PP@LHC 2016, PISA - 16 MAY 2016

DM SEARCH @ LHC (THEORY)

Andrea De Simone

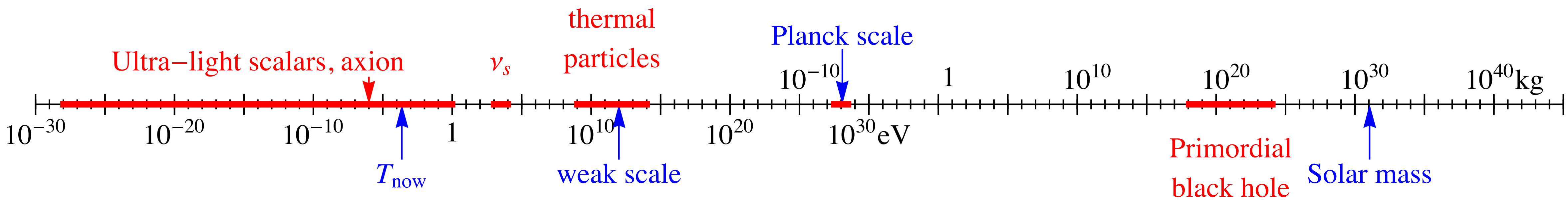
MOSTLY BASED ON:

DS, JACQUES - ARXIV:1603.08002 (REVIEW)

BOVEIA ET AL. - ARXIV:1603.04156 (LHCDMWG)

Outline

- a quick journey in theory space
- simplified models (*s*-channel, *t*-channel)
- some recommendations & future directions



[courtesy A. Strumia]

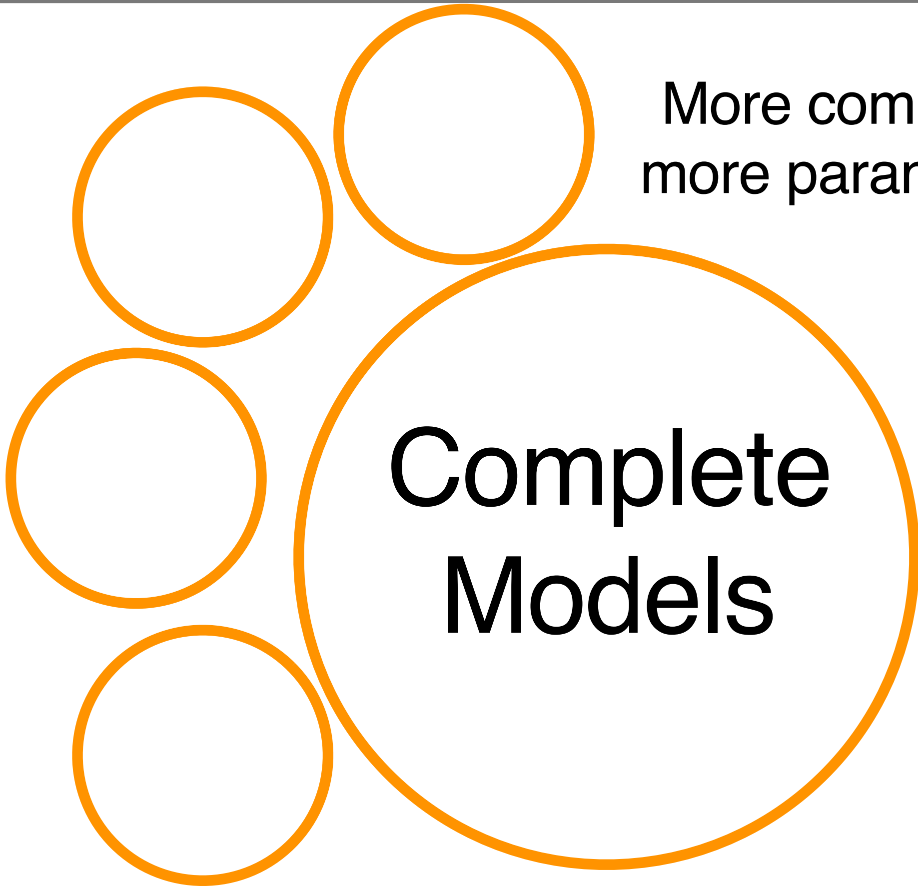
we are only sure that DM has **gravitational** interactions

WIMP

neutralino
minimal DM
heavy neutrino
inert Higgs doublet
LKP
LTP
...

non-WIMP

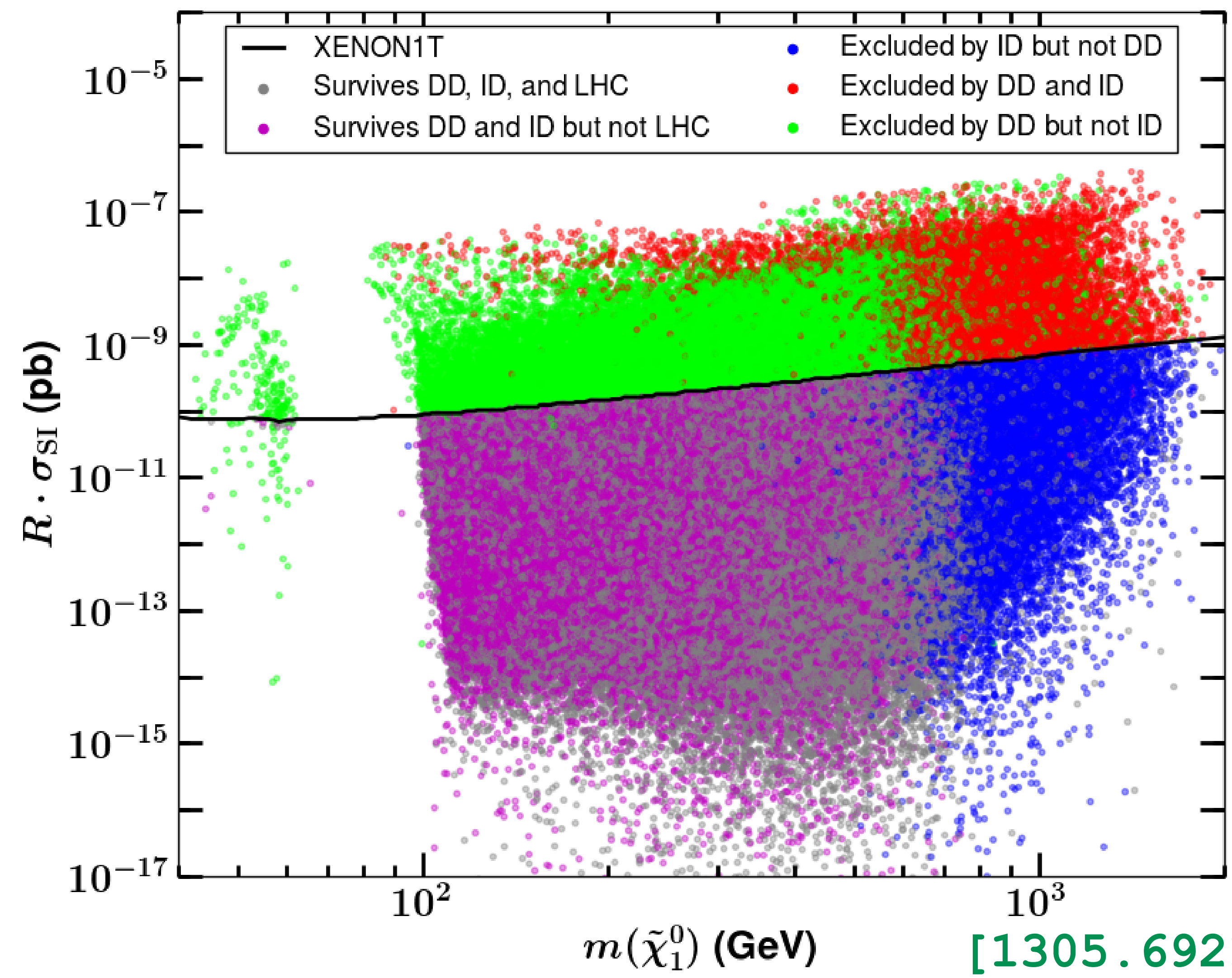
axion
gravitino
axino
sterile neutrino
techni-baryon,
Q-balls
...



More complete/
more parameters

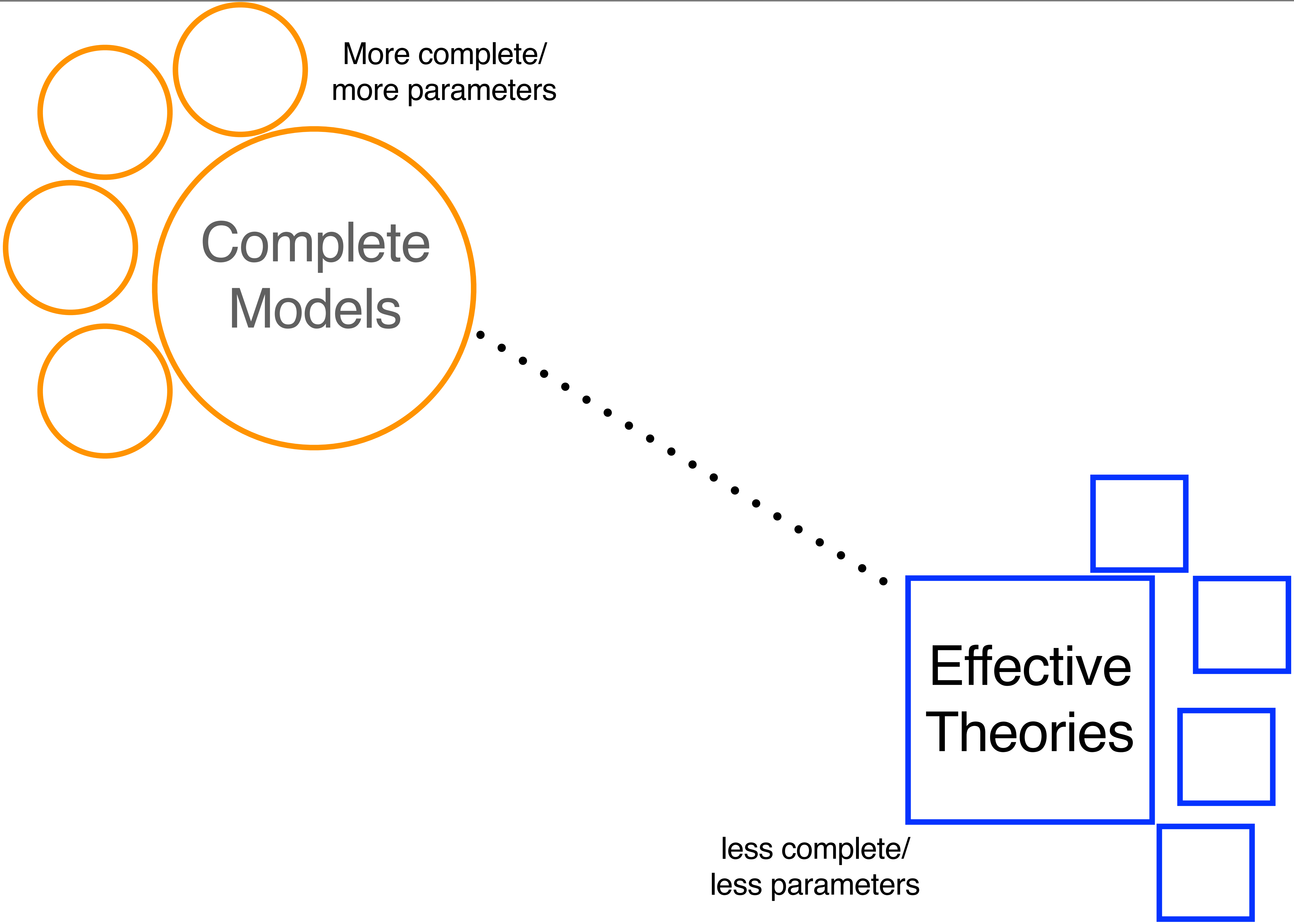
MSSM, Composite Higgs, Extra-Dim...

pMSSM scan

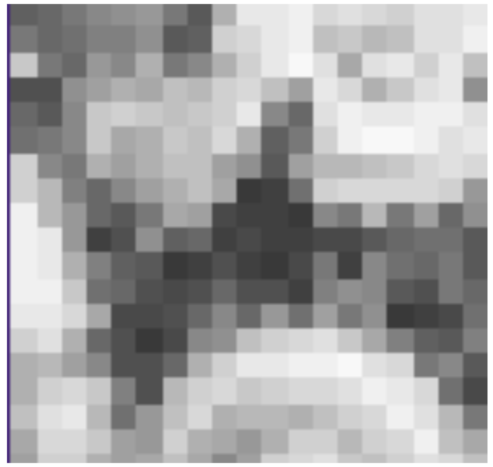


[1305.6921]

lots of parameters...


More complete/
more parameters
Complete
Models
Effective
Theories
less complete/
less parameters

effective low-energy description



($\Lambda \sim 1$ TeV)

New States

(say, 10 TeV)

M_Z

E

EFT OK

Integrate out the UV physics connecting DM-SM and describe interactions with eff. ops.:

$$\frac{1}{\Lambda^2}(\bar{\chi}\Gamma^A\chi)(\bar{q}\Gamma_A q)$$

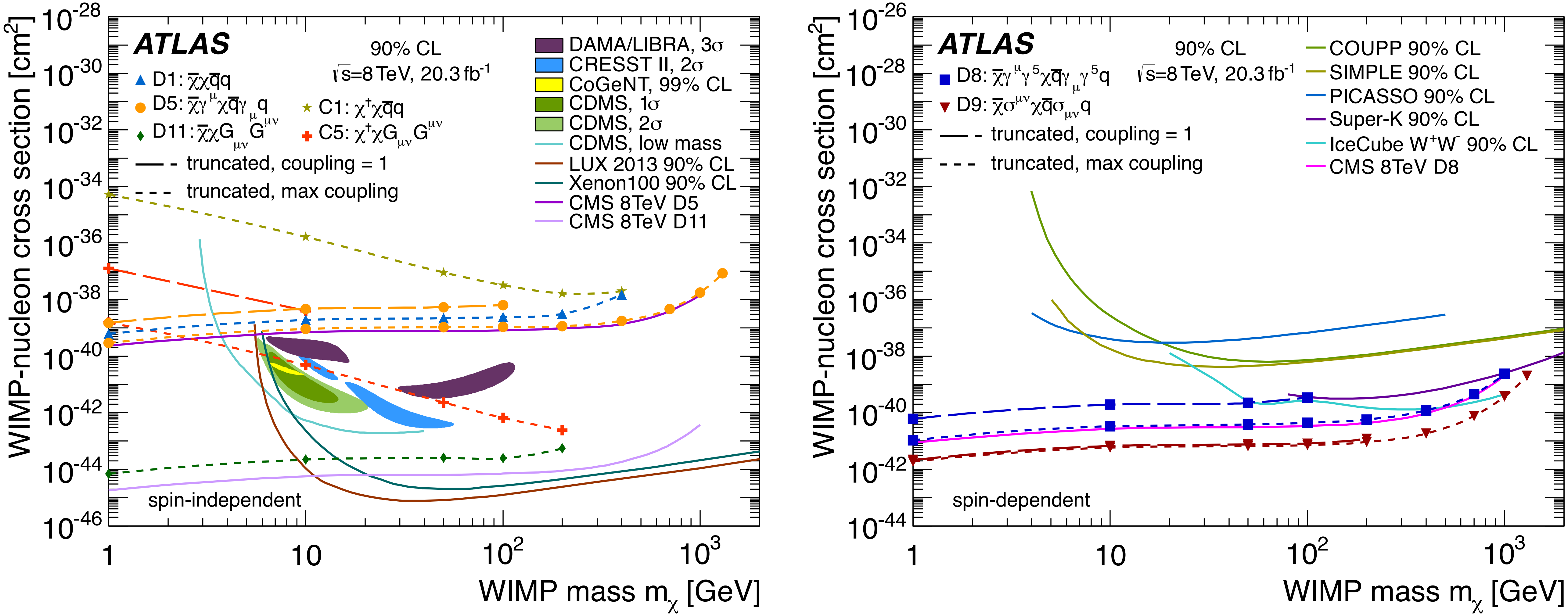
LHC can access regions beyond the validity of the eff. description

