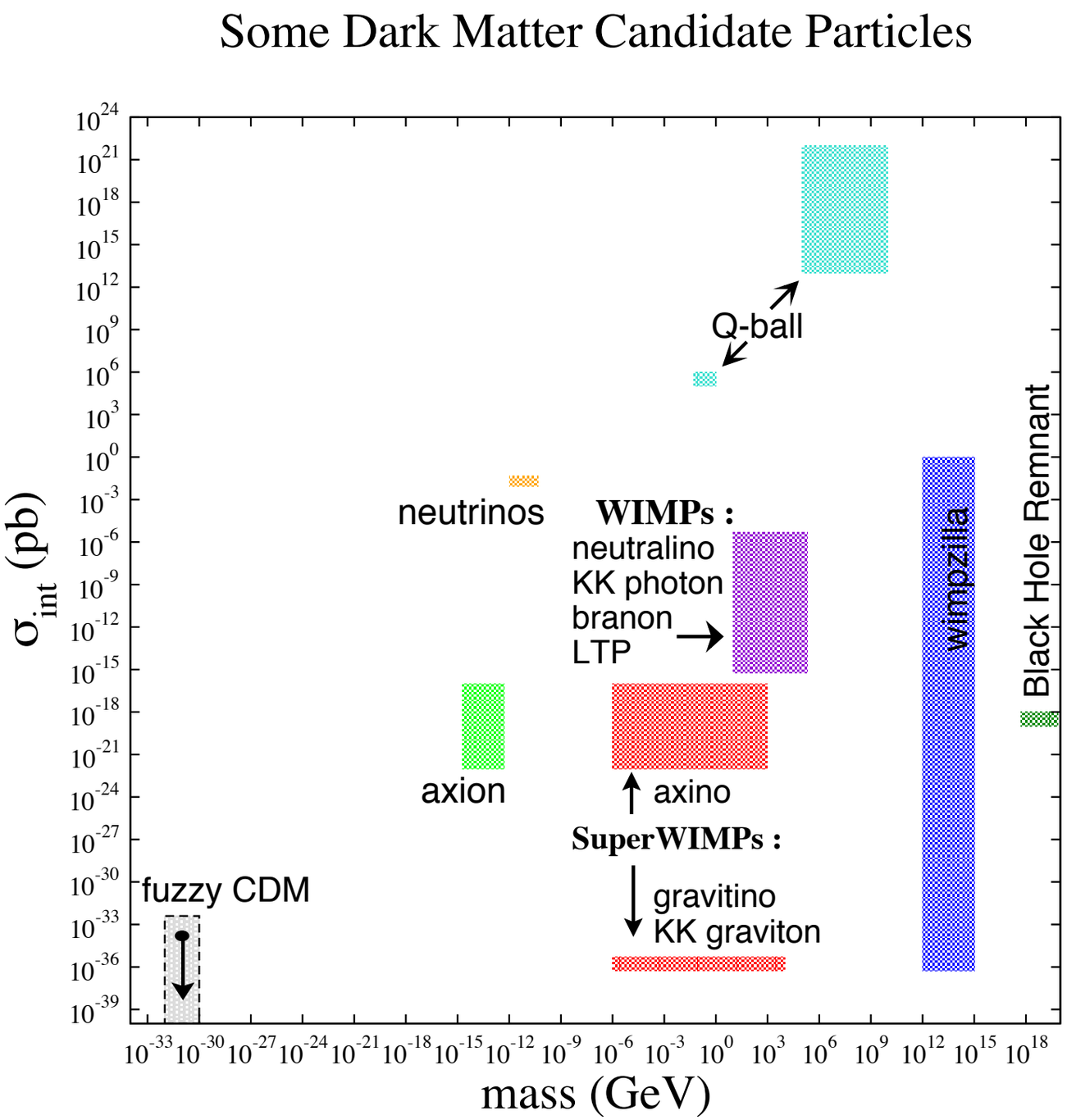
Impact of LHC monojet searches on new physics scenarios

