Physics Beyond the Standard Model in Charmonium Sector

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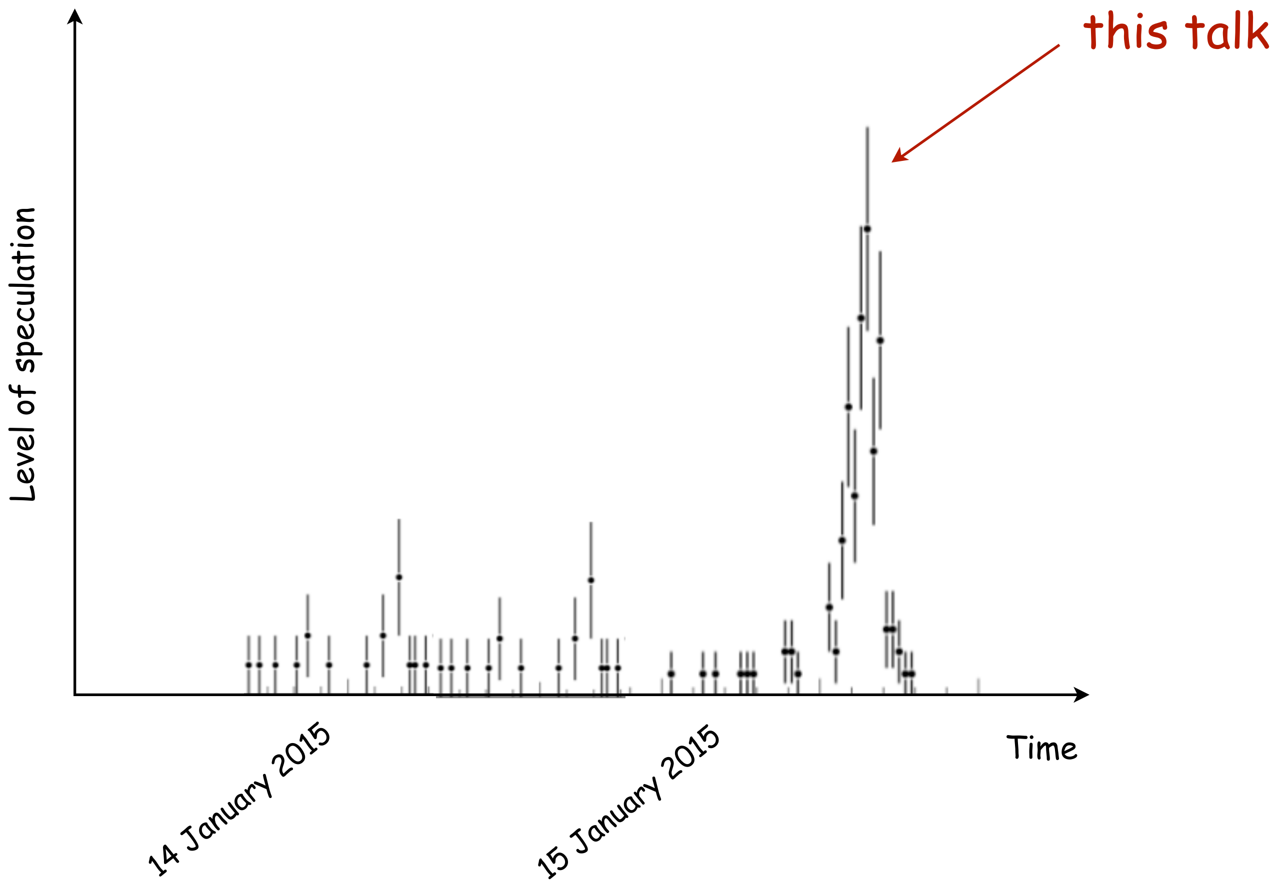
HIEPA-2015 presentations: level of speculation



Introduction

- New physics can affect quarkonium decays
- … but its contribution can be masked by QCD/QED processes
- We have to look at decays models where SM contribution is either small or under firm theoretical control

  - Processes with SM particles in the final state only ("heavy" NP)
    - quark FCNC transitions
    - lepton FCNC transitions

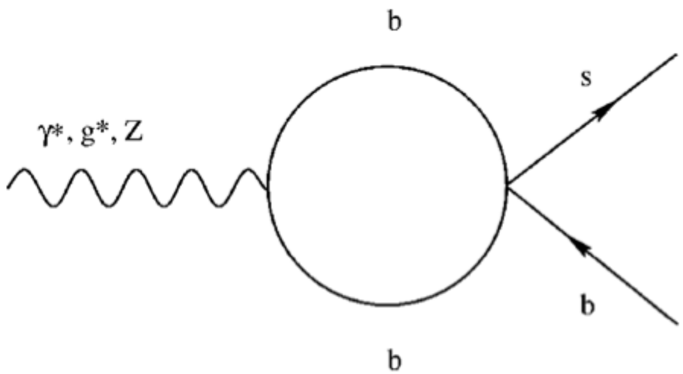
  - Processes with SM and NP particles in the final state ("light" NP)
    - light Dark Matter particles
    - dark photons
    - exotic light scalars, etc.

“Heavy” New Physics

Heavy New Physics

- FCNC processes can be probed in heavy quarkonium decays
  - FCNC in quark sector (b -> s): $\Upsilon \to BX_s$ or (c -> u): $J/\psi \to DX_u$

Datta, O'Donnel, Pakvasa, Zhang (1999)



  - This can be studied with a generic Lagrangian,

$$L_{new} = \frac{R_1}{\Lambda^2}\bar{s}(1-\gamma^5)b\bar{b}(1+\gamma^5)b + \frac{R_2}{\Lambda^2}\bar{s}(1+\gamma^5)b\bar{b}(1-\gamma^5)b$$

  - … or in particular models, i.e. FCNC Higgs, where

$$R_1 = \frac{1}{4}\frac{m_t^2}{f_{\tilde{\pi}}^2 m_H^2}|D_{Lbb}|^2 D_{Rbb} D_{Rbs}^*,$$

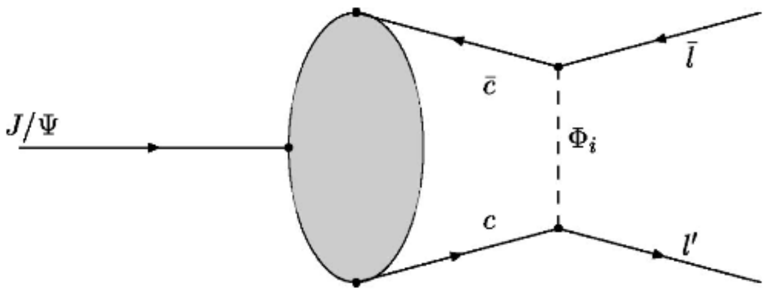
  - DOPZ claim: $Br(J/\psi \to DX_u) \sim 10^{-5}$!

