DM@LHC: Loose ends

Uli Haisch, University of Oxford, 25th of September 2014

Try to fill in some of the blanks

& discuss existing/future LHC constraints on

- couplings between DM & gauge bosons
- interactions of DM & top quarks

Talk based on ongoing work with Crivellin, Hibbs & Re.
Many of shown results are preliminary

DM gauge boson couplings

[Cotta et al., 1210.0525;
Carpenter et al., 1212.3352;
Nelson et al., 1307.5064;
Lopez et al.,1403.6734;
ATLAS, 1404.0051]

Motivation

"The weakness of interactions is often understood in field theory as a sign that the corresponding operators are irrelevant. Consequently, the "darkness" of DM may be naturally interpreted as a consequence of DM having only irrelevant interactions with light, and more generally with the electroweak gauge bosons."

[Liu et al., 1303.4404]

Motivation

In fact, in case of Majorana DM, dimension-5 operators of dipole type are absent, so leading $SU(2)_L \times U(1)_Y$ invariant interactions of DM with photons are dimension 7:

$$\mathcal{L}_{\text{eff}} = \sum_{k=B,W,\tilde{B},\tilde{W}} \frac{C_k(\mu)}{\Lambda^3} O_k$$

$$O_B = \bar{\chi}\chi\, B_{\mu\nu} B^{\mu\nu}\,, \qquad O_W = \bar{\chi}\chi\, W^i_{\mu\nu} W^{i,\mu\nu}\,,$$

$$O_{\tilde{B}} = \bar{\chi}\chi\, B_{\mu\nu} \tilde{B}^{\mu\nu}\,, \qquad O_{\tilde{W}} = \bar{\chi}\chi\, W^i_{\mu\nu} \tilde{W}^{i,\mu\nu}$$

Motivation

Latter operators special:

- annihilation into photon pairs velocity suppressed
  → indirect detection probably never provide limits
- DM-nucleon interactions loop suppressed
  → present direct detection bounds quite weak[†]
- for $m_\chi < O(100\ \text{GeV})$ relic density too large
  → additional operators or dark sector structure

[†]for future sensitivity see [Crevillin & UH, 1408.5046]

Motivation

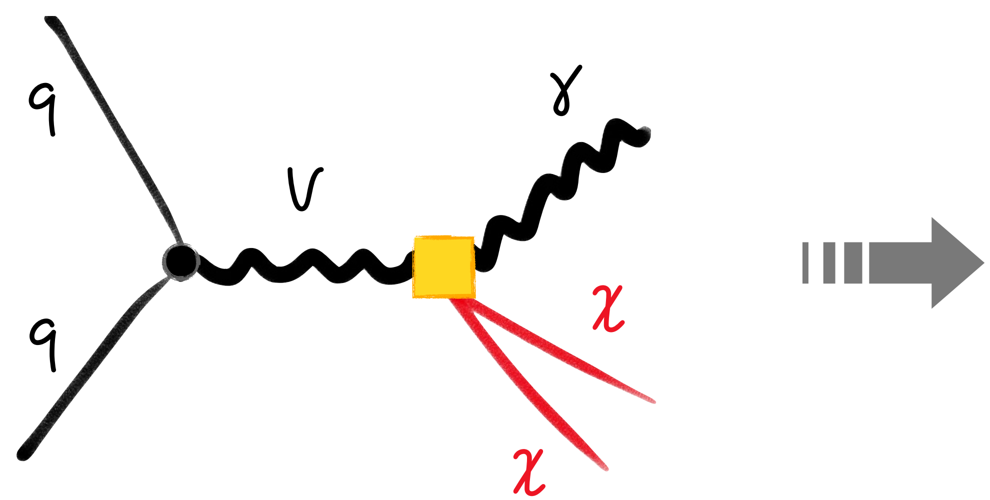
Latter operators special:

- annihilation into photon pairs velocity suppressed
  → indirect detection probably never provide limits
- DM-nucleon interactions loop suppressed
  → present direct detection bounds quite weak†

Attractive DM scenario with room to be explored by LHC

†for future sensitivity see [Crevillin & UH, 1408.5046]

LHC signals & searches



mono-photon

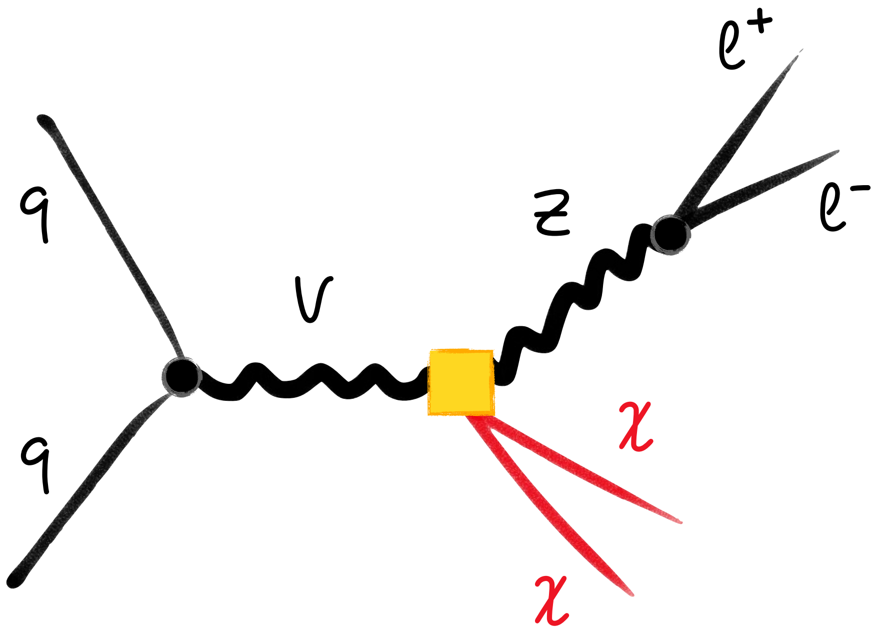
$\underline{\text{CMS, 8 TeV, 19.6 fb}^{-1}\ :}$

$\not{E}_T > 140\,\text{GeV}, \quad p_{T,\gamma} > 700\,\text{GeV} \quad |\eta_\gamma| < 1.4442$

$\sigma_{\text{fid}}(pp \to \not{E}_T + \gamma) < 0.22\,\text{fb}$

[CMS-PAS-EXO-12-047]

LHC signals & searches



$$\not{E}_T + Z\,(\to \ell^+\ell^-)$$

$\underline{\text{ATLAS, 8 TeV, 20.3 fb}^{-1}:}$

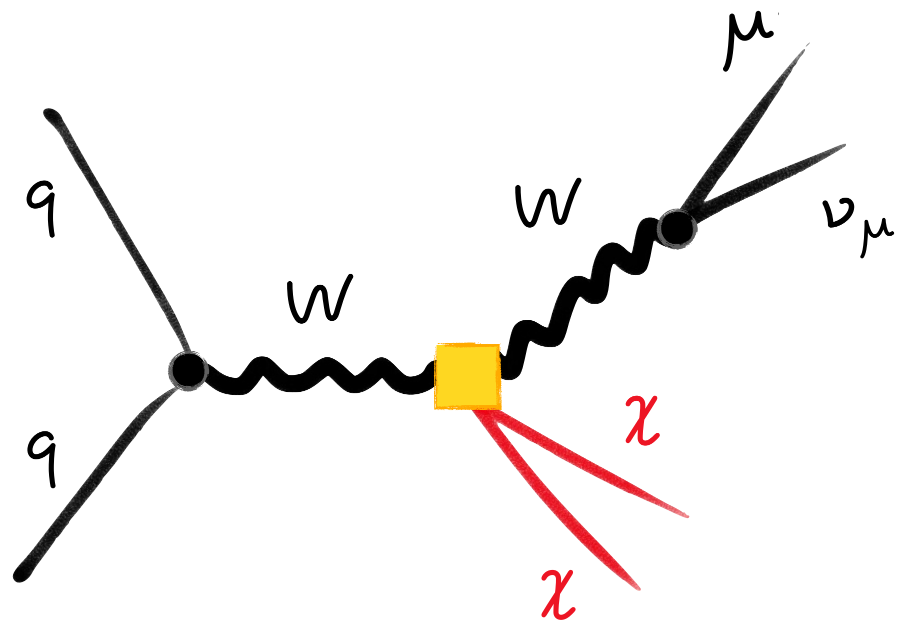
$$\not{E}_T > 350\,\text{GeV}, \quad p_{T,\ell} > 20\,\text{GeV}, \quad |\eta_\ell| < 2.5,$$

$$m_{\ell\ell} \in [76, 106]\,\text{GeV}, \quad |\eta_{\ell\ell}| < 2.5, \quad \frac{|p_{T,\ell\ell} - \not{E}_T|}{p_{T,\ell\ell}} < 0.5$$

$$\sigma_{\text{fid}}\left(pp \to \not{E}_T + Z\,(\to \ell^+\ell^-)\right) < 0.27\,\text{fb}$$

[ATLAS, 1404.0051]

LHC signals & searches



$$\not{E}_T + W\,(\to \mu\nu_\mu)$$

$\underline{\mathrm{ATLAS,\ 8\,TeV,\ 20.3\,fb^{-1}:}}$

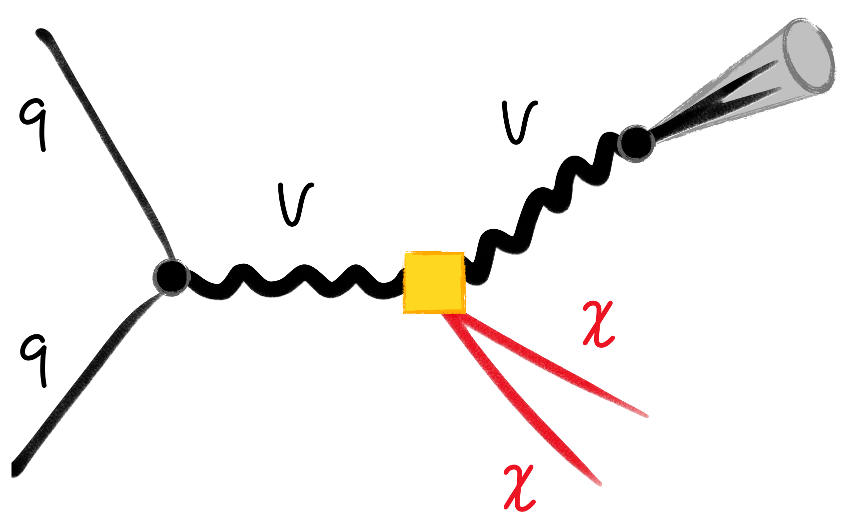
$$p_{T,\mu} > 45\,\mathrm{GeV}\,, \qquad |\eta_\mu| \in [0,1] \cup [1.3,2]$$

$$m_T = \sqrt{2 p_{T,\mu} \not{E}_T \left(1 - \cos\varphi_{\mu \not{E}_T}\right)} > 843\,\mathrm{GeV}$$

$$\sigma_{\rm fid}\left(pp \to \not{E}_T + W\,(\to \mu\nu_\mu)\right) < 0.54\,\mathrm{fb}$$