Suchita Kulkarni
HEPHY, Vienna

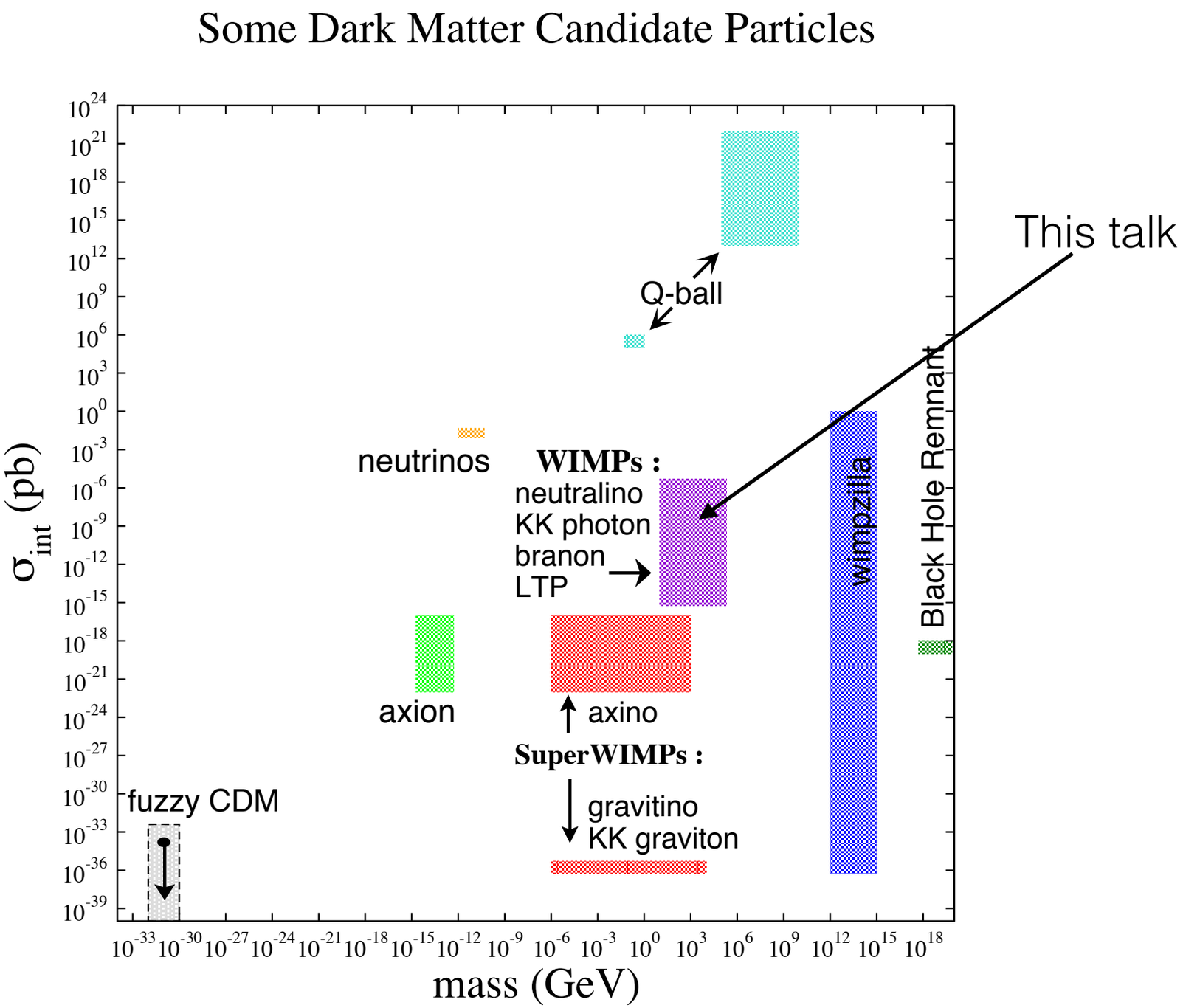
16 March 2016, UCL, Louvain, Belgium

Dark matter landscape