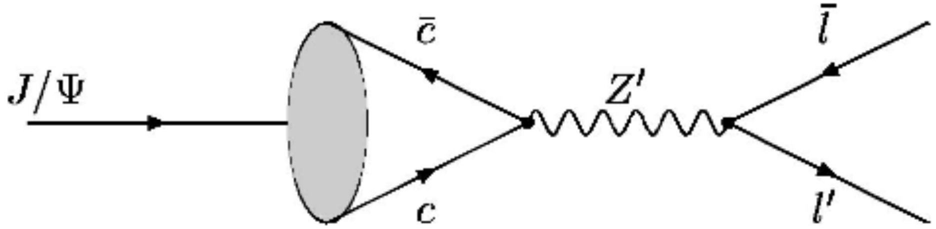
$$R_2 = \frac{1}{4}\frac{m_t^2}{f_{\tilde{\pi}}^2 m_H^2}|D_{Rbb}|^2 D_{Lbb} D_{Lbs}^*,$$

Heavy New Physics

- FCNC processes can be probed in heavy quarkonium decays
  - FCNC in lepton sector ($J/\psi \to e\mu$, etc.)

Hue, Yue, Feng (2003)



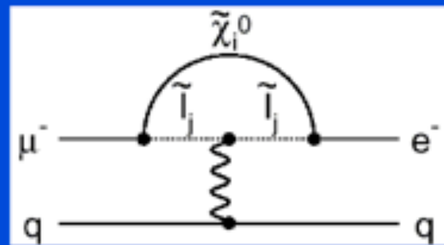


  - Very much complimentary to muon conversion/FCNC tau decay experiments
  - Recent BES constraint $\mathcal{B}(J/\psi \to e\mu) < 1.6 \times 10^{-7}$

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}

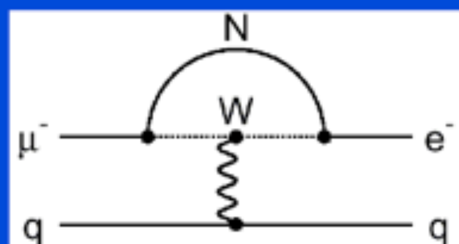


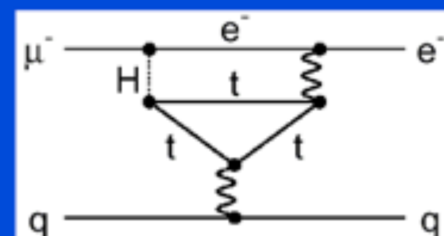
Compositeness

$\Lambda_c = 3000$ TeV

Heavy Neutrinos

$\left|U^*_{\mu N} U_{eN}\right|^2 = 8 \times 10^{-13}$





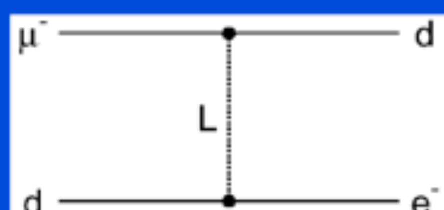
Second Higgs doublet

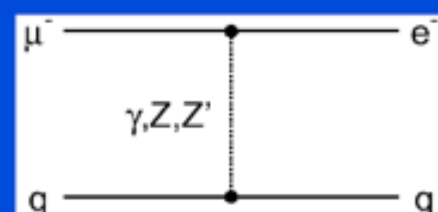
$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L =$

$3000\sqrt{\lambda_{\mu d}\lambda_{ed}}$ TeV/c^2





Heavy Z', Anomalous Z coupling

$M_{Z'} = 3000$ TeV/c^2

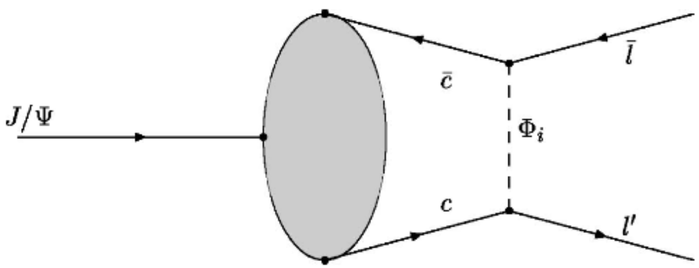
$B(Z \to \mu e) < 10^{-17}$

After W. Marciano

James Miller, 2006

Heavy New Physics

- Example: leptoquarks



$$\mathrm{Br}(J/\psi \to \mu\tau) = \frac{9}{2^9 \pi^2 \alpha^2} m_\tau^2 M_{J/\psi}^2 \left(1 + 2\frac{M_{J/\psi}^2}{m_\tau^2}\right) \times \left(1 - \frac{m_\tau^2}{M_{J/\psi}^2}\right)^2 \cdot \frac{|\lambda_L^{c\mu}\lambda_L^{c\tau}|^2 + \lambda_R^{c\mu}\lambda_R^{c\tau}|^2}{M_\Phi^4} \times \mathrm{Br}(J/\psi \to e^+ e^-).$$

- From tau-decay: $$\frac{|\lambda_L^{c\mu}\lambda_L^{c\tau}|^2 + |\lambda_R^{c\mu}\lambda_R^{c\tau}|^2}{M_\Phi^4} < 1.5 \times 10^{-10}.$$

- Prediction: $$\mathrm{Br}(J/\psi \to \mu\tau) < 3.0 \times 10^{-8}$$

Huo, Yue, Feng (2003)