→ need to use EFT carefully and consistently

the momentum transfer in the relevant process must be $Q_{\rm tr} \lesssim M_{\rm med}$

The “money plots”

L=20.3 fb^{-1}

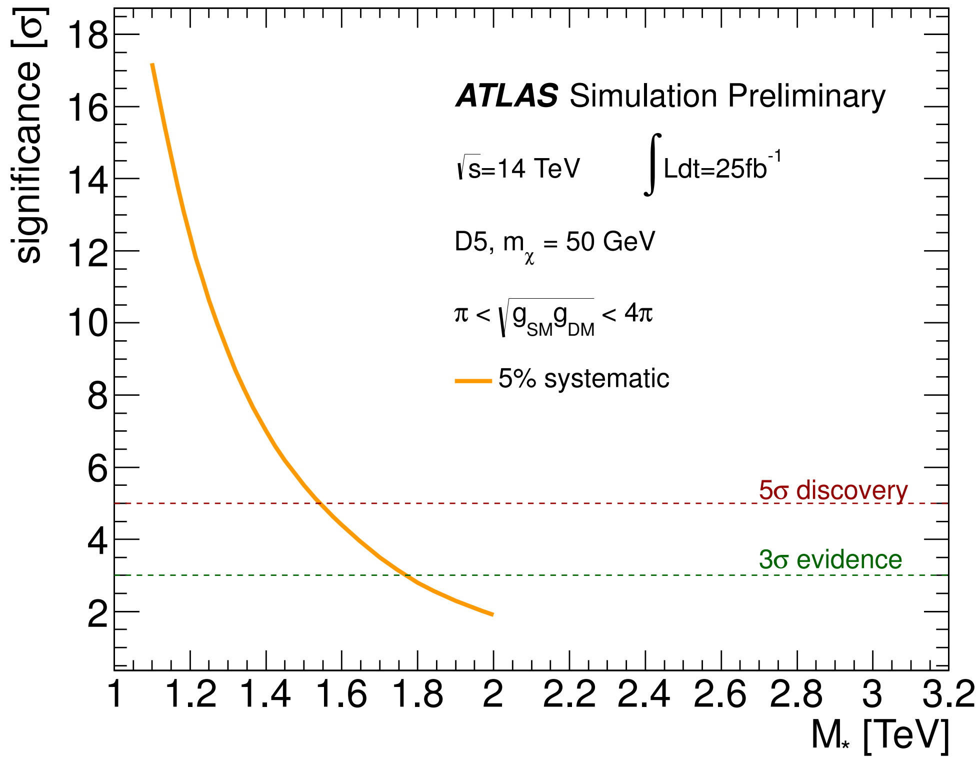


[ATLAS - 1502.01518]

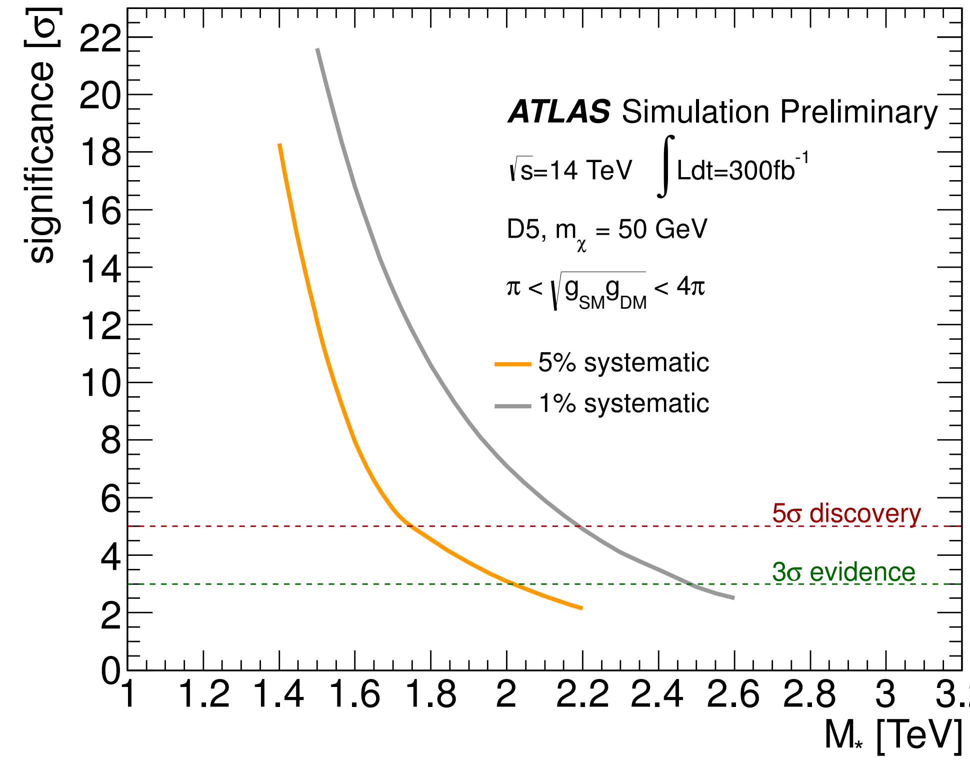
- after truncation: theoretically robust limits
- still relevant at low DM masses

$\sqrt{s} = 14\,\mathrm{TeV}$

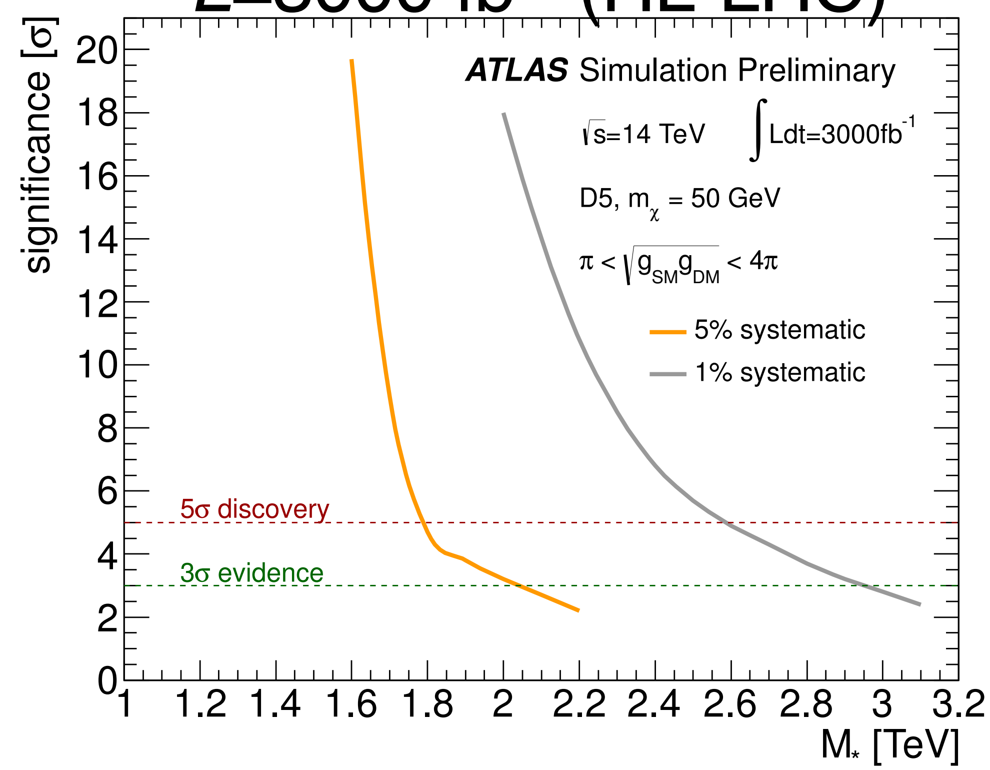
L=25 fb^{-1}



L=300 fb^{-1}



L=3000 fb^{-1} (HL-LHC)



Effective Operator

$$(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)$$

$$m_{\mathrm{DM}} = 50\ \mathrm{GeV}$$

EFT validity <u>assumed</u>

[ATL-PHYS-PUB-2014-0087]

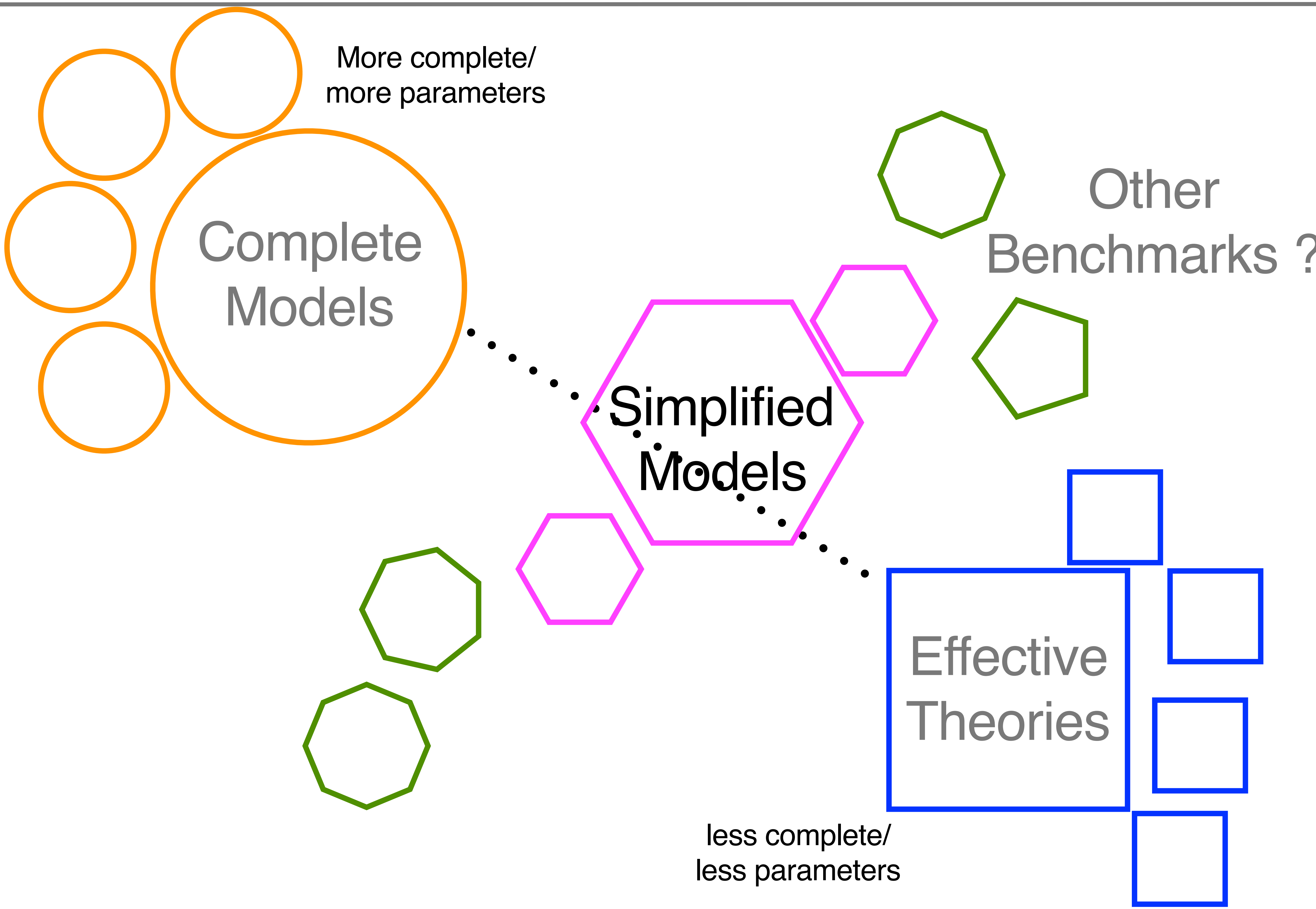
> *"There's a way to do it better.* ***Find it.***"
> *T.A. Edison*

EFT approach

- limited validity
- not entirely model-independent

How to go beyond that (but keeping generality), in view of LHC Run 2?

- **Simplified Models**

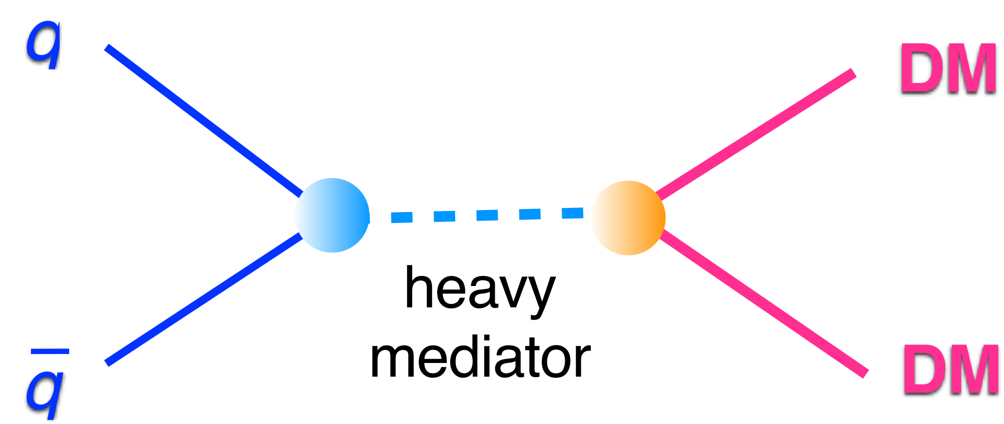

More complete/
more parameters
Complete
Models
Other
Benchmarks ?
Simplified
Models
Effective
Theories
less complete/
less parameters

... just means extending the SM with:

- 1 Dark Matter particle
- 1 Mediator particle connecting DM-SM

>> just another parametrization of unknown high energy physics <<

correspondence
eff ops ⟷ simplified models



✘ more parameters (g's)

✓ exploit other searches for mediators (e.g. di-jet), complementary to mono-jet

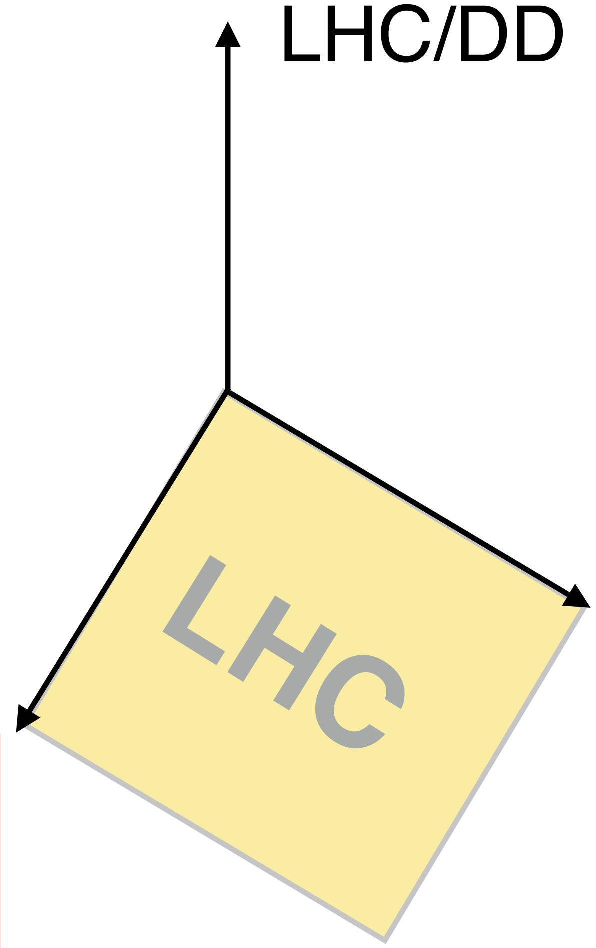
✓ theoretically consistent, no worries about EFT, widths, etc.