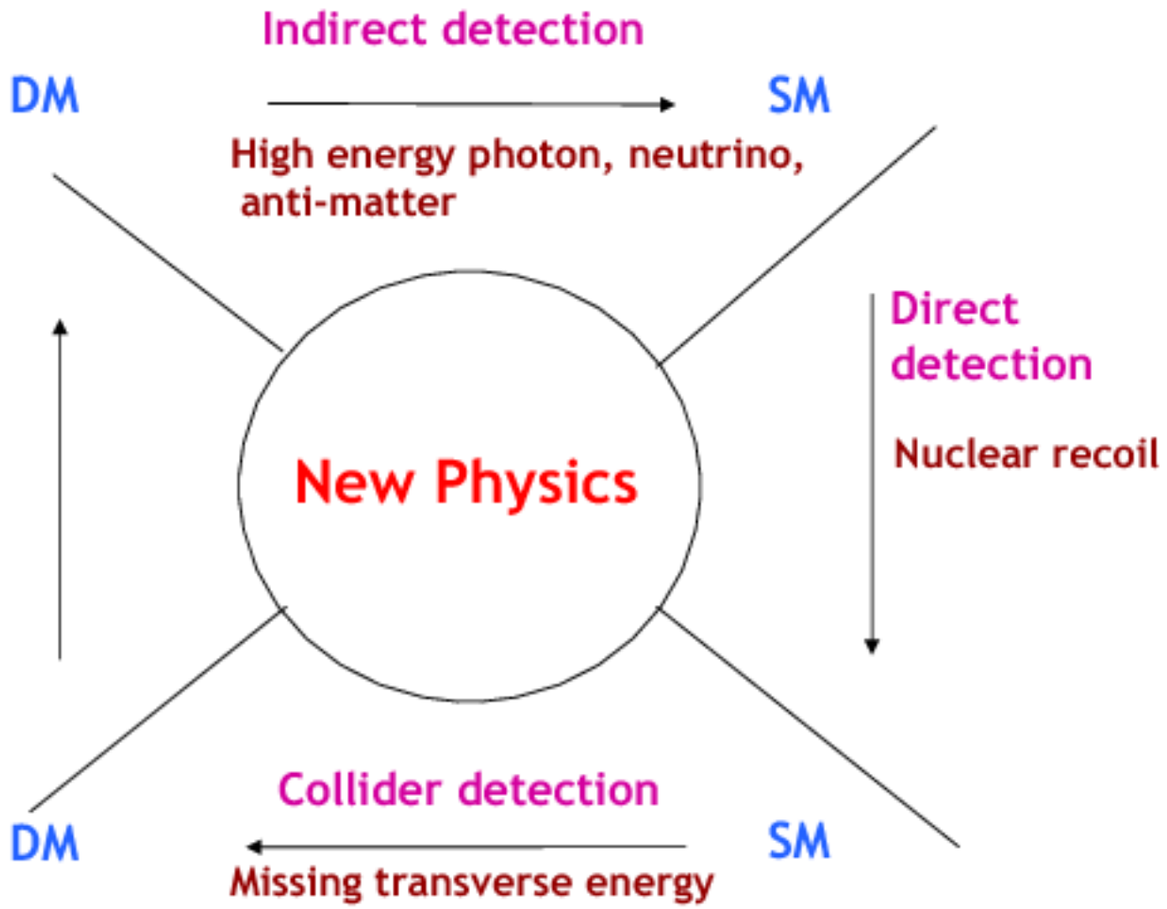
- *NB: Henceforth for this talk the term dark matter will shamelessly be substituted for WIMPs*