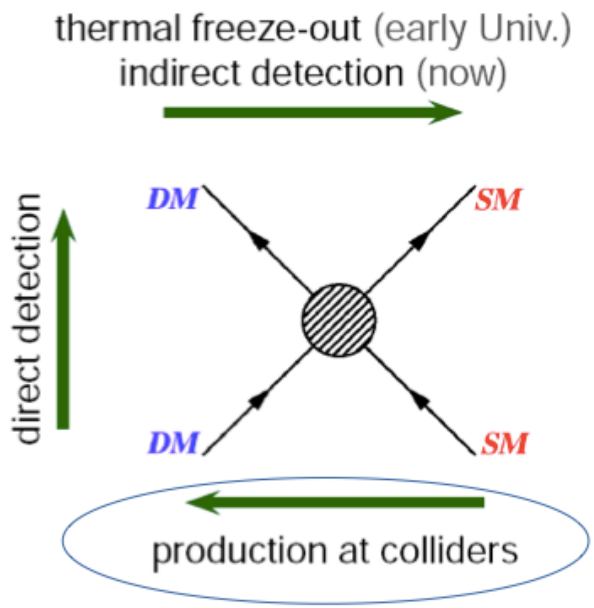
“Light” New Physics

Introduction: light Dark Matter

- DM does not have to be EW-scale (WIMP miracle)

$$\Omega_{DM}h^2 \sim \langle \sigma_{ann} v_{rel} \rangle^{-1} \propto \frac{M^2}{g^4}$$

- If DM is light, can use quarkonium decays to probe its properties



Fermion-mass-dependent couplings?

Backgrounds: decays to neutrino pairs

- Any studies of [cc] -> missing energy + X would have SM background
  - Invisible decays of heavy quarkonium (BR)

Chang, Lebedev, Ng (1998); Yeghiyan (2009)

$$B(\Upsilon(1S) \to \nu\bar{\nu}) = \frac{\Gamma(\Upsilon(1S) \to \nu\bar{\nu})}{\Gamma_{\Upsilon(1S)}}$$

$$= \frac{N_\nu G_F^2}{48\pi}\left(1 - \frac{4}{3}\sin^2\theta_W\right)^2 \frac{f_{\Upsilon(1S)}^2 M_{\Upsilon(1S)}^3}{\Gamma_{\Upsilon(1S)}}$$

Theory: $\mathcal{B}(\Upsilon(1S) \to \nu\bar{\nu}) = 9.85 \times 10^{-6}$, $\mathcal{B}(J/\Psi \to \nu\bar{\nu}) = 2.70 \times 10^{-8}$.

Experiment: $\mathcal{B}(\Upsilon(1S) \to \text{invisible}) < 3.0 \times 10^{-4}$, $\mathcal{B}(J/\Psi \to \text{invisible}) < 7.2 \times 10^{-4}$.

BaBar (2009), BES (2008)

  - Decays with photons and missing energy (BR & γ-spectrum)

$$B(\Upsilon(3S) \to \nu\bar{\nu}\gamma) = \frac{N_\nu G_F^2}{243\pi}\frac{\alpha}{4\pi}\frac{f_{\Upsilon(3S)}^2 M_{\Upsilon(3S)}^3}{\Gamma_{\Upsilon(3S)}}$$

Theory: $B(\Upsilon(3S) \to \nu\bar{\nu}\gamma) = (3.14^{+0.38}_{-0.32}) \times 10^{-9}$

Experiment: $B(\Upsilon(3S) \to \gamma + \text{invisible}) < (0.7\text{–}31) \times 10^{-6}$

Currently, SM “physics” background in not an issue.

Low-mass New Physics: light Dark Matter

- Effective Lagrangian analysis of low-mass Dark Matter

  - Leading-order operators for DM of different spin for 1^{--} decays

Fernandez, Kumar, Seong, Stengel (2014)

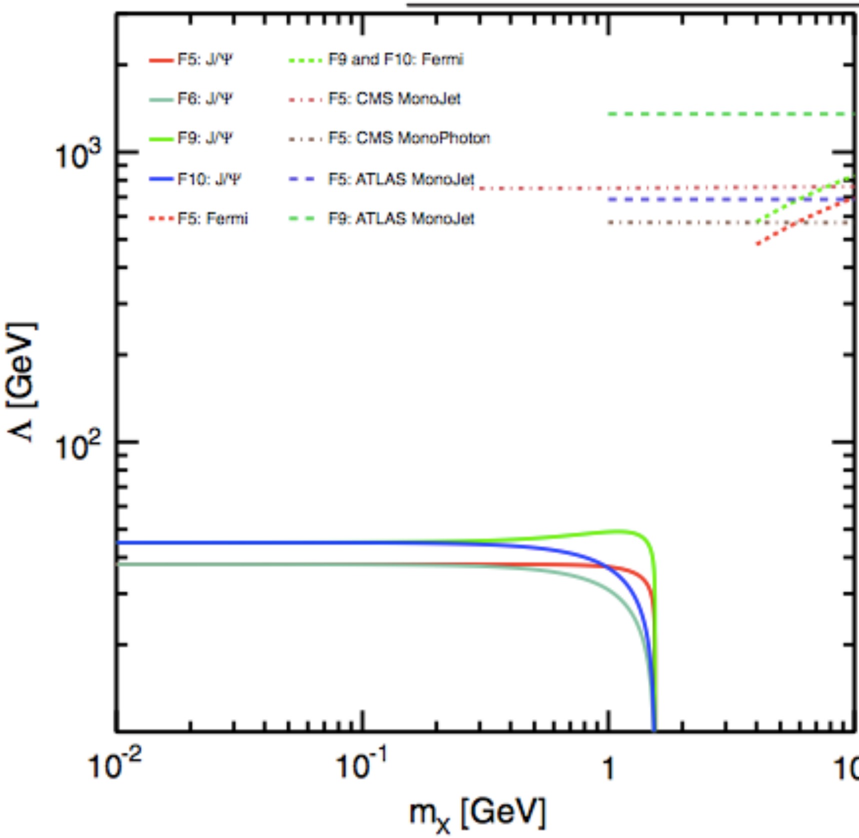
Name	Interaction structure	Annihilation	Scattering
F5	$(1/\Lambda^2)\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$	Yes	SI
F6	$(1/\Lambda^2)\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	No	No
F9	$(1/\Lambda^2)\bar{X}\sigma^{\mu\nu}X\bar{q}\sigma_{\mu\nu}q$	Yes	SD
F10	$(1/\Lambda^2)\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu}q$	Yes	No
S3	$(1/\Lambda^2)\imath\,\mathrm{Im}(\phi^\dagger\partial_\mu\phi)\bar{q}\gamma^\mu q$	No	SI
V3	$(1/\Lambda^2)\imath\,\mathrm{Im}(B^\dagger_\nu\partial_\mu B^\nu)\bar{q}\gamma^\mu q$	No	SI
V5	$(1/\Lambda)(B^\dagger_\mu B_\nu - B^\dagger_\nu B_\mu)\bar{q}\sigma^{\mu\nu}q$	No	SD
V7	$(1/\Lambda^2)B^{(\dagger)}_\nu\partial^\nu B_\mu\bar{q}\gamma^\mu q$	No	No
V9	$(1/\Lambda^2)\varepsilon^{\mu\nu\rho\sigma}B^{(\dagger)}_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu q$	No	No

