Portorož - 8 apr 2015

DM @ LHC
Status & Outlook

Andrea De Simone

ma per seguir virtute e canoscenza

SISSA

mostly based on:

Busoni, DS, Morgante, Riotto - arXiv:1307.2253

DS, Giudice, Strumia - arXiv:1402.6287

ATLAS - ATLAS-PHYS-PUB-2014-007

ATLAS - arXiv:1502.01518

3 Pillars of Dark Matter Searches

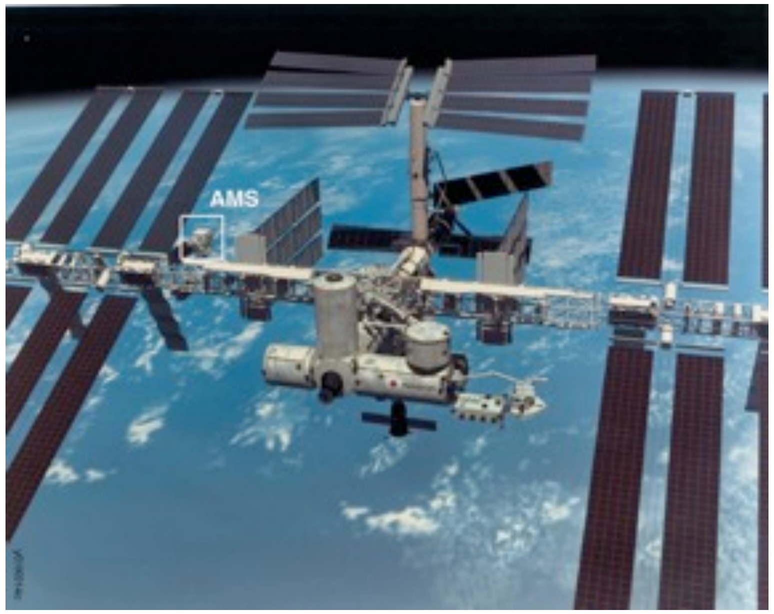
COLLIDER

$$p\,p \to \mathrm{DM} + X$$

(in LHC we trust...)

INDIRECT DETECTION

$$\mathrm{DM}\ \ \mathrm{DM} \to e^+e^-\,,\ldots$$



DIRECT DETECTION

$$\mathrm{DM}\ \ \mathrm{Nucleus} \to \mathrm{DM}\ \ \mathrm{Nucleus}$$

Outline

- **Dark Matter searches @ LHC:**

  mono-jets, effective operators and all that...

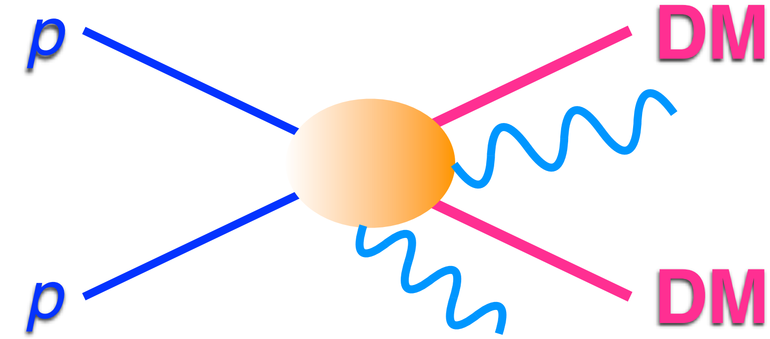
- *dead ends? way out?*

- **outlook for the next LHC Run**

Some trivial considerations:

- Dark Matter in a collider is like a neutrino (missing E_T)

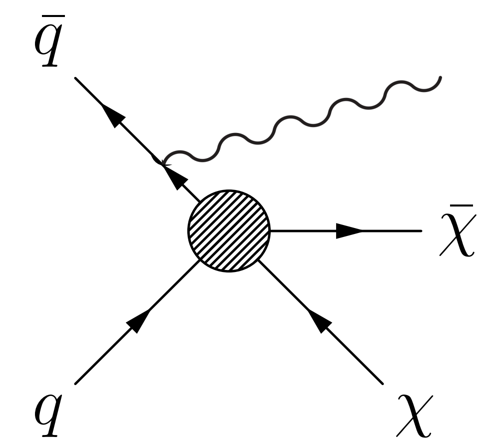
- if stabilized by a Z_2 symmetry $\longrightarrow$ DM produced in pairs



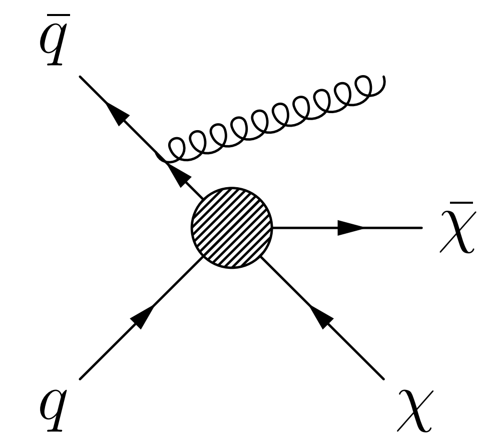
- Difficult search, unless correlating missing E_T with other handles

[- jets/photons from initial state radiation?
- displaced vertices?
- accompanying particles?]

- **NEED NEW IDEAS!**

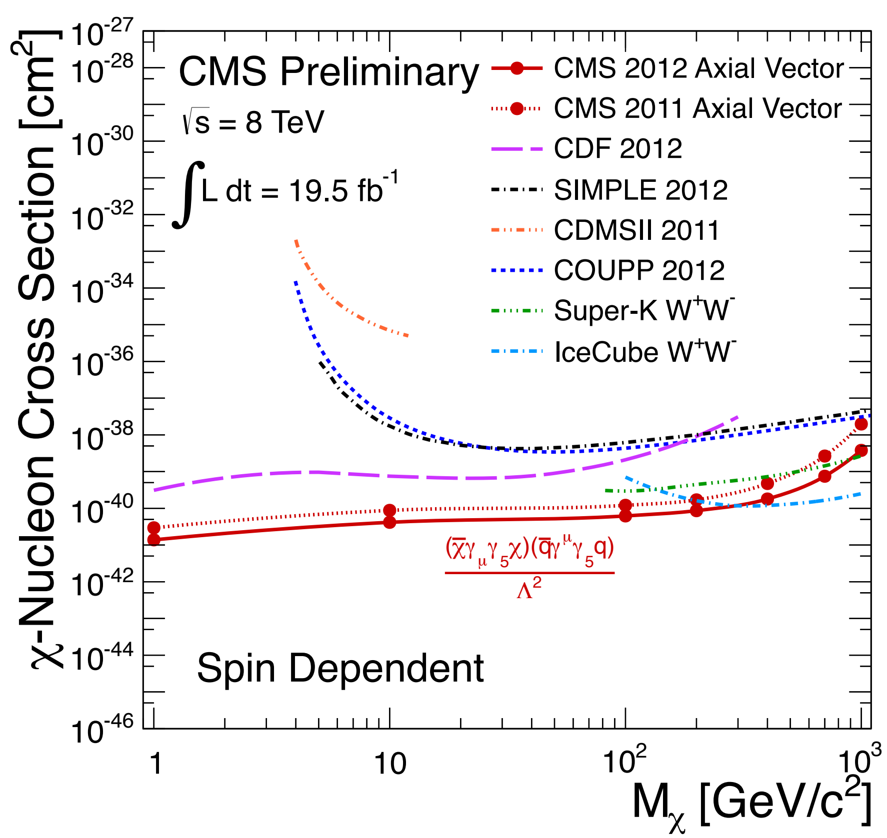


Monophoton + MET

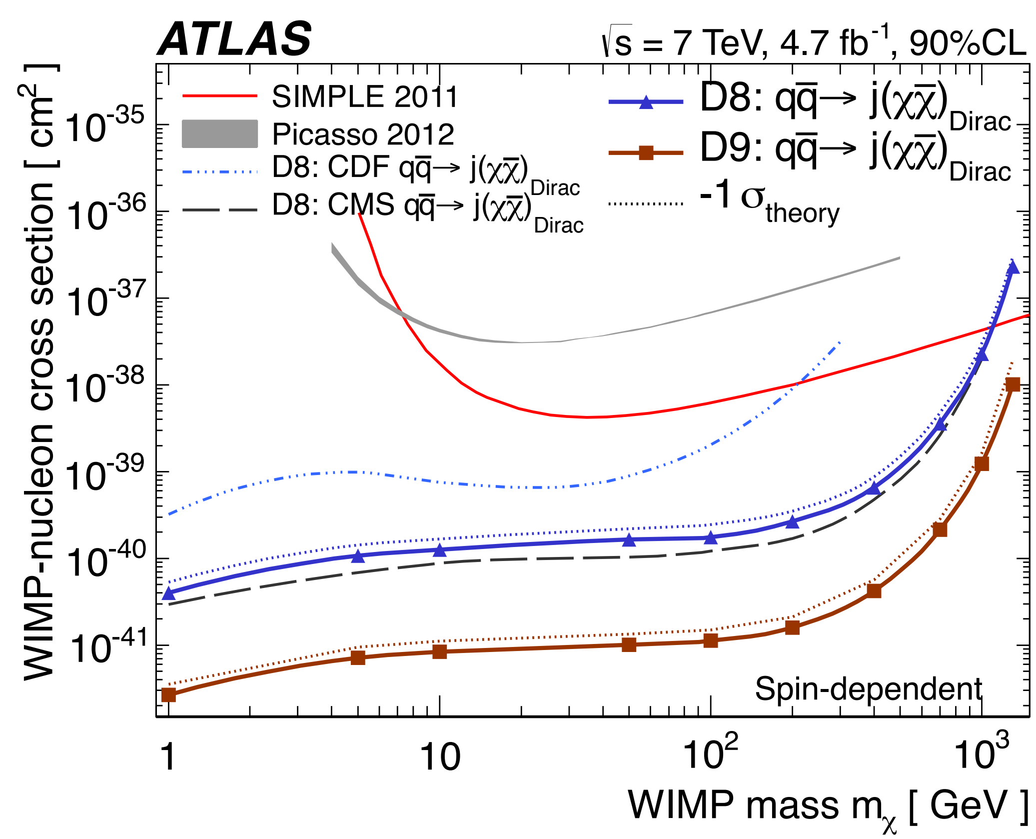


Monojet + MET

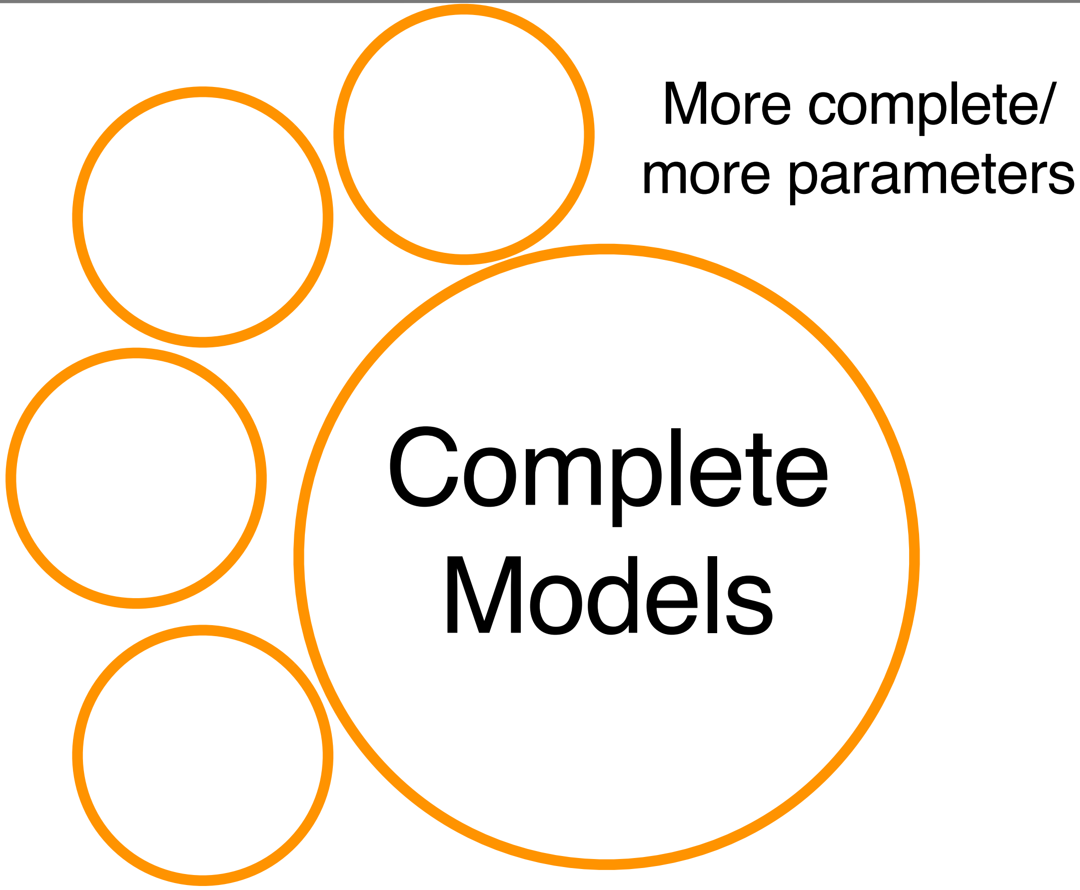
- ✓ constrain DM-quarks interactions and translate into limits on DM-nucleon cross-section
- ✓ complementary/ competitive with direct detection
- ✓ no astrophysical uncertainties



[CMS PAS EXO-12-048]

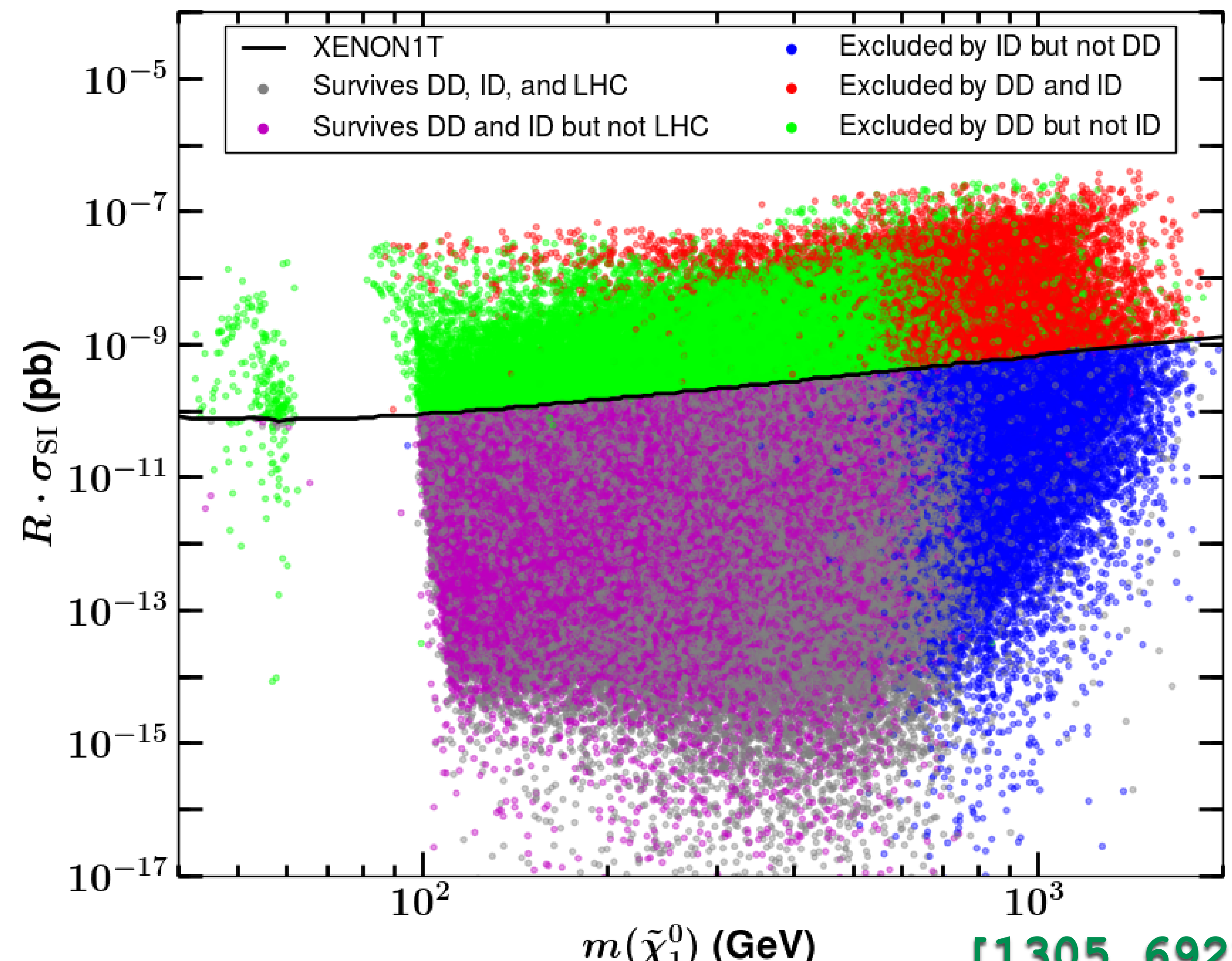


[ATLAS 1210.4491]



