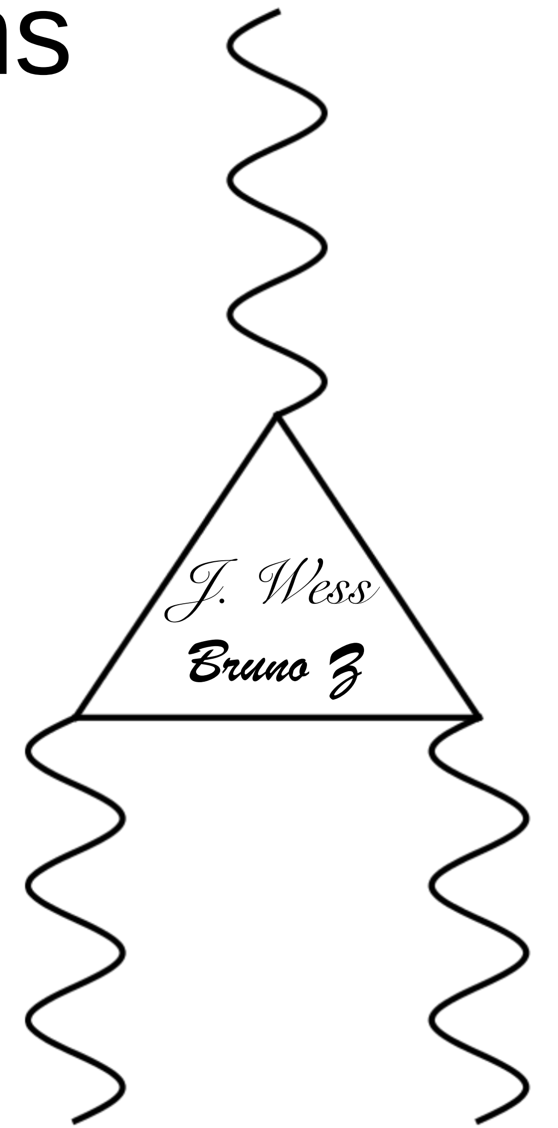
Signatures of New Anomalous Gauge Bosons



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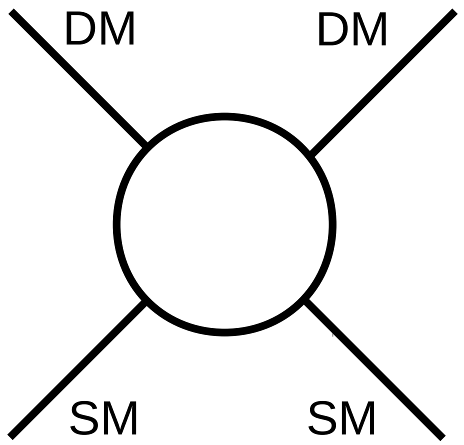
University of Pittsburgh

Mitchell Conference 2018

May 22, 2018

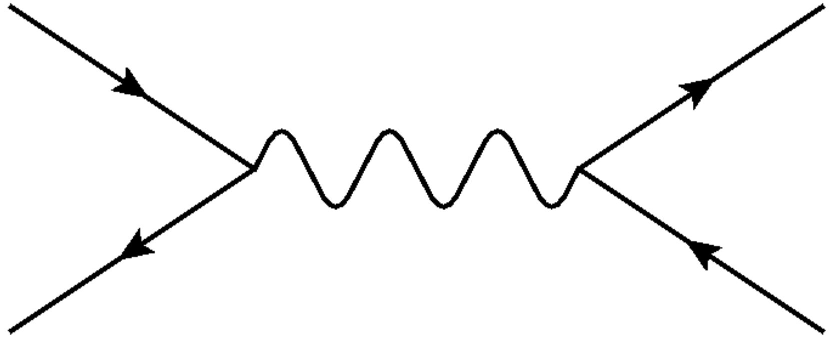
1707.00709, with A. Katz and D. Racco

Motivation: dark matter



~weak-scale masses and interactions reproduce the observed relic density

EFT operators with spin 0 (1) Lorentz structure suggest scalar (vector) mediators in UV completion

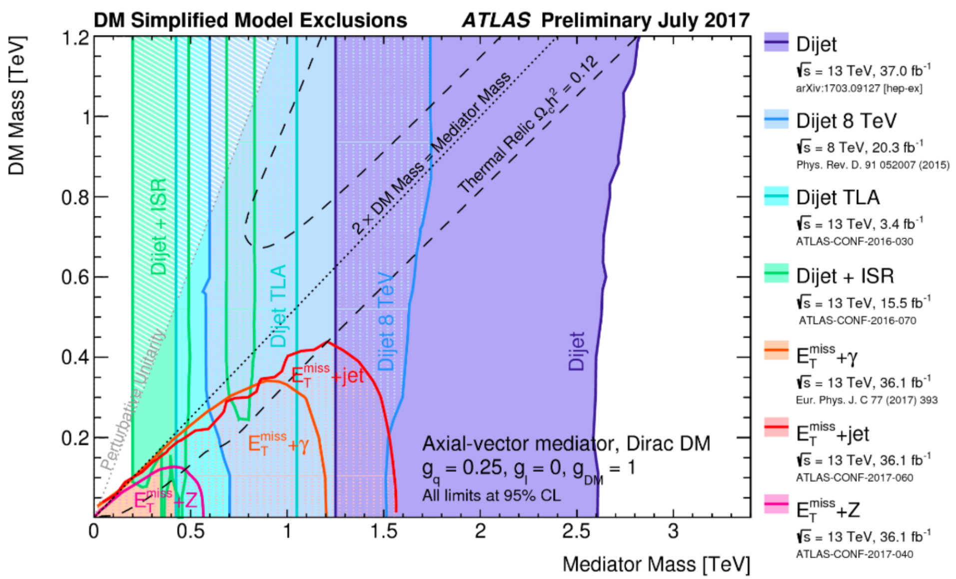


$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu(\gamma^5)\chi\bar{f}\gamma_\mu(\gamma^5)f$$

Goodman et al.
1005.1286, 1008.1783

Z' mediator $\leftrightarrow$ gauge boson of new group

Consistency of simplified models



Useful tool for comparing different experiments

What is required to complete these theories?

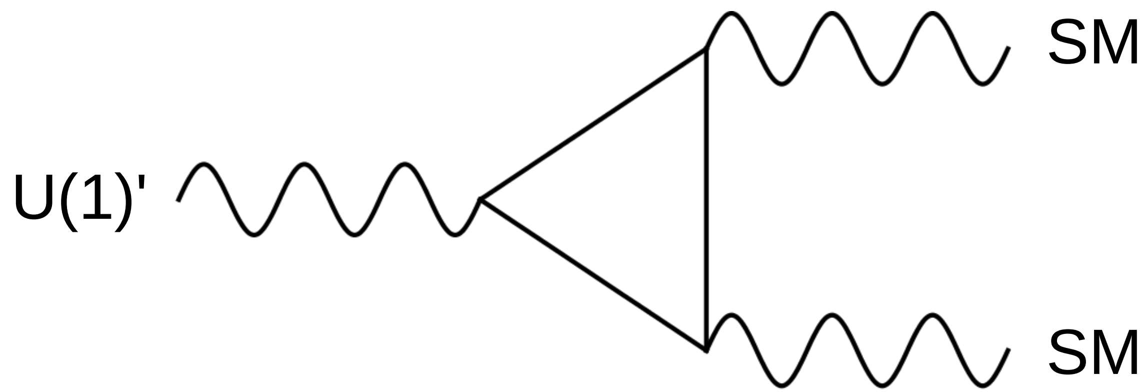
e.g. dark Higgs for Z' models (Kahlhoefer et al., 1510.02110)

e.g. extra scalars for pseudoscalar mediator (Goncalves, Machado, No 1611.05493)

Today: gauge anomaly considerations

Spin 1 mediators for dark matter

Chiral anomalies with weak interactions if SM is vector-like under U(1)', or EM/color otherwise