  - These operators are relevant only for invisible decays of quarkonia
  - Note that Wilson coefficients are redefined in the scale Λ

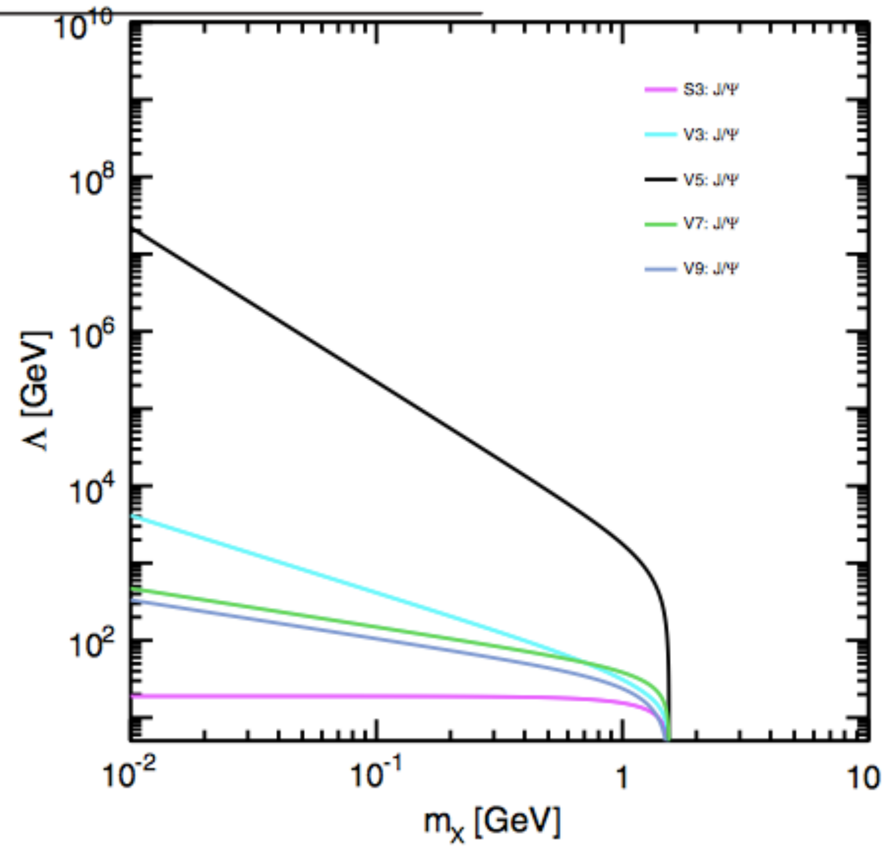
Light Dark Matter I

- Constraints on NP scale Λ from J/ψ decays (use dipion decays of ψ'')

Fermionic DM



Bosonic DM



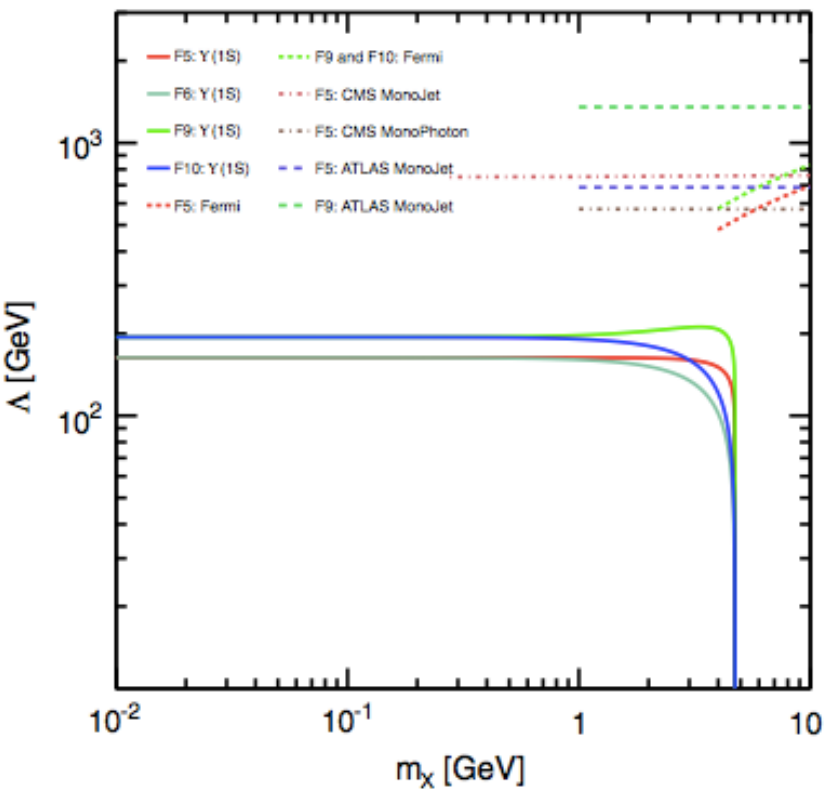
- Higher luminocities will provide more stringent constraints

Fernandez, Kumar, Seong, Stengel (2014)

