Distinguishing interactions in direct detection experiments

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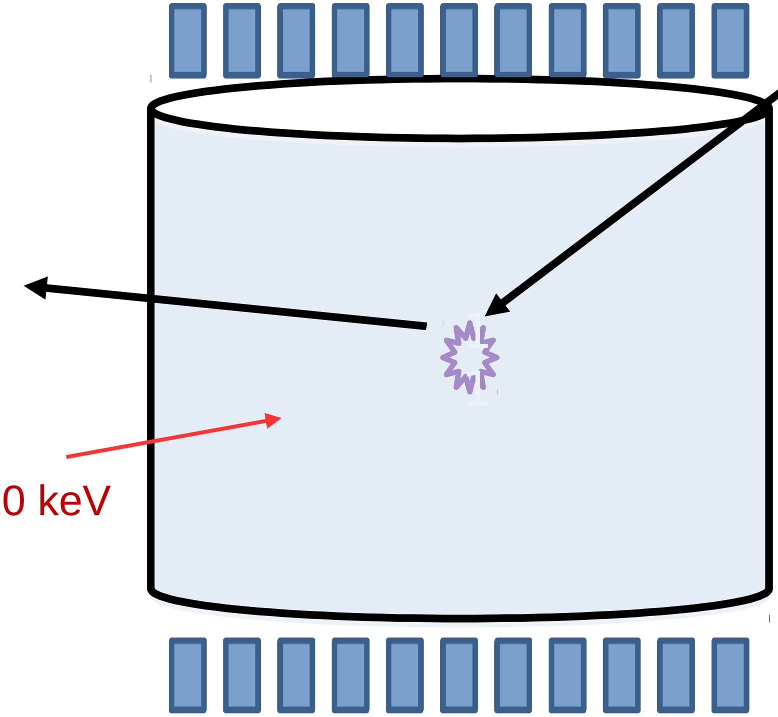
Outline

1. Introduction
2. Simplified models for direct detection
3. Distinguishability of operators
4. Summary

1. Introduction

Direct detection: overview

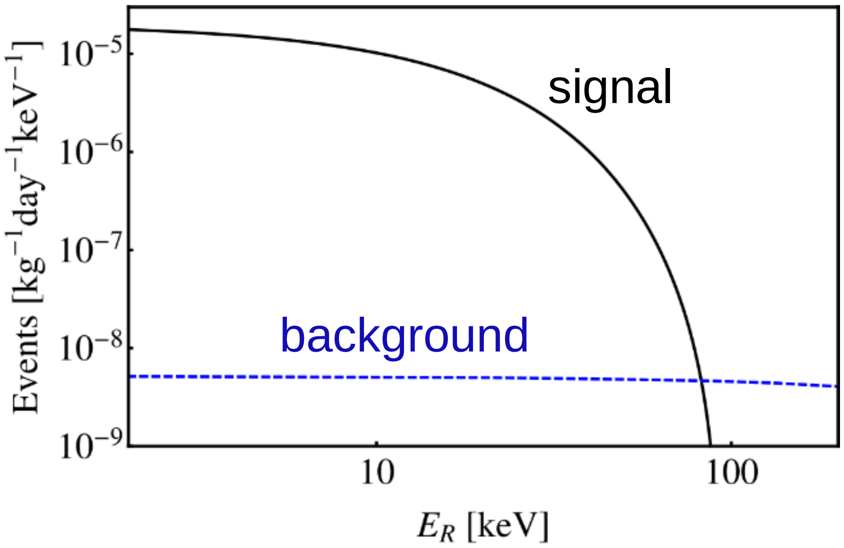


v ~ 200km/s

ρ ~ 0.3GeV/cm³

Er ~ 10 keV

- Nuclear recoils from halo WIMPs
- We don't collect much information
- from the collisions (this is no collider
- experiment)

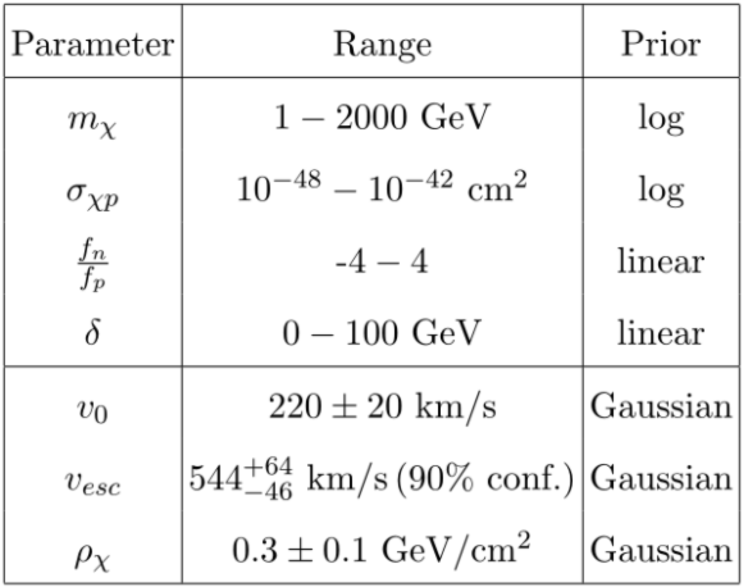


10^{-45} cm^2

$$\frac{dR}{dE_R} = \frac{\sigma_{\chi p}}{2m_\chi \mu_{\chi N}}\left(Z + \frac{f_n}{f_p}(A-Z)\right)^2 F^2(E_R) \int_{v_{min}}^{\infty} \rho_\chi \frac{f(\vec{v})}{v} d^3v.$$

Direct detection: parameter estimation

- Generate random or Asimov events
- Apply Bayesian inference:

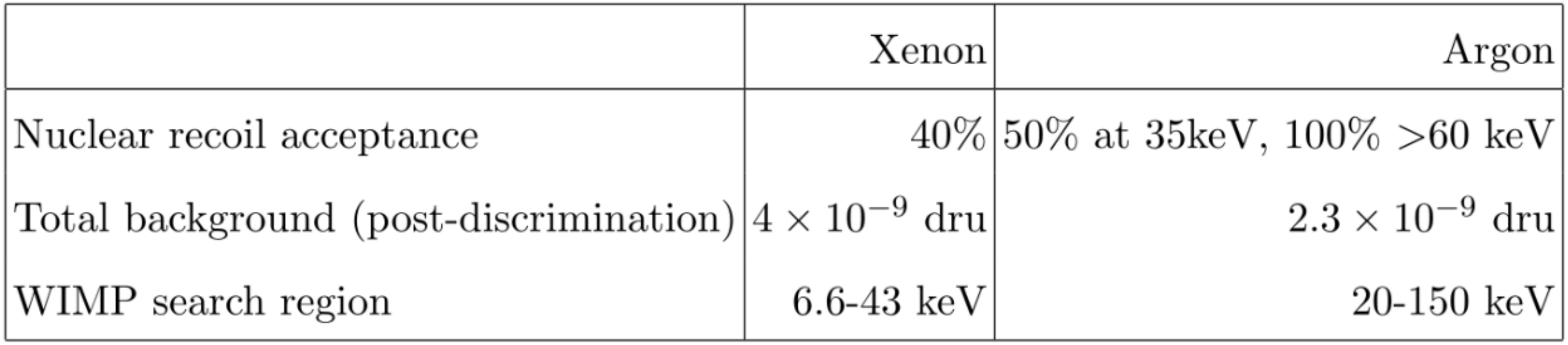


Parameter	Range	Prior
m_χ	$1 - 2000$ GeV	log
$\sigma_{\chi p}$	$10^{-48} - 10^{-42}$ cm^2	log
$\frac{f_n}{f_p}$	-4 – 4	linear
δ	$0 - 100$ GeV	linear
v_0	220 ± 20 km/s	Gaussian
v_{esc}	544^{+64}_{-46} km/s (90% conf.)	Gaussian
ρ_χ	0.3 ± 0.1 GeV/cm^2	Gaussian

$$\mathcal{P}(\theta, D|I) = \frac{\mathcal{L}(D|\theta, I)\pi(\theta, I)}{\epsilon(D, I)}$$

$$\mathcal{L}(\sigma, \theta) = \prod_{i=1}^{N} P(E_i(\sigma, \theta), A_i)$$

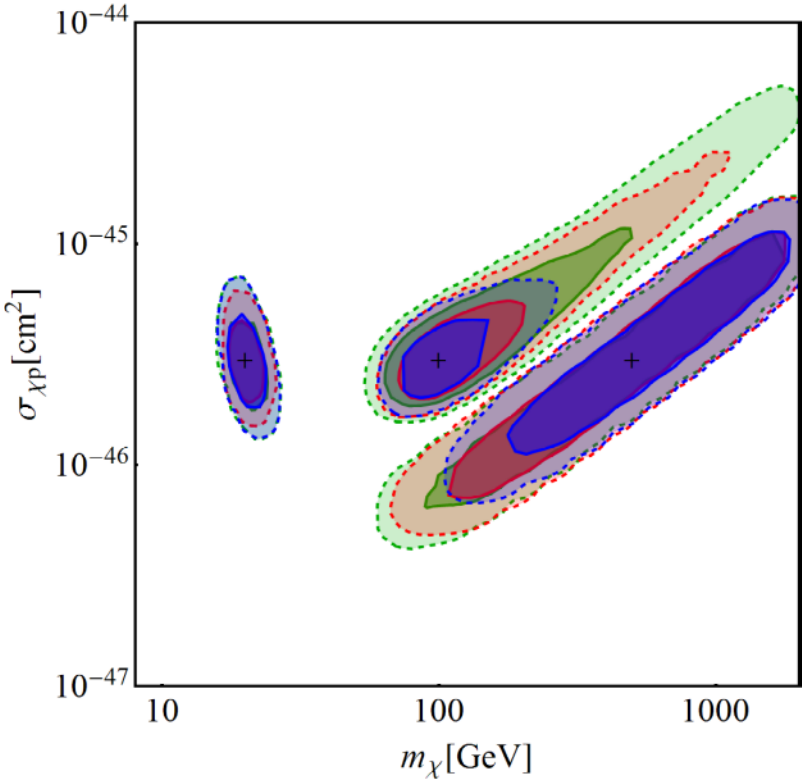
Detector specifications:



	Xenon	Argon
Nuclear recoil acceptance	40%	50% at 35keV, 100% >60 keV
Total background (post-discrimination)	4×10^{-9} dru	2.3×10^{-9} dru
WIMP search region	6.6-43 keV	20-150 keV

Direct detection: parameter estimation

σ = 3x10^{-46} cm^2
m_x = 20, 100, 500 GeV



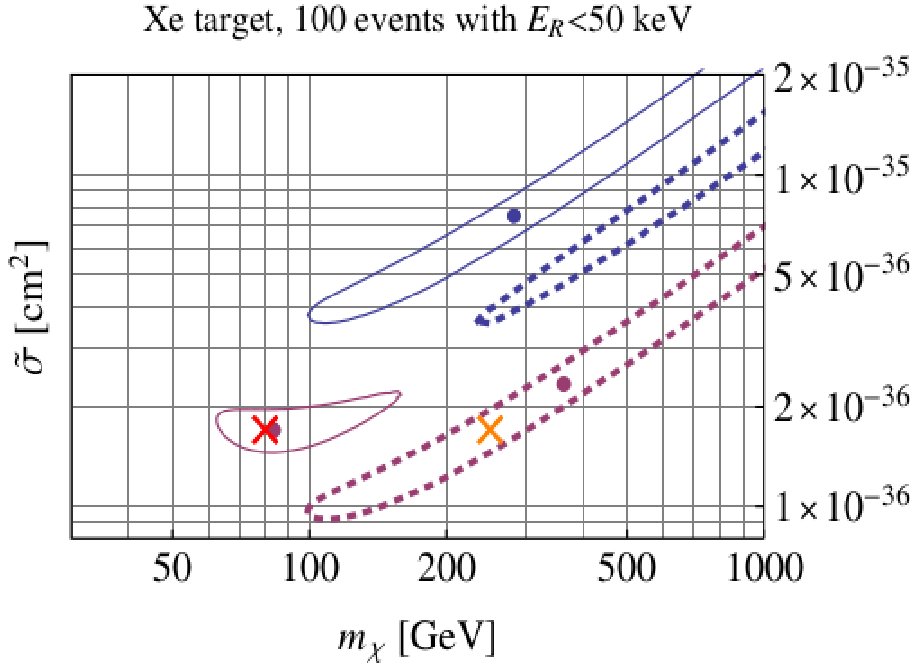
Xenon 10 t y
Xenon 20 t y
Xenon 10 t y
+Argon 20 t y

- - - 2 σ
— 1 σ

Having two different target materials provides complementary information, improving parameter estimation ability

Shortcomings of SI/SD formalism

- Treats nucleus as a point → form factor encodes energy dependence
- Does not include degrees of freedom for nucleon velocities (ignores responses related to transverse spin and orbital angular momentum)
- Result: you will estimate recoil energy dependence wrongly and over/under estimate total rate



Example from Gresham & Zurek
arXiv:1401.3739

3. Simplified Models for direct detection

Based on
arXiv:1505.03117

Non-relativistic EFT for DD

WIMP spin
Nucleon spin
Momentum transfer
velocity

$\mathcal{O}_1$	$1_\chi 1_N$
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$

Formalism due to
Fitzpatrick et. al.
arXiv:1203.3542 and
arXiv:1308.6288

Non-relativistic EFT for DD

WIMP spin
Nucleon spin
Momentum transfer
velocity

SI	$\mathcal{O}_1$	$1_\chi 1_N$
	$\mathcal{O}_2$	$(\vec{v}^\perp)^2$
	$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
SD	$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$
	$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
	$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
	$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$
	$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
	$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
	$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
	$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
	$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
	$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
	$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
	$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$

"The standard SI/SD analysis grossly misrepresents the physics of these operators, leading to errors that can exceed several orders of magnitude"
arXiv:1308.6288

New vector operators:

$$\mathcal{O}_{17} \equiv \frac{i\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{v}_\perp,$$

$$\mathcal{O}_{18} \equiv \frac{i\vec{q}}{m_N} \cdot \mathcal{S} \cdot \vec{S}_N,$$

Formalism due to Fitzpatrick et. al. arXiv:1203.3542 and

arXiv:1308.6288

Nuclear responses

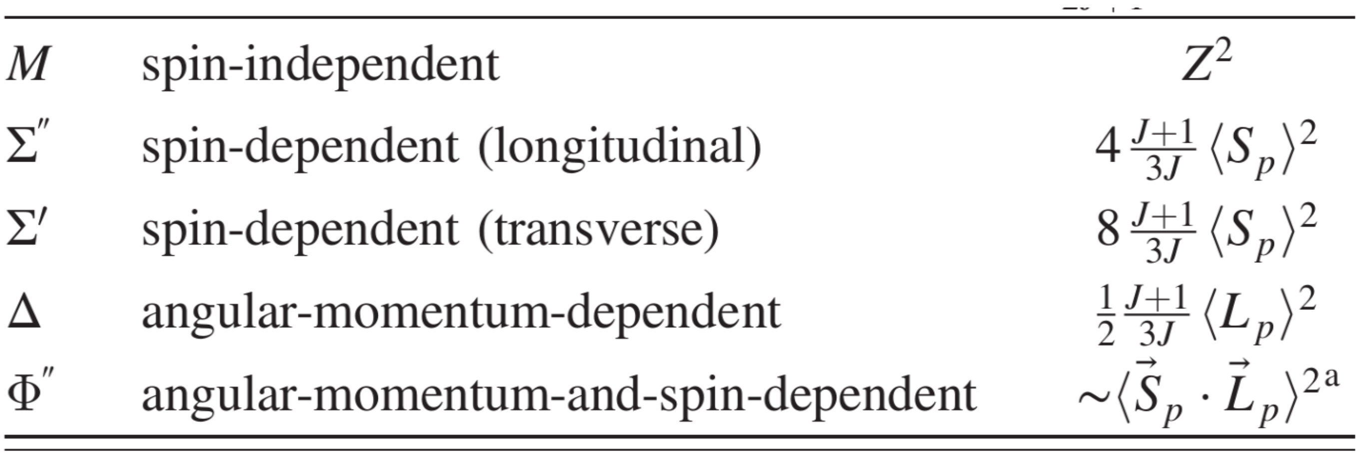
1. Form an interaction lagrangian:

$$\mathcal{L}_{NR} = \sum_{\alpha=n,p} \sum_{i=1}^{15} c_i^\alpha \mathcal{O}_i^\alpha$$

2. Perform a spherical decomposition,

$$\vec{M}_{JLM}(q\vec{x}_i) \equiv j_L(qx_i)\vec{Y}_{JLM}(\Omega_{x_i}), \quad \vec{Y}_{JLM}(\Omega_{x_i}) \equiv \sum_{m\lambda} Y_{LM}(\Omega_{x_i})\vec{e}_\lambda \langle Lm1\lambda|(L1)JM\rangle,$$