[ATLAS, 1407.7494]

LHC signals & searches



$$\not{E}_T + W/Z\,(\to \text{hadrons})$$

ATLAS, $8\,\text{TeV}$, $20.3\,\text{fb}^{-1}$:

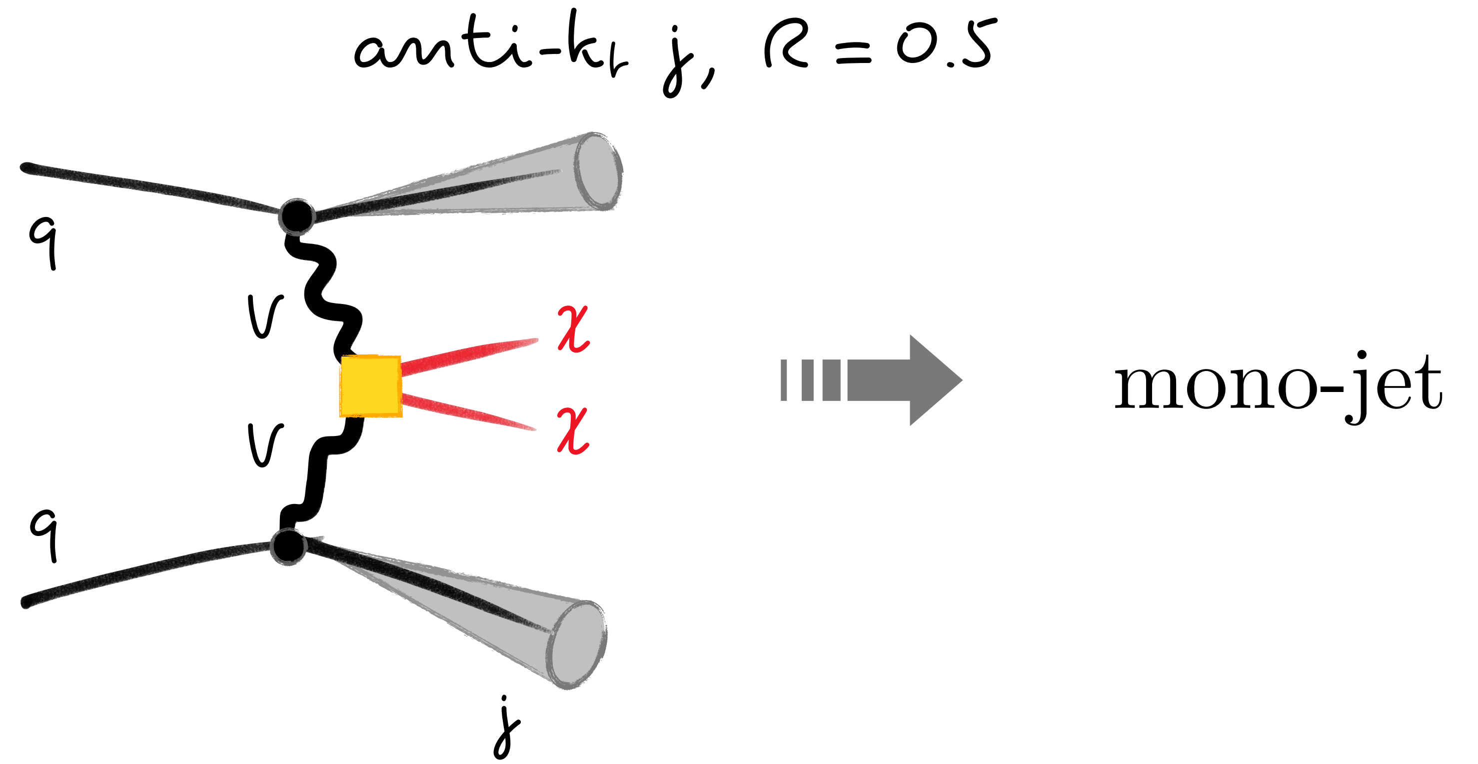
$$\not{E}_T > 500\,\text{GeV}\,, \quad p_{T,j} > 250\,\text{GeV}\,, \quad |\eta_j| < 1.2\,,$$

$$m_j \in [50, 120]\,\text{GeV}\,, \quad \sqrt{y} > 0.4$$

$$\sigma_{\text{fid}}\big(pp \to \not{E}_T + W/Z\,(\to \text{hadrons})\big) < 2.2\,\text{fb}$$

[ATLAS, 1309.4014]

LHC signals & searches



CMS, 8 TeV, 19.7 fb^{-1} :

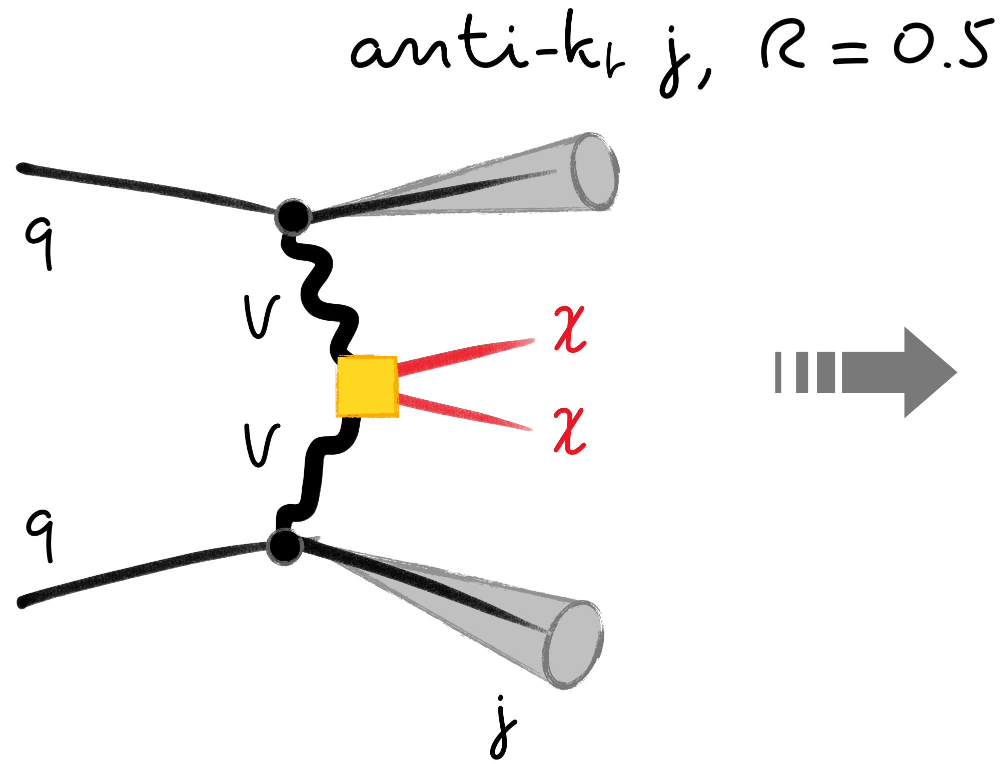
$$\not{E}_T > 500\,\mathrm{GeV}\,, \quad p_{T,j_1} > 110\,\mathrm{GeV}\,, \quad |\eta_{j_1}| < 2.4\,,$$

$$p_{T,j_2} > 30\,\mathrm{GeV}\,, \quad |\eta_{j_2}| < 4.5\,, \quad \Delta\phi_{j_1 j_2} < 2.5\,, \quad N_j \le 2$$

$$\sigma_{\mathrm{fid}}(pp \to \not{E}_T + 2j) < 6.1\,\mathrm{fb}$$

[CMS, 1408.2745]

LHC signals & searches



VBF $h \to$ invisible

CMS, 8 TeV, $19.5\,\mathrm{fb}^{-1}$:

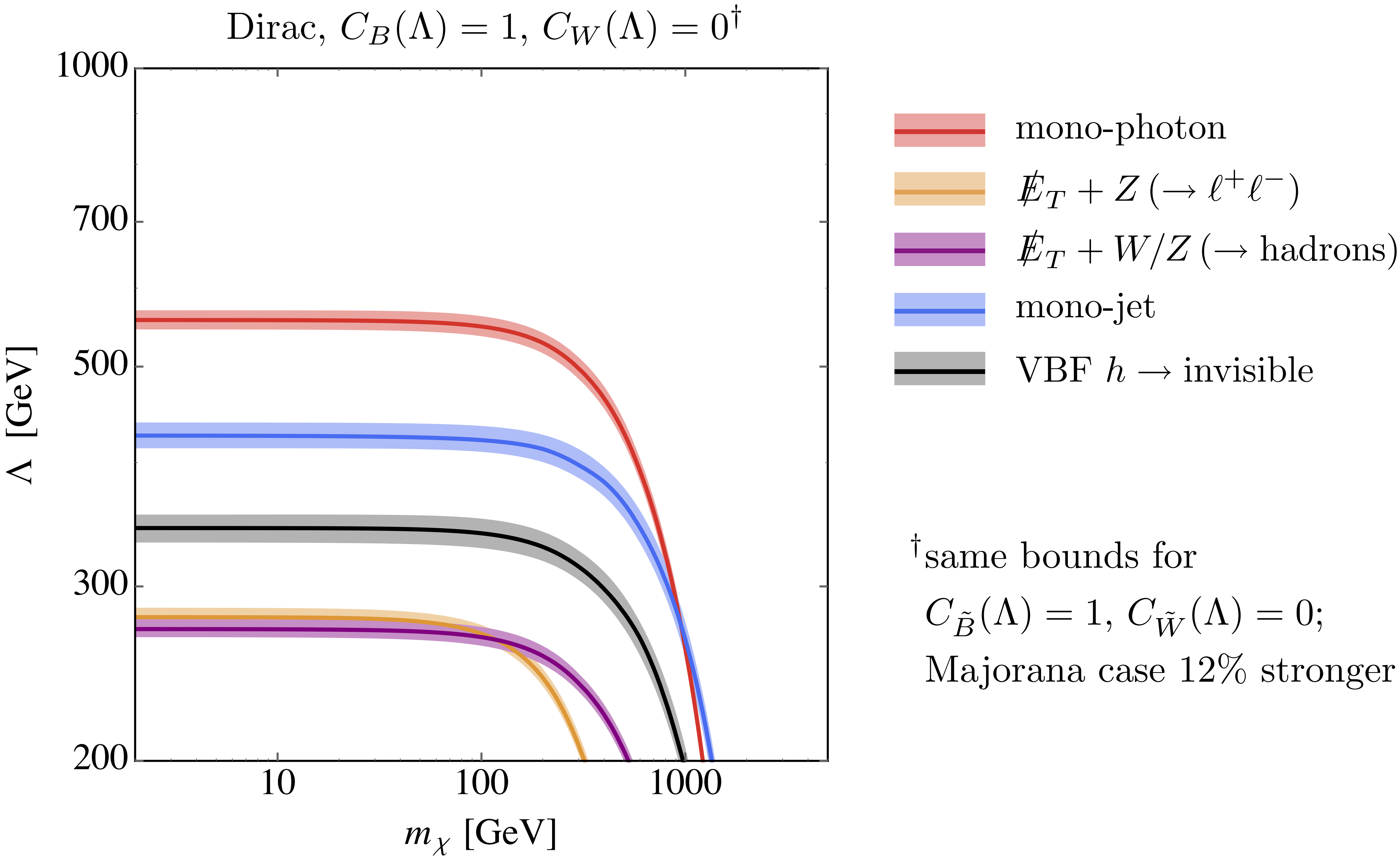
$\not{E}_T > 130\,\mathrm{GeV}, \quad p_{T,j_1}, p_{T,j_2} > 50\,\mathrm{GeV}, \quad |\eta_{j_1}|, |\eta_{j_2}| < 4.7,$