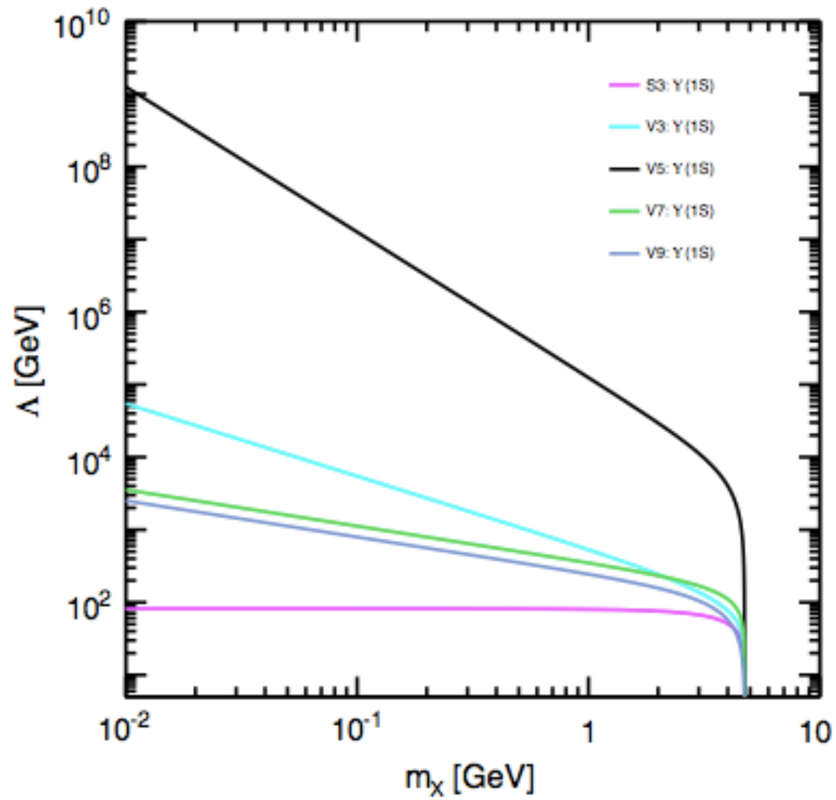
Light Dark Matter I

- Constraints on NP scale Λ from ϒ decays (use dipion decays of ϒ(3S))

Fermionic DM



Bosonic DM



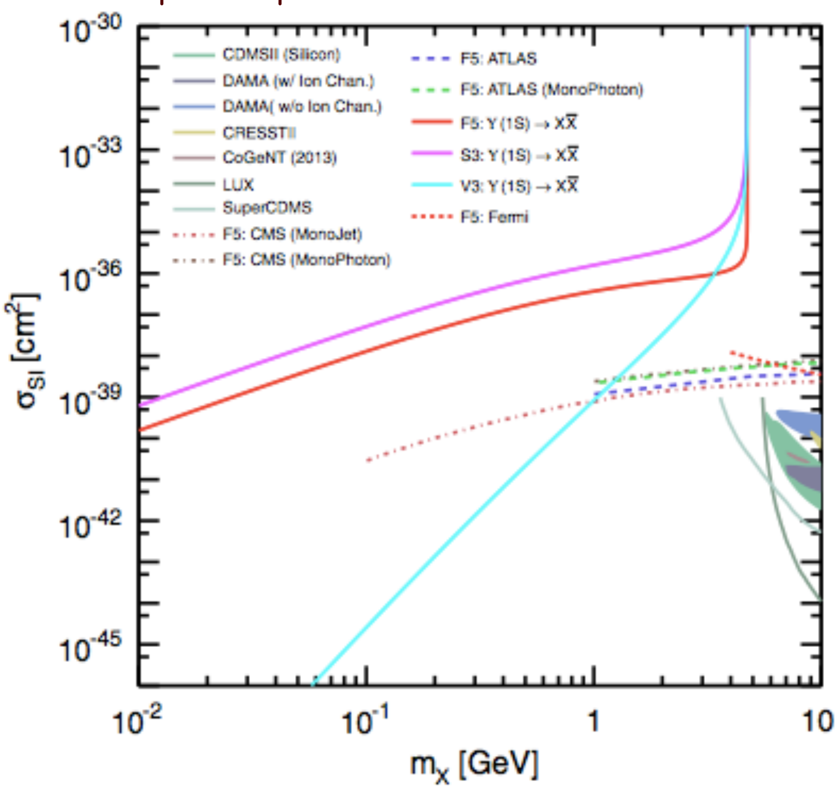
- Higher luminocities will provide more stringent constraints

Fernandez, Kumar, Seong, Stengel (2014)

