\chi \to S_i + S_j$$

$$\Upsilon_\chi \to 3g_d$$

$$\Upsilon_\chi \to \gamma + 2g_d$$

$$\Upsilon_\chi \to e^+ + e^-$$

$$S_i \to 2\nu$$

$$S_i \to 2\gamma$$

Gluons form glueballs

$$0^{++} \to S_i + S_j$$

$$0^{++} \to 2\gamma$$

$$0^{-+} \to S_i + S_j$$

$$0^{-+} \to 2\gamma$$

$$0^{-+} \to 2\gamma + 0^{++}$$

Require:

1) **Upsilon, glueballs, S lifetime shorter than SN core size**
2) **Visible decay channels have negligible branching ratio (to evade DP search)**

Not difficult to satisfy all due to millicharge suppression

Hidden confined sector(s)

Summary of decay channels

$$\Upsilon_\chi \to S_i + S_j$$

$$\Upsilon_\chi \to 3g_d$$

$$\Upsilon_\chi \to \gamma + 2g_d$$

$$\Upsilon_\chi \to e^+ + e^-$$

mCP mass >>
Hidden confinement scale ~ a few MeV
> BBN scale

$$S_i \to 2\nu$$
$$S_i \to 2\gamma$$

$$0^{++} \to S_i + S_j$$

$$0^{++} \to 2\gamma$$

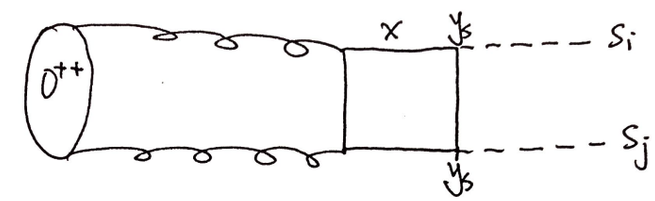
$$0^{-+} \to S_i + S_j$$

$$0^{-+} \to 2\gamma$$

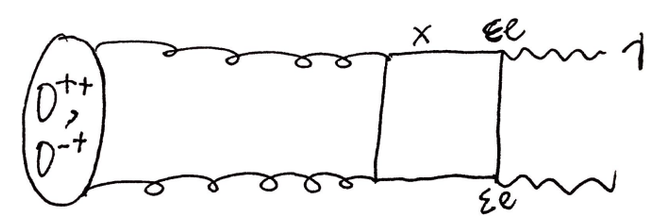
$$0^{-+} \to 2\gamma + 0^{++}$$

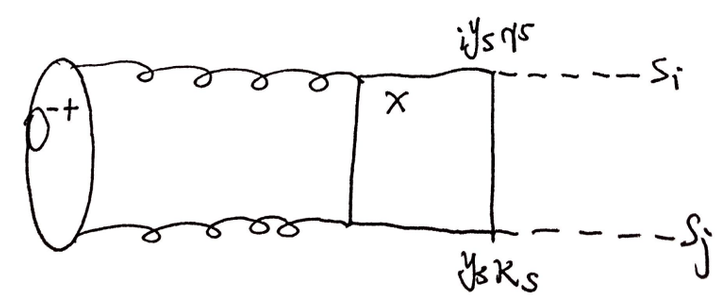
Hidden confined sector(s)

$$0^{++} \to 2\gamma \qquad N_d \frac{g_d^2 e^2 \varepsilon^2}{16\pi^2 m_\chi^4} F_{\mu\nu}^2 G_d^{\mu\nu\,2}$$



$$0^{++} \to S_i + S_j \qquad N_d \frac{g_d^2 y_s^2}{16\pi^2 m_\chi^2} S^2 G_d^{\mu\nu\,2}$$