$\Delta\eta_{j_1 j_2} > 4.2, \quad m_{j_1 j_2} > 1100\,\mathrm{GeV}, \quad \Delta\phi_{j_1 j_2} < 1.0, \quad$ central jet veto

$\sigma_{\mathrm{fid}}(pp \to \not{E}_T + 2j) < 6.5\,\mathrm{fb}$

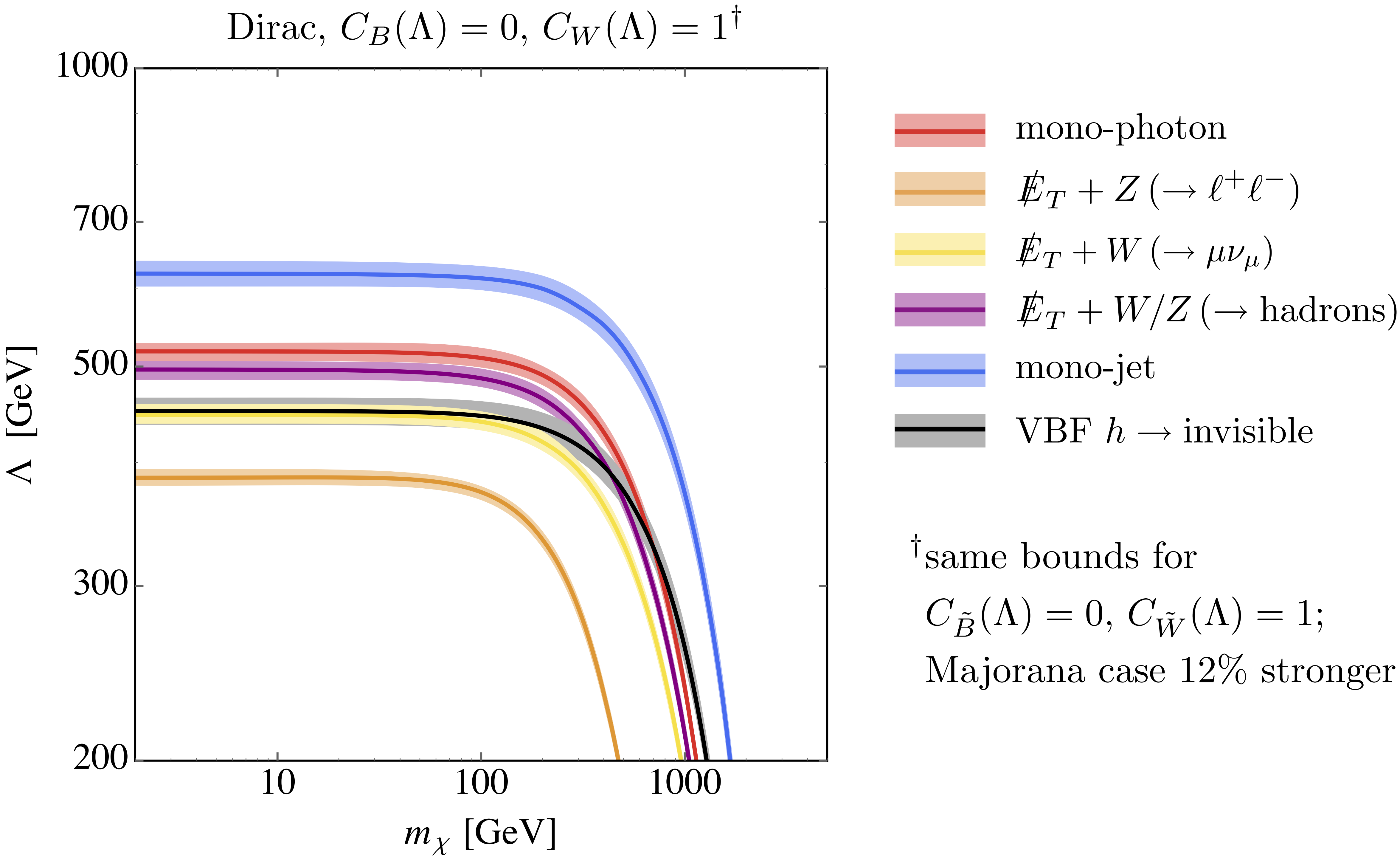
[CMS, 1408.3583]

Bounds on new-physics scale



†same bounds for $C_{\tilde{B}}(\Lambda) = 1$, $C_{\tilde{W}}(\Lambda) = 0$; Majorana case 12% stronger

Bounds on new-physics scale



†same bounds for $C_{\tilde{B}}(\Lambda) = 0$, $C_{\tilde{W}}(\Lambda) = 1$; Majorana case 12% stronger

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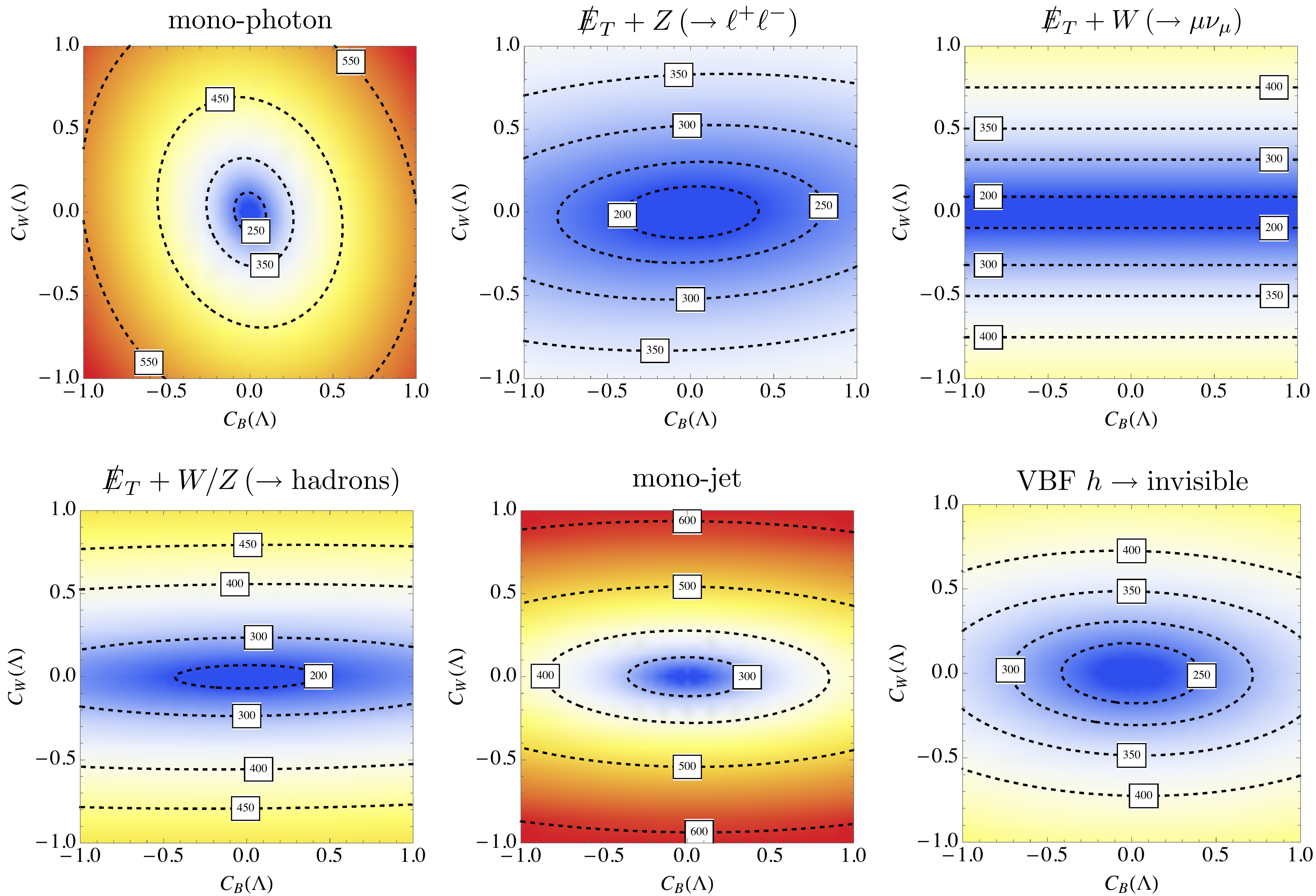
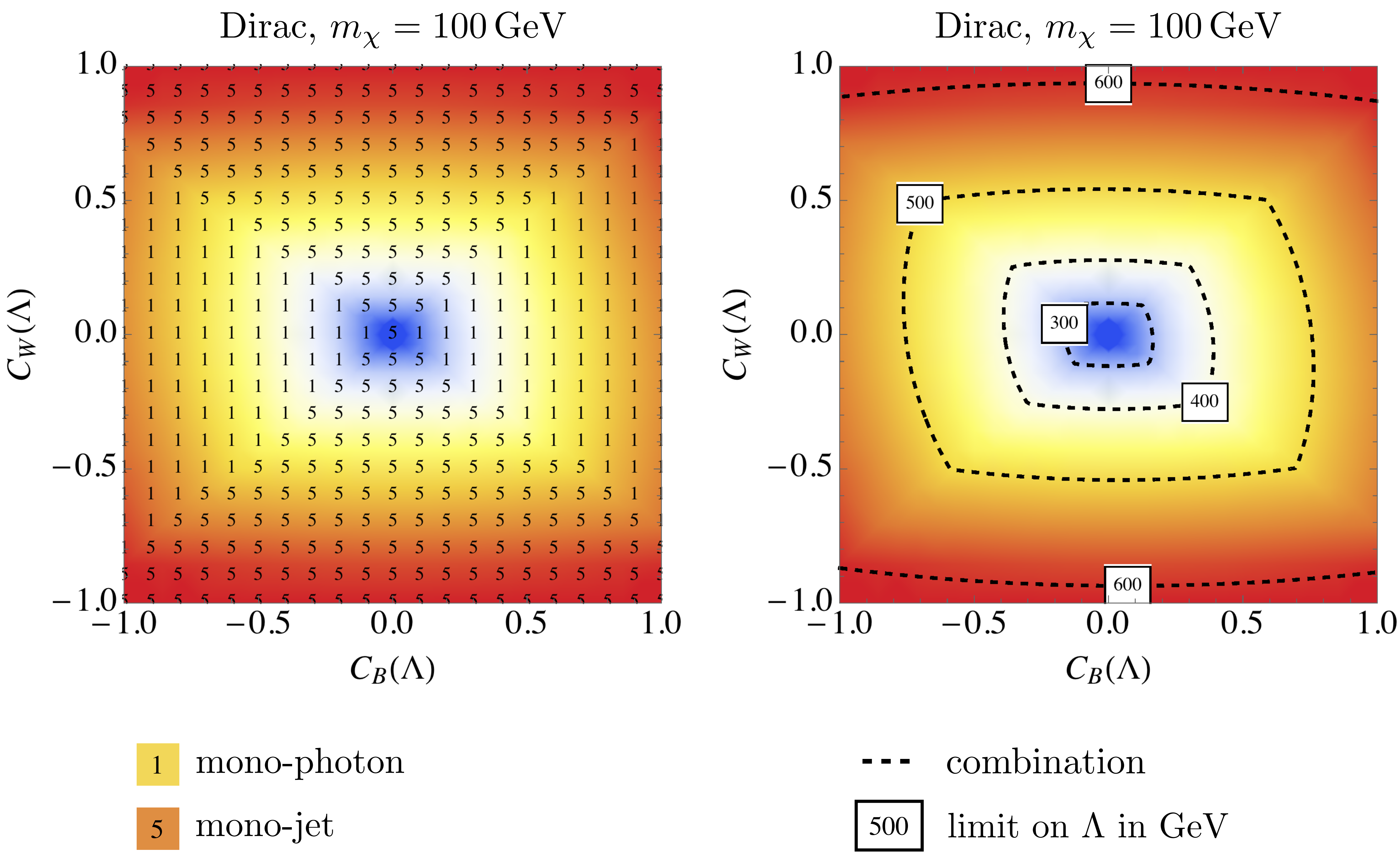