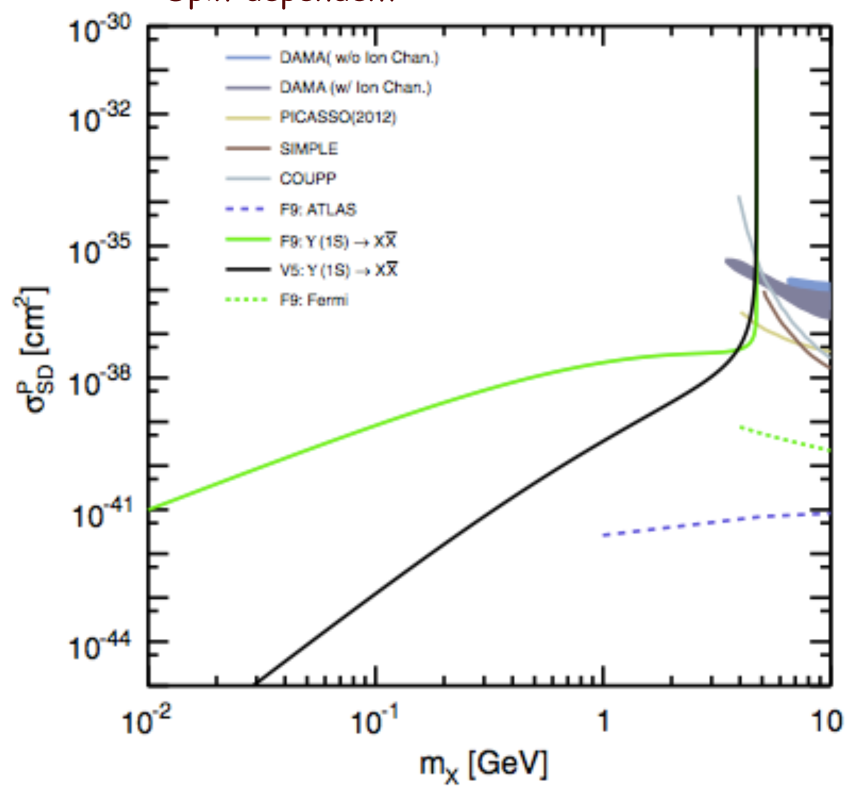
Light Dark Matter I

- Constraints on NP scale Λ from direct detection

Spin-independent



Spin-dependent



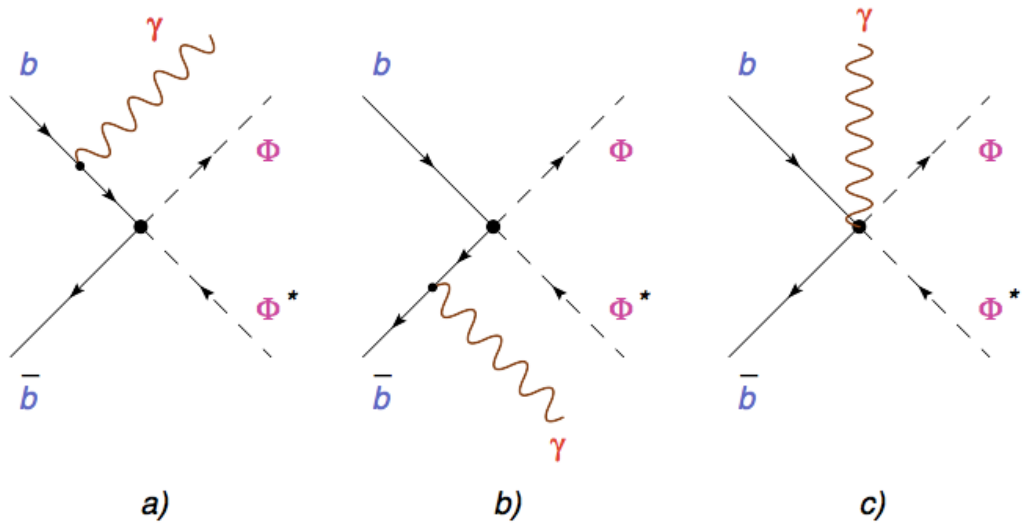
- Complimentary constraints if coupling universality is assumed

Fernandez, Kumar, Seong, Stengel (2014)

Light Dark Matter II

- Effective Lagrangian analysis of low-mass Dark Matter
  - New operators would appear for $\Upsilon(nS) \to \gamma$ + missing energy

Yeghiyan (2009)



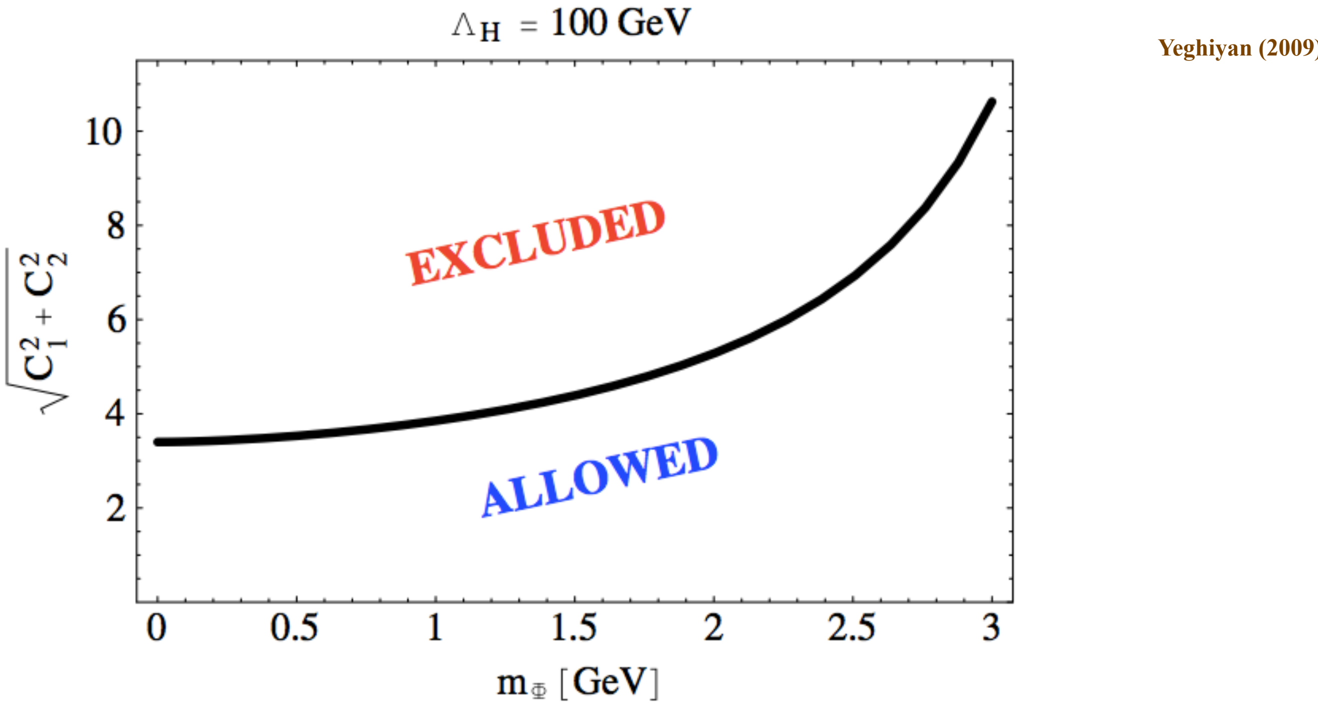
  - For scalar DM only two new operators contribute, $H_{\text{eff}} = \frac{2}{\Lambda_H^2} \sum_i C_i O_i,$

$$O_1 = m_b(\bar{b}b)(\Phi^*\Phi), \qquad O_2 = i m_b(\bar{b}\gamma_5 b)(\Phi^*\Phi),$$

$$O_3 = (\bar{b}\gamma^\mu b)(\Phi^* i \overleftrightarrow{\partial}_\mu \Phi), \qquad O_4 = (\bar{b}\gamma^\mu \gamma_5 b)(\Phi^* i \overleftrightarrow{\partial}_\mu \Phi),$$

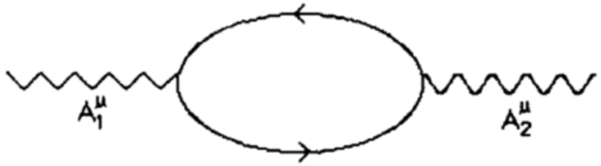
Light Dark Matter II

- Constraints on Wilson coefficients from Υ (ns) decays



- Higher luminocities will provide more stringent constraints
- Easy to provide specific models for DM, e.g. $-\mathcal{L} = \frac{m_0^2}{2}\Phi^2 + \lambda_1 \Phi^2 |H_1|^2 + \lambda_2 \Phi^2 |H_2|^2 + \lambda_3 \Phi^2 (H_1 H_2 + \text{H.c}),$
- … in which case, $|\lambda_3| < \left(\frac{17.4}{\tan\beta}\right)\left(\frac{m_{H^0}}{160\ \text{GeV}}\right)^2 f^{-1/2}(x_\Phi).$