3. Write in terms of nuclear electroweak responses



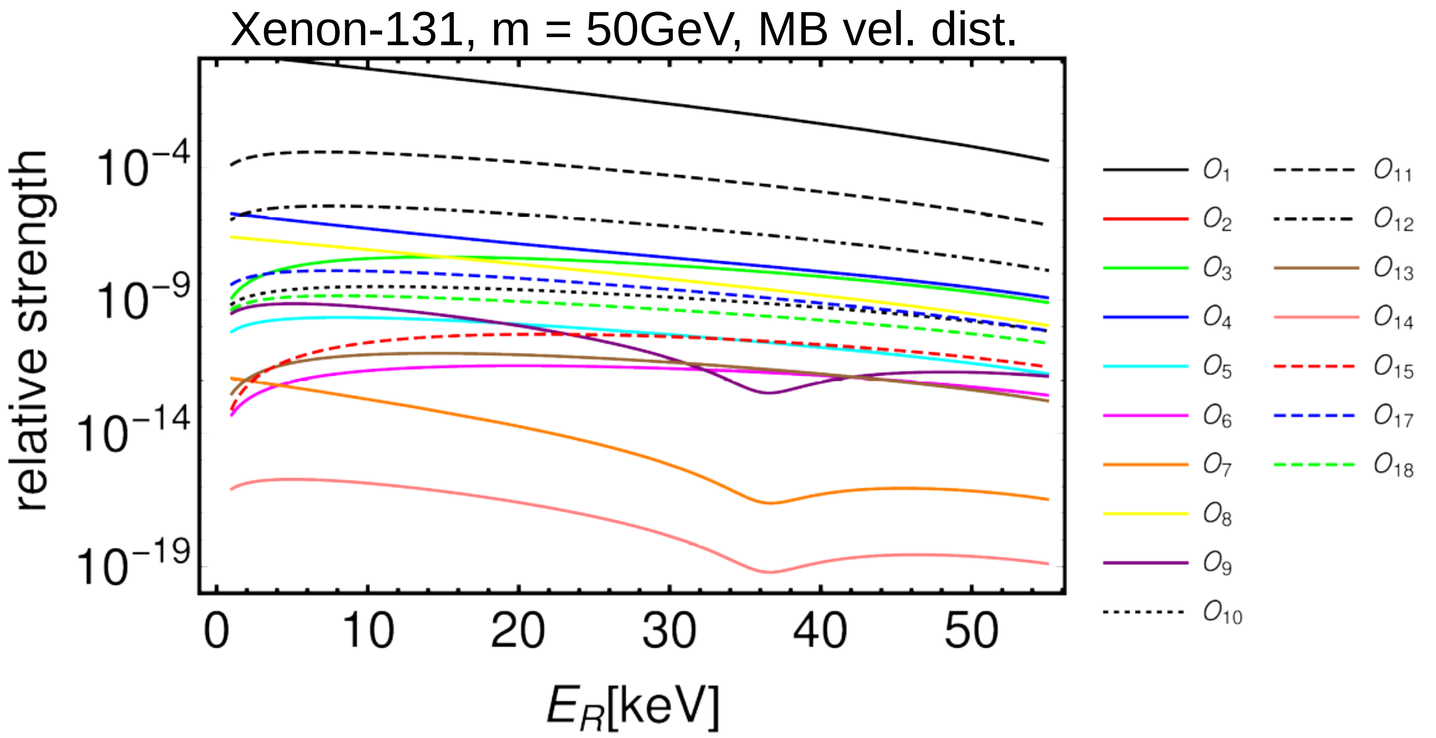
M	spin-independent	Z^2
Σ''	spin-dependent (longitudinal)	$4\,\frac{J+1}{3J}\,\langle S_p\rangle^2$
Σ'	spin-dependent (transverse)	$8\,\frac{J+1}{3J}\,\langle S_p\rangle^2$
Δ	angular-momentum-dependent	$\frac{1}{2}\,\frac{J+1}{3J}\,\langle L_p\rangle^2$
Φ''	angular-momentum-and-spin-dependent	$\sim\langle \vec{S}_p \cdot \vec{L}_p\rangle^{2\,\mathrm{a}}$

M.I. Gresham and K.M. Zurek, PRD 89 123521 (2014) arXiv:1401.3739

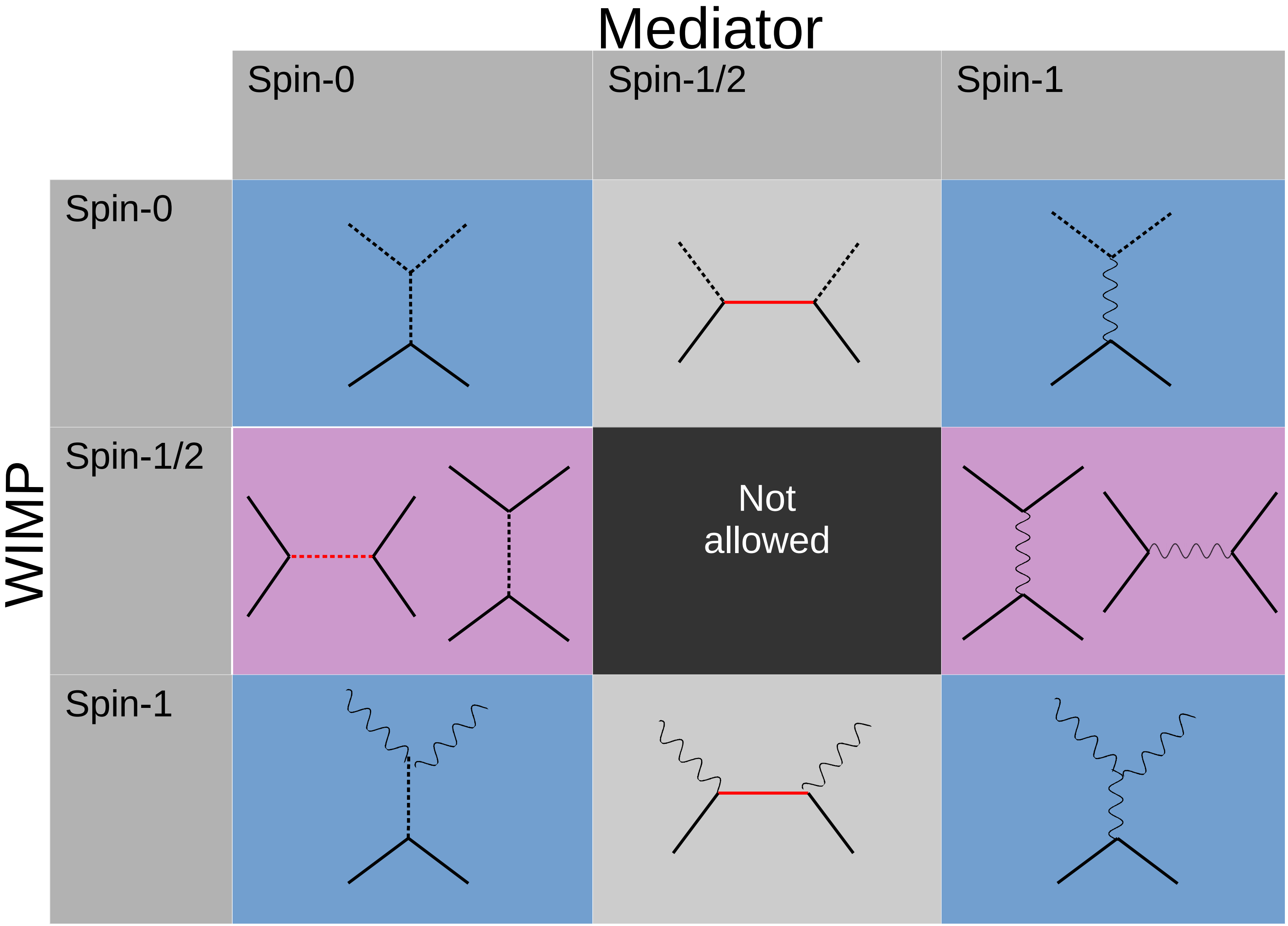
Non-relativistic EFT for DD

$$\frac{1}{2j_\chi+1}\frac{1}{2j_N+1}\sum_{\text{spins}}|\mathcal{M}|^2 \equiv \sum_k \sum_{\tau=0,1}\sum_{\tau'=0,1} \underbrace{\boxed{R_k\left(\vec{v}_T^{\perp 2}, \frac{\vec{q}^{\,2}}{m_N^2}, \left\{c_i^\tau c_j^{\tau'}\right\}\right)}}_{\text{particle}} \underbrace{\boxed{W_k^{\tau\tau'}(\vec{q}^{\,2} b^2)}}_{\text{nuclear}}$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi M}{2\pi m_\chi} \int_{v_{min}} dv \frac{f(v)}{v} \frac{1}{2j_\chi+1}\frac{1}{2j_N+1} \sum_{spins} |\mathcal{M}|^2$$



Tree-level WIMP-quark interactions



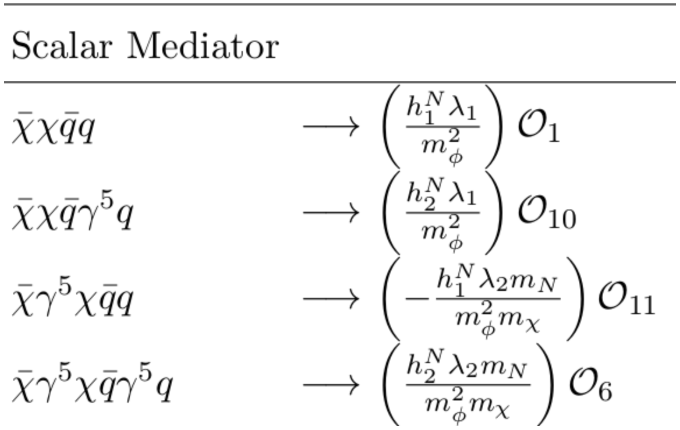
Mediator

WIMP

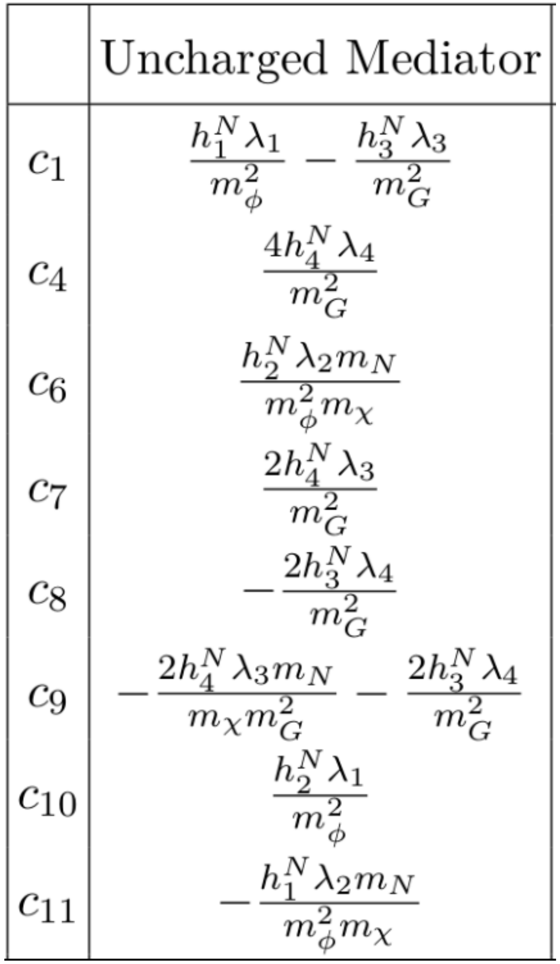
	Spin-0	Spin-1/2	Spin-1
Spin-0			
Spin-1/2		Not allowed	
Spin-1			