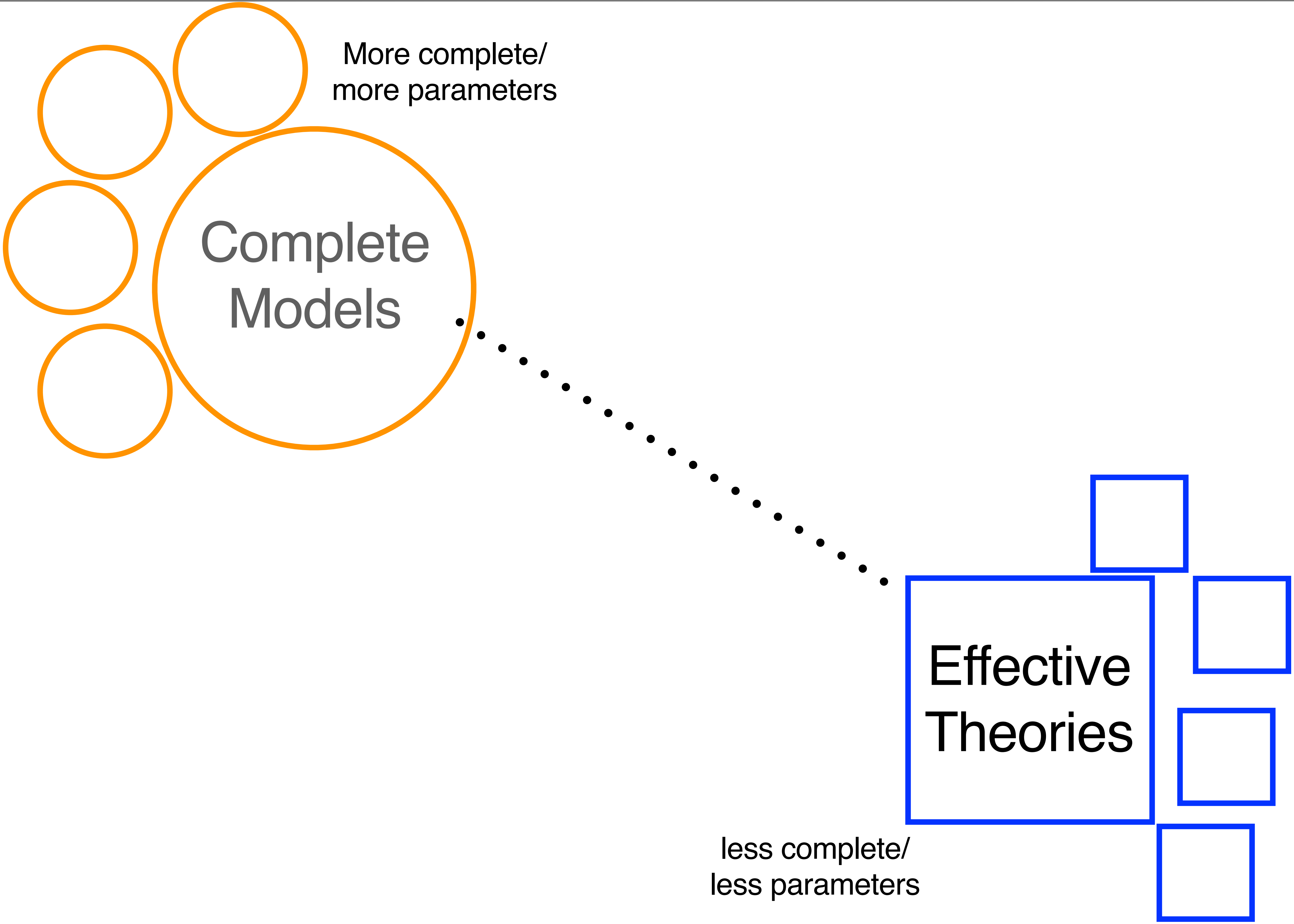
MSSM, Composite Higgs, Extra-Dim...

pMSSM scan



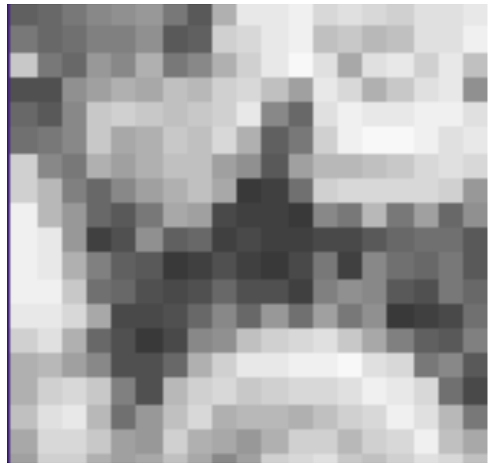
[1305.6921]

lots of parameters...


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

Effective Field Theory Description

effective
low-energy
description



(Λ ~ 1 TeV)

New States

(say, 10 TeV)

M_Z

E

EFT OK

Integrate out the UV physics connecting Dark Matter-SM

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

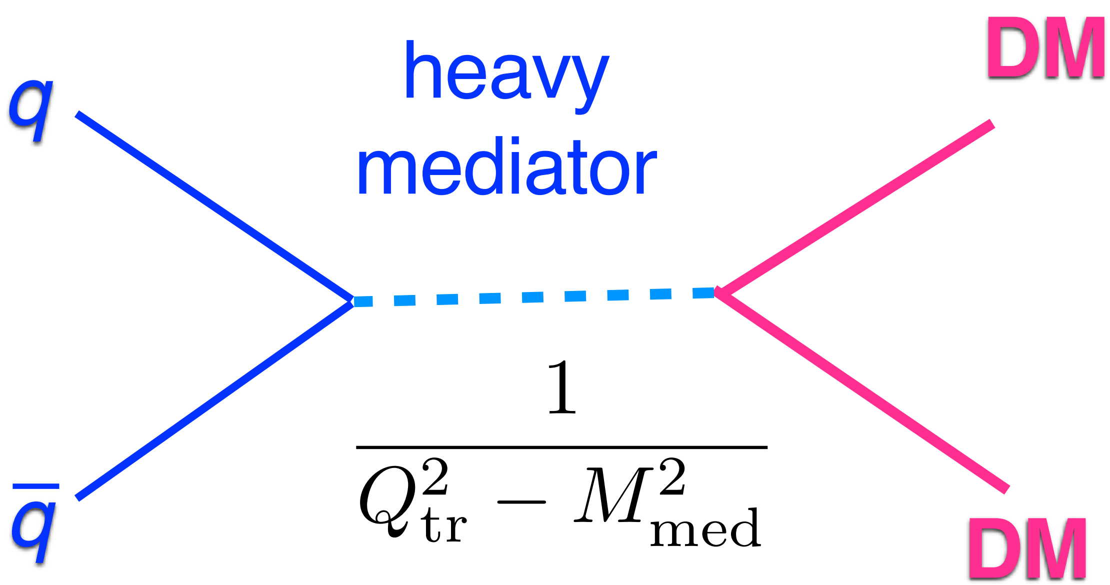
LHC can access regions beyond the validity of the eff. description

=

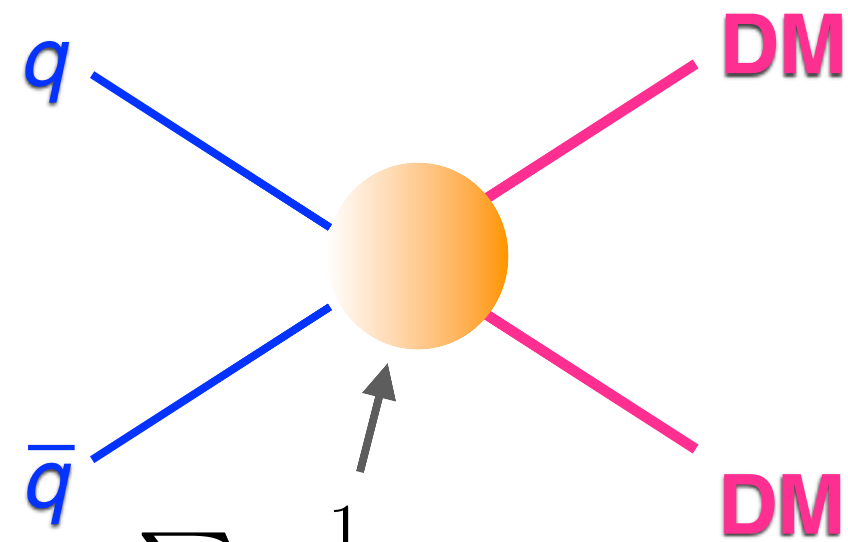
→ need to use EFT <u>carefully</u> and <u>consistently</u>

Effective Field Theory Description

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



$$\frac{1}{Q^2_{\rm tr} - M^2_{\rm med}}$$



$$\sum_{d>4} \frac{1}{M_*^{d-4}} \mathcal{O}_d$$

(tower of ops.)

$$M_{\rm med} = f(g_i, M_*)$$

$$\frac{1}{Q^2_{\rm tr} - M^2_{\rm med}} = -\frac{1}{M^2_{\rm med}} \left[\overbrace{1}^{\text{dim-6}} + \overbrace{\frac{Q^2_{\rm tr}}{M^2_{\rm med}}}^{\text{dim-8}} + \mathcal{O}\left(\frac{Q^4_{\rm tr}}{M^4_{\rm med}} \right) \right]$$

- $Q_{\rm tr}/M_{\rm med}$ measures the badness of the truncation of the tower of effective ops to the lowest dimensional ones

- Usually, lowest order is OK. Not a problem for direct/indirect searches. Situation can be different @ LHC.

