Signatures of Non-minimal Dark Matter

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Non-minimal model-indirect detection

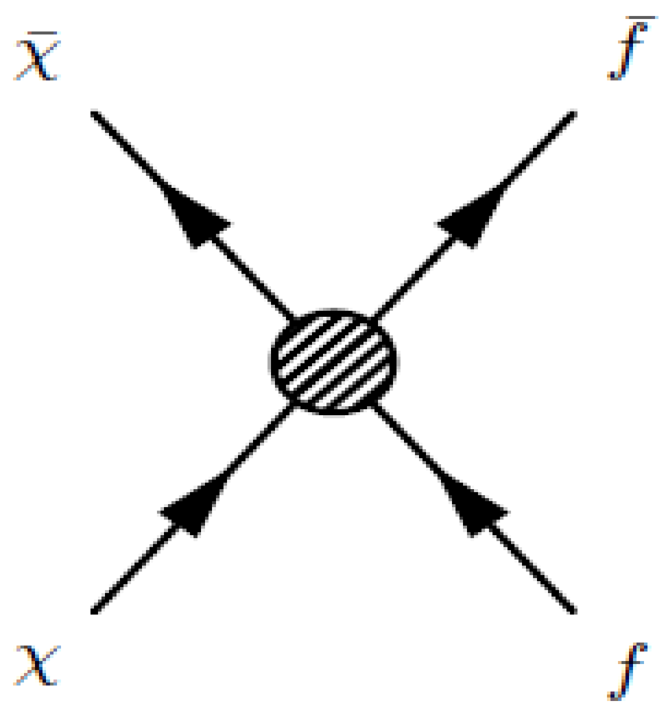
Unbiased theoretical justification requires less than simplified model.

- One DM candidate?(Dark Sector)
- Single Mediator?
- Single SM Final State For Process?

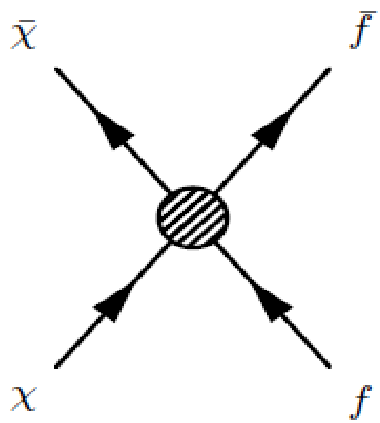
Fermion Portal

Simplest EFT model: 1 operator 1 channel

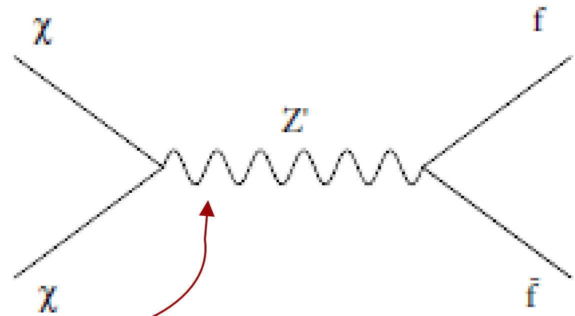
$$\mathcal{L}_{\mathrm{f}} = \frac{\kappa_t}{\Lambda_t^2}\chi\Gamma\overline{\chi}t\Gamma\overline{t} + \frac{\kappa_b}{\Lambda_b^2}\chi\Gamma\overline{\chi}b\Gamma\overline{b} + \frac{\kappa_\tau}{\Lambda_\tau^2}\chi\Gamma\overline{\chi}\tau\Gamma\overline{\tau} \text{ -}$$



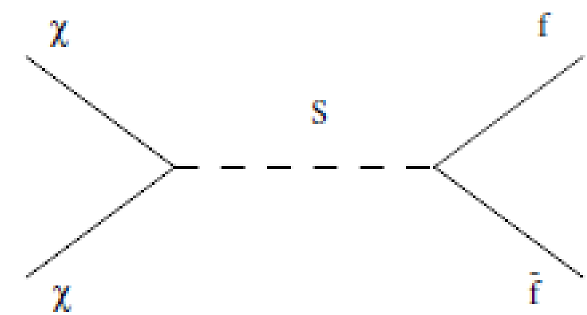
EFT to Simplified Model



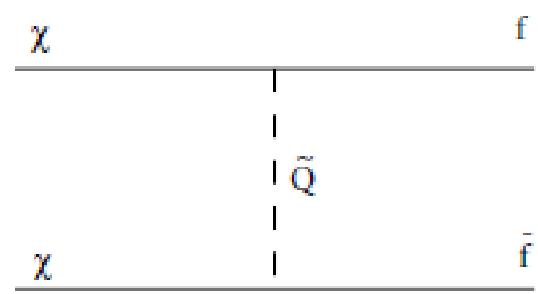
S channel vector



S channel scalar



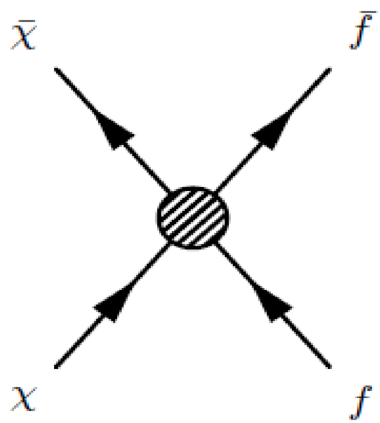
t channel scalar: 'fake SUSY'



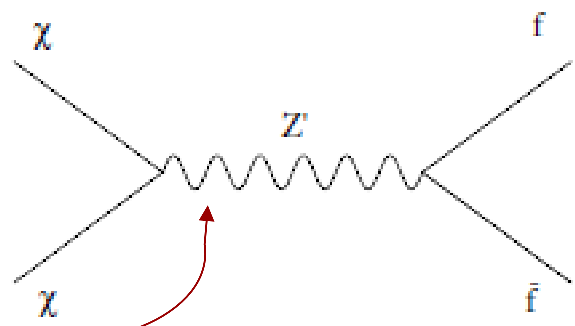
$$\mathcal{L} = V_\mu \bar\chi \gamma^\mu (g^V_\chi - g^A_\chi \gamma^5)\chi + \sum_f V_\mu \bar f \gamma^\mu (g^V_f - g^A_f \gamma^5) f$$

$$\mathcal{L} = \sum_i g_i \phi_i^* \bar\chi P_R f_i + h.c.,$$

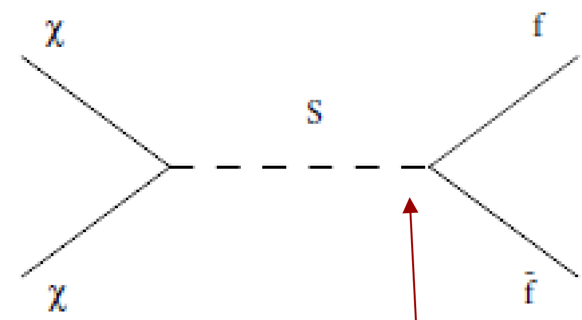
EFT to Simplified Model



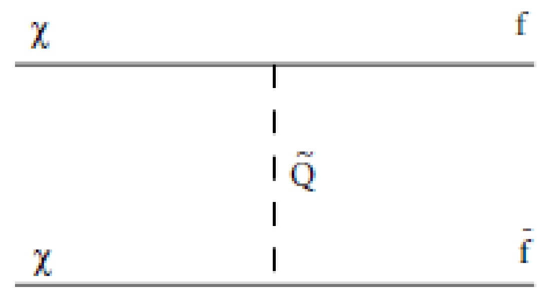
S channel vector



S channel scalar



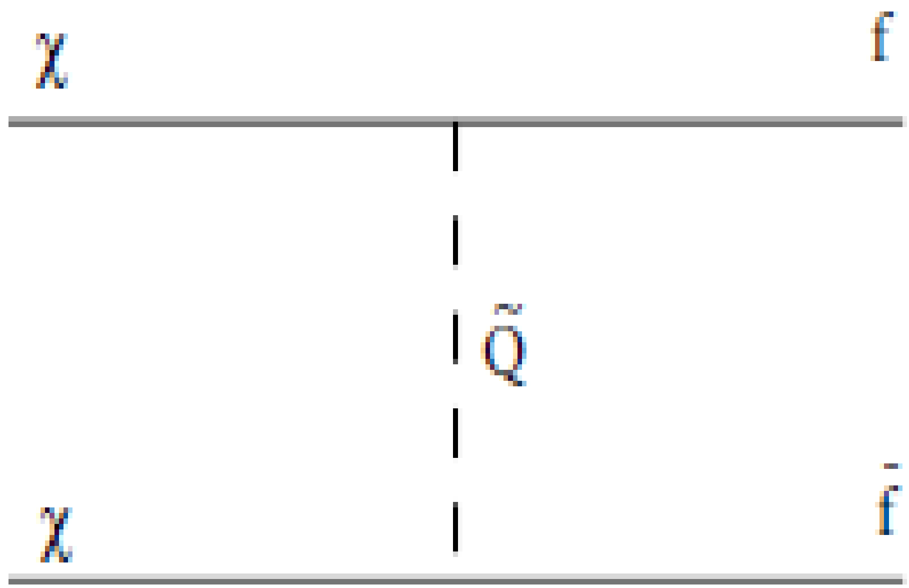
t channel scalar: 'fake SUSY'



Gauge invariance?

Supersymmetry

Chiral
Symmetry
Breaking



Minimal gauge mediation implies equality of squark or slepton masses.