Exceptions: B – L, Y (Jacques et al., 1605.06513) or inter-generational

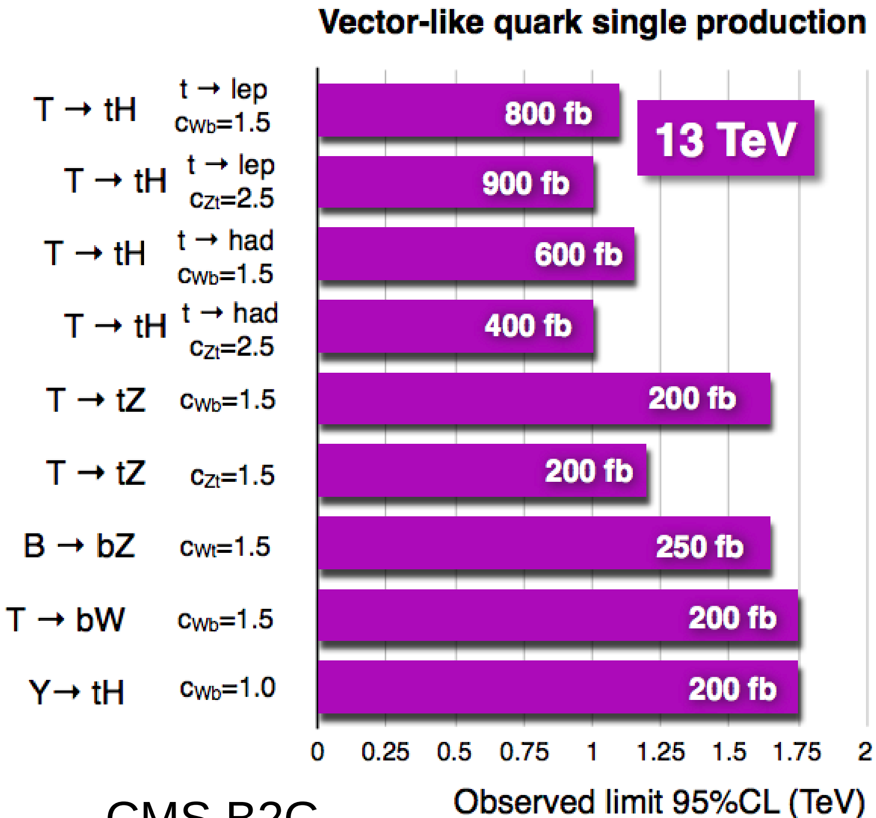
Implies new states charged under U(1)' and SM

New fermions can be heavy

Must be present to cancel anomalies
e.g. Al et al., 1609.02188

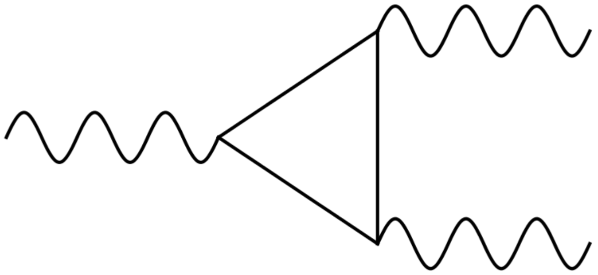
Should be vector-like under SM to avoid large Yukawas, strong constraints

Chiral under U(1)'



CMS B2G

Very massive fermions do not decouple in triangle diagrams

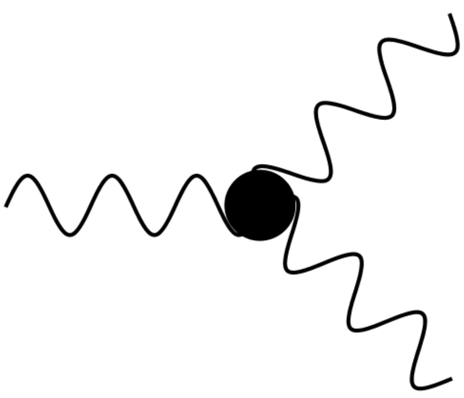


Effectively anomalous gauge theories

Below scale of heaviest fermions, U(1)' appears anomalous

Integrating out heavy fermions adds Wess-Zumino terms to action which parametrize the symmetry breaking but restore SM gauge invariance

$$\frac{g' g_w^2}{12\pi^2} \mathcal{A}^{Z'WW} \epsilon^{\mu\nu\rho\sigma} Z'_\mu \left(W^a_\nu \partial_\rho W^a_\sigma + \frac{1}{3} \epsilon^{abc} W^a_\nu W^b_\rho W^c_\sigma \right)$$



required by Wess-Zumino consistency condition

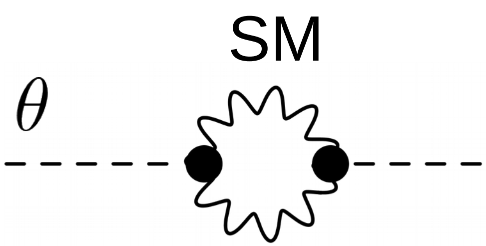
Effectively anomalous gauge theories

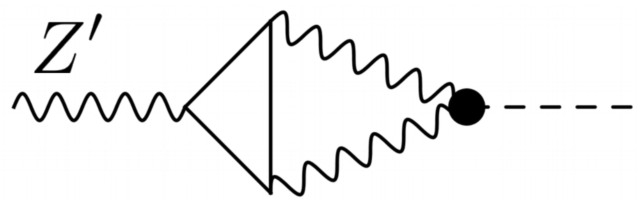
Under U(1)' transformation, action gets extra term

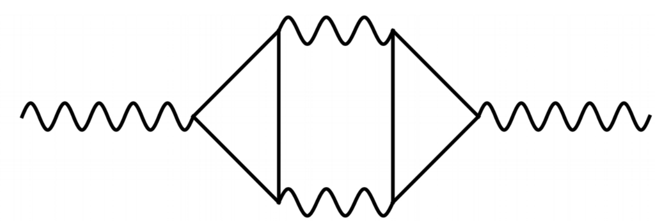
$$\Delta\mathcal{L} \propto W^{\mu\nu}\tilde{W}_{\mu\nu}$$

Can remove by introducing shift degree of freedom

$$\theta W^{\mu\nu}\tilde{W}_{\mu\nu}, \theta \to \theta + \epsilon$$







Leads to Stückelberg mass for Z', set by loop cutoff

$$M \lesssim \frac{64\pi^3 m_{Z'}}{g' g_w^2 \mathcal{A}^{Z'WW}}$$

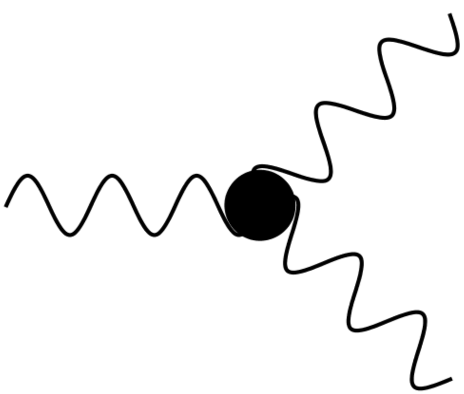
→ correspondence between Z' and anomaly-canceling fermion masses (Preskill, 1991)

