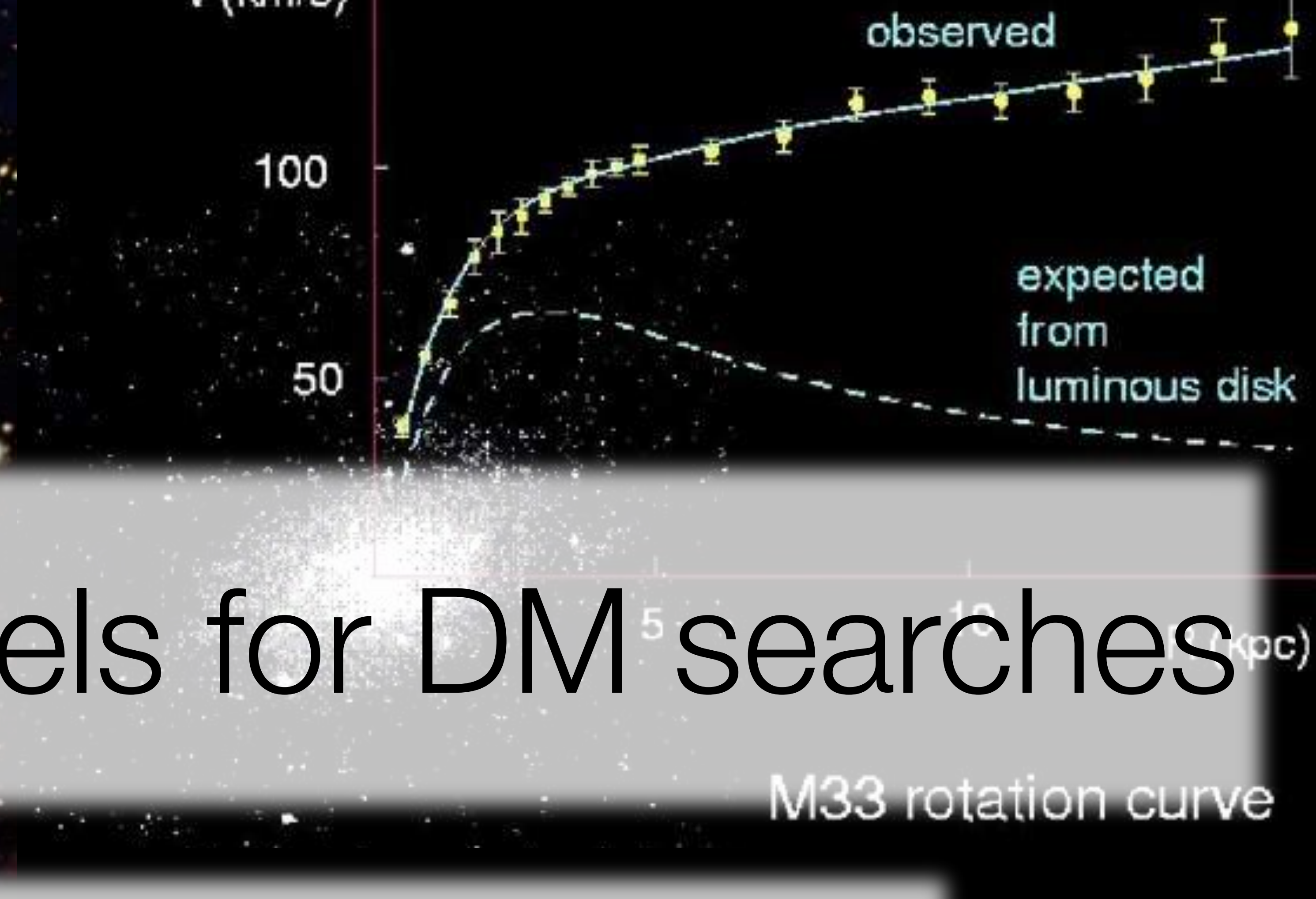
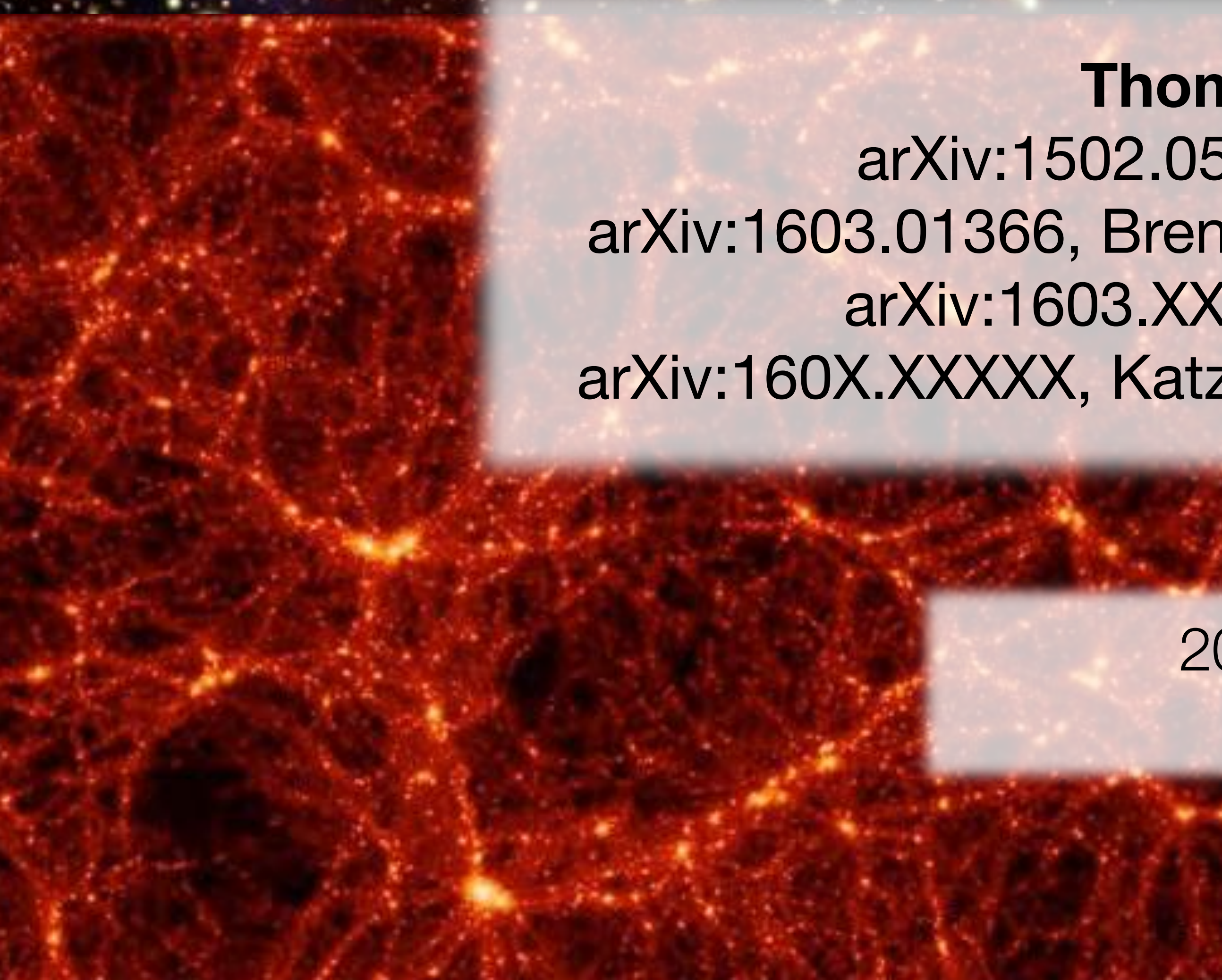
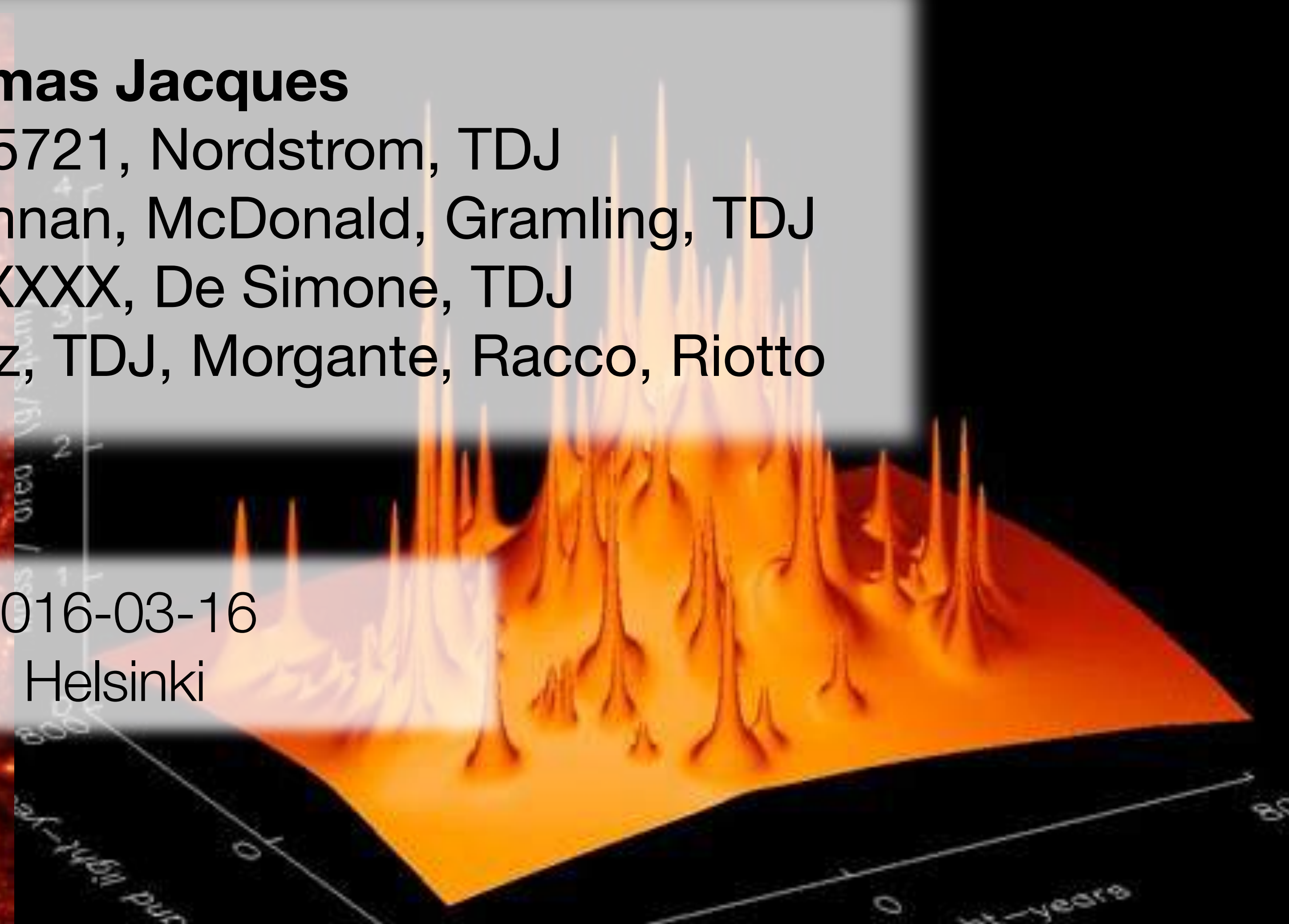
Simplified Models for DM searches

Thomas Jacques
arXiv:1502.05721, Nordstrom, TDJ
arXiv:1603.01366, Brennan, McDonald, Gramling, TDJ
arXiv:1603.XXXXX, De Simone, TDJ
arXiv:160X.XXXXX, Katz, TDJ, Morgante, Racco, Riotto

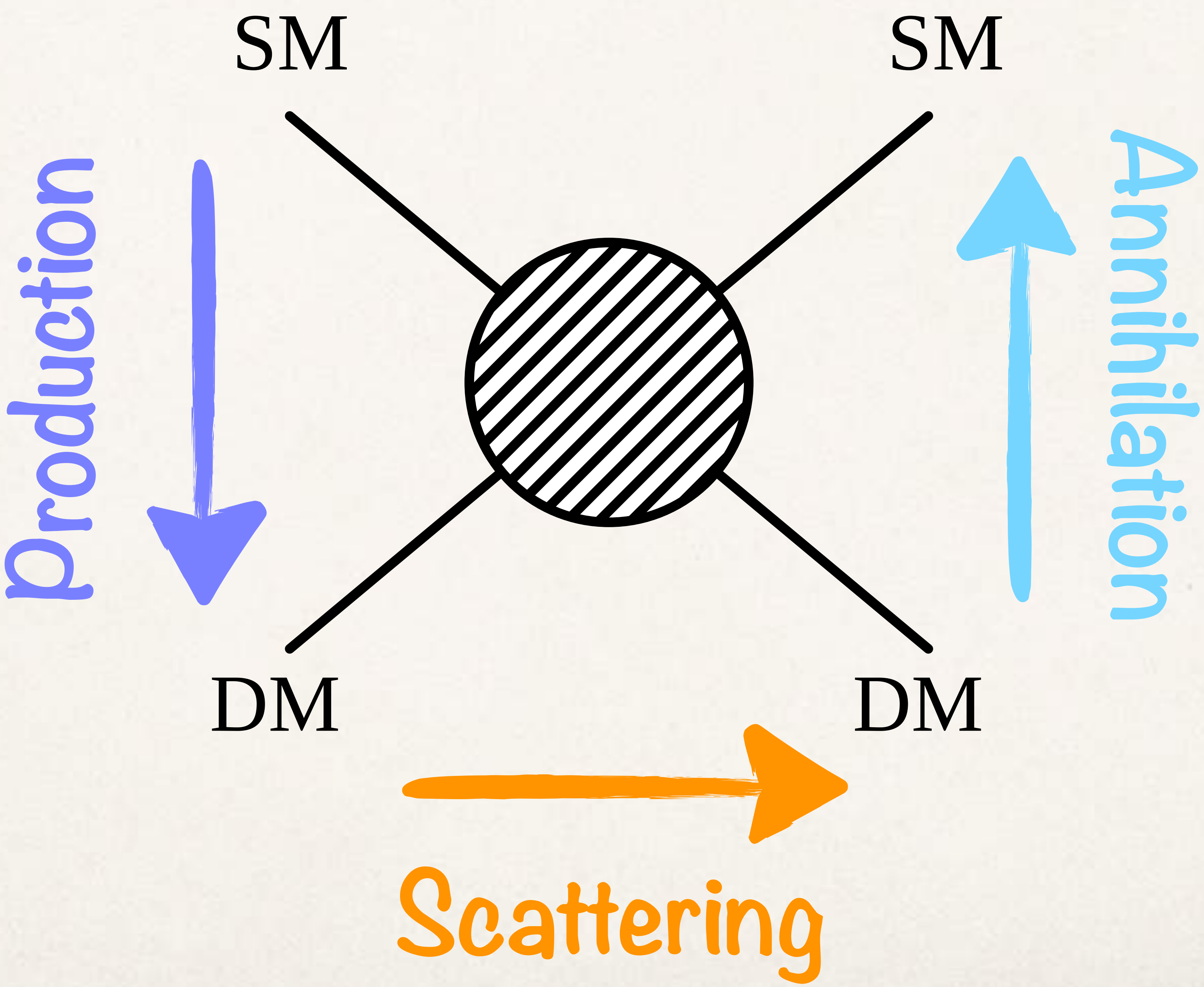
2016-03-16
Helsinki

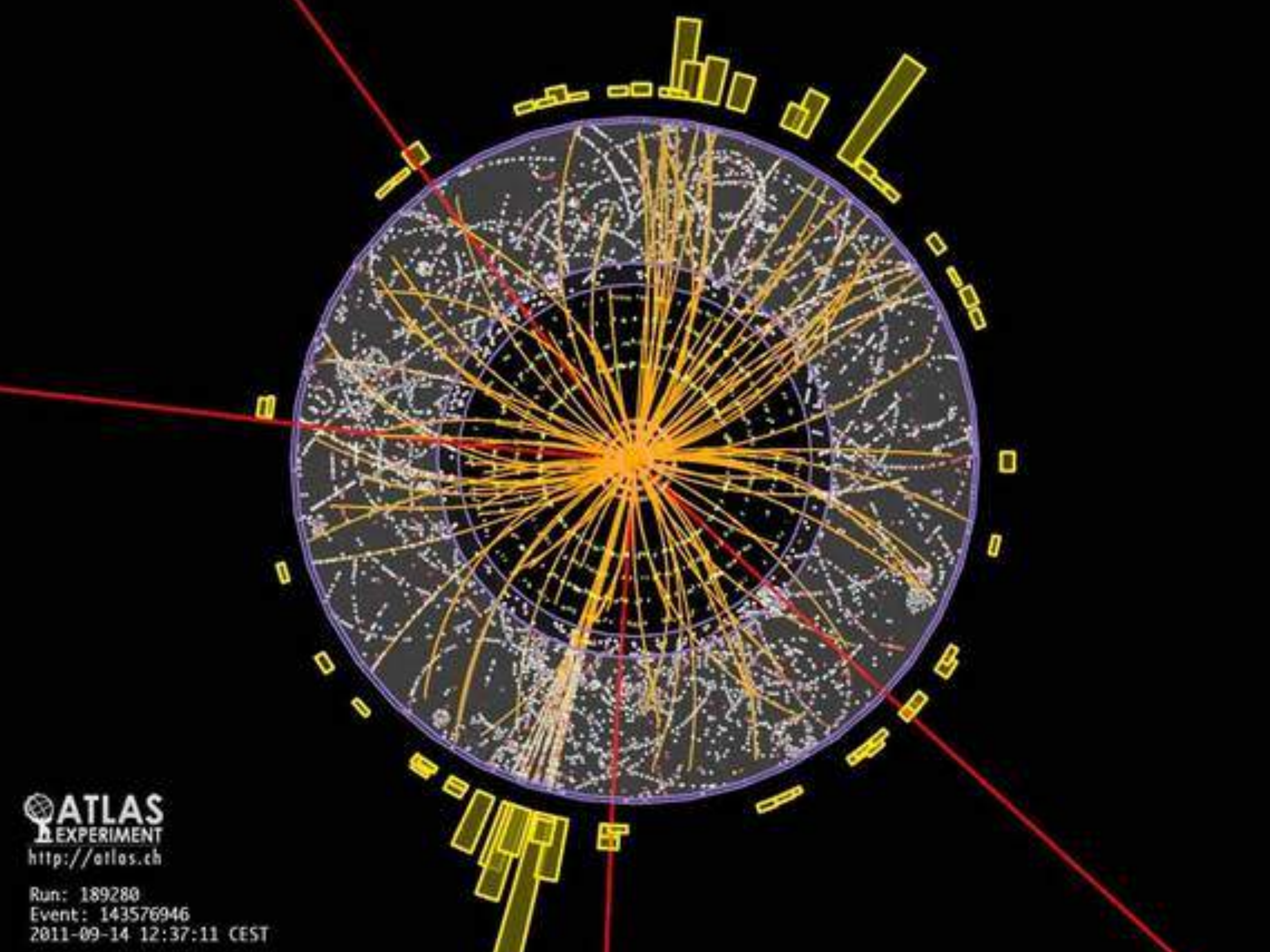






Dark matter searches

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EXPERIMENT
http://atlas.ch
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Event: 143576946
2011-09-14 12:37:11 CEST

What exactly are we constraining?