from DM search to MEDIATOR search

Complementarity

3-dimensional
combinations

LHC/DD



combine different process involving DM (mono-jet+mono-W/Z +mono-H…)

combine DM + mediator searches (di-jet…)

still, a lot to do here…

[more in Valerio's talk…]

Simplified Models for Dark Matter and Missing Energy Searches at the LHC

Jalal Abdallah,[1] Adi Ashkenazi,[2] Antonio Boveia,[3] Giorgio Busoni,[4] Andrea De Simone,[4] Caterina Doglioni,[5] Aielet Efrati,[6] Erez Etzion,[2] Johanna Gramling,[5] Thomas Jacques,[5] Tongyan Lin,[7] Enrico Morgante,[5] Michele Papucci,[8,9] Bjoern Penning,[3,10] Antonio Walter Riotto,[5] Thomas Rizzo,[11] David Salek,[12] Steven Schramm,[13] Oren Slone,[2] Yotam Soreq,[6] Alessandro Vichi,[8,9] Tomer Volansky,[2] Itay Yavin,[14,15] Ning Zhou,[16] and Kathryn Zurek[8,9]

[1409.2893] ATLAS/CMS DM Forum

[1603.04156]

Recommendations on presenting LHC searches for missing transverse energy signals using simplified *s*-channel models of dark matter

Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3] Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6] Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest,[8] Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1] Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*] Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17] Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*] Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21] Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22] Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*] Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]

Interplay and Characterization of Dark Matter Searches at Colliders and in Direct Detection Experiments

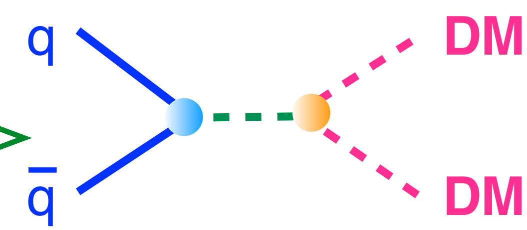
Sarah A. Malik,[a] Christopher McCabe,[b,c] Henrique Araujo,[a] Alexander Belyaev,[d,e] Céline Bœhm,[b] Jim Brooke,[f] Oliver Buchmueller,[a] Gavin Davies,[a] Albert De Roeck,[g,h] Kees de Vries,[a] Matthew J. Dolan,[i] John Ellis,[g,j] Malcolm Fairbairn,[j] Henning Flaecher,[f] Loukas Gouskos,[k] Valentin V. Khoze,[b] Greg Landsberg,[l] Dave Newbold,[f] Michele Papucci,[m] Timothy Sumner,[a] Marc Thomas[d,e] and Steven Worm[e]

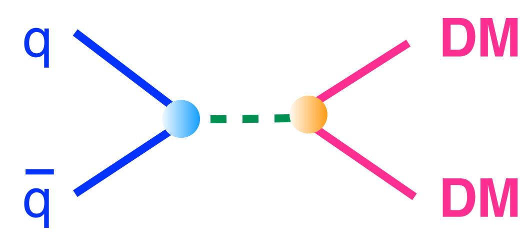
[1409.4075]

LHC DM WG

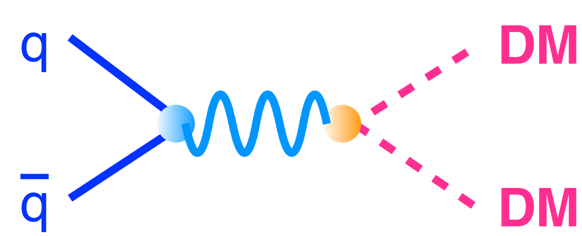
Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$





generic
s-channel models



DM is a Dirac Fermion

Scalar and Pseudo-Scalar Models:

$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\phi\bar{\chi}\chi - g_q\frac{\phi}{\sqrt{2}}\sum_{q=u,d,s,c,b,t} y_q\bar{q}q\,, \qquad (0_S s1/2)$$

$$\mathcal{L}_{\text{pseudo-scalar}} = -ig_{\text{DM}}\phi\bar{\chi}\gamma_5\chi - ig_q\frac{\phi}{\sqrt{2}}\sum_{q=u,d,s,c,b,t} y_q\bar{q}\gamma_5 q\,, \qquad (0_{PS} s1/2)$$

Vector and Axial-Vector Models:

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}}Z'_\mu\bar{\chi}\gamma^\mu\chi - g_q\sum_{q=u,d,s,c,b,t} Z'_\mu\bar{q}\gamma^\mu q\,, \qquad (1_V s1/2)$$

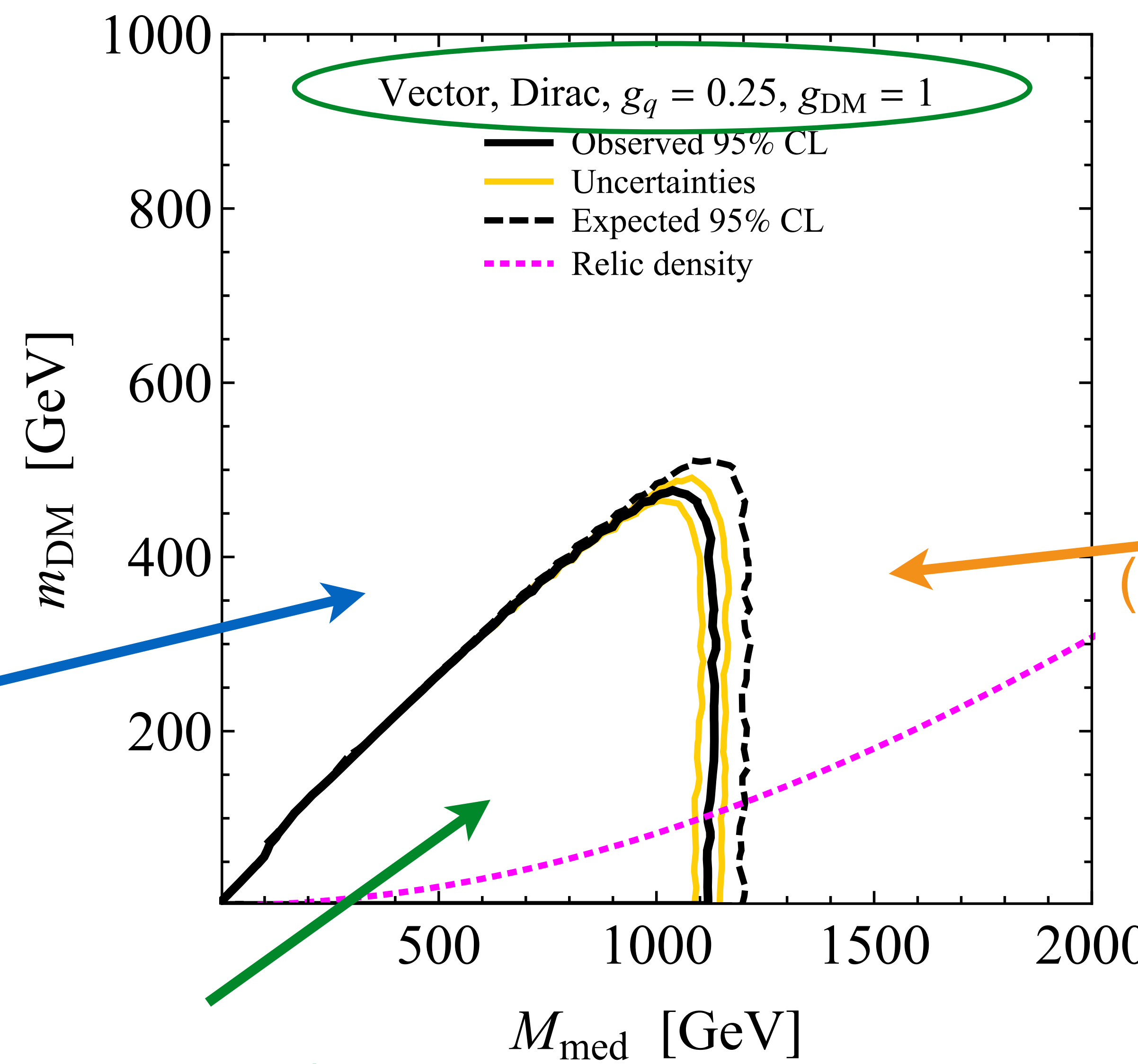
$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}}Z'_\mu\bar{\chi}\gamma^\mu\gamma_5\chi - g_q\sum_{q=u,d,s,c,b,t} Z'_\mu\bar{q}\gamma^\mu\gamma_5 q\,. \qquad (1_A s1/2)$$

4-dimensional parameter space: $\{m_{\text{DM}}, M_{\text{med}}, g_{\text{DM}}, g_q\}$

[1604.04156]

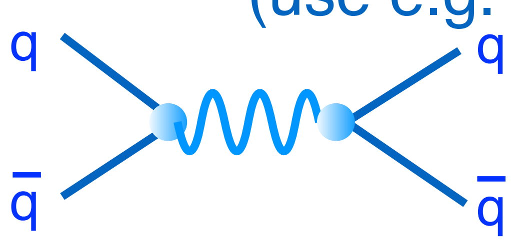
slice of par space with fixed couplings

95% CL exclusion contour



EFT
(large $M_{\rm med}$)

off-shell ($M_{\rm med} < 2m_{\rm DM}$)
(use e.g. di-jet)



on-shell ($M_{\rm med} > 2m_{\rm DM}$)

Recommended choices of couplings:

(universal g_q)

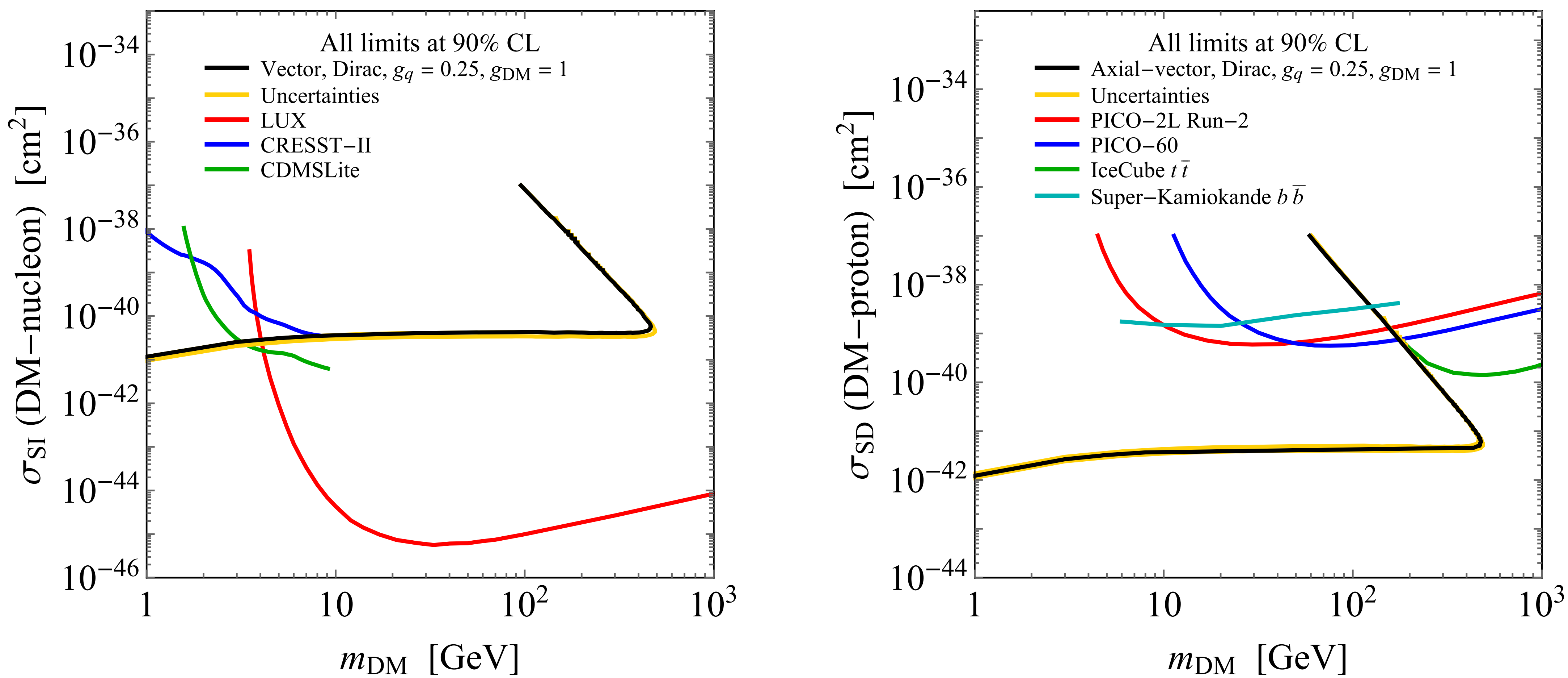
Vector mediator: $g_{\rm DM} = 1$ and $g_q = 0.25$.

Axial-vector mediator: $g_{\rm DM} = 1$ and $g_q = 0.25$.

Scalar mediator: $g_q = 1$ and $g_{\rm DM} = 1$.

Pseudo-scalar mediator: $g_q = 1$ and $g_{\rm DM} = 1$.