Number of valid events are a fraction

$$[R^{\text{tot}}_{M_*}] = \sigma|_{Q_{\text{tr}}<M_*}/\sigma$$

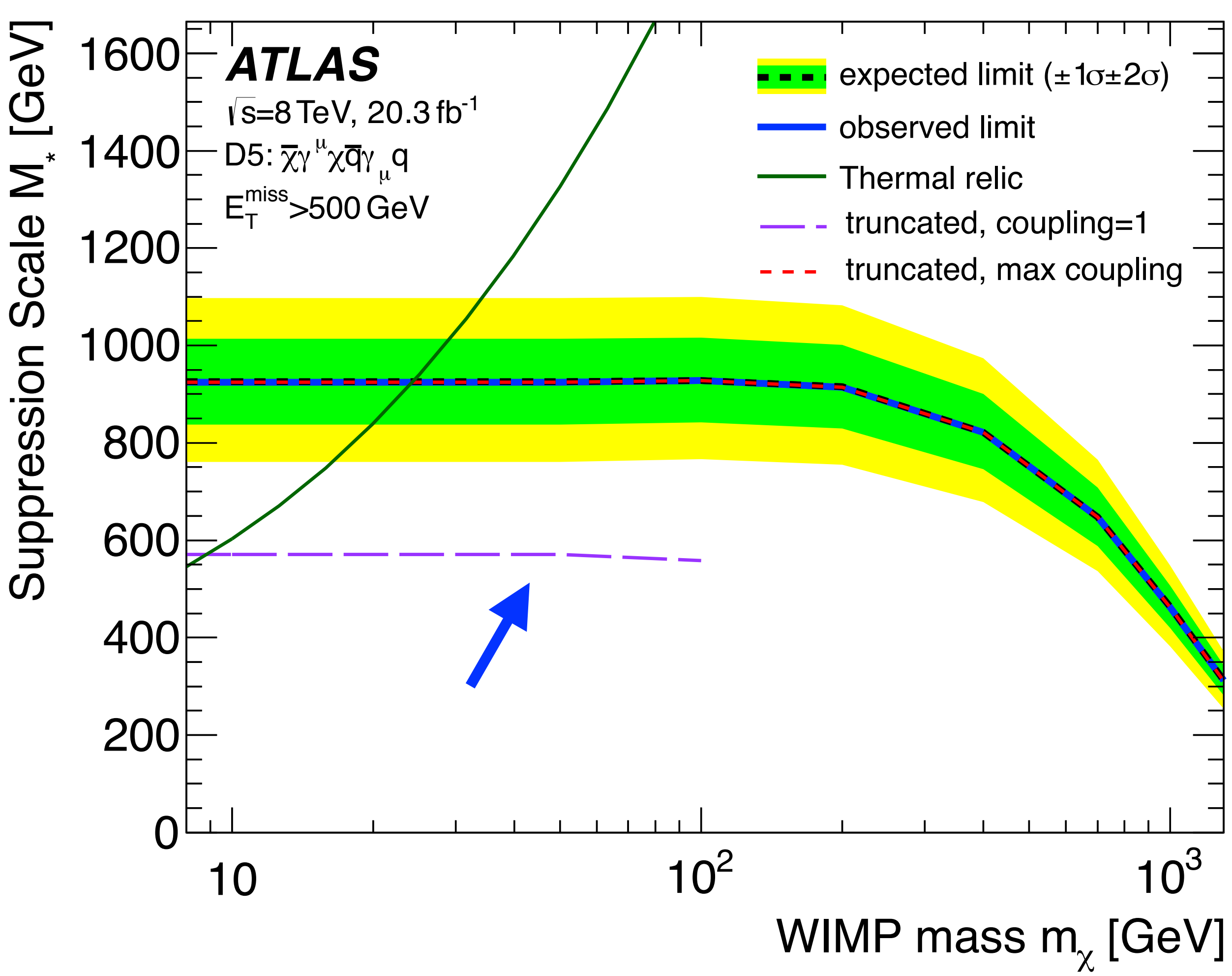
of the total events

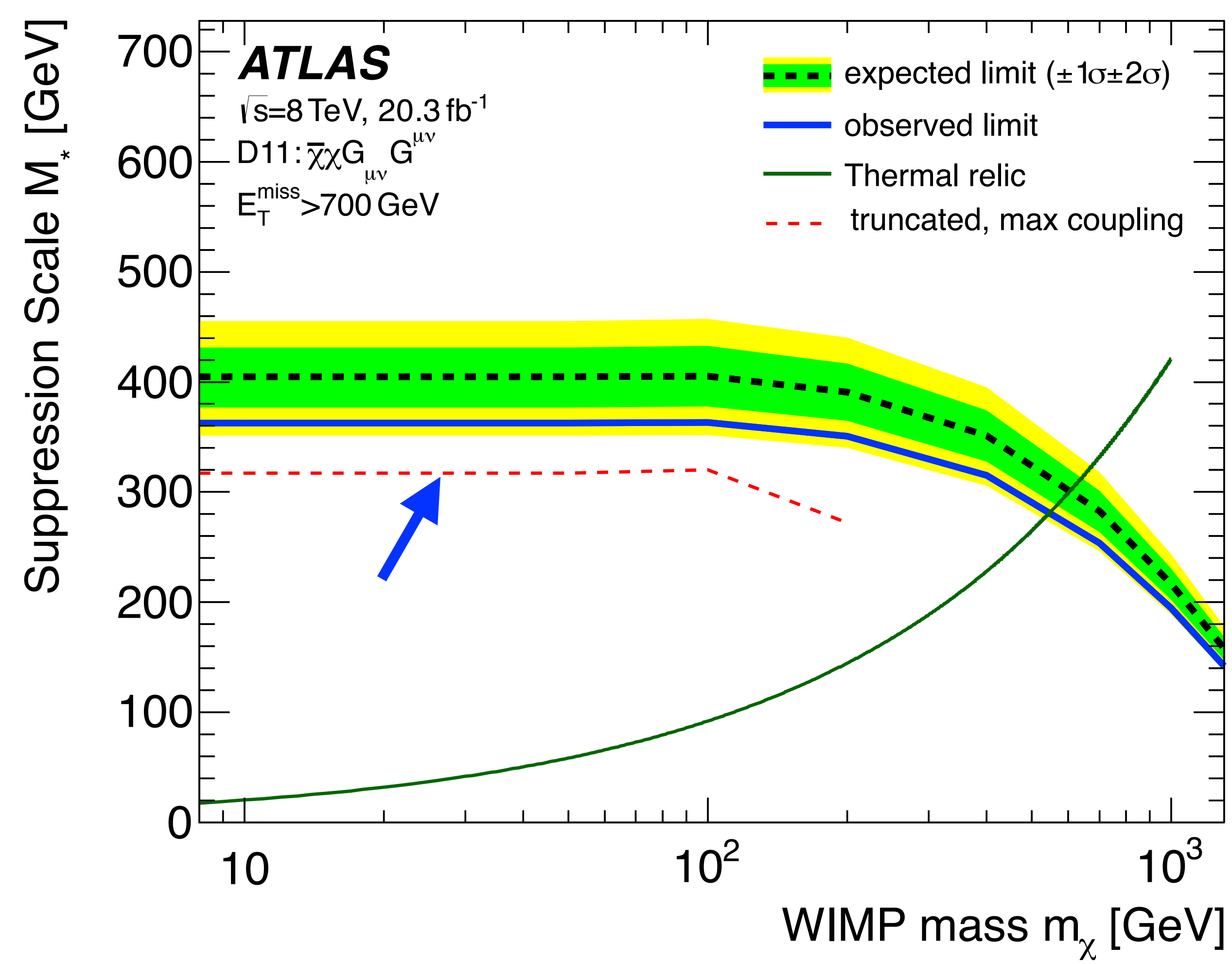
Signal cross section scales as:

$$\sigma \propto M_*^{-4}$$

(for dim-6 ops)

So the new limits are found by: $M_*^{\text{valid}} = [R^{\text{tot}}_{M_*^{\text{valid}}}]^{1/4} M_*^{\text{exp}}$

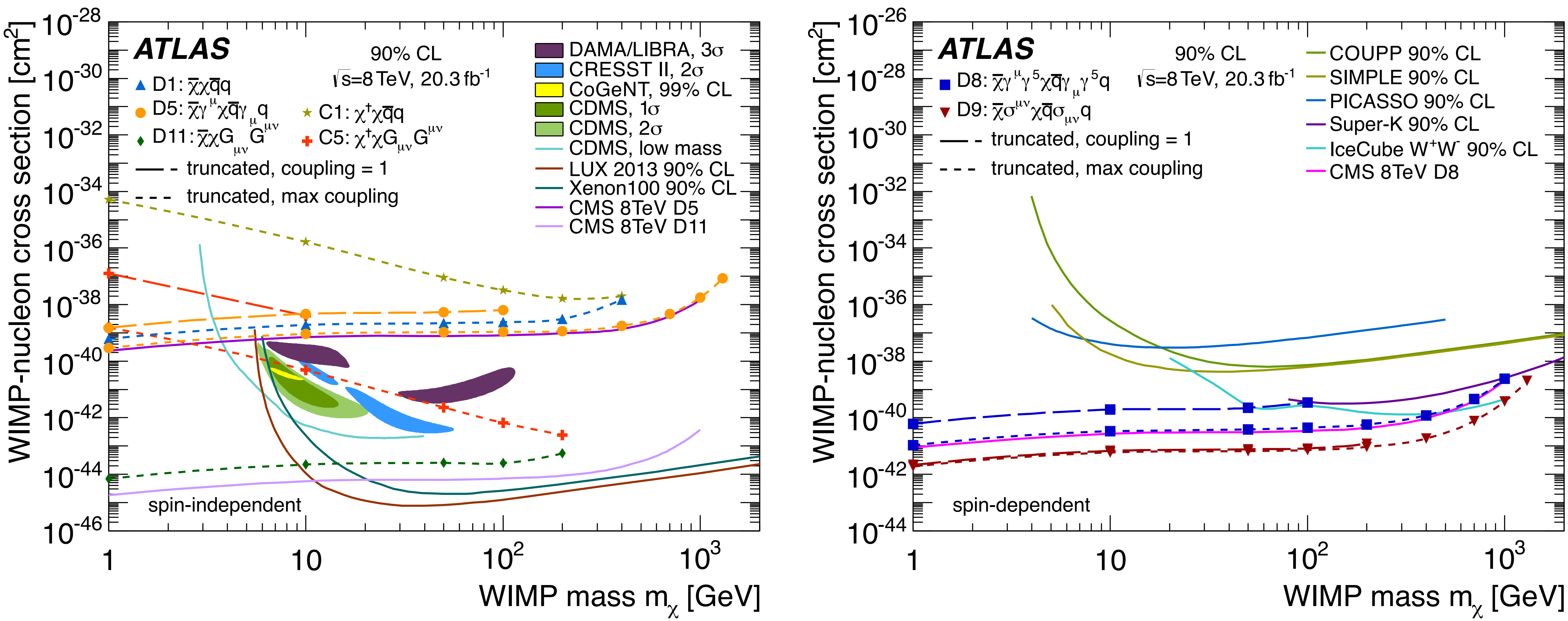




[ATLAS - 1502.01518]

the "money plots"

L=20.3 fb^{-1}

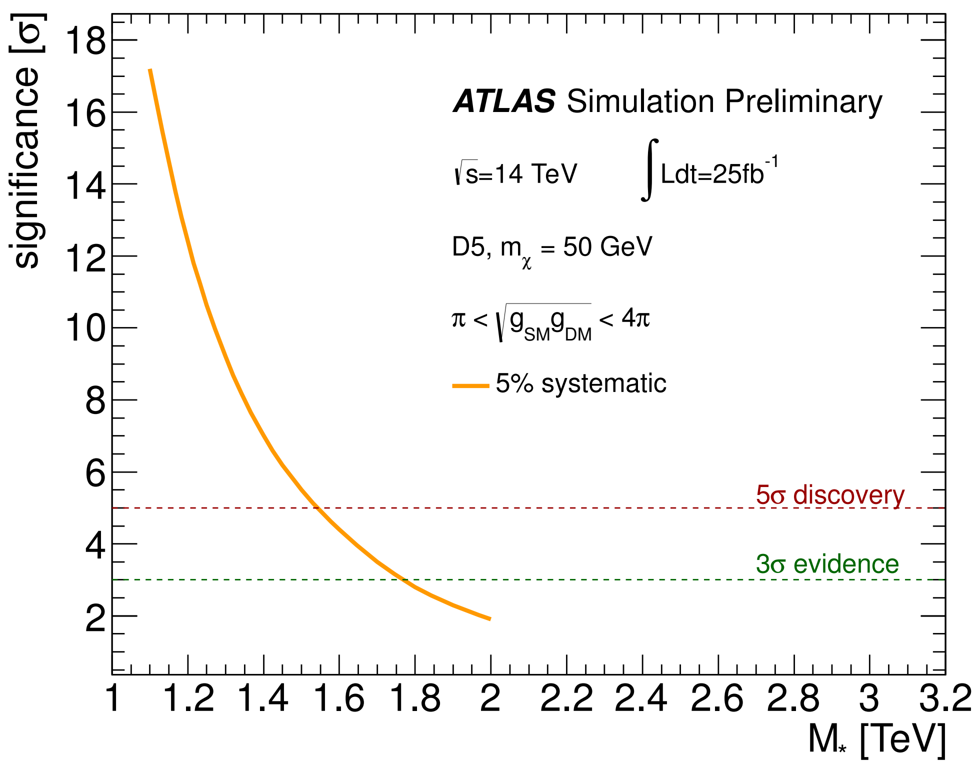


- after truncation: theoretically robust limits
- still relevant at low DM masses

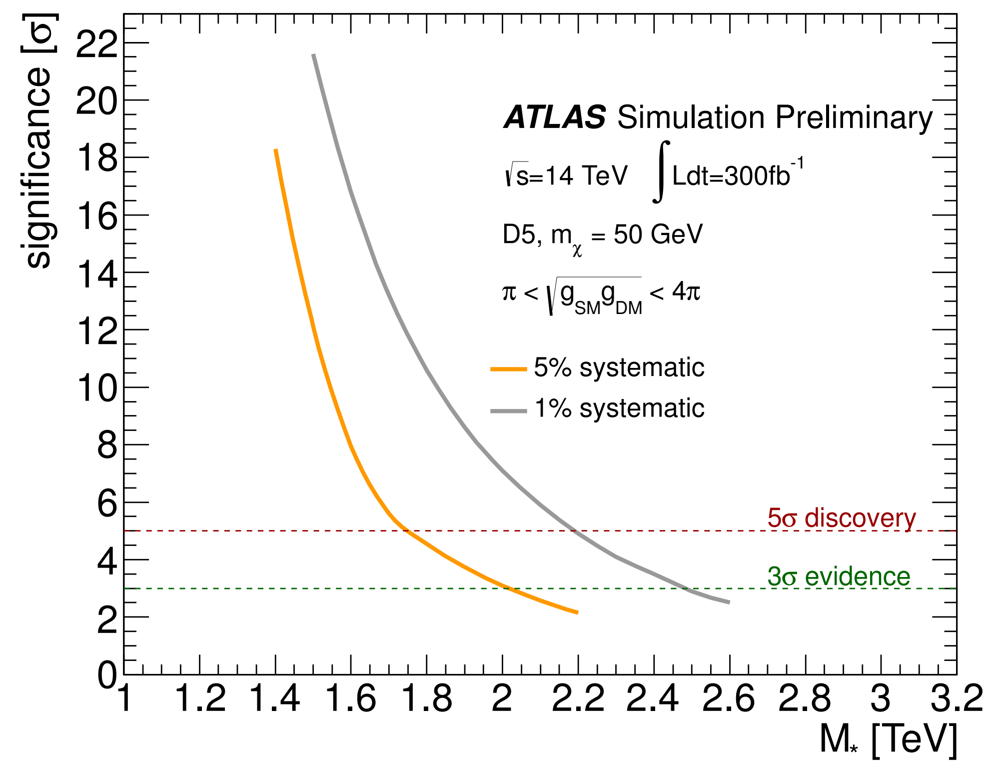
[ATLAS - 1502.01518]

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

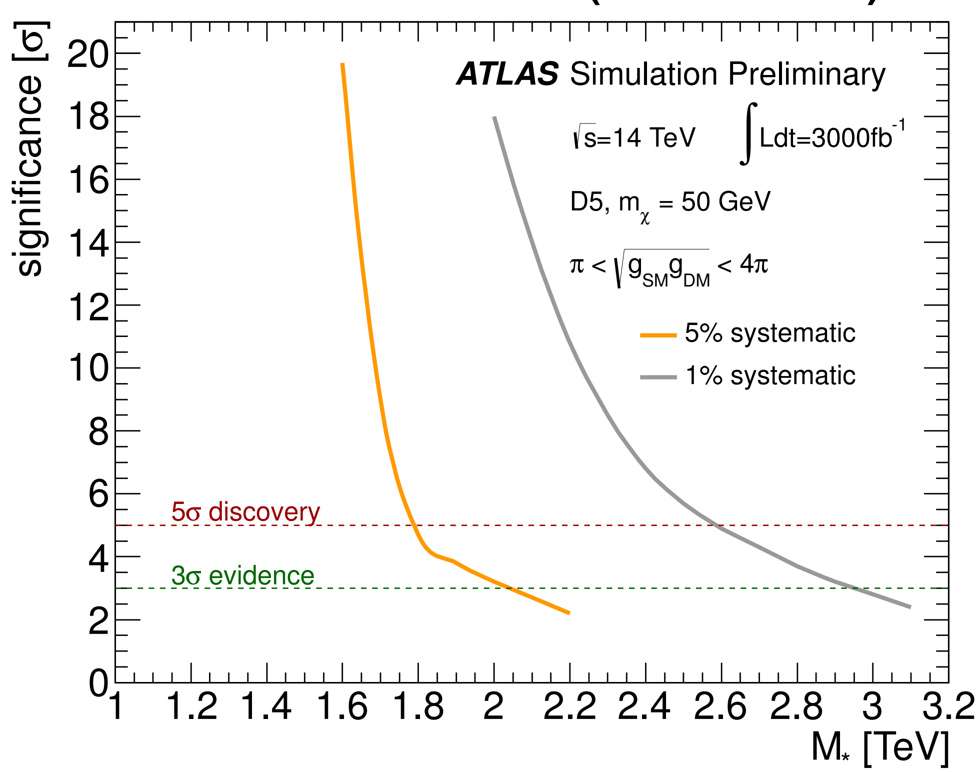
L=25 fb^{-1}



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]

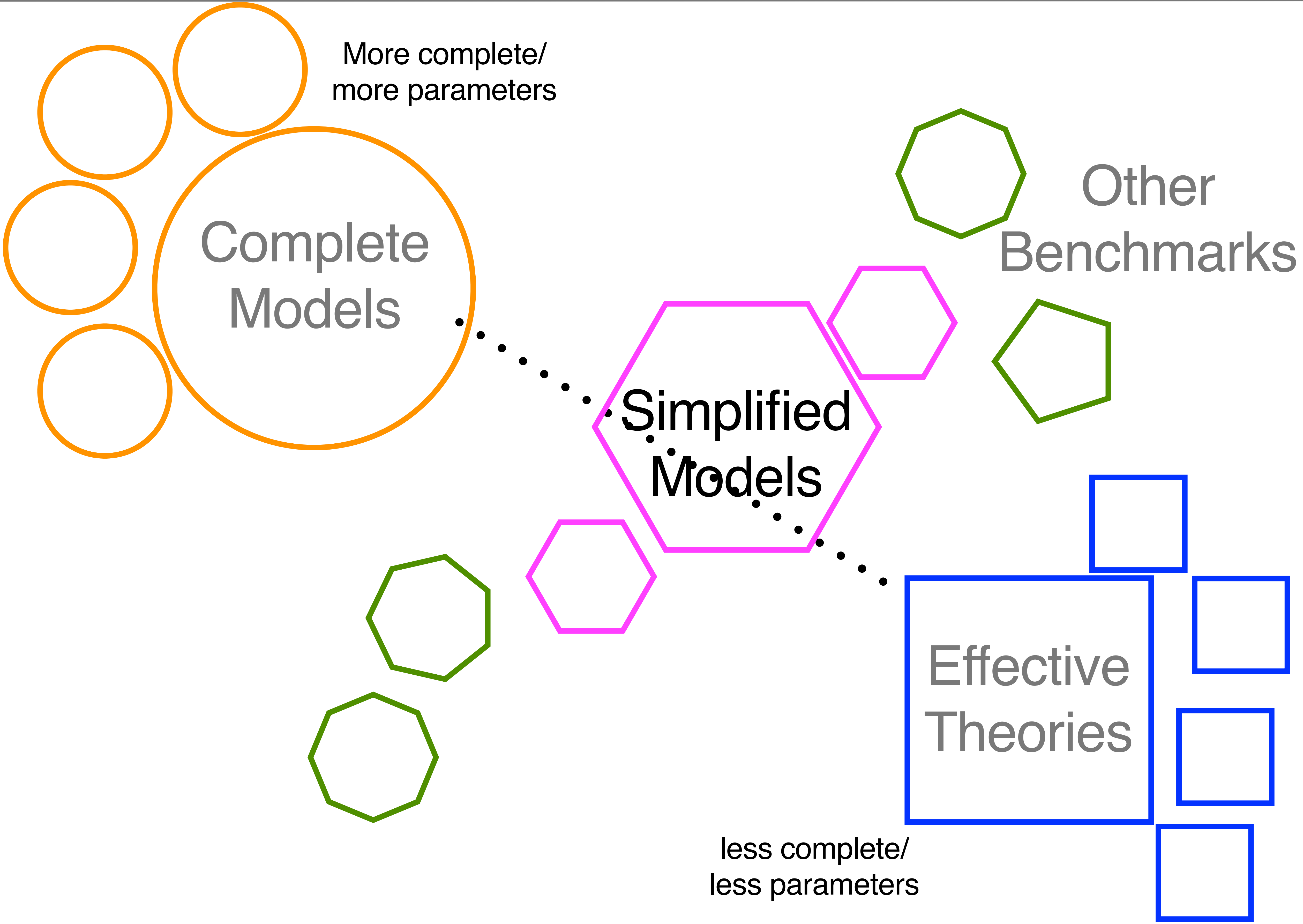
> "*There's a way to do it better.* ***Find it.***"
> *T.A. Edison*

EFT approach

- limited validity
- not entirely model-independent
  (still rather general...)