Simplified model lagrangians

$$\begin{aligned}\mathcal{L}_{\chi\phi q} = & \; i\bar{\chi}\not{D}\chi - m_\chi\bar{\chi}\chi \\ & +\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \frac{m_\phi\mu_1}{3}\phi^3 - \frac{\mu_2}{4}\phi^4 \\ & +i\bar{q}\not{D}q - m_q\bar{q}q \\ & -\lambda_1\phi\bar{\chi}\chi - i\lambda_2\phi\bar{\chi}\gamma^5\chi - h_1\phi\bar{q}q - ih_2\phi\bar{q}\gamma^5 q,\end{aligned}$$



Scalar Mediator		
$\bar{\chi}\chi\bar{q}q$	$\longrightarrow$	$\left(\frac{h_1^N\lambda_1}{m_\phi^2}\right)\mathcal{O}_1$
$\bar{\chi}\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{h_2^N\lambda_1}{m_\phi^2}\right)\mathcal{O}_{10}$
$\bar{\chi}\gamma^5\chi\bar{q}q$	$\longrightarrow$	$\left(-\frac{h_1^N\lambda_2 m_N}{m_\phi^2 m_\chi}\right)\mathcal{O}_{11}$
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$\longrightarrow$	$\left(\frac{h_2^N\lambda_2 m_N}{m_\phi^2 m_\chi}\right)\mathcal{O}_6$



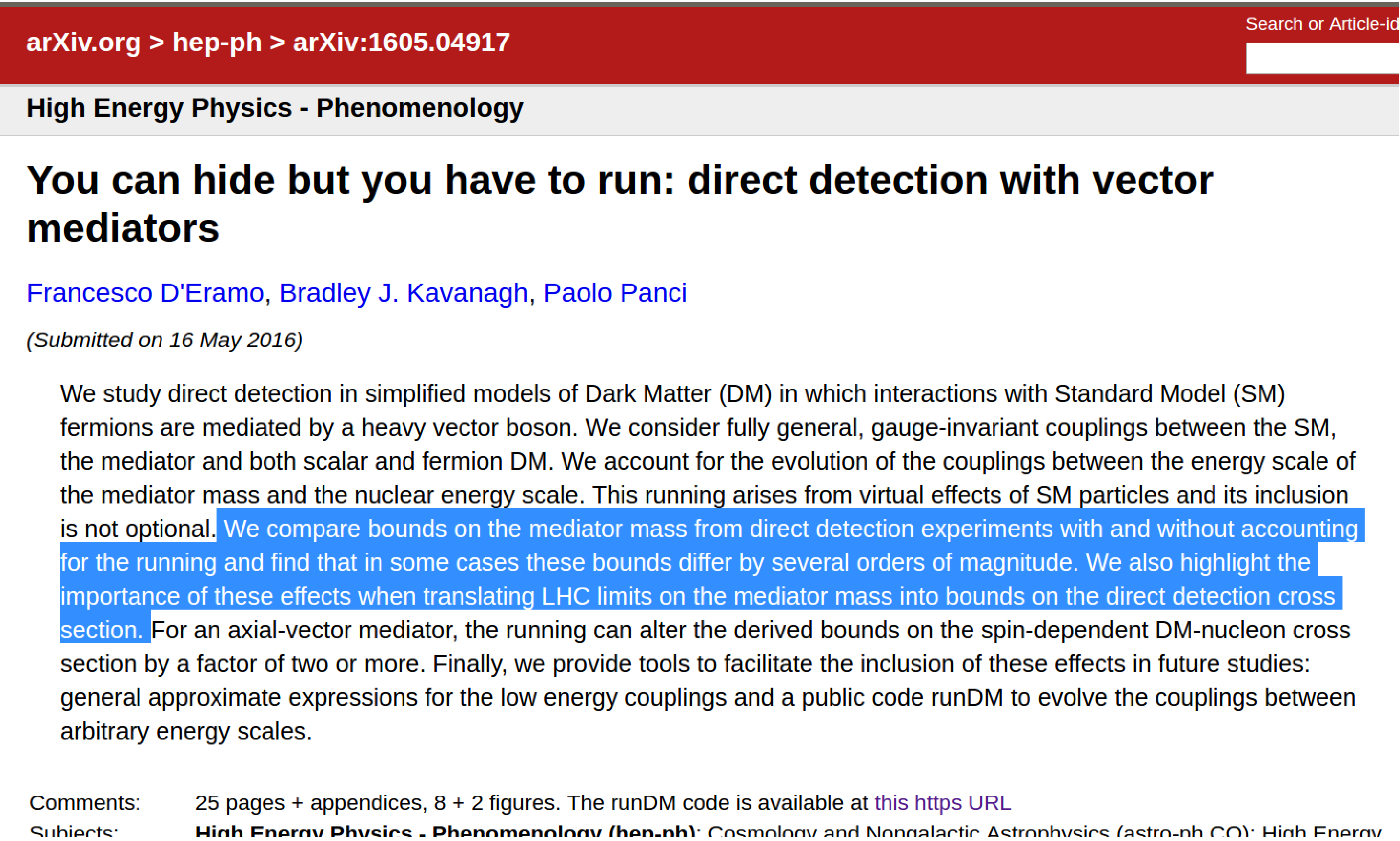
	Uncharged Mediator
c_1	$\frac{h_1^N\lambda_1}{m_\phi^2} - \frac{h_3^N\lambda_3}{m_G^2}$
c_4	$\frac{4h_4^N\lambda_4}{m_G^2}$
c_6	$\frac{h_2^N\lambda_2 m_N}{m_\phi^2 m_\chi}$
c_7	$\frac{2h_4^N\lambda_3}{m_G^2}$
c_8	$-\frac{2h_3^N\lambda_4}{m_G^2}$
c_9	$-\frac{2h_4^N\lambda_3 m_N}{m_\chi m_G^2} - \frac{2h_3^N\lambda_4}{m_G^2}$
c_{10}	$\frac{h_2^N\lambda_1}{m_\phi^2}$
c_{11}	$-\frac{h_1^N\lambda_2 m_N}{m_\phi^2 m_\chi}$

Results

- 32 distinct 'scenarios'
- We could not produce all operators, even at sub-leading order
- Huge variation in intrinsic strength of interaction (many scenarios may not be WIMP DM)
- Some unique NR reductions
- O1 and O10 generic to all spins

WIMP spin	Mediator spin	$\mathcal{L}$ terms	leading NR operator	Eqv. M_m
0	0	h_1, g_1	$\mathcal{O}_1$	13 TeV
0	0	h_2, g_1	$\mathcal{O}_{10}$	14 GeV
0	1	h_4, g_4	$\mathcal{O}_{10}$	8 GeV
0	$\frac{1}{2}^\dagger$	y_1	$\mathcal{O}_1$	3.2 PeV
0	$\frac{1}{2}^\dagger$	y_2	$\mathcal{O}_1$	3.2 PeV
0	$\frac{1}{2}^\dagger$	y_1, y_2	$\mathcal{O}_{10}$	41 GeV
$\frac{1}{2}$	0	h_1, λ_1	$\mathcal{O}_1$	12.7 TeV
$\frac{1}{2}$	0	h_2, λ_1	$\mathcal{O}_{10}$	293 GeV
$\frac{1}{2}$	0	h_1, λ_2	$\mathcal{O}_{11}$	14 GeV
$\frac{1}{2}$	0	h_2, λ_2	$\mathcal{O}_6$	1.9 GeV
$\frac{1}{2}$	1	h_3, λ_3	$\mathcal{O}_1$	6.3 TeV
$\frac{1}{2}$	1	h_4, λ_3	$\mathcal{O}_9$	6.4 GeV
$\frac{1}{2}$	1	h_3, λ_4	$\mathcal{O}_8$	180 GeV
$\frac{1}{2}$	1	h_4, λ_4	$\mathcal{O}_4$	135 GeV
$\frac{1}{2}$	$0^\dagger$	l_1	$\mathcal{O}_1$	7.1 TeV
$\frac{1}{2}$	$0^\dagger$	l_2	$\mathcal{O}_1$	5.5 TeV
$\frac{1}{2}$	$1^\dagger$	d_1	$\mathcal{O}_1$	5.9 TeV
$\frac{1}{2}$	$1^\dagger$	d_2	$\mathcal{O}_1$	6.7 TeV
1	0	h_1, b_1	$\mathcal{O}_1$	13 TeV
1	0	h_2, b_1	$\mathcal{O}_{10}$	10 GeV
1	1	h_4, b_5	$\mathcal{O}_{10}$	5.1 GeV
1	1	$h_3, b_6^{\mathrm{Re}}(b_6^{\mathrm{Im}})$	$\mathcal{O}_5(\mathcal{O}_{17})$	5.5 GeV(23 GeV)
1	1	$h_4, b_6^{\mathrm{Re}}(b_6^{\mathrm{Im}})$	$\mathcal{O}_9(\mathcal{O}_{18})$	3 GeV(4.6 GeV)
1	1	$h_3, b_7^{\mathrm{Re}}(b_7^{\mathrm{Im}})$	$\mathcal{O}_{11}(\mathcal{O}_8)$	186 GeV(228 GeV)
1	1	$h_4, b_7^{\mathrm{Re}}(b_7^{\mathrm{Im}})$	$\mathcal{O}_4(\mathcal{O}_4)$	78 MeV (172 GeV)
1	$\frac{1}{2}^\dagger$	y_3	$\mathcal{O}_1$	3.2 PeV
1	$\frac{1}{2}^\dagger$	y_4	$\mathcal{O}_1$	3.2 PeV
1	$\frac{1}{2}^\dagger$	y_3, y_4	$\mathcal{O}_{11}$	120 TeV