Bounds on new-physics scale



Comments on bounds

- Only mono-photon channel more sensitive to $C_B(\Lambda)$ than $C_W(\Lambda)$ & interference effects between operators smallish
- Since $Br(V \to \text{leptons})/Br(V \to \text{hadrons}) \simeq 0.1$, channels with final state leptons less constraining than hadronic searches
- Given higher-dimensional nature of O_B & O_W, searches with harder $\not{E}_T$ cut fare better (e.g. mono-jet vs. VBF $h \to$ invisible)

LHC 14 TeV forecast

Imposed mono-jet cuts :

$$\not{E}_T > 800\,\mathrm{GeV}\,, \quad p_{T,j_1} > 300\,\mathrm{GeV}\,,$$

$$|\eta_{j_1}| < 2.0\,, \quad p_{T,j_1} > 50\,\mathrm{GeV}\,, \quad |\eta_{j_2}| < 3.6$$

Limits improve by factor of at least 2 in first year. Then progress slows down given imperfect understanding of SM background (assumed to be known to 5% accuracy)†

$8\,\mathrm{TeV\ LHC},\ 20\,\mathrm{fb}^{-1}$:
$\Lambda \gtrsim 600\,\mathrm{GeV}$

↓

$14\,\mathrm{TeV\ LHC},\ 25\,\mathrm{fb}^{-1}$:
$\Lambda \gtrsim 1.3\,\mathrm{TeV}$

↓

$14\,\mathrm{TeV\ LHC},\ 300\,\mathrm{fb}^{-1}$:
$\Lambda \gtrsim 1.5\,\mathrm{TeV}$

†findings agree with [ATL-COM-PHYS-2014-549]

Jet-jet angular correlations

Imposed VBF cuts :

$$\Delta\eta_{j_1 j_2} > 2\,,$$

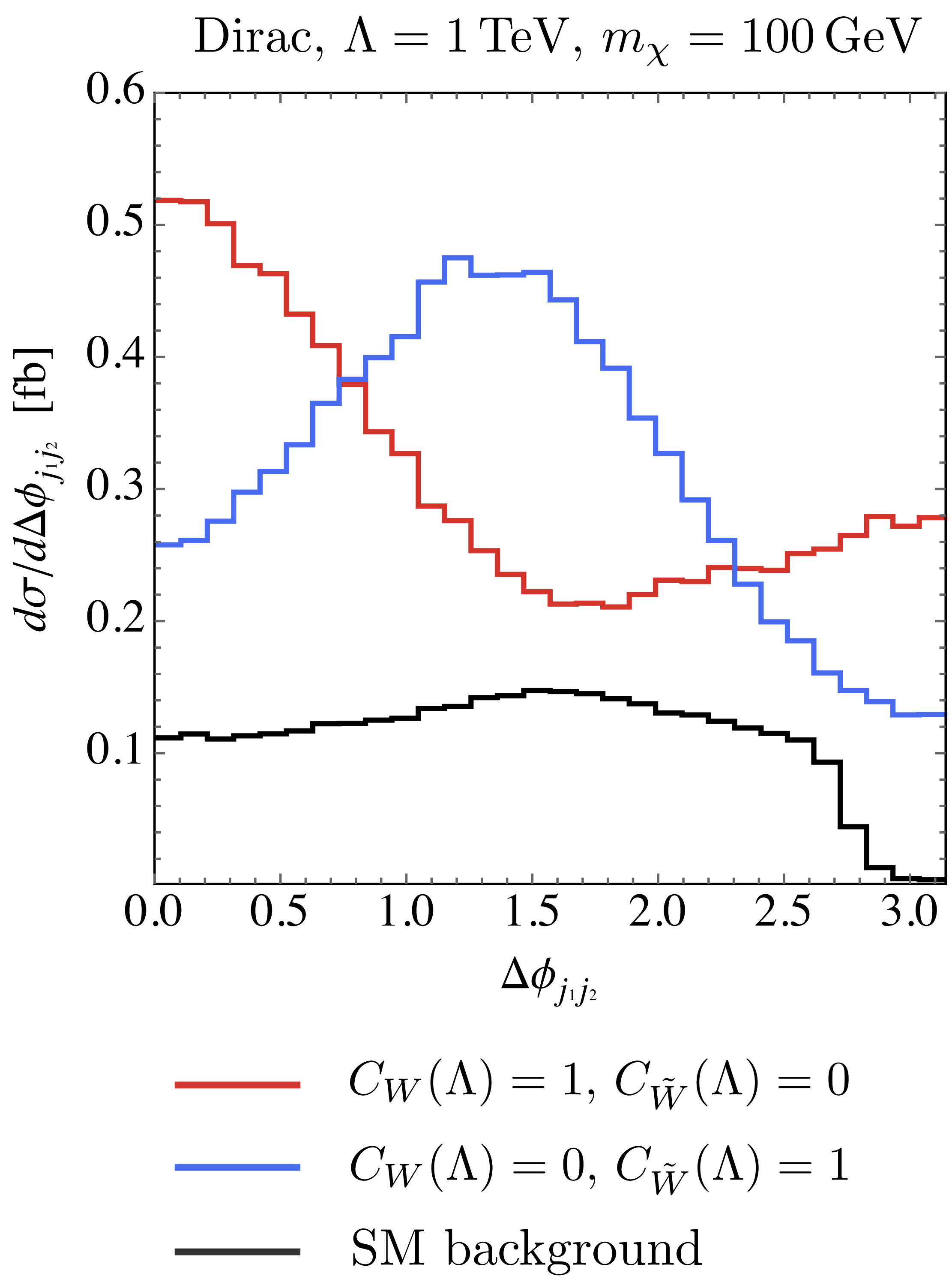
$$m_{j_1 j_2} > 1100\,\text{GeV}$$

$$\sigma_{\text{fid}}\left(pp \to \not{E}_T + 2j\right) = 1.0\,\text{fb}$$

$$\sigma_{\text{fid}}\left(pp \to Z\,(\to \bar{\nu}\nu) + 2j\right) = 0.35\,\text{fb}$$

$$S/\sqrt{B} = 8.4\;\;(25\,\text{fb}^{-1})\,,$$

$$S/\sqrt{B} = 29\;\;(300\,\text{fb}^{-1})$$



Jet-jet angular correlations

Angular decomposition :

$$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi_{j_1 j_2}} = \sum_{n=0}^{2} a_n \cos(n\Delta\phi_{j_1 j_2})$$