Models of light Dark Matter and friends



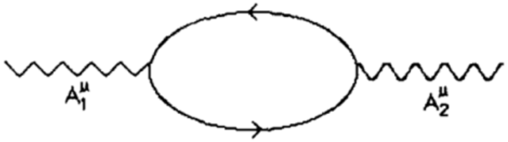
Low-mass New Physics: "dark photons"

- "Dark photons:" extra U(1) symmetries

  - Assume there is an extra U(1) state V kinetically mixed with photons

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + \mathcal{L}_{h'}$$

B. Holdom



Note: no direct couplings of V with fermions!

  - Redefine (diagonalize) vector states…

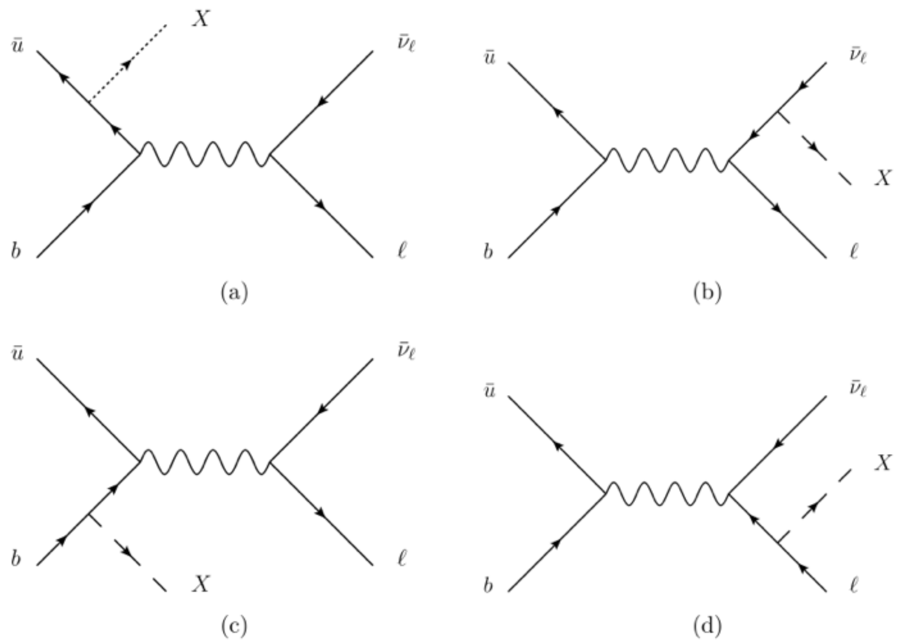
$$A \to A' - \frac{\kappa}{\sqrt{1-\kappa^2}}V', \qquad V \to \frac{1}{\sqrt{1-\kappa^2}}V'$$

  - … to get a direct coupling of V' with fermion currents!

$$\mathcal{L}_f = -eQ_f A'_\mu \bar{\psi}_f \gamma^\mu \psi_f - \frac{\kappa e Q_f}{\sqrt{1-\kappa^2}} V'_\mu \bar{\psi}_f \gamma^\mu \psi_f$$

Low-mass New Physics: "dark photons"

- "Dark photons:" masses in the eV-MeV range
  - low-energy states (mesons/baryons) can decay into "dark photons"