Fermi Dwarf Analysis

Dwarf Spheroidal Galaxies large amount of DM

Low Astrophysical Background

photon flux

$$\Phi_\gamma = \frac{1}{4\pi} \sum_f \frac{\langle \sigma v \rangle_f}{2m_\chi^2} \int_{E_{\min}}^{E_{\max}} \left(\frac{dN_\gamma}{dE_\gamma} \right)_f dE_\gamma J.$$

averaged annihilation xsec

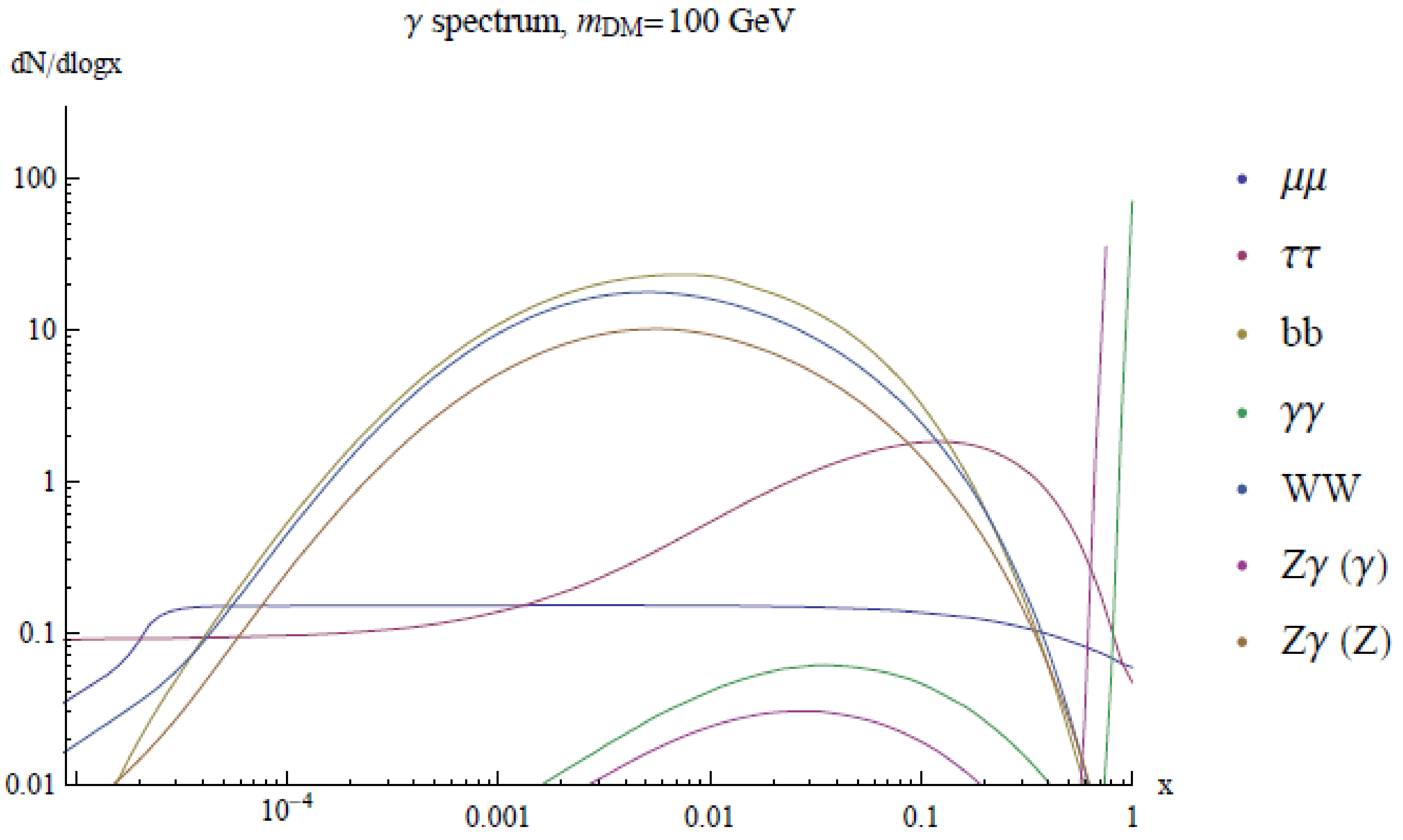
DM mass

Photon energy spectrum

Line of sight integral of DM density

$$J = \int_{\Delta\Omega} \int_{l.o.s} \rho^2(\mathbf{r}) dl d\Omega'.$$

Spectrum

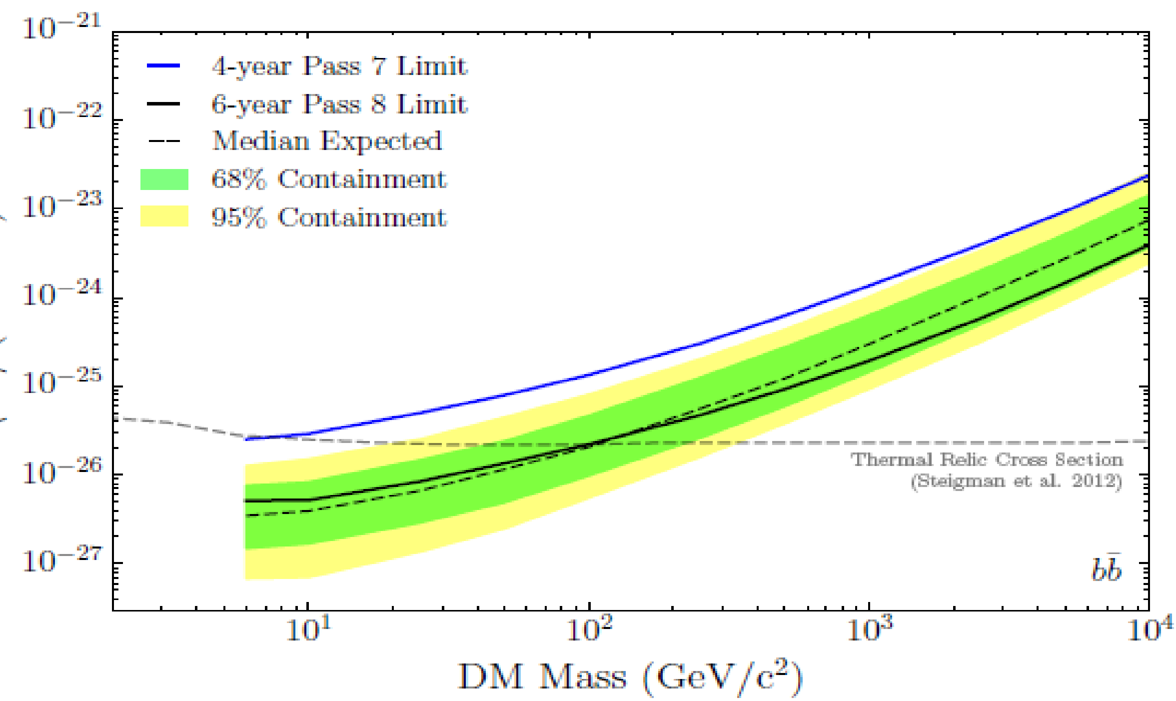


DM annihilates to various SM final states each with a characteristic photon spectrum

Fermi Analysis combine 15 dwarf's with largest J factors, set 95% c.l. upper bound assuming 100% annihilation into a single channel,e.g. b's

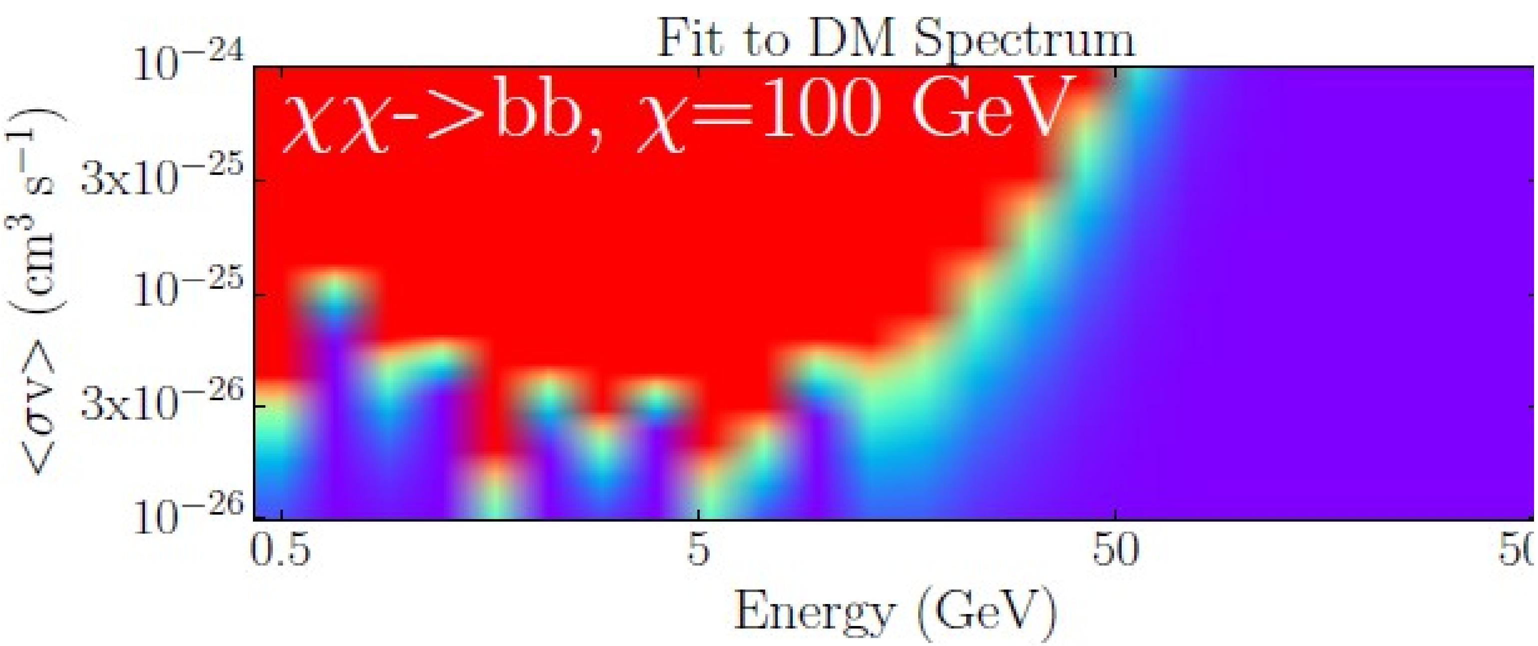
TABLE I. Properties of Milky Way dSphs.