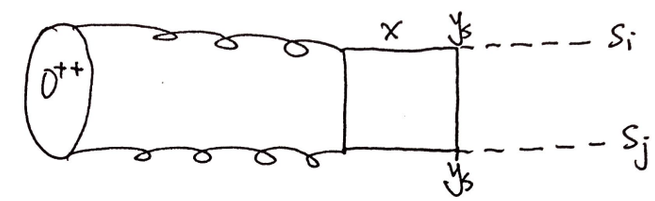


$$\Gamma(\mathcal{G}_d^{0^{++}} \to SS) = \frac{1}{8\pi}\left(\frac{N_d \alpha_d\, y_s^2}{4\pi m_\chi^2}\right)^2 \Lambda_d^5 \gg \Gamma(\mathcal{G}_d^{0^{++}} \to \gamma\gamma) = \frac{1}{8\pi}\left(\frac{N_d \alpha_d\, \alpha\varepsilon^2}{m_\chi^4}\right)^2 \Lambda_d^9$$

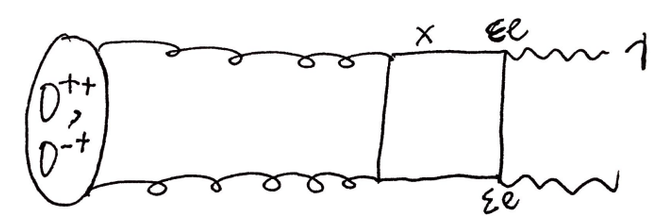
$$\varepsilon \ll \frac{y_s}{\sqrt{4\pi\alpha}} \frac{m_\chi}{\Lambda_d} \approx 3.3 \times y_s \frac{m_\chi}{\Lambda_d}$$

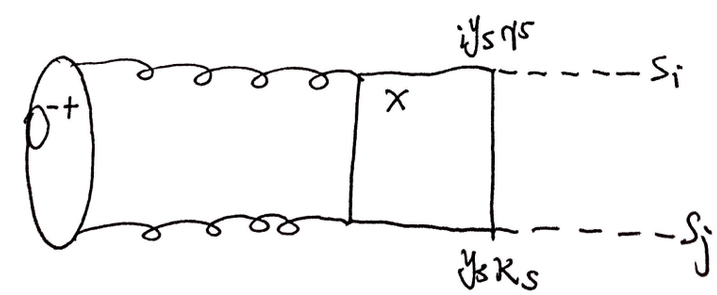
Hidden confined sector(s)

$$0^{-+} \to S_i + S_j \qquad N_d \frac{g_d^2 \kappa_s y_s^2}{16\pi^2 m_\chi^2} S^2 G_{d\,\mu\nu} \tilde{G}_d^{\mu\nu}$$



$$0^{-+} \to 2\gamma \qquad N_d \frac{g_d^2 \varepsilon^2 e^2}{16\pi^2 m_\chi^4} F_{\mu\nu}^2 (\tilde{G}_d^{\rho\sigma})^2$$

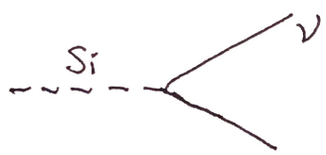




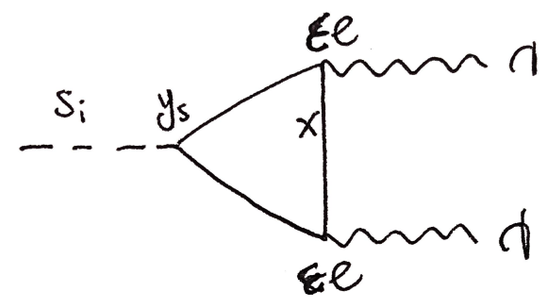
$$\Gamma(\mathcal{G}_d^{0^{-+}} \to SS) = \frac{1}{8\pi}\left(\frac{N_d \alpha_d\, \kappa_s y_s^2}{4\pi m_\chi^2}\right)^2 \Lambda_d^5 \gg \Gamma(\mathcal{G}_d^{0^{-+}} \to \gamma\gamma) = \frac{1}{8\pi}\left(\frac{N_d \alpha_d\, \alpha \varepsilon^2}{m_\chi^4}\right)^2 \Lambda_d^9$$

$$\frac{\varepsilon}{\sqrt{\kappa_s}} \ll \frac{y_s}{\sqrt{4\pi\alpha}} \frac{m_\chi}{\Lambda_d} \approx 3.3 \times y_s \frac{m_\chi}{\Lambda_d}$$