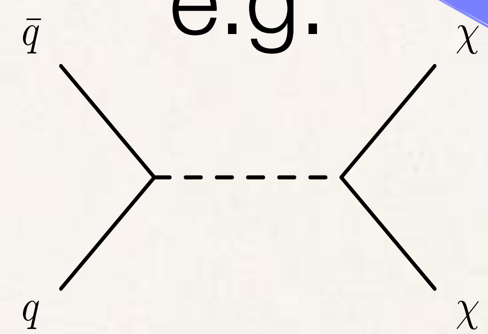
Effective operators

e.g. $\frac{1}{M_\star^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$

$\frac{1}{M_\star^2}(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q)$

Simplified Models

e.g.



Full Models

e.g. MSSM, UED

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 e,μ + γ	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^\pm)=2\, m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 e,μ + τ	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	$m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^\pm)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

10^{-1} | 1 | Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

What exactly are we constraining?

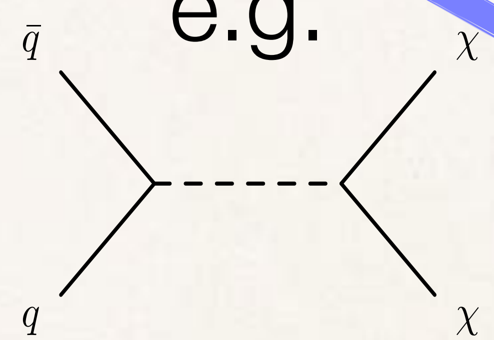
Effective operators

e.g. $\frac{1}{M_\star^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$

$\frac{1}{M_\star^2}(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q)$

Simplified Models

e.g.

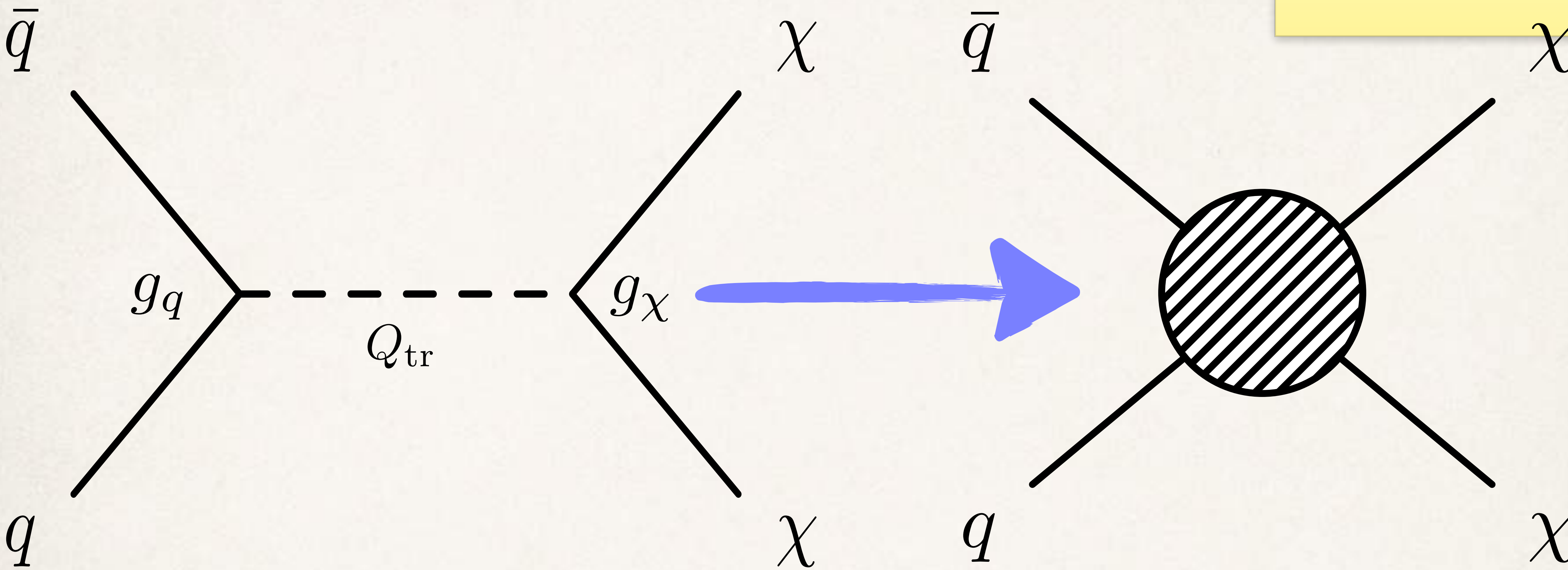


Full Models

e.g. MSSM, UED

Effective operators

List of DD operators...



$$\frac{g_q g_\chi}{M^2 - Q_{\rm tr}^2} \simeq \frac{g_q g_\chi}{M^2} \equiv \frac{1}{{M_\star}^2}$$

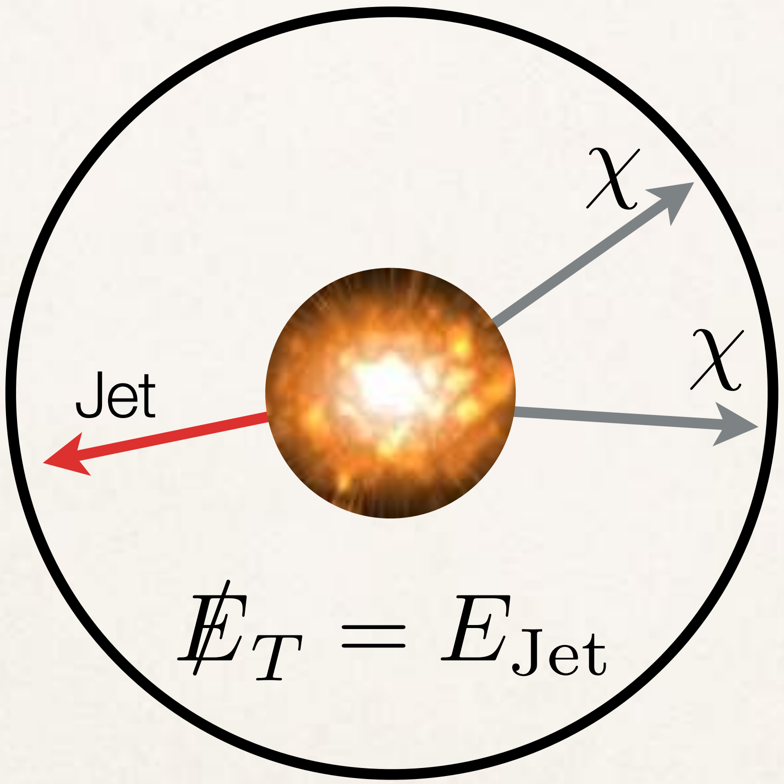
- Integrate out the mediator
- Reduce parameters to $m_\chi,\ M_\star$ for each operator

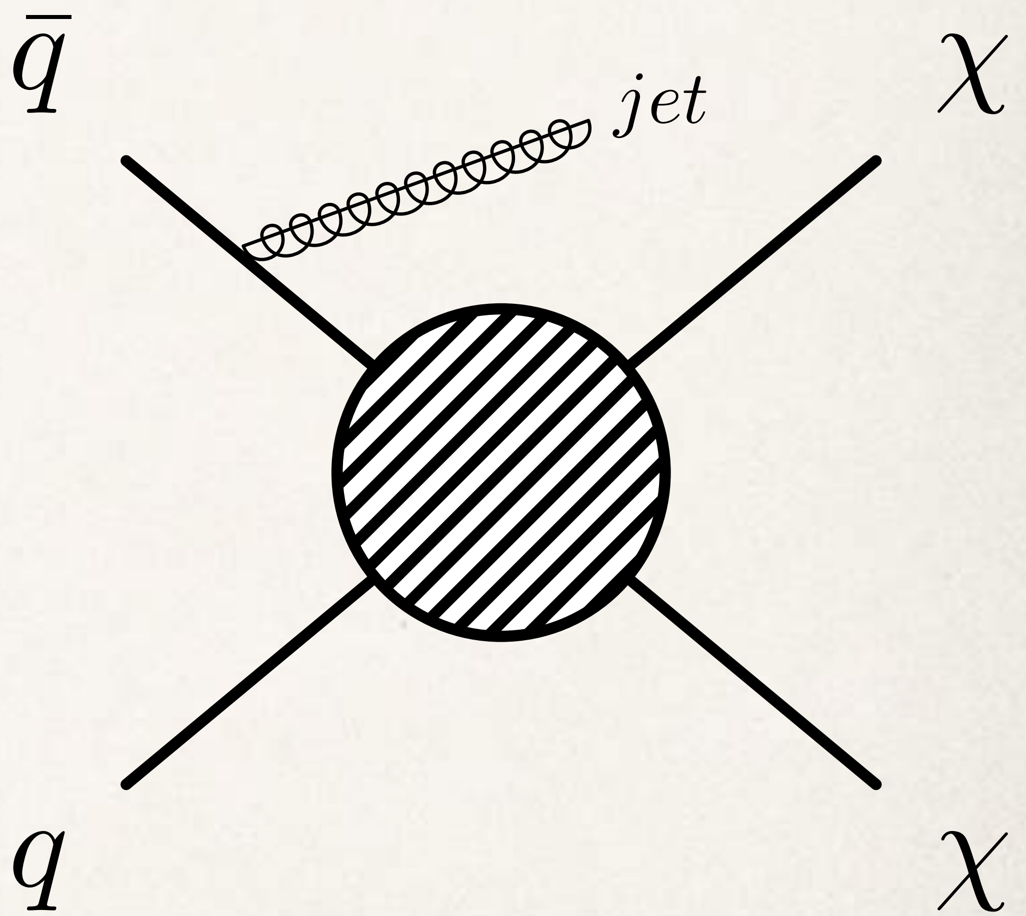
Effective operators

- Left with a small 'basis' set of operators
- Most common operators are for Dirac fermion WIMPs:
  - scalar mediator-like coupling $$\mathrm{D1} = \frac{m_q}{M_\star^3}(\bar{\chi}\chi)(\bar{q}q)$$
  - vector coupling $$\mathrm{D5} = \frac{1}{M_\star^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$$
  - axial-vector coupling $$\mathrm{D8} = \frac{1}{M_\star^2}(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q)$$
  - gluon initial state $$\mathrm{D11} = \frac{i\alpha_S}{4M_\star^3}(\bar{\chi}\chi)(G_{\mu\nu}\tilde{G}^{\mu\nu})$$

Search channels

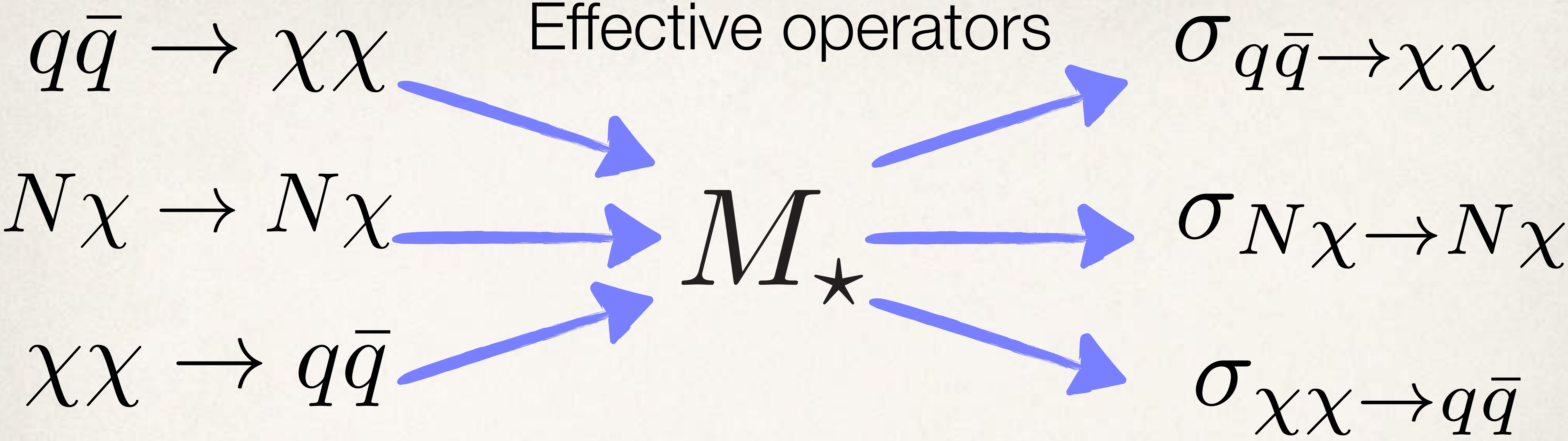
- The most generic search channel is missing energy + jet(s): DM production inferred by non-zero transverse momentum sum