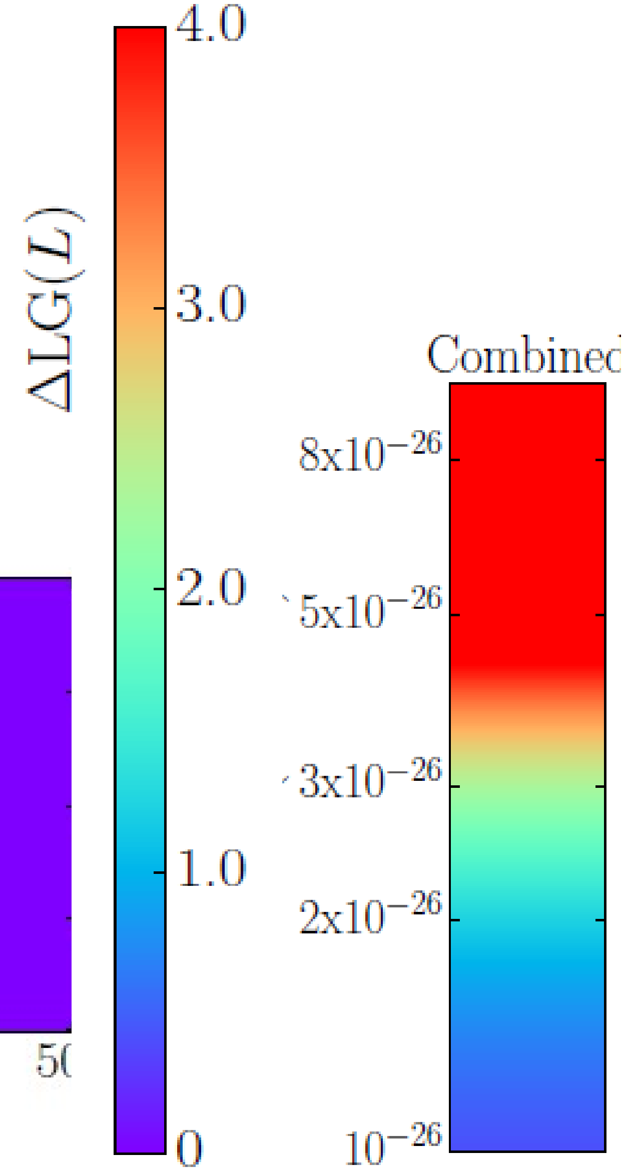
Name	ℓ^a (deg)	b^a (deg)	Distance (kpc)	$\log_{10}(J_{obs})^b$ $(\log_{10}[\text{GeV}^2\,\text{cm}^{-5}])$
Bootes I	358.1	69.6	66	18.8 ± 0.22
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25
Carina	260.1	−22.2	105	18.1 ± 0.23
Coma Berenices	241.9	83.6	44	19.0 ± 0.25
Draco	86.4	34.7	76	18.8 ± 0.16
Fornax	237.1	−65.7	147	18.2 ± 0.21
Hercules	28.7	36.9	132	18.1 ± 0.25
Leo II	220.2	67.2	233	17.6 ± 0.18
Leo IV	265.4	56.5	154	17.9 ± 0.28
Sculptor	287.5	−83.2	86	18.6 ± 0.18
Segue 1	220.5	50.4	23	19.5 ± 0.29
Sextans	243.5	42.3	86	18.4 ± 0.27
Ursa Major II	152.5	37.4	32	19.3 ± 0.28
Ursa Minor	105.0	44.8	76	18.8 ± 0.19
Willman 1	158.6	56.8	38	19.1 ± 0.31
Bootes II [c]	353.7	68.9	42	–
Bootes III	35.4	75.4	47	–
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26
Canis Major	240.0	−8.0	7	–
Leo I	226.0	49.1	254	17.7 ± 0.18
Leo V	261.9	58.5	178	–
Pisces II	79.2	−47.1	182	–
Sagittarius	5.6	−14.2	26	–
Segue 2	149.4	−38.1	35	–
Ursa Major I	159.4	54.4	97	18.3 ± 0.24



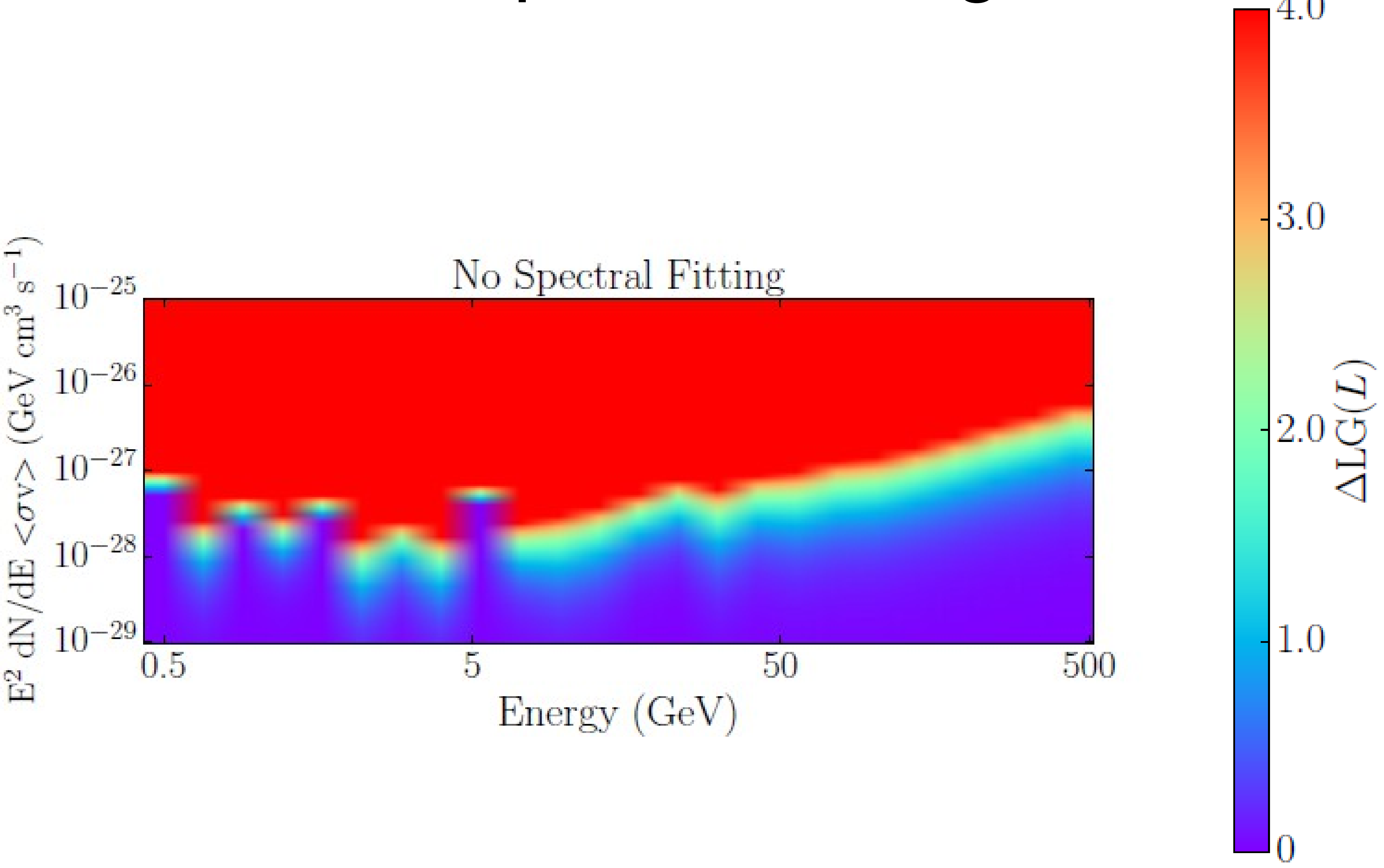
ArXiv:1503.02641

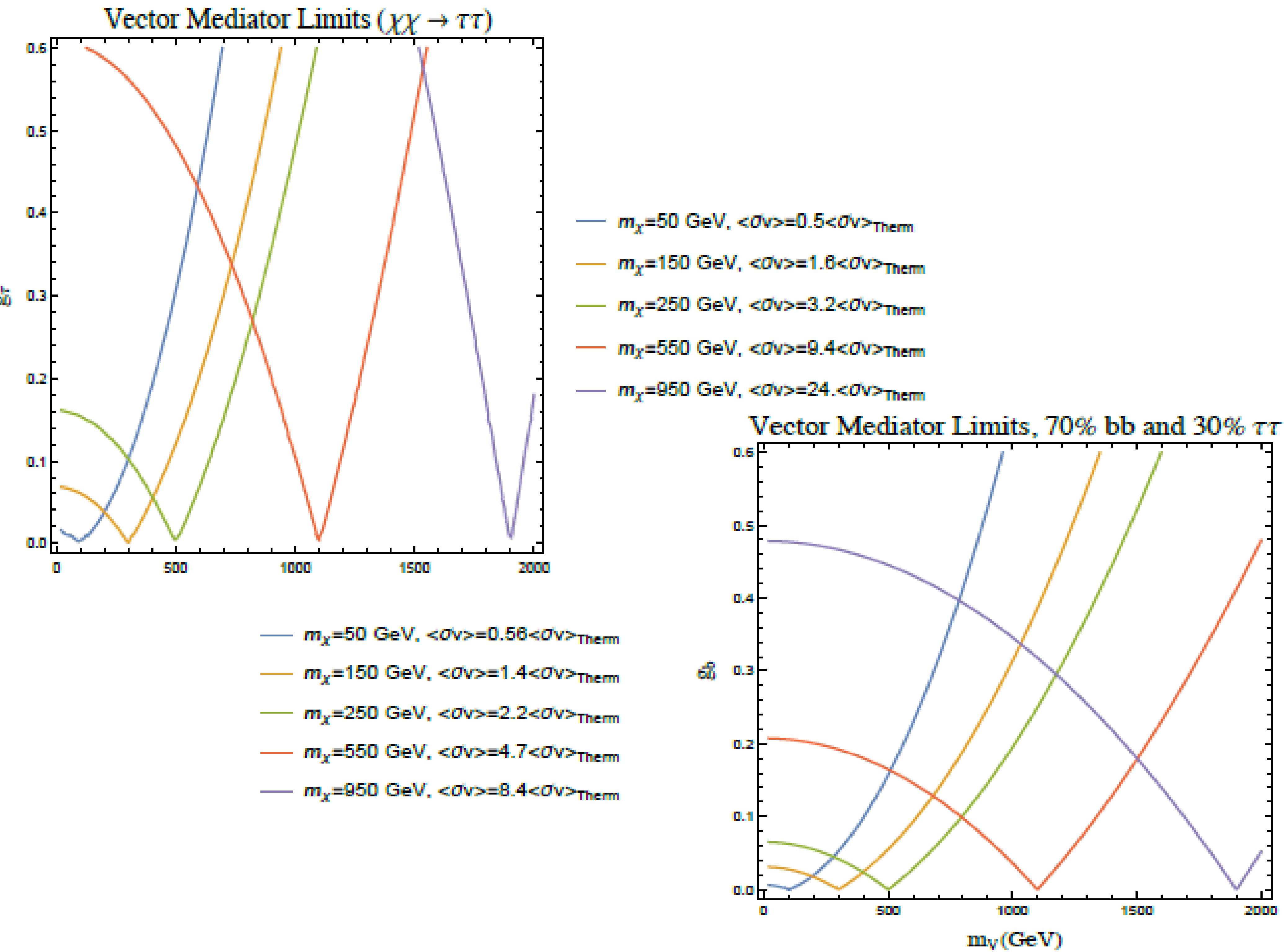
- Choose DM mass and annihilation channel
- Allow J factor to float with Least Log Likelihood cost $\Delta\mathrm{LG}(\mathcal{L}) = (\mathrm{J}_{bf} - \mathrm{J}_{meas})^2 \,/\, (2\sigma_J^2)$
- Compare to null hypothesis no DM to set limit on upper bound of annihilation xsec in each bin with 95%~ LLL 2.71/2
- Infer combined xsec limit