- ensure $\Gamma_{\rm med}/M_{\rm med} \lesssim 10\%$
- avoid current limits



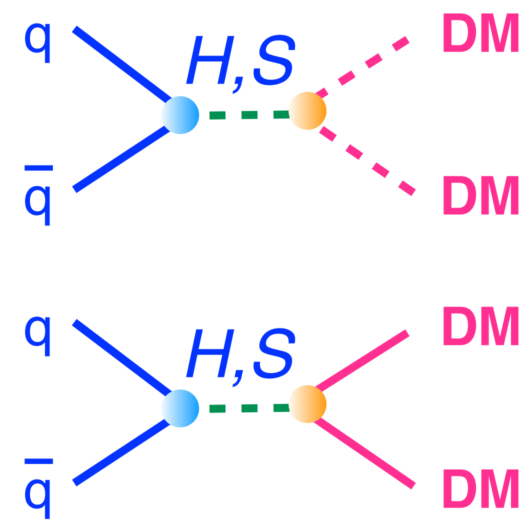
[only for illustration, not real data]

$$\sigma_{SI,SD} \propto \frac{(g_q g_{DM})^2}{M_{med}^4}$$

then plug in M_{med} from the mass-mass plane

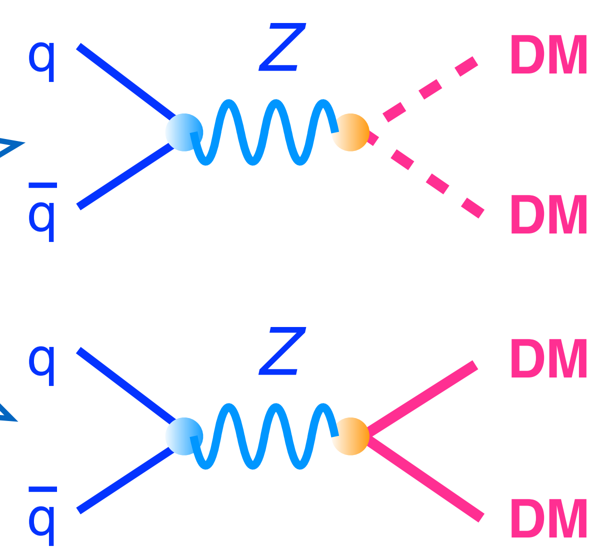
recommend to plot 90% CL (instead of 95% CL) to comply with DD standards

Mediator spin	Channel	DM spin	Model Name
0	s	0	$\boxed{0s0}$
0	s	$\frac{1}{2}$	$\boxed{0s\frac{1}{2}}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$\boxed{1s0}$
1	s	$\frac{1}{2}$	$\boxed{1s\frac{1}{2}}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$



Higgs mediator,
Scalar-Higgs Portal

s-channel models
(special cases)



Z mediator

1s1/2 Model (Z Mediator)

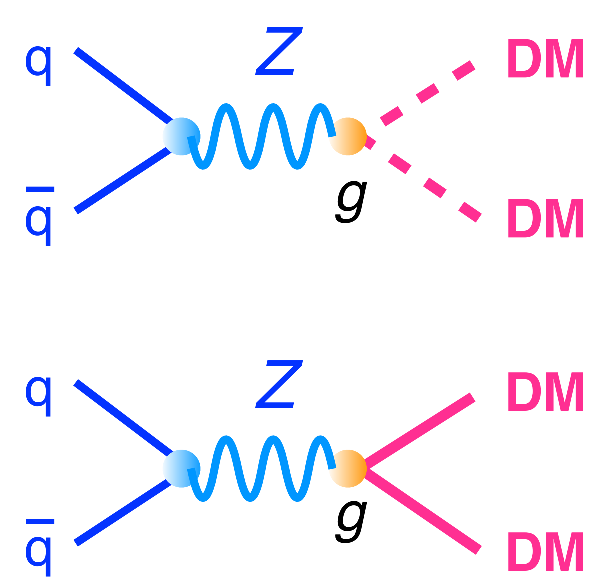
Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$\boxed{1s0}$
1	s	$\frac{1}{2}$	$\boxed{1s\frac{1}{2}}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$

model parameters: $\{m_{\rm DM}, g\}$

relevant constraints:

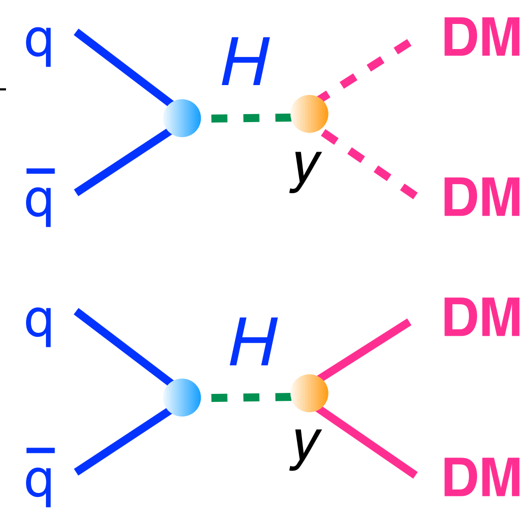
- Direct detection ($m_{\rm DM} > m_Z/2$)
- Z invisible width ($m_{\rm DM} < m_Z/2$ and SD scattering)

mono-jet searches not competitive



[DS, Giudice, Strumia - 1402.6287]

Mediator spin	Channel	DM spin	Model Name
0	s	0	$\boxed{0s0}$
0	s	$\frac{1}{2}$	$\boxed{0s\frac{1}{2}}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$



Model parameters: $\{m_{\rm DM}, y\}$

relevant constraints:
- Direct detection ($m_{\rm DM} > m_h/2$)
- Higgs invisible width ($m_{\rm DM} < m_h/2$)

mono-jet searches not competitive

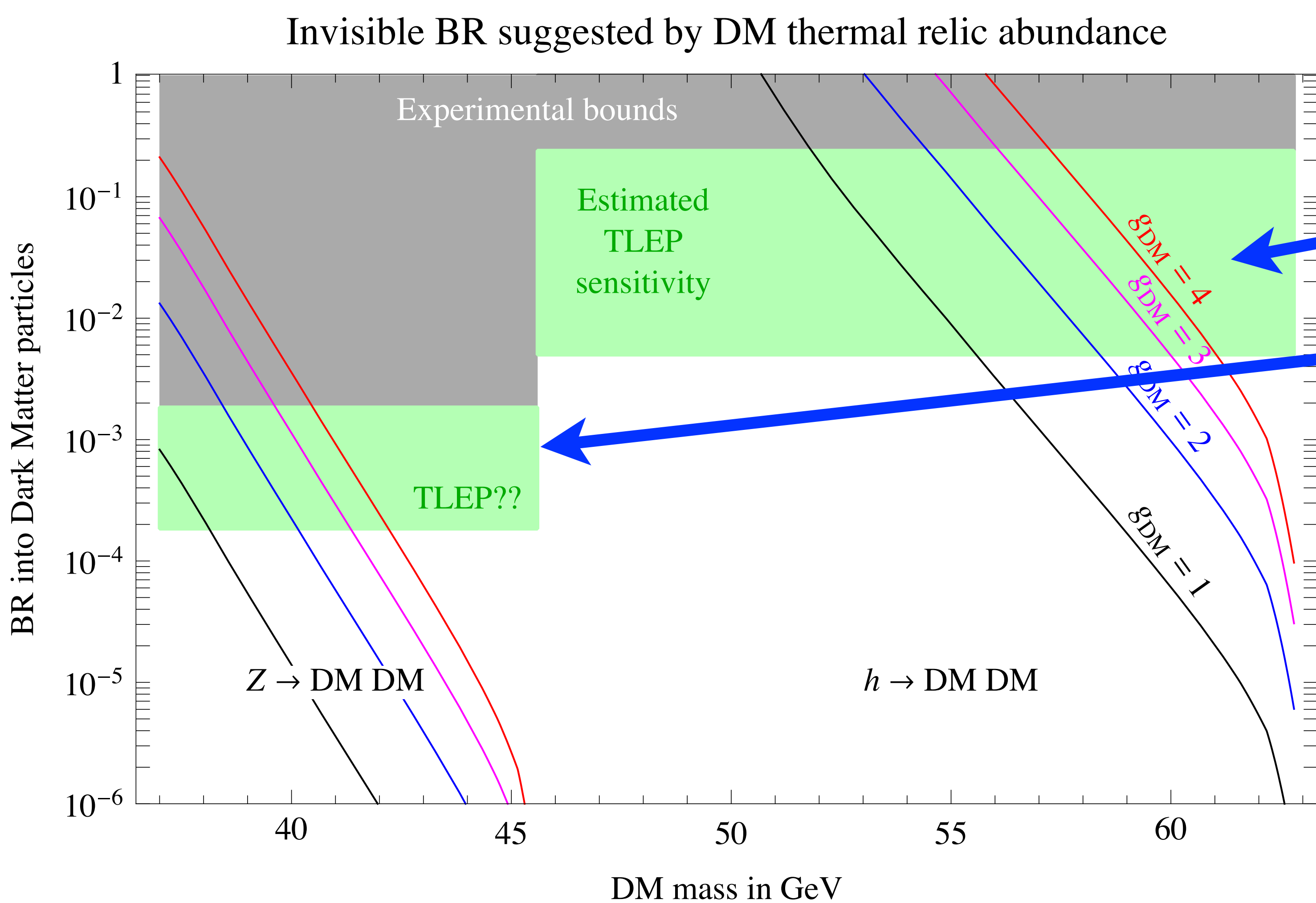
[DS, Giudice, Strumia - 1402.6287]

[DS, Giudice, Strumia - 1402.6287]

Near resonance m_{DM}~$M_{Z,h}/2$, relic density fixed by the width

Curves for correct DM relic abundance:

invisible BR



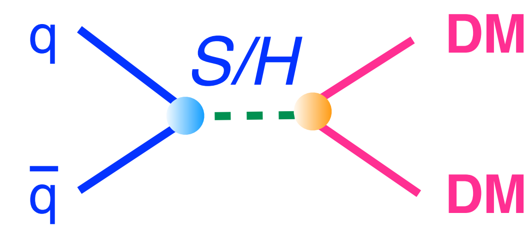
room for improvement, exploring invisible widths of Z and h

(LHC, future Higgs factories, GigaZ...)

DM mass

- motivation to improve on Z/h invisible BRs

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$\boxed{0s\frac{1}{2}}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$



S "talks" to SM only via H

mixing of real scalar mediator S and Higgs looks like a 2HDM, with <S>=0

$$\mathscr{L} \supset \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - \frac{h}{\sqrt{2}}\sum_f y_f \bar{f} f$$
$$- y_\chi S\bar{\chi}\chi - \mu_S S|H|^2 - \lambda_S S^2 |H|^2 \, .$$

Model parameters: $\{m_\chi, m_S, \lambda_S, \mu_S\}$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix} \Longrightarrow \begin{array}{l} m_{h_1} \simeq m_h \\ m_{h_2} \simeq \sqrt{m_S^2 + \lambda_S^2 v^2} \end{array}$$

$$\tan(2\theta) = 2v\mu_S/(m_S^2 - m_h^2 + \lambda_S v^2)$$

In the mass-eigenstate basis:

$$\mathscr{L} \supset -(h_1 \cos\theta - h_2 \sin\theta)\sum_f \frac{y_f}{\sqrt{2}} \bar{f} f - (h_1 \sin\theta + h_2 \cos\theta) y_\chi \bar{\chi}\chi$$

Higgs Yukawas reduced by $\cos\theta$

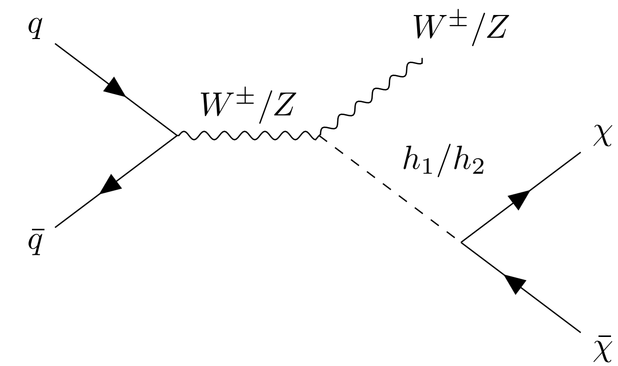
0s1/2 Model (Scalar-Higgs Portal)

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$\boxed{0s\frac{1}{2}}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$

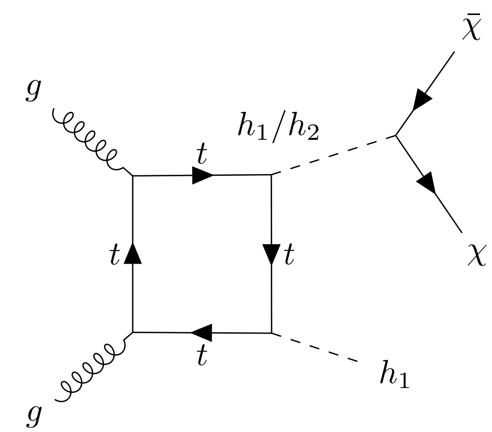
LHC signals

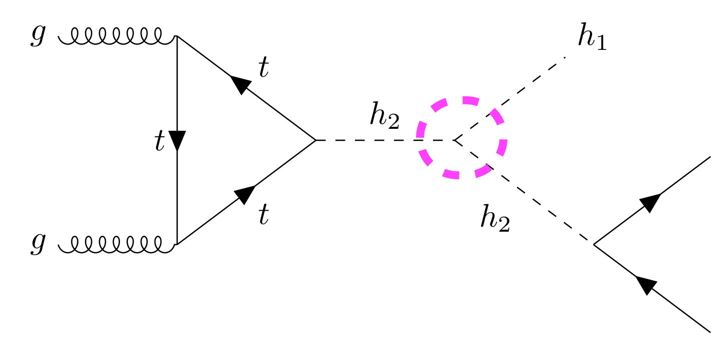
mono-jet +

mono-W/Z



mono-Higgs





>> combine with inv. width, VBF…

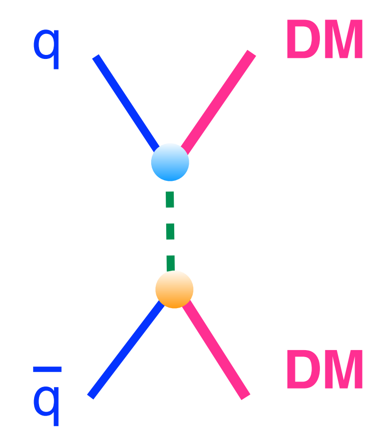
A playground for testing complementarity techniques

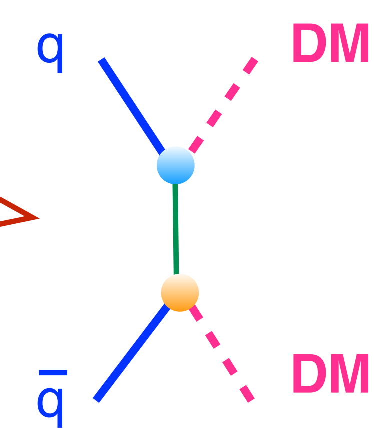
Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$\boxed{0t\frac{1}{2}}$
$\frac{1}{2}$	t	0	$\boxed{\frac{1}{2}t0}$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$

t-channel models

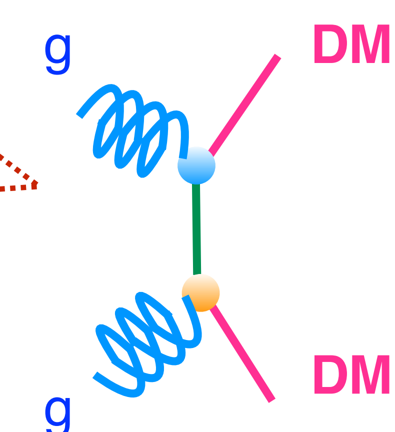
Leitmotiv: mediator carries non-trivial quantum numbers

no tree-level

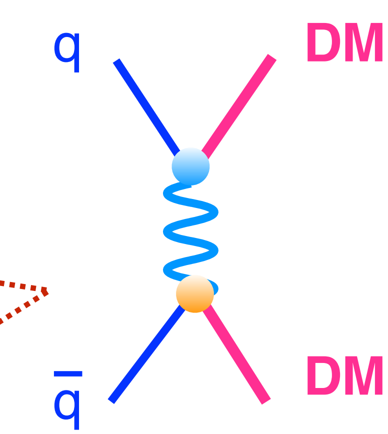




~ 0t1/2
except for ID/DD



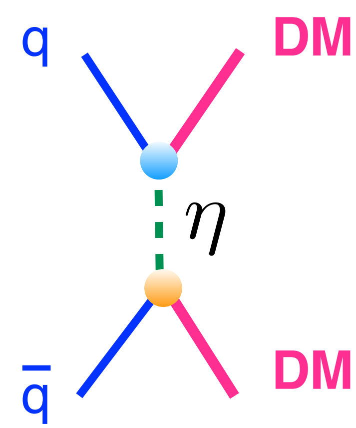
dim-5 dipole
operator



~0t1/2

0t1/2 Model

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$\boxed{0t\frac{1}{2}}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$



η carries **color, EW, flavor** (if DM total singlet)

⇨ squark-like mediator

possible to couple **η** to: u_R, d_R, Q_L

choose u_R:

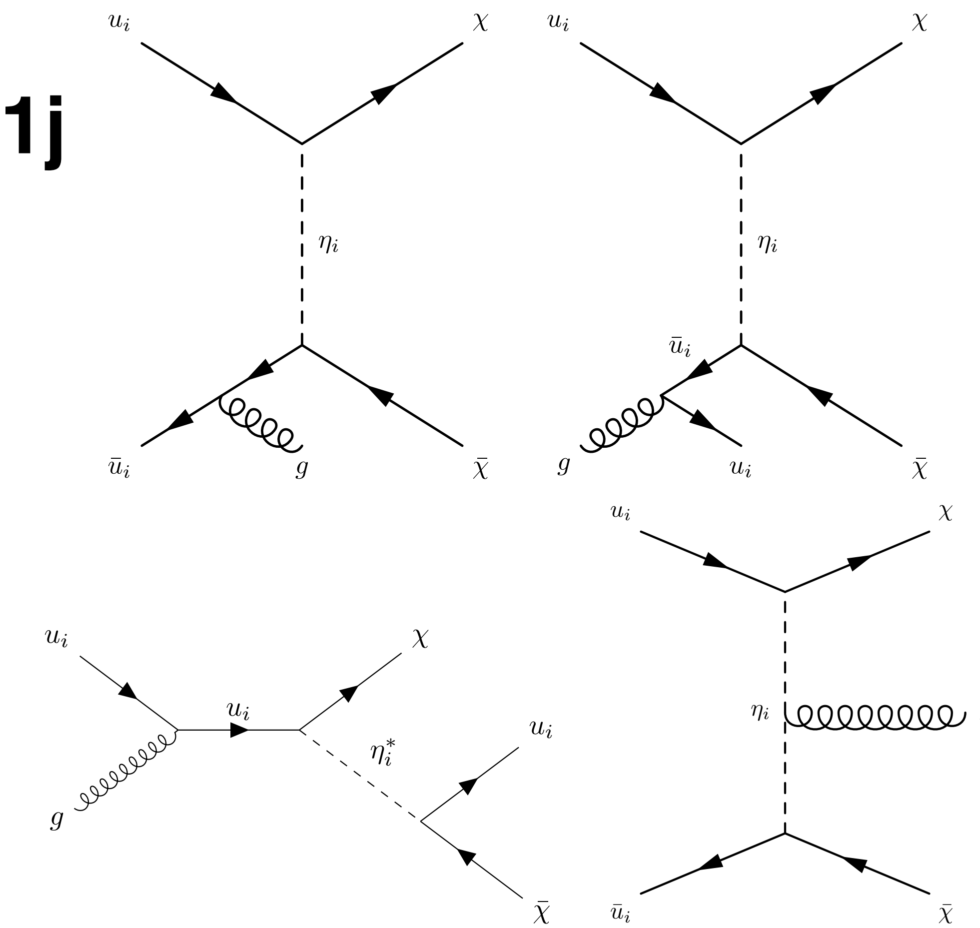
$$\mathscr{L}_{0t\frac{1}{2}} \supset \sum_{i=1,2,3}\left[\frac{1}{2}(\partial_\mu \eta_i)^2 - \frac{1}{2}M_i^2\eta_i^2 + (g_i \eta_i^* \bar{\chi} u_i + \text{h.c.})\right]$$

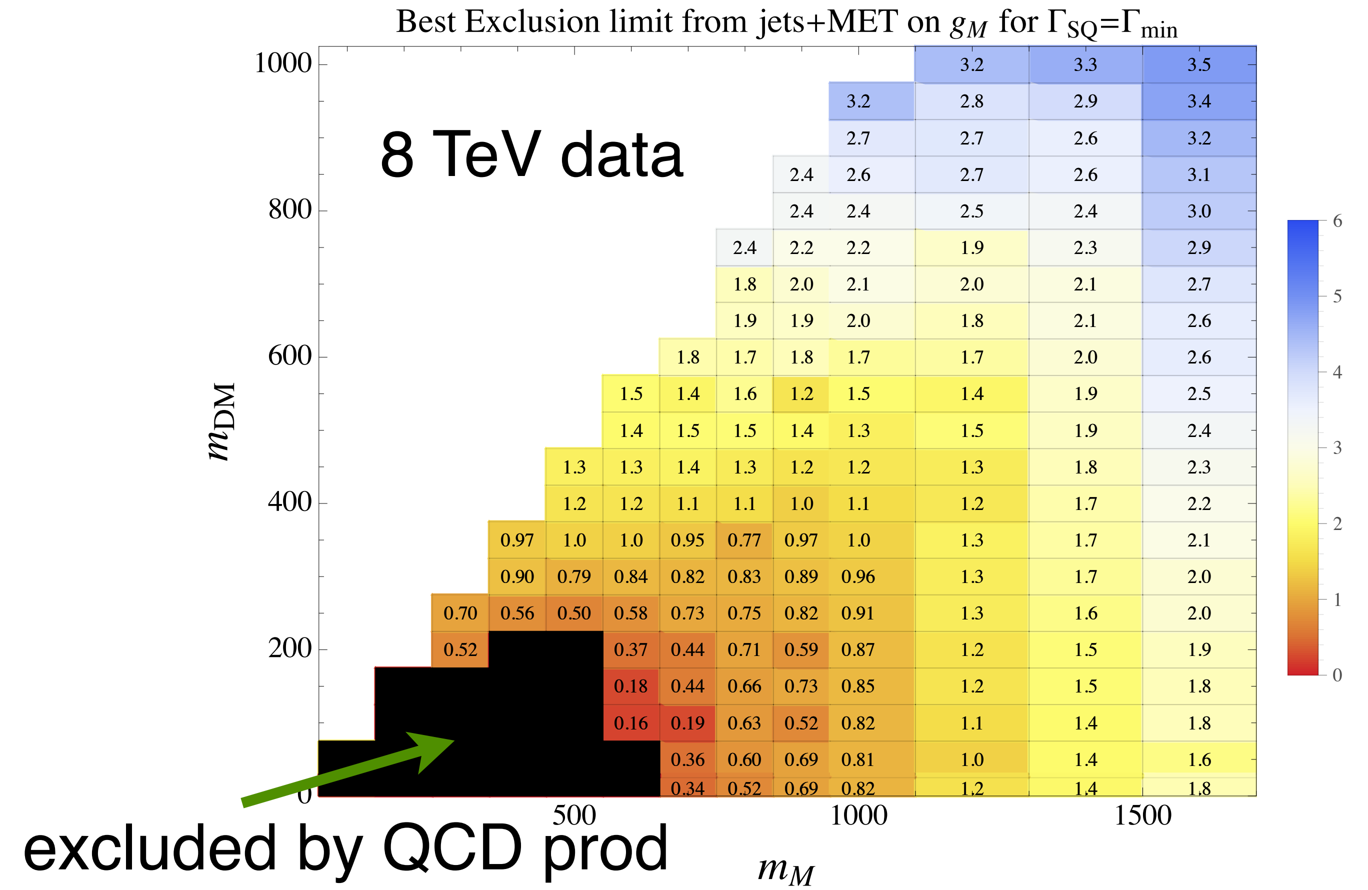
MFV:
$$M_1 = M_2 = M_3 \equiv M$$
$$g_1 = g_2 = g_3 \equiv g$$

Model parameters: $\{m_\chi, M, g\}$

g is a free parameter (<u>unlike SUSY</u>)

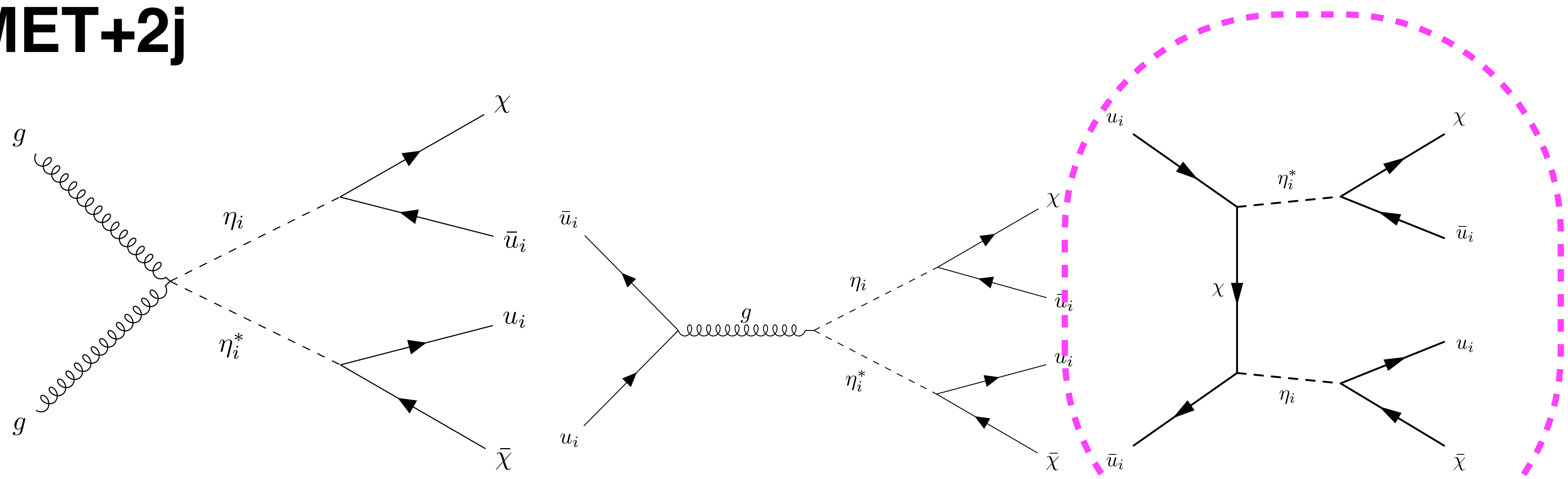
MET+1j





[Papucci, Vichi, Zurek - 1402.2285]

MET+2j

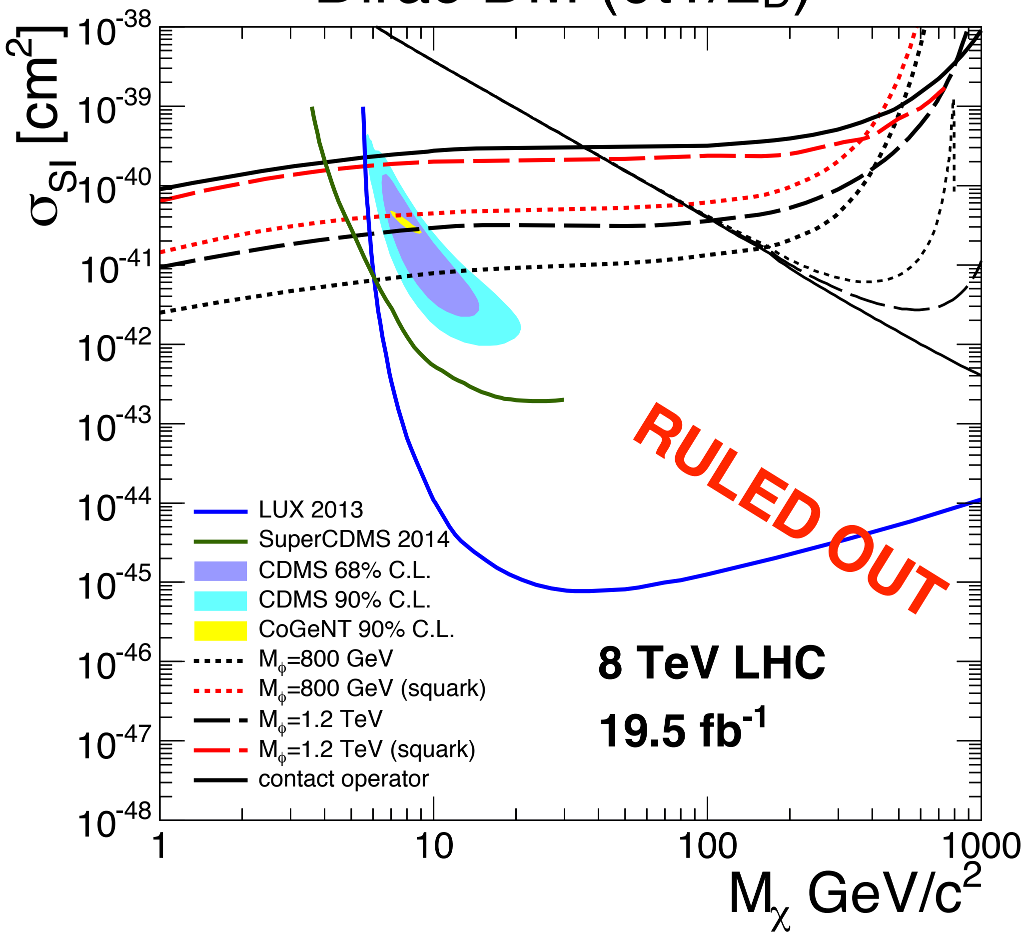


QCD (also EW)

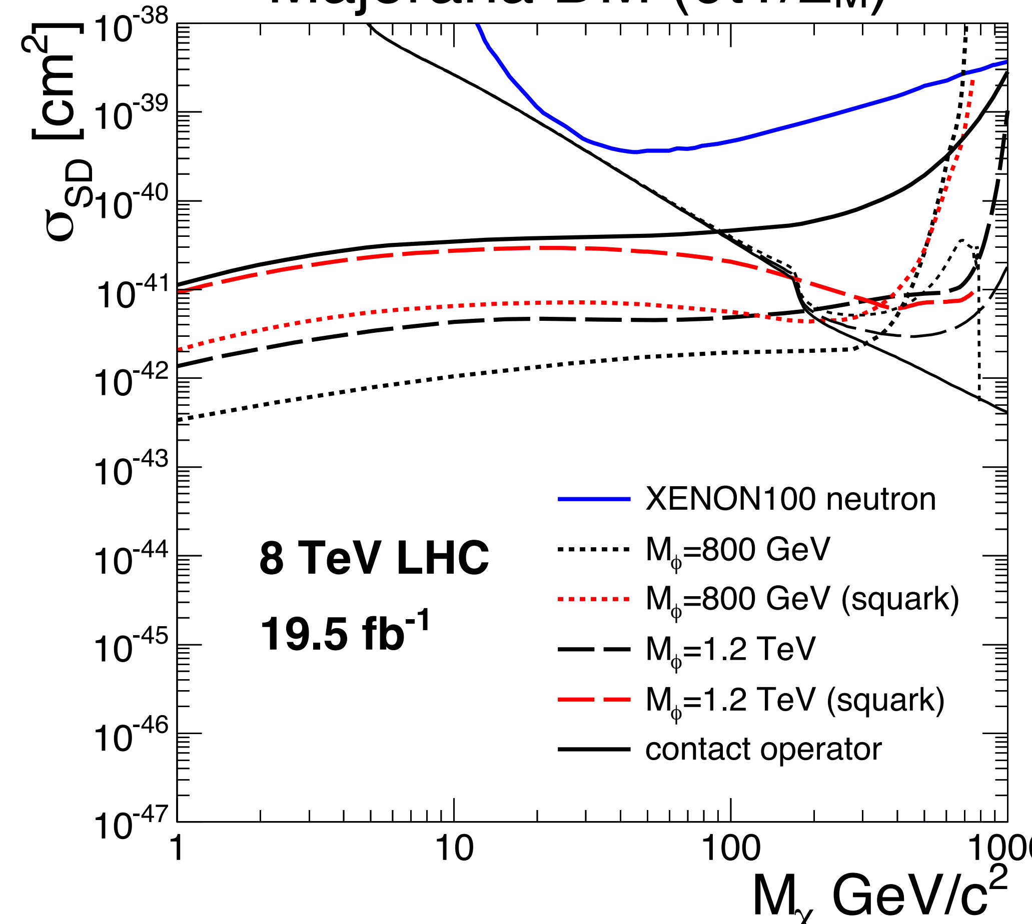
DM exchange

relative importance can be upset by value of g

Dirac DM (0t1/2D)



Majorana DM (0t1/2M)

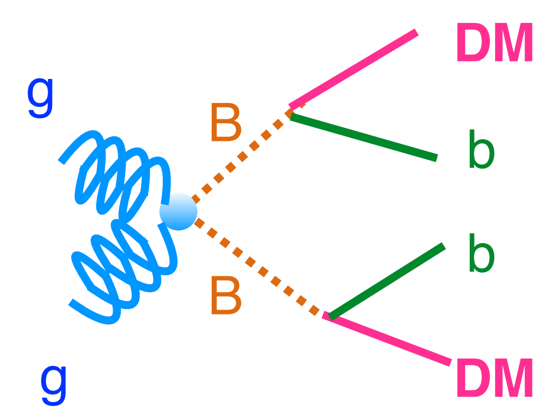


[An, Wang, Zhang - 1308.0592]

LHC + Direct Detection + Relic density:
- impossible for Dirac DM
- still viable for Majorana DM (with m_{DM} >~100 GeV)

Models with 3rd generation quarks

e.g. sbottom-like mediator $\mathcal{L} \supset -\lambda \tilde{B} \bar{b}_R \chi + \mathrm{h.c.}$



exploit *b*-tagging and squark searches

[also 2-tops]

- In **s-channel** models: play with Scalar-Higgs Portal model

- In **t-channel** models: the mediator typically carries charges (QCD, EW produciton possible)
  Next-in-line to be explored

- **>> Fully exploit complementarity <<**

- then what? simplified models v. 2.0?