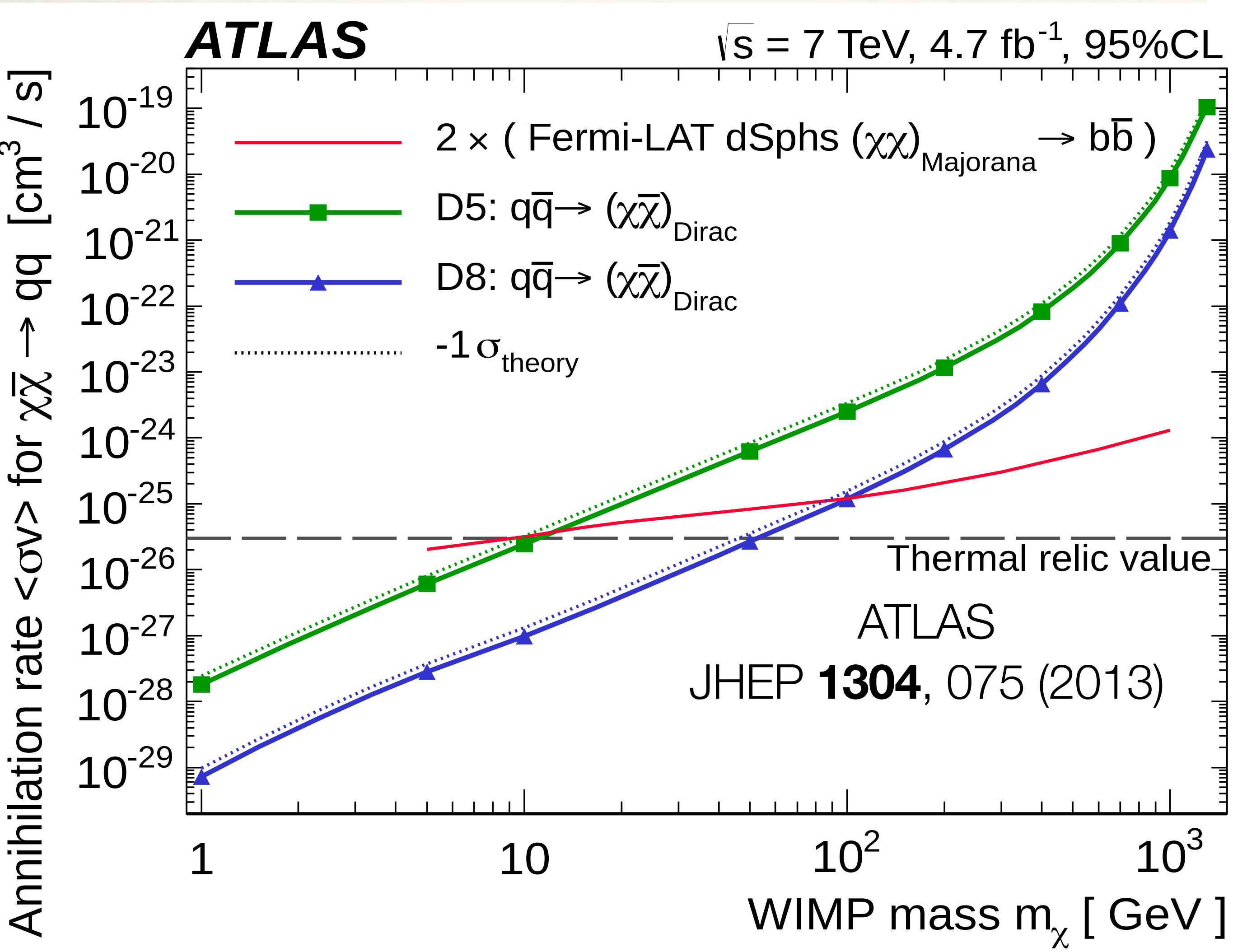


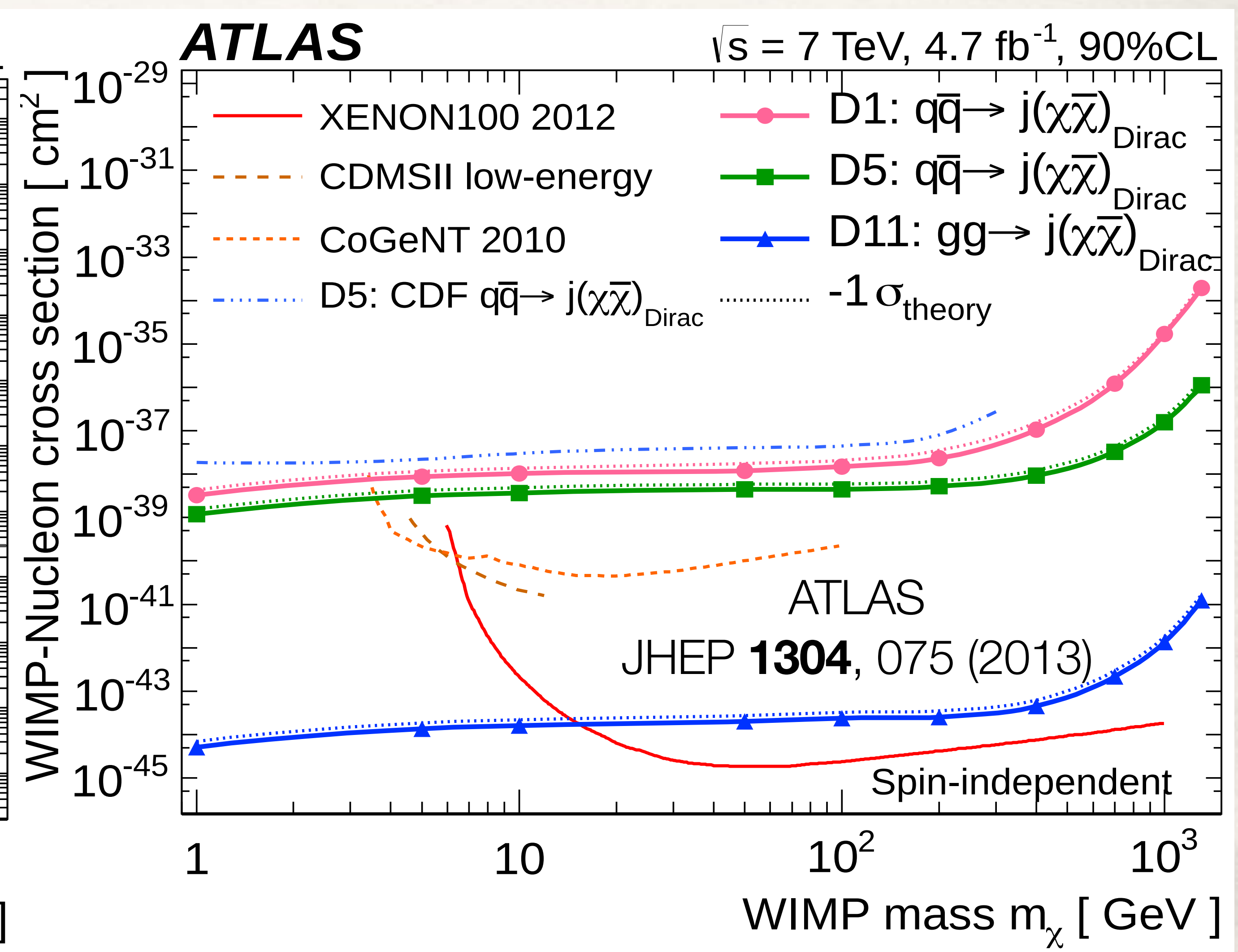


- Other channels can be important but they are more model-dependent

Effective operators



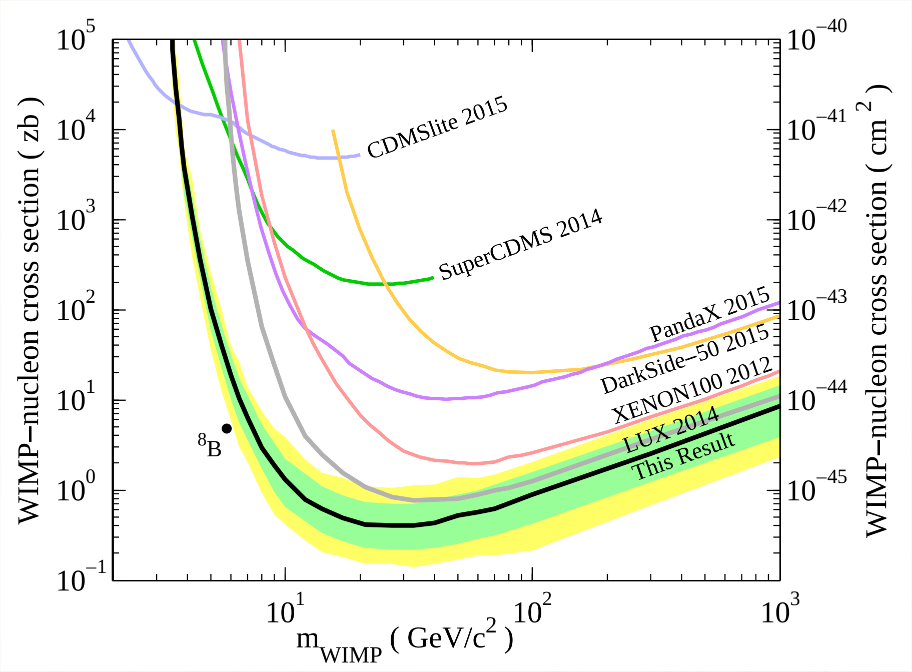




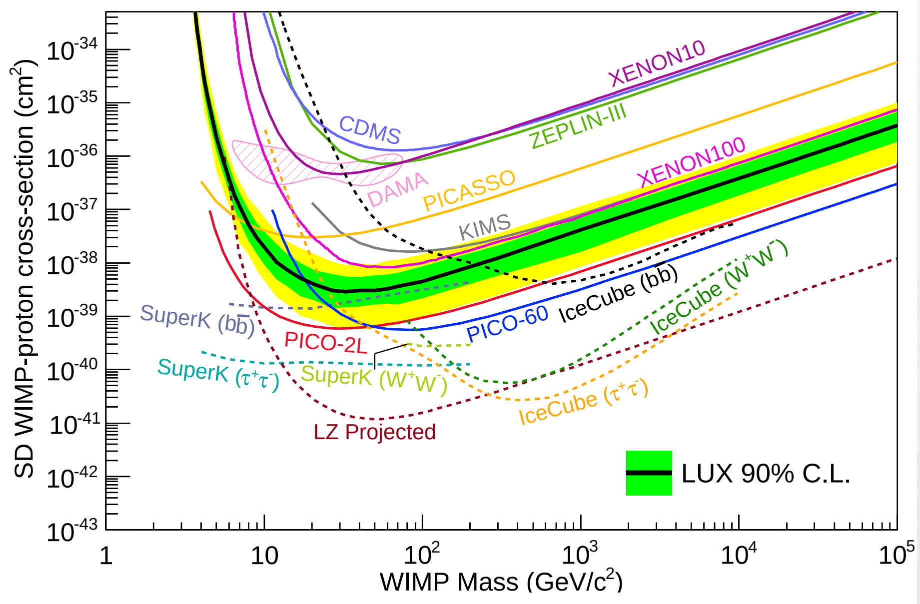
Effective operators for direct detection

- Note that the ‘usual’ direct detection constraints on σ_{SI} and σ_{SD} are a constraint on some, not all effective operators

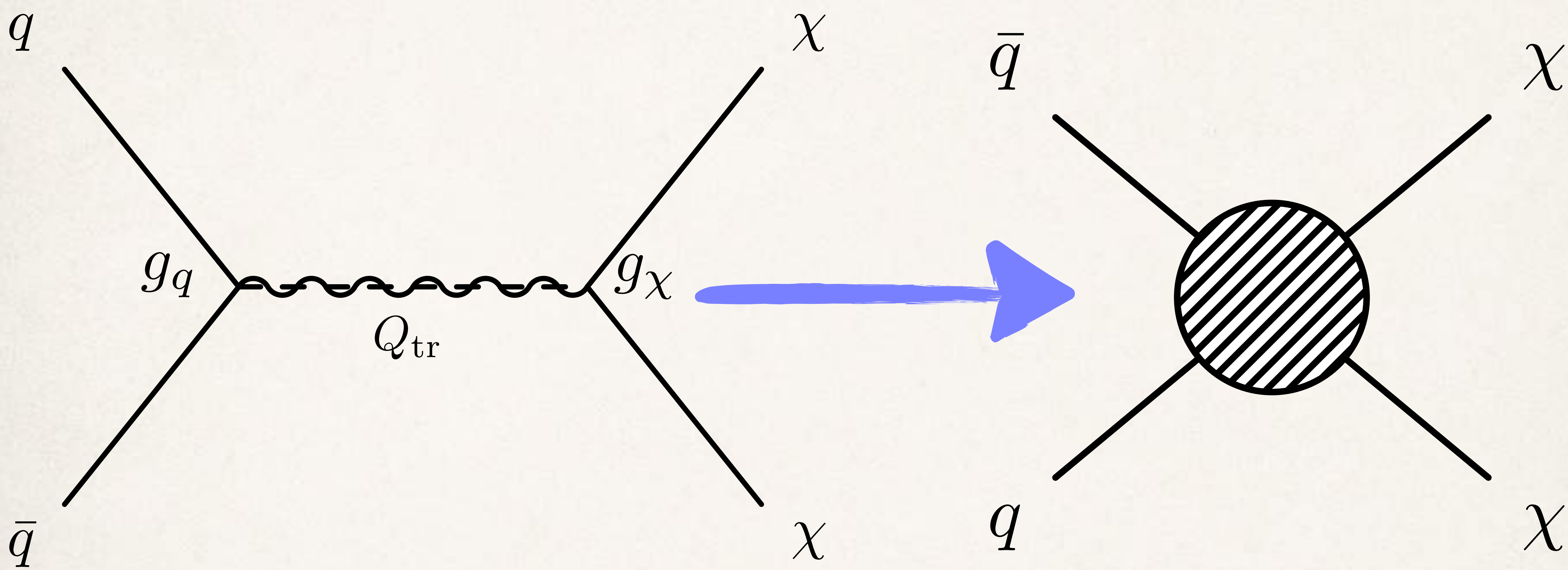
$$\left.\begin{array}{r}(\bar{\chi}\chi)(\bar{q}q)\\ (\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)\\ (\bar{\chi}\chi)(G^{a}_{\mu\nu}G^{a}_{\mu\nu})\\ (\phi^{*}\phi)(\bar{q}q)\\ (\phi^{*}\overleftrightarrow{\partial}_{\mu}\phi)(\bar{q}\gamma^{\mu}q)\\ (\phi^{*}\phi)(G^{a}_{\mu\nu}G^{a}_{\mu\nu})\end{array}\right\}\leftrightarrow\sigma_{\rm SI}$$



$$\left.\begin{array}{r}(\bar{\chi}\gamma^{\mu}\gamma^{5}\chi)(\bar{q}\gamma_{\mu}\gamma^{5}q)\\ (\bar{\chi}\sigma^{\mu\nu}\chi)(\bar{q}\sigma_{\mu\nu}q)\end{array}\right\}\leftrightarrow\sigma_{\rm SD}$$



Effective operators



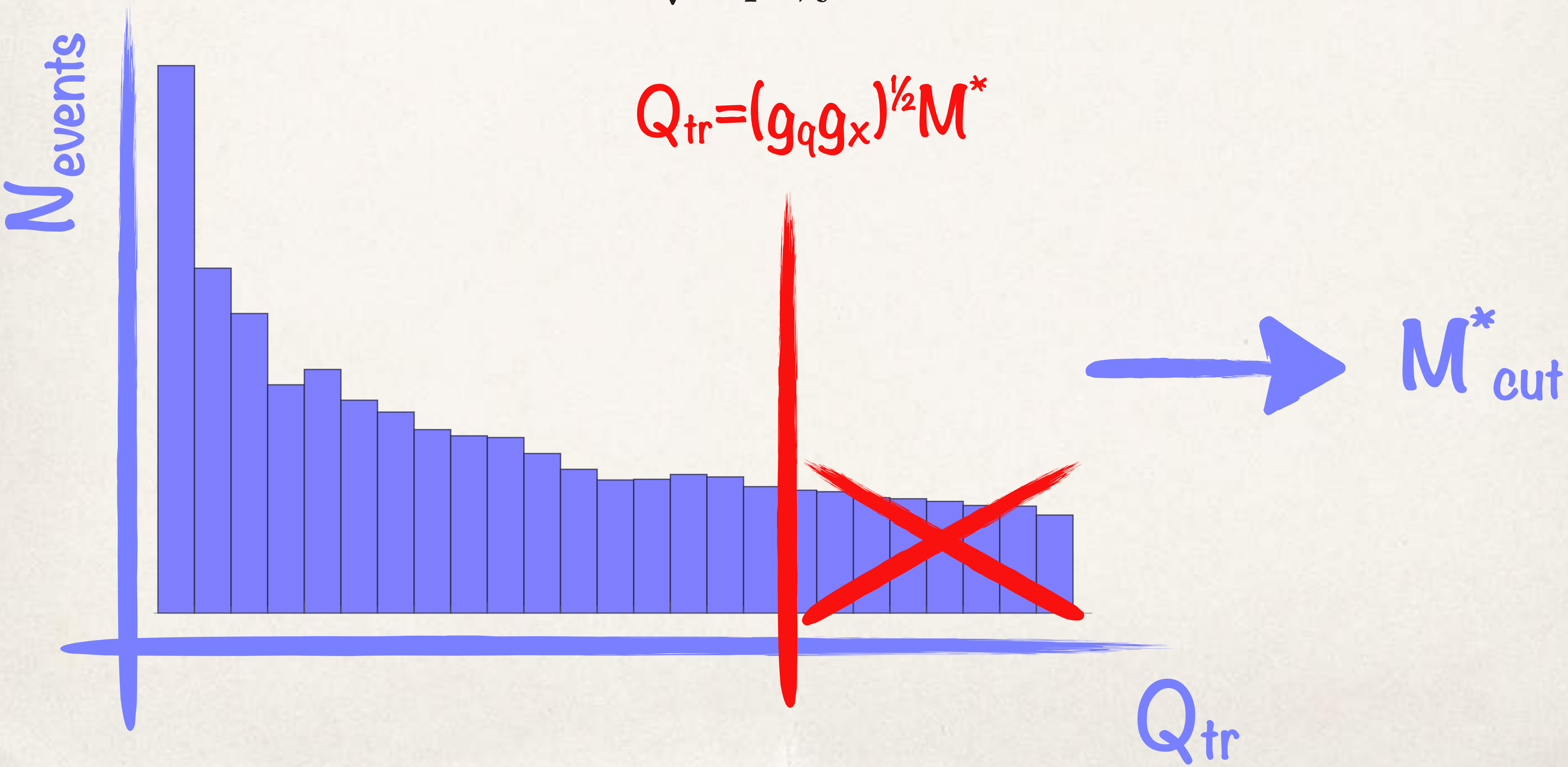
$$\frac{g_q g_\chi}{M^2 - Q_{\rm tr}^2} \simeq \frac{g_q g_\chi}{M^2} \equiv \frac{1}{{M_\star}^2}$$

$$Q_{\rm tr} < M \equiv \sqrt{g_q g_\chi} M_\star$$

Rescaling operator constraints

- For a given choice of $\sqrt{g_q g_\chi}$, only use events that satisfy

$$M \equiv \sqrt{g_q g_\chi} M^* \geq Q_{\rm tr}$$



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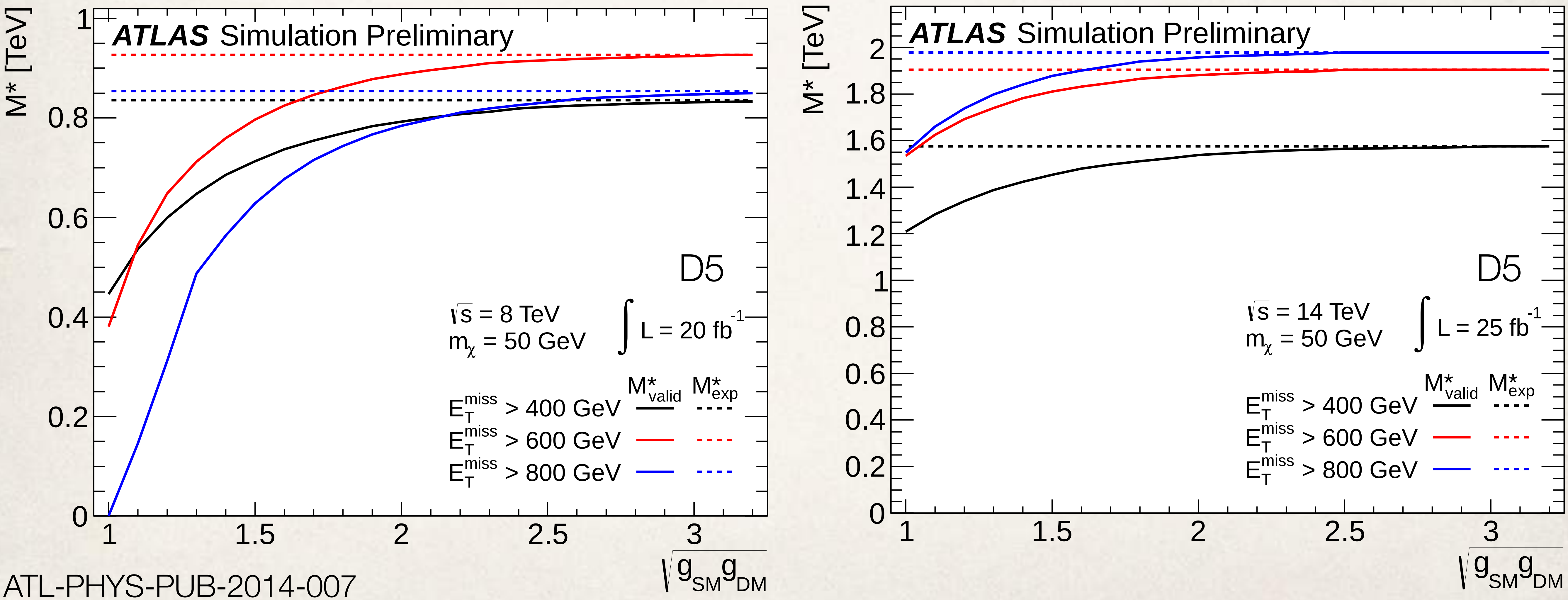
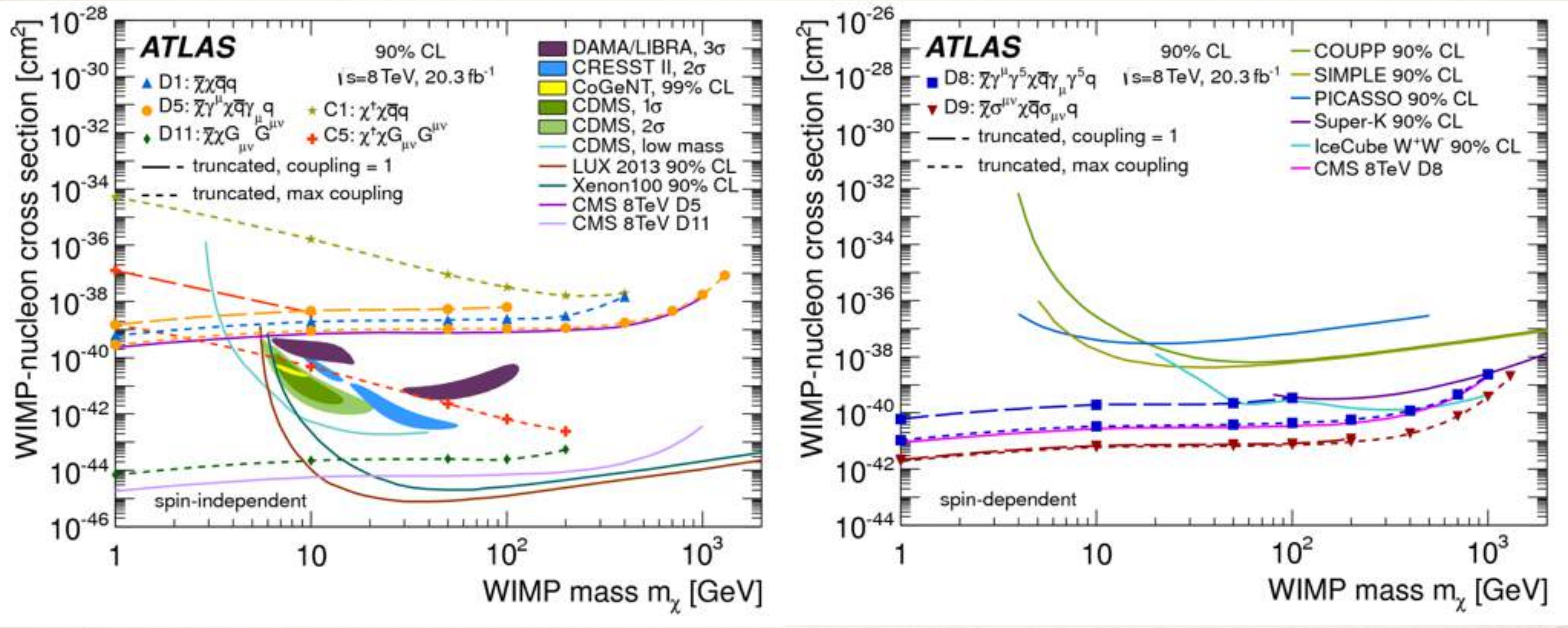


ATL-PHYS-PUB-2014-007

ATLAS + Busoni, De Simone, TDJ, Morgante, Riotto

Rescaling operator constraints



Eur. Phys. J. C (2015) 75:299
ATLAS + Busoni, De Simone, TDJ, Morgante, Riotto

So what now?