How to go beyond that (but keeping generality), in view of LHC14?

- **Simplified Models**
- **Selected benchmarks cases**


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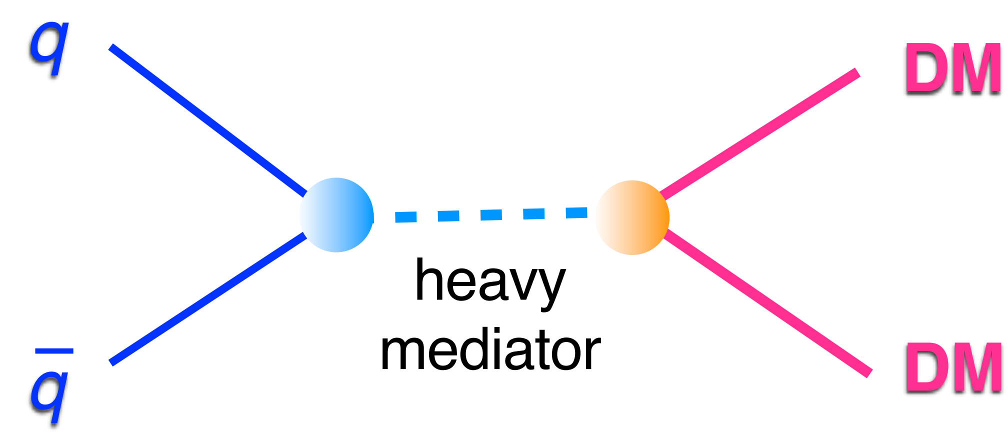
Other
Benchmarks
Simplified
Models
Effective
Theories
less complete/
less parameters

... 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



✘ 1 or 2 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.

[1409.2893]

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]

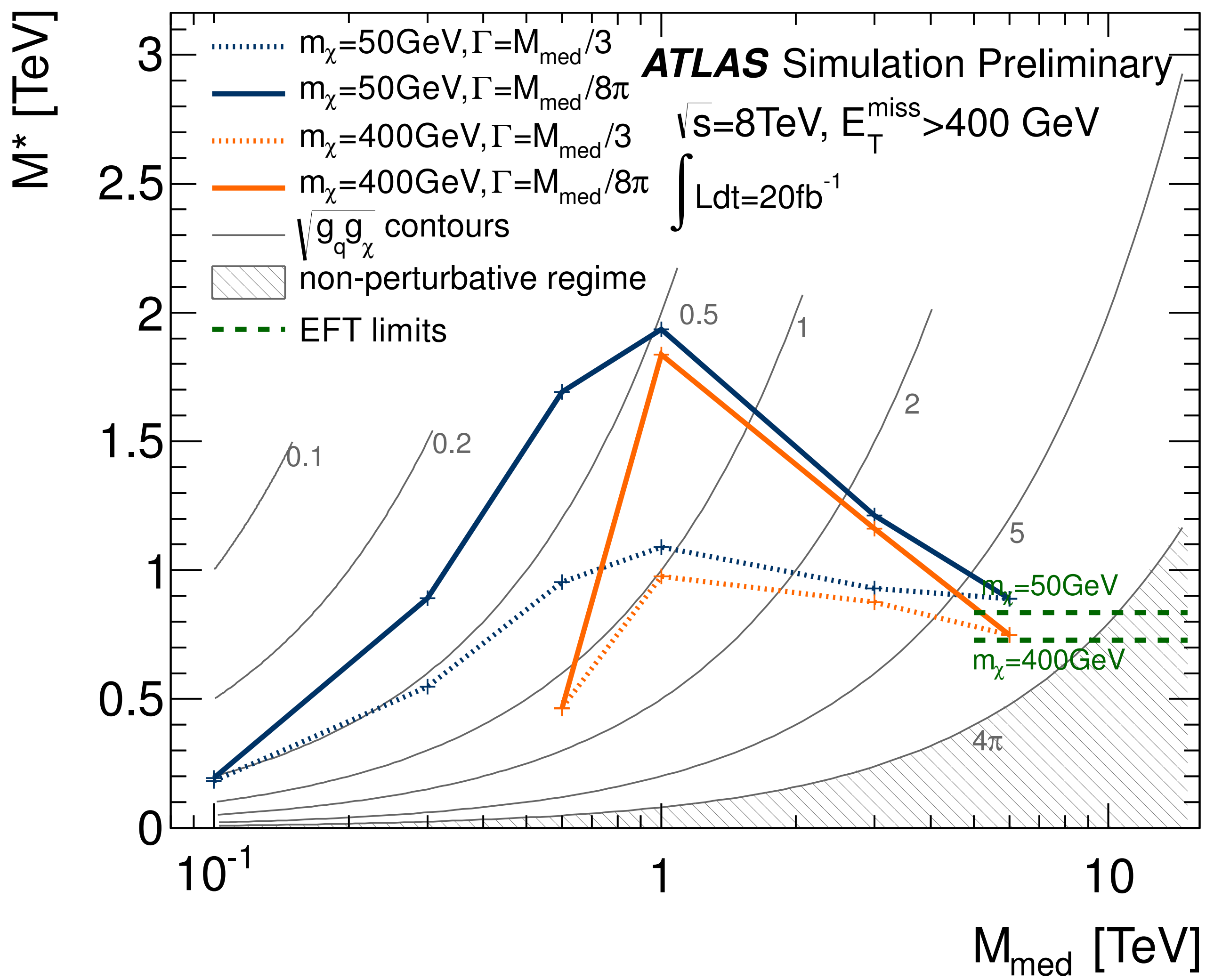
Interplay and Characterization of Dark Matter Searches at Colliders and in Direct Detection Experiments

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]

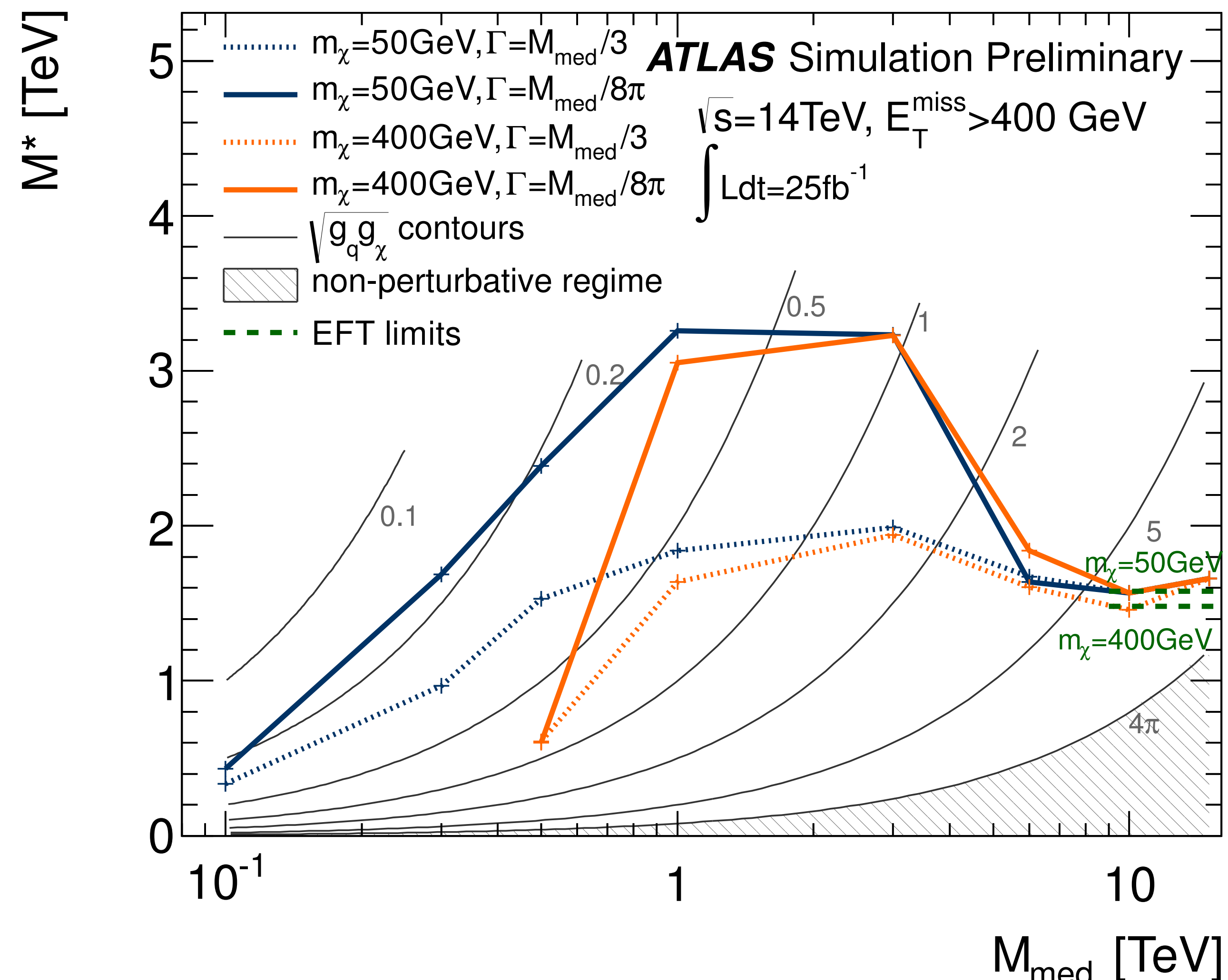
[1409.4075]

Z' vector mediator model: $\mathcal{L} = -\sum_f g_f Z'_\mu [\bar{f}\gamma^\mu f] - g_{\rm DM} Z'_\mu\ [\bar{\chi}\gamma^\mu \chi]$