Implications

Enhanced Z'VV couplings in resulting EFT

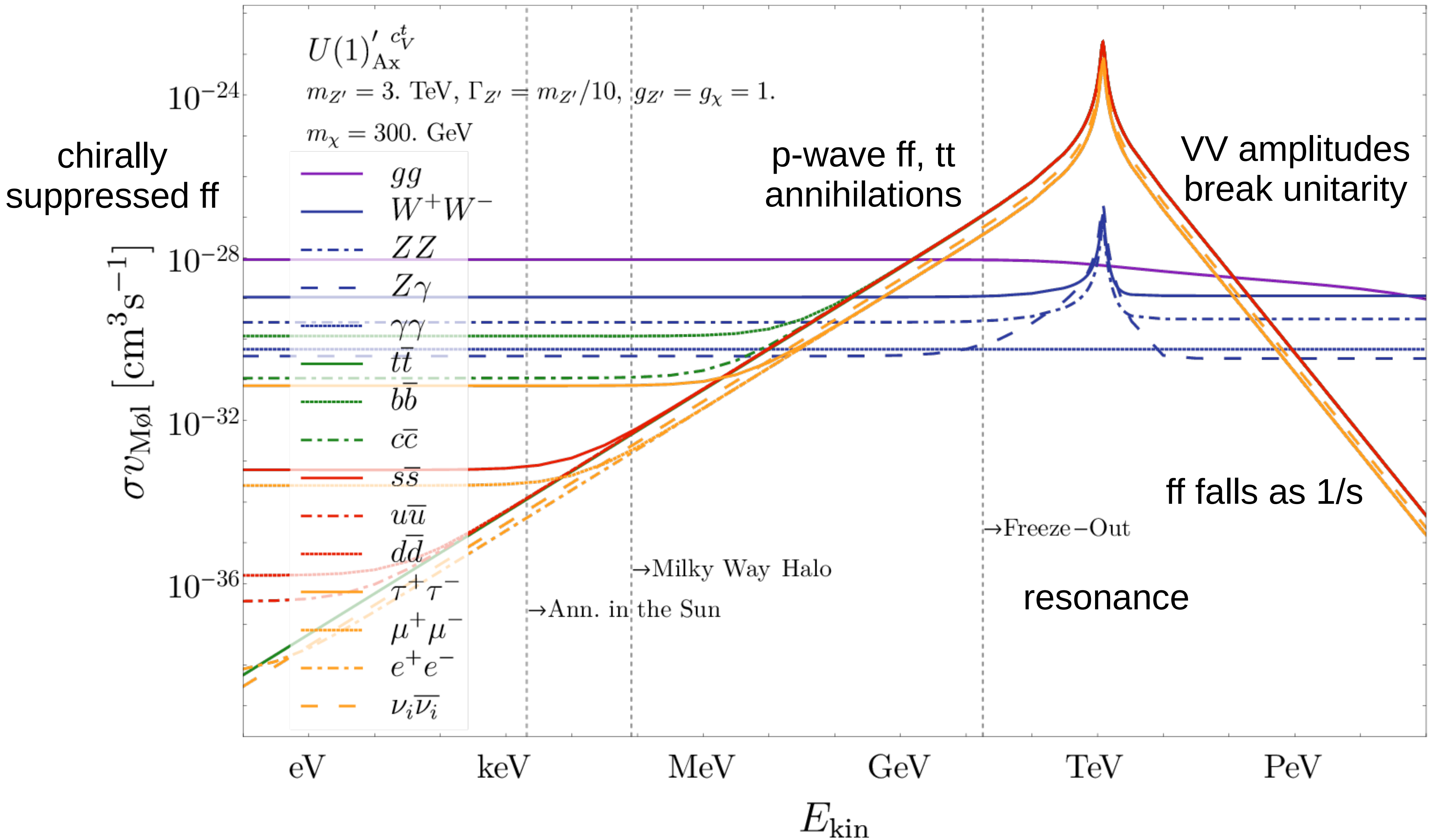
Dimension 5 axion-like terms cut off by Z' mass scale