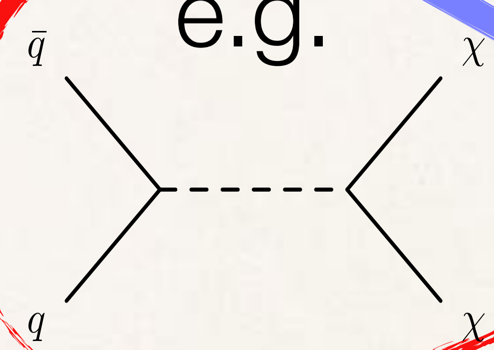
Effective operators

e.g. $\frac{1}{M_\star^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$

$\frac{1}{M_\star^2}(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q)$

Simplified Models

e.g.



Full Models

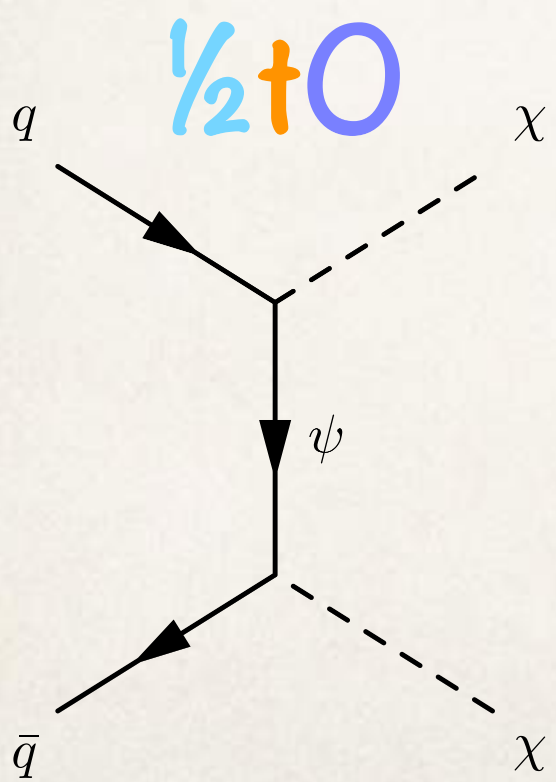
e.g. MSSM, UED

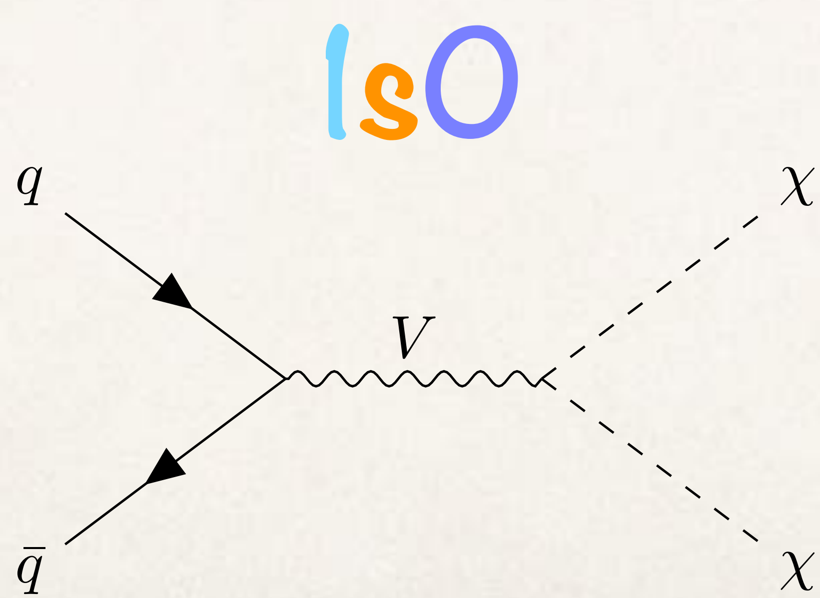
Classification of simplified models

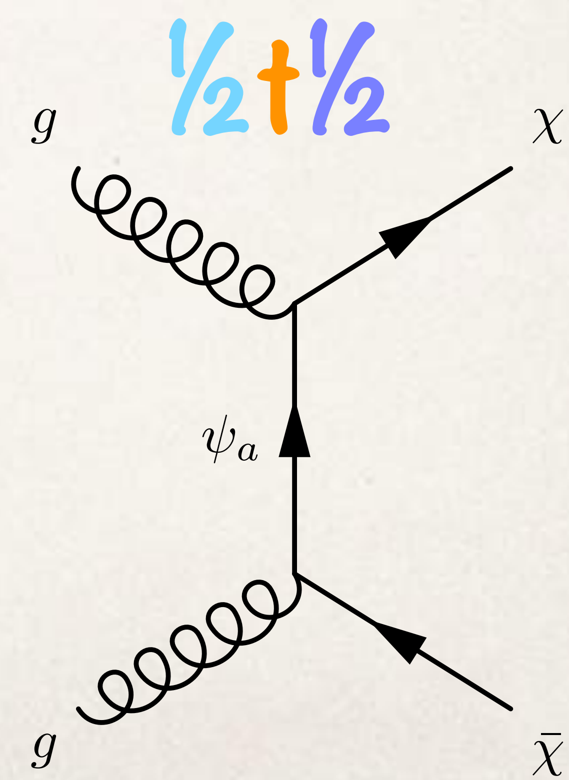
- There are many simplified models to choose from and they can be organized in a logical way. The most important features are

Mediator spin **Geometry of diagram** **DM spin**

- If DM is neutral, this defines most features of the model

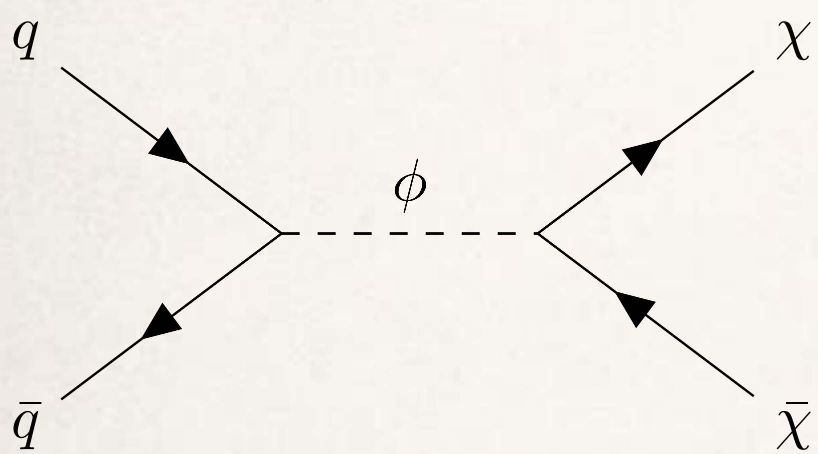






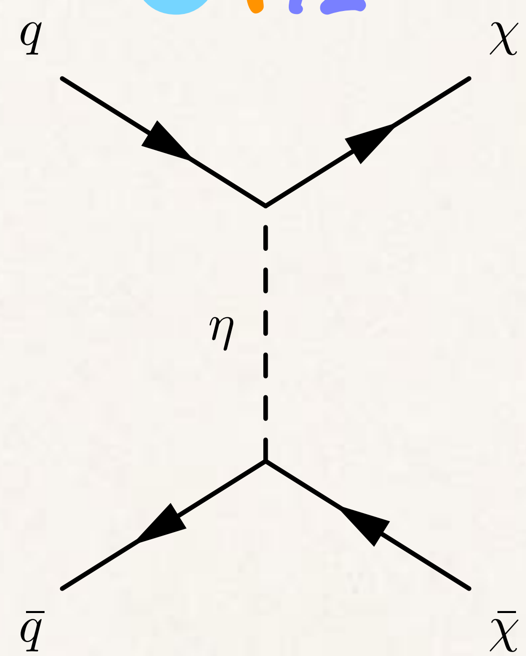
The usual suspects

0s½



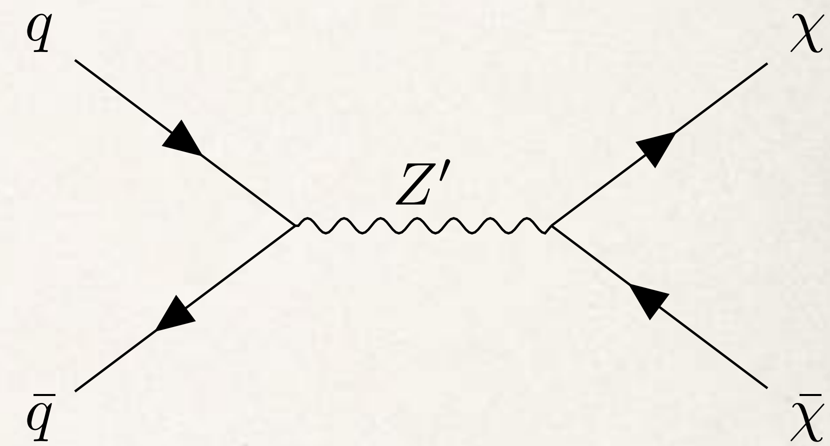
“Higgs portal”

0t½



“Squark-like”

1s½



“Z-prime”

- Each is associated with a particular UV-completion

Simplicity

- Even then there are choices to make - for example, for 1s½, there is a choice of vector or axial-vector couplings

$$\mathcal{L} \supset g_\chi Z'_\mu (c_V^\chi\, \bar{\chi}\gamma^\mu\chi + c_A^\chi\, \bar{\chi}\gamma^\mu\gamma^5\chi)$$
$$+ \sum_q g_q Z'_\mu (c_V^q\, \bar{q}\gamma^\mu q + c_A^q\, \bar{q}\gamma^\mu\gamma^5 q)$$
$$+ \sum_l g_l Z'_\mu (c_V^l\, \bar{l}\gamma^\mu l + c_A^l\, \bar{l}\gamma^\mu\gamma^5 l)$$

Vector Axial-vector

- Including couplings to both quarks and leptons, up to 28 free parameters, even in such a simple model!

- Necessary to make simplifying assumptions to keep the number of parameters small

Simplicity

For 1s½ (Z'):

I. Direct detection constraints: $c^q_V = c^\chi_V = 0$

II. Dilepton constraints: $g_l = 0$

III. Minimal Flavor Violation:

g_q equal for each quark

$$\mathcal{L} \supset g_\chi Z'_\mu (c^\chi_V\, \bar{\chi}\gamma^\mu \chi + c^\chi_A\, \bar{\chi}\gamma^\mu\gamma^5\chi) + \sum_q g_q Z'_\mu (c^q_V\, \bar{q}\gamma^\mu q + c^q_A\, \bar{q}\gamma^\mu\gamma^5 q) + \sum_l g_l Z'_\mu (c^l_V\, \bar{l}\gamma^\mu l + c^l_A\, \bar{l}\gamma^\mu\gamma^5 l)$$

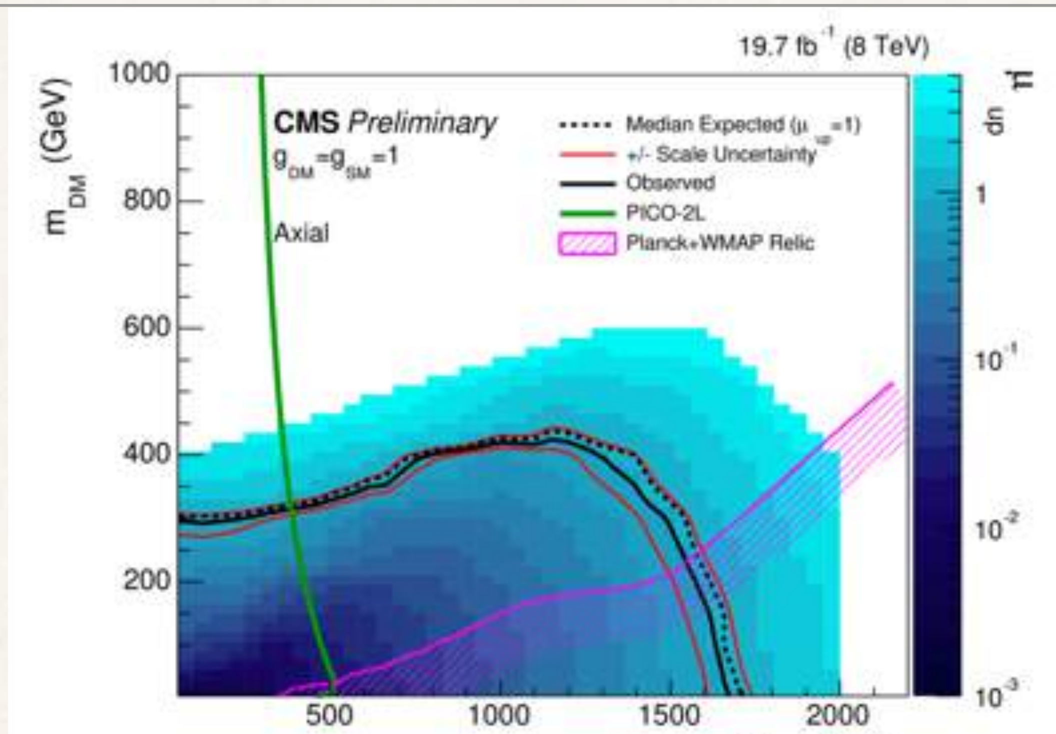
Vector   Axial-vector

$$\left\{m_{\rm DM},\ M_{\rm med},\ g_{\rm DM},\ g_{\rm SM}\right\} \to \left\{m_{\rm DM},\ M_{\rm med},\ g_{\rm DM}\cdot g_{\rm SM},\ g_{\rm DM}/g_{\rm SM}\right\}$$

Even with these simplifying assumptions, a full scan over the 4D parameter space can be computationally prohibitive

Parameter space

Benchmark coupling



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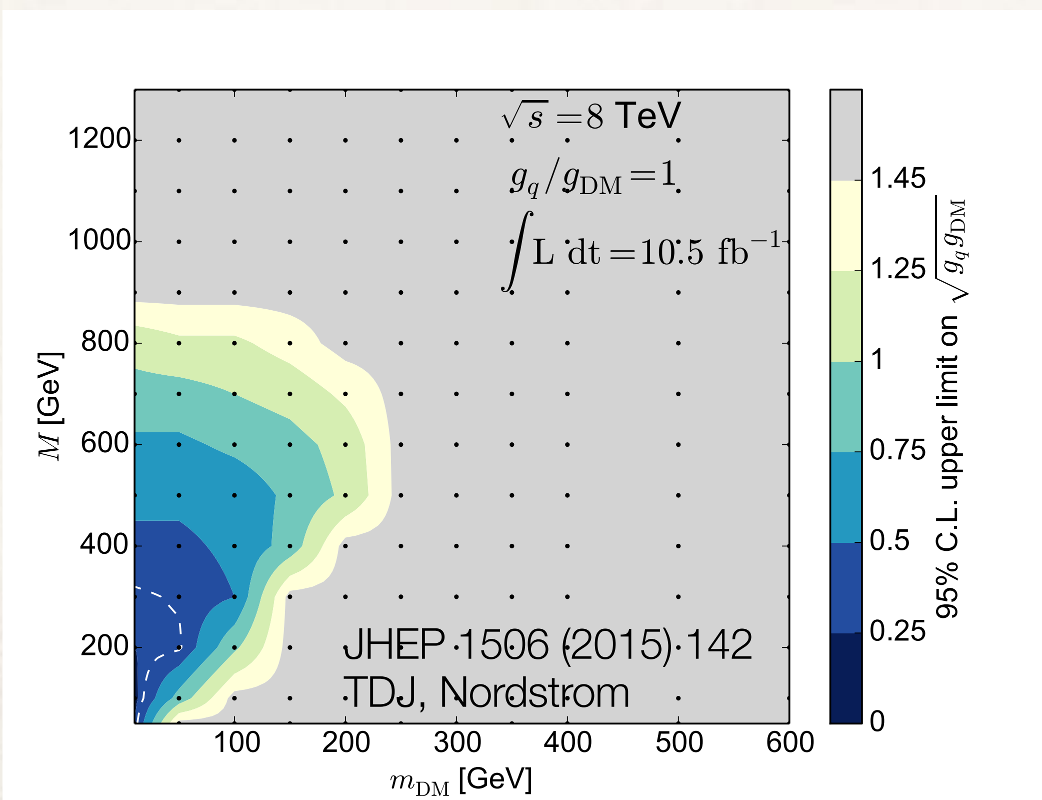
- ✓ Only 2 parameters to scan
- ✓ Easier comparison between experiments
- ✗ Semi-arbitrary choice of coupling
- ✗ Less comprehensive: Difficult to translate to other couplings

3-D scan



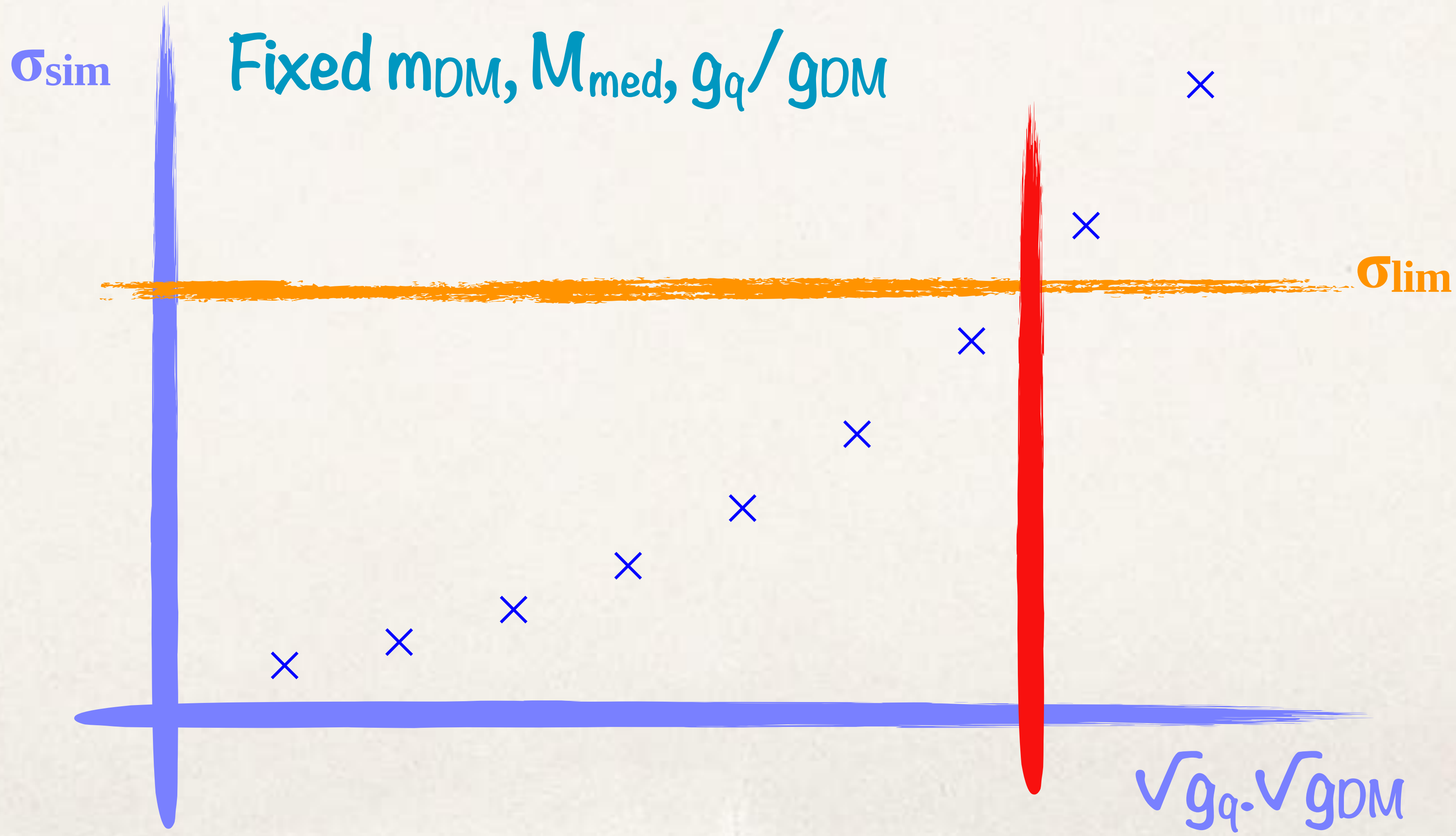
- ✓ Easy to interpret
- ✓ More comprehensive
- ✗ Approximations become necessary - important to avoid regions where these break down
- ✗ Difficult to compare results