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



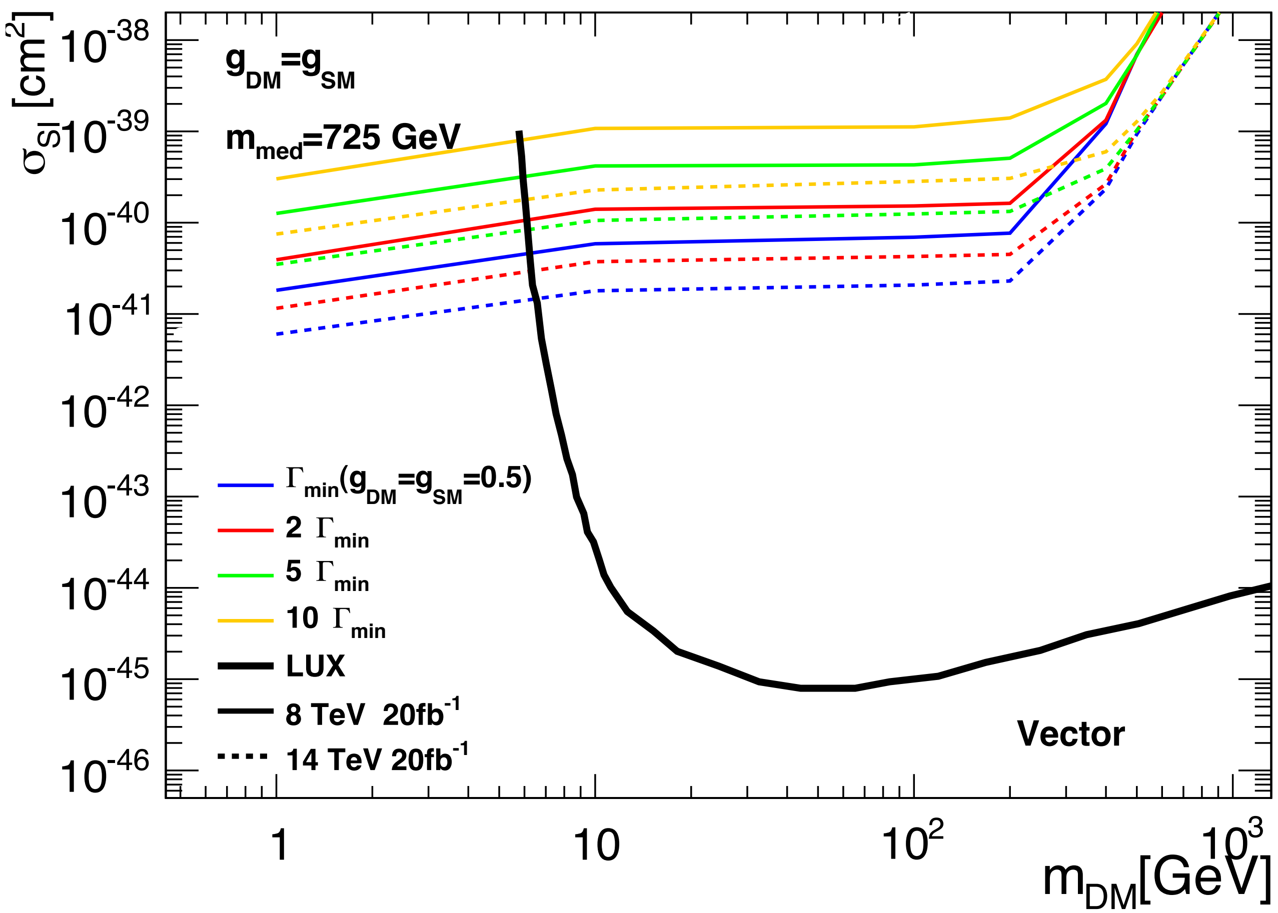
$\sqrt{s} = 14\,\mathrm{TeV}$

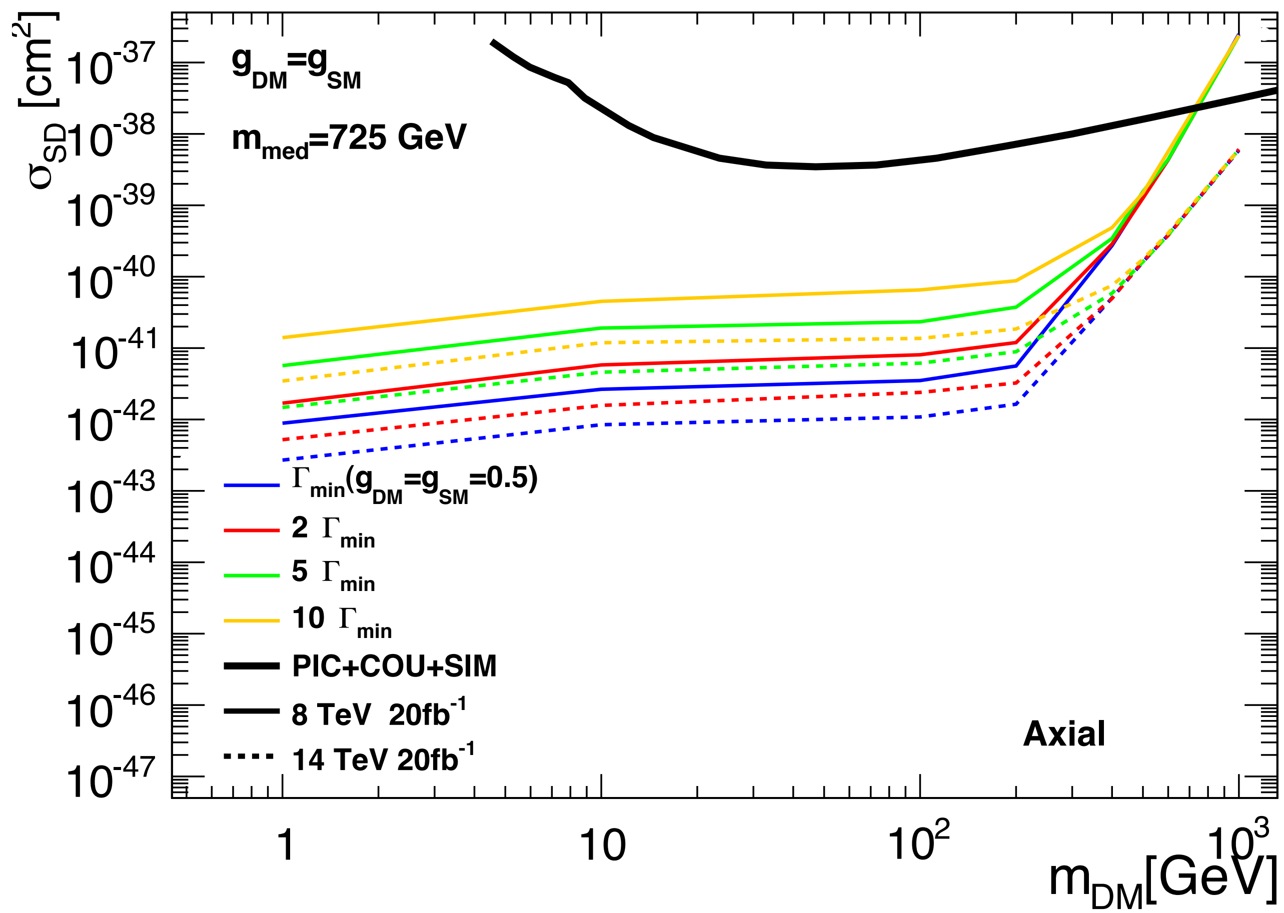


$$M^* = \frac{M_{\rm med}}{\sqrt{g_f g_{\rm DM}}}$$

[ATL-PHYS-PUB-2014-0087]

projecting 90%CL exclusions
(from CMS data)
onto direct-detection plane

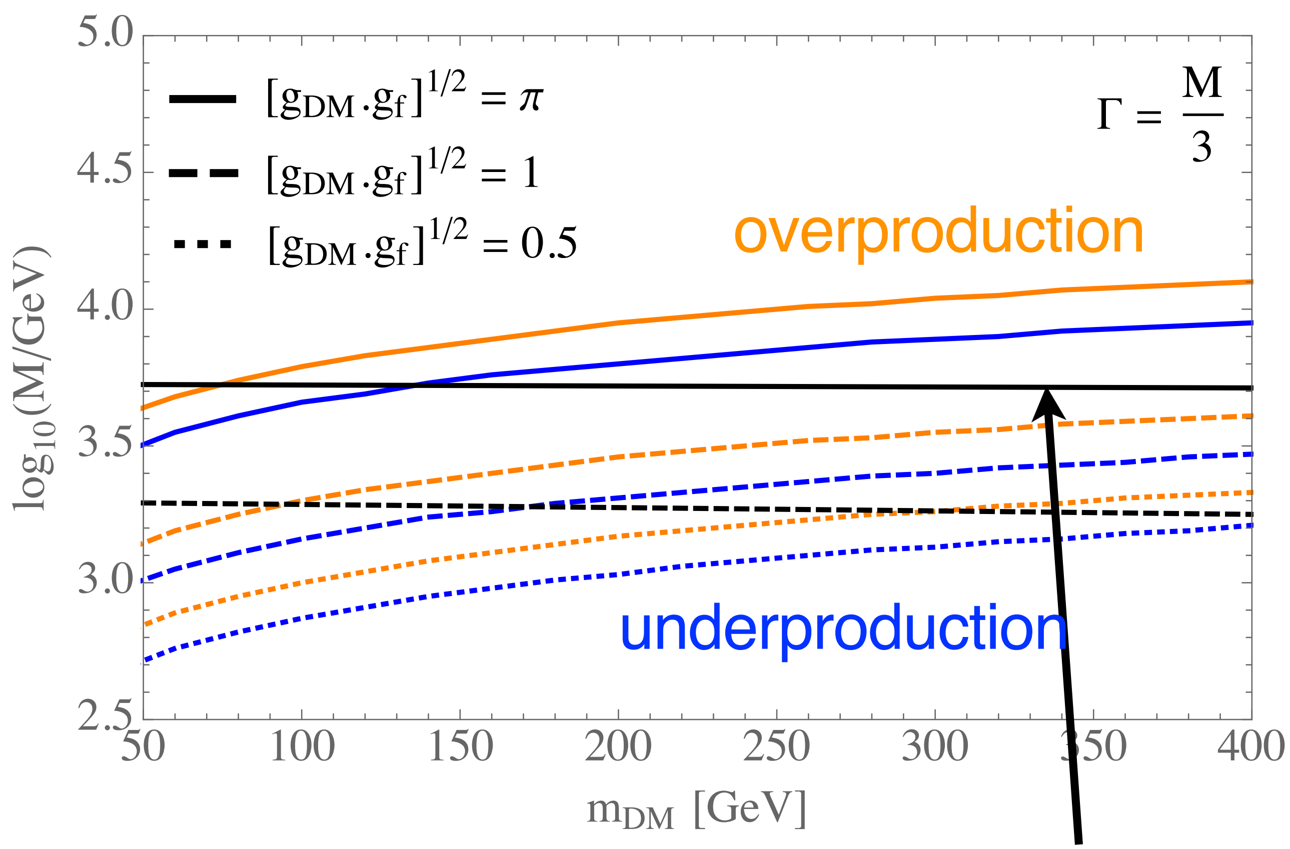


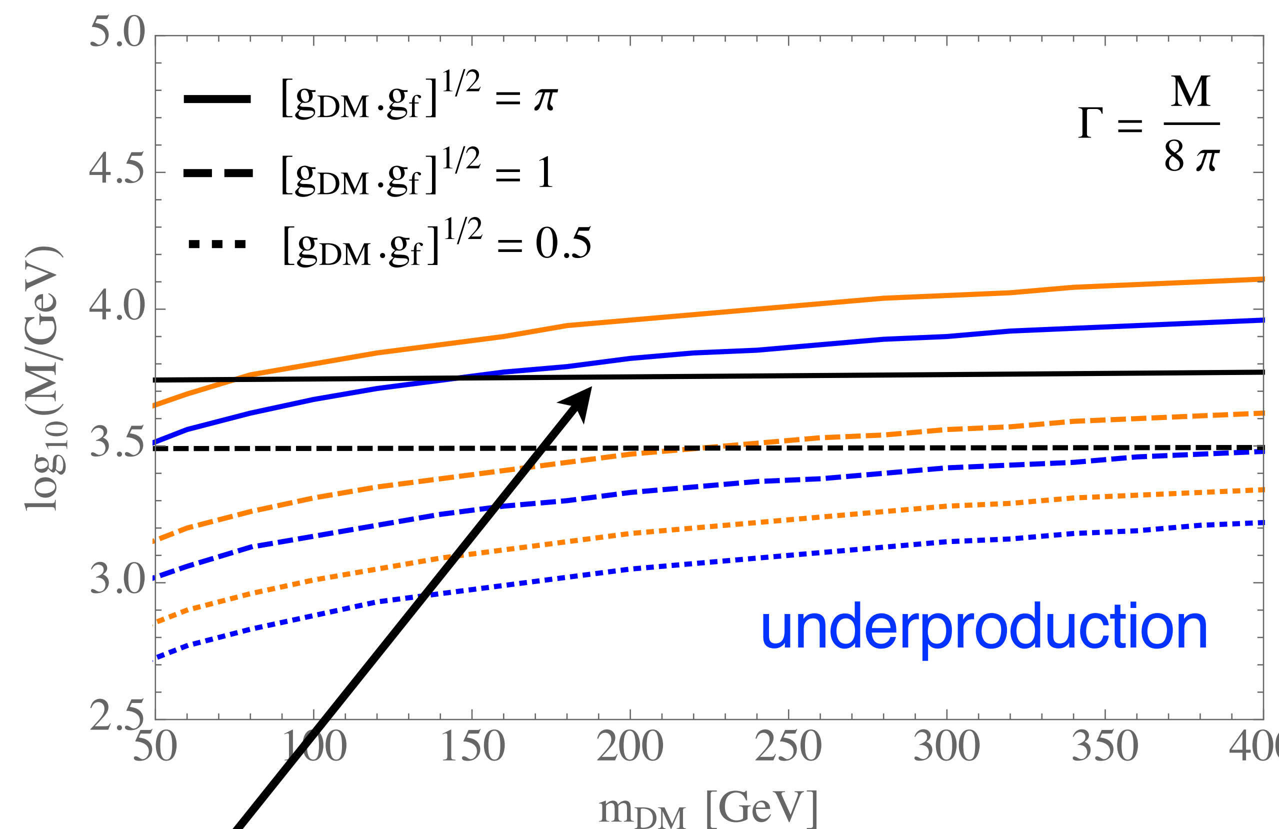


[Harris et al - 1411.0535]

[Busoni, DS, Jacques, Morgante, Riotto - 1410.7409]

Z' vector mediator model: $$\mathcal{L} = -\sum_f g_f Z'_\mu [\bar{f}\gamma^\mu f] - g_{\rm DM} Z'_\mu \, [\bar{\chi}\gamma^\mu \chi]$$



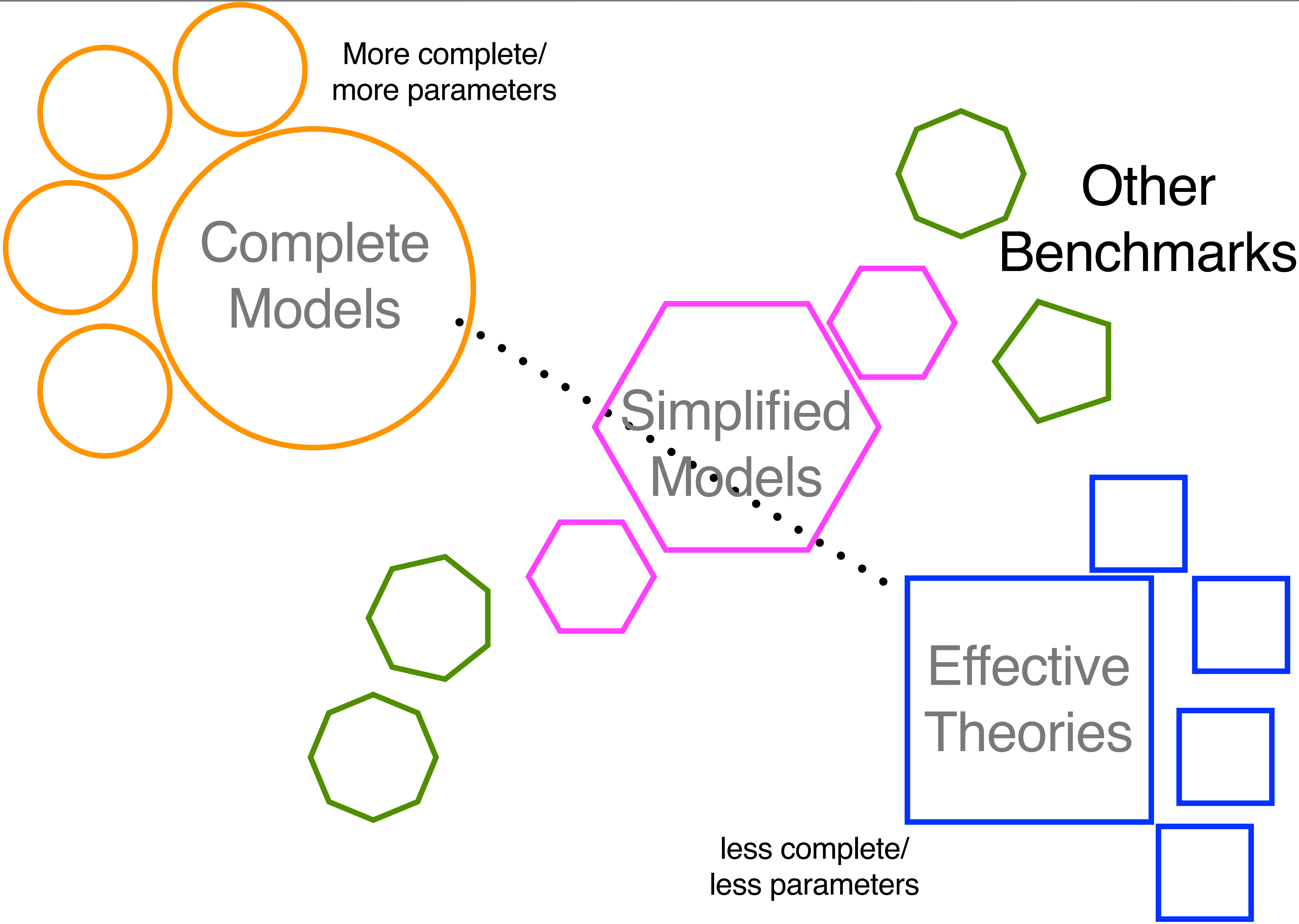


ATLAS 95% CL bound
L=25 fb^{-1} at 14 TeV

overproduction $\langle \sigma v \rangle_{\rm ann} < \# \langle \sigma v \rangle_*$

underproduction $\langle \sigma v \rangle_{\rm ann} > \langle \sigma v \rangle_*$

Hypothesis: $g_f \leq g_{u,d}$


More complete/
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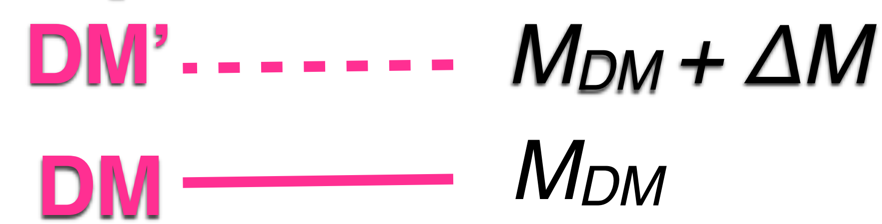
Models
Other
Benchmarks
Simplified
Models
Effective
Theories
less complete/
less parameters