e.g. for large DM mass, annihilation to VV can be significant

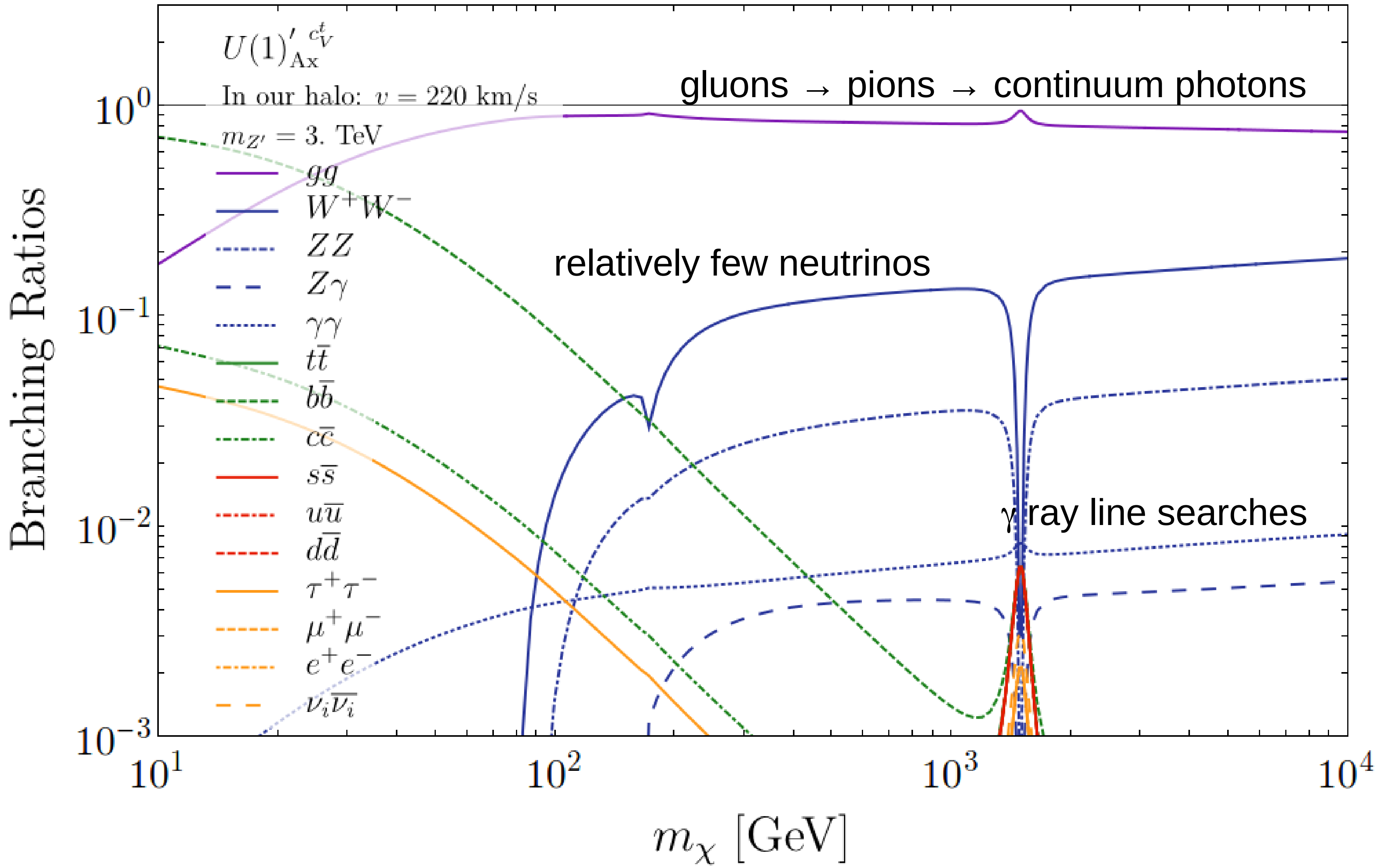


Still have to pay loop factor, but gain power of momentum

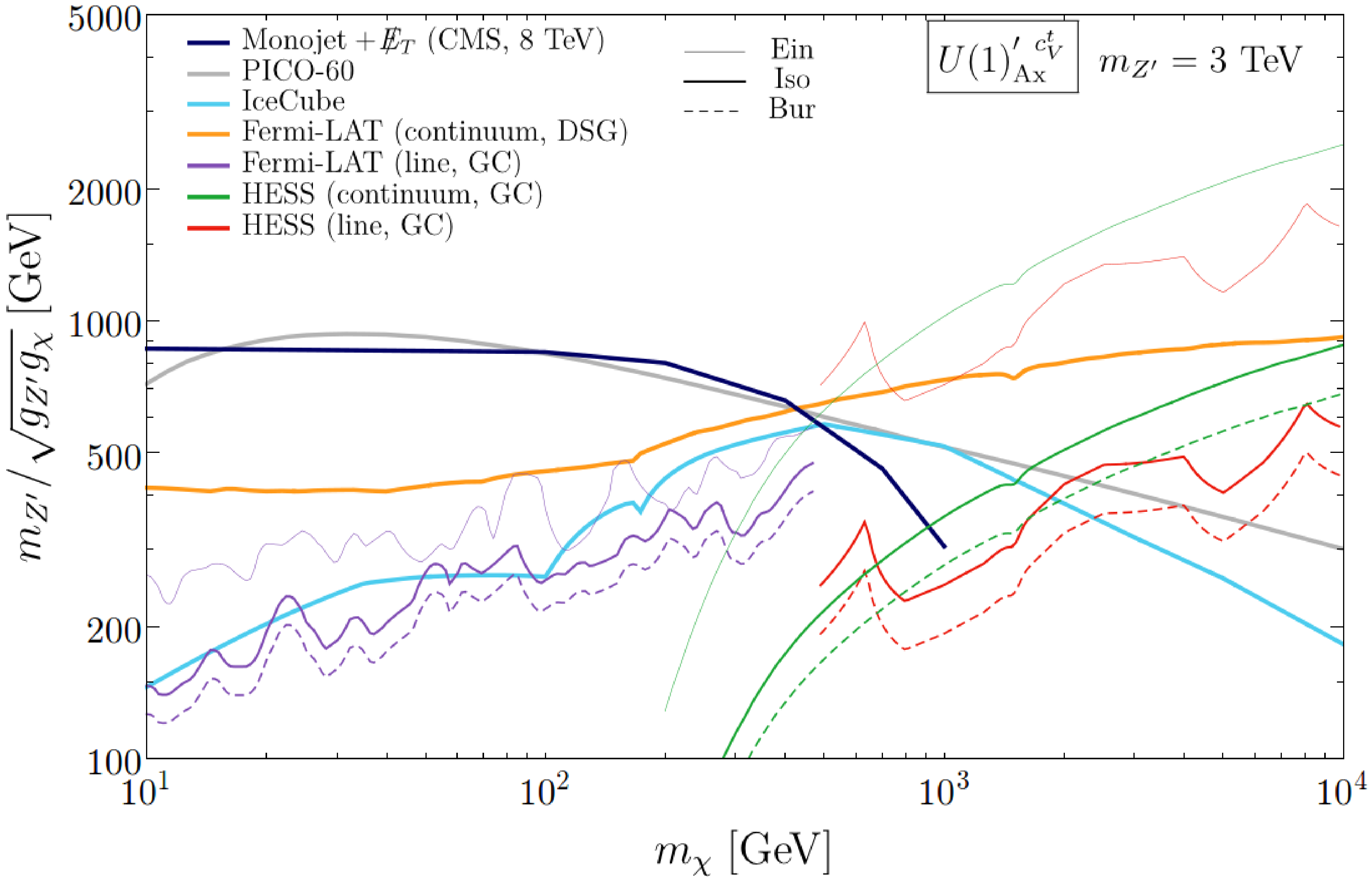
DM annihilation, mostly axial couplings



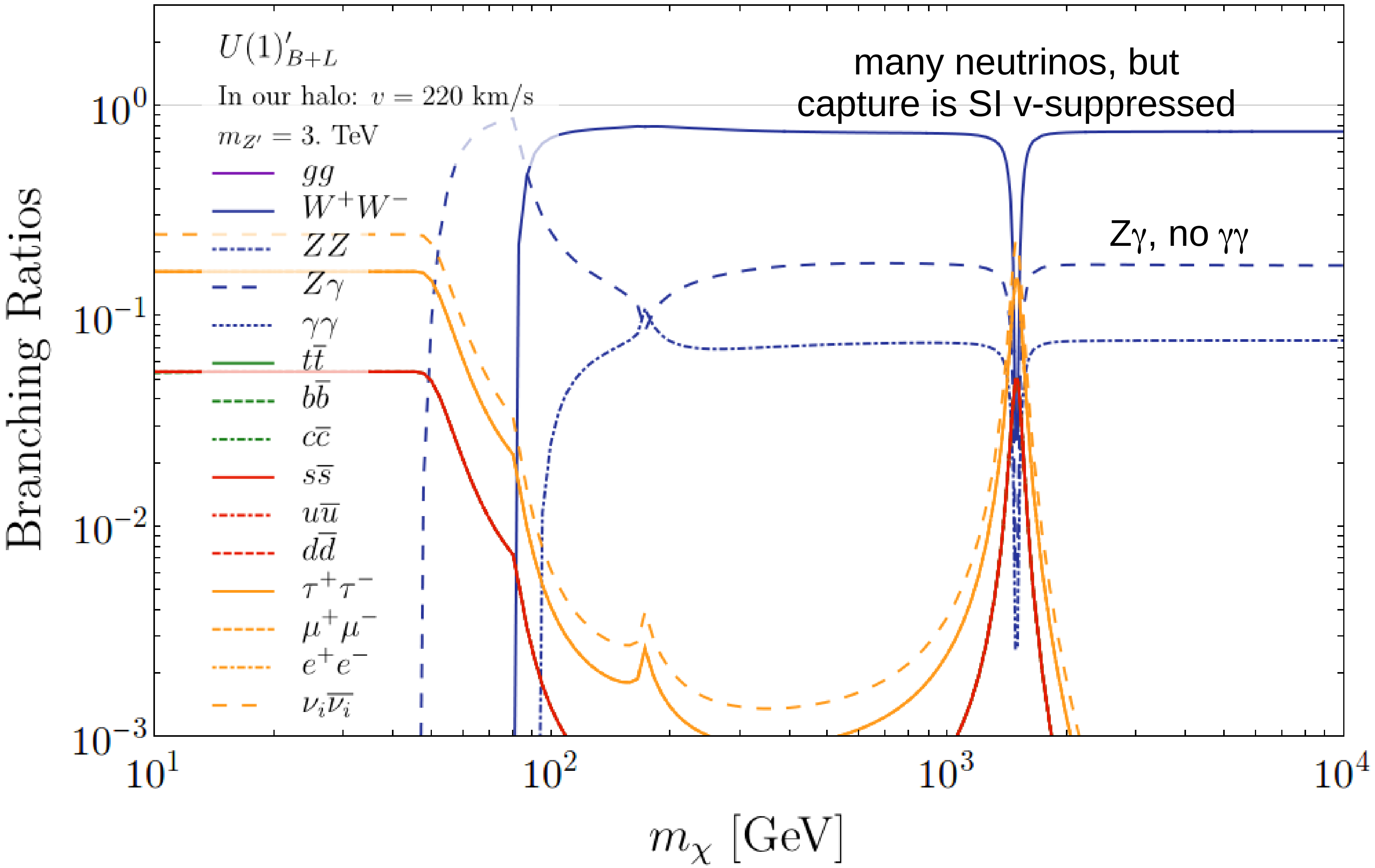
Indirect detection: Z'GG present



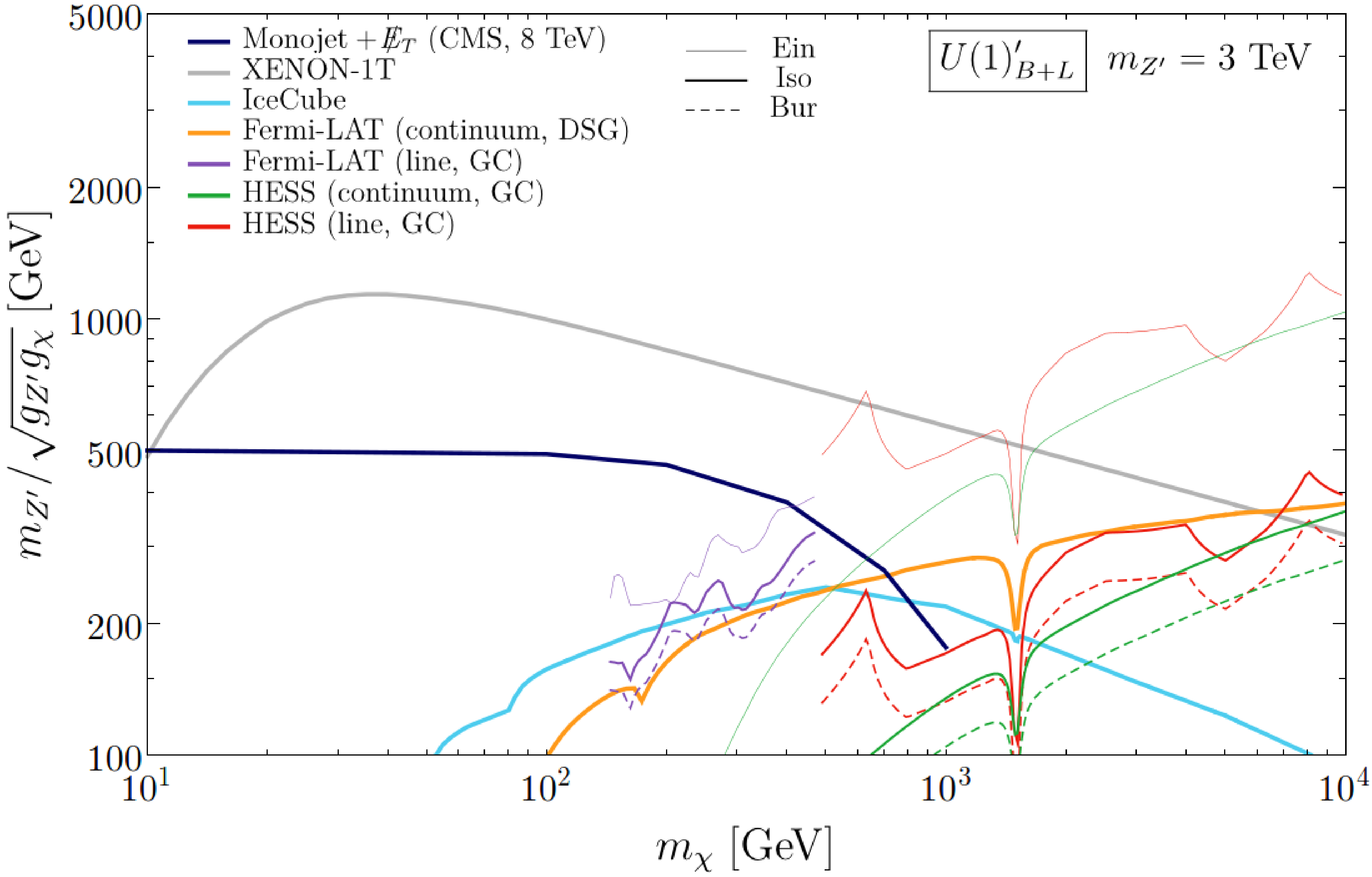
Indirect detection best at high masses



Indirect detection: vectorial U(1)'



Vectorial U(1)': DD usually wins if present



Summary

Most spin-1 DM simplified models are anomalous