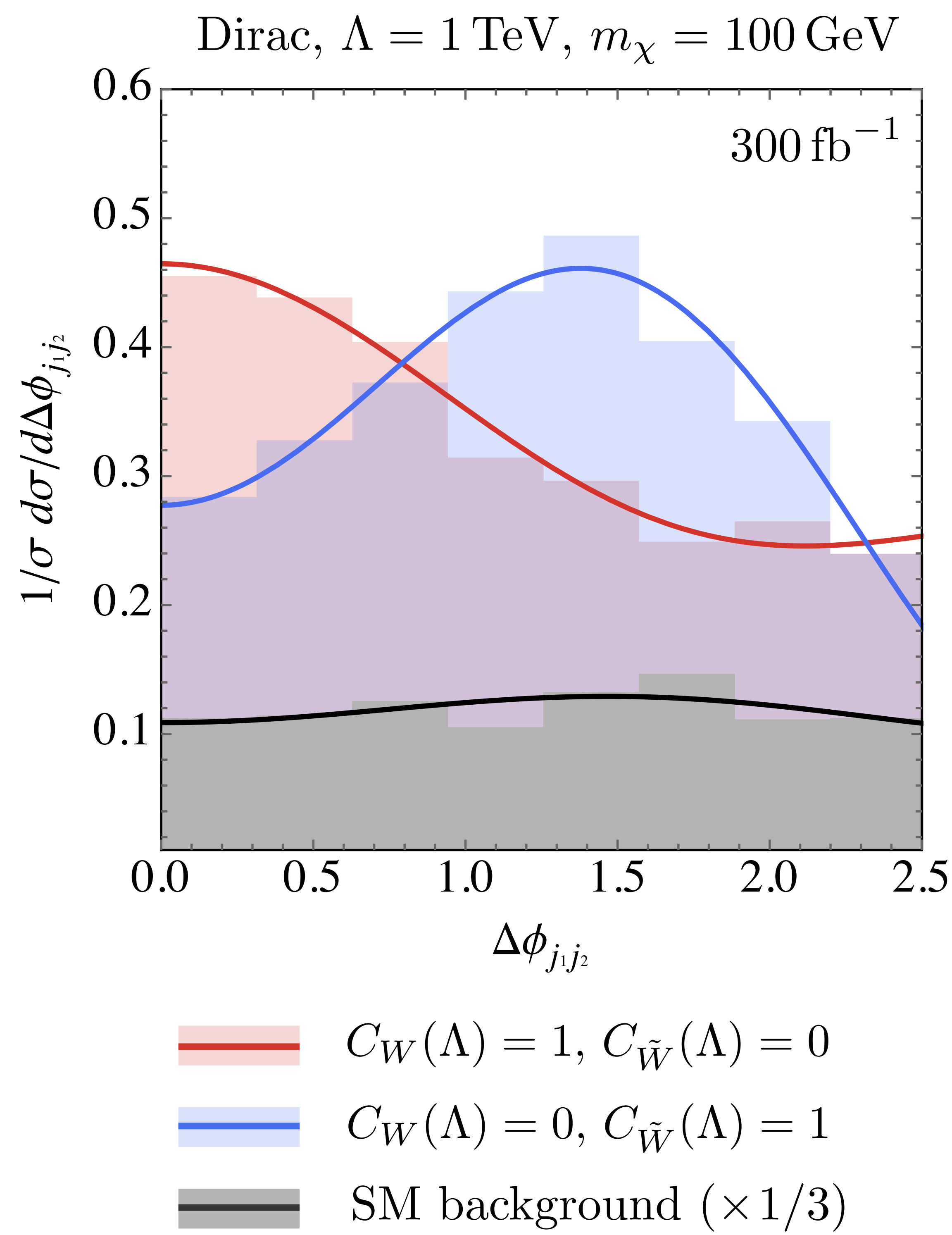
$\Downarrow$ $300\,\mathrm{fb}^{-1}$

$$(a_2/a_0)_{W+\mathrm{SM}} = 0.15 \pm 0.10,$$

$$(a_2/a_0)_{\tilde{W}+\mathrm{SM}} = -0.45 \pm 0.14,$$

$$(a_2/a_0)_{\mathrm{SM}} = -0.12 \pm 0.22$$

significance : 2.7, 2.4, 5.1



Jet-jet angular correlations

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$$\frac{1}{\sigma}\frac{d\sigma}{d\Delta\phi_{j_1 j_2}} = \sum_{n=0}^{2} a_n \cos\left(n\Delta\phi_{j_1 j_2}\right)$$

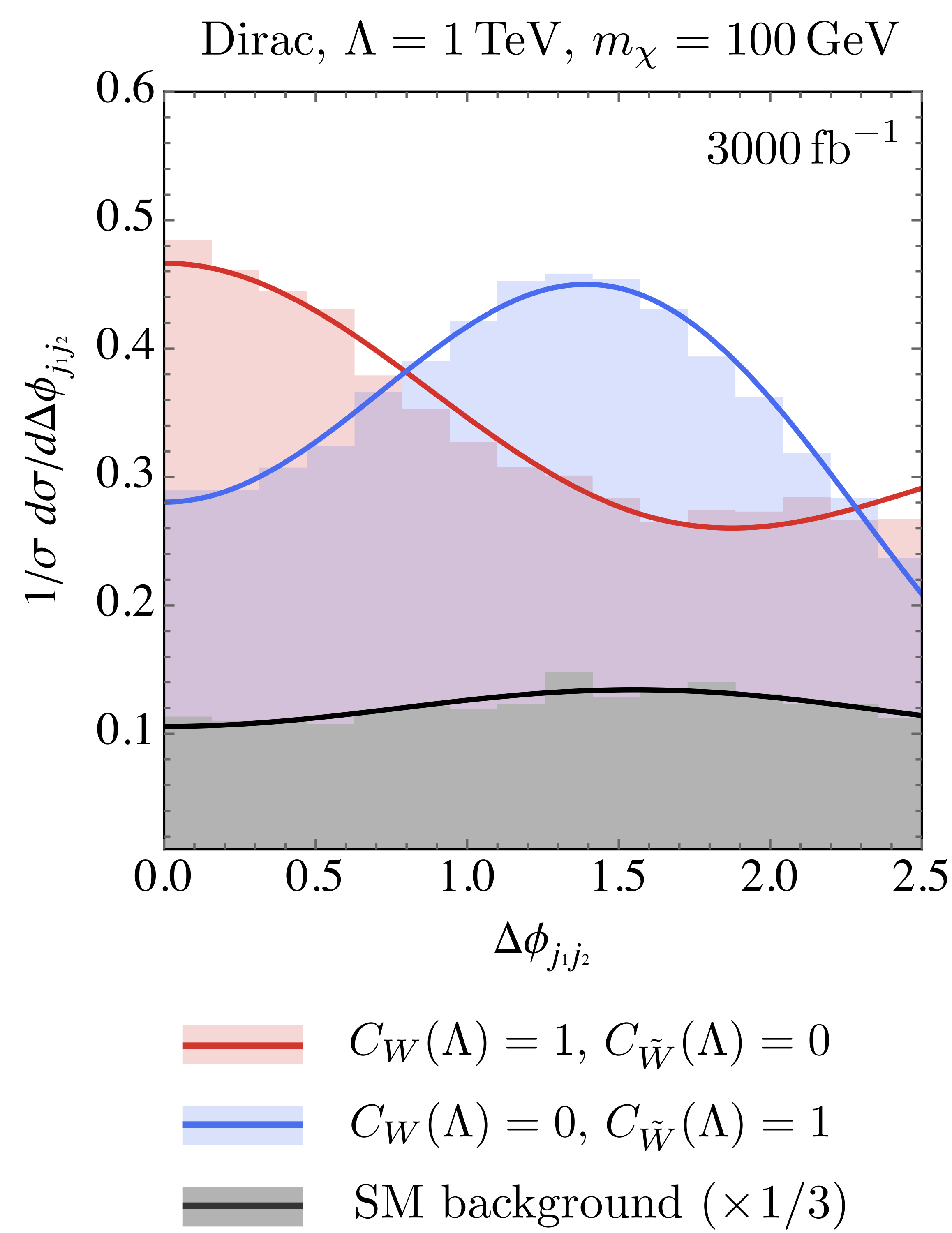
⇓ $3000\,\mathrm{fb}^{-1}$

$$(a_2/a_0)_{W+\mathrm{SM}} = 0.18 \pm 0.03,$$

$$(a_2/a_0)_{\tilde{W}+\mathrm{SM}} = -0.40 \pm 0.04,$$

$$(a_2/a_0)_{\mathrm{SM}} = -0.13 \pm 0.07$$

significance : 10.3, 6.8, 17.1



DM top quark couplings

[UH, Kahlhoefer & Unwin, 1208.4605;
Lin et al., 1303.6638;
CMS-PAS-B2G-14-004]

Introduction

Below we will consider $\not{E}_T$ signals associated to effective dimension-7 DM quark couplings of form

$$O_S = \sum_q \frac{m_q}{\Lambda^3}\,\bar{q}q\,\bar{\chi}\chi\,, \qquad O_P = \sum_q \frac{m_q}{\Lambda^3}\,\bar{q}\gamma_5 q\,\bar{\chi}\gamma_5\chi$$

Factors m_q motivated by hypothesis of minimal flavour violation (MFV), which both curbs size of flavour-changing neutral currents & leads to stable DM candidate

[Batell et al., 1105.1781]

Introduction

Scalar DM quark couplings of this type can be generated, if there is an extra singlet S with following interactions:

$$\mathcal{L} \supset -\lambda \bar{\chi}\chi S - \mu \phi^\dagger \phi S - \frac{m_S^2}{2} S^2 - y_q \bar{q} \phi q - V(\phi^\dagger \phi)$$

$$\phi \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} \qquad \begin{pmatrix} h \\ S \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ S_1 \end{pmatrix}$$

$$\mathcal{L}_{\rm eff} \supset \frac{\lambda\theta}{v m_S^2} m_q \bar{q} q \bar{\chi}\chi - \lambda\theta h_1 \bar{\chi}\chi \,, \qquad \theta \simeq \frac{\mu v}{m_S^2}$$

Introduction

If kinematically allowed, 2nd term gives rise to h→invisible decays. LHC run-1 data imply

$$\mathrm{Br}\,(h \to \mathrm{invisible}) \lesssim 35\% \quad \Rightarrow \quad \lambda\theta \lesssim y_b \simeq 0.03$$

$$m_S \lesssim \frac{10^{-2}}{\mathrm{GeV}^{1/2}}\,\Lambda^{3/2} \overset{\Lambda\simeq 150\,\mathrm{GeV}}{\simeq} 20\,\mathrm{GeV}$$