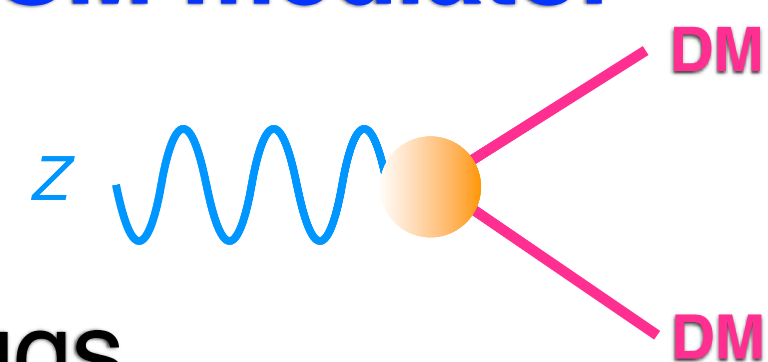
[DS, Giudice, Strumia - 1402.6287]

Some benchmark cases offering prospects for DM discovery
(alternative to EFT or simplified models):

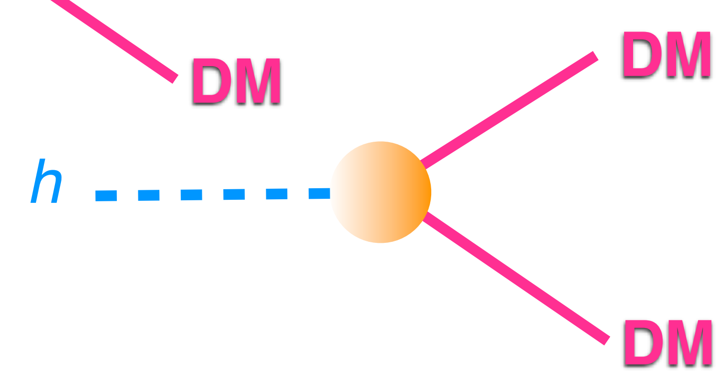
1. DM co-annihilating with a coloured partner



2. DM annihilating through a SM mediator



- DM coupled to the Z
- DM coupled to the Higgs



3. DM near Z/h thresholds

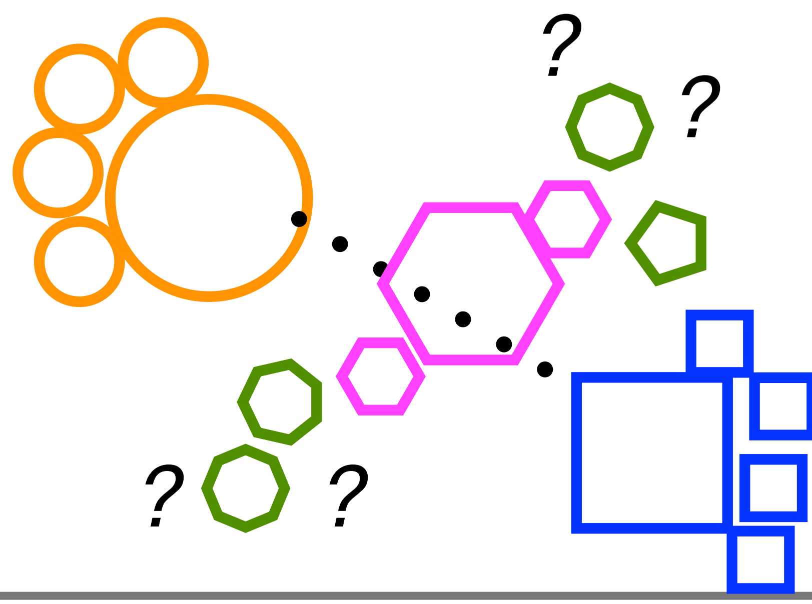
$$\Gamma_{\mathrm{med}\to\mathrm{DM}}$$

... ???

Conclusions

EFT fragile

LHC can discover **mediators** more easily than effective operators



Future of LHC searches for DM

Need to explore <u>new avenues</u>

- ***beyond EFT***
- *as model-indep. as possible*

Get ready to fail

***abandon** WIMP paradigm in N years*

or

WIMP obstinacy?

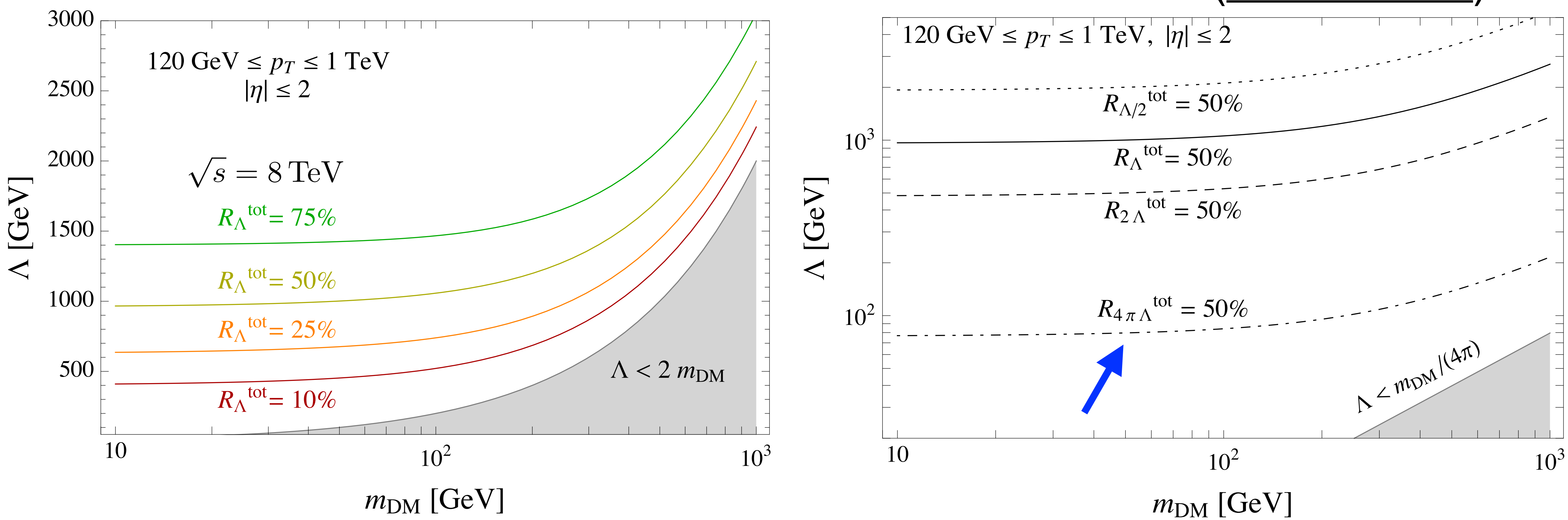
BACK UP

Effect of the EFT Cutoff

In what regions of the parameter space $\{\Lambda, m_{DM}\}$ is the effective description accurate/reliable?

$$R_\Lambda^{\rm tot} \equiv \frac{\sigma_{\rm eff}\big|_{Q_{\rm tr}<\Lambda}}{\sigma_{\rm eff}}$$

fraction of eff. cross section at low momentum transfer (valid events)

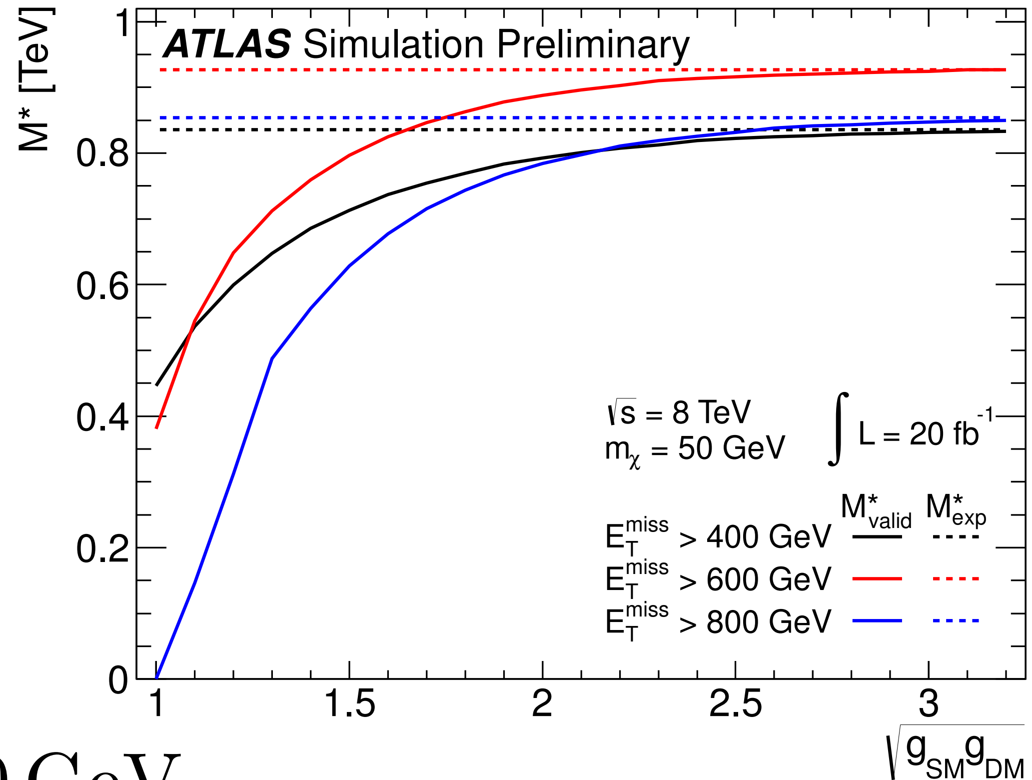


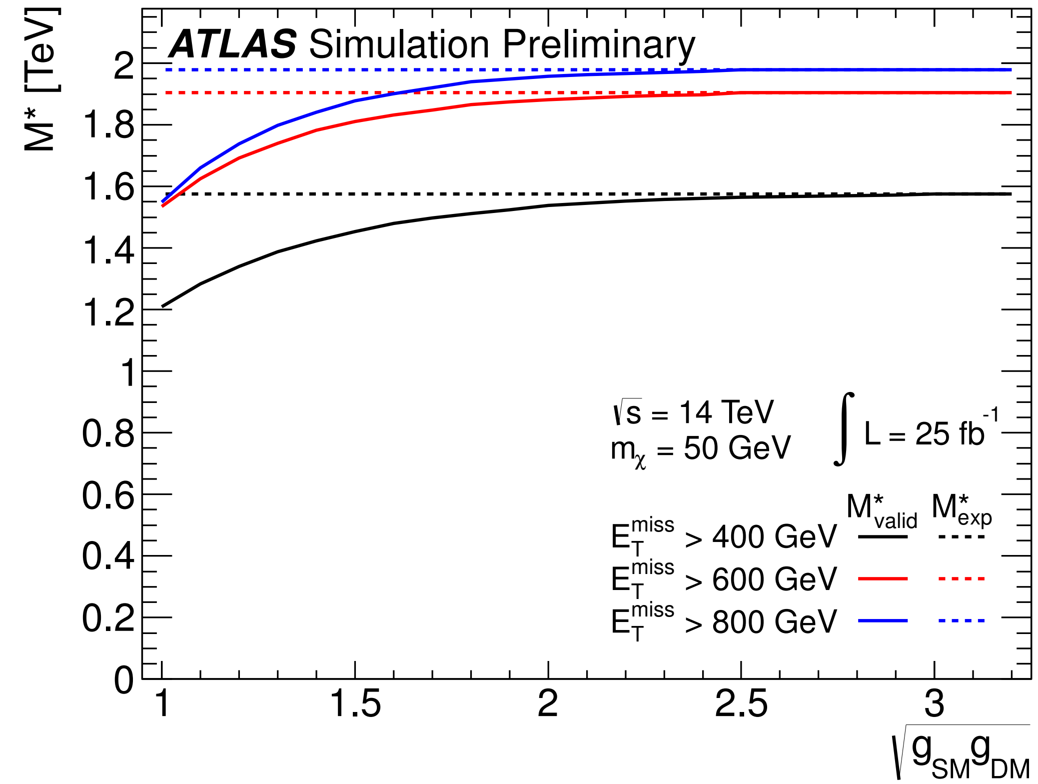
- 0<R<1. R ~ 1: negligible contribution from higher-dim ops
- EFT works better for larger Λ and smaller m_{DM}.
- Cutoff scale arbitrary: $Q_{\rm tr} < \sqrt{g_q g_\chi}\,\Lambda$ (conservatively: $Q_{\rm tr} < 4\pi\Lambda$)

Implications for LHC Limits

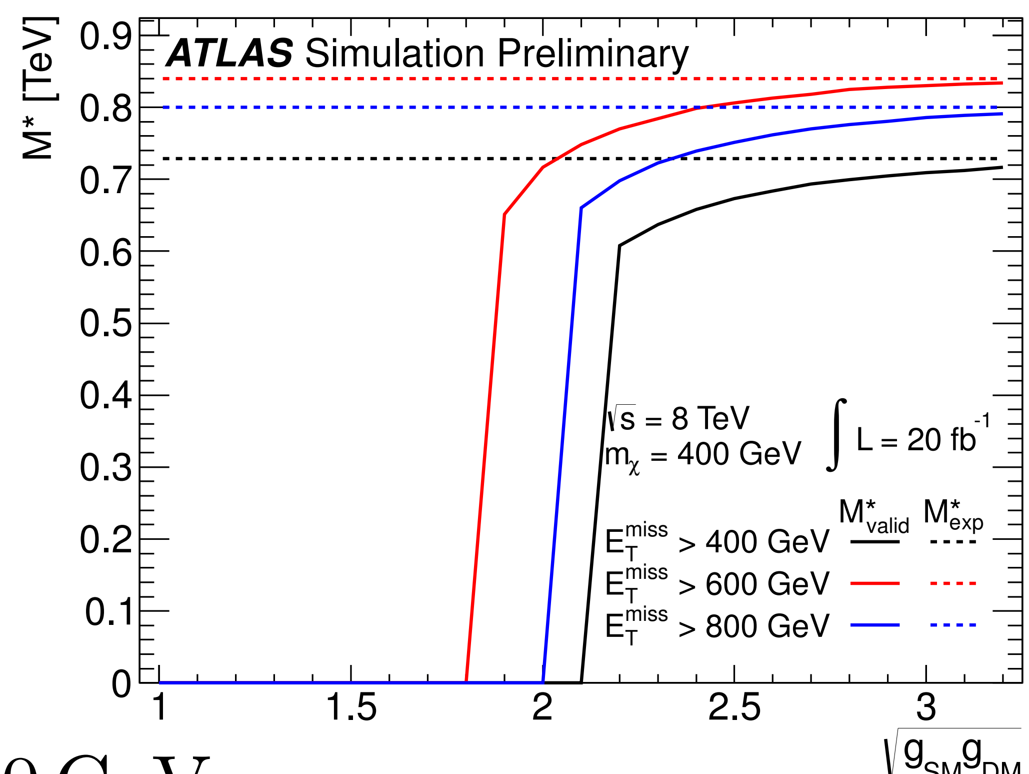
$(\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q)$

