Muon g-2 in Lepton Portal Dark Matter

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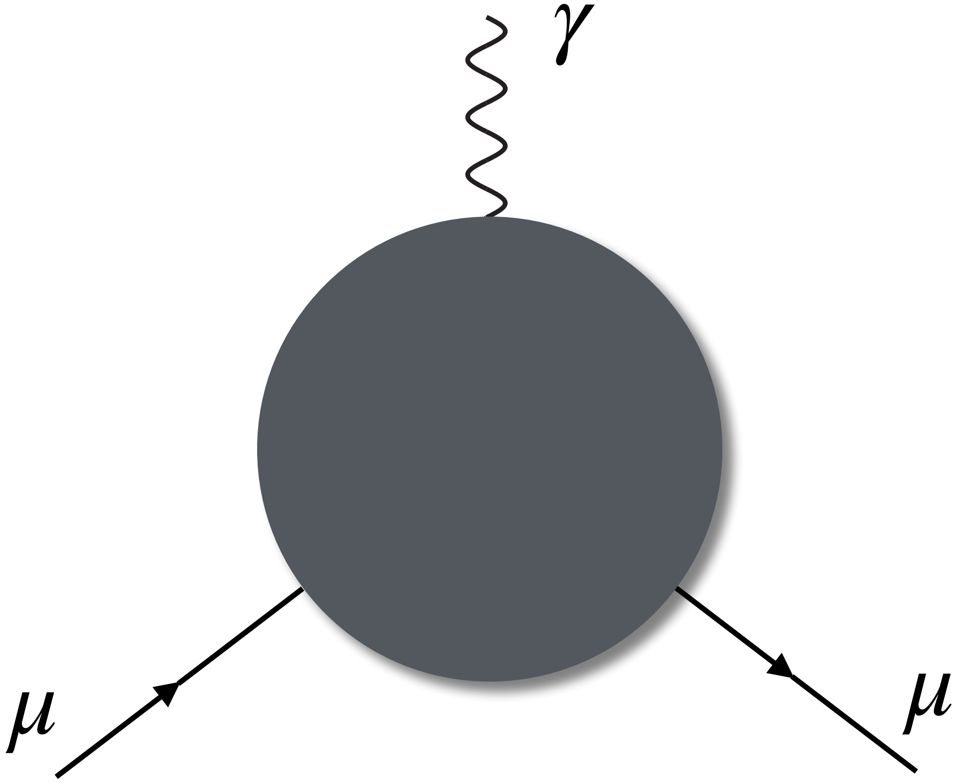
IDT-WG3-Phys Kickoff Meeting &
Mini-Symposium on Muon g-2, May 27, 2021

Scale of Muon Dipole Operator



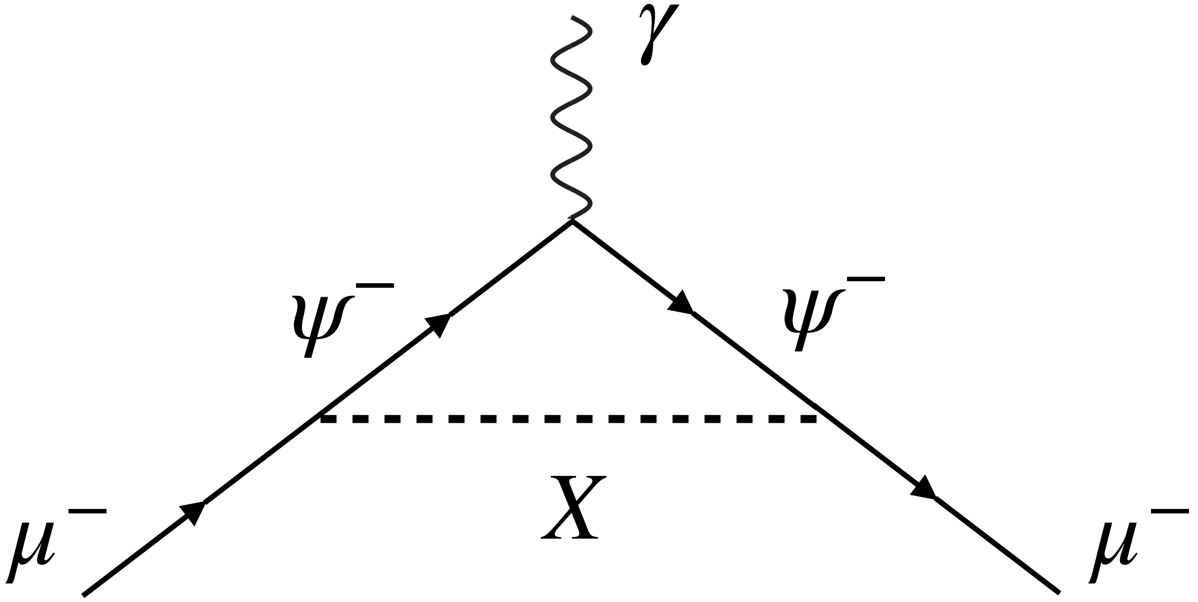
$$\mathscr{L} \supset \epsilon \, \frac{e\, m}{16\pi^2 \Lambda^2} \, \bar{\mu}\, \sigma^{\mu\nu} \mu\, F_{\mu\nu}$$

$$\Delta a_\mu = \epsilon \, \frac{m\, m_\mu}{4\pi^2 \Lambda^2} \approx \begin{cases} (251 \times 10^{-11}) \times \left(\dfrac{\epsilon}{+1}\right) \left(\dfrac{333\,\mathrm{GeV}}{\Lambda}\right)^2 & \text{for} \quad m = m_\mu \quad ✓ \\ (251 \times 10^{-11}) \times \left(\dfrac{\epsilon}{+1}\right) \left(\dfrac{103\,\mathrm{TeV}}{\Lambda}\right)^2 & \text{for} \quad m = 100\,\mathrm{GeV} \end{cases}$$

YB, Berger, 2104.03301v2

Connection to Dark Matter

- **One possibility is that the dark matter particle contributes**
- **Two states are needed to have a stable dark matter state**



- **Two Dark matter states couple to leptons:**

"Lepton-portal Dark Matter"