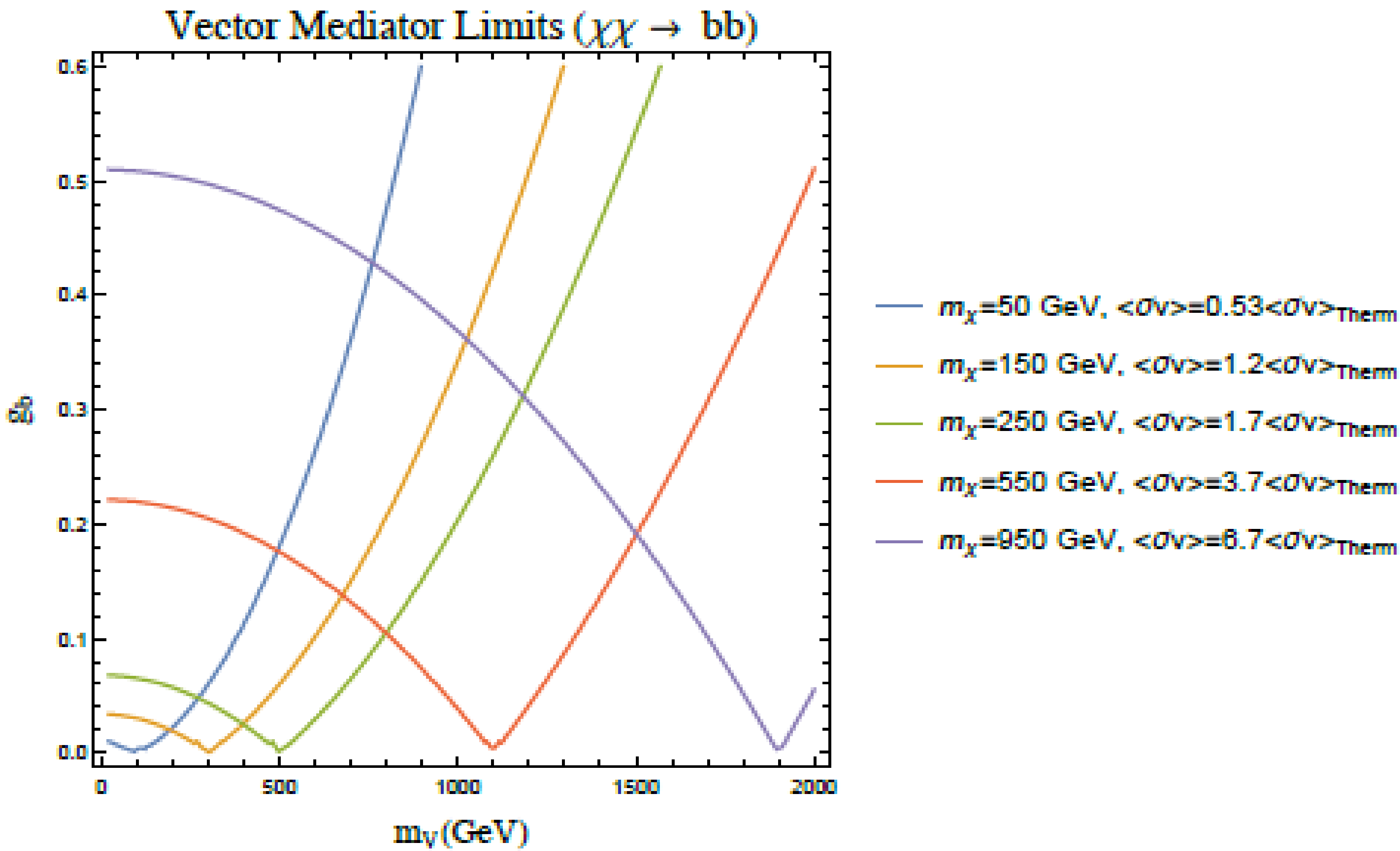


No spectral Fitting





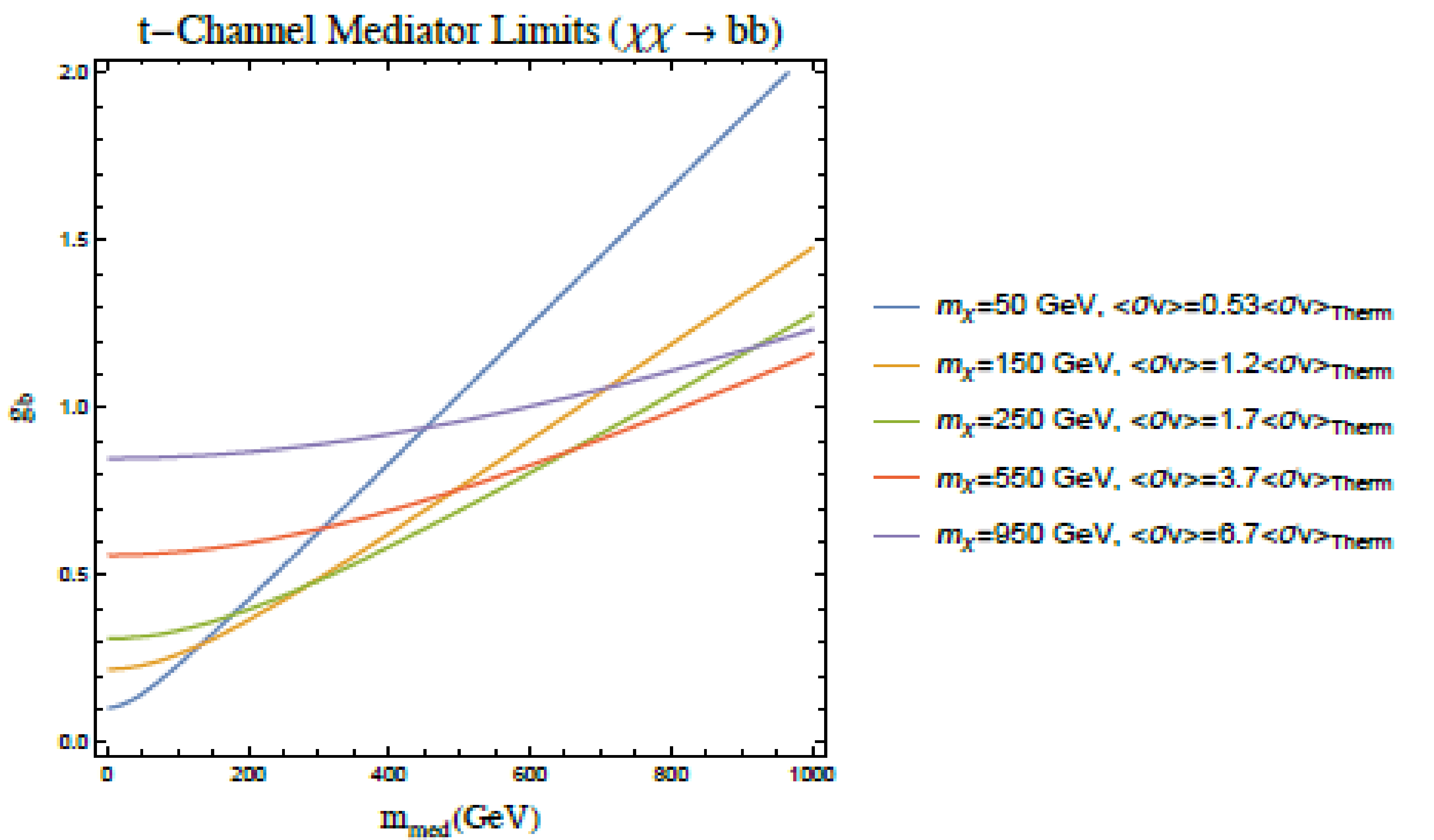
Vector Mediator Limits ($\chi\chi \to \tau\tau$)
g_τ
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
500
1000
1500
2000
m_χ=50 GeV, <σv>=0.5<σv>$_{Therm}$
m_χ=150 GeV, <σv>=1.6<σv>$_{Therm}$
m_χ=250 GeV, <σv>=3.2<σv>$_{Therm}$
m_χ=550 GeV, <σv>=9.4<σv>$_{Therm}$
m_χ=950 GeV, <σv>=24.<σv>$_{Therm}$
Vector Mediator Limits, 70% bb and 30% $\tau\tau$
g_B
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
500
1000
1500
2000
m_V (GeV)
m_χ=50 GeV, <σv>=0.56<σv>$_{Therm}$
m_χ=150 GeV, <σv>=1.4<σv>$_{Therm}$
m_χ=250 GeV, <σv>=2.2<σv>$_{Therm}$
m_χ=550 GeV, <σv>=4.7<σv>$_{Therm}$
m_χ=950 GeV, <σv>=8.4<σv>$_{Therm}$