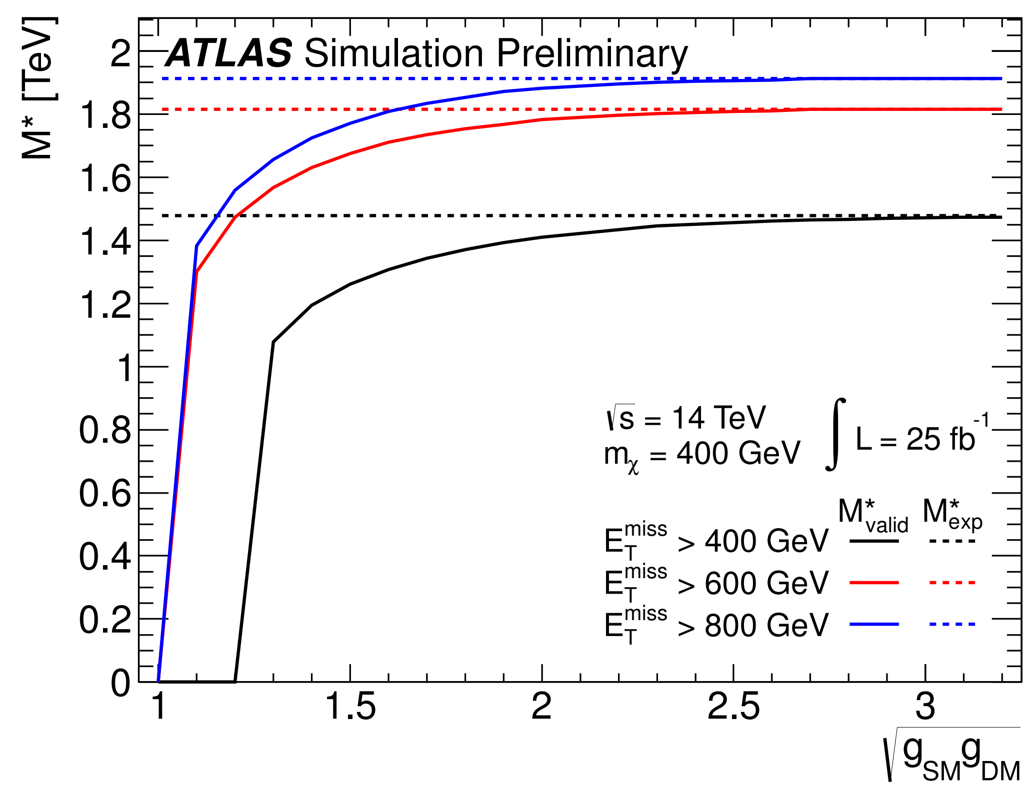
$\sqrt{s} = 8\,\text{TeV}$ $\sqrt{s} = 14\,\text{TeV}$





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



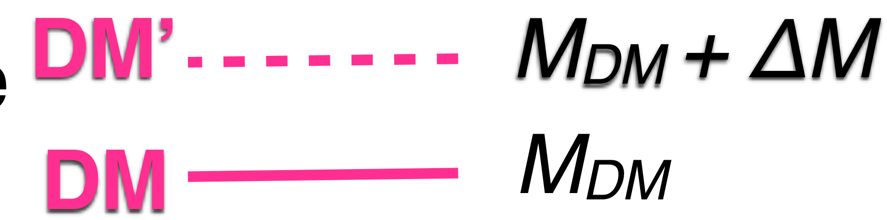


$m_{\text{DM}} = 400\,\text{GeV}$

[ATL-PHYS-PUB-2014-0087]

1. Co-Annihilations with a Coloured Partner

- DM accompanied by a nearby coloured state



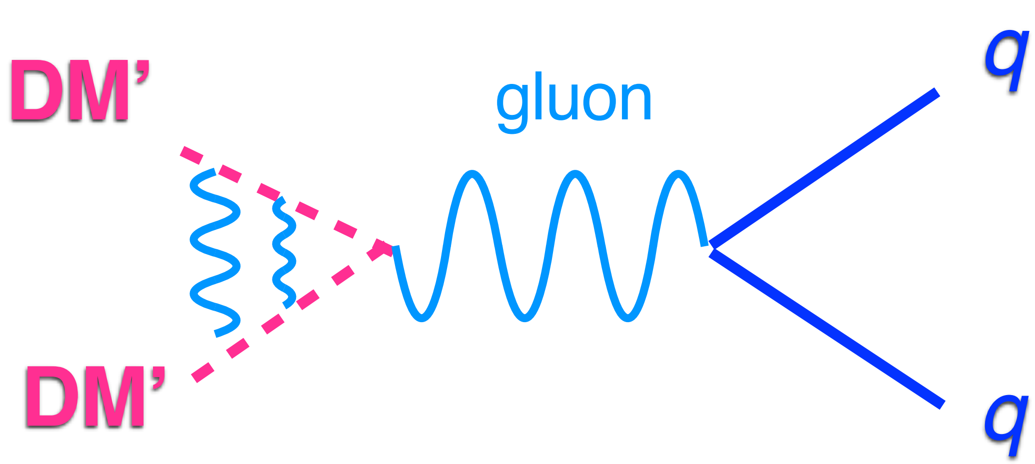
- Situation fully characterised (model-independently) by:
  - DM' quantum numbers (spin,color)
  - M_{DM}
  - ΔM

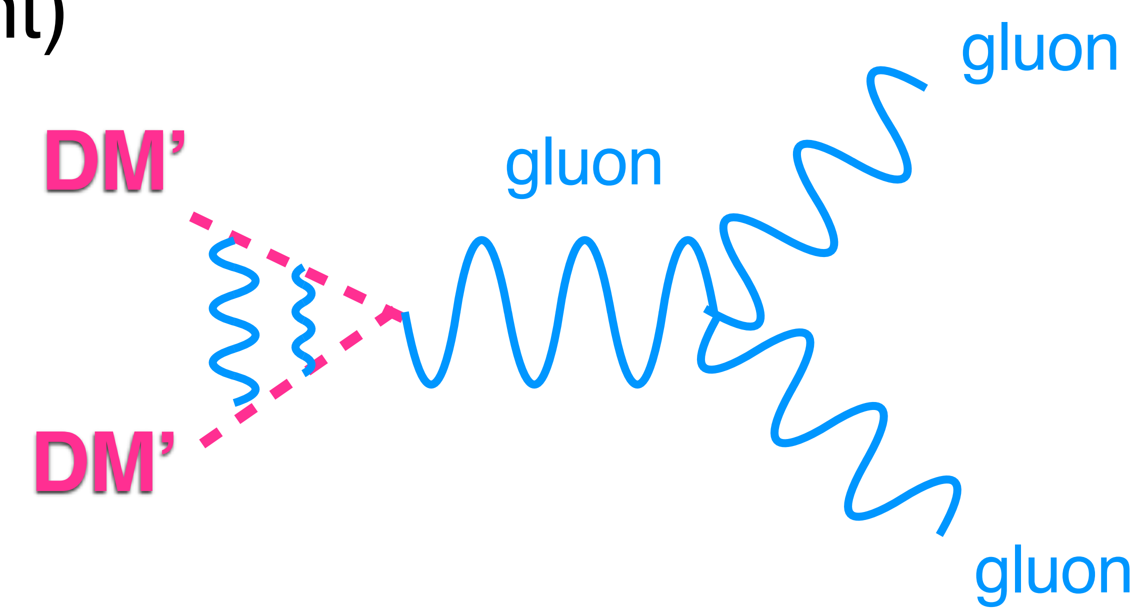
- 4 cases of interest:

DM'	Colour triplet	Colour octet
Scalar	S3	S8
Fermion	F3	F8

stop
gluino

- Relic density from co-annihilations in the early Universe (with Sommerfeld enhancement)

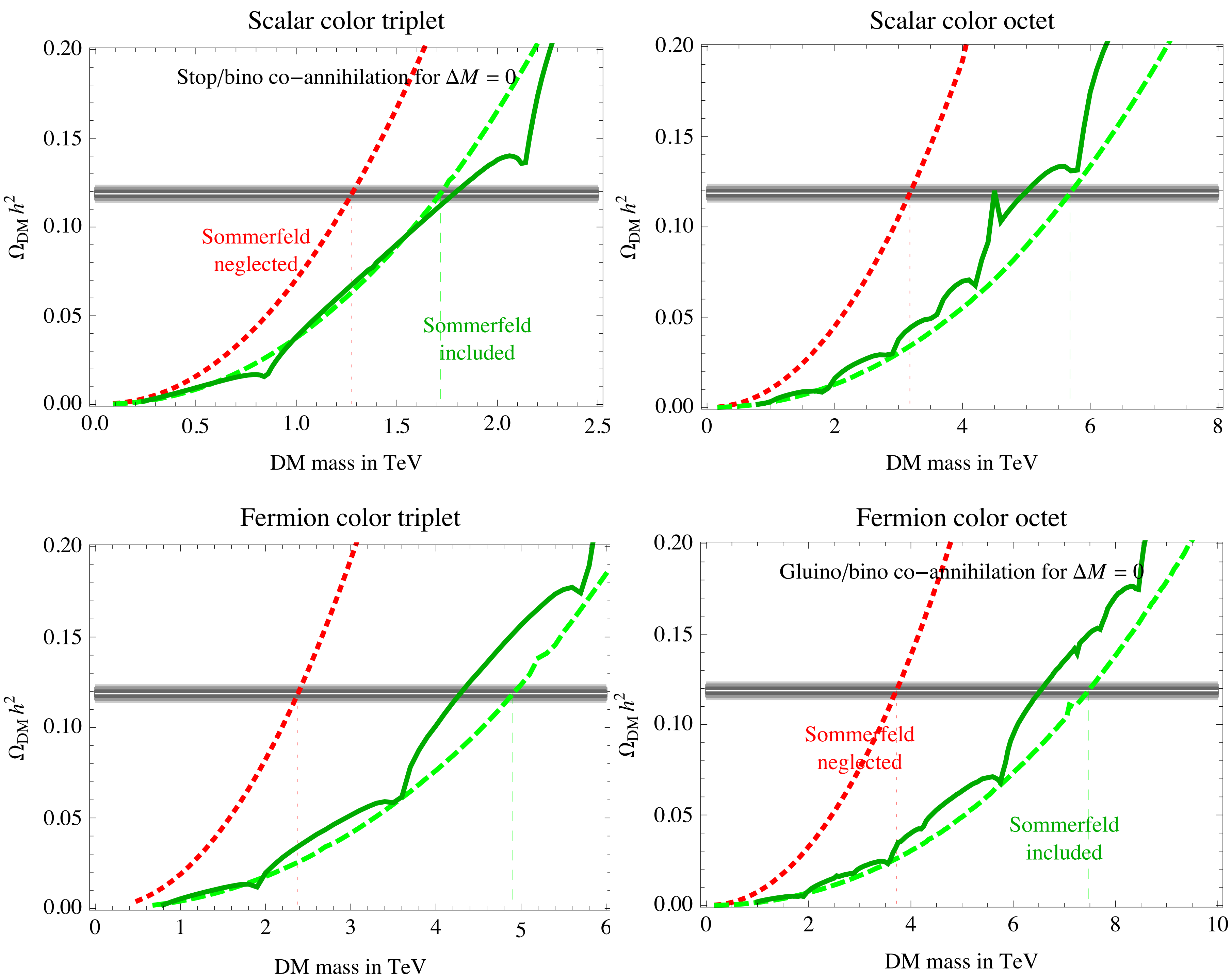




Relic density in the limit of mass degeneracy $\Delta M = 0$

S3 S8

F3 F8

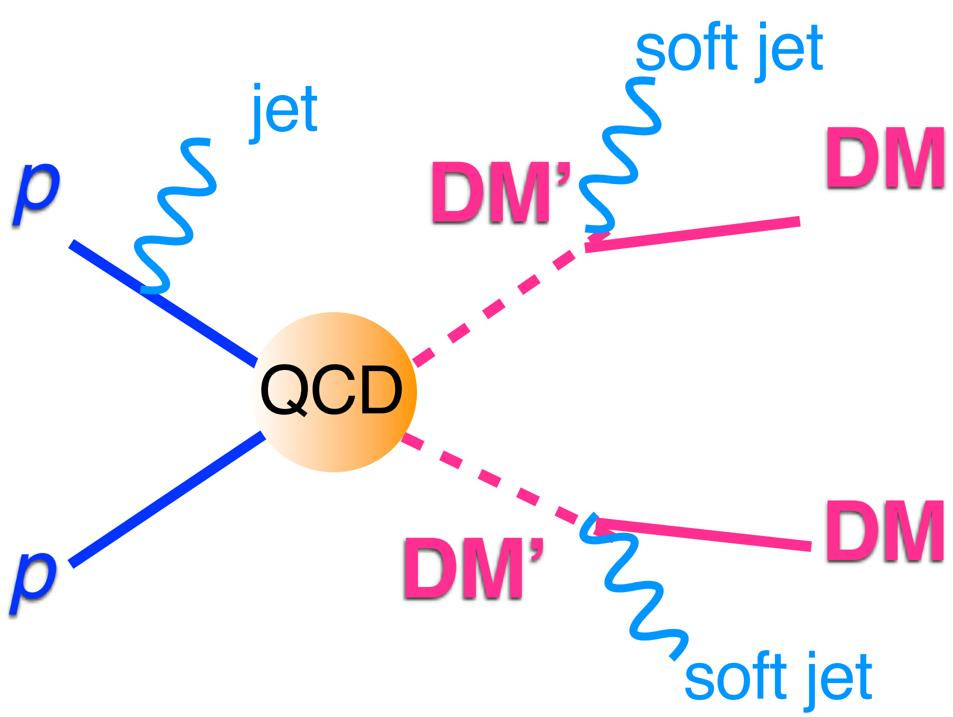


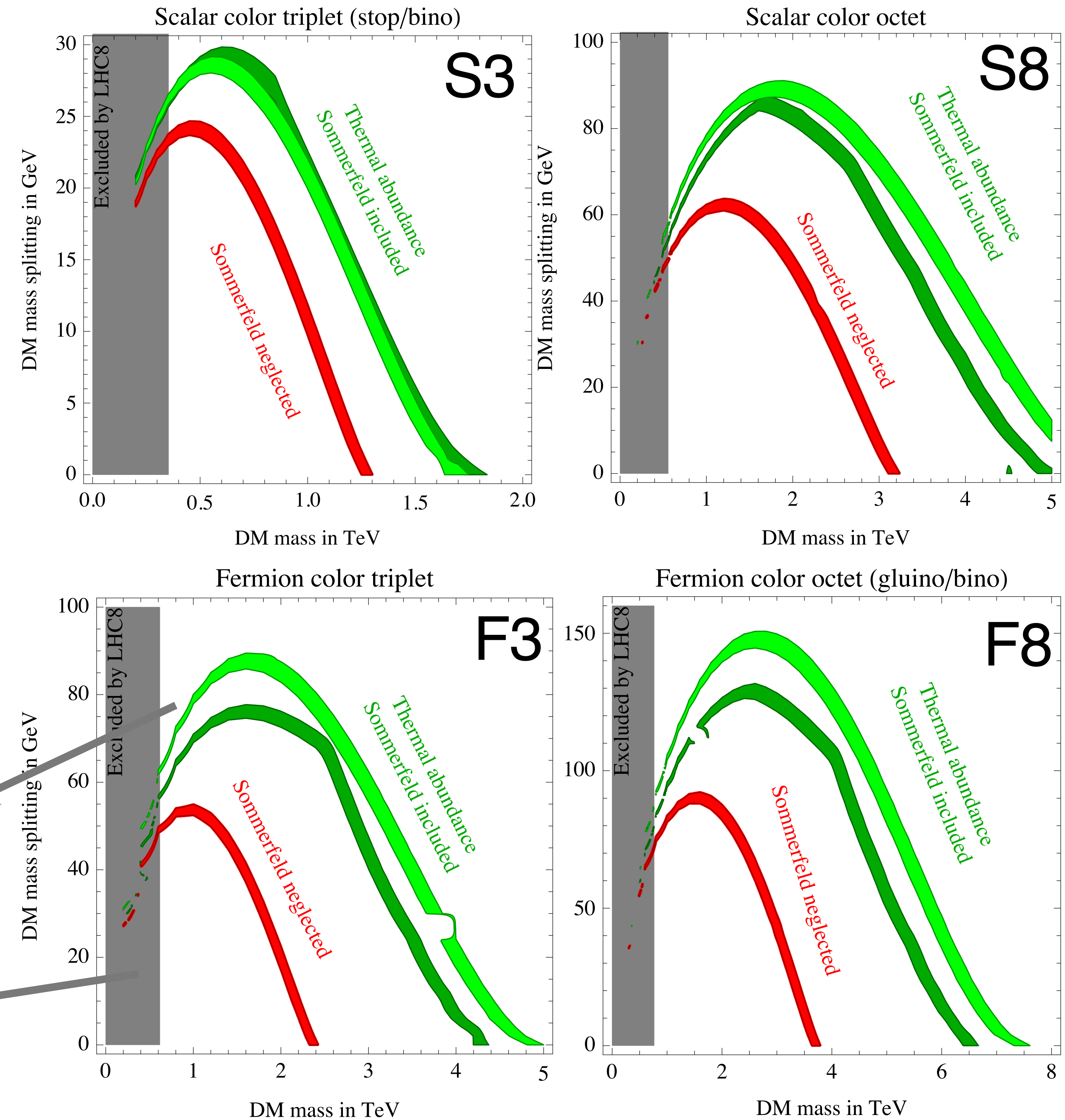
substantial effect of Sommerfeld corrections

1. Co-Annihilations with a Coloured Partner

large QCD cross section:

$$pp \to \text{DM' DM'} + \text{jet}$$



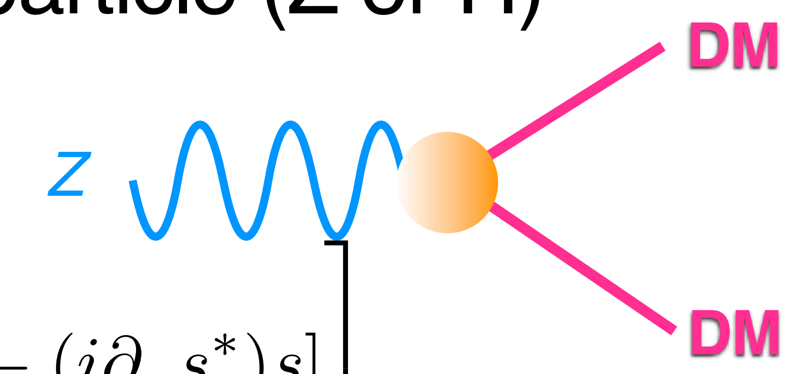


large-enough splitting to tag soft jet?