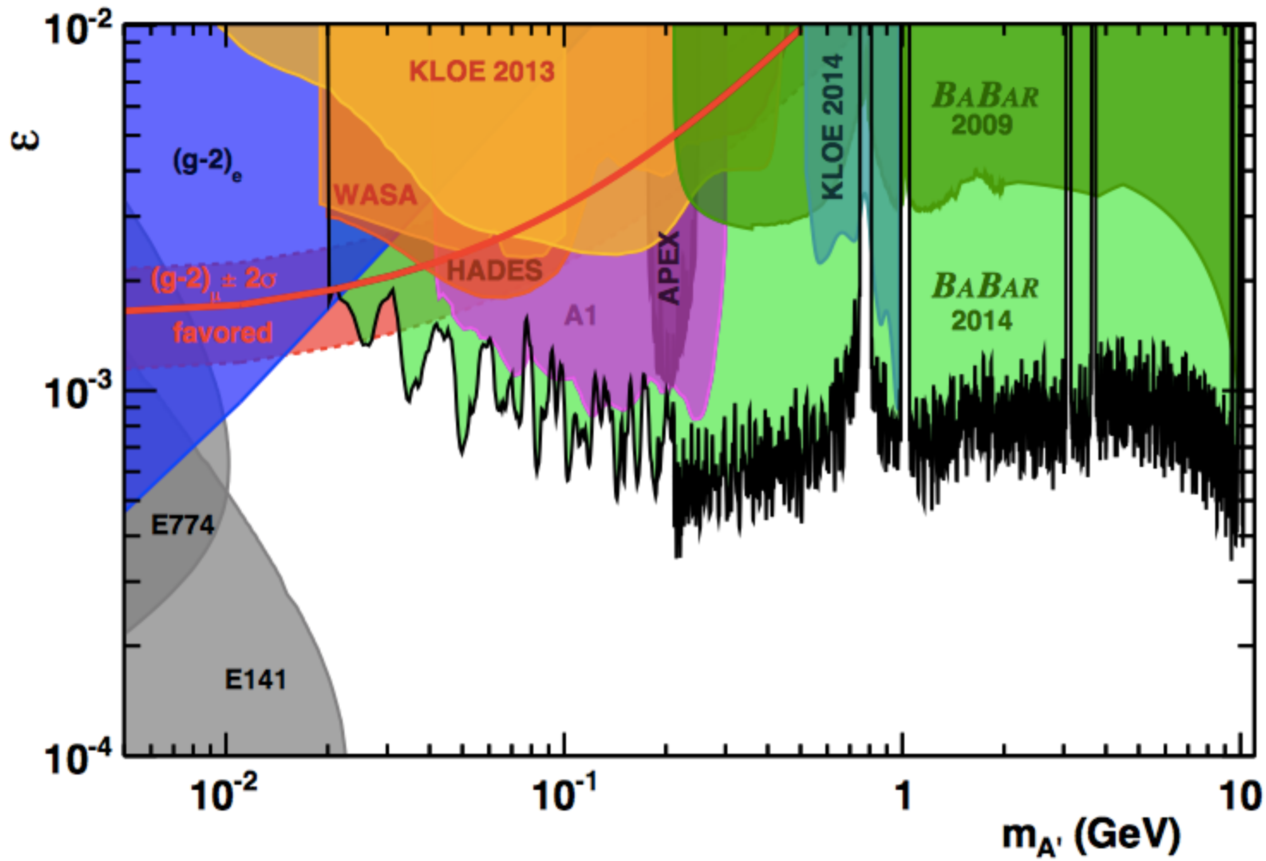


YG. Aditya, K. Healey, AAP

  - Can be seen as "missing energy" in particle decays (e.g. $J/\psi \to \gamma\gamma$+ME or $J/\psi \to$ ME+light quark meson(s))
  - … or in the lepton modes of V' decays into ee, etc.

Low-mass New Physics: "dark photons"

- BaBar recent search in $e^+e^- \rightarrow \gamma A', A' \rightarrow l^+l^- \ (l = e, \mu)$

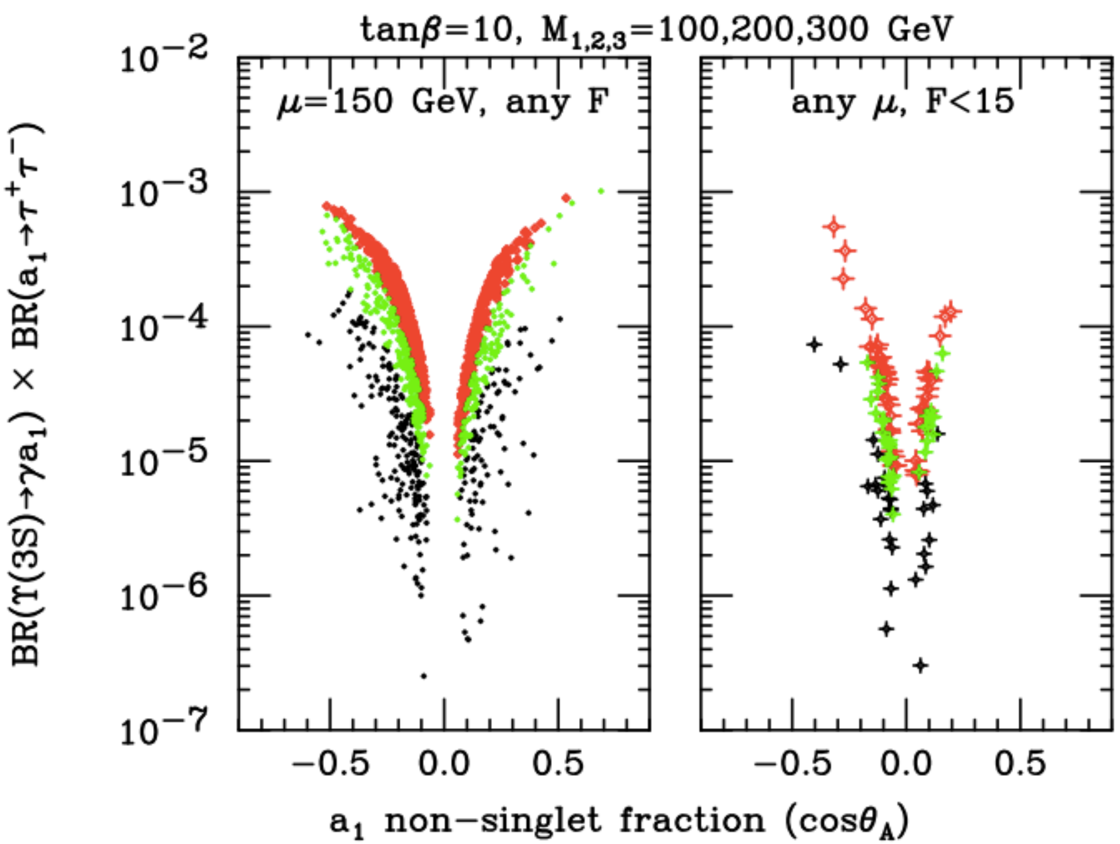


BaBar (2014)
PRL 113 (2014) 20, 201801

- can recast this search into search for low-mass BSM Higgs (m ~ several GeV)

Low-mass New Physics: pseudoscalar Higgs

- NMSSM: light scalar in $e^+e^- \to \gamma A', A' \to l^+l^-$ $(l = e, \mu)$



Dermisek, Gunion, McElrath (2007)

$2m_\tau < m_{a_1} < 7.5$ GeV

7.5 GeV $< m_{a_1} < 8.8$ GeV

8.8 GeV $< m_{a_1} < 9.2$ GeV

$$\mathcal{B}(\Upsilon(3S) \to \gamma A^0) \times \mathcal{B}(A^0 \to \tau^+\tau^-) < (1.5 - 16) \times 10^{-5} \text{ at 90\% C.L.}$$

R. Godang (QWG13)

Low-mass New Physics: "axion-like" states

- "Axion-like" states
  - Coupling similar to axion interactions (but can couple to leptons as well)

$$\mathcal{L}_a = -\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma_5\psi + \frac{C_\gamma}{f_a} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

  - … can be rewritten with

$$\mathcal{L}_a = -\left(\frac{1}{f_a} + \frac{4\pi C_\gamma}{f_a \alpha}\right)\partial_\mu a \bar{\psi}\gamma^\mu\gamma_5\psi - i m_\psi \left(\frac{8\pi C_\gamma}{f_a \alpha}\right) a \bar{\psi}\gamma_5\psi$$

- New constraints from $J/\psi \to \gamma\gamma$+ME or $J/\psi \to$ ME+light quark meson(s)?

Conclusions

- New Physics particles can be searched for in quarkonium decays
  - SM final states: heavy new physics
  - SM+NP final states: light NP particles
- Interesting reach for a variety of models
  - complimentarity to muon conversion experiments
  - complimentarity to searches for Dark Matter
- Possible observations of exotic modes
  - small decay branching ratios…
  - … but some models predict NP reach in the next round of experiments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May 17-23, 2015
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