Rescaling relations

$$\left\{m_{\rm DM},\, M_{\rm med},\, g_{\rm DM},\, g_{\rm SM}\right\} \to \left\{m_{\rm DM},\, M_{\rm med},\, g_{\rm DM}{\cdot}g_{\rm SM},\, g_{\rm DM}/g_{\rm SM}\right\}$$

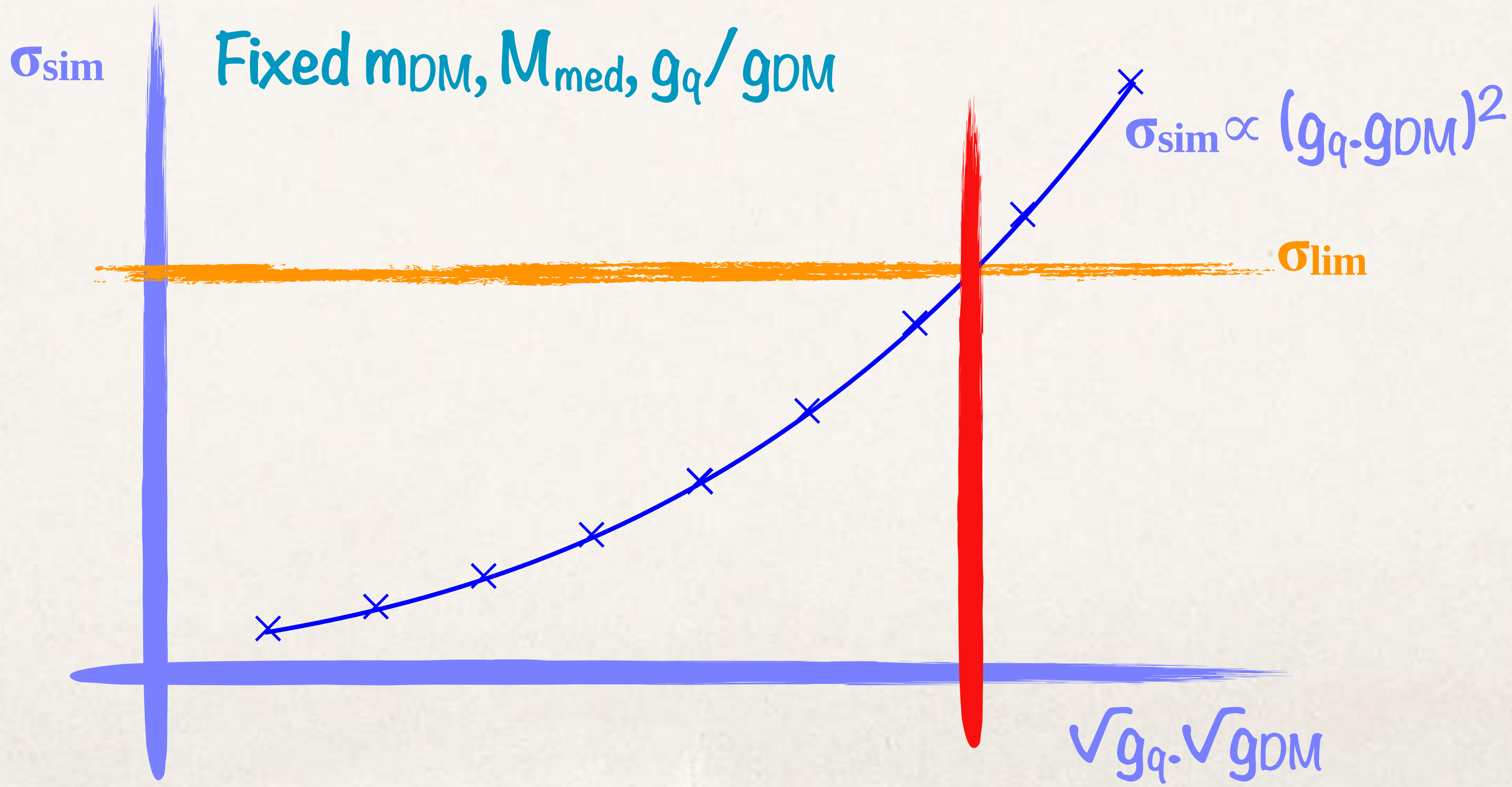
For each $\{m_{DM}, M_{med}, g_q/g_{DM}\}$, simulate signal cross section σ_{sim} for a range of $g_q.g_{DM}$, compare with the experimental limit σ_{lim}.

Value of $g_q.g_{DM}$ where $\sigma_{sim} = \sigma_{lim}$ defines the constraint on $g_q.g_{DM}$.



Rescaling relations

If we know how σ_{sim} varies with $g_q.g_{DM}$, we can simulate for one value of $g_q.g_{DM}$, avoiding the full scan

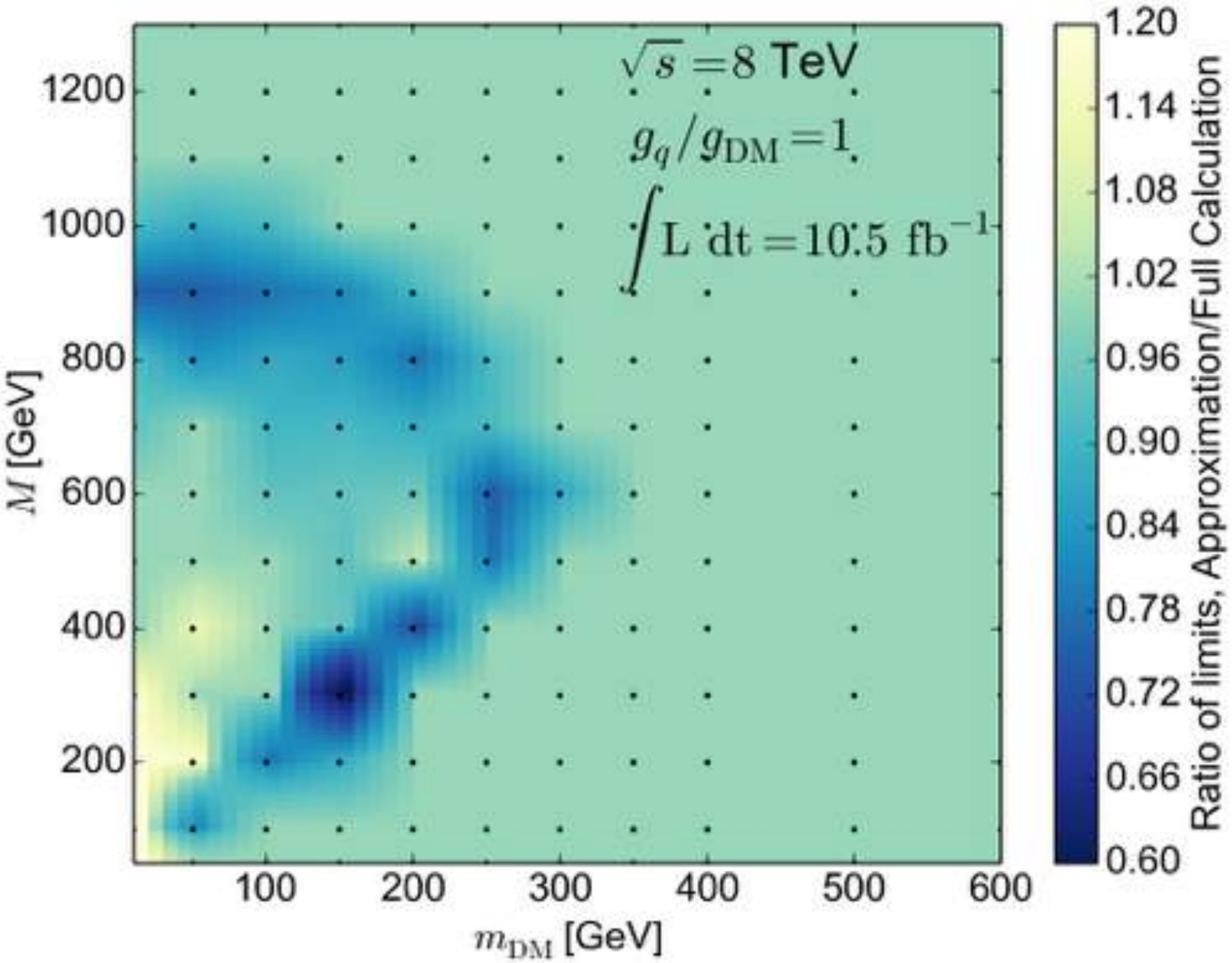


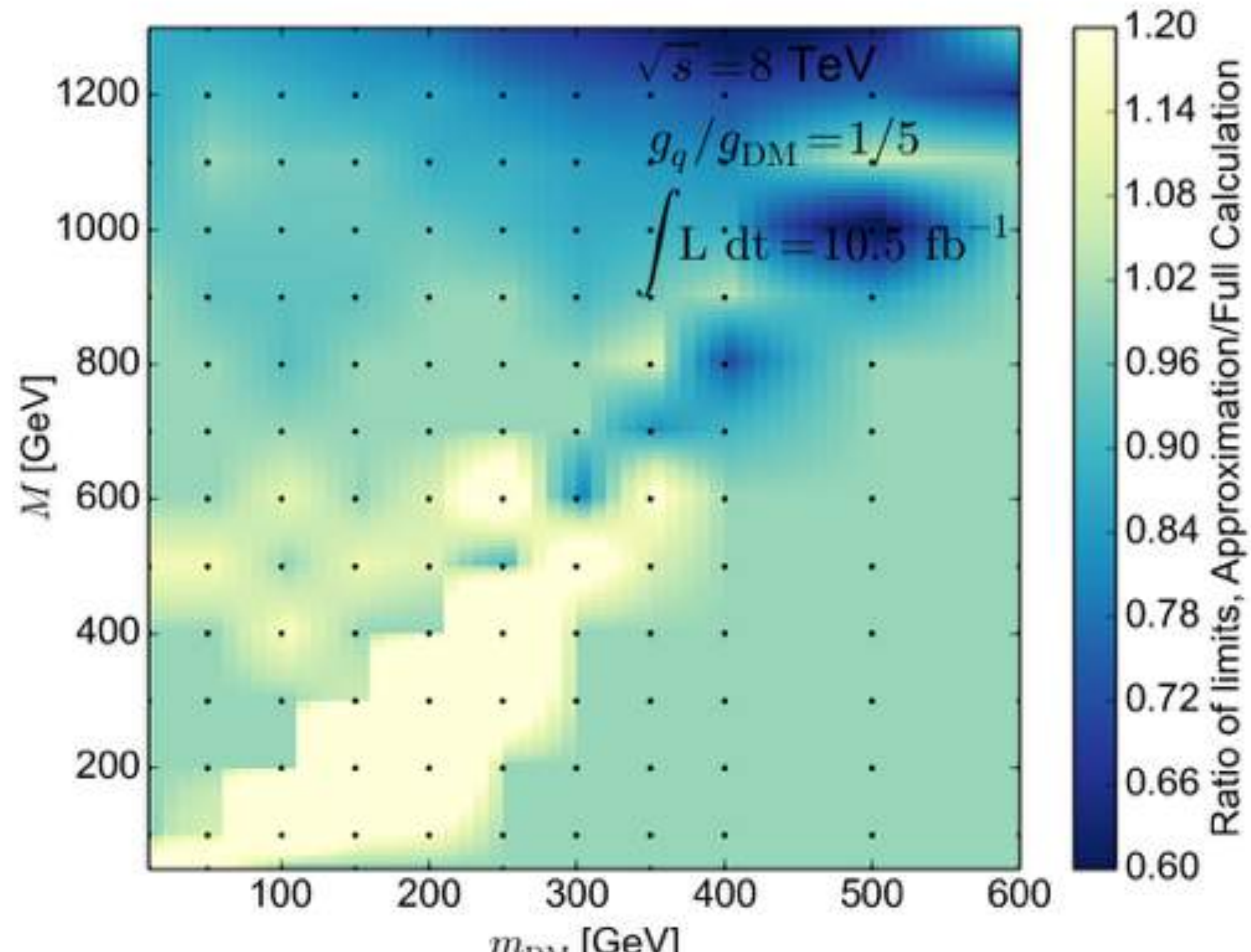
Rescaling relations

$$\sigma \propto \begin{cases} g_q^2 g_{\rm DM}^2/\Gamma_{\rm OS} & \text{if } M > 2m_{\rm DM} \\ g_q^2 g_{\rm DM}^2 & \text{if } M < 2m_{\rm DM} \end{cases}$$

How well does this approximation hold?

1s½
JHEP 1506 (2015) 142
TDJ, Nordstrom



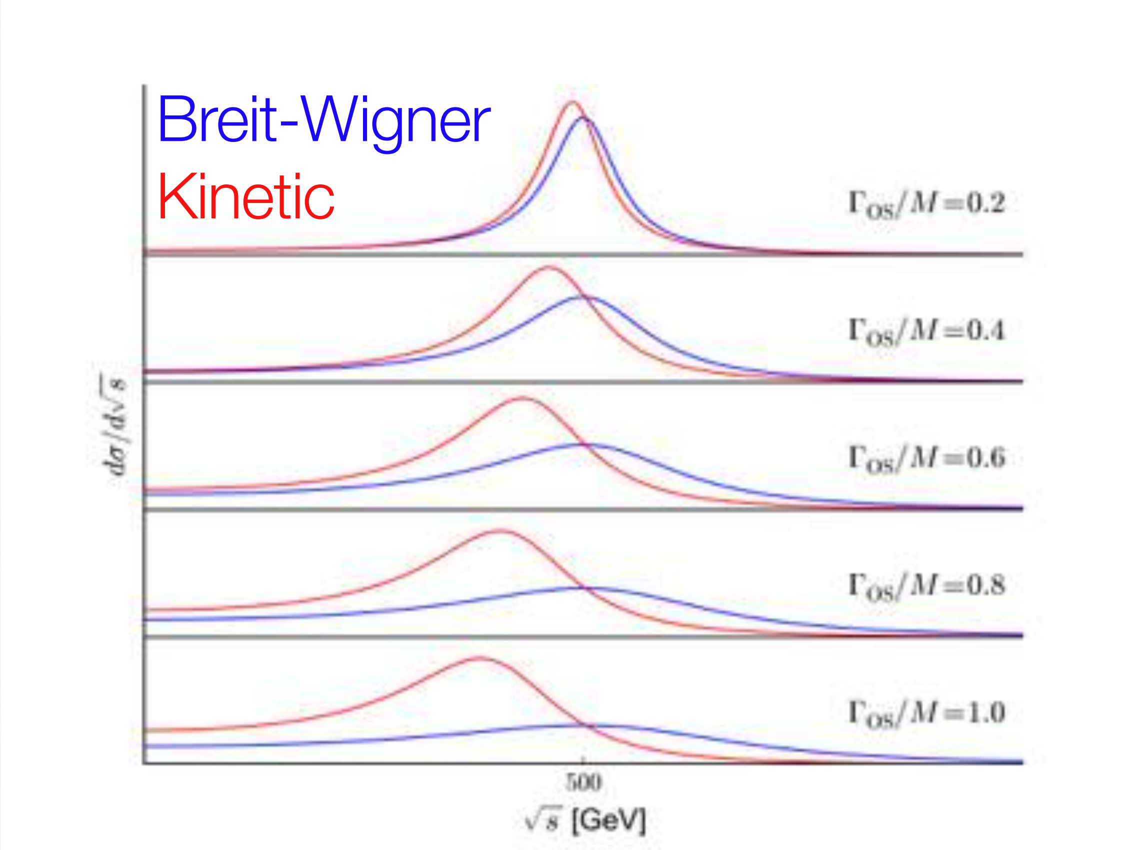


Problems with the width

- The standard Breit-Wigner propagator with on-shell width,

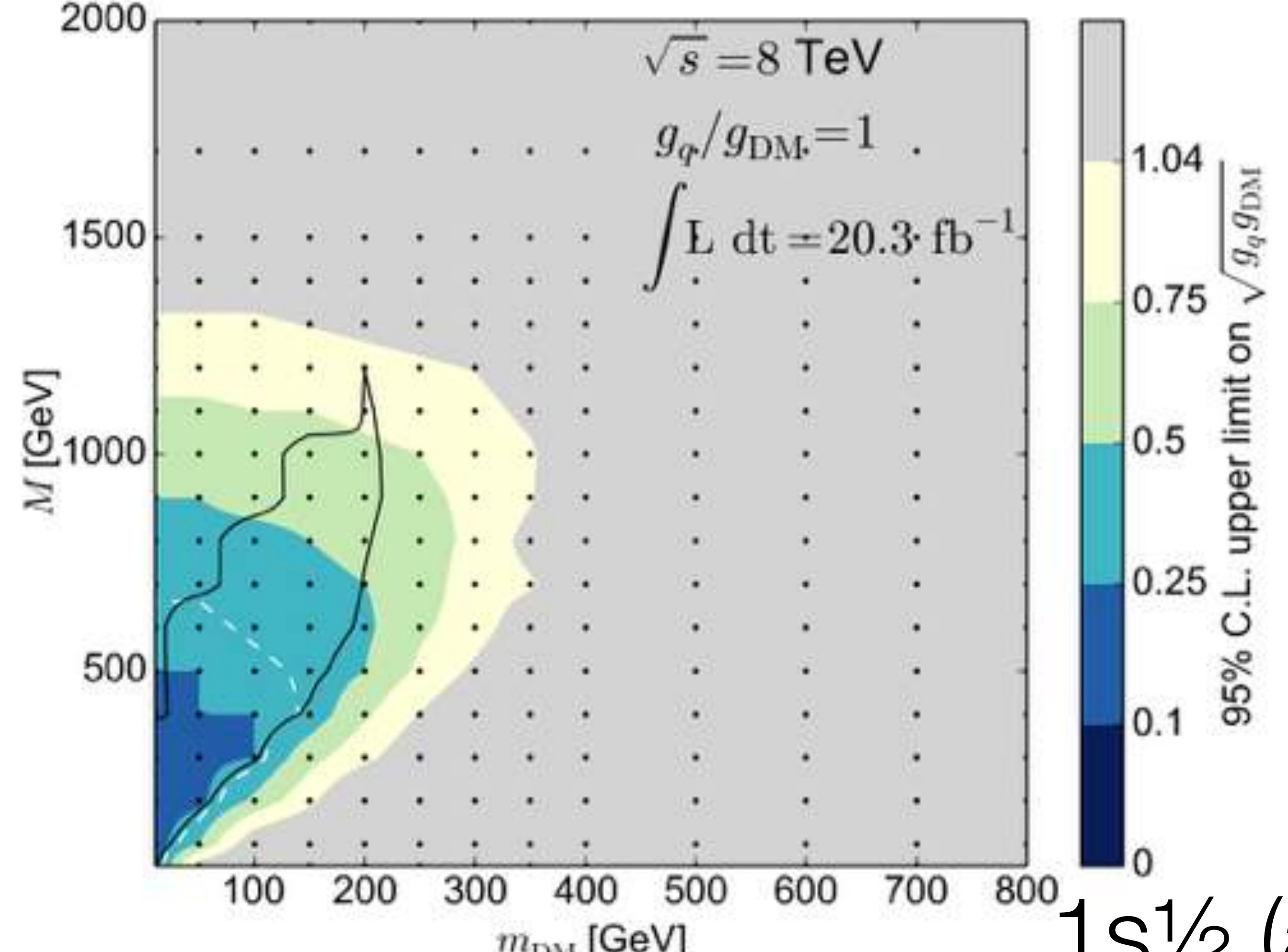
$$\Delta_{BW} = \frac{1}{s - M^2 + iM\Gamma_{\rm OS}}$$

as used by generators, only valid for $\Gamma \ll M$.