90%CL exclusion
$\sqrt{s} = 8$ TeV
L=19.6 fb^{-1}

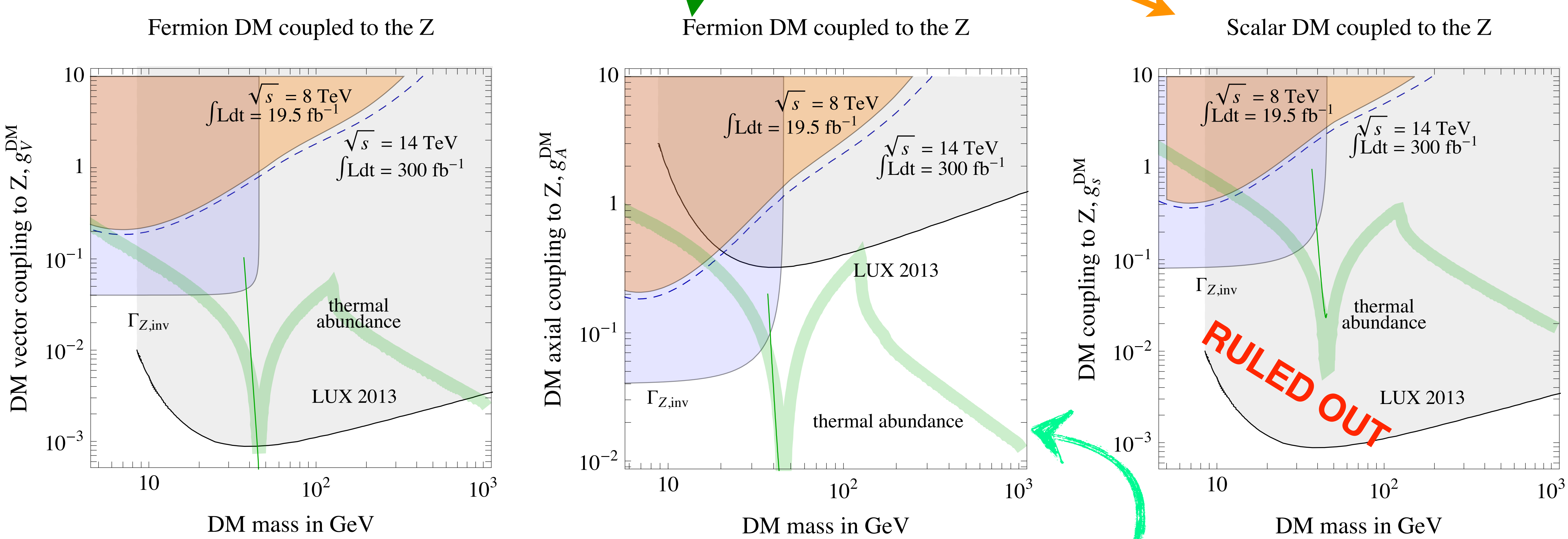
LHC will not probe the entire parameter space, $\sqrt{s} \sim 100$ TeV will.

The DM-quarks interactions are mediated by a SM particle (Z or H)



DM coupled to the Z

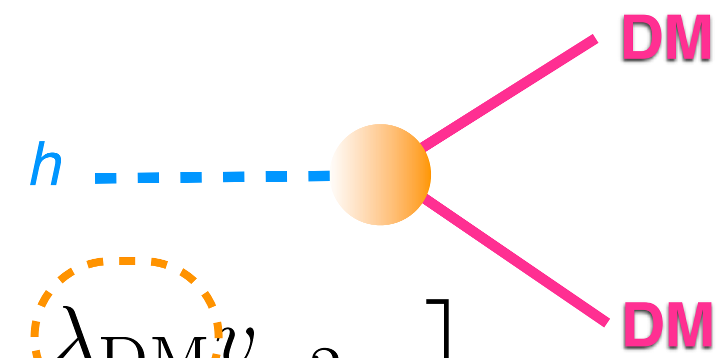
$$\mathcal{L} = -Z_\mu \frac{g_2}{\cos\theta_W}\left[\sum_f [\bar{f}\gamma_\mu(g_V^f + \gamma_5 g_A^f) f] + \sum_s g_s[s^*(i\partial_\mu s) - (i\partial_\mu s^*)s]\right]$$



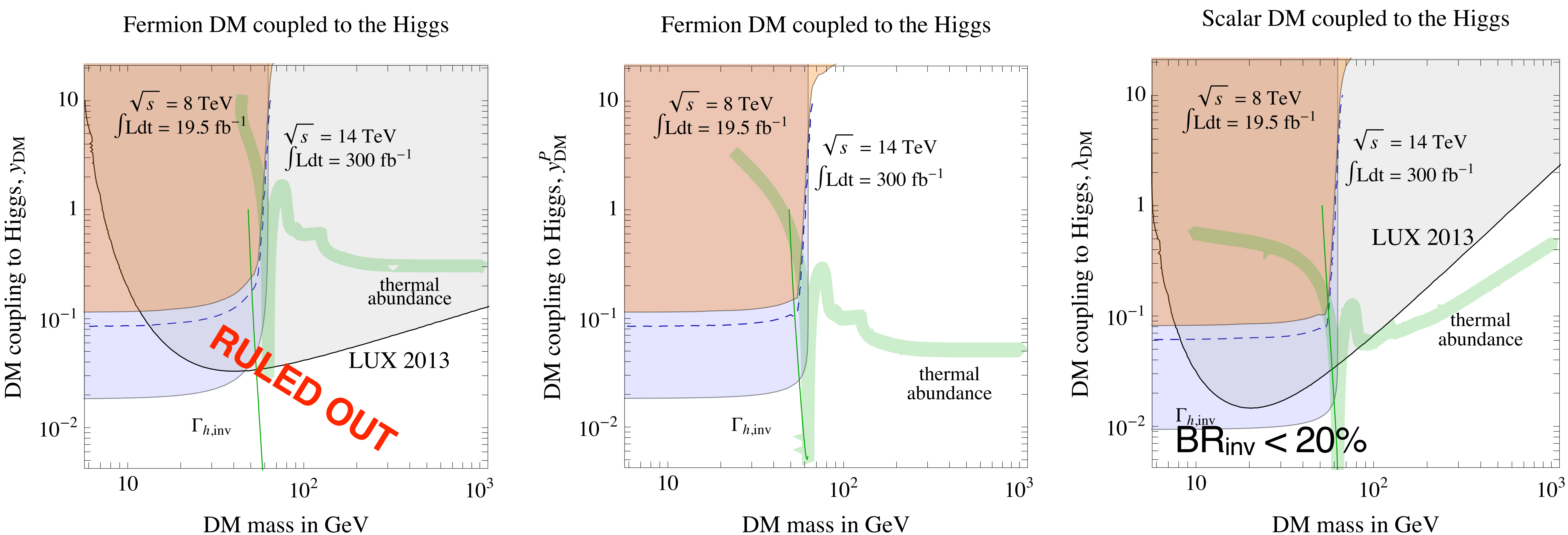
some regions still allowed for axial couplings of fermion DM (SD cross section is less constrained)

2. Annihilations Through SM Mediator

DM coupled to the Higgs



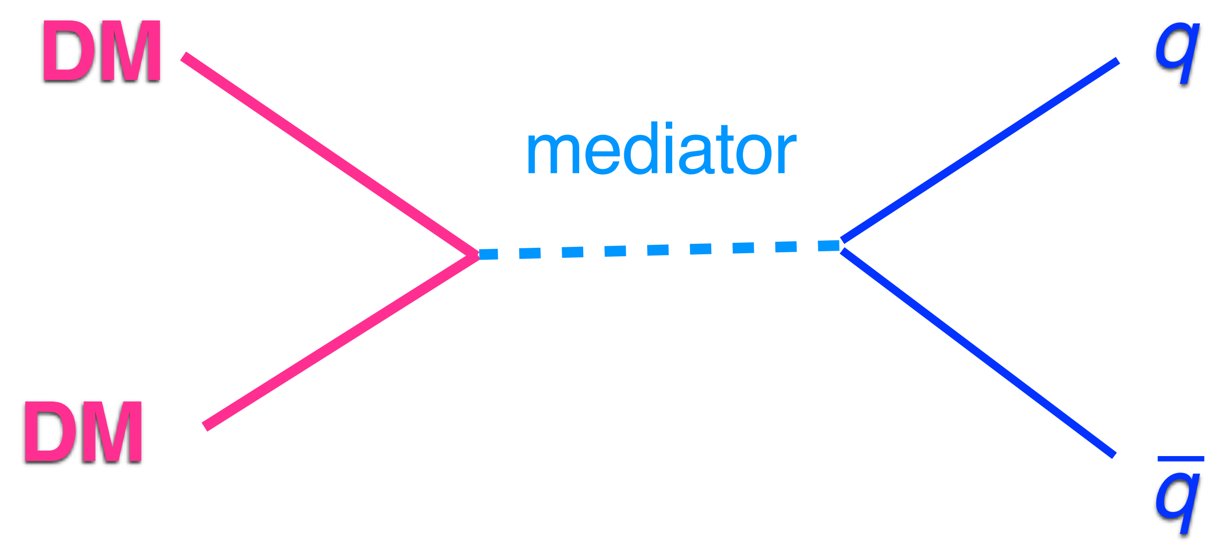
$$\mathcal{L} = -h\frac{1}{\sqrt{2}}\left[\sum_f y_f \bar{f} f + \bar{\psi}_{\rm DM}\left(y_{\rm DM} + i y^P_{\rm DM}\gamma_5\right)\psi_{\rm DM} + \frac{\lambda_{\rm DM} v}{2} s^2_{\rm DM}\right]$$



some regions still allowed for scalar DM (M>100 GeV)

and fermion DM with axial couplings

in the early Universe:
DM annihilations with s-channel exchange of a mediator



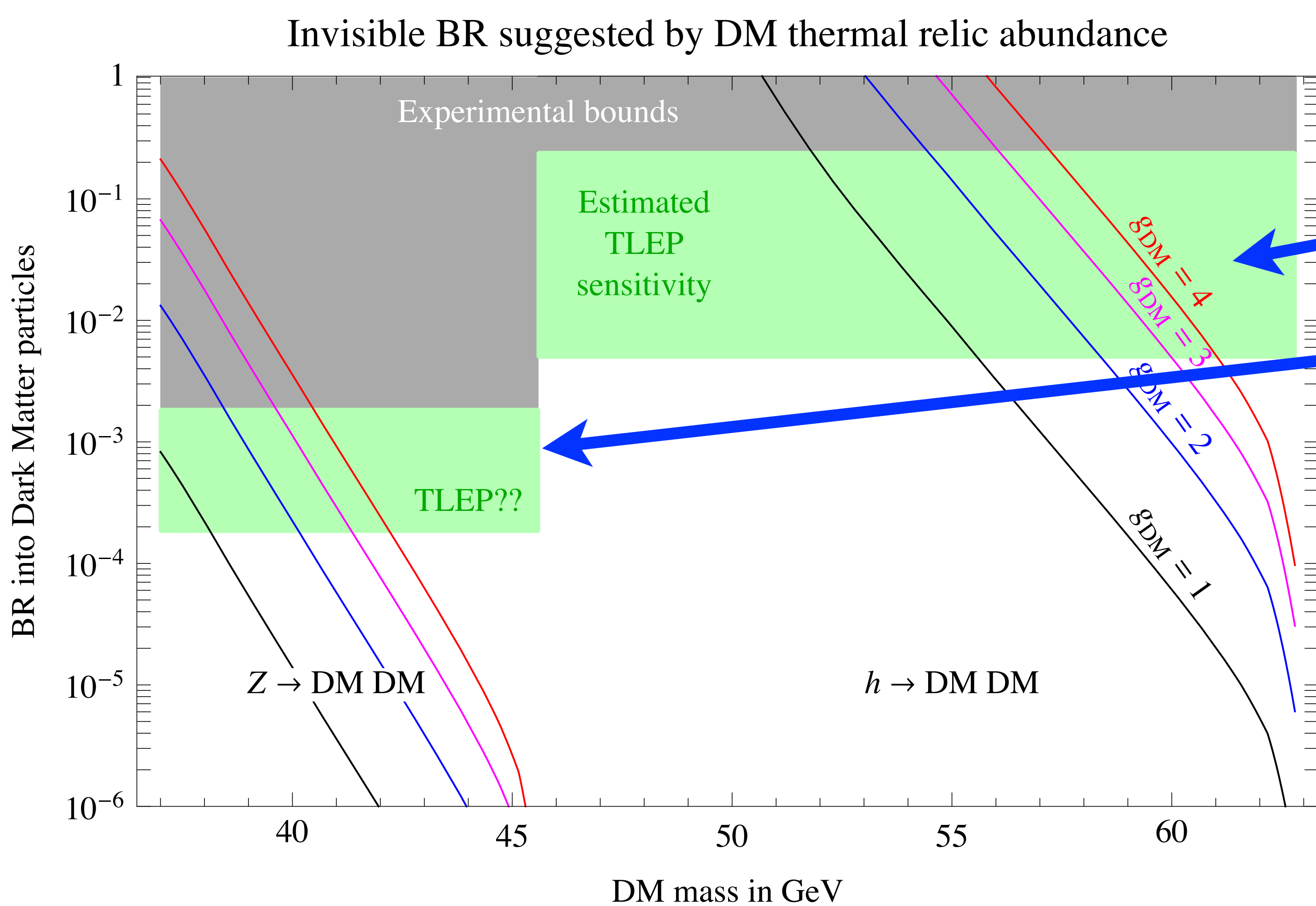
Near resonance ($M_{\rm med} - 2M_{\rm DM} \lesssim 2\Gamma_{\rm med\to DM}$), the annihilation cross section is driven by the on-shell term, which is model-independent (Breit-Wigner)

The relic abundance is determined model-independently by the width: $\Gamma_{\rm med\to DM}$

DM freezes out via decays

Simple situation when the mediator is Z or H.

Curves for correct DM relic abundance:



invisible BR

DM mass

room for improvement, exploring invisible widths of Z and h

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

- motivation to improve on Z/h invisible BRs