YB, Berger, 1402.6696; Chang, et.al, 1402.7358; Agrawal, et. al, 1402.7369

Kawamura, Okawa, Omura, 2002.12534

(almost) Minimal Model

- **Dark matter is a real scalar. The heavier charged states are vector-like Dirac fermions with the same gauge charge as the right-handed electron**

$$\mathscr{L} \supset -\lambda\, X^a \,\overline{\psi^i_L}\, e^i_R - m_\psi \overline{\psi^i_L} \psi^i_R + h.c. - \frac{1}{2} M_X^2 X^a X^a$$

$$i = 1,2,3 \qquad\qquad a = 1,\cdots,n_f$$

- **Dark matter phenomenology cares whether X is a real or complex scalar as well as its internal degrees of freedom**

- **The case with a fermion dark matter state predicts opposite sign for the muon g-2 excess**

Muon g-2

$$\Delta a_\mu^{(X,\psi)} = \frac{n_f\,\lambda^2\,m_\mu^2}{16\pi^2\,M_X^2}\left[\frac{2+3x-6x^2+x^3+6x\ln x}{6(1-x)^4}\right] \qquad x \equiv m_\psi^2/M_X^2$$

$$\begin{tikzcd} & \left[\frac{2+3x-6x^2+x^3+6x\ln x}{6(1-x)^4}\right] \arrow[dl, "x=1"'] \arrow[dr, "x\to\infty"] & \\ \frac{1}{12} & & \frac{1}{6}\,\frac{M_X^2}{m_\psi^2} \end{tikzcd}$$

- **In the approximately degenerated region and to fit the central experimental value $\Delta a_\mu \approx 251 \times 10^{-11}$, one needs**

$$n_f\,\lambda^2 \approx 4.3 \times \left(\frac{M_X}{100\,\mathrm{GeV}}\right)^2$$

Running and Landau-pole Scales

- **For a large λ, the perturbative Landau-pole could be low**

$$\frac{d\lambda}{d\ln\mu} \equiv \beta_\lambda(\lambda) = 5\, n_f \, \frac{\lambda^3}{(4\pi)^2} - \frac{57}{4}\, n_f^2\, \frac{\lambda^5}{(4\pi)^4}$$

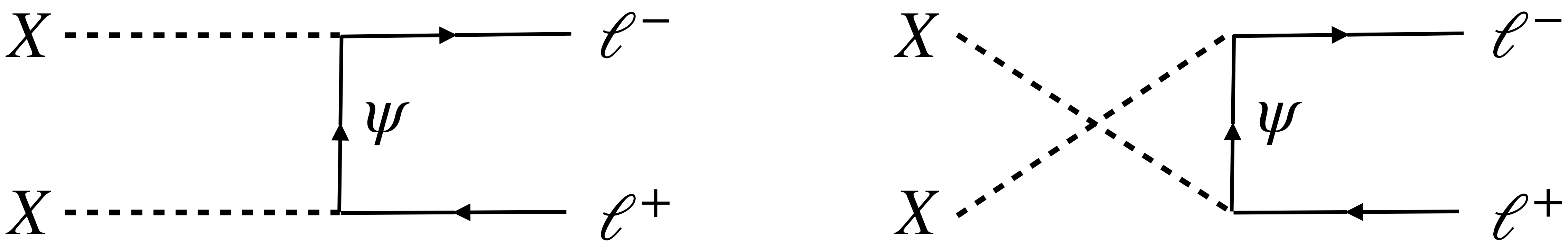
- **There exists a possible UV-fixed point for the coupling, but at the non-perturbative region**

$$\lambda_* = \frac{4\pi}{\sqrt{n_f}}\sqrt{\frac{20}{57}} \approx \frac{7.4}{\sqrt{n_f}}$$

- **We will use the Landau-pole scale to denote the rough cutoff scale of our model**

Dark Matter Abundance

- **The dark matter abundance could be satisfied by a thermal relic abundance or other non-standard cosmology**
- **We will not use the thermal relic one as a must condition**



$$\sigma v(XX \to \ell^+\ell^-) = \frac{\lambda^4\, m_\ell^2}{4\pi(M_X^2 + m_\psi^2)^2} - v^2\, \frac{\lambda^4\, m_\ell^2\, M_X^2(M_X^2 + 2m_\psi^2)}{6\pi\,(M_X^2 + m_\psi^2)^4} + v^4\, \frac{\lambda^4\, M_X^6}{60\pi(M_X^2 + m_\psi^2)^4}$$

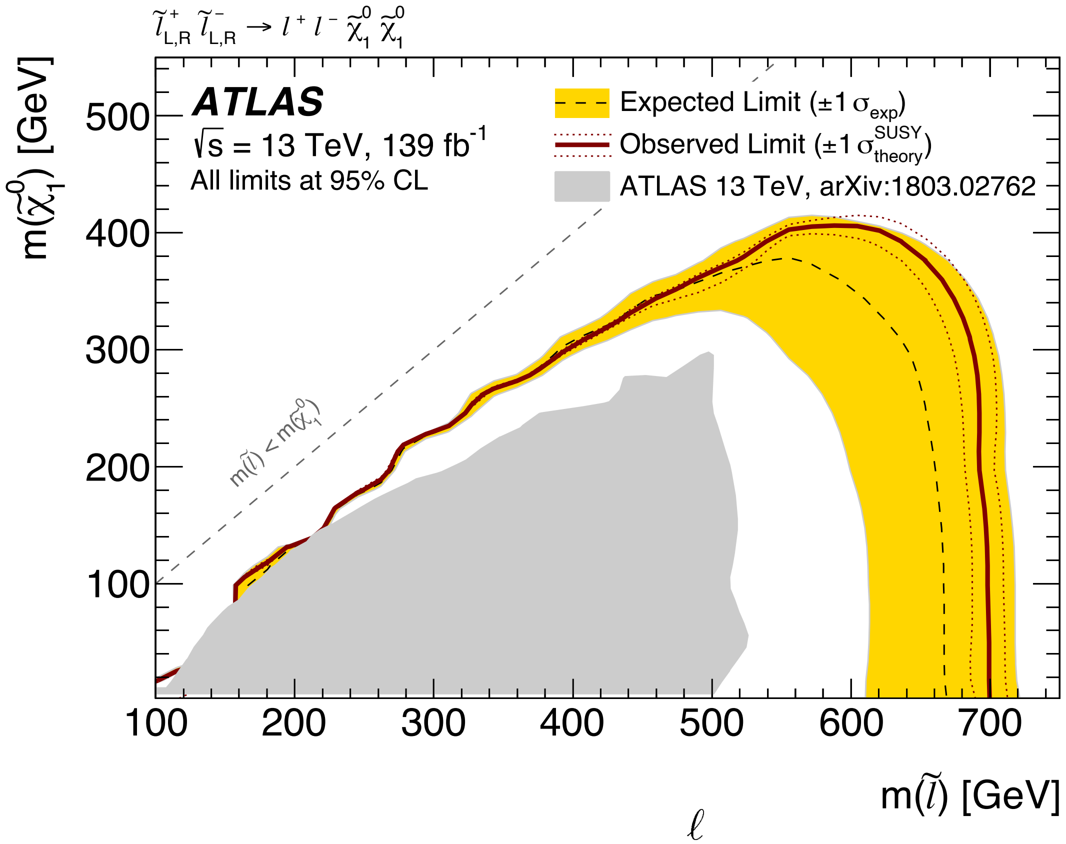
- **It is d-wave suppressed for negligible lepton masses**