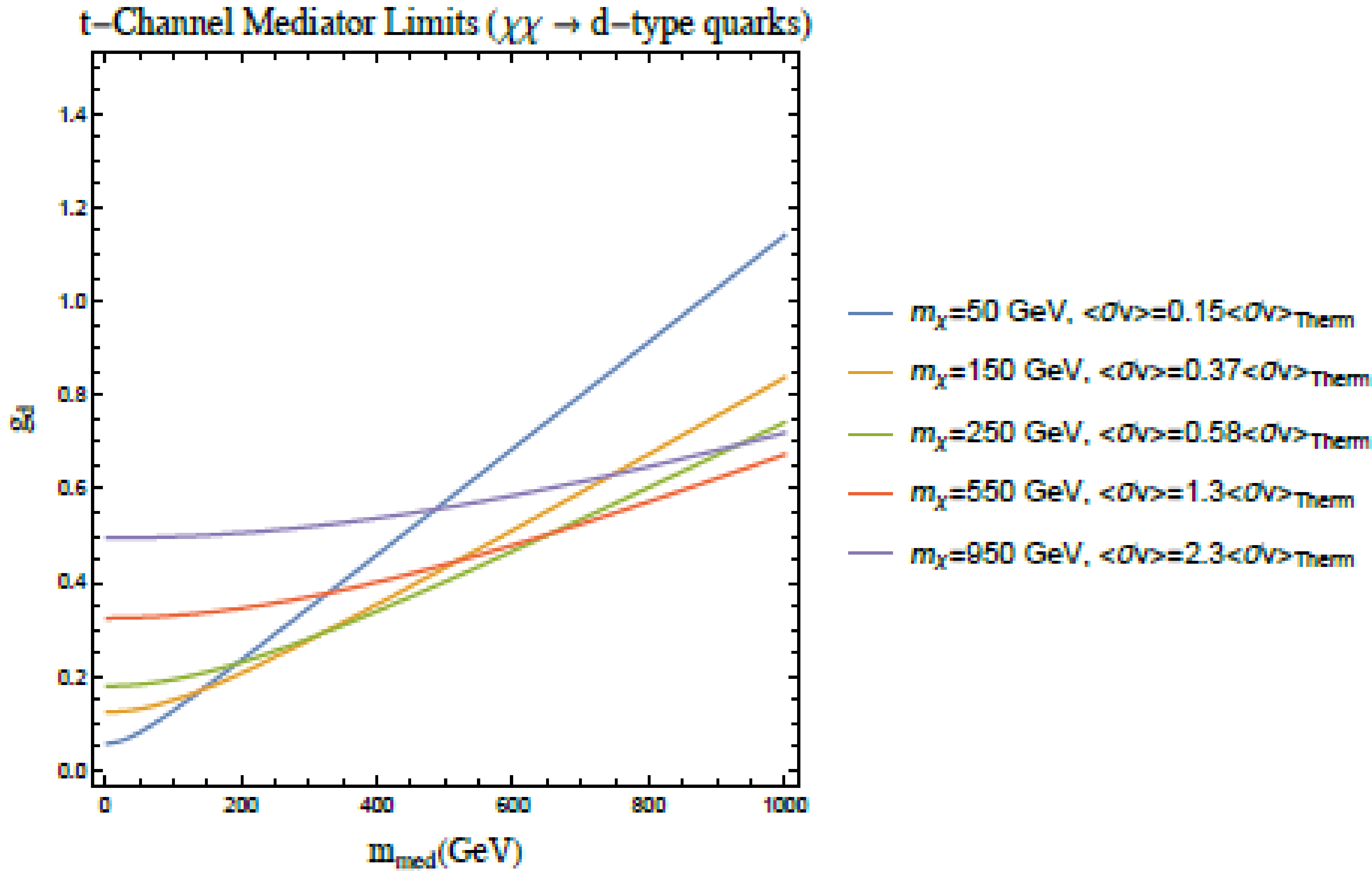


Vector Mediator Limits (χχ → bb)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
500
1000
1500
2000
m_V(GeV)
m_χ=50 GeV, <σv>=0.53<σv>_Therm
m_χ=150 GeV, <σv>=1.2<σv>_Therm
m_χ=250 GeV, <σv>=1.7<σv>_Therm
m_χ=550 GeV, <σv>=3.7<σv>_Therm
m_χ=950 GeV, <σv>=6.7<σv>_Therm

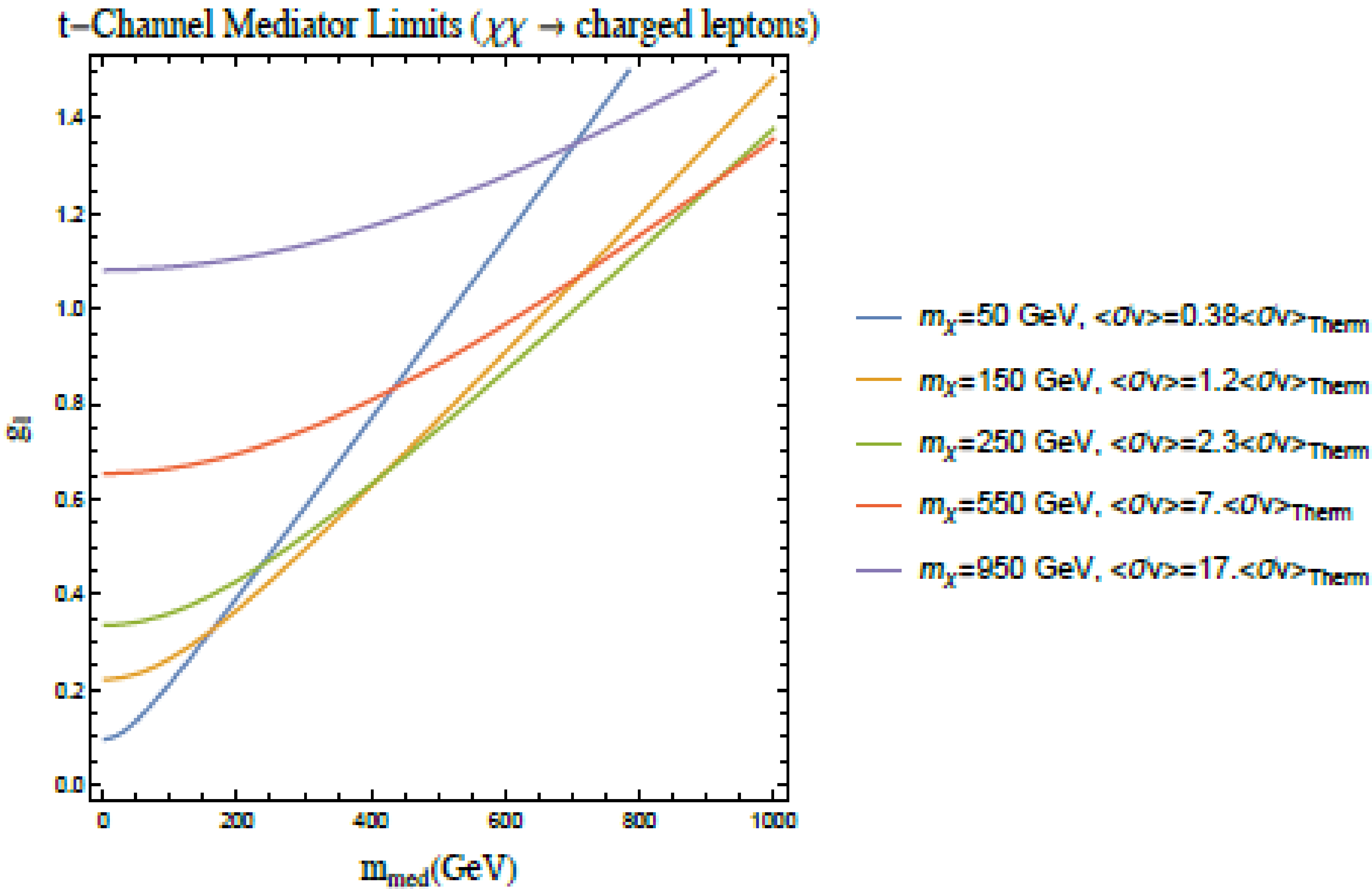
t-channel

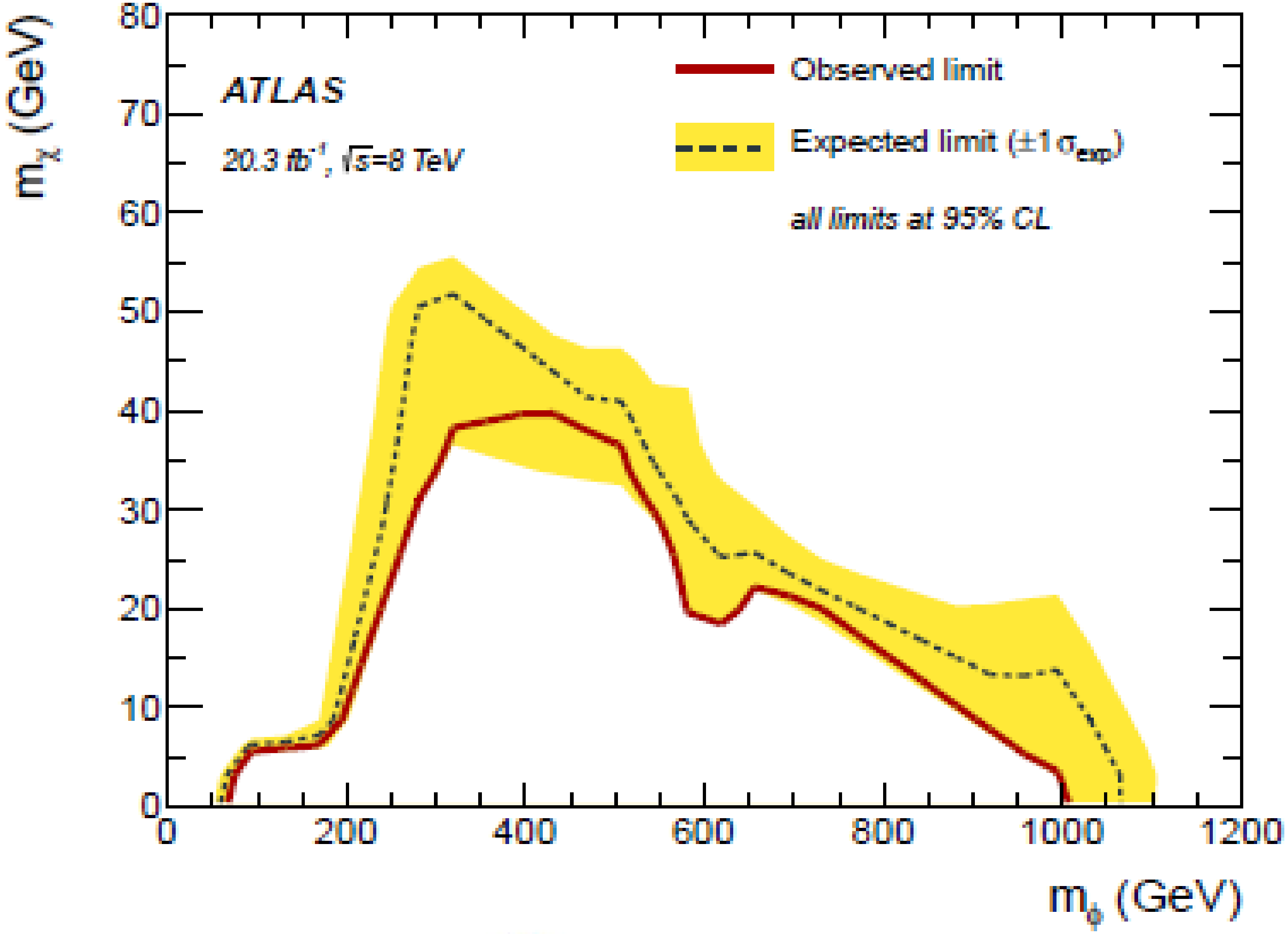
$$(\sigma v)(\bar{\chi}\chi \to f_i \bar{f}_i) = \frac{N_c^f g_i^4 m_\chi^2}{32\pi (M_i^2 + m_\chi^2)^2},$$