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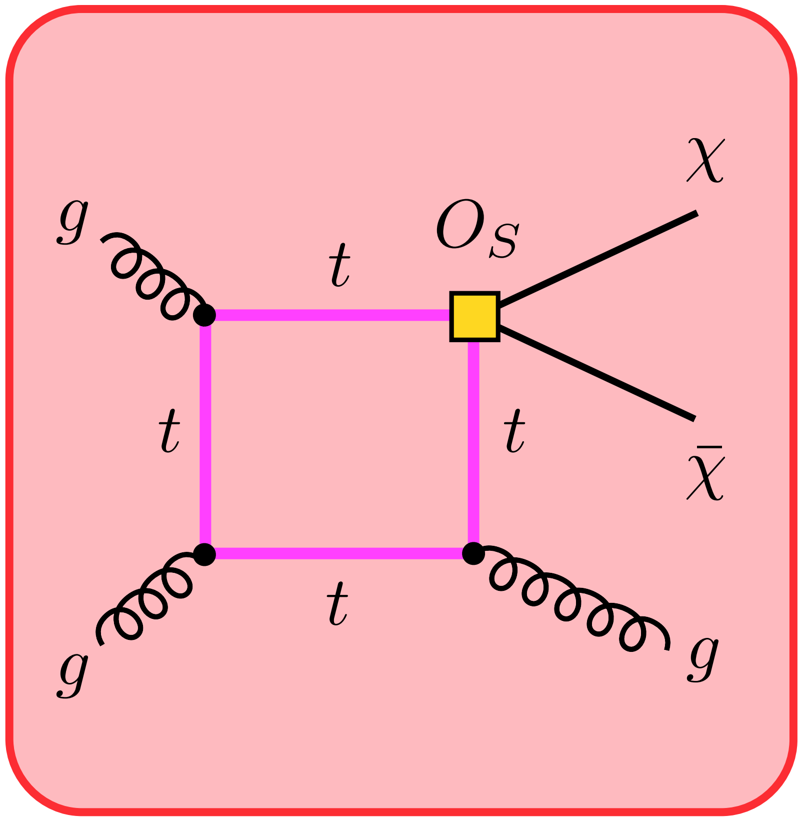
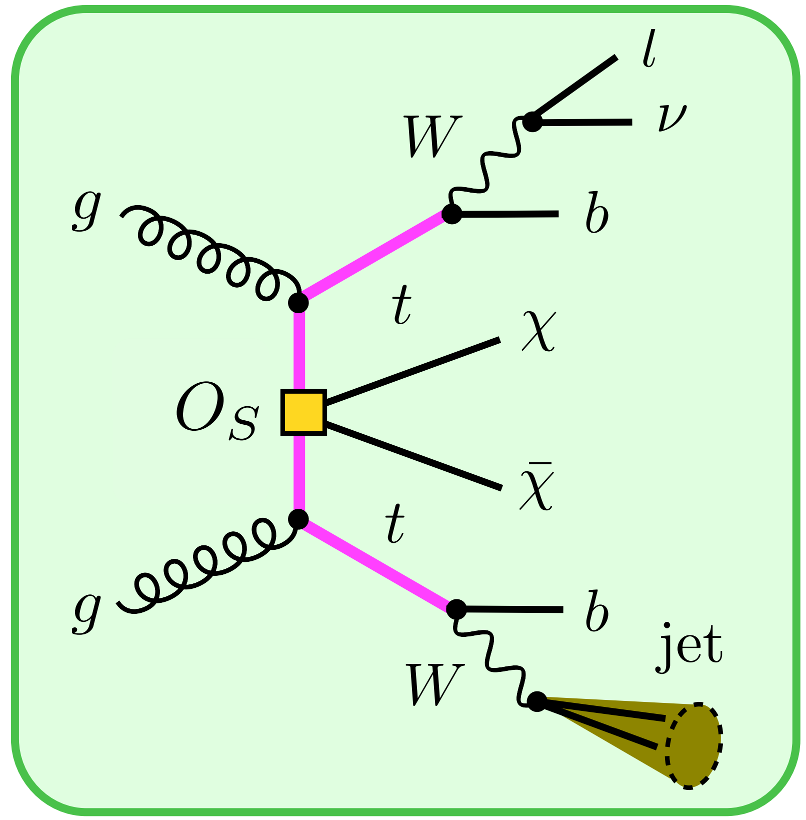
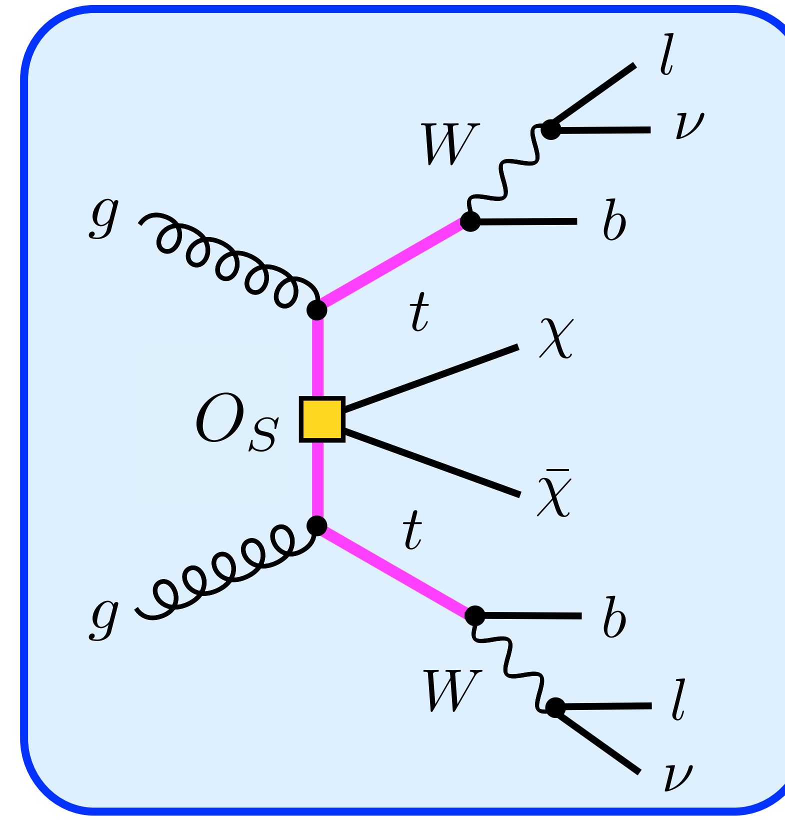
UV theories of DM quark couplings of MFV-type may have rich LHC phenomenology beyond mono-jets, …

Explored channels







mono-jet

[UH, Kahlhoefer & Unwin, 1208.4605]

$\not{E}_T + \bar{t}t \, (\rightarrow bjb\ell\nu)$

[Lin et al., 1303.6638]

$\not{E}_T + \bar{t}t \, (\rightarrow b\ell\nu b\ell\nu)$

[CMS-PAS-B2G-14-004]

8 TeV comparison of strategies

mono-jet

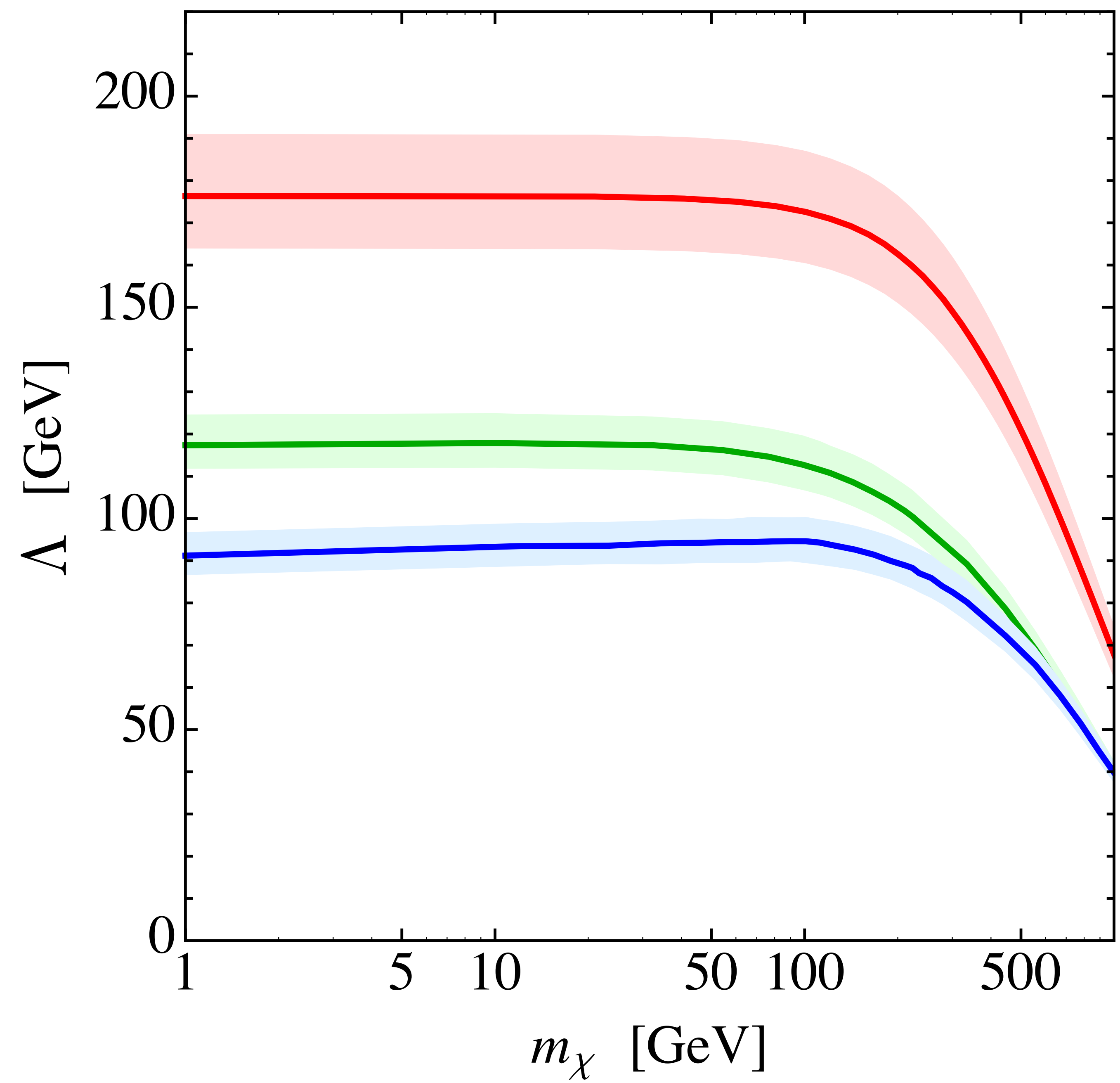
[CMS, 1408.2745]

$\not{E}_T + \bar{t}t\,(\to bjb\ell\nu)$

[CMS, 1308.1586]

$\not{E}_T + \bar{t}t\,(\to b\ell\nu b\ell\nu)$

[CMS-PAS-B2G-14-004]



Comments & thoughts

- Potential of $\not{E}_T$ + bjblν search not fully exploited, because existing analyses are recasts of SUSY searches that feature lowish $\not{E}_T$ cuts (e.g. $\not{E}_T$ > 250 GeV)