Caveat:



arXiv.org > hep-ph > arXiv:1605.04917

Search or Article-id

High Energy Physics - Phenomenology

You can hide but you have to run: direct detection with vector mediators

Francesco D'Eramo, Bradley J. Kavanagh, Paolo Panci

(Submitted on 16 May 2016)

We study direct detection in simplified models of Dark Matter (DM) in which interactions with Standard Model (SM) fermions are mediated by a heavy vector boson. We consider fully general, gauge-invariant couplings between the SM, the mediator and both scalar and fermion DM. We account for the evolution of the couplings between the energy scale of the mediator mass and the nuclear energy scale. This running arises from virtual effects of SM particles and its inclusion is not optional. We compare bounds on the mediator mass from direct detection experiments with and without accounting for the running and find that in some cases these bounds differ by several orders of magnitude. We also highlight the importance of these effects when translating LHC limits on the mediator mass into bounds on the direct detection cross section. For an axial-vector mediator, the running can alter the derived bounds on the spin-dependent DM-nucleon cross section by a factor of two or more. Finally, we provide tools to facilitate the inclusion of these effects in future studies: general approximate expressions for the low energy couplings and a public code runDM to evolve the couplings between arbitrary energy scales.

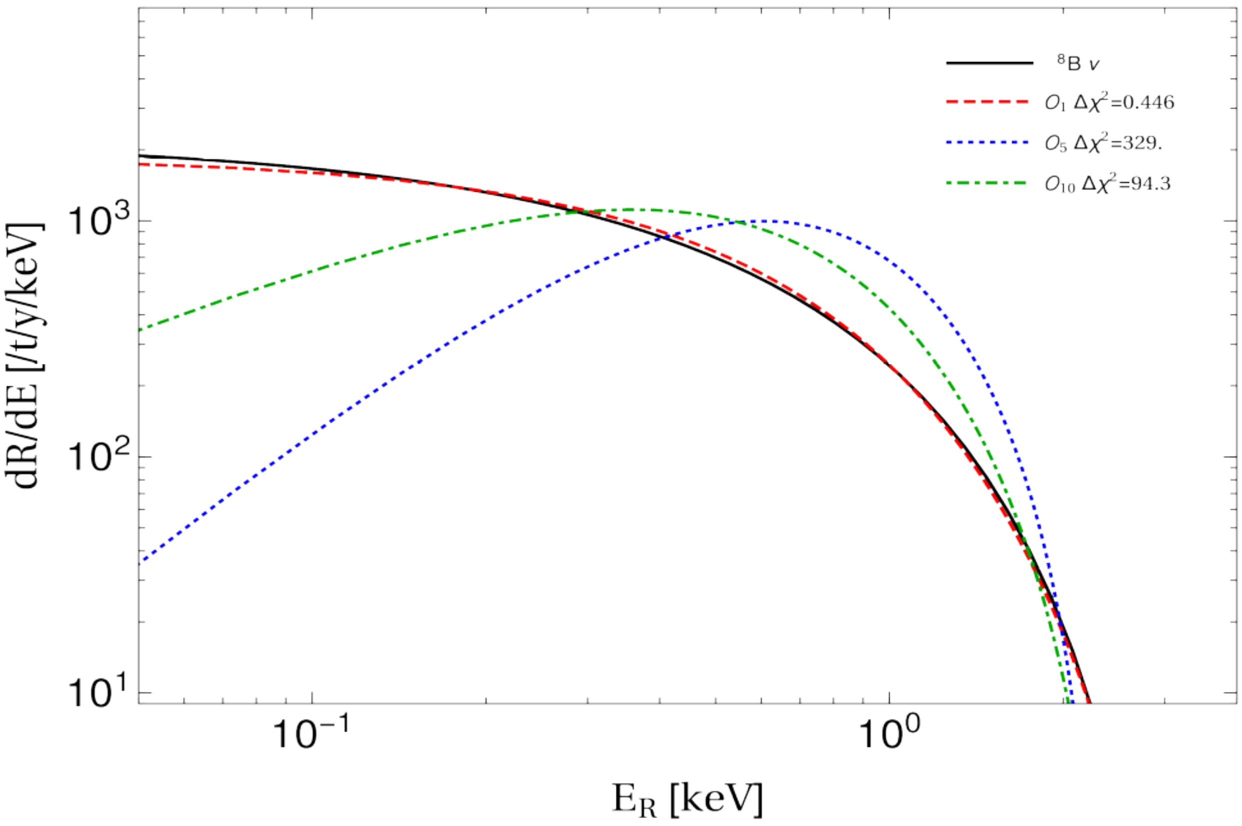
Comments: 25 pages + appendices, 8 + 2 figures. The runDM code is available at this https URL

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); High Energy

3. Operator Distinguishability

See also:
Catena, 1405.2367
Glusevic, 1506.04454

EFT parameter estimation: groups



- Generate random or Asimov events
- Apply Bayesian inference:

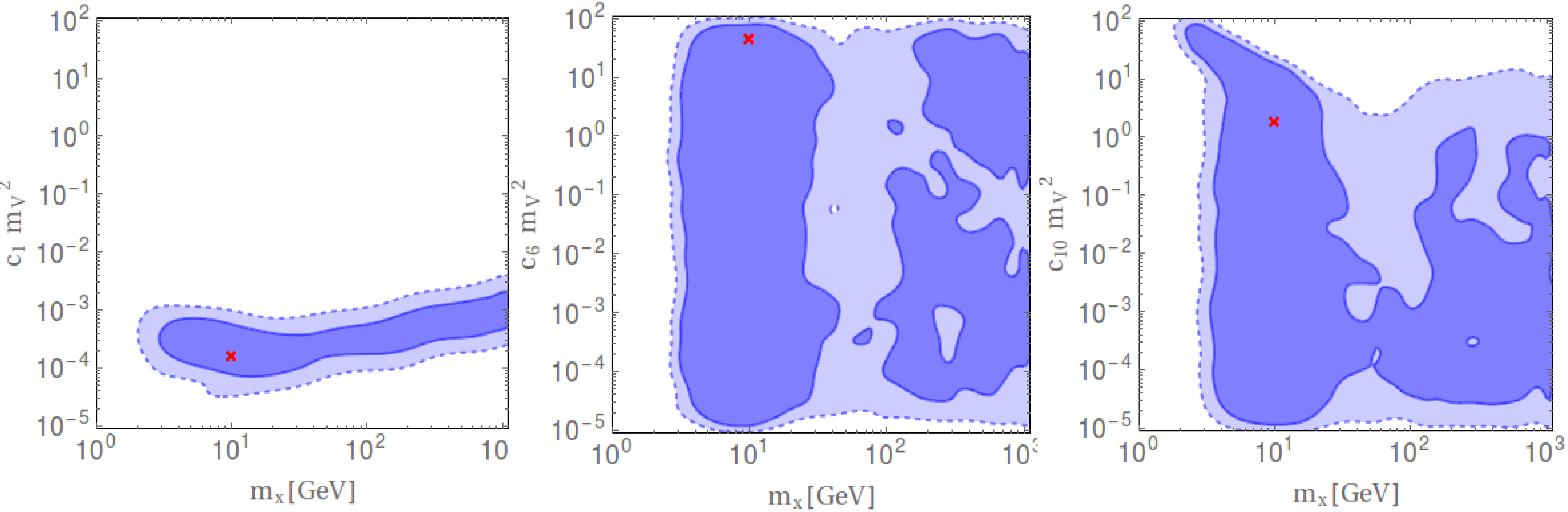
$$\mathcal{P}(\theta, D|I) = \frac{\mathcal{L}(D|\theta, I)\pi(\theta, I)}{\epsilon(D, I)}$$

Operator
$\mathcal{O}_1$
$\mathcal{O}_4$
$\mathcal{O}_7$
$\mathcal{O}_8$
q^2 and $q^2 v_T^2$
$\mathcal{O}_5$
$\mathcal{O}_9$
$\mathcal{O}_{10}$
$\mathcal{O}_{11}$
$\mathcal{O}_{12}$
$\mathcal{O}_{14}$
$q^2 v_T^2$, q^4 and $q^4 v_T^2$
$\mathcal{O}_3$
$\mathcal{O}_6$
$\mathcal{O}_{13}$
$\mathcal{O}_{15}$