$$d = \frac{\lambda^4\, M_X^6}{60\pi(M_X^2 + m_\psi^2)^4} = (27\,\mathrm{pb}\cdot\mathrm{c}) \times \left(\frac{\lambda}{3}\right)^4 \left(\frac{100\,\mathrm{GeV}}{M_X}\right)^2 \left(\frac{2}{1 + x/4}\right)^4$$

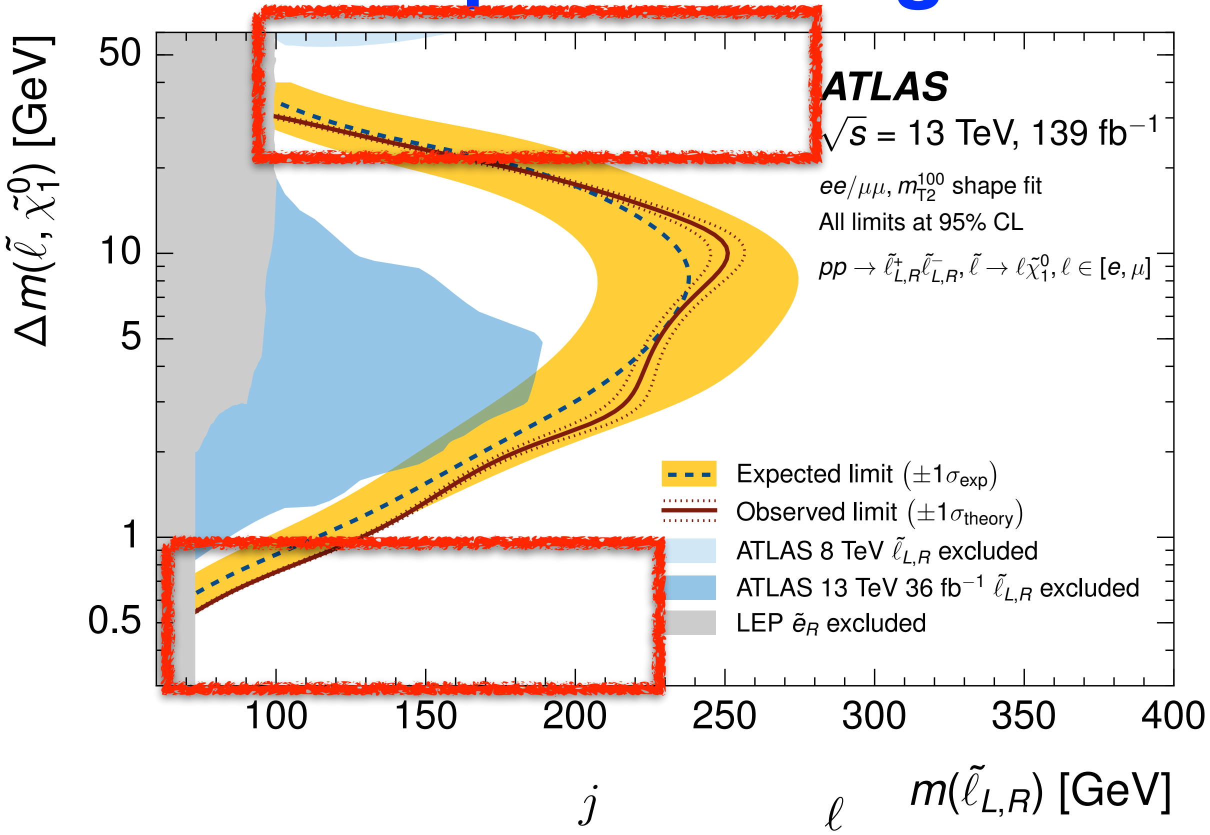
- $d = 27$ **pb · c provides the right dark matter relic abundance**

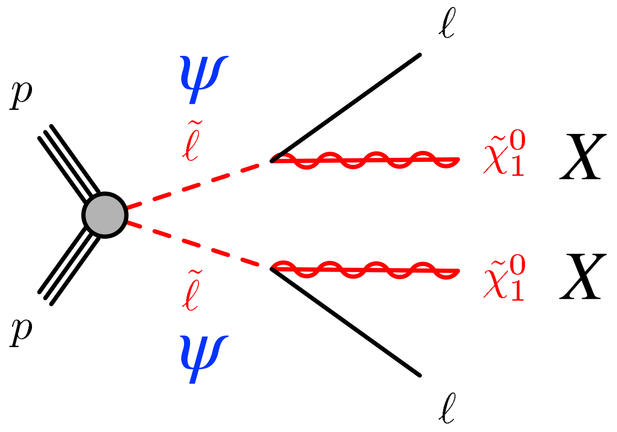
Collider Constraints

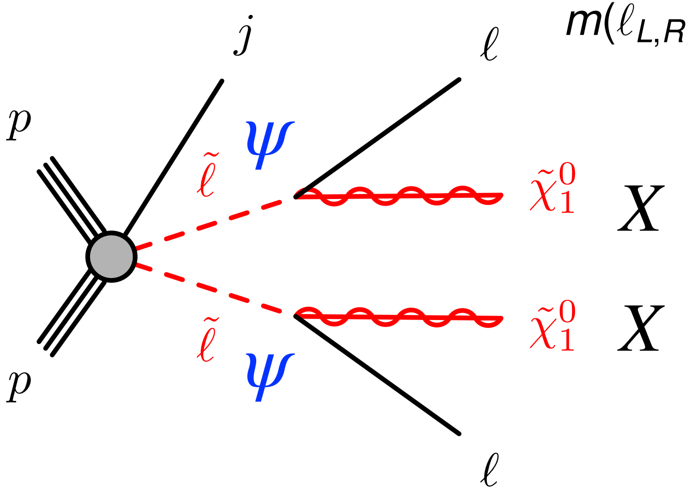
- Similar to the slepton searches in SUSY, but with a larger production cross section for fermion $\psi^{\pm}$