Hidden confined sector(s)



$\frac{v^2}{2\Lambda^2}$ $\langle H^0 \rangle \to \frac{v}{\sqrt{2}}$



$$\Gamma(S \to \nu\nu) \approx \frac{1}{16\pi}\left(\frac{v^2}{2\Lambda^2}\right)^2 m_s \gg \Gamma(S \to \gamma\gamma) = \frac{\alpha^2}{256\pi^3}\frac{y_s^2}{2}\frac{m_s^3}{m_\chi^2}\left|N_d\varepsilon^2 F(\tau)\right|^2$$

$$\to \frac{\alpha^2}{256\pi^3}\frac{y_s^2}{2}\frac{m_s^3}{m_\chi^2}\left|N_d\varepsilon^2\frac{4}{3}\right|^2 \quad (\tau \gg 1) \ ,$$

$$N_d\varepsilon^2 \ll \frac{3\pi}{\sqrt{2}\,y_s\alpha}\frac{m_\chi}{m_s}\left(\frac{v}{\Lambda}\right)^2 \approx 9.13\times 10^2\,\frac{1}{y_s}\frac{m_\chi}{m_s}\left(\frac{v}{\Lambda}\right)^2$$

Hidden confined sector(s)

One benchmark point

$m_\chi \sim 15$ MeV,

$\Lambda_d \sim 3$ MeV,

$\Lambda \sim 10^3$ MeV (scale of dim-6 operator $(LH)^2 S$),

$N_\chi = N_d = 10$,

$\varepsilon \sim 10^{-2}$,

$y_s \sim 1$,

$\kappa_s \sim 10^{-6}$

Upsilon mixing with photon

$$-\frac{e}{2g_\rho}F^{\mu\nu}\rho_{\mu\nu} \qquad \rho_{\mu\nu} = \partial_\mu\rho_\nu - \partial_\nu\rho_\mu$$

normalized Upsilon field

$$\Gamma(\Upsilon_\chi \to e^+e^-) = \frac{4\pi}{3}\frac{\alpha^2\varepsilon^2}{g_\rho^2}\left(1+\frac{2m_e^2}{M_{\Upsilon_\chi}^2}\right)\sqrt{M_{\Upsilon_\chi}^2 - 4m_e^2}$$

$$= N_d\frac{16\pi\alpha^2\varepsilon^2}{3}\frac{|\psi_{\Upsilon_\chi}(0)|^2}{M_{\Upsilon_\chi}^2} \ .$$

$$\frac{1}{g_\rho} \approx \sqrt{N_d}\frac{2|\psi_{\Upsilon_\chi}(0)|}{M_{\Upsilon_\chi}^{3/2}} \approx 2\sqrt{N_d}\left(\frac{C_F\alpha_d(m_\chi)}{4}\right)^{3/2}$$