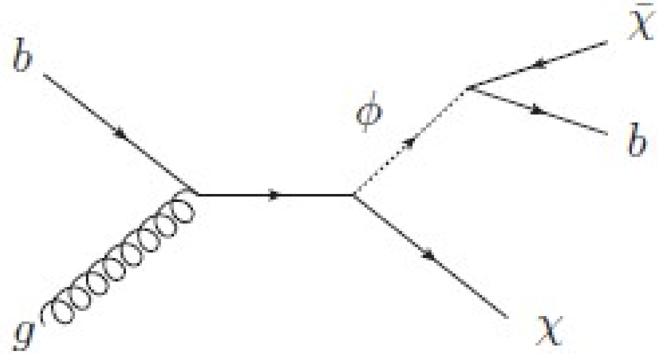




t−Channel Mediator Limits (χχ → d−type quarks)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
m_med(GeV)
m_χ=50 GeV, <σv>=0.15<σv>_Therm
m_χ=150 GeV, <σv>=0.37<σv>_Therm
m_χ=250 GeV, <σv>=0.58<σv>_Therm
m_χ=550 GeV, <σv>=1.3<σv>_Therm
m_χ=950 GeV, <σv>=2.3<σv>_Therm


t–Channel Mediator Limits (χχ → charged leptons)
m_med(GeV)
0 200 400 600 800 1000
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
m_χ=50 GeV, <σv>=0.38<σv>_Therm
m_χ=150 GeV, <σv>=1.2<σv>_Therm
m_χ=250 GeV, <σv>=2.3<σv>_Therm
m_χ=550 GeV, <σv>=7.<σv>_Therm
m_χ=950 GeV, <σv>=17.<σv>_Therm





Eur Phys J c(2015) 75:92

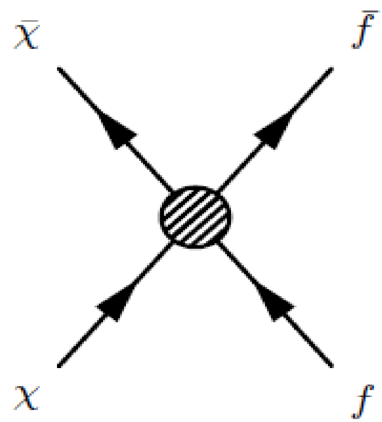
Fermion Portal

Simplest EFT model: 1 operator 1 channel

$$\mathcal{L}_{\rm f} = \frac{\kappa_t}{\Lambda_t^2}\chi\Gamma\overline{\chi}t\Gamma\overline{t} + \frac{\kappa_b}{\Lambda_b^2}\chi\Gamma\overline{\chi}b\Gamma\overline{b} + \frac{\kappa_\tau}{\Lambda_\tau^2}\chi\Gamma\overline{\chi}\tau\Gamma\overline{\tau} + \frac{\kappa_\nu}{\Lambda_\nu^2}\chi\Gamma\overline{\chi}\nu\Gamma\overline{\nu}.$$

Allow visible total annihilation rate below the thermal rate
Without over-closing the universe

Light DM For now consider annihilation to b, τ and invisible channel



$$\langle\sigma v\rangle_{\rm tot} = \langle\sigma v\rangle_{\rm b} + \langle\sigma v\rangle_\tau + \langle\sigma v\rangle_\nu.$$

$$\propto a\left(\kappa_b/\Lambda_b^2\right)^2 + b\left(\kappa_\tau/\Lambda_\tau^2\right)^2 + c\left(\kappa_\nu/\Lambda_\nu^2\right)^2$$

First Fix the Annihilation rate as desired

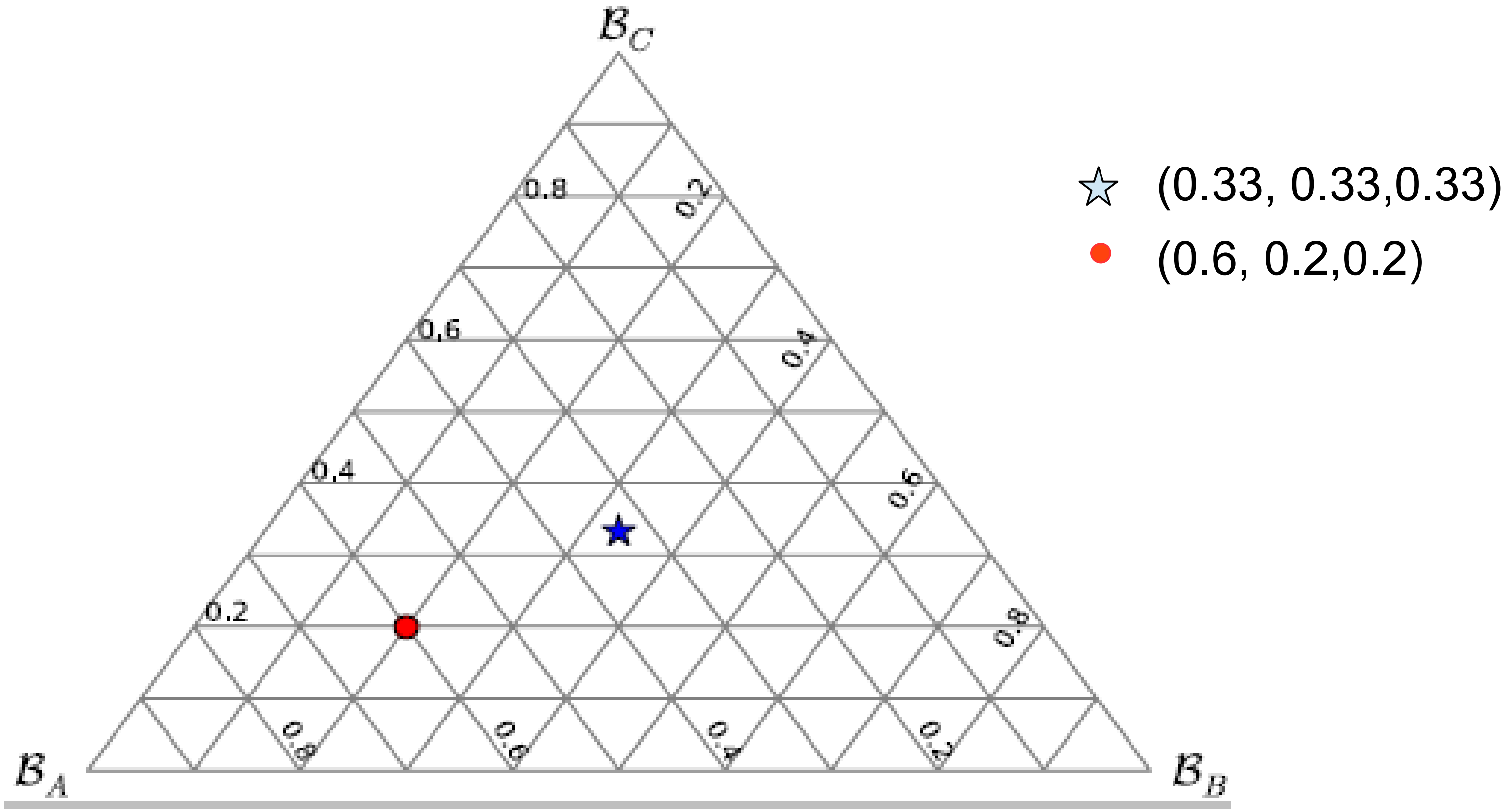
Dividing out by the total rate to define partial rate $R_i = \langle\sigma v\rangle_i/\langle\sigma v\rangle_{\rm tot}$

get a constraint between the partial annihilation rates

$$R_1 + R_2 + R_3 + \cdots = 1.$$

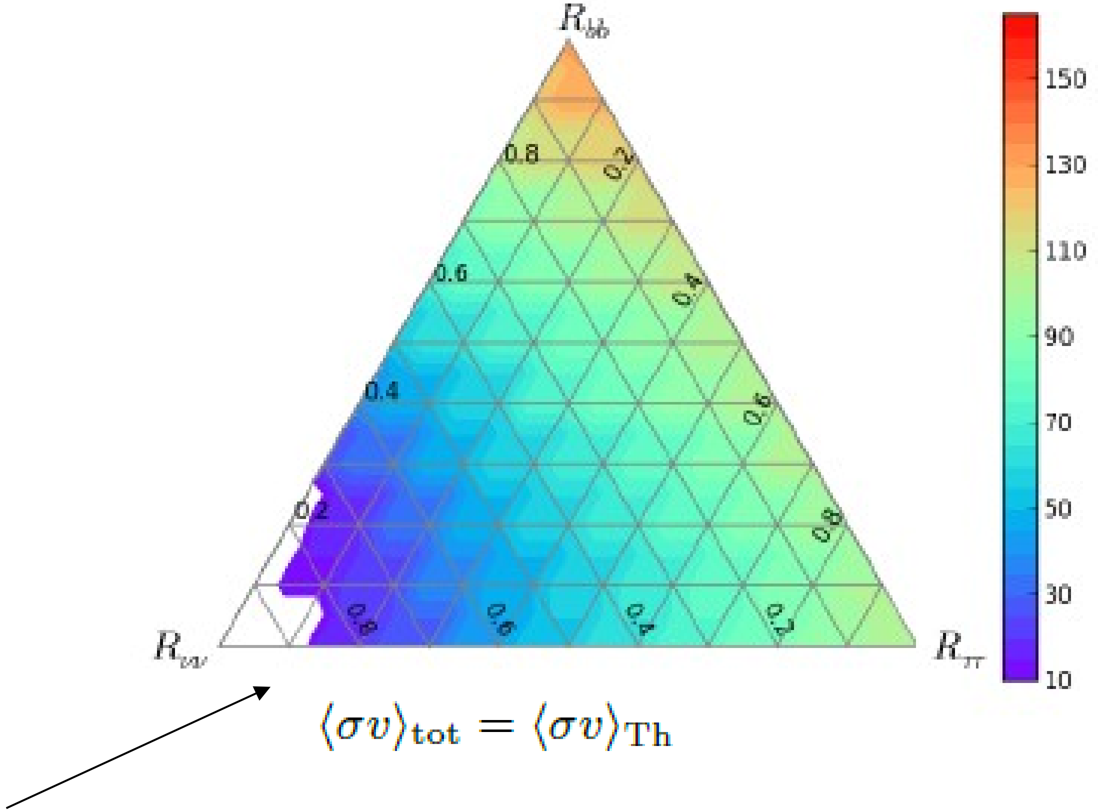
Three Parameters and 1 constraint may be visualized on 2-D surface as triangle