compressed region

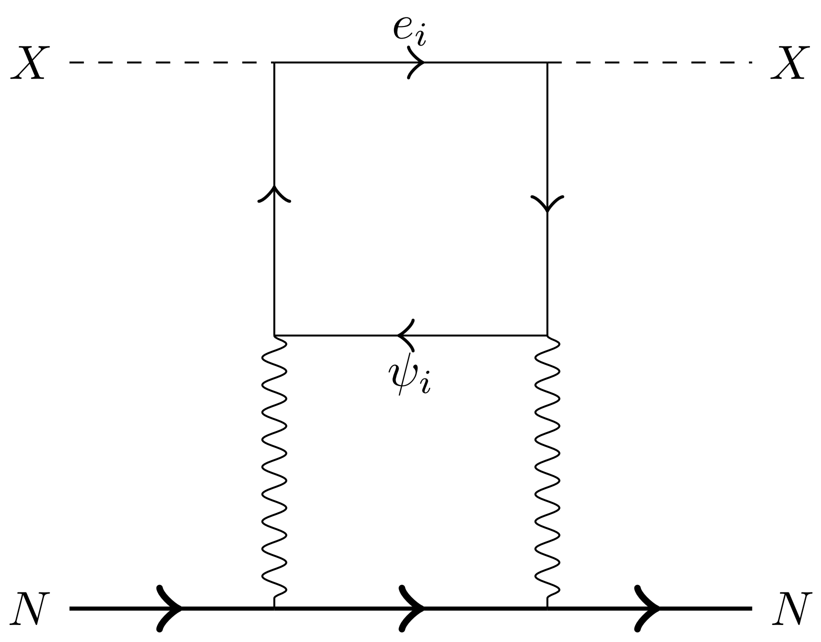






Direct Detection

- For a real scalar dark matter, it does not couple to a single photon. The leading one is the Rayleigh interaction



- Match to the effective Rayleigh (Polarizability) operator

$$\mathscr{L} \supset -\, C_1 \frac{\lambda^2 \alpha}{4\,\pi\, m_\psi^2} X^2 F_{\mu\nu} F^{\mu\nu} \qquad C_1 = \frac{4}{3} \underbrace{\frac{m_\psi^2 M_X^2}{(m_\psi^2 - M_X^2)^2}}_{\text{enhanced in the degenerate region}} \sum_i \left[\ln\left(\frac{m_{e_i} m_\psi}{m_\psi^2 - M_X^2} \right) + 1 \right]$$

Direct Detection

$$\sigma_{XA} \approx \frac{\mu_{XA}^2}{\pi M_X^2} \left(\frac{C_1 \lambda^2 \alpha}{4 \pi m_\psi^2} \right)^2 |f_F^A|^2$$

$$f_F^A \equiv \langle A | F_{\mu\nu} F^{\mu\nu} | A \rangle$$

$$f_F^A \sim \frac{3 Z^2 \alpha}{r_0} \qquad r_0 \sim 1.2\, A^{1/3}\ \text{fm}$$

- **Some uncertainties for the nuclear matrix element**
- **Converting to spin-independent scattering off a nucleon**

$$\sigma_{Xn} = \sigma_{XA} \frac{\mu_{Xn}^2}{\mu_{XA}^2 A^2}$$

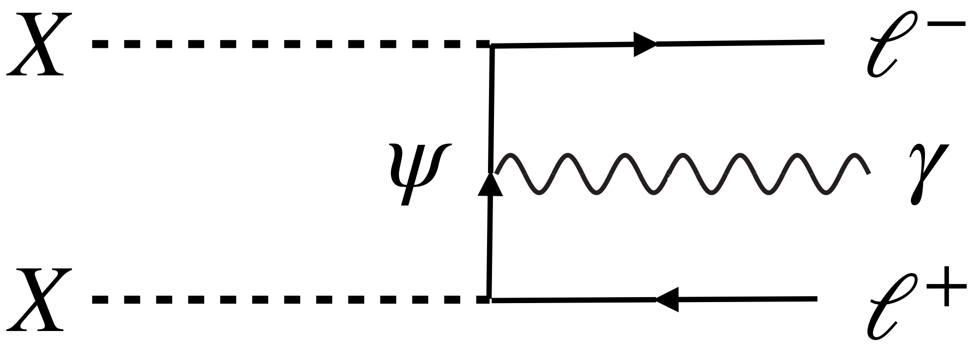
$$\sigma_{Xn} \sim (4.5 \times 10^{-47}\ \text{cm}^2) \left(\frac{\lambda}{2.5} \right)^4 \left(\frac{100\ \text{GeV}}{M_X} \right)^2 \left(\frac{60\ \text{GeV}}{\Delta m} \right)^4$$

for Xe

- **Scattering off electrons does not provide stringent constraints**

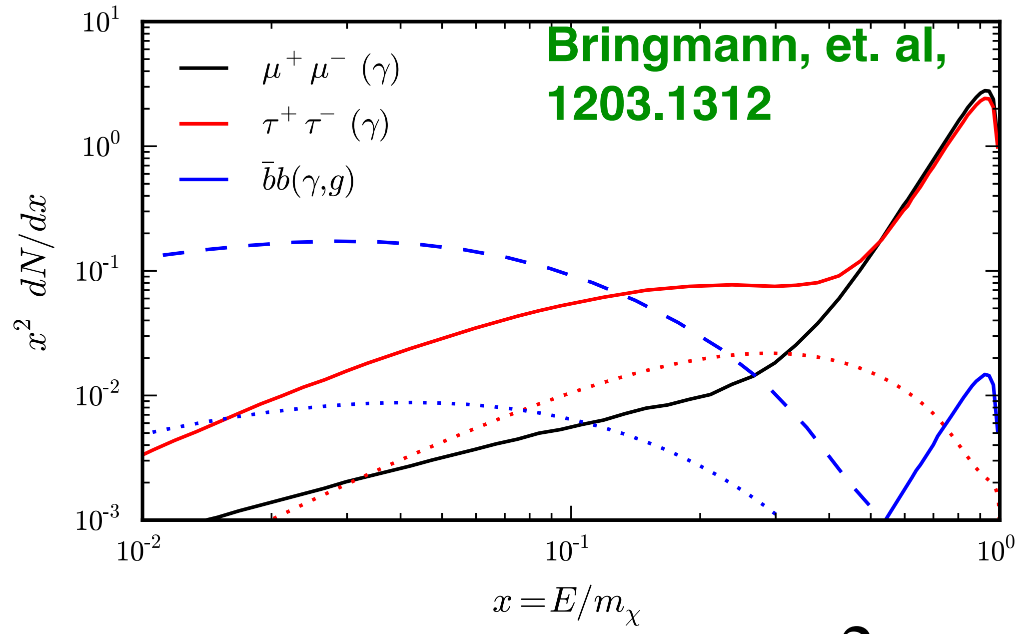
Indirect Detection

- The two-body final state is d-wave suppressed or v^4
- But not for three-body final state