Mandatory Wess-Zumino terms couple Z' to pairs of SM bosons, with strength proportional to momentum

A vectorial Z' has anomalies with WW, and any other Z' couples to GG and/or BB

Depending on the coupling structure, these can modify phenomenology, particularly indirect detection

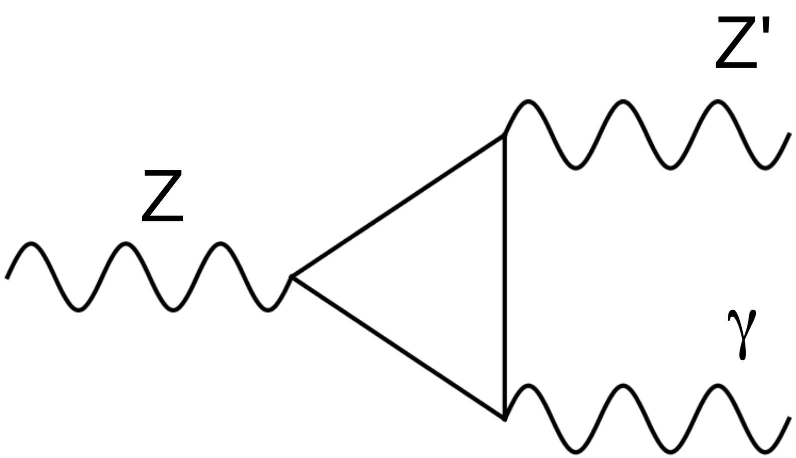
Backup

Other uses of anomalies: light Z' probes

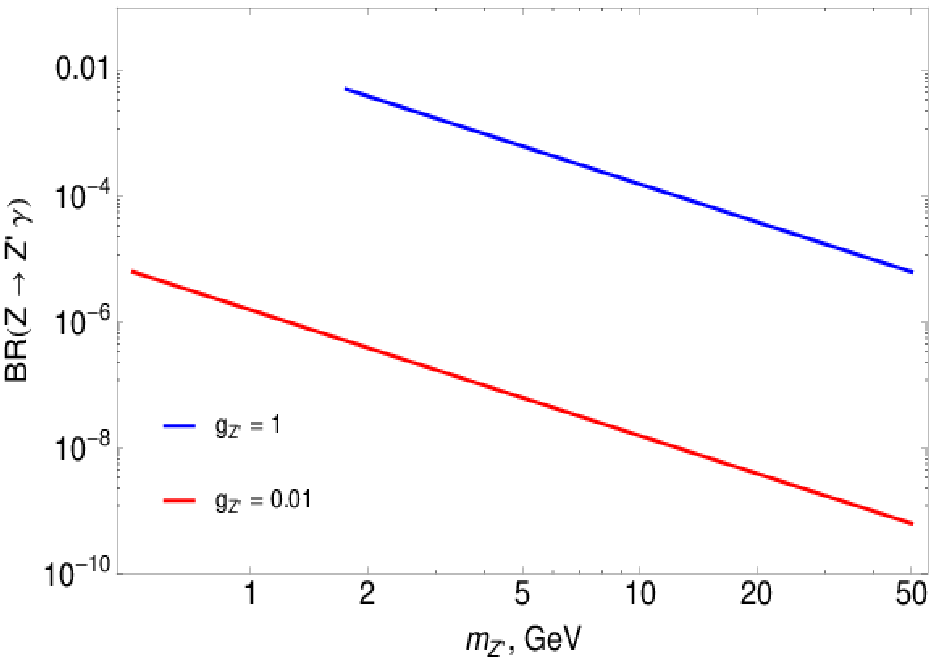
If kinematically accessible and anomaly exists, can look for Z' in rare Z decays at colliders