The partial rates are saturated at the corners of the triangle



$$\Phi_\gamma = \frac{1}{4\pi} \sum_f \frac{\langle \sigma v \rangle_f}{2m_\chi^2} \int_{E_{\min}}^{E_{\max}} \left(\frac{dN_\gamma}{dE_\gamma} \right)_f dE_\gamma J.$$

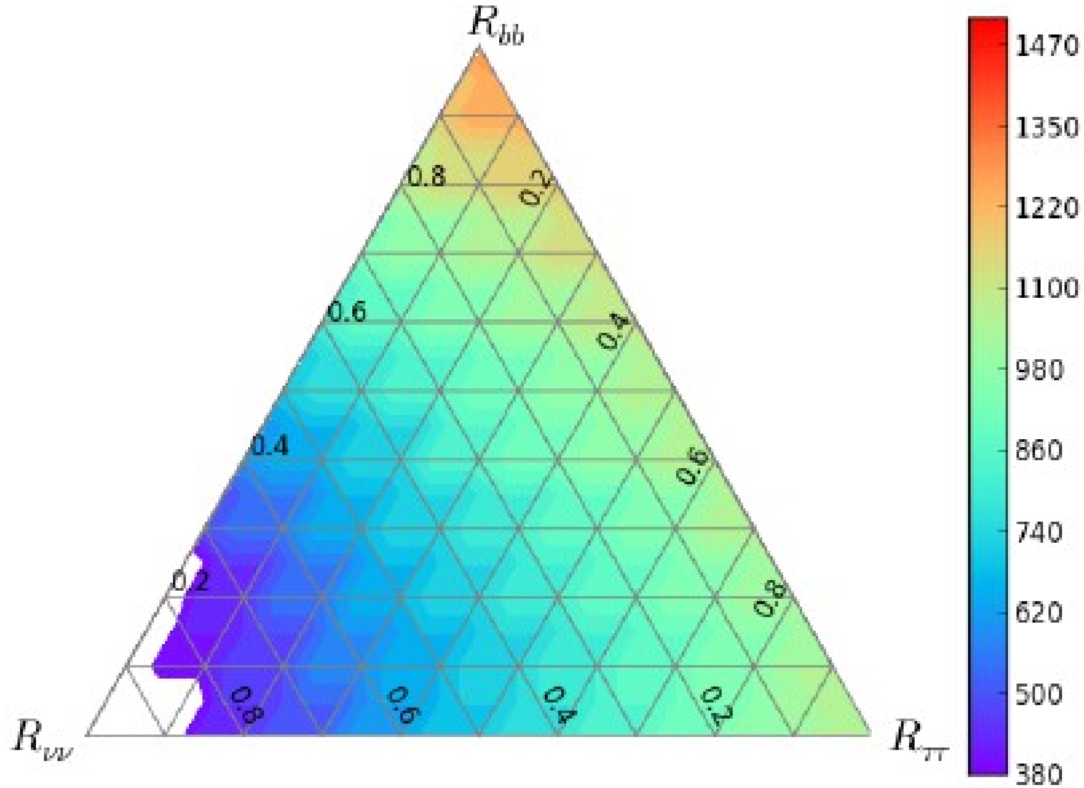
Pass 8



order 10s GeV min mass bounds even for visible annihilation rates at 30% of thermal rate

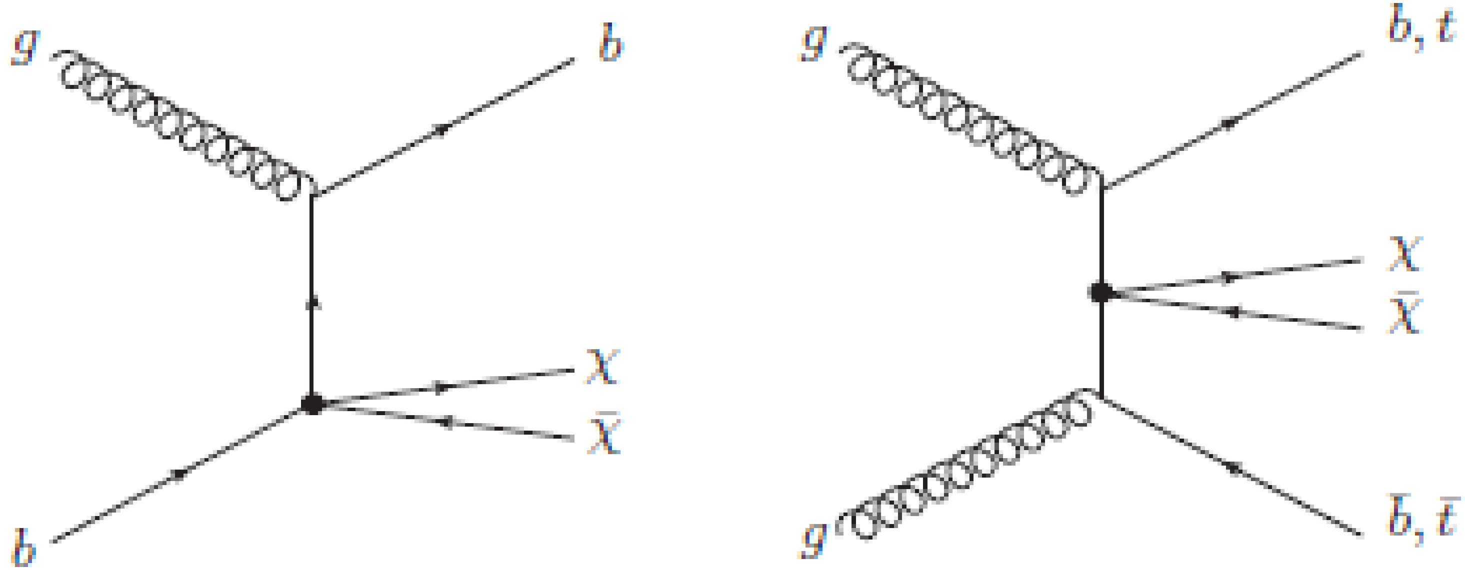
.

EFT bounds

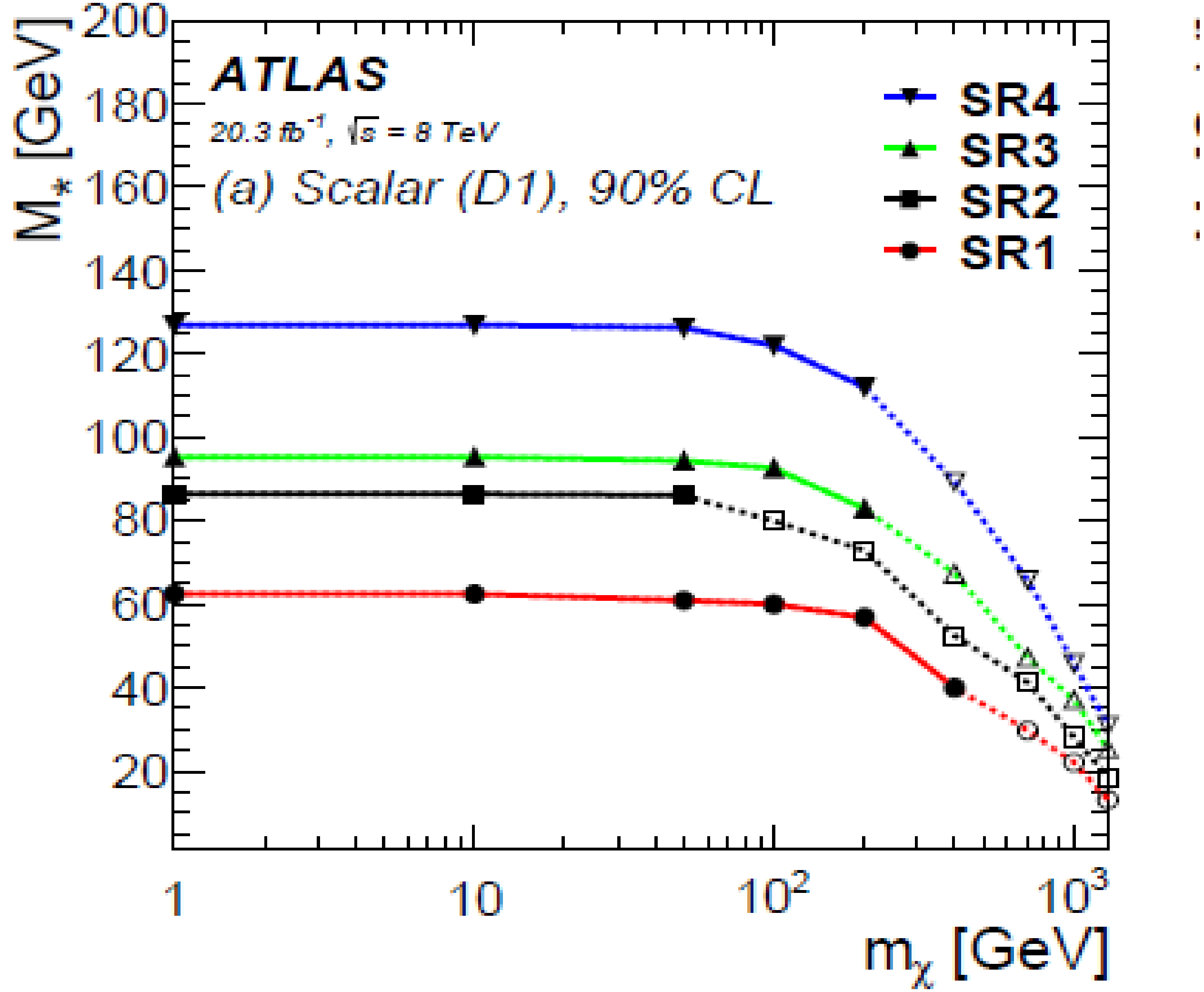


R_{bb}
$R_{\nu\nu}$
$R_{\tau\tau}$
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
0.8
0.6
0.4
0.2
1470
1350
1220
1100
980
860
740
620
500
380