  - guided by new hints/excesses/discoveries in future data
  - new collider signatures, different from mono-X ?
  - more degrees of freedom/more parameters? loop mediation?
  - …?

BACK UP

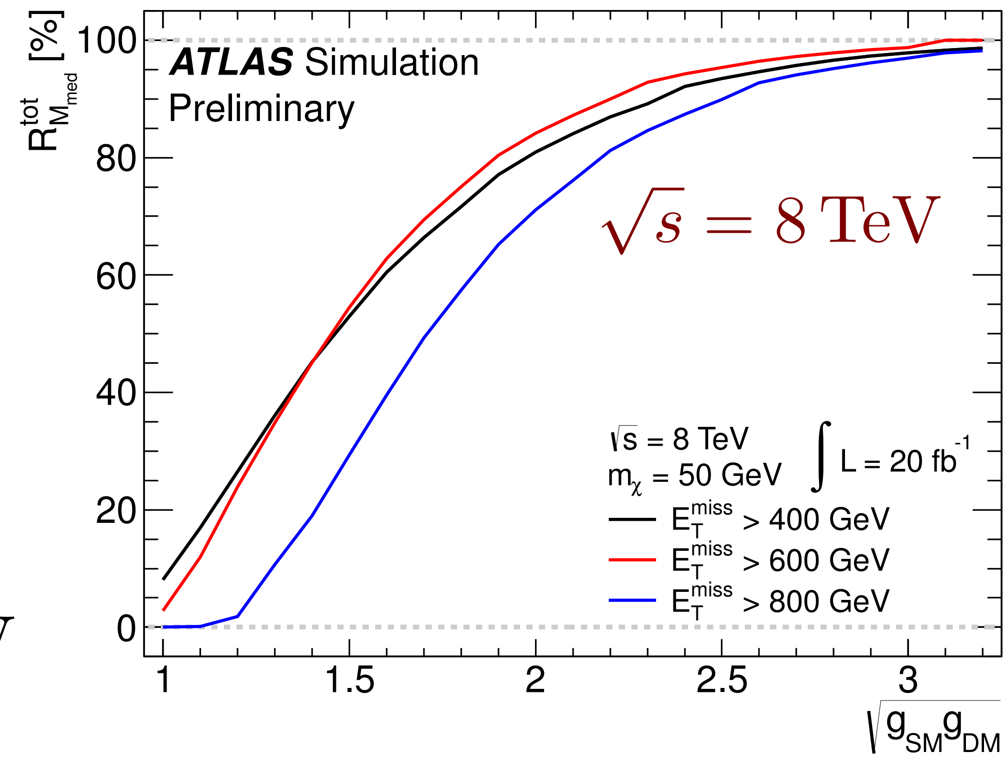
Effect of the EFT Cutoff

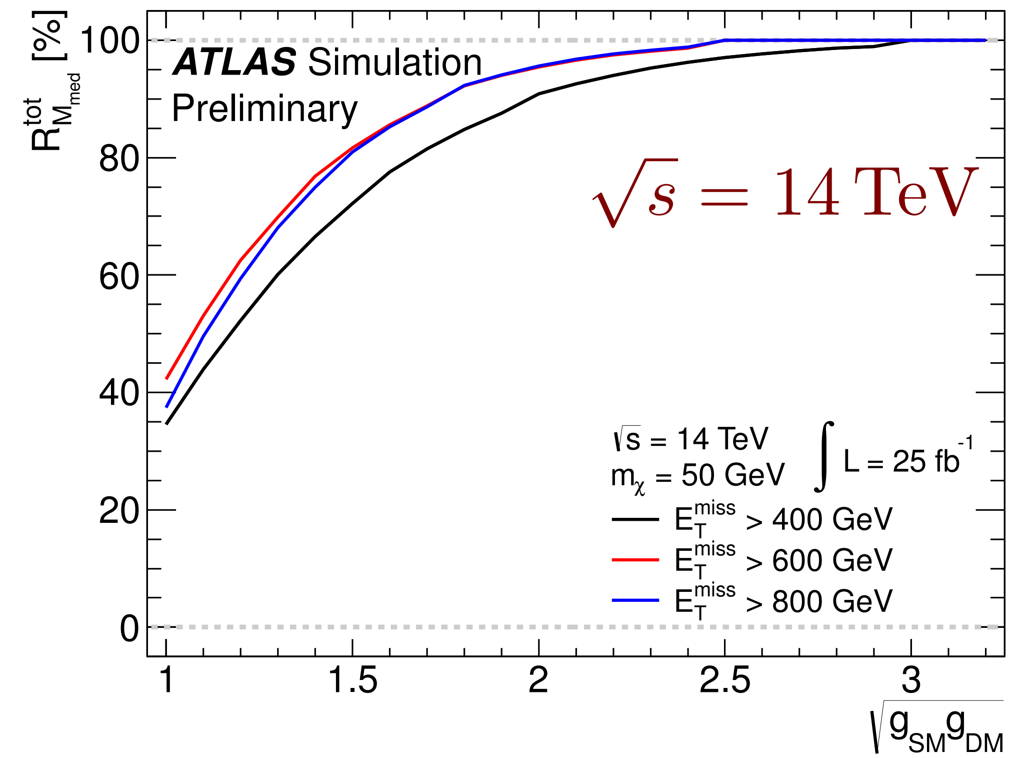
$$R^{\rm tot}_{\rm M_{med}} \equiv \frac{\sigma_{\rm eff}|_{Q_{\rm tr}<M_{\rm med}}}{\sigma_{\rm eff}}$$

fraction of events at low momentum transfer (**valid events**)

$$(\bar\chi\gamma^\mu\chi)(\bar q\gamma_\mu q)$$

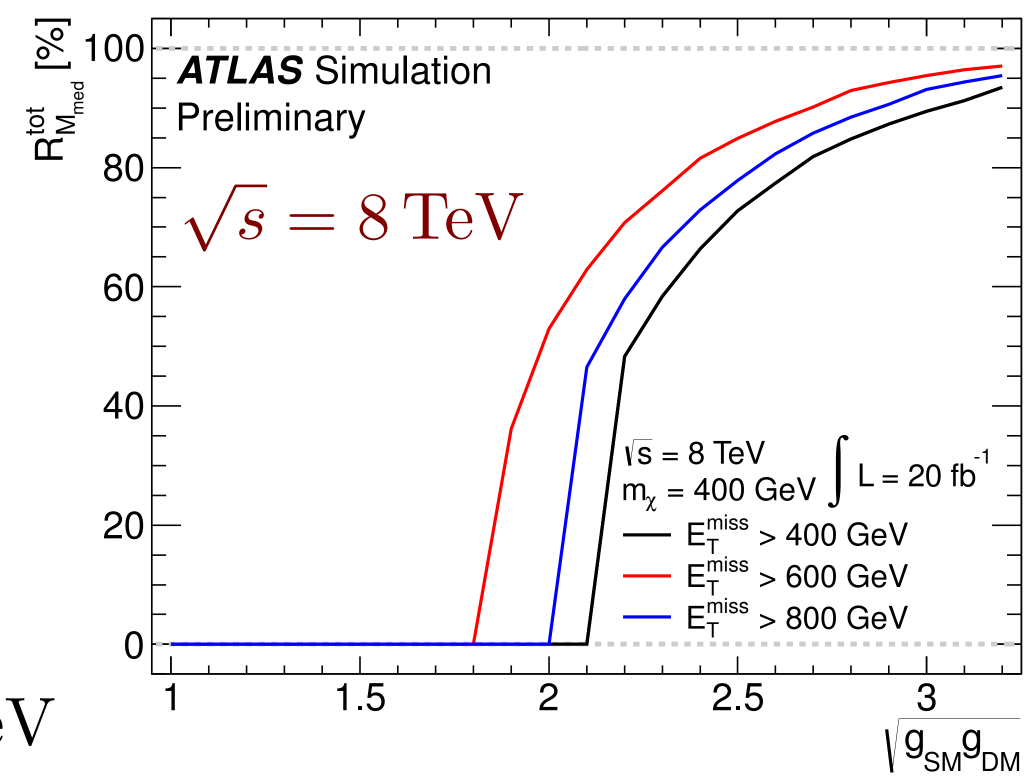
$m_{\rm DM} = 50\,{\rm GeV}$

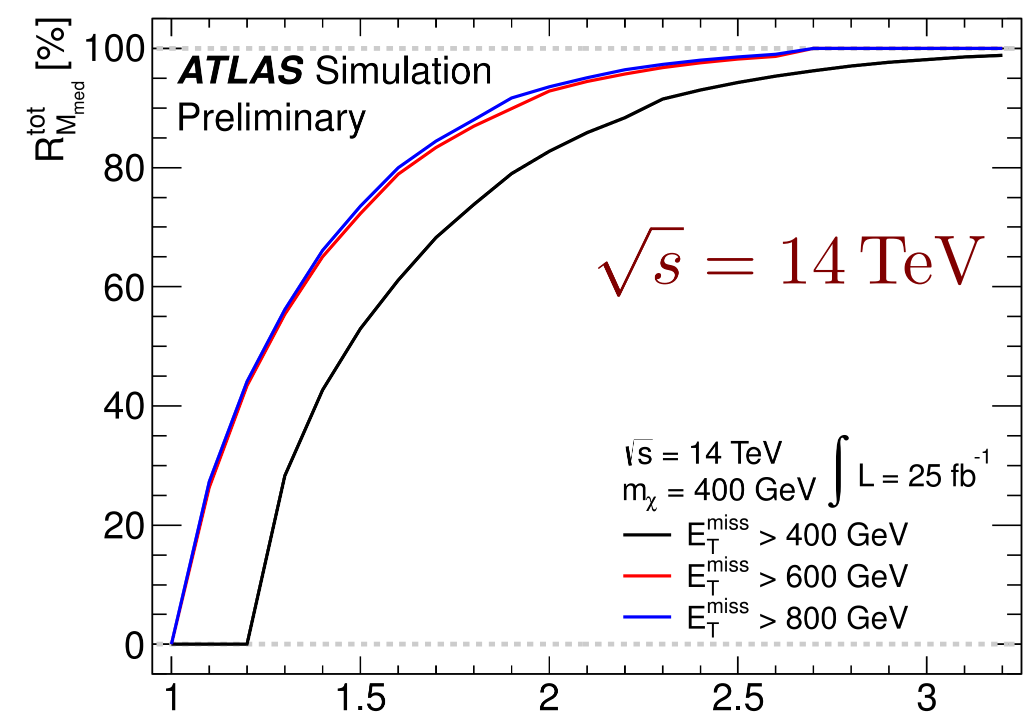




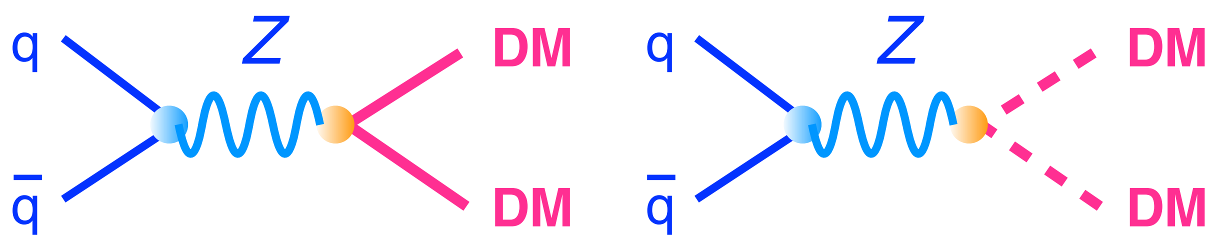
$Q_{\rm tr} > 2m_{\rm DM}$

$m_{\rm DM} = 400\,{\rm GeV}$





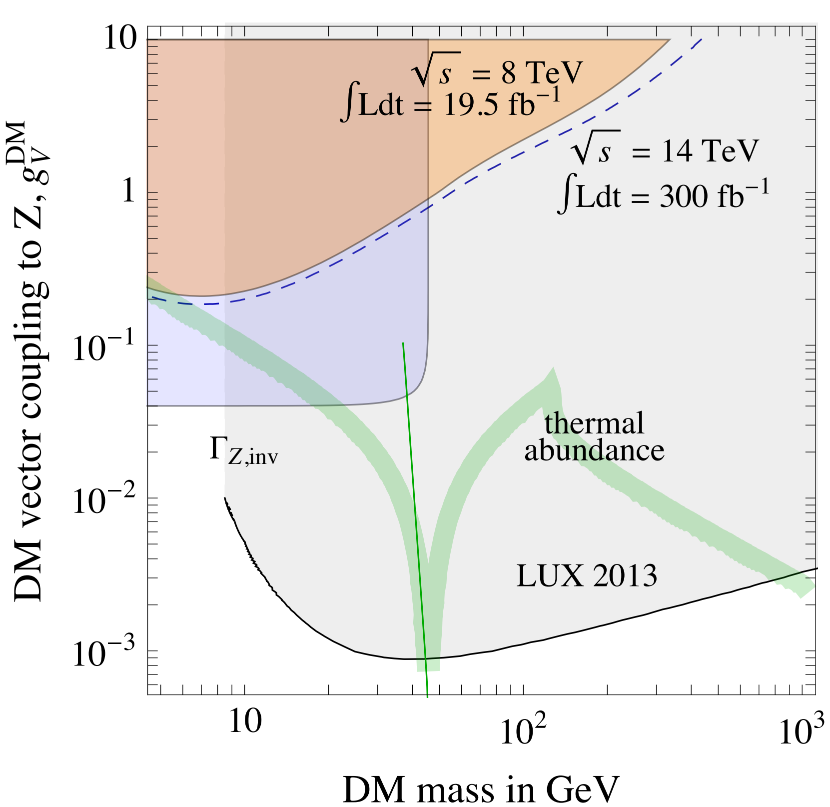
[ATL-PHYS-PUB-2014-0087]