EFT parameter estimation

M = 10 GeV, 20 events

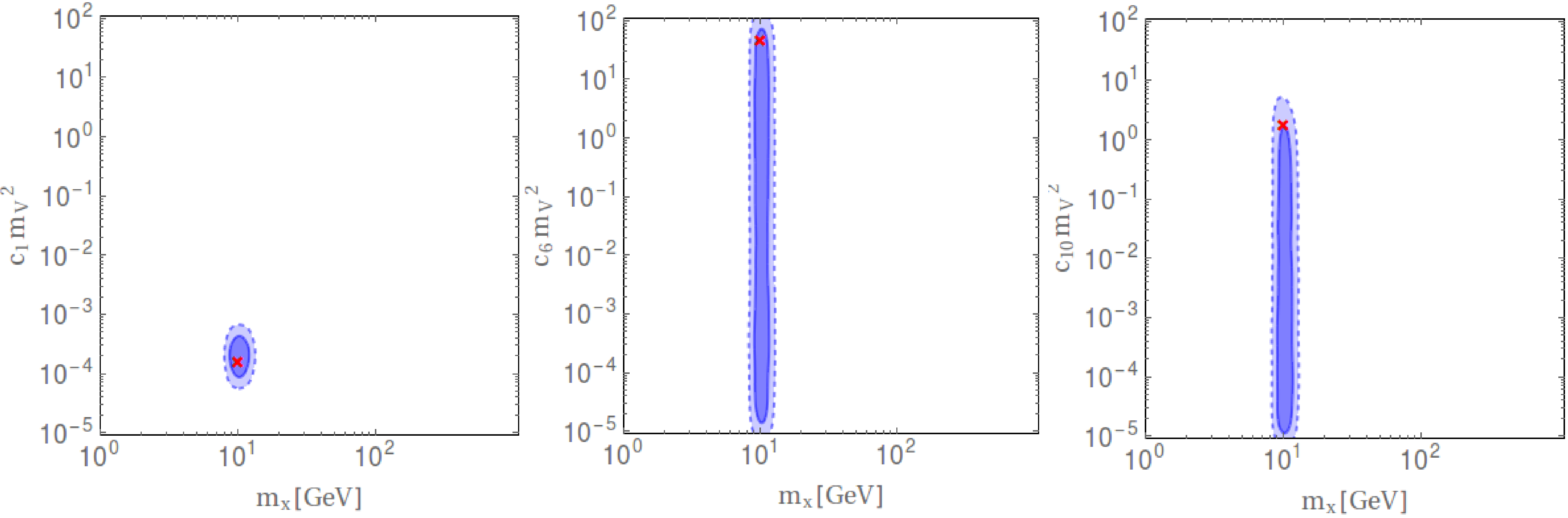
O1 simulated



EFT parameter estimation

M = 10 GeV, 200 events

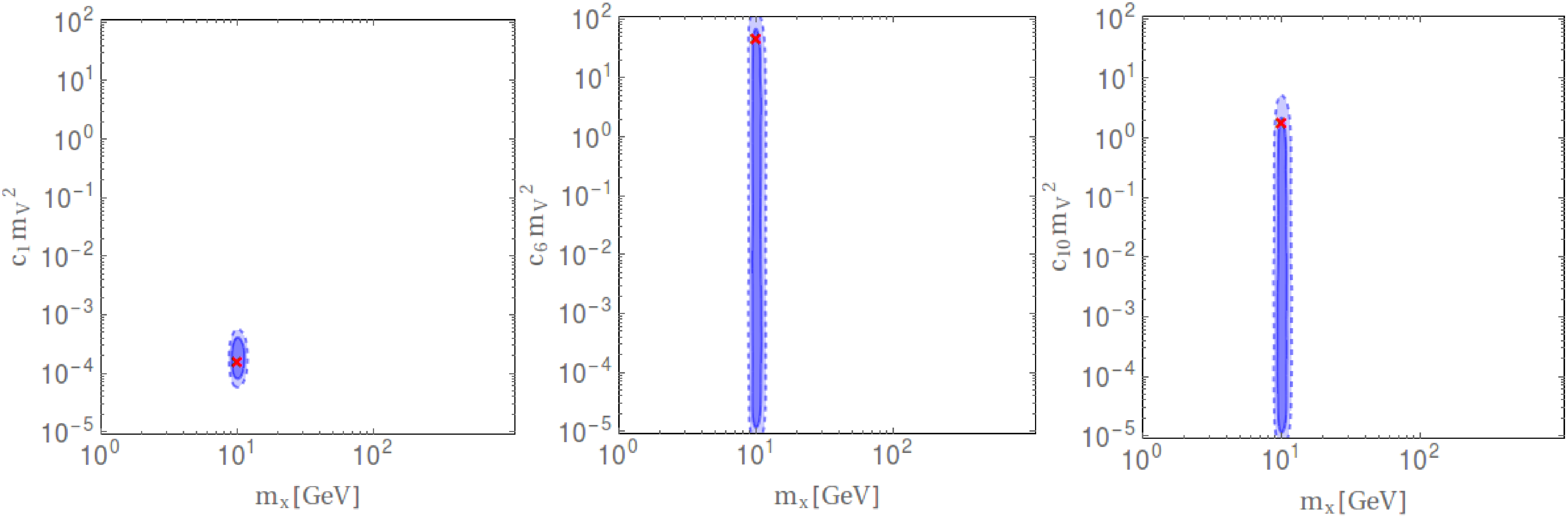
O1 simulated



EFT parameter estimation

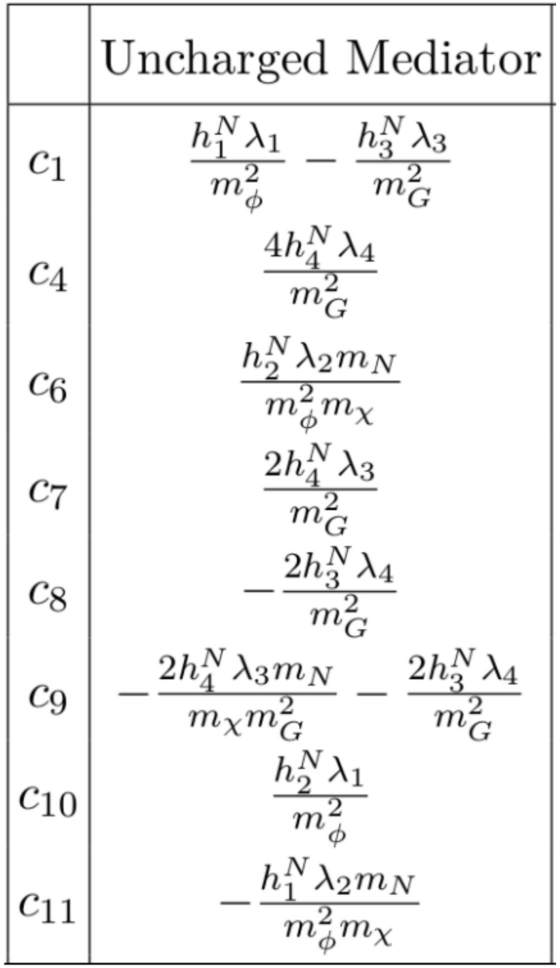
M = 10 GeV, 2,000 events

O1 simulated

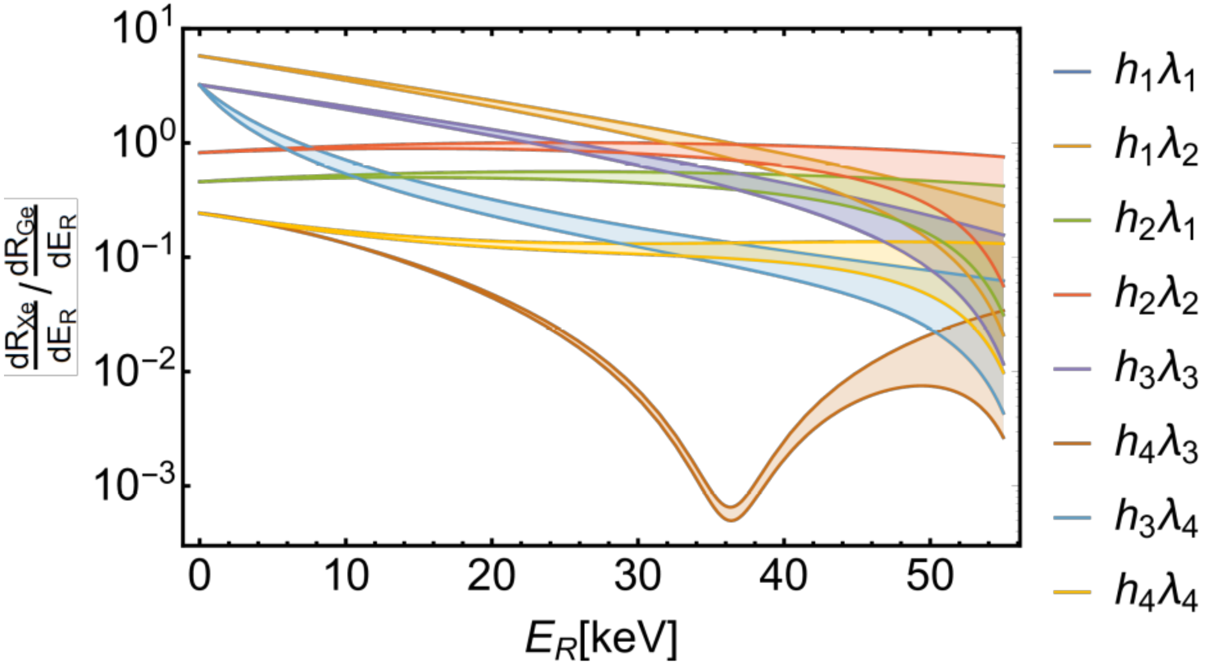


Operator distinguishability

Spin-1/2 WIMP

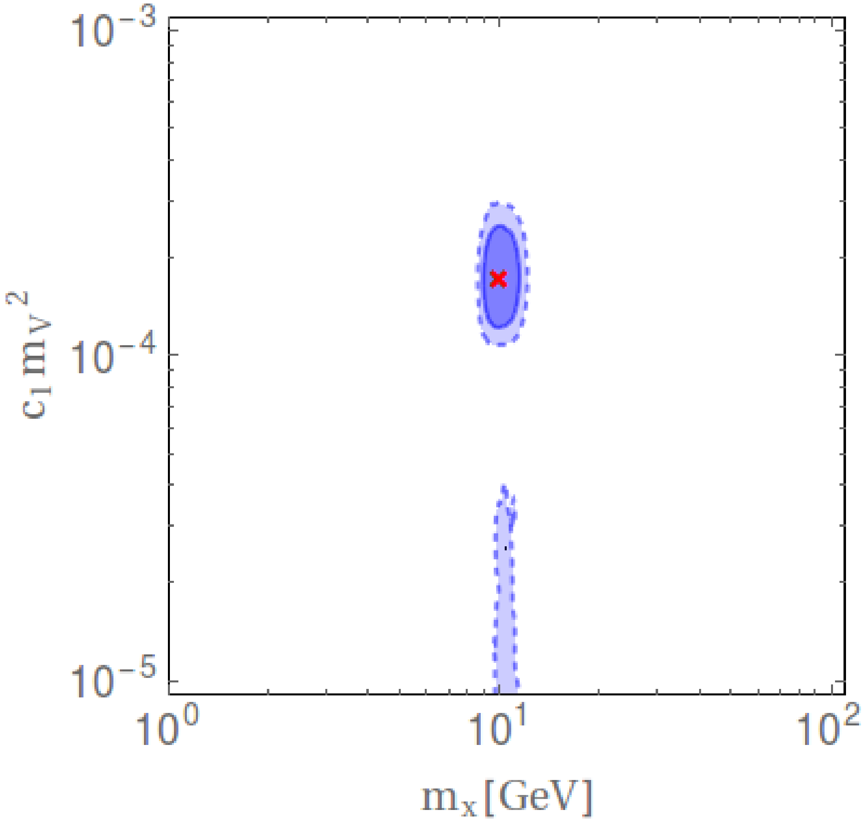


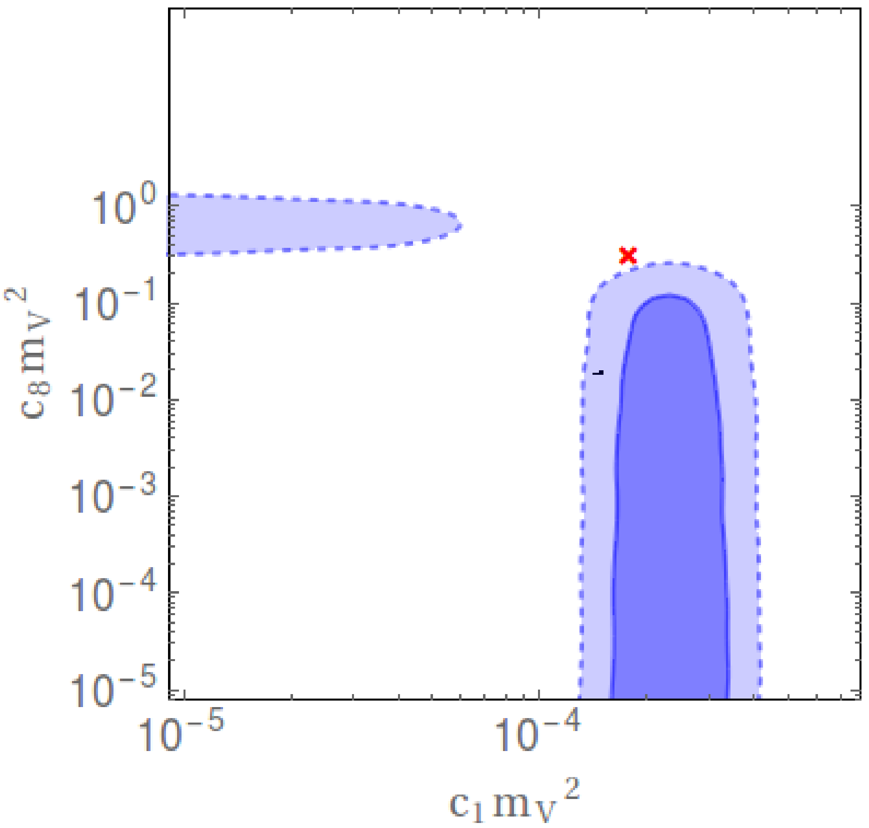
	Uncharged Mediator
c_1	$\frac{h_1^N \lambda_1}{m_\phi^2} - \frac{h_3^N \lambda_3}{m_G^2}$
c_4	$\frac{4 h_4^N \lambda_4}{m_G^2}$
c_6	$\frac{h_2^N \lambda_2 m_N}{m_\phi^2 m_\chi}$
c_7	$\frac{2 h_4^N \lambda_3}{m_G^2}$
c_8	$-\frac{2 h_3^N \lambda_4}{m_G^2}$
c_9	$-\frac{2 h_4^N \lambda_3 m_N}{m_\chi m_G^2} - \frac{2 h_3^N \lambda_4}{m_G^2}$
c_{10}	$\frac{h_2^N \lambda_1}{m_\phi^2}$
c_{11}	$-\frac{h_1^N \lambda_2 m_N}{m_\phi^2 m_\chi}$



Operator degeneracy