$$Z \to Z' \gamma$$

13 TeV LHC Z production is ~60 nb



1712.01840, AI and A. Katz



Weak LHC limits if no direct coupling to quarks

Z' coupling to leptons

Lepton separation in Z decay is characteristic of Z' mass scale

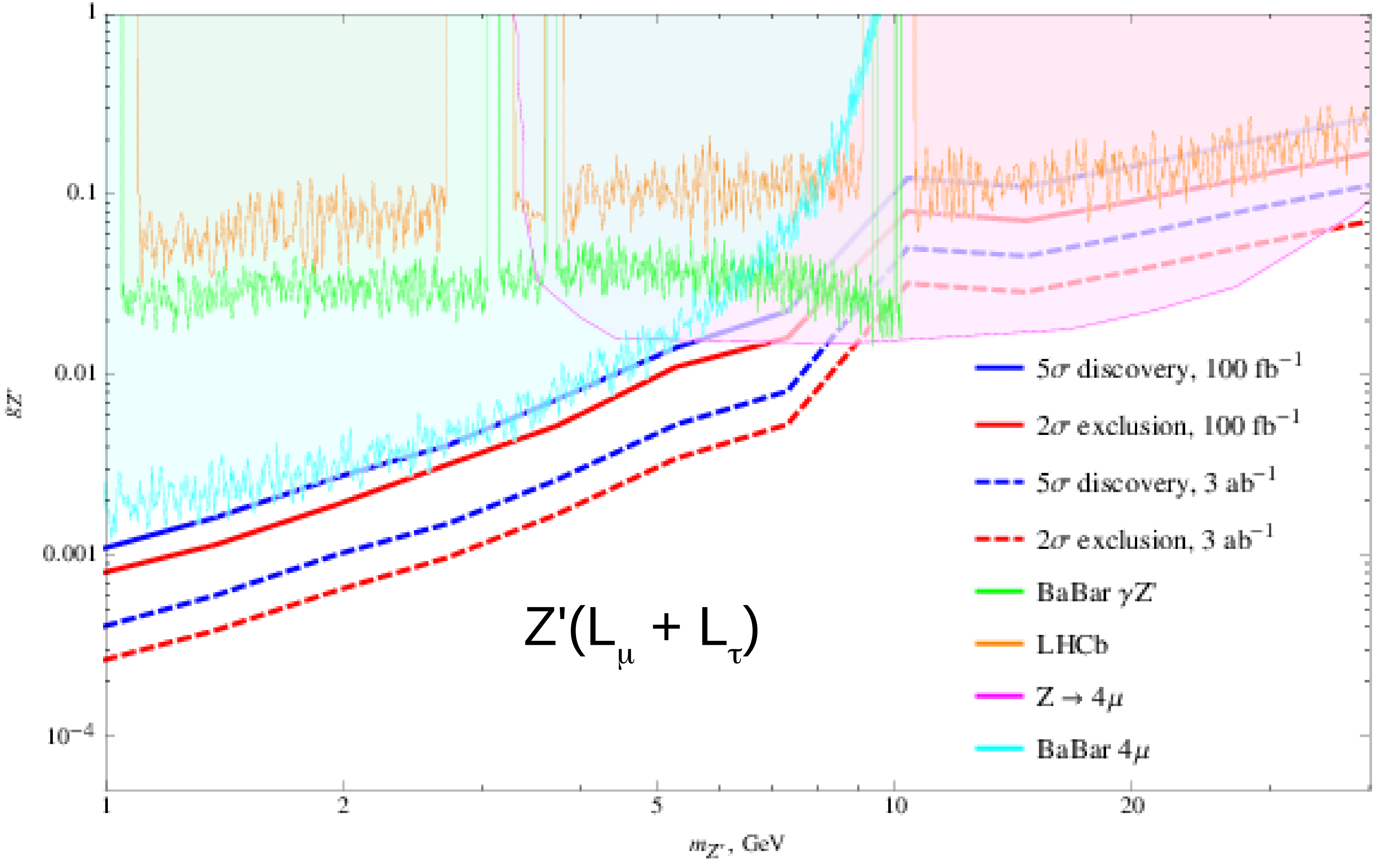
$$\Delta R(\ell,\ell) \sim 2m_{\ell\ell}/p_T \sim 4\frac{m_Z m_{Z'}}{m_Z^2 - m_{Z'}^2}$$

Photon monochromatic in Z rest frame

→ Kinematics significantly different from radiative Z decay background

For Z' lighter than 10 GeV, leptons nearly overlap, motivating lepton-jet search

Most useful for Z' not coupling to electrons



Summary: collider probes

Large Z production cross section at LHC enables study of rare anomaly-mediated decays

Limits complement other searches for new light gauge bosons, especially without 1^{st} generation couplings

<u>Other models, low mass</u>

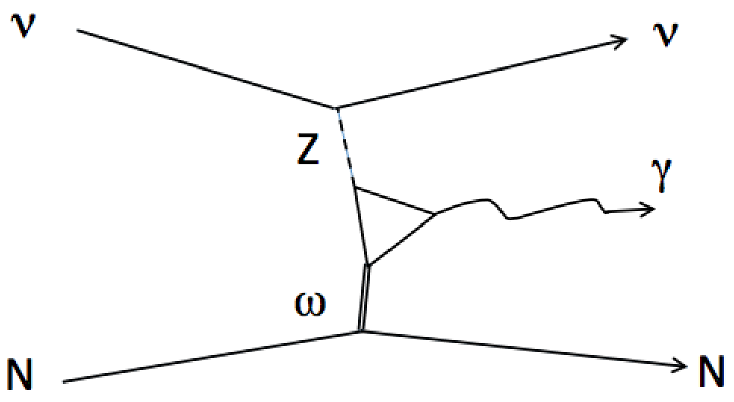
Quark couplings give rare meson decays

Even lighter masses: astro cooling limits

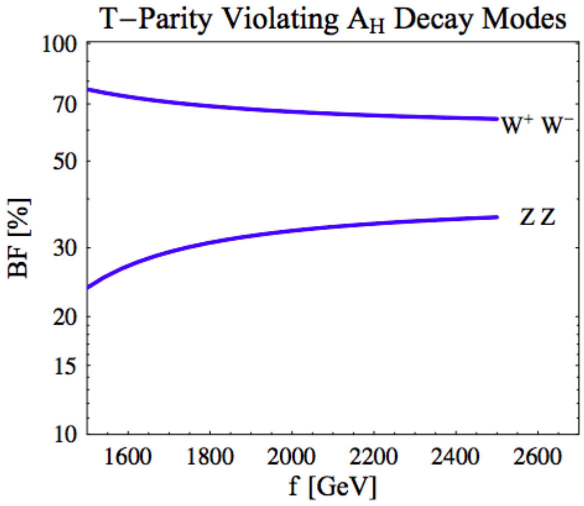
More applications

SM: decoupling top spoils anomaly cancellation and gives Wess-Zumino terms (d'Hoker and Farhi, 1984)

Chiral QCD: ω meson is a $U(1)_B$ vector, inducing photons at MiniBooNE (Harvey, Hill and Hill, 2007)



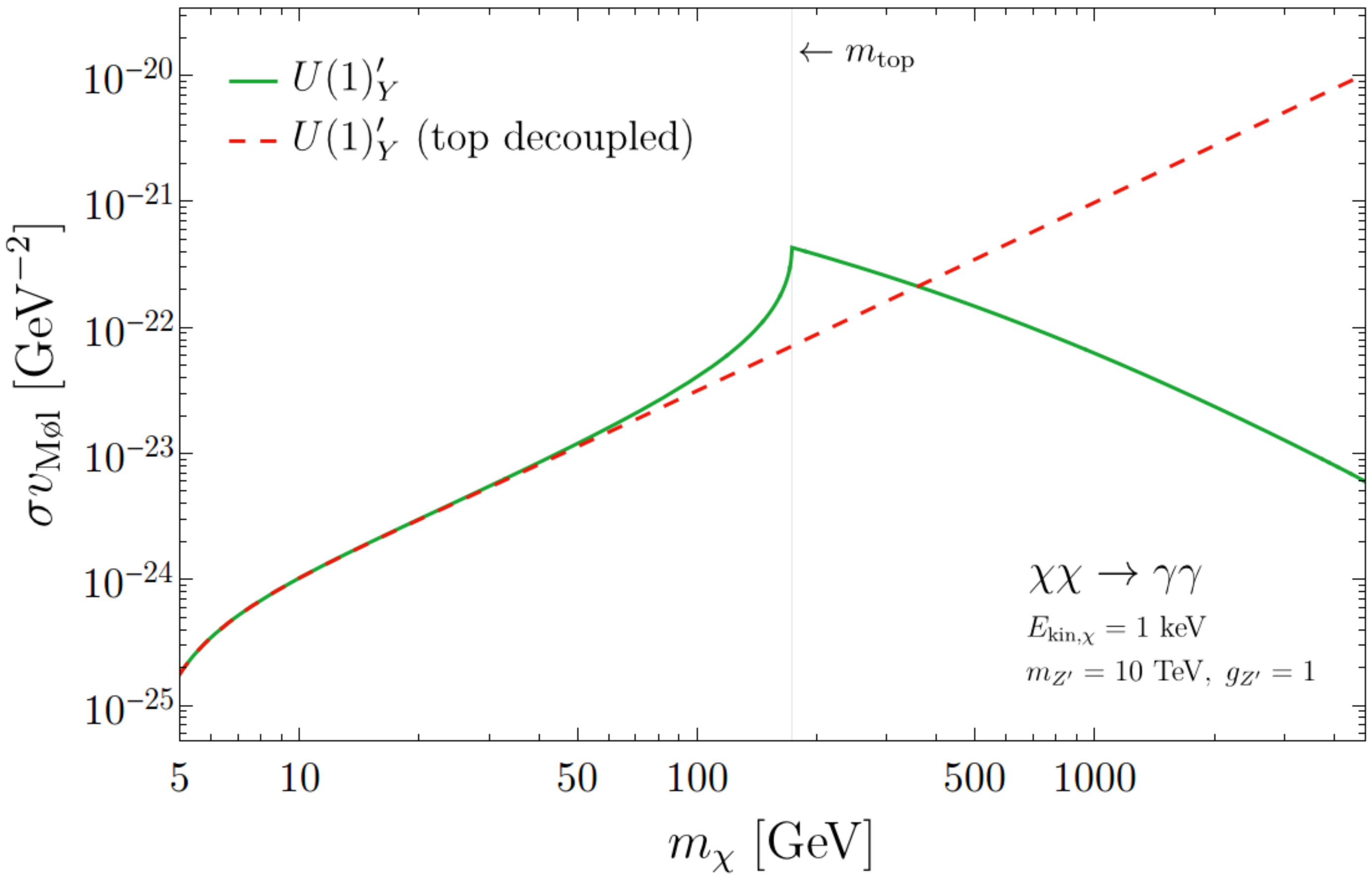
Katori and Conrad, 1404.7759



Barger, Gao and Keung, 0707.3648

Little Higgs: some constructions violate T-parity through Wess-Zumino terms (Hill and Hill, 2007)