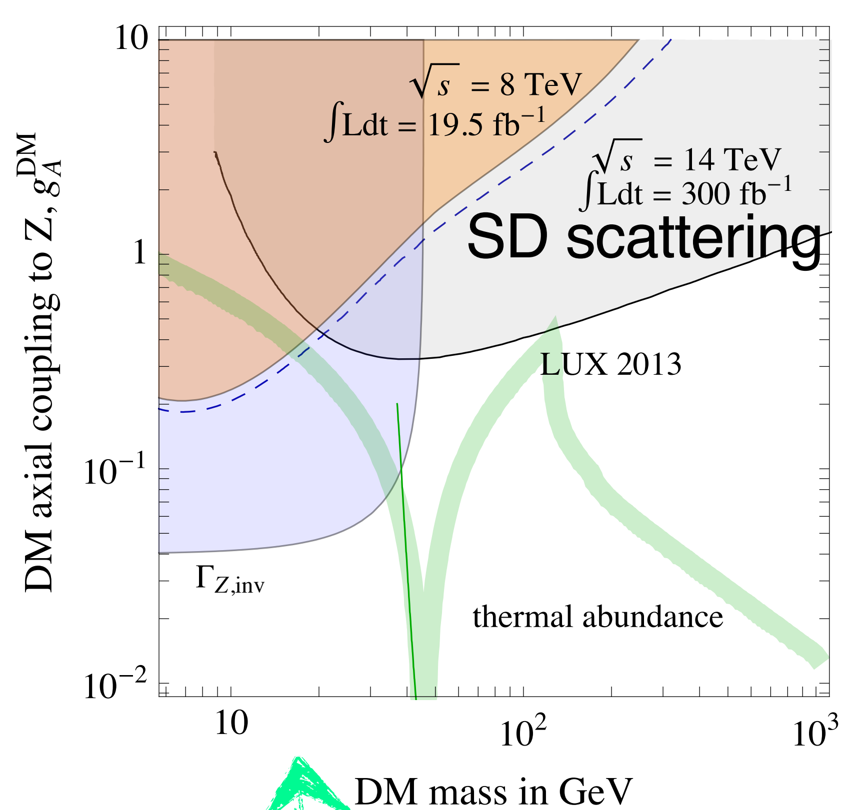
[DS, Giudice, Strumia - 1402.6287]

$$\mathcal{L} = -Z_\mu \frac{g_2}{\cos\theta_W}\left[\sum_f [\bar{f}\gamma_\mu(g_V^f + \gamma_5 g_A^f)f] + \sum_s g_s[s^*(i\partial_\mu s) - (i\partial_\mu s^*)s]\right]$$

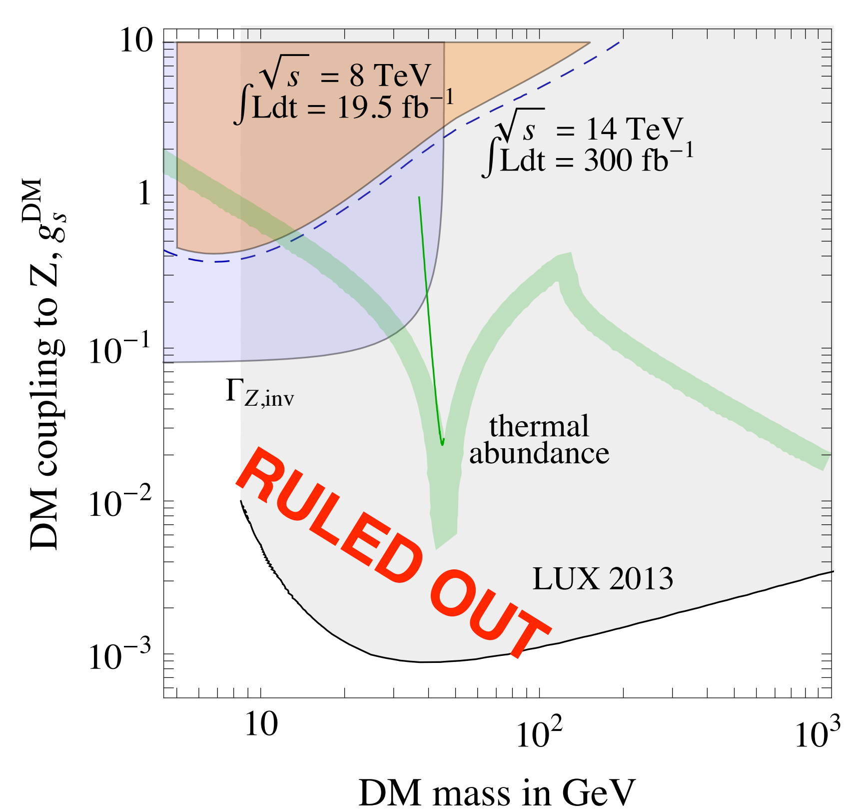
Fermion DM coupled to the Z



Fermion DM coupled to the Z

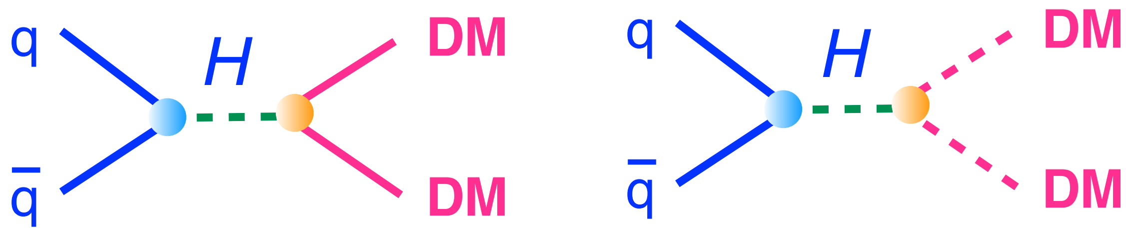


Scalar DM coupled to the Z



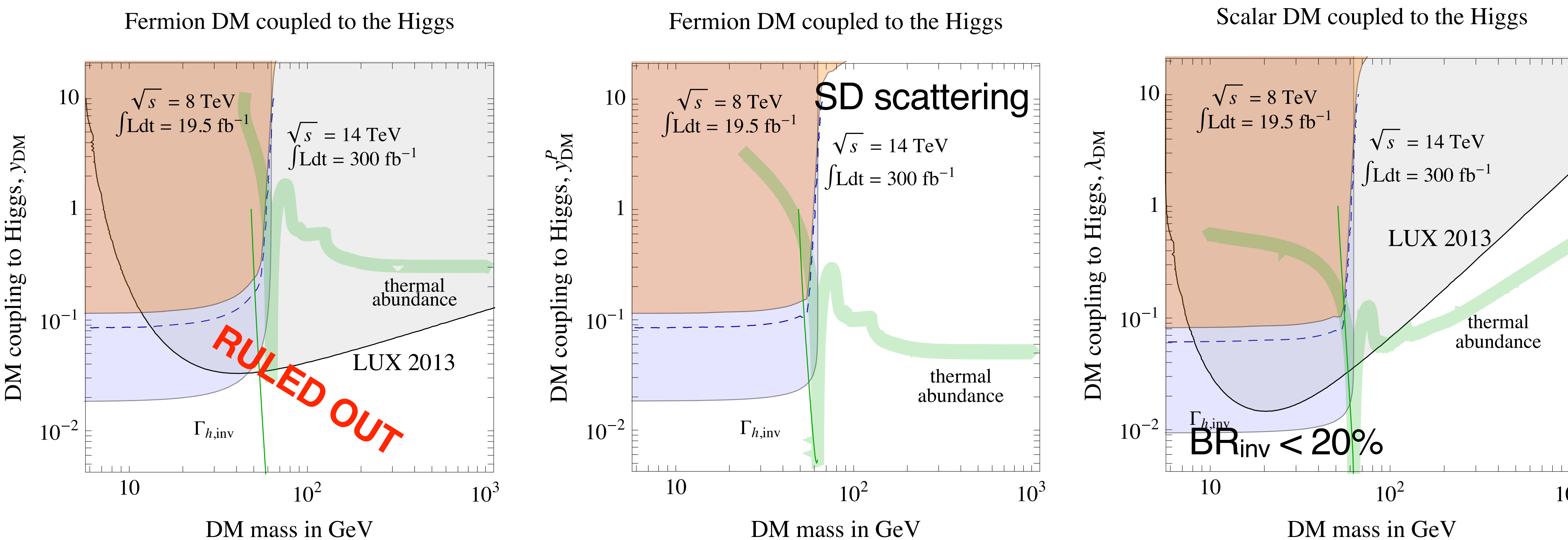
some regions still allowed for
axial couplings of fermion DM

(not much to say for LHC…)



[DS, Giudice, Strumia - 1402.6287]

$$\mathcal{L} = -h\frac{1}{\sqrt{2}}\left[\sum_f y_f \bar{f} f + \bar{\psi}_{\rm DM}(y_{\rm DM} + i y^P_{\rm DM}\gamma_5)\psi_{\rm DM} + \frac{\lambda_{\rm DM} v}{2} s^2_{\rm DM}\right]$$

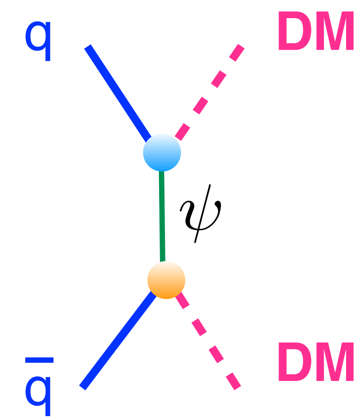


still allowed: scalar DM (m_{DM}> 100 GeV)
and fermion DM with axial couplings

LHC: improve on Higgs $BR_{inv.}$
(not much else…)

1/2t0 Model

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\boxed{\frac{1}{2}t0}$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$



mediator ψ is a vector-like fermion carrying **color**, **EW** and **flavor**

(if DM total singlet)

possible to couple to: q_R, Q_L

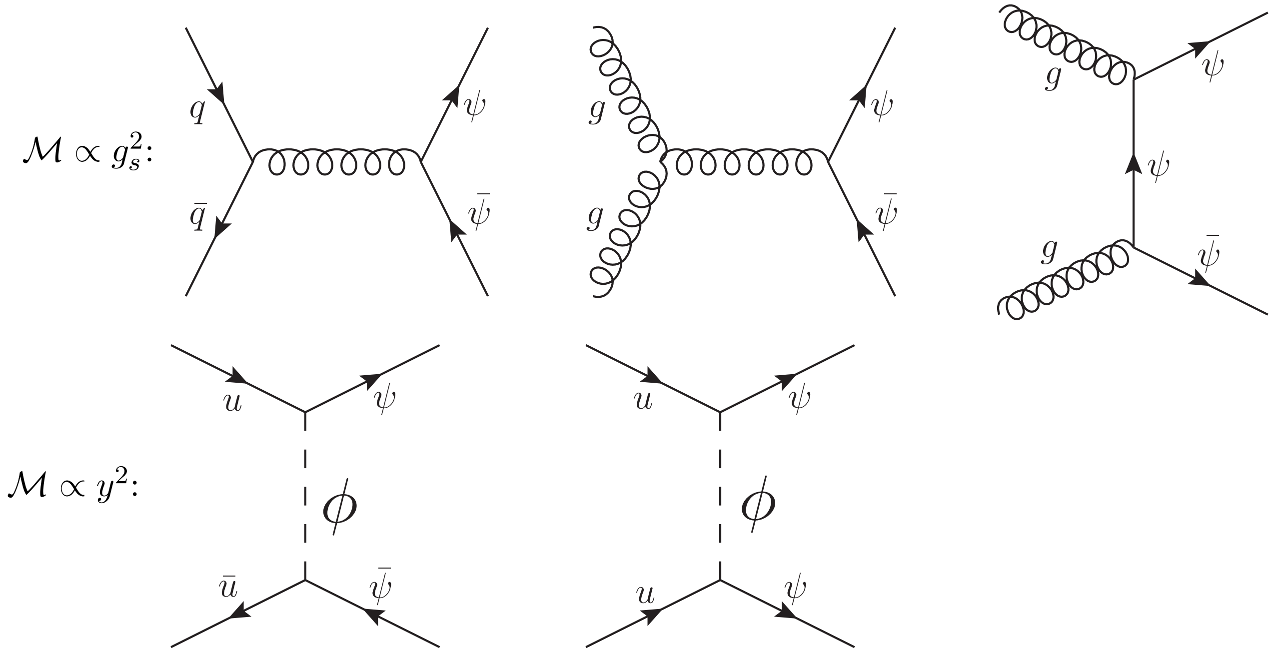
choose q_R:

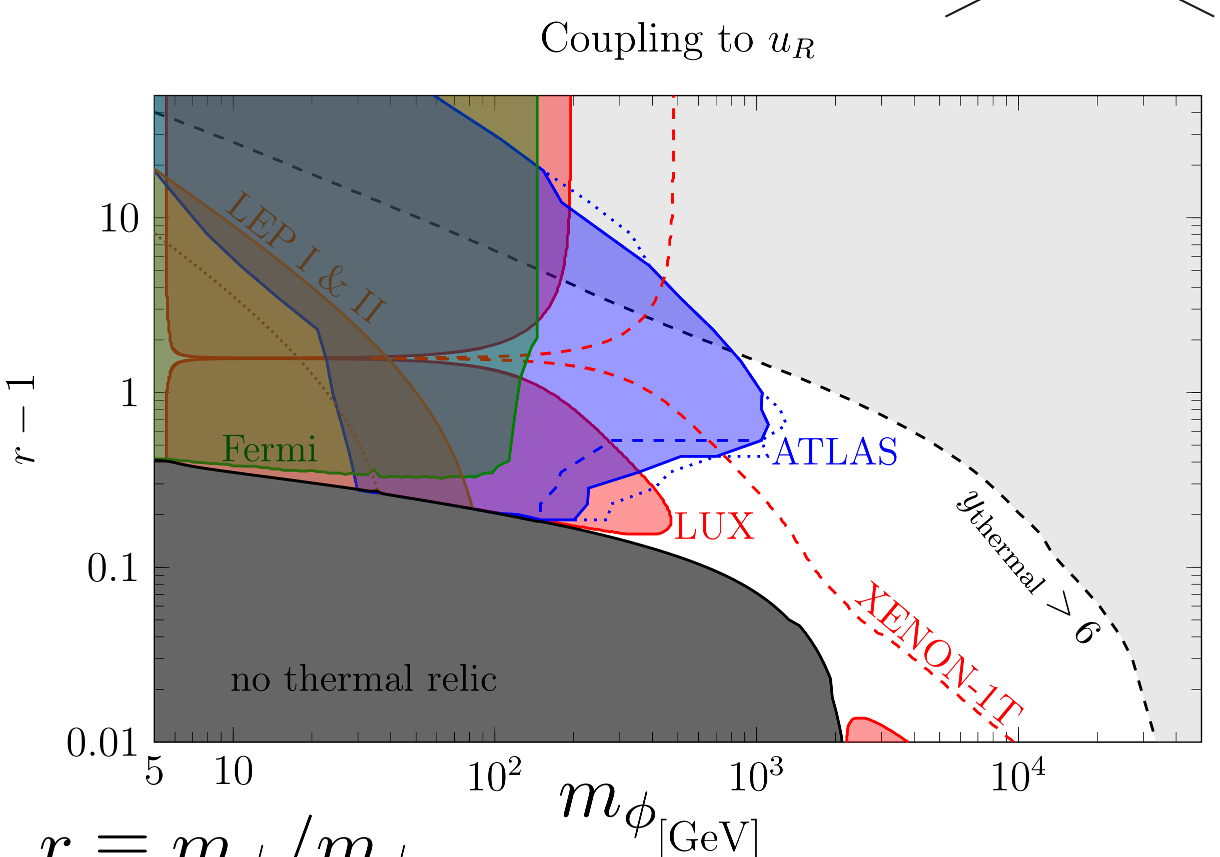
$$\mathscr{L}_{\frac{1}{2}t0} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_\phi \phi^2 + \bar{\psi}(i\not{D} - M_\psi)\psi + (y\phi\bar{\psi}q_R + \text{h.c.})$$