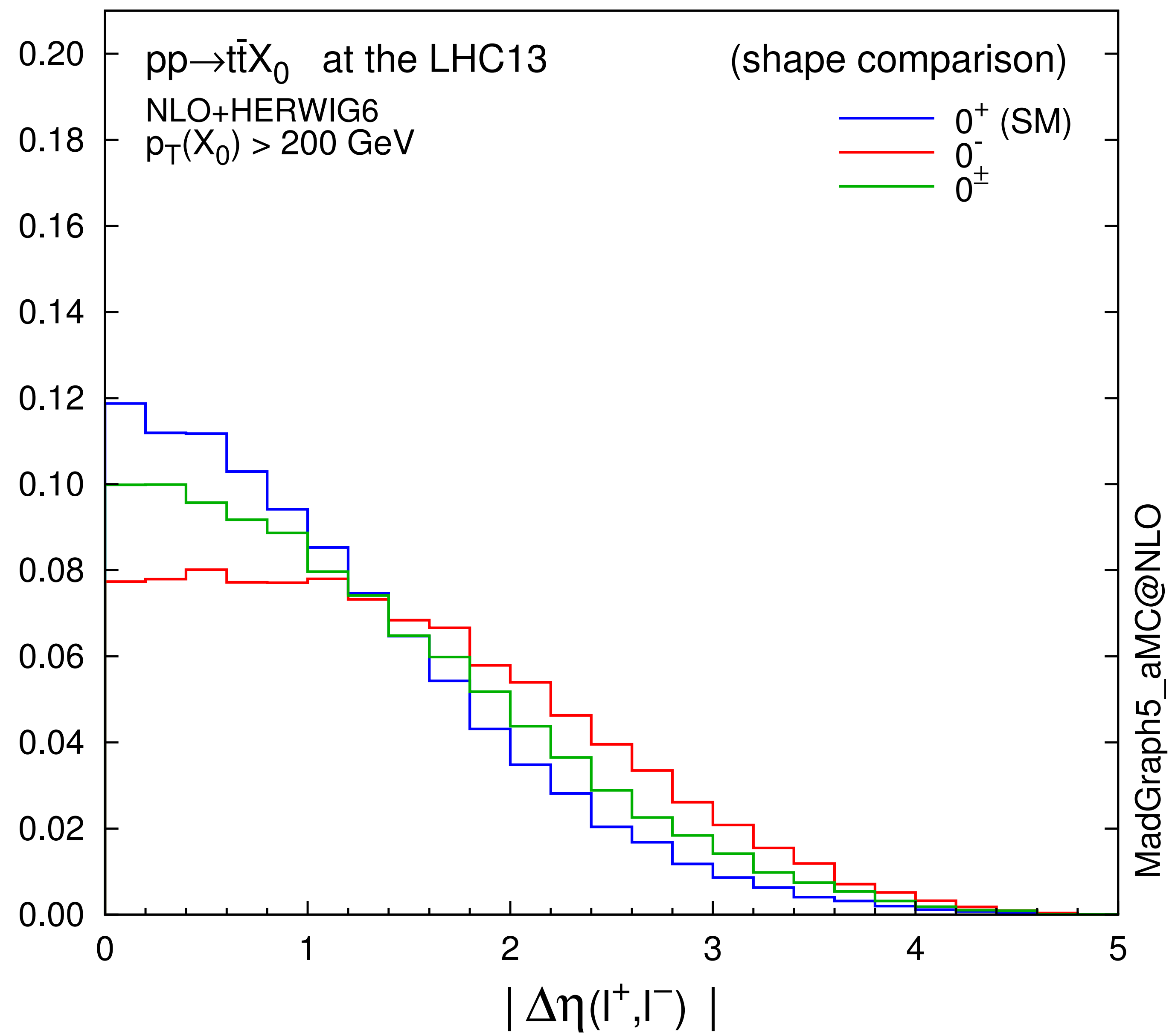
- Another way to look for DM $\bar{t}t$ couplings is $\not{E}_T$ + single-top production. Seems possible to find cuts that separate signal from SM background, but resulting fiducial cross sections very small. Prospects at 14 TeV?

- No dedicated $\not{E}_T$ + b/$\bar{b}$b searches ☹ until today ☺

Scalar vs. Pseudoscalar couplings

Can also try to infer if DM $\bar{t}t$ operators are scalar or pseudoscalar by considering decay distributions (works like methods suggested to determine CP nature of Higgs interactions in $h\bar{t}t$ production)

[Demartin, 1407.5089]



Conclusions

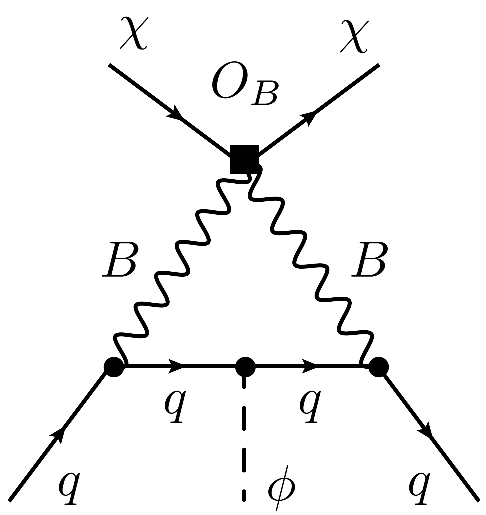
- DM-SM interactions of given type lead to signals in various channels. Can learn more from a global analysis than from a single $\not{E}_T$ mode

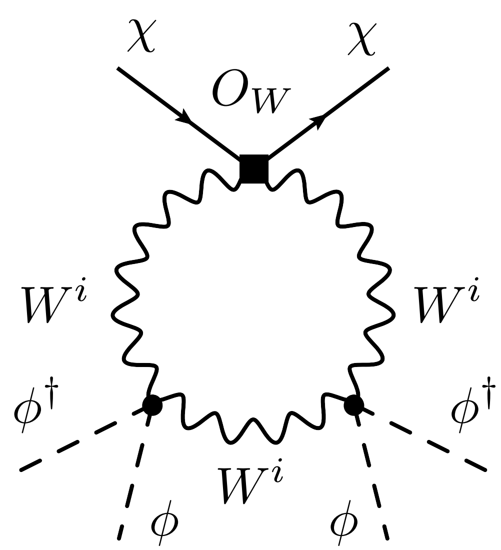
- Cross section measurements may lead to discovery of DM, but are insufficient to determine its precise nature. Studies of decay distributions can help to overcome this limitation

- Compared to cross sections for normalised distributions theoretical errors are reduced & predictions depend only weakly on whether EFT applicable or not

A $295K backup

Loop-induced direct detection





$$O_B \overset{\text{mixing}}{\longrightarrow} O_q = y_q\,\bar\chi\chi\,\bar q\phi q\,,$$

$$O_W \overset{\text{mixing}}{\longrightarrow} O_\phi = \bar\chi\chi\left(\phi^\dagger\phi\right)^2$$

$$C_q(\mu_l) \simeq \left(\frac{3Y_{q_L}Y_{q_R}\alpha_1}{\pi}\,C_B(\Lambda) + \frac{9\alpha_2^2}{2}\frac{v^2}{m_h^2}\,C_W(\Lambda)\right)\ln\left(\frac{m_W^2}{\Lambda^2}\right) + \ldots\,,$$

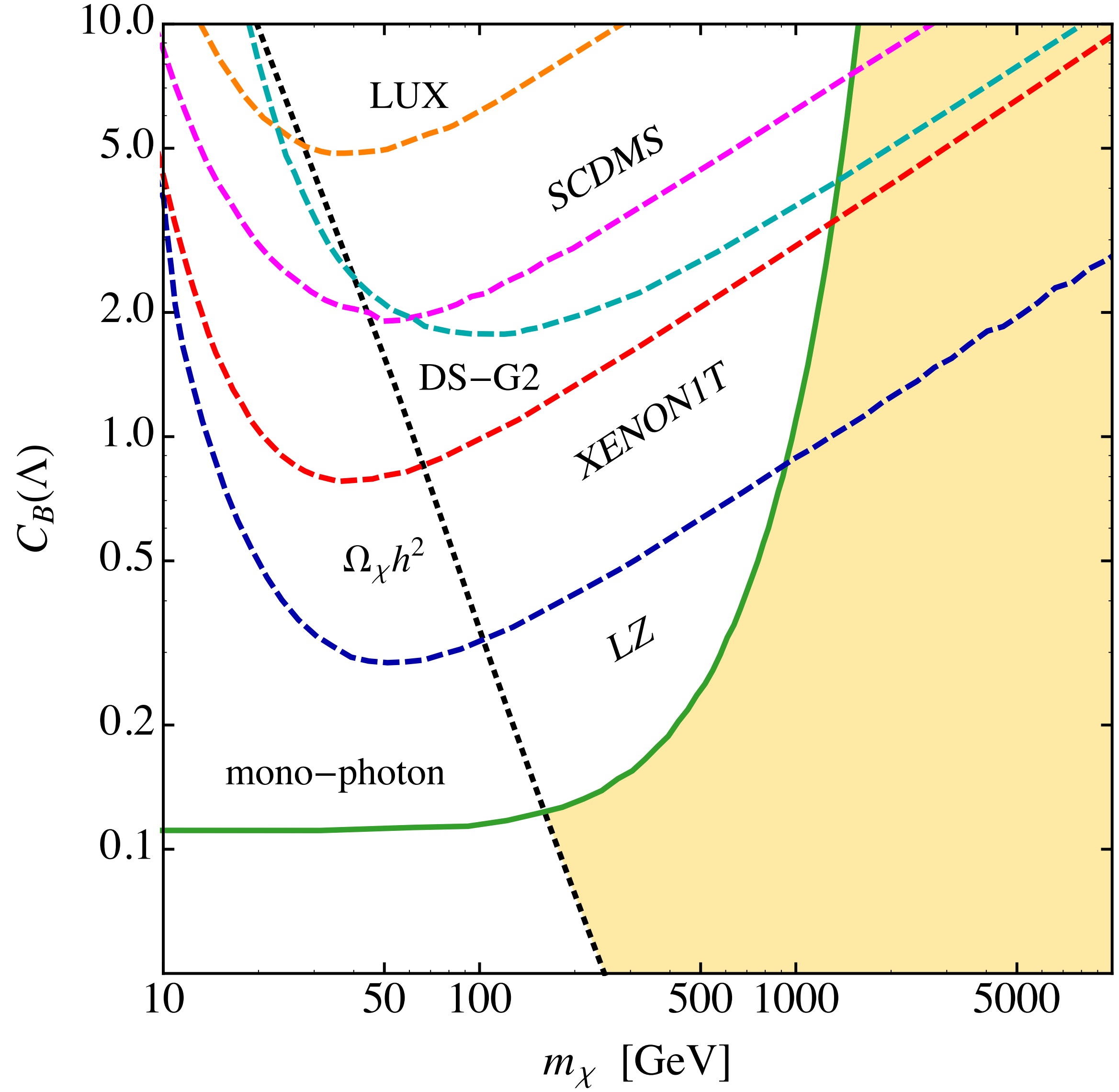
$$C_G(\mu_l) \simeq -\frac{1}{12\pi}\left\{\left(\frac{\alpha_1}{2\pi}\,C_B(\Lambda) + \frac{27\alpha_2^2}{2}\frac{v^2}{m_h^2}\,C_W(\Lambda)\right)\ln\left(\frac{m_W^2}{\Lambda^2}\right) + \ldots\right\}$$