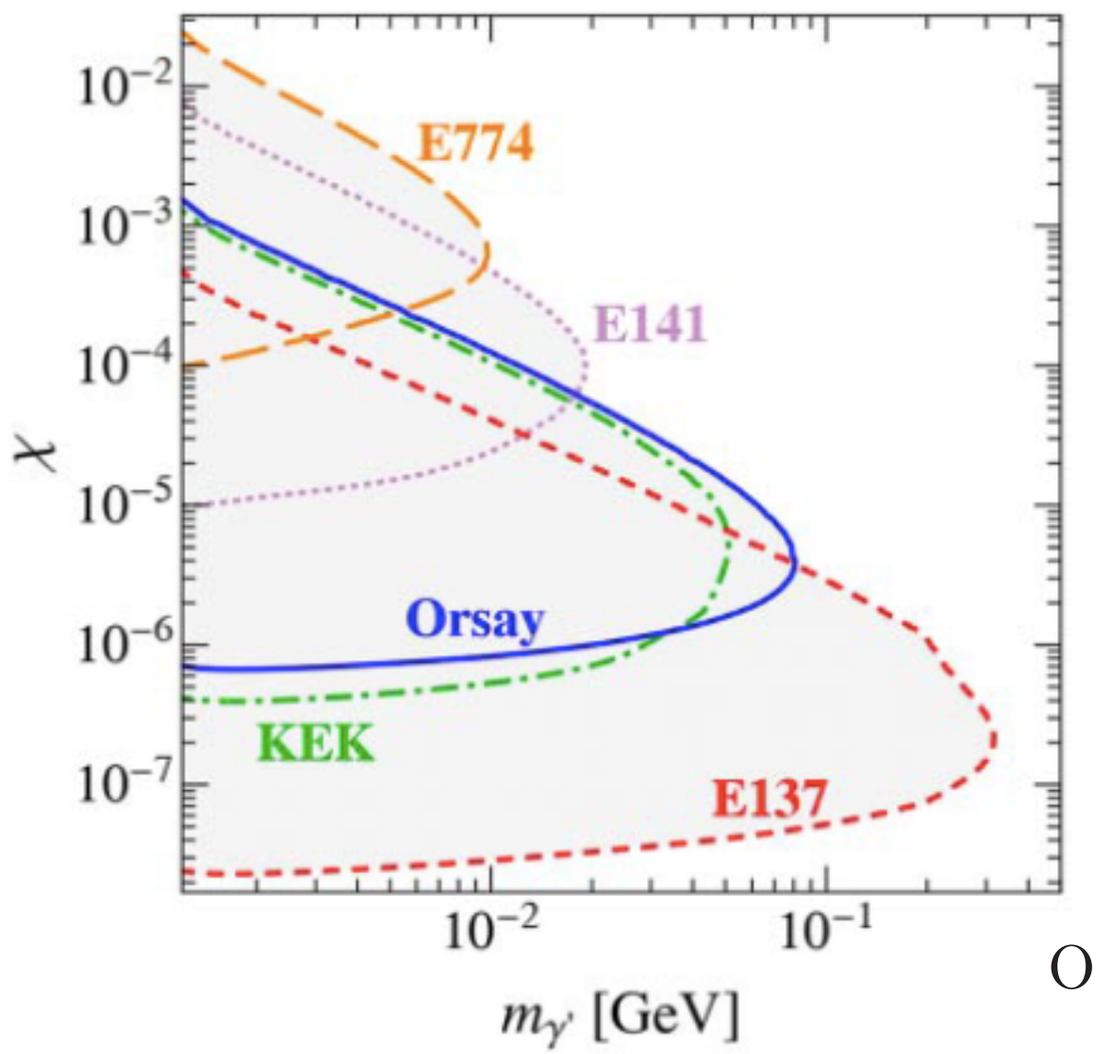
$$-\frac{1}{2}\epsilon F_{\mu\nu}F'^{\mu\nu}$$

$$\epsilon = \frac{e\varepsilon}{g_\rho} \sim 2e\varepsilon\sqrt{N_d}\left(\frac{N_d^2-1}{2N_d}\frac{\alpha_d(m_\chi)}{4}\right)^{3/2} \ , \quad m' = M_{\Upsilon_\chi} \sim 2m_\chi$$