Simulated:
Spin-1/2 WIMP, m=10GeV, spin-independent





Model selection

Model evidence: $\epsilon(D, M_1) = \int \mathcal{L}(D|\theta_1, M_1)\pi(\theta_1, M_1)d\theta_1$

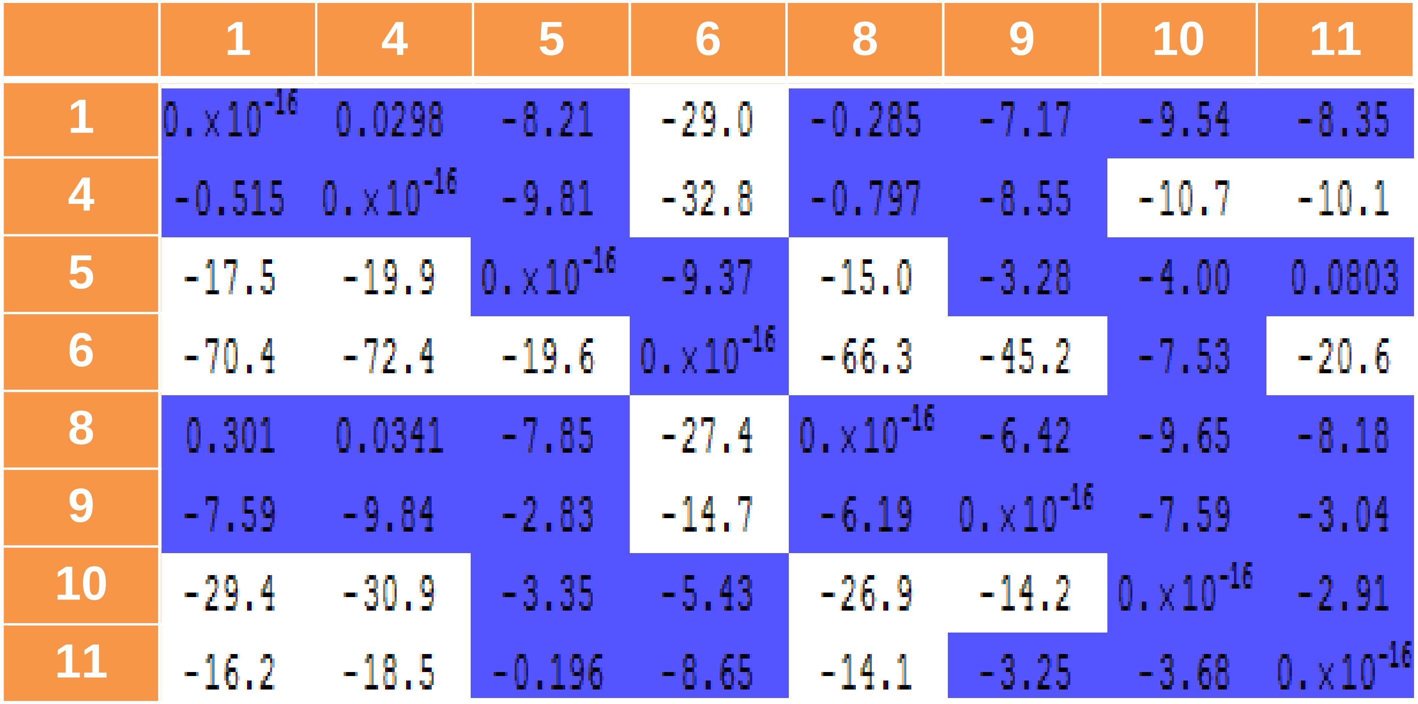
Bayes factor: $$\boxed{K = \frac{\epsilon(D, M_1)}{\epsilon(D, M_2)}}$$

- Simulate 20, 200 and 2000 events in both xenon and germanium detectors
- Calculate Bayes factors between each model

Model selection

Fitted operator

Simulated operator



	1	4	5	6	8	9	10	11
1	0.x10^{-16}	0.0298	-8.21	-29.0	-0.285	-7.17	-9.54	-8.35
4	-0.515	0.x10^{-16}	-9.81	-32.8	-0.797	-8.55	-10.7	-10.1
5	-17.5	-19.9	0.x10^{-16}	-9.37	-15.0	-3.28	-4.00	0.0803
6	-70.4	-72.4	-19.6	0.x10^{-16}	-66.3	-45.2	-7.53	-20.6
8	0.301	0.0341	-7.85	-27.4	0.x10^{-16}	-6.42	-9.65	-8.18
9	-7.59	-9.84	-2.83	-14.7	-6.19	0.x10^{-16}	-7.59	-3.04
10	-29.4	-30.9	-3.35	-5.43	-26.9	-14.2	0.x10^{-16}	-2.91
11	-16.2	-18.5	-0.196	-8.65	-14.1	-3.25	-3.68	0.x10^{-16}