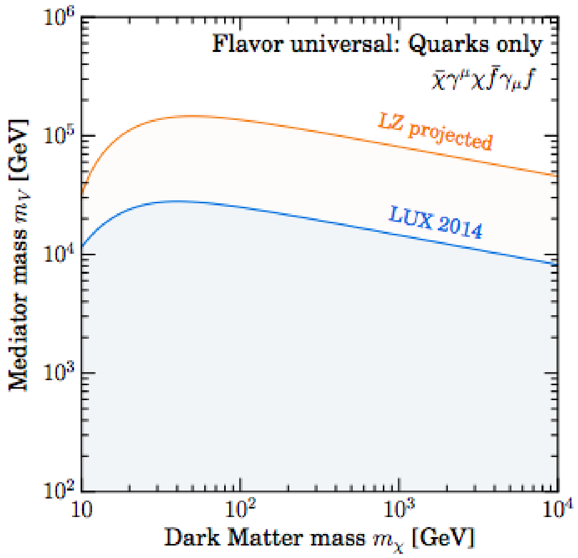
How heavy to be integrated out?



Wess-Zumino term clearly visible at energies a few times below heavy fermion mass, scales as E / m(Z')

Vector vs. axial vector couplings

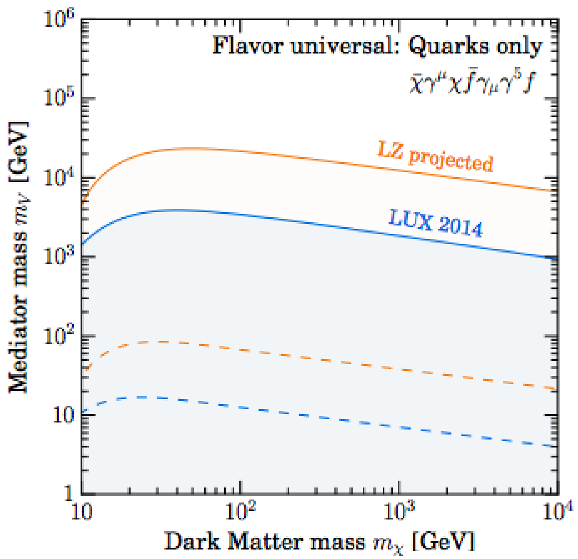
DM side: vector coupling leads to strong direct detection constraints



SM side: axial U(1)' charge breaks usual mass terms

$$H^c\bar{Q}U, H\bar{Q}D$$

Can get around with more complicated scalar sector (AI, Keung, Tsao, Unwin, 1609.02188)



D'Eramo, Kavanagh, Panci 1605.04917

Vector vs. axial vector couplings

DM: choose Majorana DM → vector coupling vanishes, direct detection cross section is spin-dependent and/or velocity-suppressed

Majorana mass forbidden for unbroken gauge group, but usual mass generated from U(1)' scalar vev

$$\langle \Phi \rangle \bar{\chi} \chi$$

Fermion mixing can change effective Z' couplings such that SM and DM charges are different

Vector vs. axial vector couplings

SM (1): allow fermions to couple axially, but require top to couple vectorially to Z', avoiding issue of generating large Yukawa

$$\left(\frac{\langle\Phi\rangle}{\Lambda}\right)^{2n} H\bar{f}f, n = [f]/[\Phi]$$

flavor violation in RH up quark sector, can be constrained by meson mixing but model-dependent

SM(2): couple all fermions vectorially, e.g. B and/or L

→ no anomalies with color (or hypercharge), but Z'WW triangle remains

DM annihilation to fermions

$$\sigma(\chi\chi \to f\bar{f}) = \frac{g_\chi^2 g_{Z'}^4\, N_c^f}{3\pi s\big((s-m_{Z'}^2)^2 + \Gamma_{Z'}^2 m_{Z'}^2\big)} \sqrt{\frac{s-4m_f^2}{s-4m_\chi^2}} \Bigg(g_V^2 (s - 4m_\chi^2)(s + 2m_f^2)$$

$$+ \; g_A^2 \Bigg(s(s-4m_\chi^2) + 4m_f^2 \bigg(m_\chi^2 \bigg(7 - 6\frac{s}{m_{Z'}^2} + 3\frac{s^2}{m_{Z'}^4} \bigg) - s \bigg) \Bigg) \Bigg) \, .$$

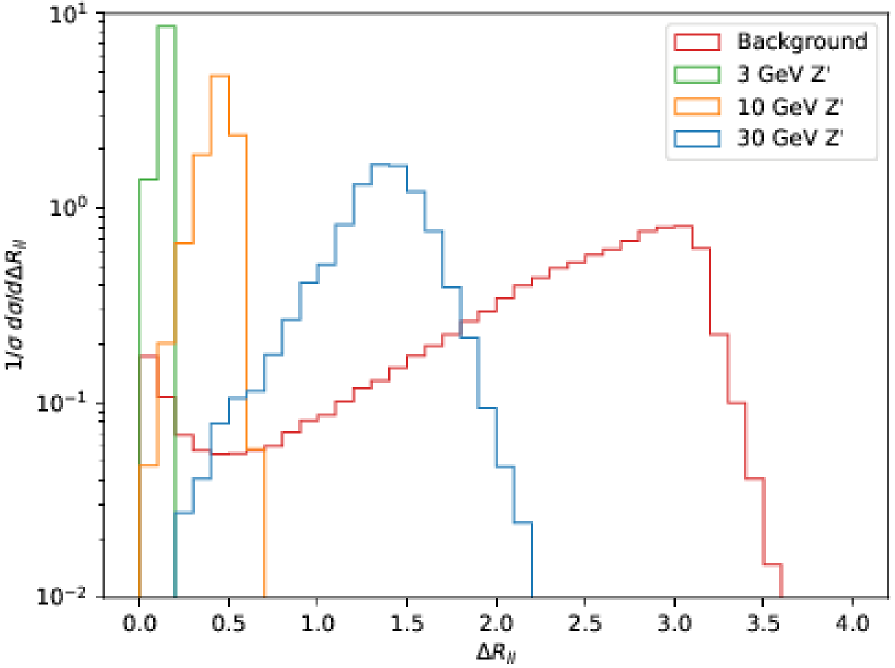
chirally suppressed s-wave

Conventional search

Look for $Z \rightarrow l^+ l^- \gamma$

Put upper cut on separation between leptons, and lower cut on lepton-photon separation