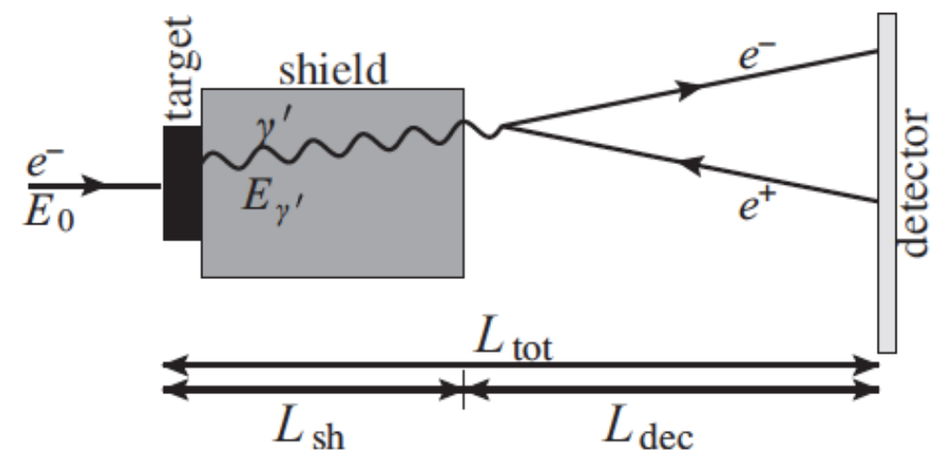
kinetic mixing parameter

Constraints from dark photon search experiments

Dump experiments



From [Raggi and Kozhuharov, 15]



From [Raggi and Kozhuharov, 15]

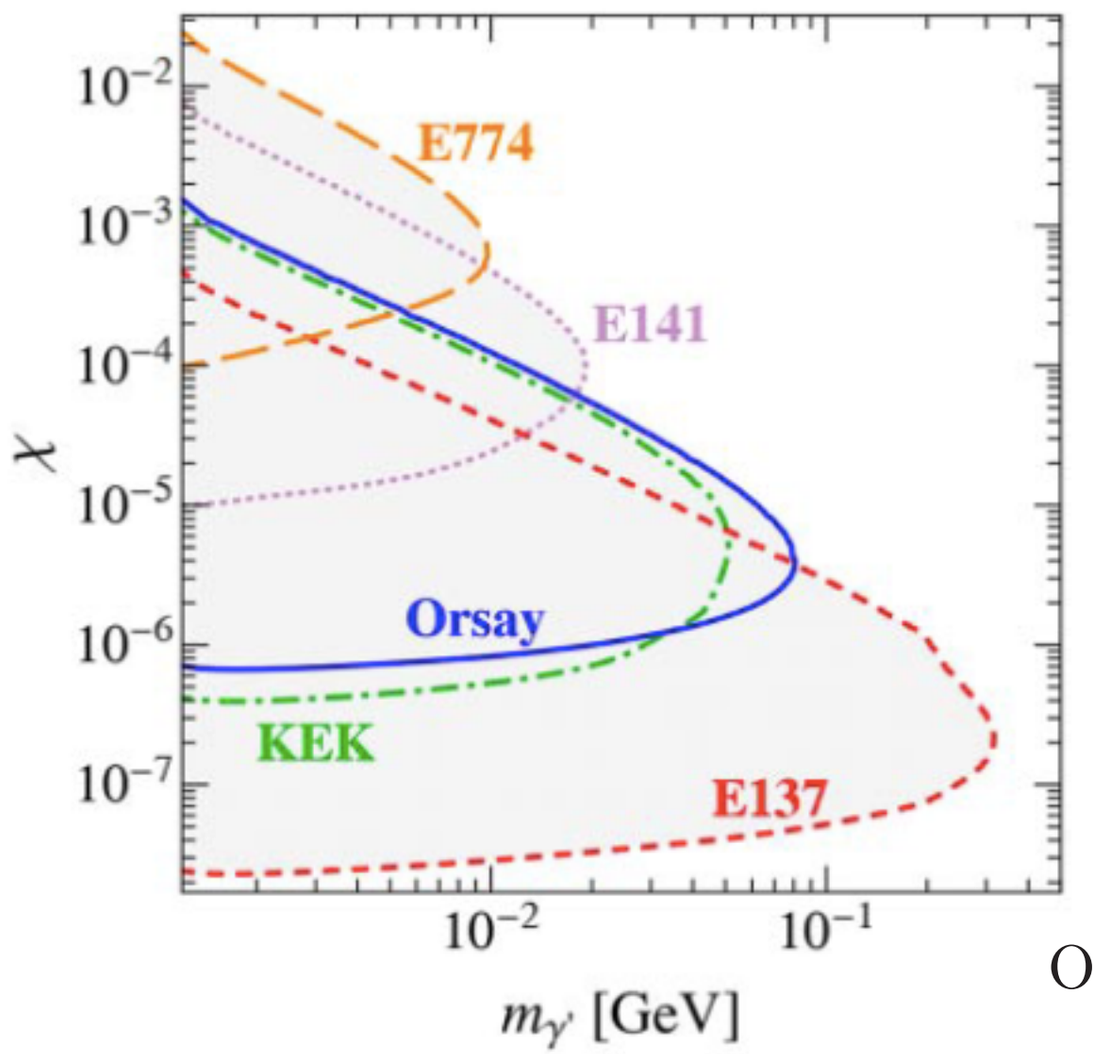
DP search:
DP all decays to electrons/photons