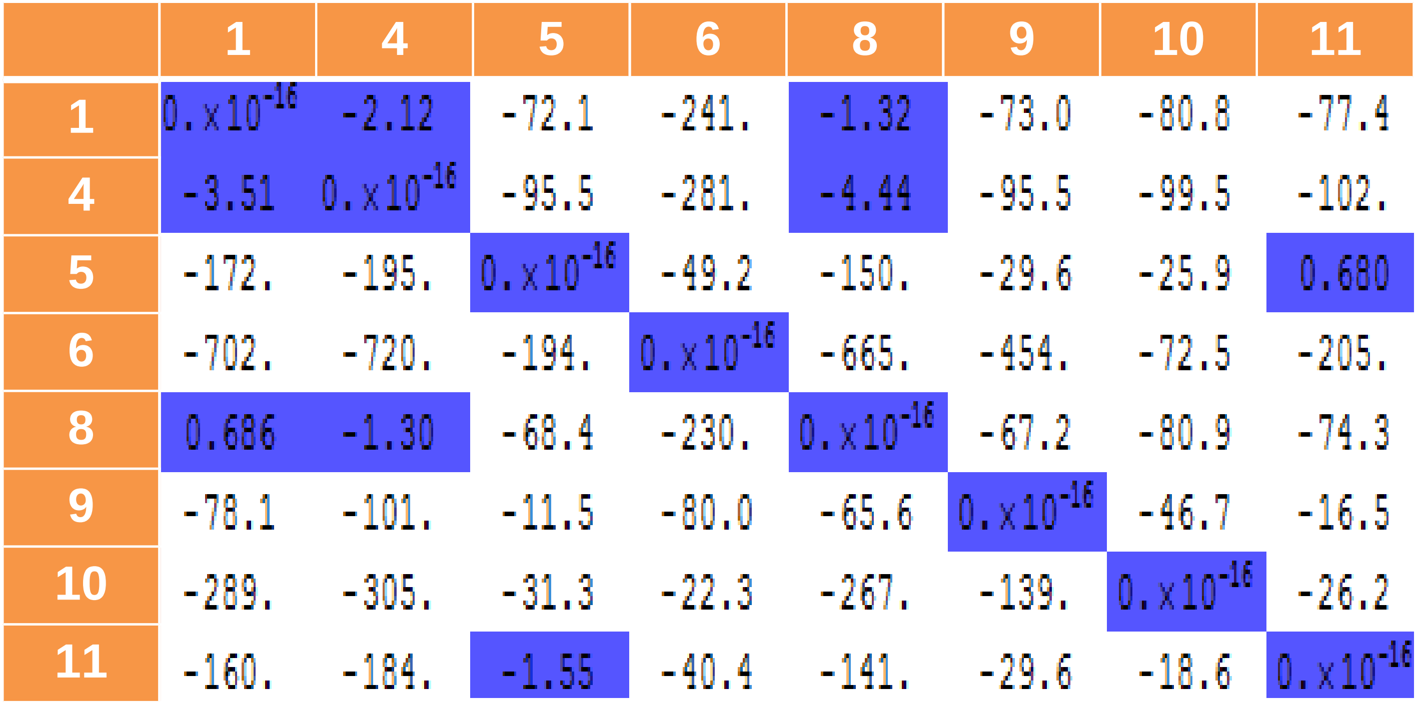
20 events

Cells contain 2 log K_{ij} , value < -10 is decisive evidence in favor of model i

Model selection

Fitted operator

Simulated operator



	1	4	5	6	8	9	10	11
1	$0.\times10^{-16}$	-2.12	-72.1	-241.	-1.32	-73.0	-80.8	-77.4
4	-3.51	$0.\times10^{-16}$	-95.5	-281.	-4.44	-95.5	-99.5	-102.
5	-172.	-195.	$0.\times10^{-16}$	-49.2	-150.	-29.6	-25.9	0.680
6	-702.	-720.	-194.	$0.\times10^{-16}$	-665.	-454.	-72.5	-205.
8	0.686	-1.30	-68.4	-230.	$0.\times10^{-16}$	-67.2	-80.9	-74.3
9	-78.1	-101.	-11.5	-80.0	-65.6	$0.\times10^{-16}$	-46.7	-16.5
10	-289.	-305.	-31.3	-22.3	-267.	-139.	$0.\times10^{-16}$	-26.2
11	-160.	-184.	-1.55	-40.4	-141.	-29.6	-18.6	$0.\times10^{-16}$

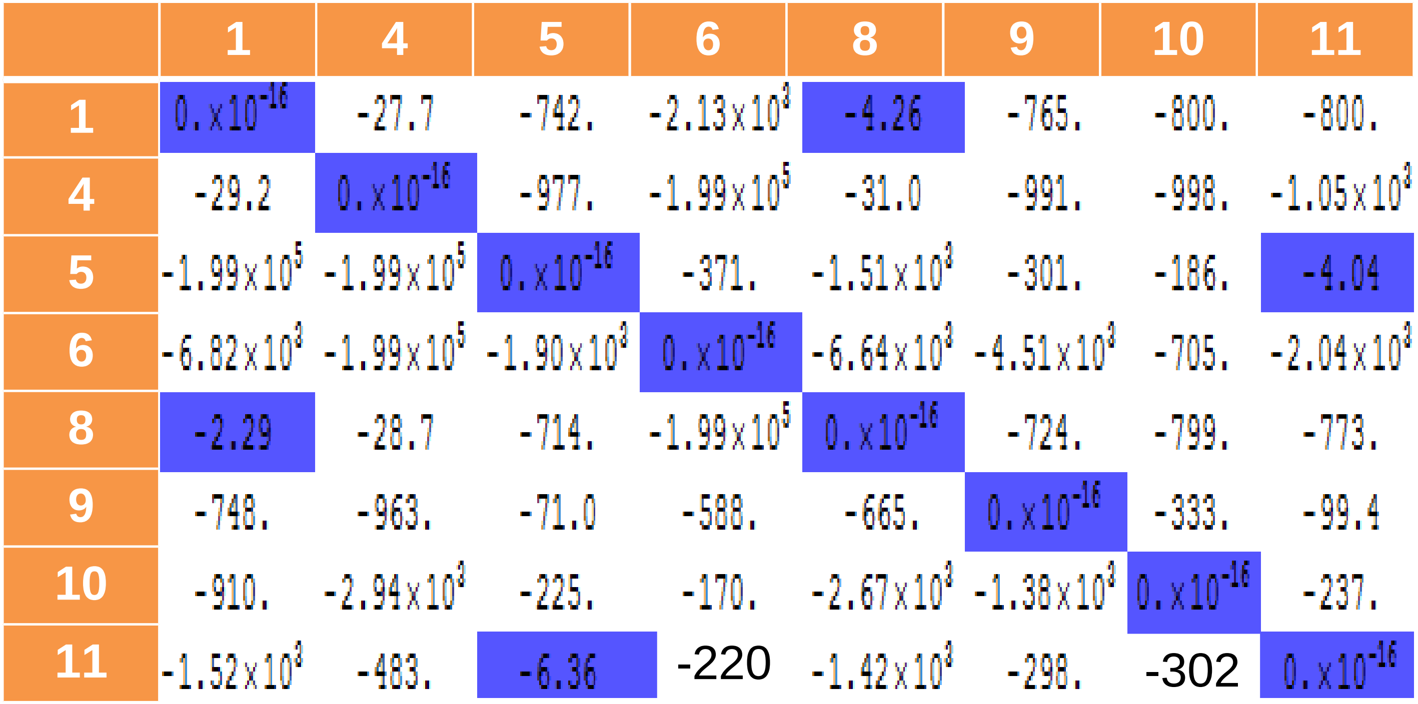
200 events

Cells contain 2 log K_{ij} , value < -10 is decisive evidence in favor of model i

Model selection

Fitted operator

Simulated operator



	1	4	5	6	8	9	10	11
1	$0.\times10^{-16}$	-27.7	-742.	-2.13×10^{3}	-4.26	-765.	-800.	-800.
4	-29.2	$0.\times10^{-16}$	-977.	-1.99×10^{5}	-31.0	-991.	-998.	-1.05×10^{3}
5	-1.99×10^{5}	-1.99×10^{5}	$0.\times10^{-16}$	-371.	-1.51×10^{3}	-301.	-186.	-4.04
6	-6.82×10^{3}	-1.99×10^{5}	-1.90×10^{3}	$0.\times10^{-16}$	-6.64×10^{3}	-4.51×10^{3}	-705.	-2.04×10^{3}
8	-2.29	-28.7	-714.	-1.99×10^{5}	$0.\times10^{-16}$	-724.	-799.	-773.
9	-748.	-963.	-71.0	-588.	-665.	$0.\times10^{-16}$	-333.	-99.4
10	-910.	-2.94×10^{3}	-225.	-170.	-2.67×10^{3}	-1.38×10^{3}	$0.\times10^{-16}$	-237.
11	-1.52×10^{3}	-483.	-6.36	-220	-1.42×10^{3}	-298.	-302	$0.\times10^{-16}$

2000 events

Cells contain 2 log K_{ij} , value < -10 is decisive evidence in favor of model i

5. Summary

- The standard SI/SD formalism is inadequate
- Simplified models cannot reproduce all WIMP-nucleus EFT operators
- A new way to discriminate between fundamental WIMP models(*)
- Need lots of events and multiple detector types to distinguish interactions