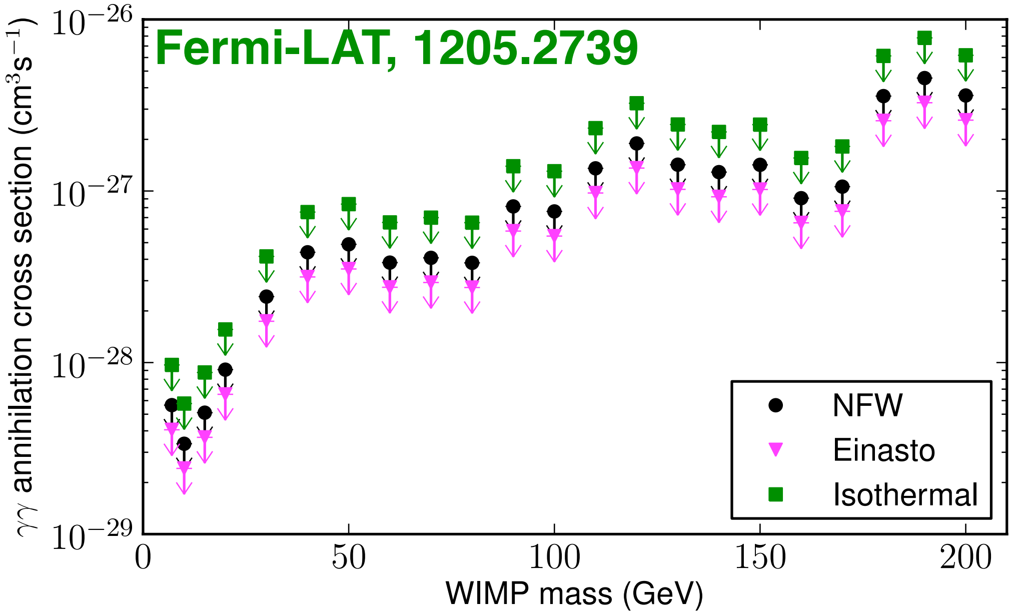


$\propto \lambda^4$

- Searching for gamma rays from internal bresstrahlung



Bringmann, et. al, 1203.1312

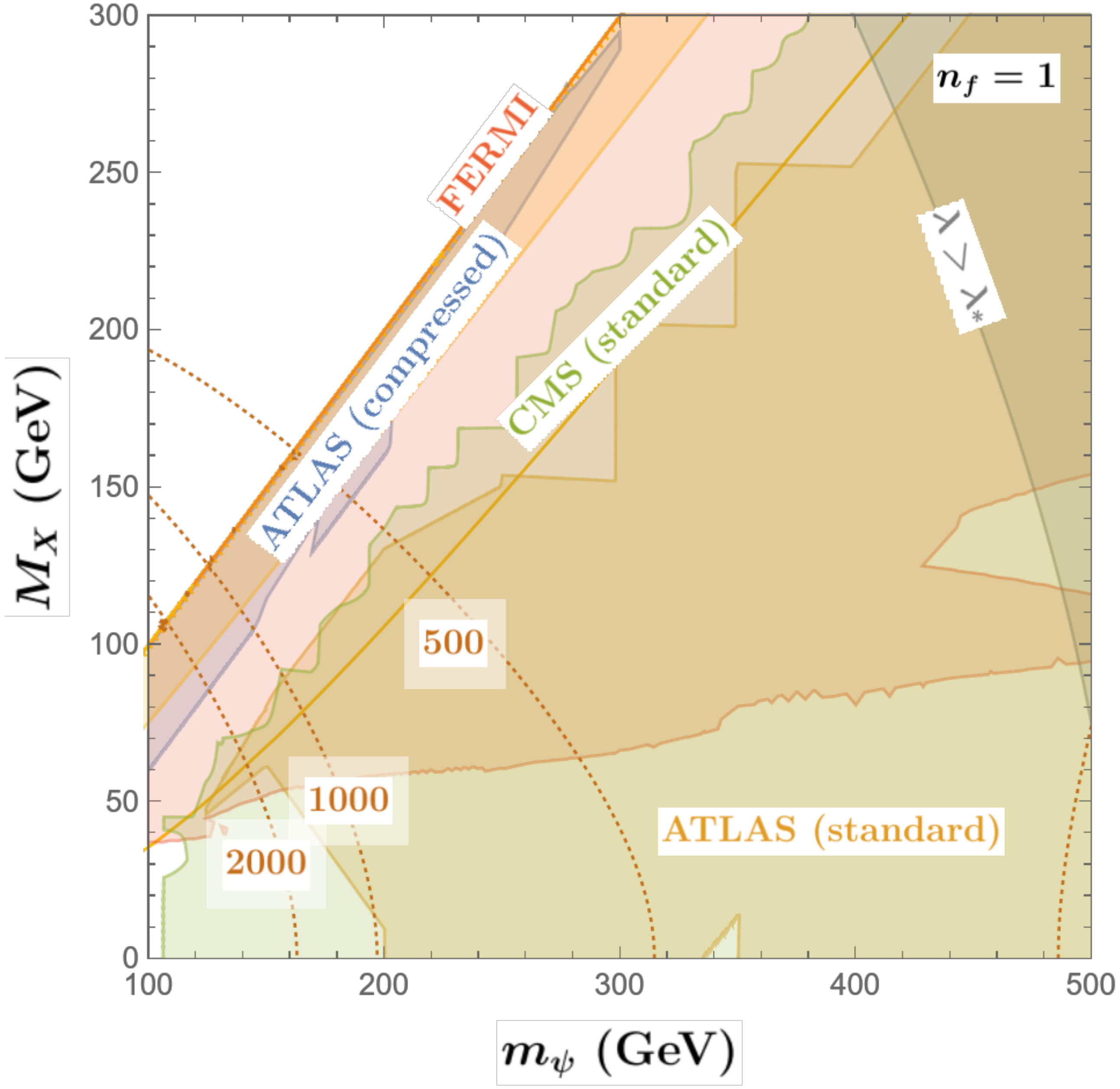