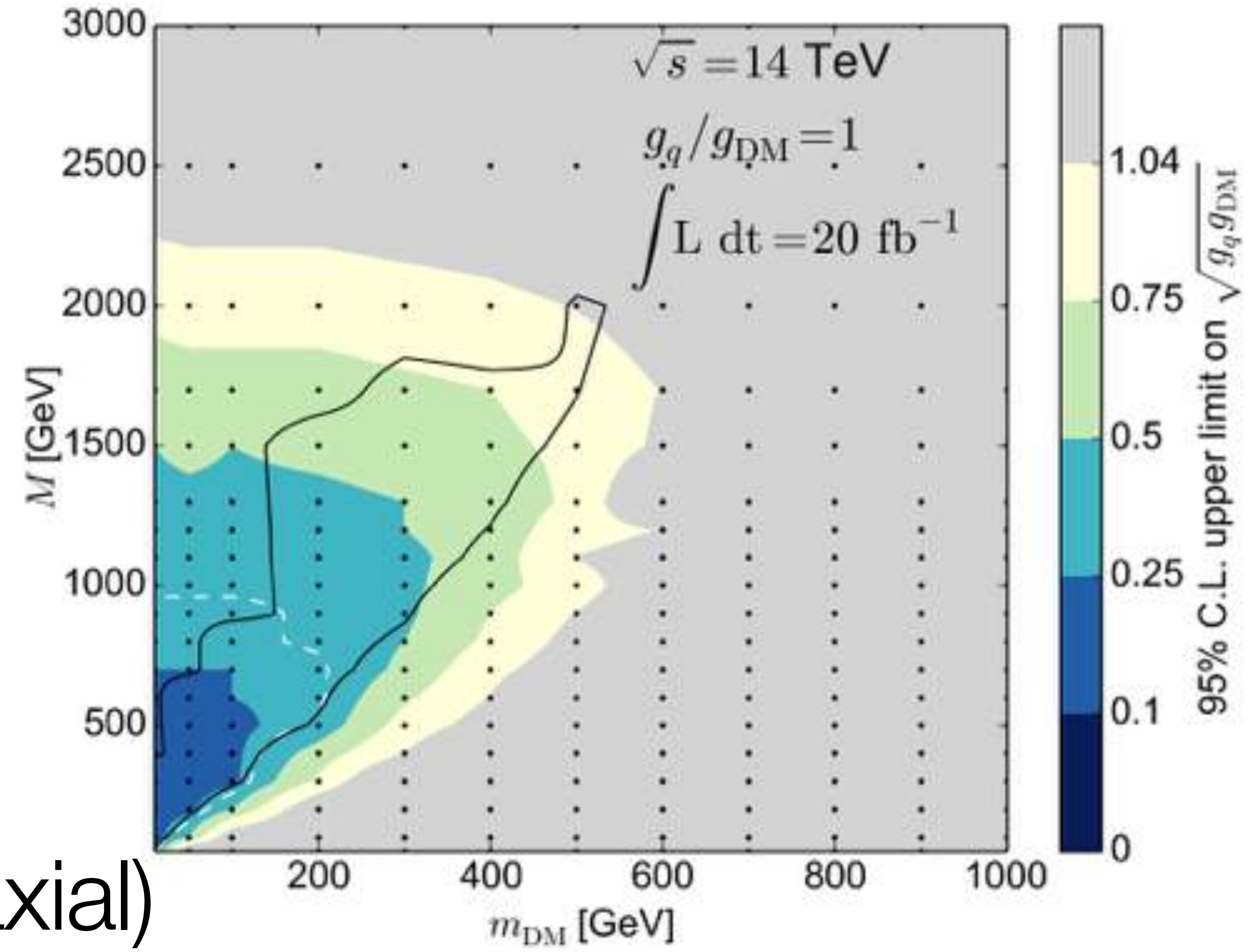


- Restrict parameter space to regions where $\Gamma < M$.
Current strength of constraints give $\Gamma/M \sim 0.5$;
In the transition region, rescale by the ratio of the BW and kinetic propagators after convolution with the PDF

$$\frac{\int_{x_1,x_2} \text{PDF} \times \Delta_{\text{Kinetic}}}{\int_{x_1,x_2} \text{PDF} \times \Delta_{BW}}$$

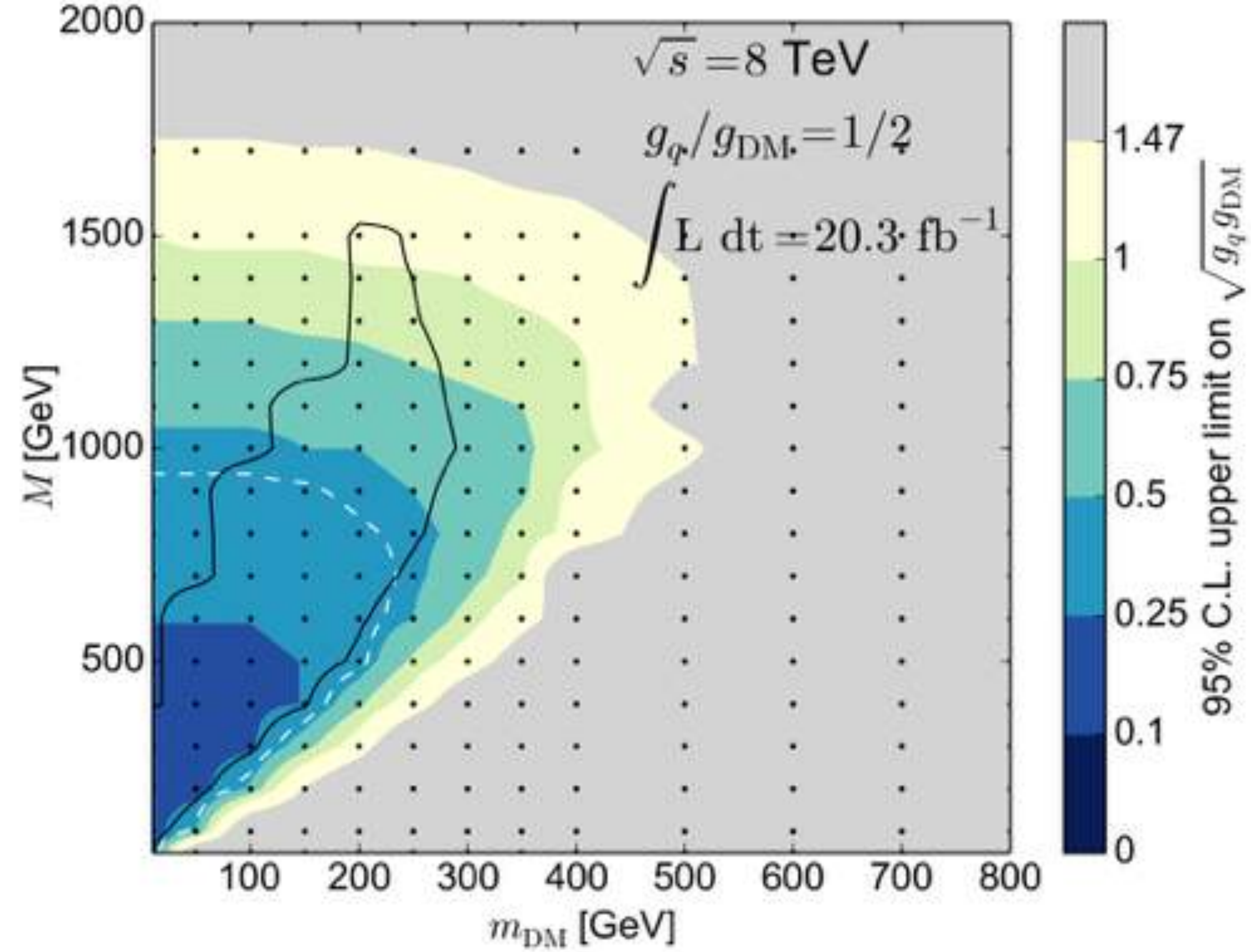


$\sqrt{s} = 8$ TeV
$g_q/g_{\rm DM} = 1$
$\int$L dt = 20.3 fb^{-1}
M [GeV]
$m_{\rm DM}$ [GeV]
95% C.L. upper limit on $\sqrt{g_q g_{\rm DM}}$
1.04
0.75
0.5
0.25
0.1
0

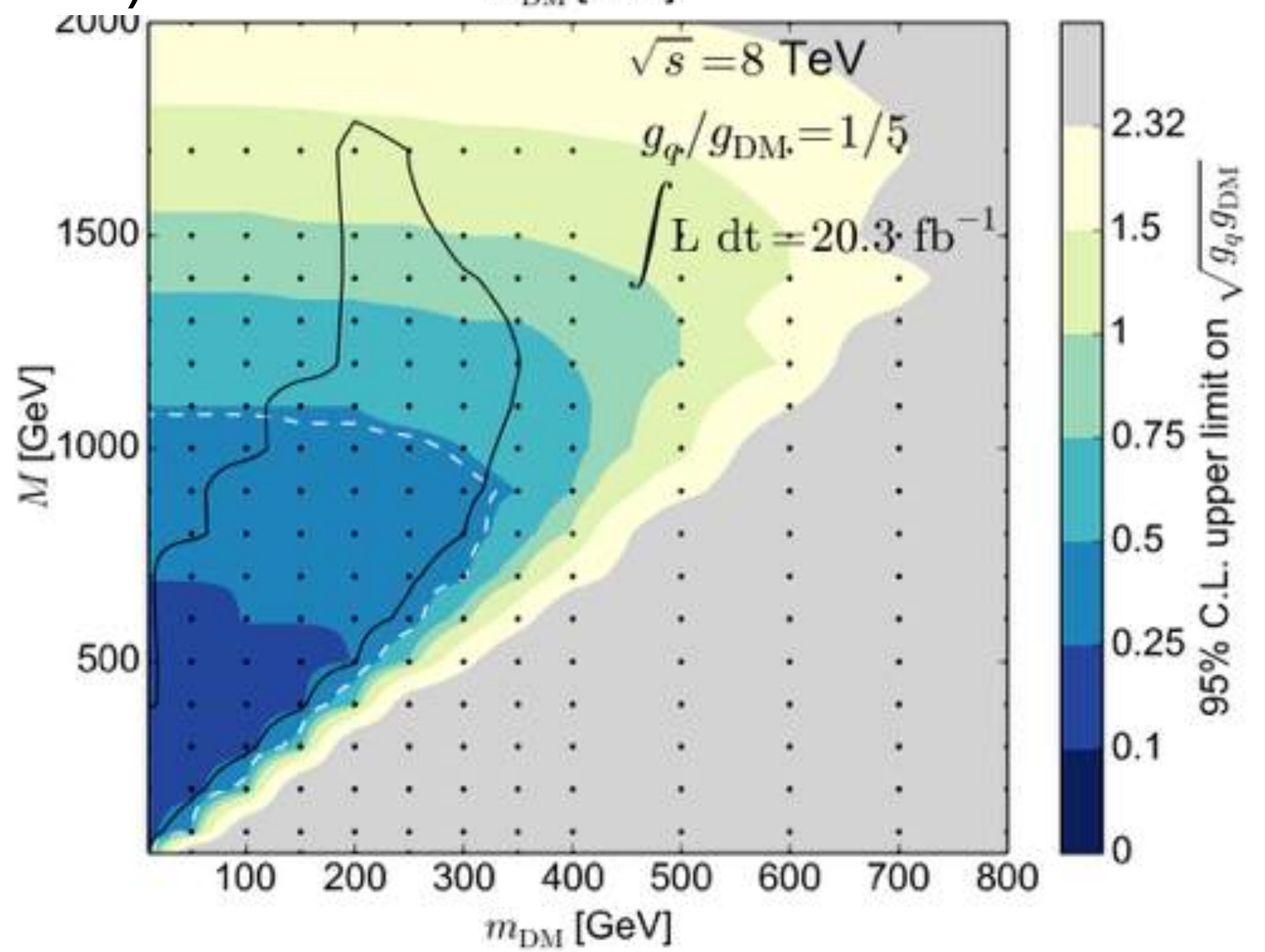


$\sqrt{s} = 14$ TeV
$g_q/g_{\rm DM} = 1$
$\int$L dt = 20 fb^{-1}
M [GeV]
$m_{\rm DM}$ [GeV]
95% C.L. upper limit on $\sqrt{g_q g_{\rm DM}}$
1.04
0.75
0.5
0.25
0.1
0

1s½ (axial)



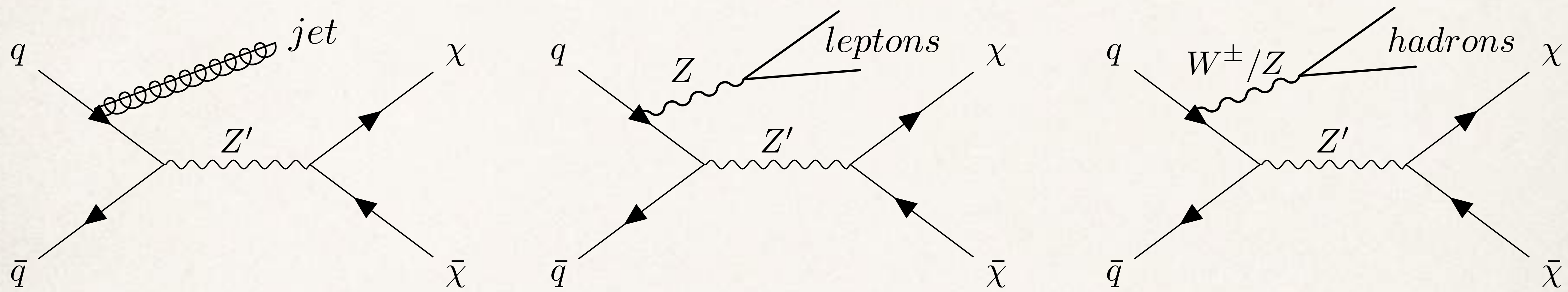
$\sqrt{s} = 8$ TeV
$g_q/g_{\rm DM} = 1/2$
$\int$L dt = 20.3 fb^{-1}
M [GeV]
$m_{\rm DM}$ [GeV]
95% C.L. upper limit on $\sqrt{g_q g_{\rm DM}}$
1.47
1
0.75
0.5
0.25
0.1
0

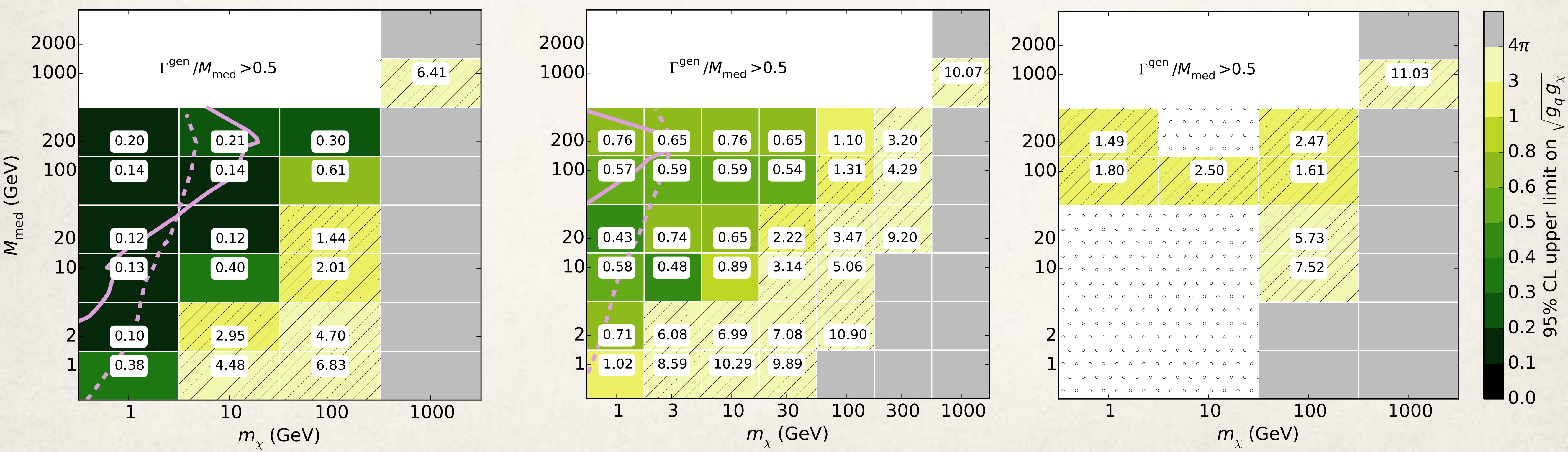


$\sqrt{s} = 8$ TeV
$g_q/g_{\rm DM} = 1/5$
$\int$L dt = 20.3 fb^{-1}
M [GeV]
$m_{\rm DM}$ [GeV]
95% C.L. upper limit on $\sqrt{g_q g_{\rm DM}}$
2.32
1.5
1
0.75
0.5
0.25
0.1
0

Search channels

- To be comprehensive, study other search channels





1s½ (axial) - Similar results for 1s½ (vector)