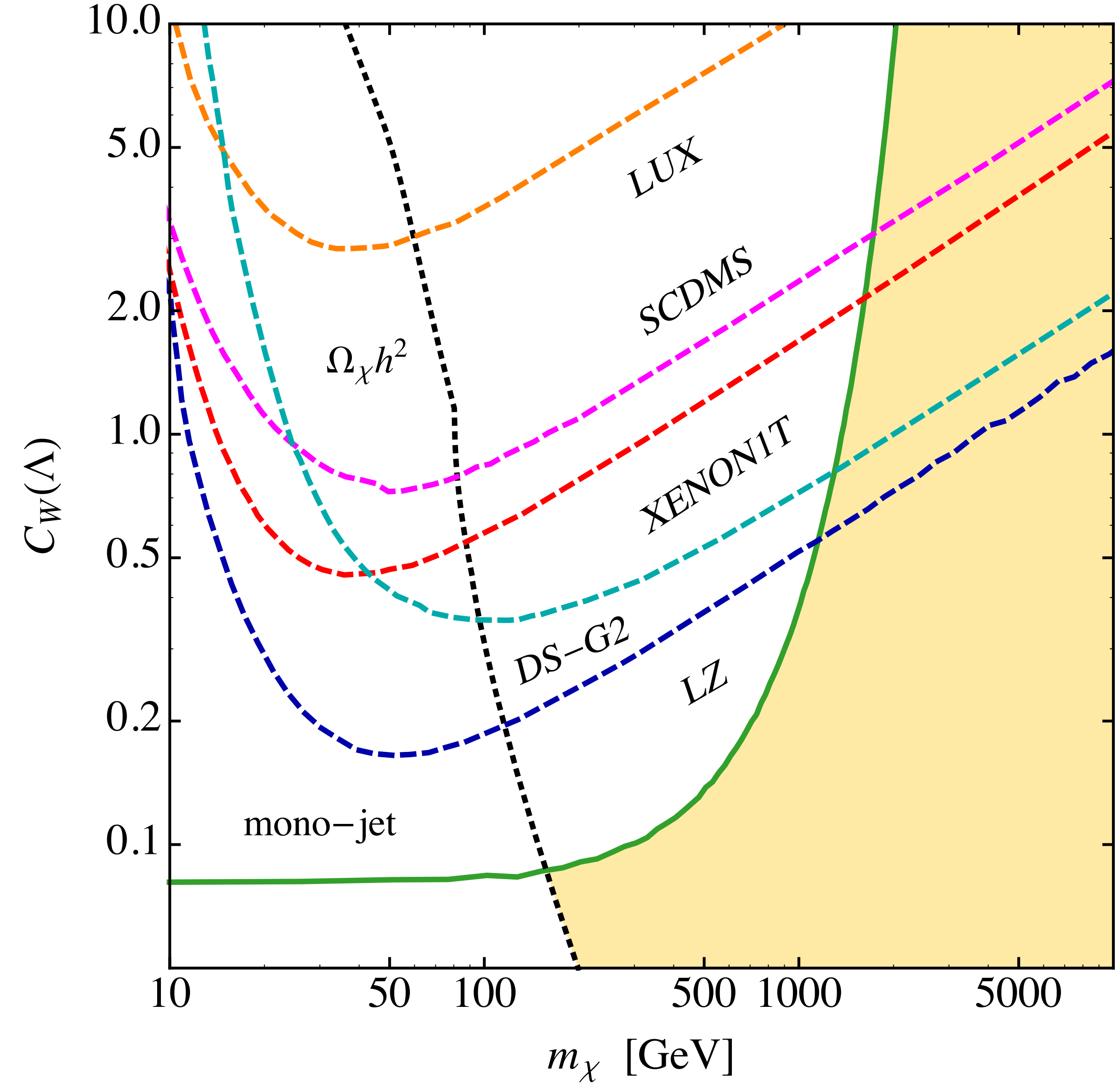
$$\sigma_N^{\rm SI} \simeq \frac{m_{\rm red}^2\,m_N^2}{\pi\,\Lambda^6}\left|\sum_{q=u,d,s} f_q^N\,C_q(\mu_l) - \frac{8\pi}{9}\,f_G^N\,C_G(\mu_l) + \ldots\right|^2$$

[Crevillin & UH, 1408.5046]

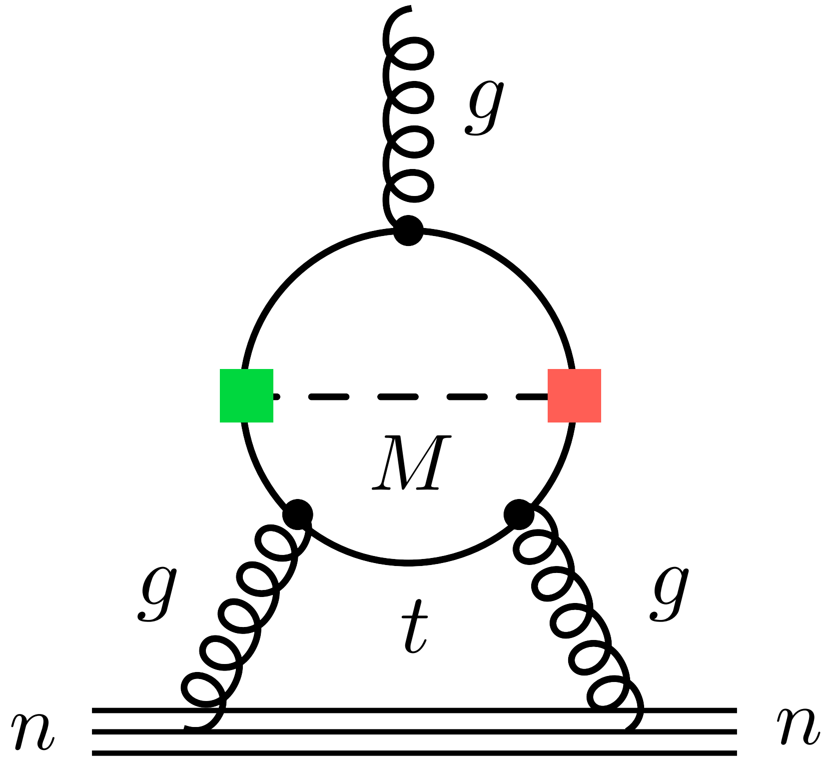
Bounds on O_B & O_W

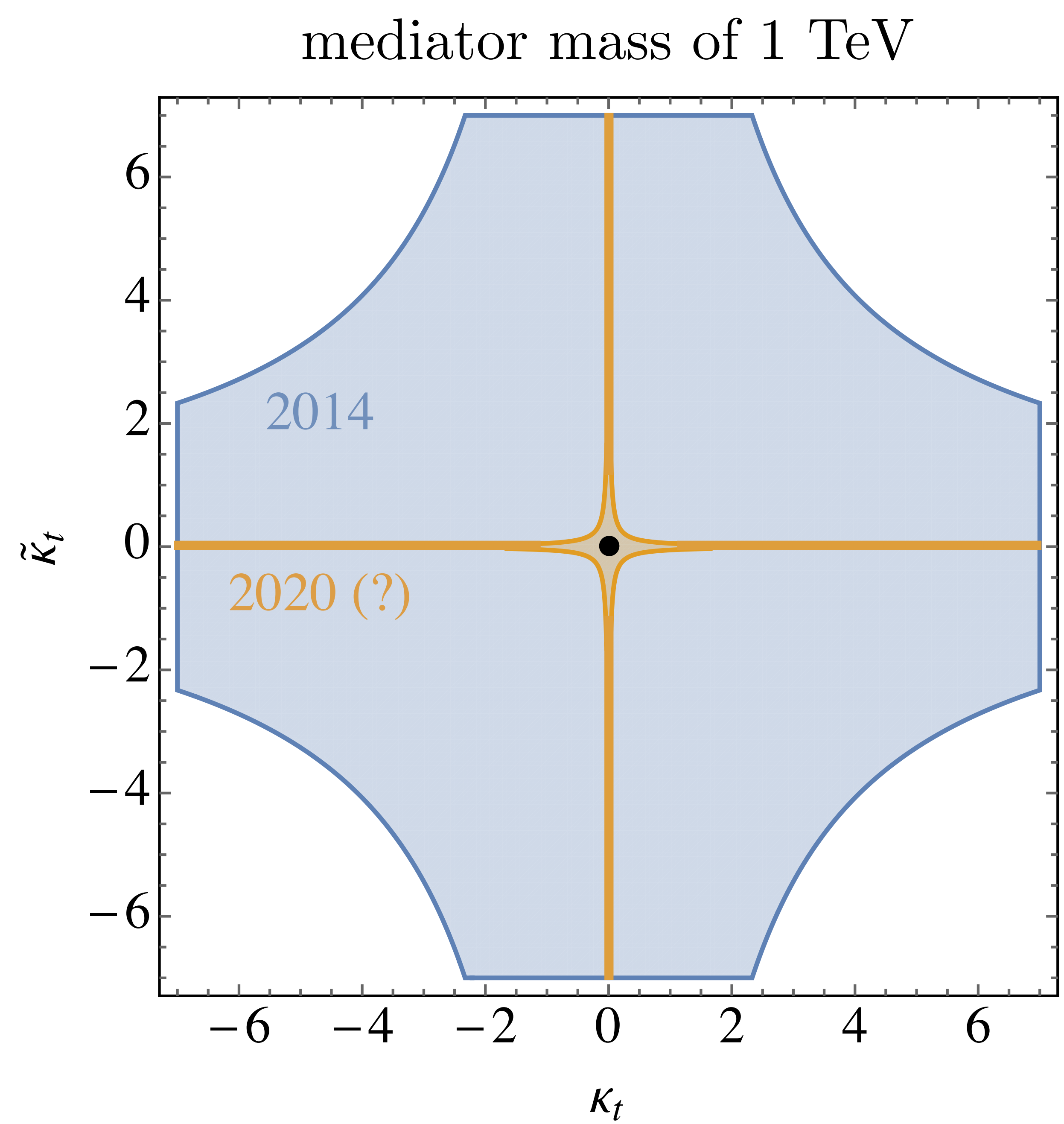
[Crevillin & UH, 1408.5046]





Constraint from neutron EDM





$$\mathcal{L} \supset (\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t)\, M + (\kappa_\chi\, \bar{\chi}\chi + i\,\tilde{\kappa}_\chi\, \bar{\chi}\gamma_5\chi)\, M$$

Single-top vs. $\not{E}_T$ + single-top