Our model:
Only a tiny fraction of Upsilon decays to visible

Our $\epsilon^2\, Br(\Upsilon_\chi \to e^+e^-)$ to be matched with their χ^2

Constraints from dark photon search experiments

Dump experiments



From [Raggi and Kozhuharov, 15]

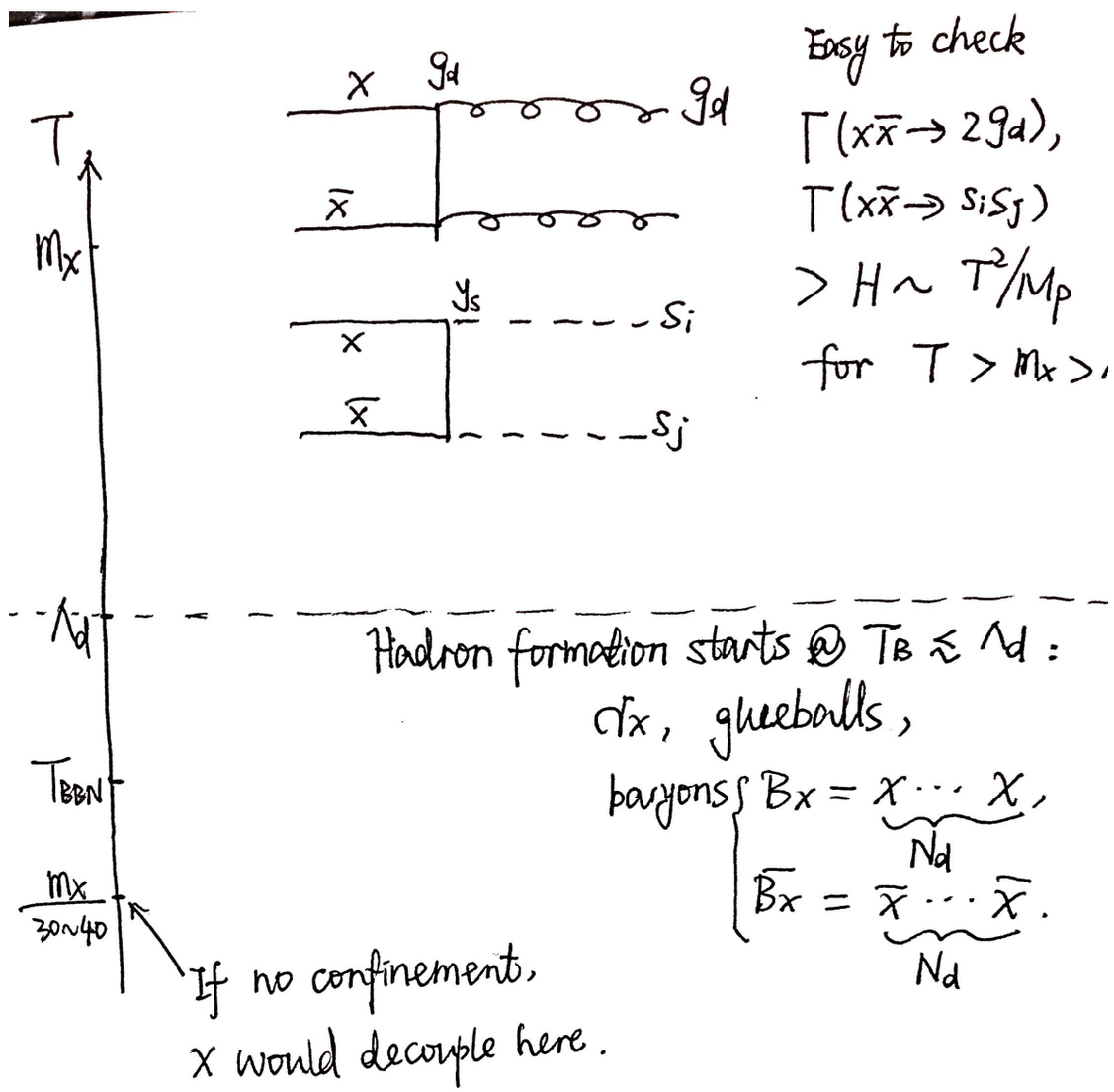
For benchmark point

$m_\chi \sim 15$ MeV,
$\Lambda_d \sim 3$ MeV,
$\Lambda \sim 10^3$ MeV (scale of dim-6 operator $(LH)^2 S$),
$N_\chi = N_d = 10$,
$\varepsilon \sim 10^{-2}$,
$y_s \sim 1$,
$\kappa_s \sim 10^{-6}$
$\epsilon \sim 10^{-6}$
$Br(\Upsilon \to \text{ vis}) \sim 10^{-5}$
$\epsilon^2\, Br(\Upsilon \to \text{ vis}) \sim 10^{-17}$ below 10^-16

Evading the bounds

Our $\epsilon^2\, Br(\Upsilon_\chi \to e^+e^-)$ to be matched with their χ^2

Relic abundance



Relic abundance

- σ_x, glueballs all decay before BBN

(τ_{σ_x}, $\tau_{\text{glueballs}}$ < SN size $L \sim 1$ km < $\tau_{BBN} \sim 1$ sec)

- B_x, $\bar{B}_x$: long lived [Kang, Luty, Nasri, 06]

$B_x - \bar{B}_x$ annihilation $\sigma_{ann} \sim \pi R_{rad}^2$, $|v| \sim \left(\frac{T_B}{m_x}\right)^{1/2}$

$$\langle \sigma |v| \rangle_{ann} \sim \pi R_{rad}^2 \left(\frac{T_B}{m_x}\right)^{1/2} \underset{\text{take } T_B \sim \Lambda_d}{\sim} \pi \Lambda_d^{-2} \left(\frac{\Lambda_d}{m_x}\right)^{1/2}$$

Current abundance

$$\frac{Y_B}{s} \sim 10^{-21} \cdot \frac{N_x}{N_d} \cdot \left(\frac{\Lambda_d}{3\text{MeV}}\right)^2 \left(\frac{m_x}{15\text{MeV}}\right)^{1/2} \left(\frac{3\text{MeV}}{T_B}\right)^{3/2}$$