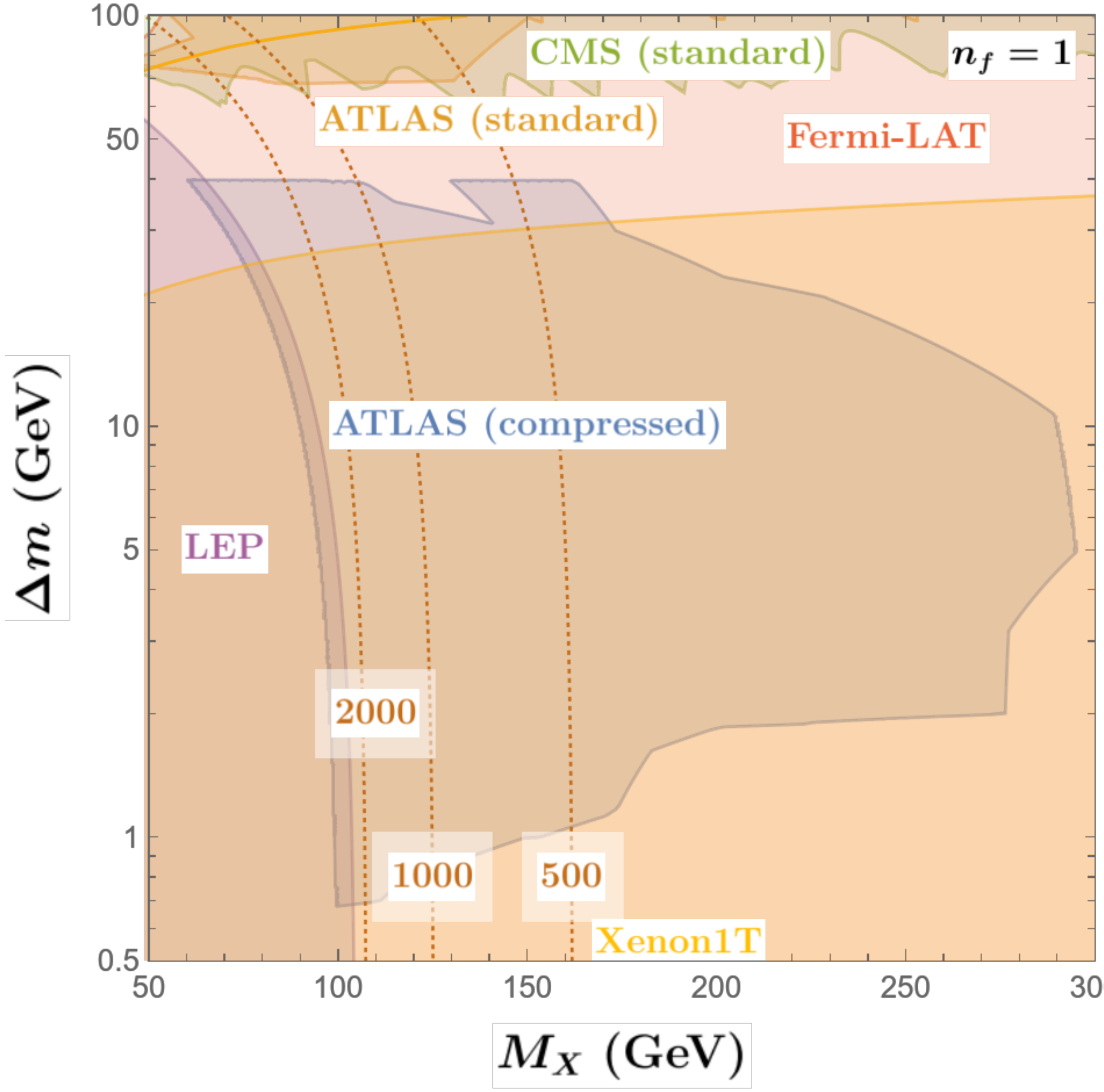
Fermi-LAT, 1205.2739

- Muon g-2 fixes $n_f\lambda^2$. Increasing n_f can relax indirect detection constraints

All Constraints ($n_f = 1$)