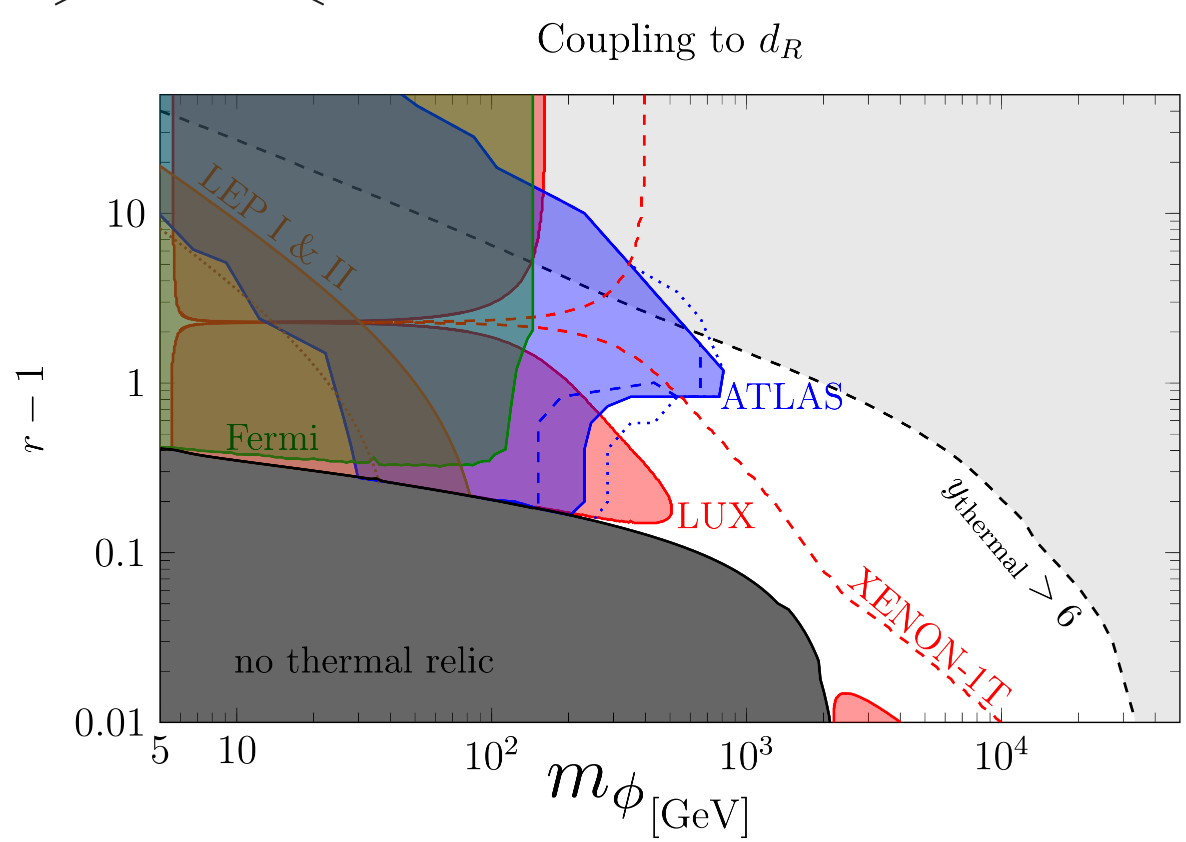
pretty much the same story as 0t1/2 (for LHC)

different results for (in)direct detection

e.g. $\langle \boldsymbol{\sigma}\, v\rangle$ is d-wave suppressed (v^4)





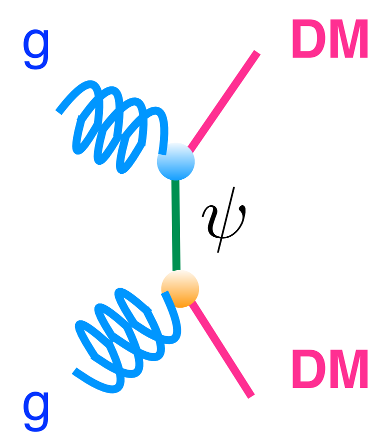


$r \equiv m_\psi / m_\phi$

[Giacchino, Ibarra, Honorez, Tytgat, Wild -1511.04452]

Xenon-1T will probe TeV region of DM mass

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\boxed{\frac{1}{2}t\frac{1}{2}}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$



ψ fermion color-octet (gluino-like)

in SUSY: gluon-gluino-bino

$$\mathcal{L}_{\frac{1}{2}t\frac{1}{2}} \supset \bar{\psi}^a(i\not{D} - M)\psi^a + \frac{1}{\Lambda} G^a_{\mu\nu}(\bar{\psi}^a \sigma^{\mu\nu}\chi + \text{h.c.})$$

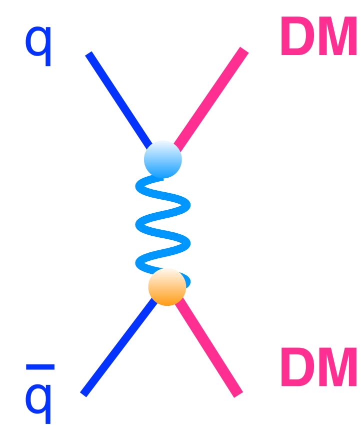
dimension-5 dipole operator

weak signals for LHC, maybe future colliders…

[details not worked out]

1t1/2 Model

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$



vector mediator carries **color**, **EW** and **flavor**

similar story as 0t1/2 (squark-like mediator)

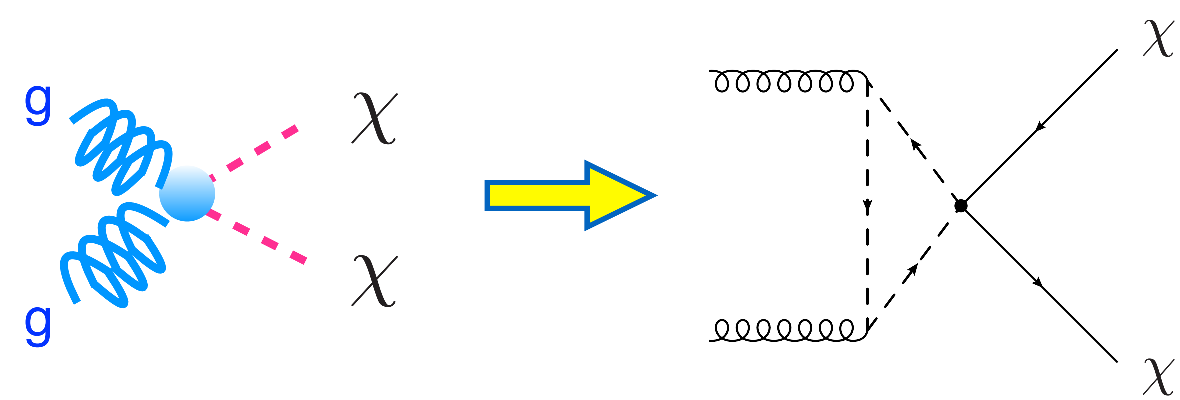
[details not worked out]

Beyond tree-level mediation?

- a model for scalar DM interacting with gluons

[Godbole, Mendiratta, Tait - 1506.01408]

$$\frac{\alpha_s}{M^2}|\chi|^2 G^a_{\mu\nu} G^{a\,\mu\nu}$$ (C5 operator)



χ : DM, complex scalar, gauge singlet

ϕ_i : scalar mediator, color-triplet, EM charged, flavour triplet

[other color reps. (e.g. octet) not explored]

$$\mathcal{L} \supset \partial_\mu \chi^* \partial^\mu \chi - m_\chi^2 |\chi|^2 + (D_\mu \phi)^\dagger D^\mu \phi - m_\phi^2 |\phi|^2$$

$+ \ \lambda_d \, |\chi|^2 |\phi|^2$ + inter. with quarks

[neglected mixing with H]

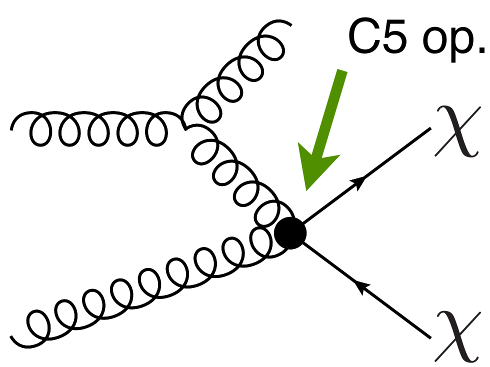
$$\epsilon_{ijk} \phi_i u_j u_k \quad \Longrightarrow \quad y_1 \ \left(\phi_1 c_R - \phi_2 u_R\right) t_R + y_2 \ \phi_3 u_R c_R$$

(flavour singlet, MFV)

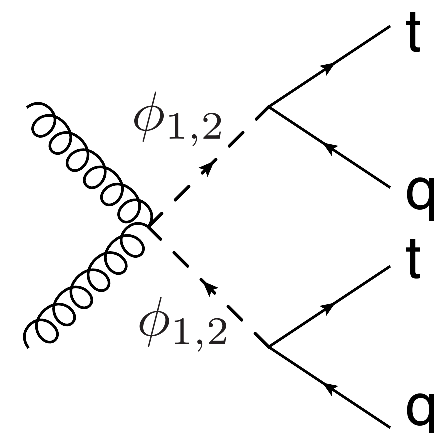
LOOP MEDIATION

[Godbole, Mendiratta, Tait - 1506.01408]

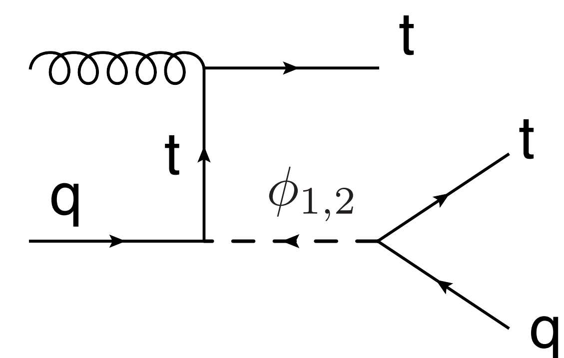
LHC pheno:



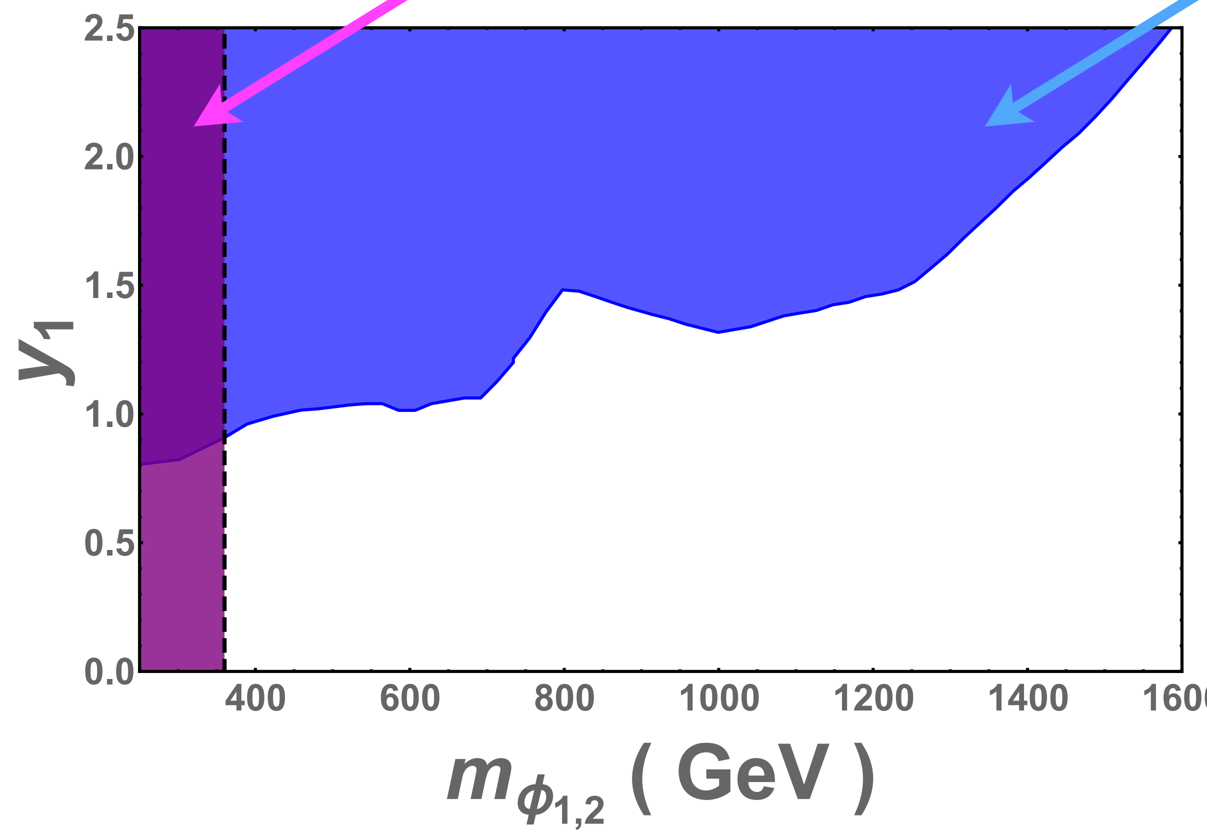
mono-jet



t t + 2 jets



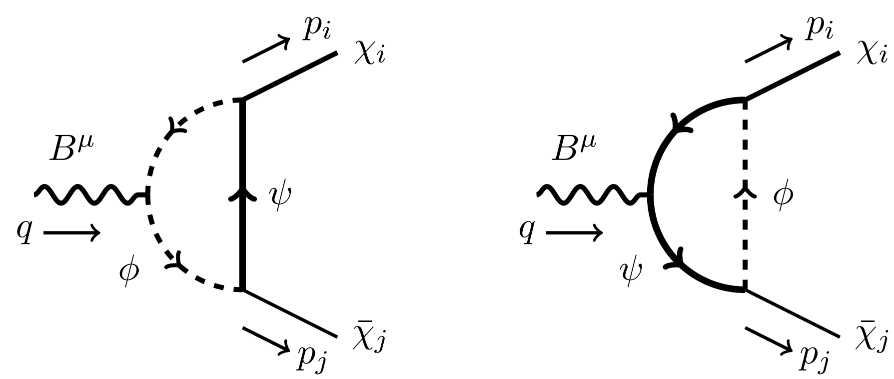
t t + 1 jet



[Godbole, Mendiratta, Tait - 1506.01408]

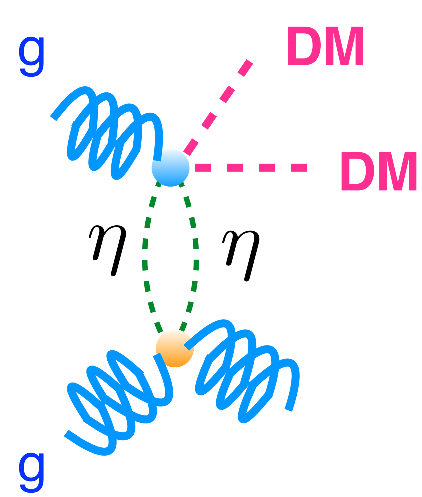
Loop Mediation

- dark penguins



[Weiner, Yavin - 1209.1093]
[Primulando, Salvioni, Tsai - 1503.04204]

- color-octet scalar mediator (0t1/2)



η interaction with DM is not renormalizable

η interaction with gluons: only in pairs $\sim \eta\eta G, \eta\eta GG$

η interaction with quarks: suppressed by m_q

[not worked out]