Collider Limits

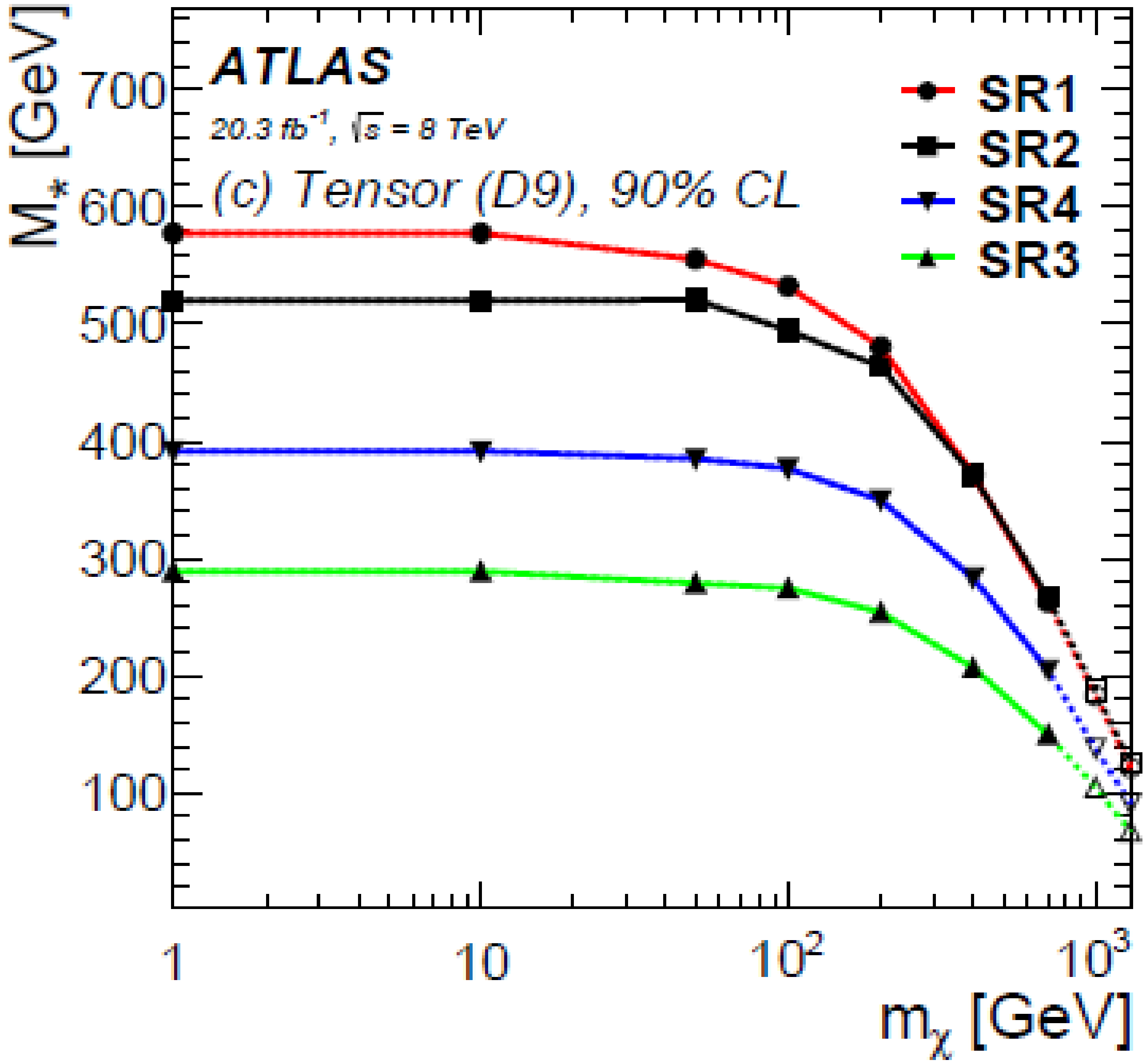


D1 operator



ATLAS
20.3 fb-1, √s = 8 TeV
(a) Scalar (D1), 90% CL
SR4
SR3
SR2
SR1
M* [GeV]
mχ [GeV]
200
180
160
140
120
100
80
60
40
20
1
10
10^2
10^3

D9 operator



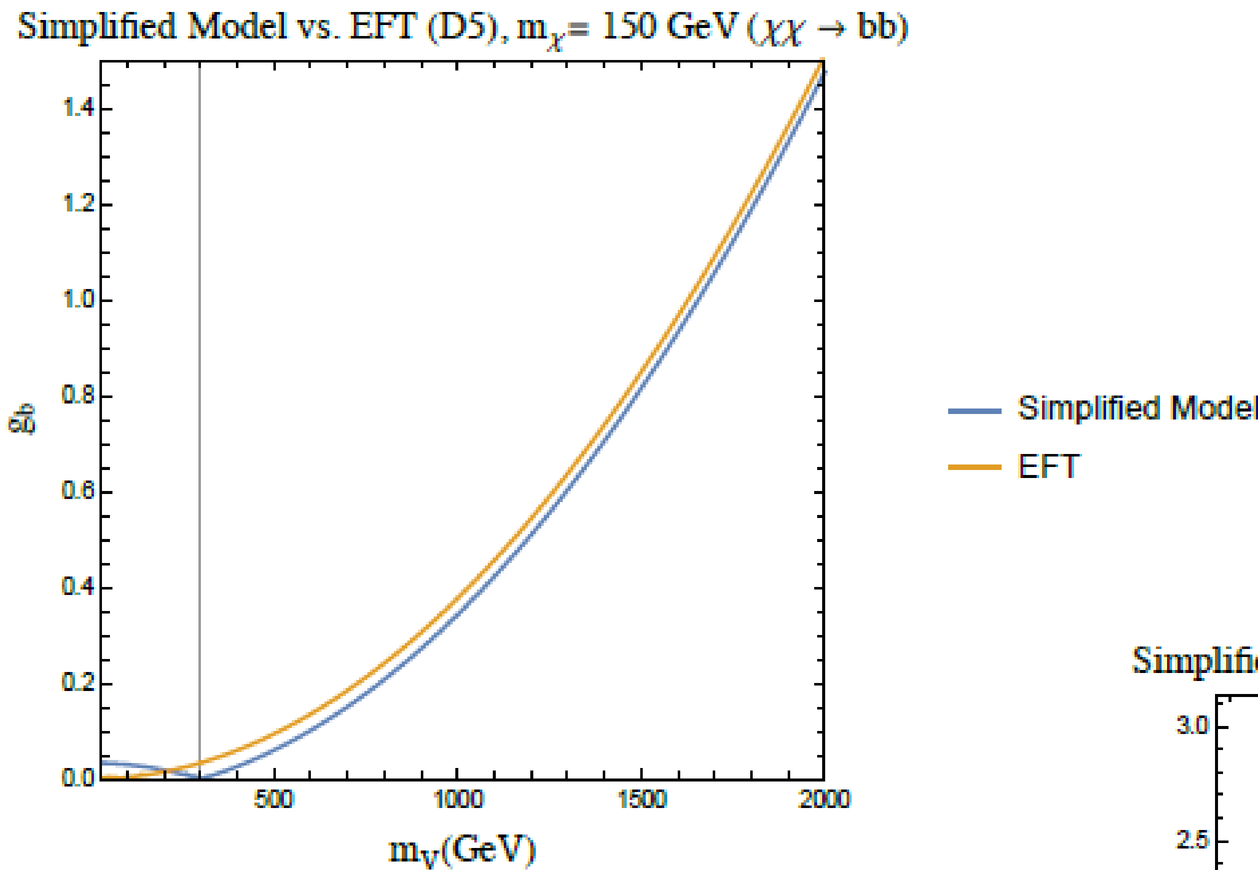
ATLAS
20.3 fb-1, √s = 8 TeV
(c) Tensor (D9), 90% CL
SR1
SR2
SR4
SR3
M* [GeV]
700
600
500
400
300
200
100
1
10
10^2
10^3
mχ [GeV]

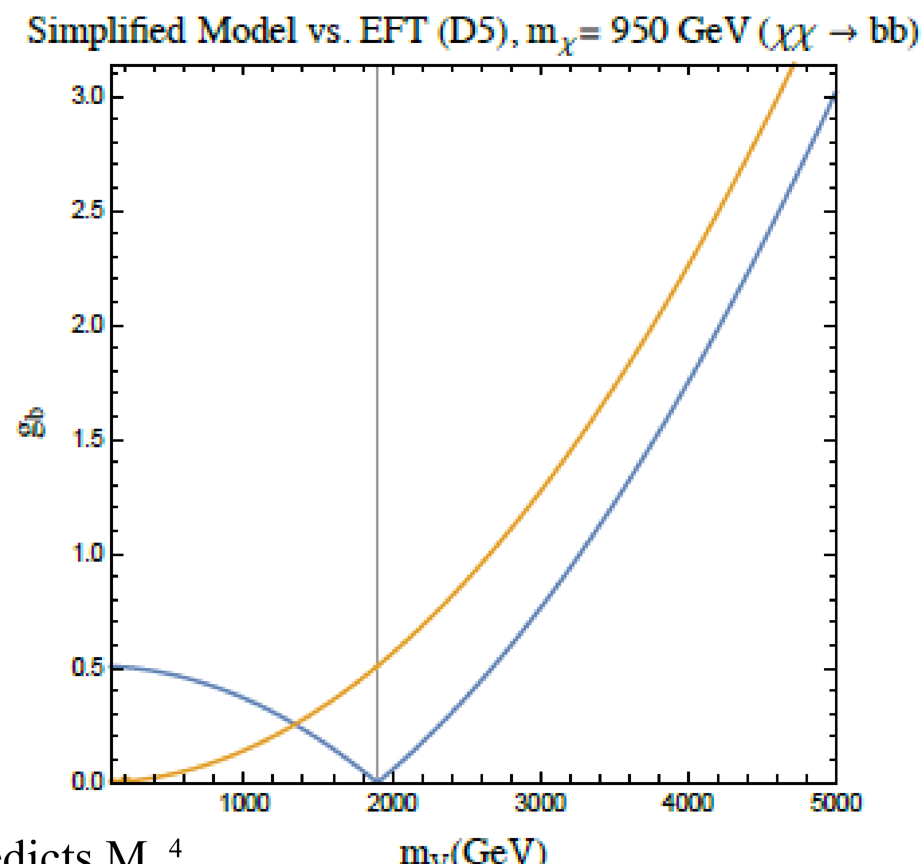
Conclusions

- For popular fermion (and other) portal models indirect detection has signif overlap with collider constraints especially given EFT limits
- Indirect and collider constraints do not in general align for model sets. a more systematic effort is needed to totally compare constraints

Extra

$$\Lambda \sim m_V / \sqrt{g_\chi g_f}$$





Upper bounds on DM-mediator coupling as a
Function of mediator mass for vector model with g=1
Compared to EFT D5 $(\bar{\chi}\gamma^\mu \chi f \gamma_\mu f)$

Recall

$$\langle \sigma v \rangle (\chi\bar{\chi} \to V \to f\bar{f}) \Rightarrow \frac{N_c^f m_\chi^2}{2\pi[(M_V^2 - 4m_\chi^2)^2 + \Gamma_V^2 M_V^2]}$$

If $m\chi$=1/4 M_V $(3/4 M_V^2)^2$ = 9/16 M_V^4 where EFT predicts M_V^4