Tiny for $N_x = N_d$

Check indirect detection for mCPs

Now, with hidden strong dynamics

- 1) Invisible decay of $\Upsilon(1S)$

O(1) $N_\chi \varepsilon^2 = \frac{\mathrm{Br}\left(\Upsilon(1S) \to \text{invisible}\right)}{\mathrm{Br}\left(\Upsilon(1S) \to e^+e^-\right)} < 1.3 \times 10^{-2}$

Invisible mCP and anti-mCP form meson and eventually have O(1) fraction decaying into neutrinos

- Mono-photon + missing E at lepton collider

Similar to the above. The bound is unchanged.

Summary

- We provide a novel explanation to muon g-2 from mCPs at 2-loop level with mass ~ O(10) MeV, $N_\chi \varepsilon^2 \sim 10^{-3}$

- MCPs in our model also transform as fundamental under hidden strong gauge groups with confinement scale < mCP mass. $\text{Minimal choice: } N_\chi = N_d = 10$

- (With the help of extra light singlet scalars S) Hidden Upsilon meson and glueballs: 1) decay into neutrinos eventually (Their branching decay into visible particles is tiny.); 2) have lifetime shorter than SN core size.

- Constraints from SN and DP search (via photon-Upsilon mixing) are both satisfied.

- The parameter space of interest is well below the bounds from indirect search for mCPs.

- MCPs with hidden confinement open up new possibilities for model building etc.

Thank you!

Backup