Dark matter landscape

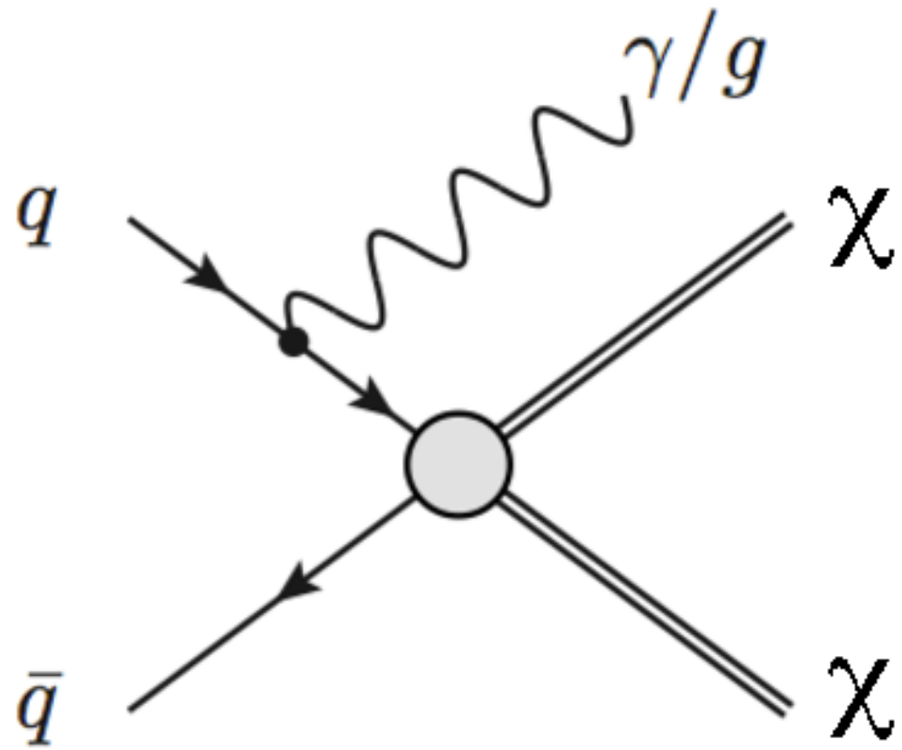


- *NB: Henceforth for this talk the term dark matter will shamelessly be substituted for WIMPs*

WIMP

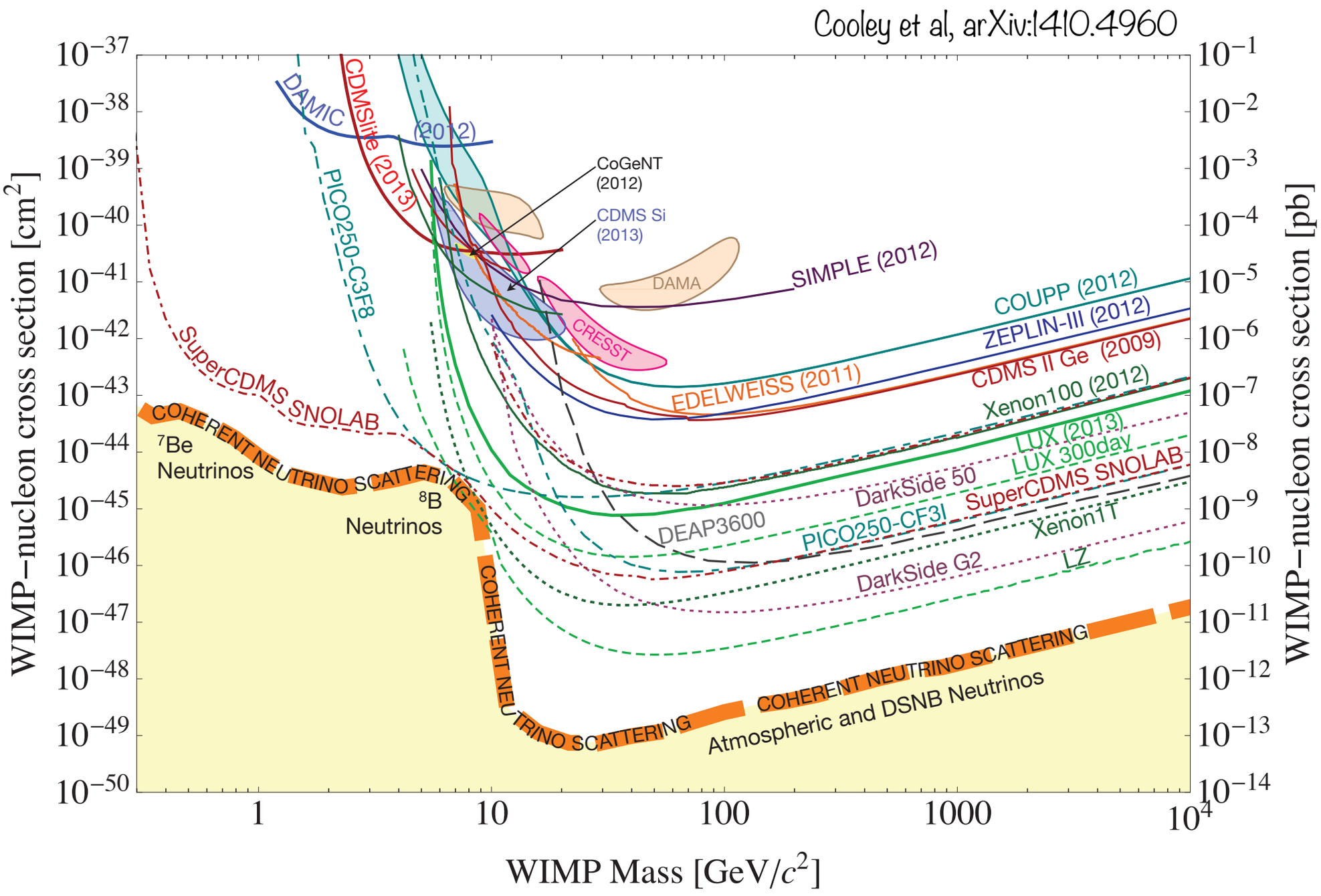

Indirect detection
DM
SM
High energy photon, neutrino,
anti-matter
Direct
detection
Nuclear recoil
New Physics
Collider detection
DM
SM
Missing transverse energy