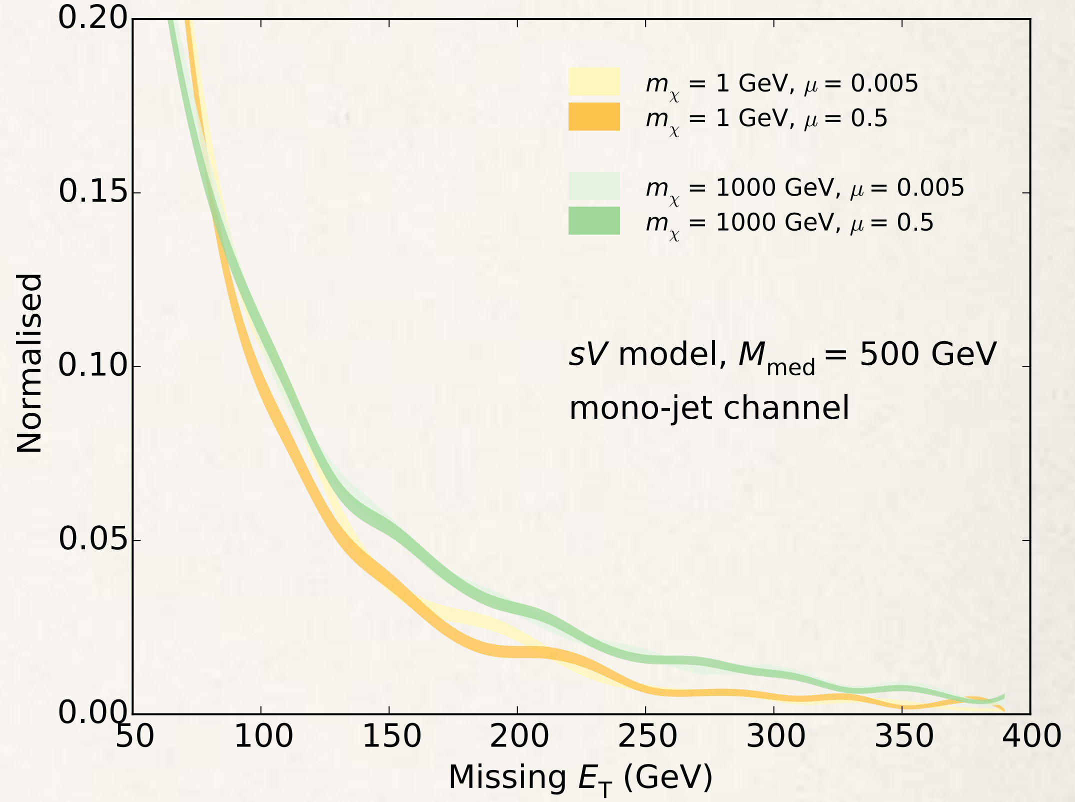
Testing the approximation

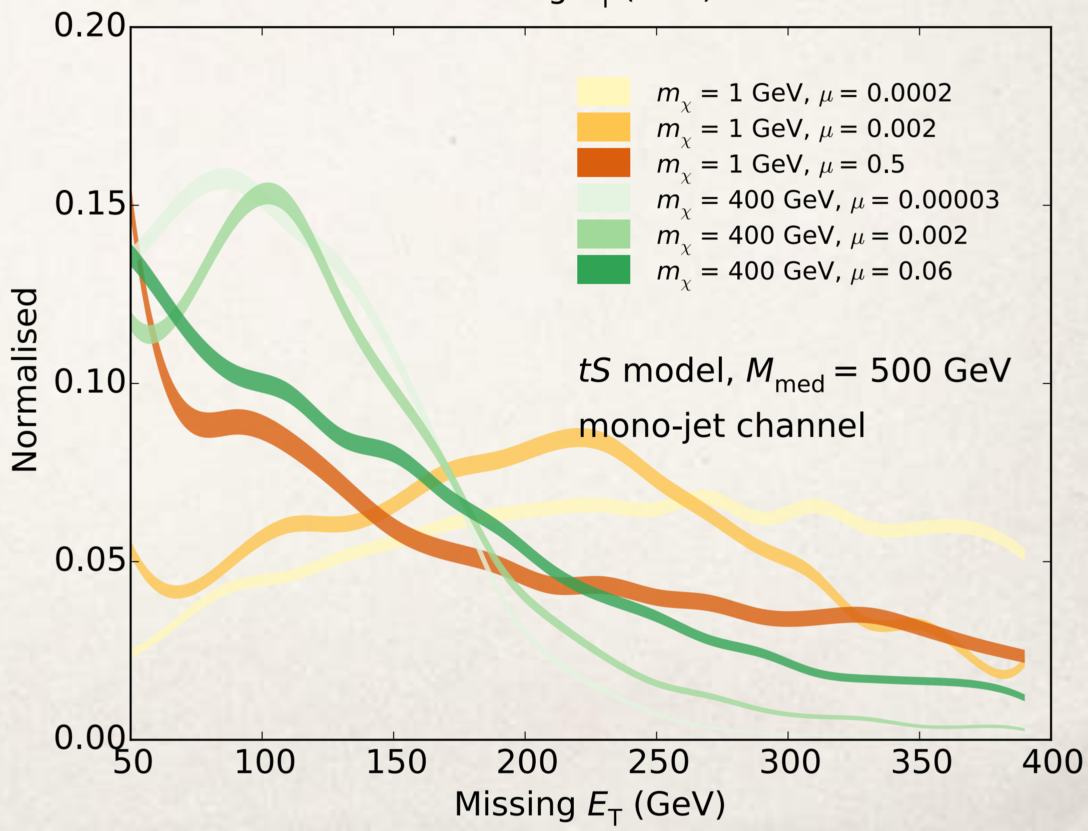
- Does the rescaling relation still hold?

$$\sigma \propto \begin{cases} g_q^2 g_{\mathrm{DM}}^2/\Gamma_{\mathrm{OS}} & \text{if } M > 2m_{\mathrm{DM}} \\ g_q^2 g_{\mathrm{DM}}^2 & \text{if } M < 2m_{\mathrm{DM}} \end{cases}$$

- Only if the kinematic distribution of missing energy is independent of the width

$$\sigma \propto \frac{g_{\mathrm{DM}}^2 g_q^2}{(s - M^2)^2 + M^2\Gamma^2},$$

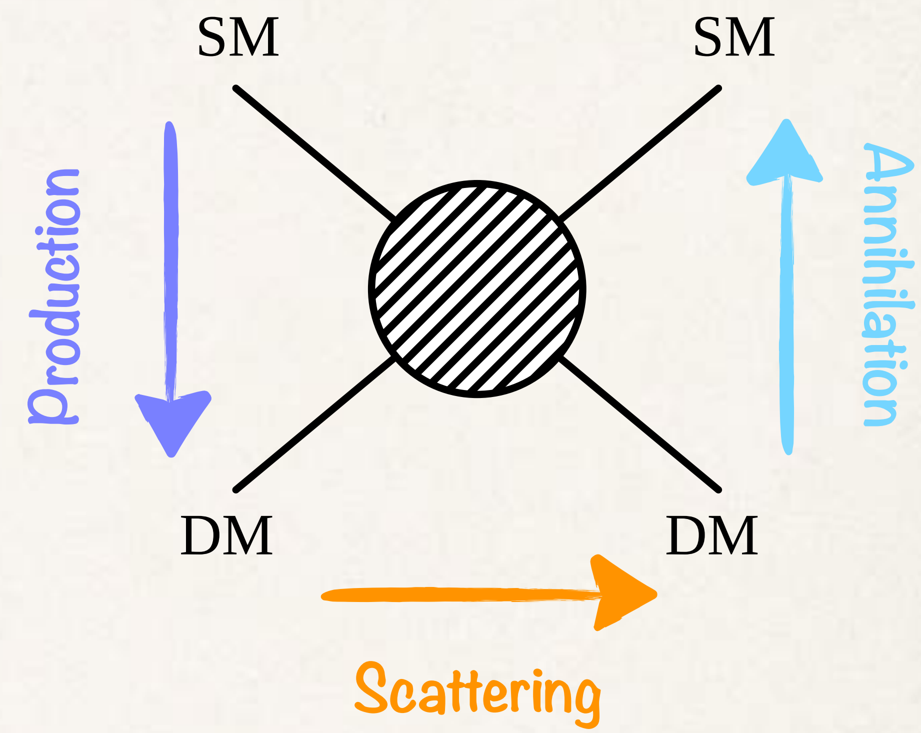


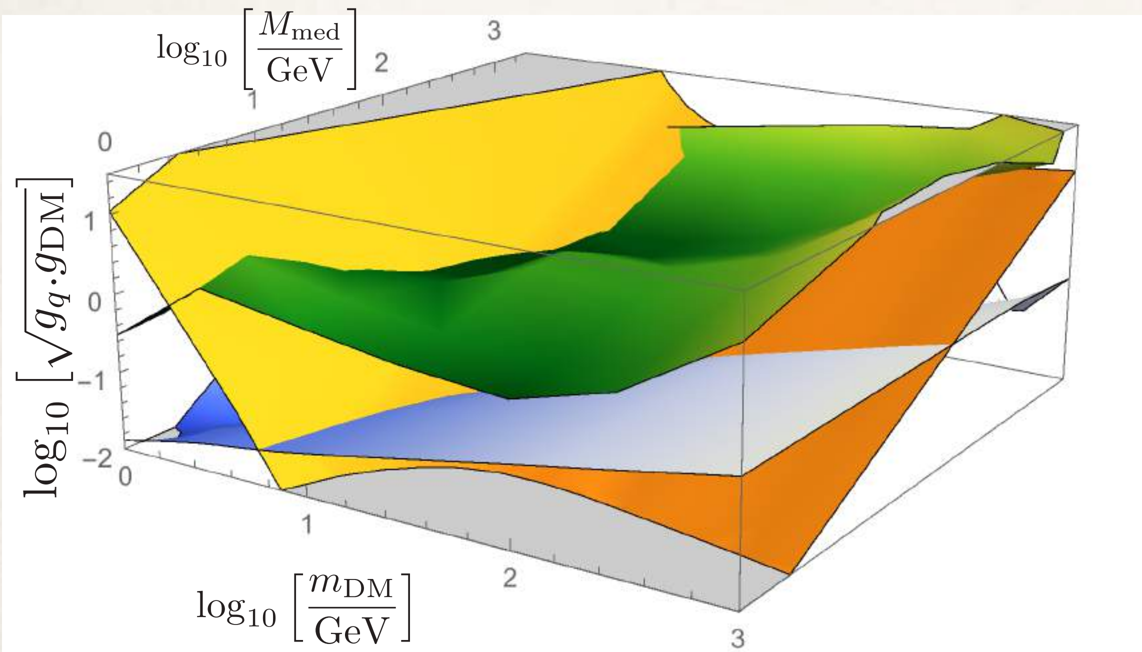


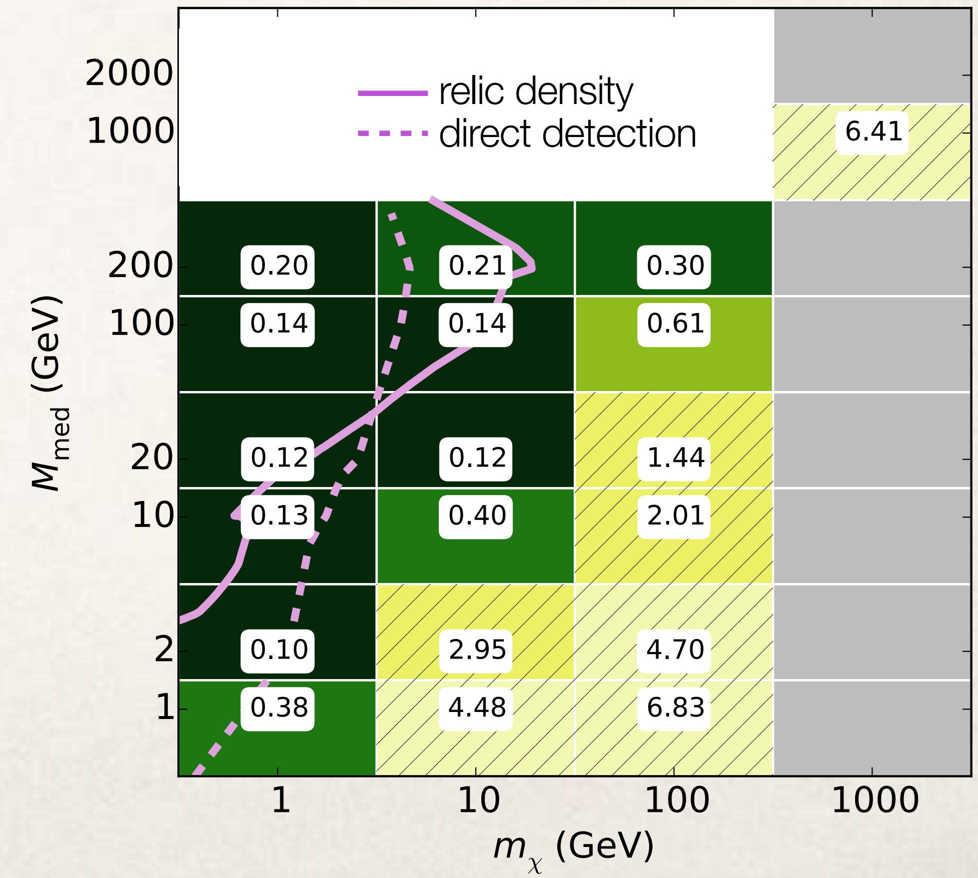
Comparing to other constraints

- Difficult to compare multiple constraints in 3D parameter space!

- Intercept shows the boundary where one constraint becomes stronger than another, indicating the region where each class of constraints performs best







Comparing to other constraints

- Direct detection assumes a local density and velocity distribution as input

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_{\rm DM} m_N} \int_{|\vec{v}|>v_{\rm min}} d^3\vec{v}|\vec{v}|f(\vec{v})\frac{d\sigma_{\chi N}}{dE_R}$$

- Relic density constraints assume DM is a thermal relicis sensitive to number of annihilation channels and relative contribution to total relic density

$$\langle\sigma v\rangle_{\rm total} \simeq \frac{4.8\times10^{-10}\,{\rm GeV}^{-2}}{\Omega_{\rm DM}h^2}.$$

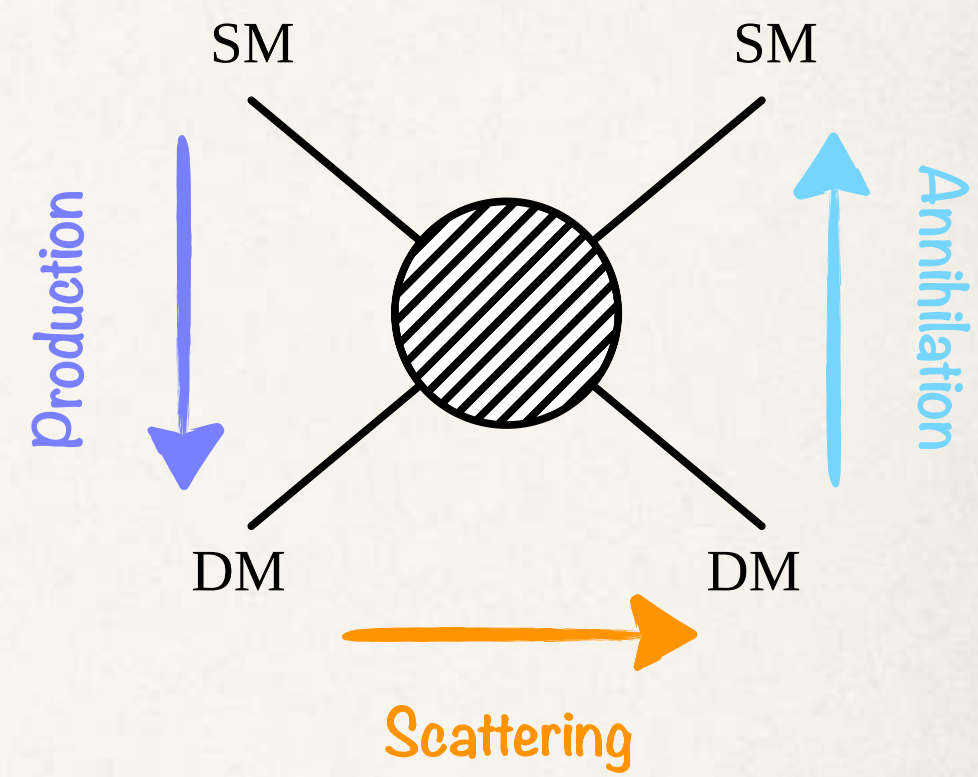
- Each constraint has strengths and weaknesses, so together are complementary, but compare with caution