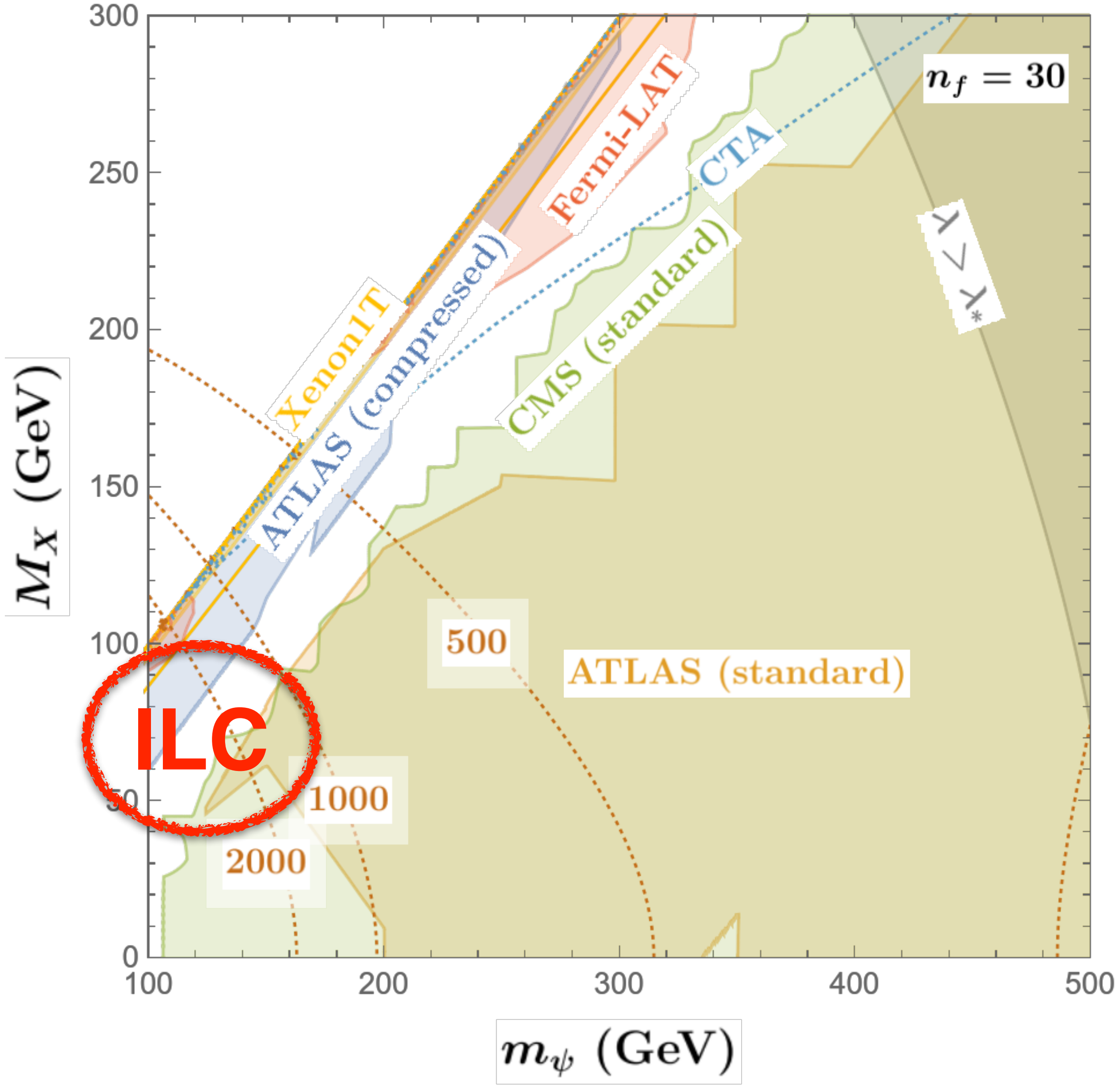
- The central value of muon g-2 has been used to fix λ

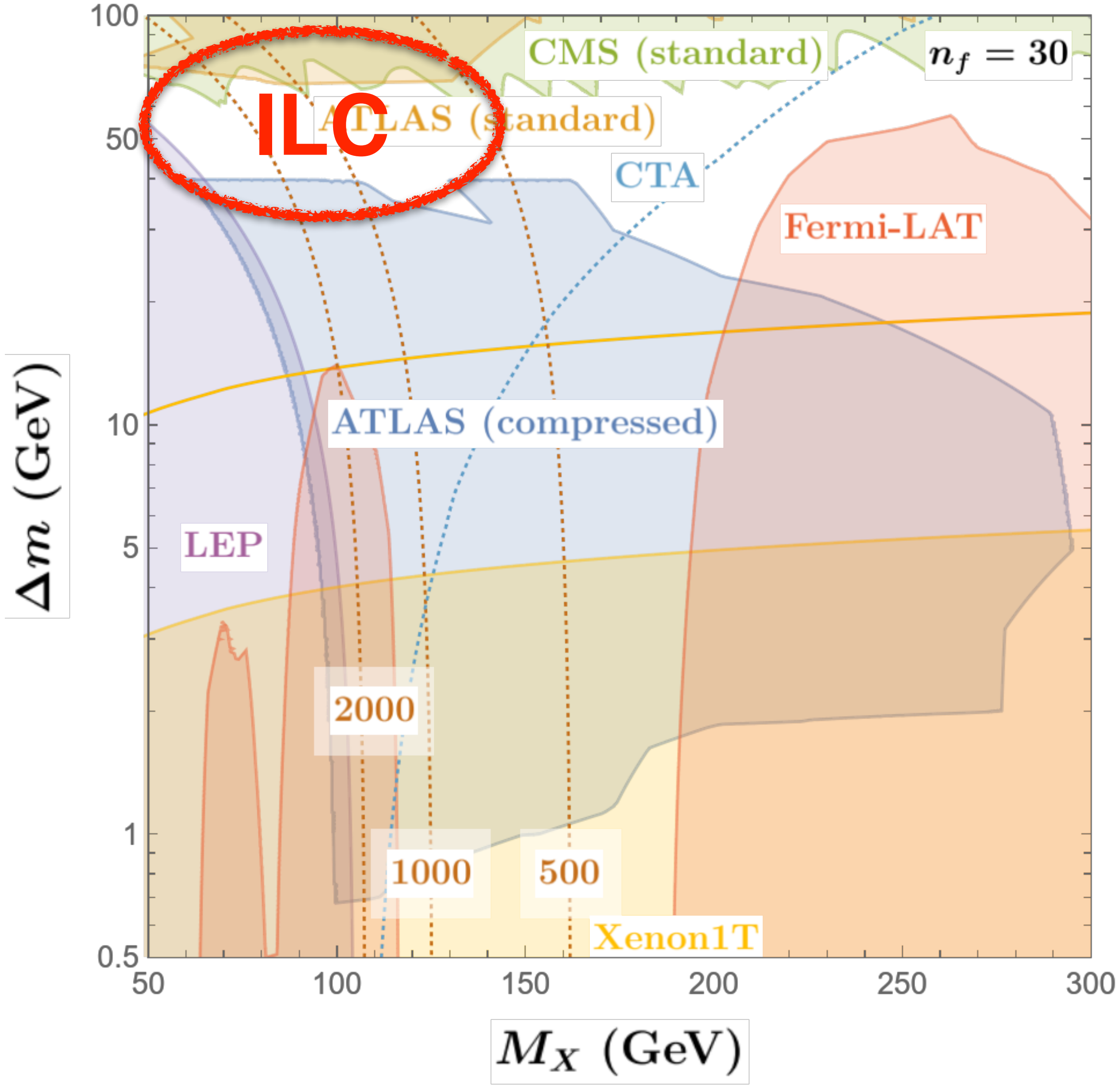




YB, Berger, 2104.03301v2

All Constraints ($n_f = 30$)