Perform bump hunt in dilepton mass distribution, assuming 2 GeV resolution

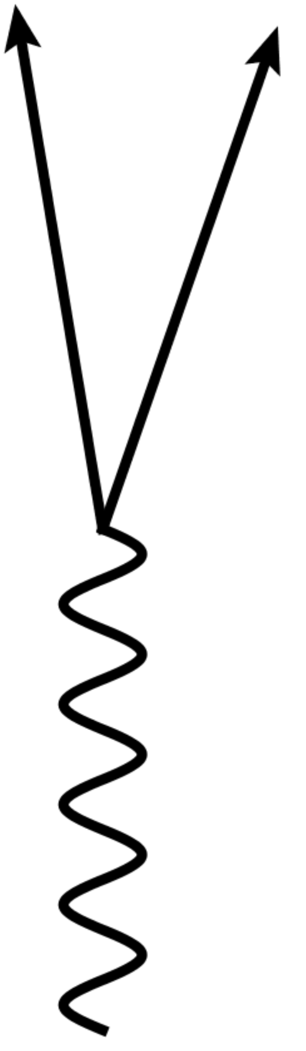


Prompt lepton-jet search

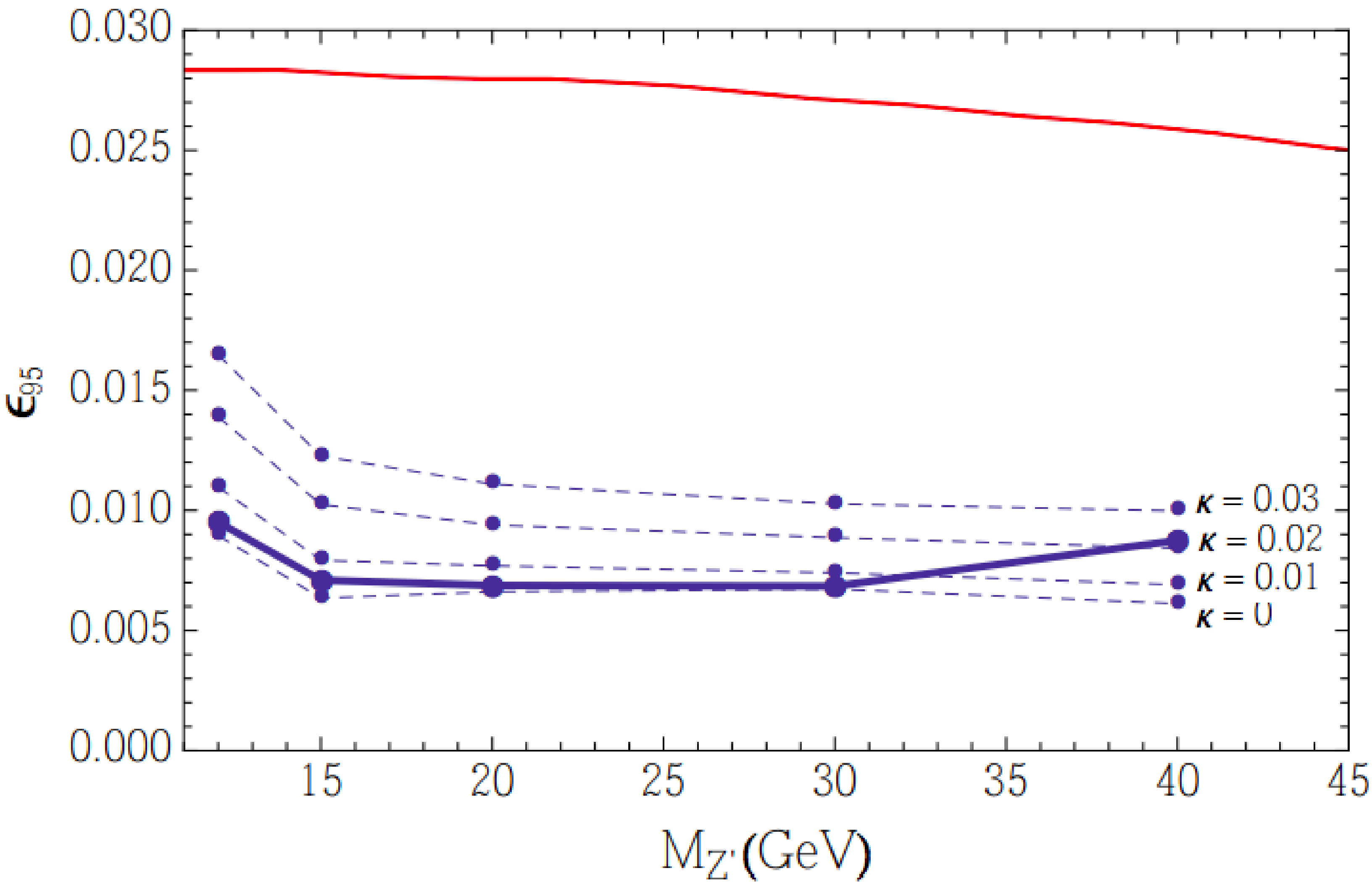
Look for two muons within $\Delta R < 0.5$ of each other

Require nearly opposite photon such that total mass reconstructs Z

20 MeV bins in dilepton mass, look for resonance



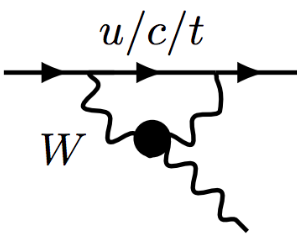
Dilepton Z' searches, 8 TeV estimate



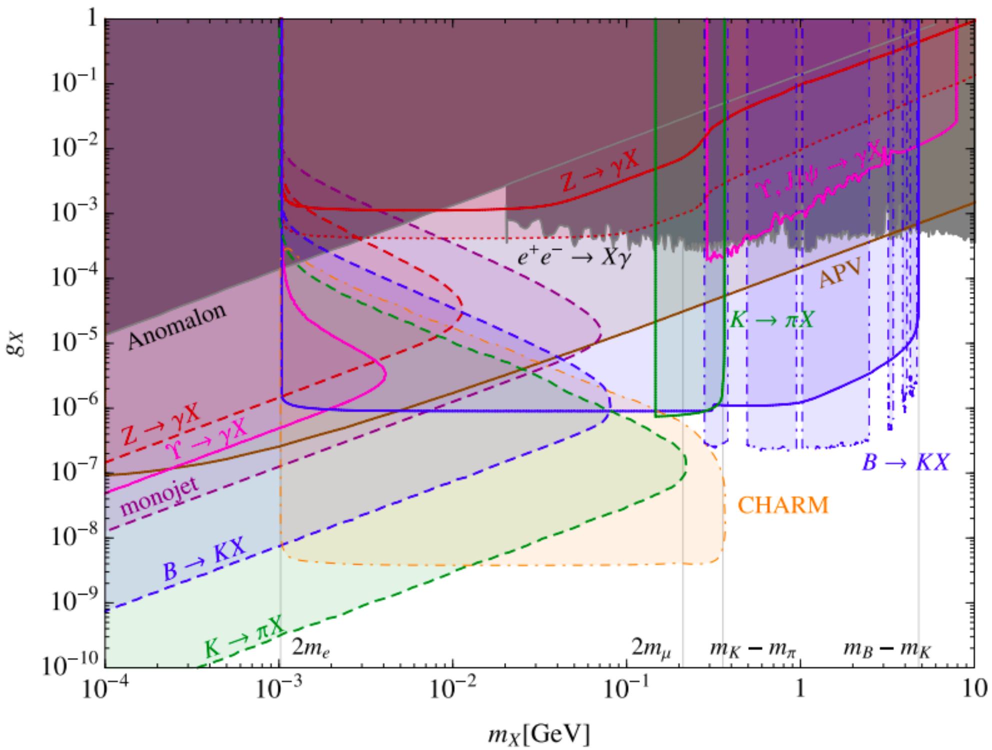
Hoenig, Samack, Tucker-Smith 1408.1075

Other bounds on a light Z'

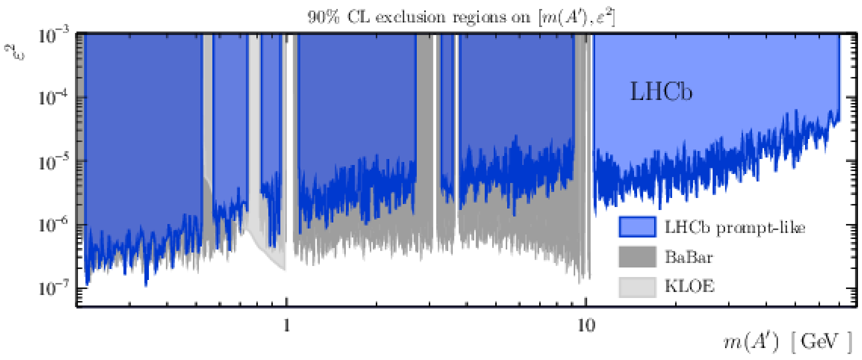
right-handed Z'



Dror, Lasenby, Pospelov
1707.01503



Most other channels use fermion couplings



LHCb, 1710.02867

Best limits on dark photons above 10 GeV

Rare Z decays depend only on anomaly and leptonic decay mode