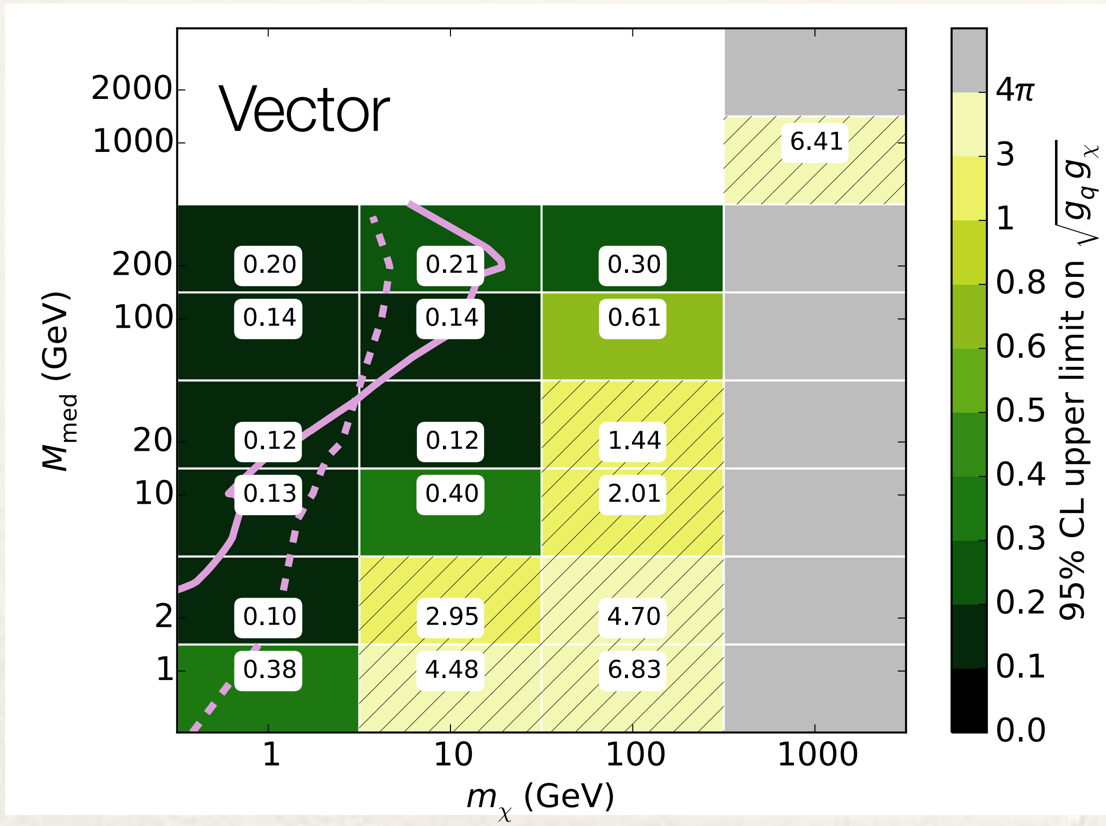
Consistency

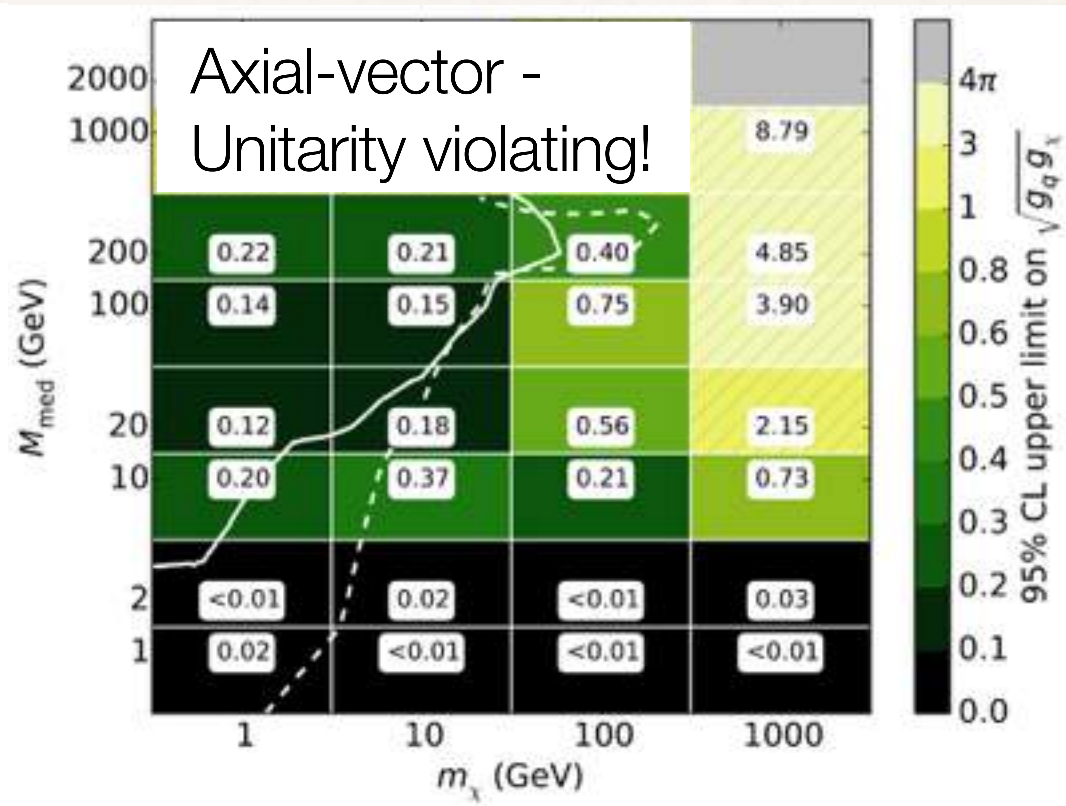
- The simplified models we've been using are not designed to be UV-complete
- Does it matter if the simplified models we're using are physical?
  - Signals and constraints can be *overestimated* if we get this wrong;
  - Some models are not just be *incomplete*, but *wrong*

Consistency

- We focus on axial-vector 1s½ (Z’), because it ‘hides’ from direct detection
    - Violates unitarity when $m_{DM} \gg M_{med}$, greatly enhancing the cross section
    - Suffers anomalies!







Building a natural, consistent axial 1s½ (Z')

- cosθ $U(1)_{B\text{-}L}$ + sinθ $U(1)_Y$ is guaranteed anomaly-free, so use this as our U(1)'
- This fixes the charge of the left- and right-handed SM fermions under U(1)'

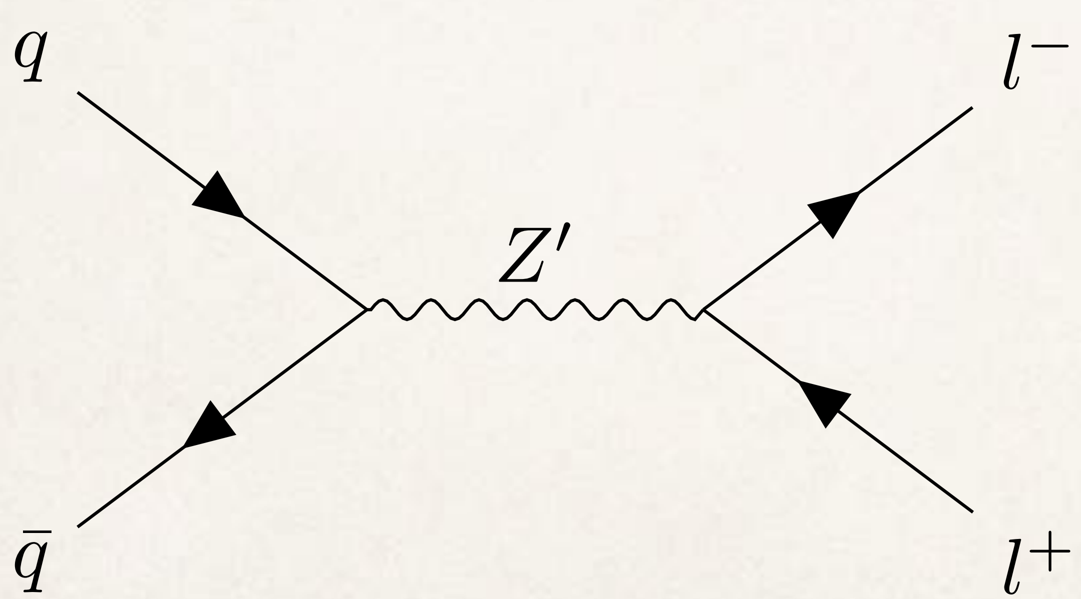
	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-L}$	$U(1)'$
$\begin{pmatrix} \nu_L^{\ell_i} \\ \ell_L^i \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}\cos\theta - \sin\theta$
$(\ell_R^i)^{\mathrm{C}}$	$\mathbf{1}$	$\mathbf{1}$	1	$+1$	$\cos\theta + \sin\theta$
$\begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$+\frac{1}{3}$	$\frac{1}{6}\cos\theta + \frac{1}{3}\sin\theta$
$(u_R^i)^{\mathrm{C}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}\cos\theta - \frac{1}{3}\sin\theta$
$(d_R^i)^{\mathrm{C}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}\cos\theta - \frac{1}{3}\sin\theta$

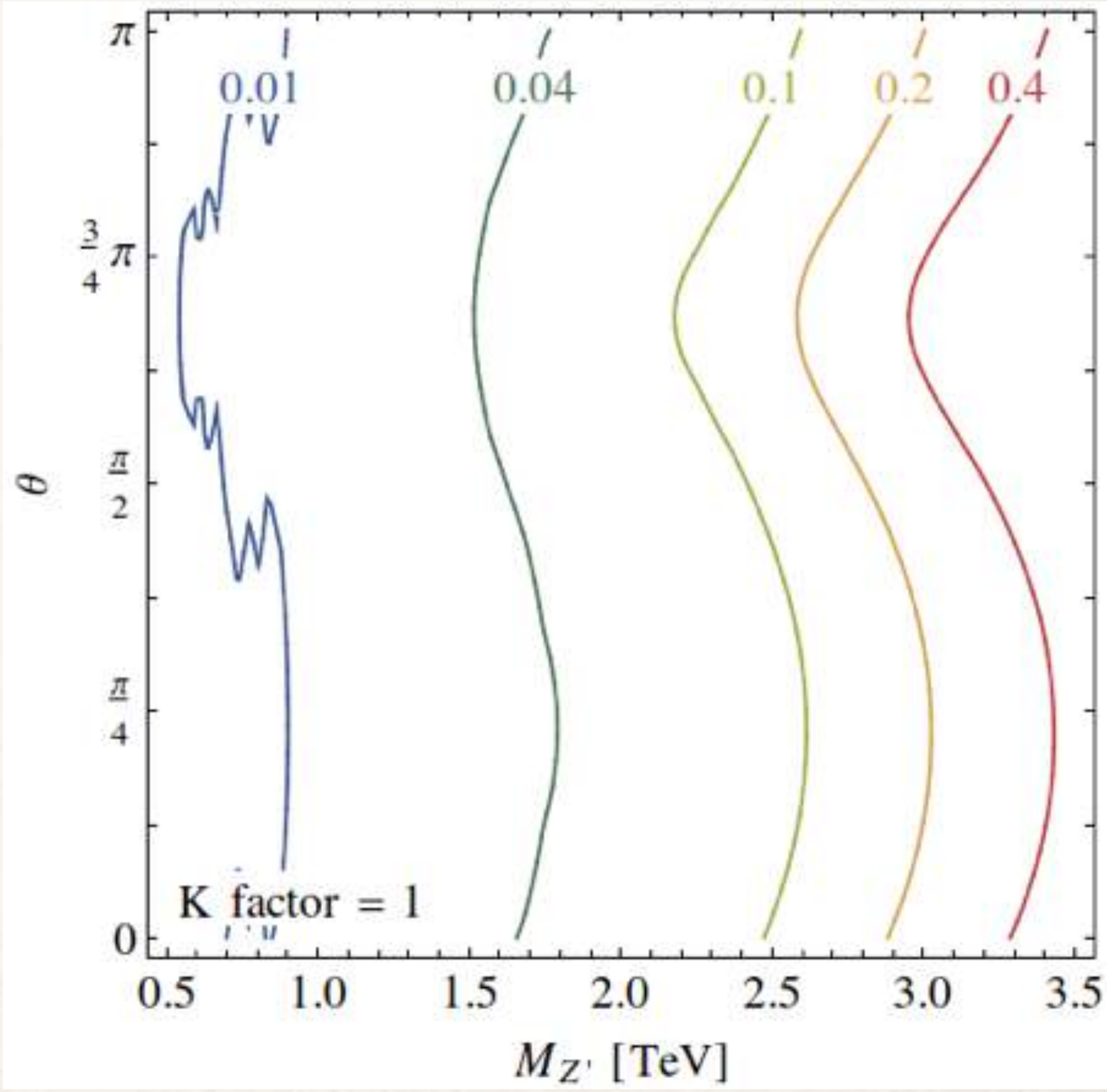
- If L and R fermions have different charge,
  Higgs must be charged to maintain gauge invariance $y_\ell \bar{L}_L \Phi \ell_R$

$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0	$\frac{1}{2}\cos\theta$

Dilepton constraints

- Induced lepton coupling subjects this model to stringent constraints from Z' decay to dileptons





Building a natural consistent axial Z'

- Mixing results in a mix of terms - no pure axial-vector term!

SM fermion f	coeff. of $g_{Z'}\bar{f}\not{Z}'f$	coeff. of $g_{Z'}\bar{f}\not{Z}'\gamma_5 f$
leptons	$-\frac{3}{4}\cos\theta - \sin\theta$	$-\frac{1}{4}\cos\theta$
neutrinos	$-\frac{1}{4}\cos\theta - \frac{1}{2}\sin\theta$	$\frac{1}{4}\cos\theta + \frac{1}{2}\sin\theta$
up quarks	$\frac{5}{12}\cos\theta + \frac{1}{3}\sin\theta$	$\frac{1}{4}\cos\theta$
down quarks	$-\frac{1}{12}\cos\theta + \frac{1}{3}\sin\theta$	$-\frac{1}{4}\cos\theta$

$$\mathcal{L} \supset g_\chi Z'_\mu (\cancel{c_V^\chi\, \bar{\chi}\gamma^\mu\chi} + c_A^\chi\, \bar{\chi}\gamma^\mu\gamma^5\chi) + g_q Z'_\mu (\underline{c_V^q\, \bar{q}\gamma^\mu q} + \underline{c_A^q\, \bar{q}\gamma^\mu\gamma^5 q})$$

Vector Axial-vector

- Induces a range of DM scattering operators, not just the 'usual' $\sigma_{\rm SI}$ and $\sigma_{\rm SD}$.

$$\longrightarrow\ \underline{\vec{s}_\chi \cdot \vec{s}_N},\ \ \underline{i\vec{s}_\chi \cdot (\vec{s}_N \times \vec{q}),\ \ \vec{s}_\chi \cdot \vec{v}^\perp}$$

σ_{SD} Suppressed, but neither σ_{SI} nor σ_{SD}

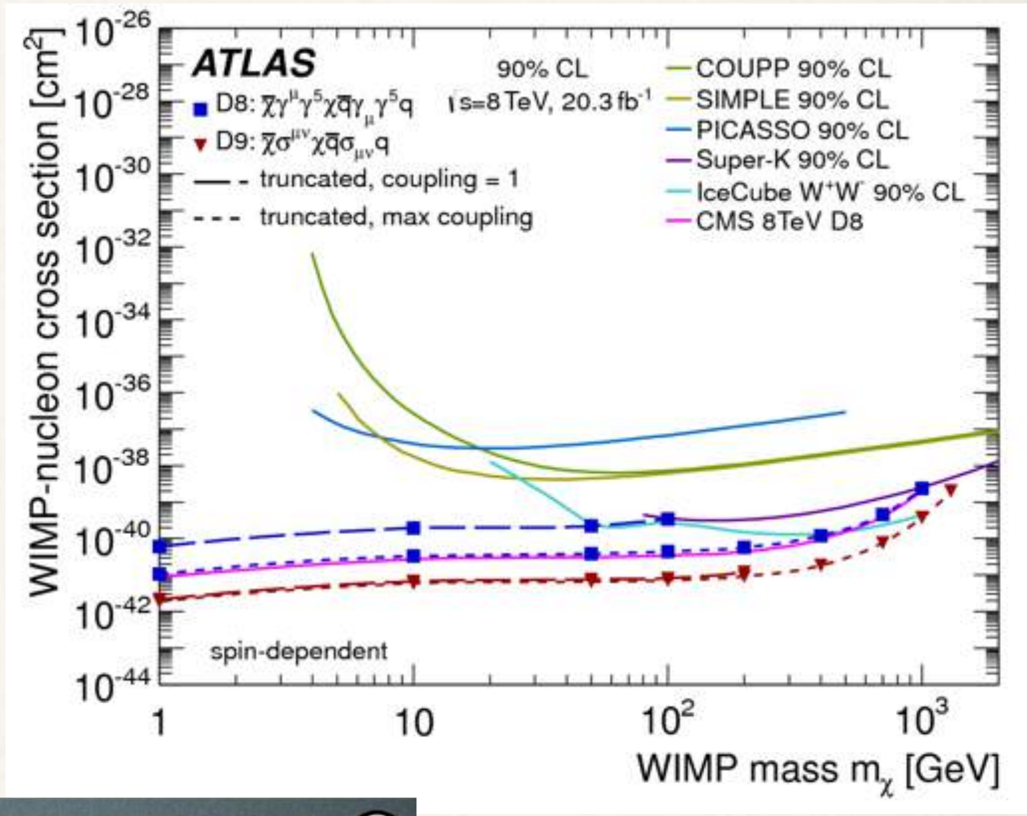
IceCube: Using annihilation to probe scattering

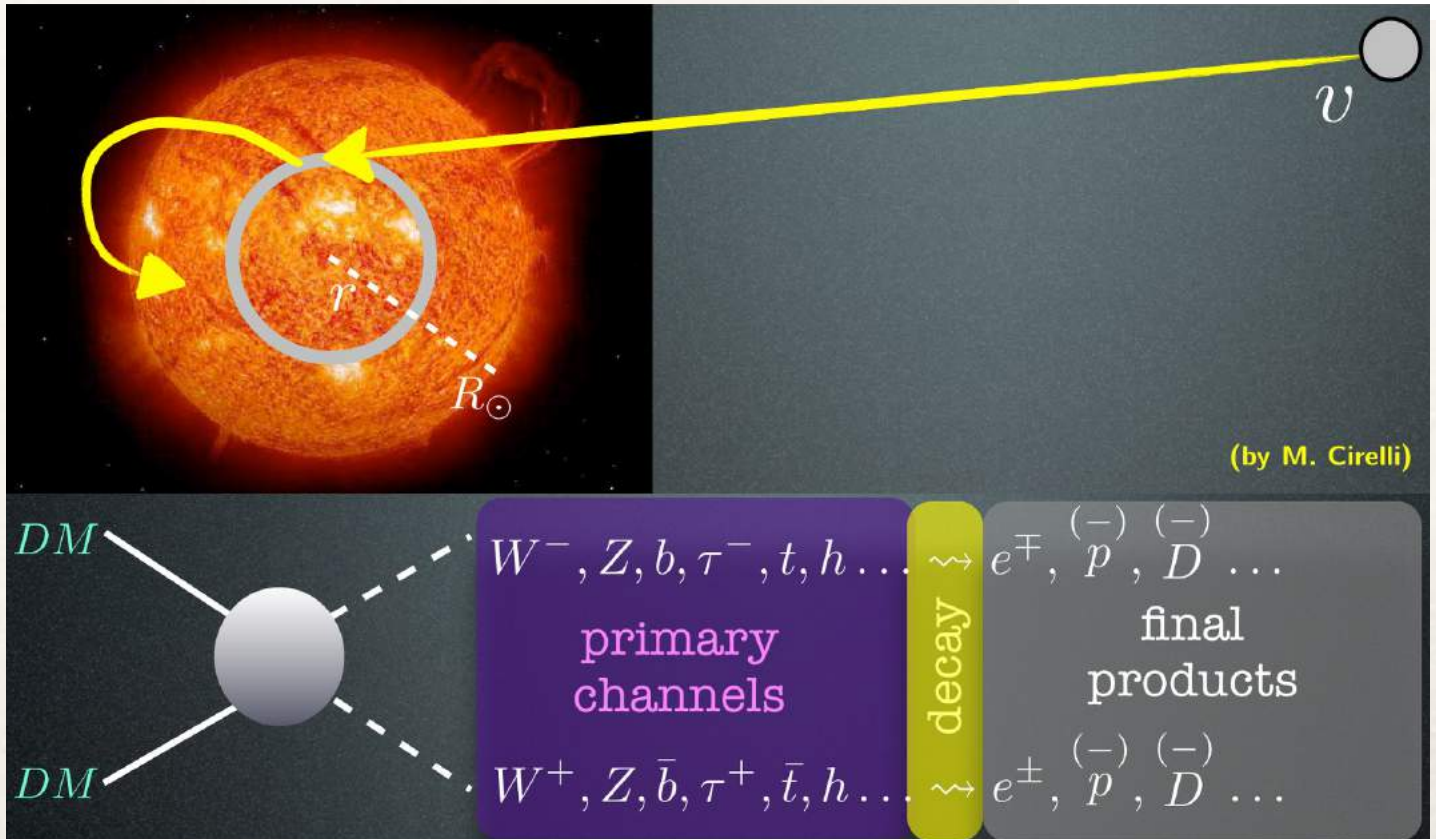
- It is difficult for DD experiments to compete with LHC constraints on these models

- Solar neutrinos provide a unique window on DM scattering

- DM accumulates in the sun

$$\Gamma_{\text{ann}} \propto \rho^2 \to \Gamma_{\text{ann}} = \Gamma_{\text{capture}}$$





Conclusion

- Effective operators remain a useful benchmark for DM searches at the LHC if used and interpreted with caution
- Simplified models are the natural next step. The size of the parameter and model space present some challenges which can be overcome with careful application of constraints and approximations
- The consistent use of simplified models is important and presents interesting phenomenology!