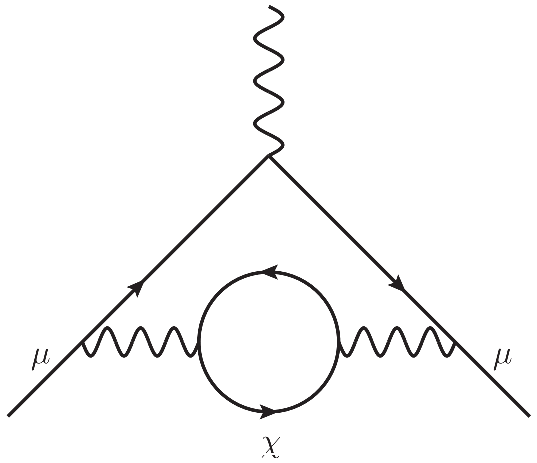


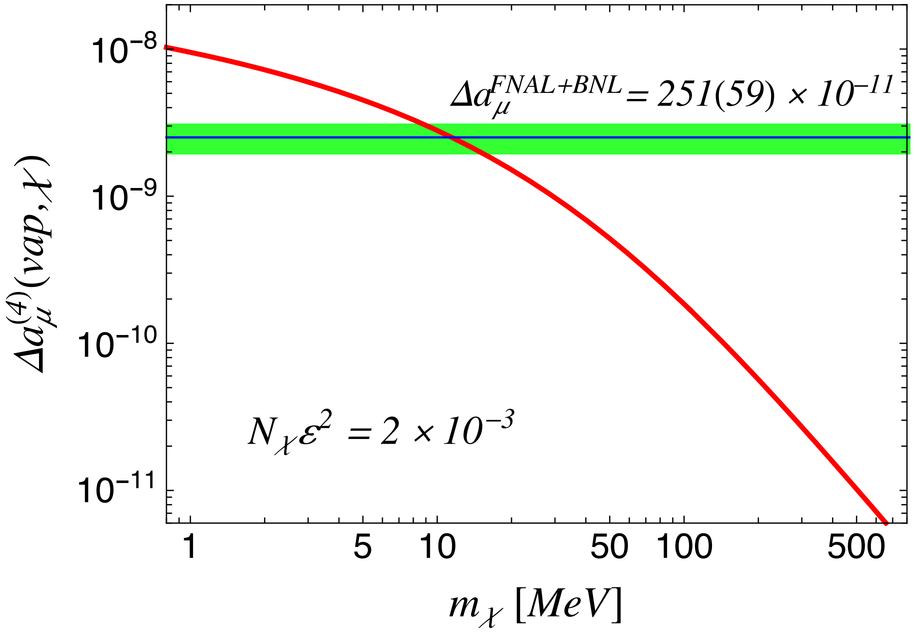


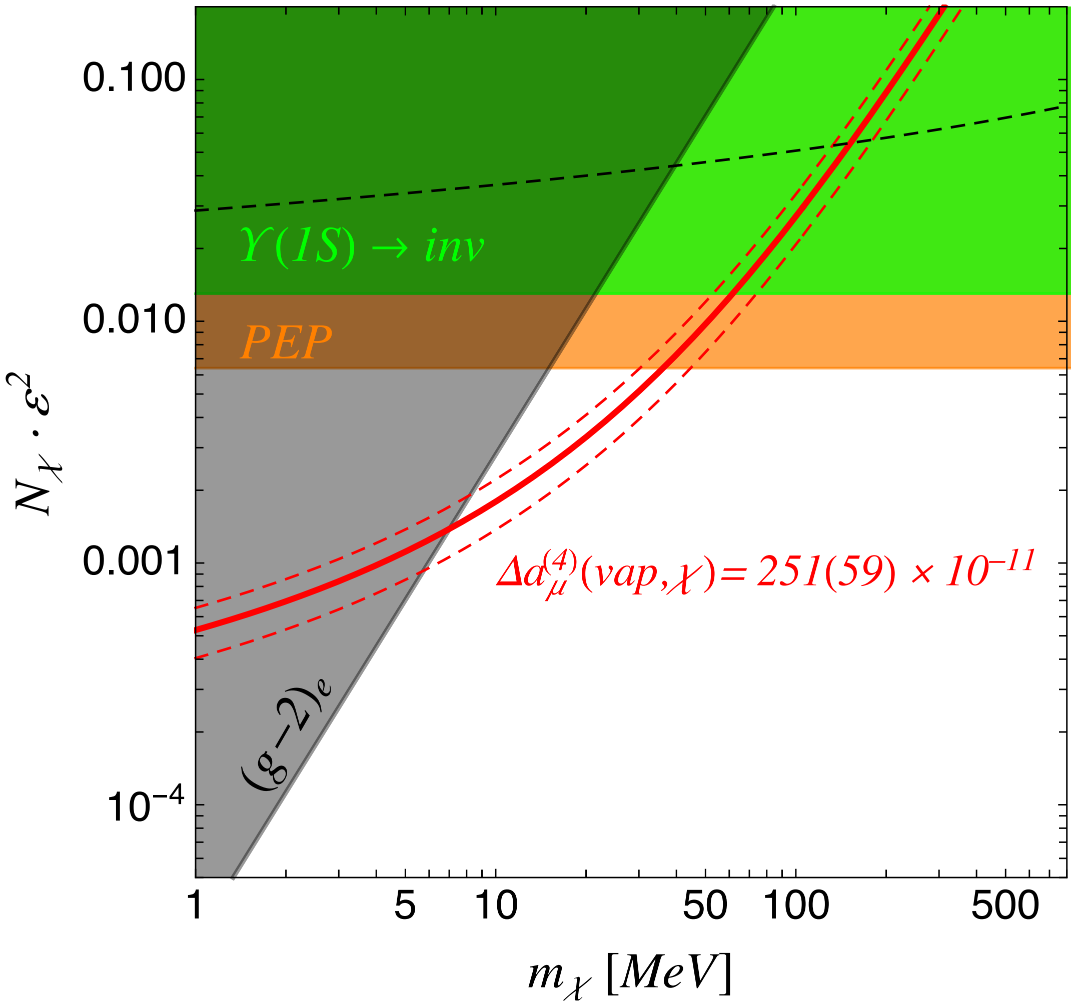
- **A lepton collider like ILC can provide a good coverage for the allowed parameter space**

Millicharged Particle Explanation

- **Millicharged dark particles could modify the photon vacuum polarization and explain Δa_μ**







YB, Lee, Son, Ye, to appear

- **Additional model-building is required to satisfy supernovae cooling and fixed-target exp. constraints**

Conclusions

- Muon g-2 excess means a possible new particle beyond the Standard Model
- The dark matter sector could mainly couple to leptons and provide a natural explanation
- For models with the muon mass flipping the chirality, the dark matter state masses are below around 200 GeV and can be well covered by a lepton collider like ILC

Thanks!