DM @ LHC

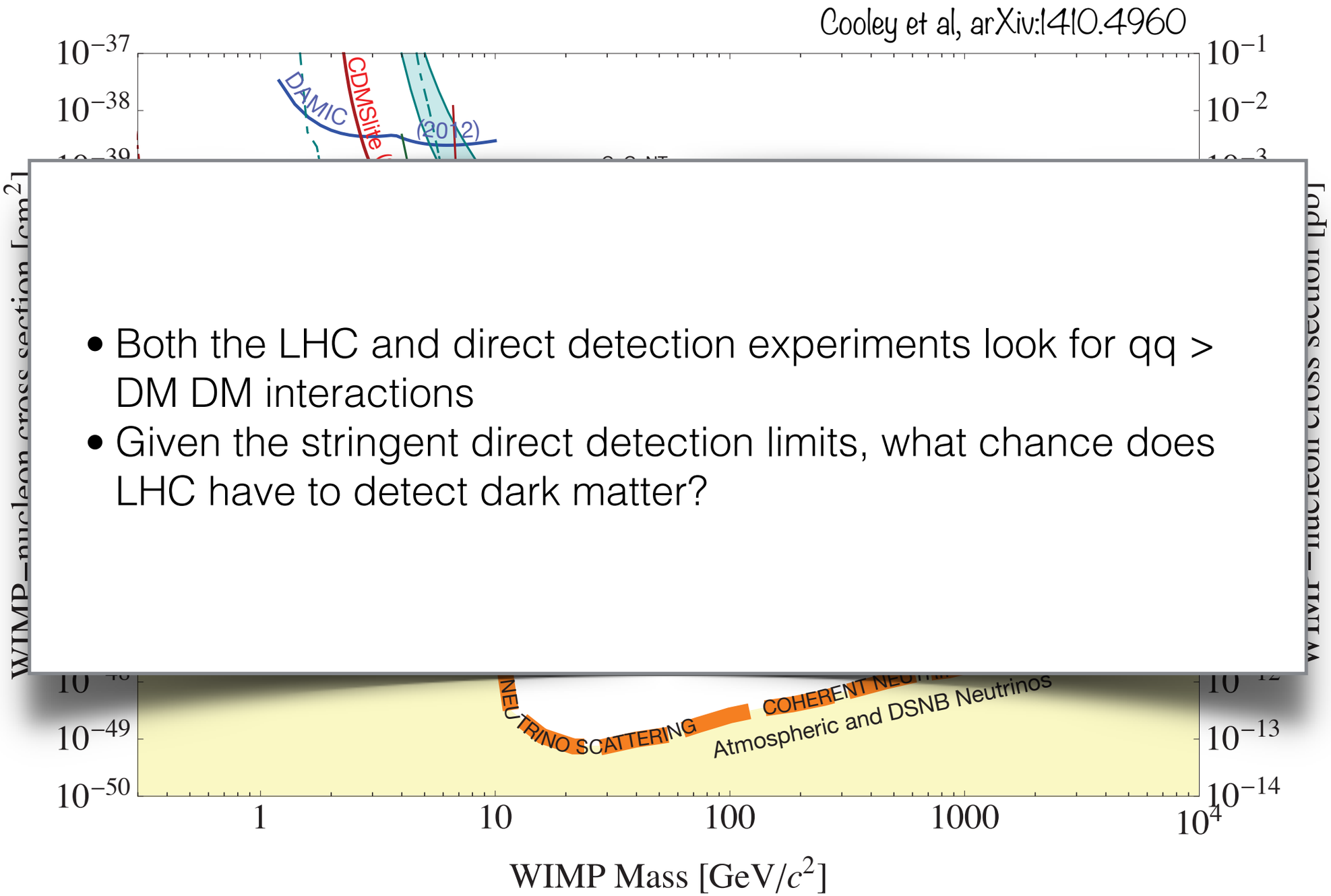


- Searches rely on emission of SM object from initial state, include mono-gamma/jet channels
- Resulting final states e.g. jets/photons/gauge bosons are required to have a high transverse momenta in order to suppress the Standard Model background

Why LHC?

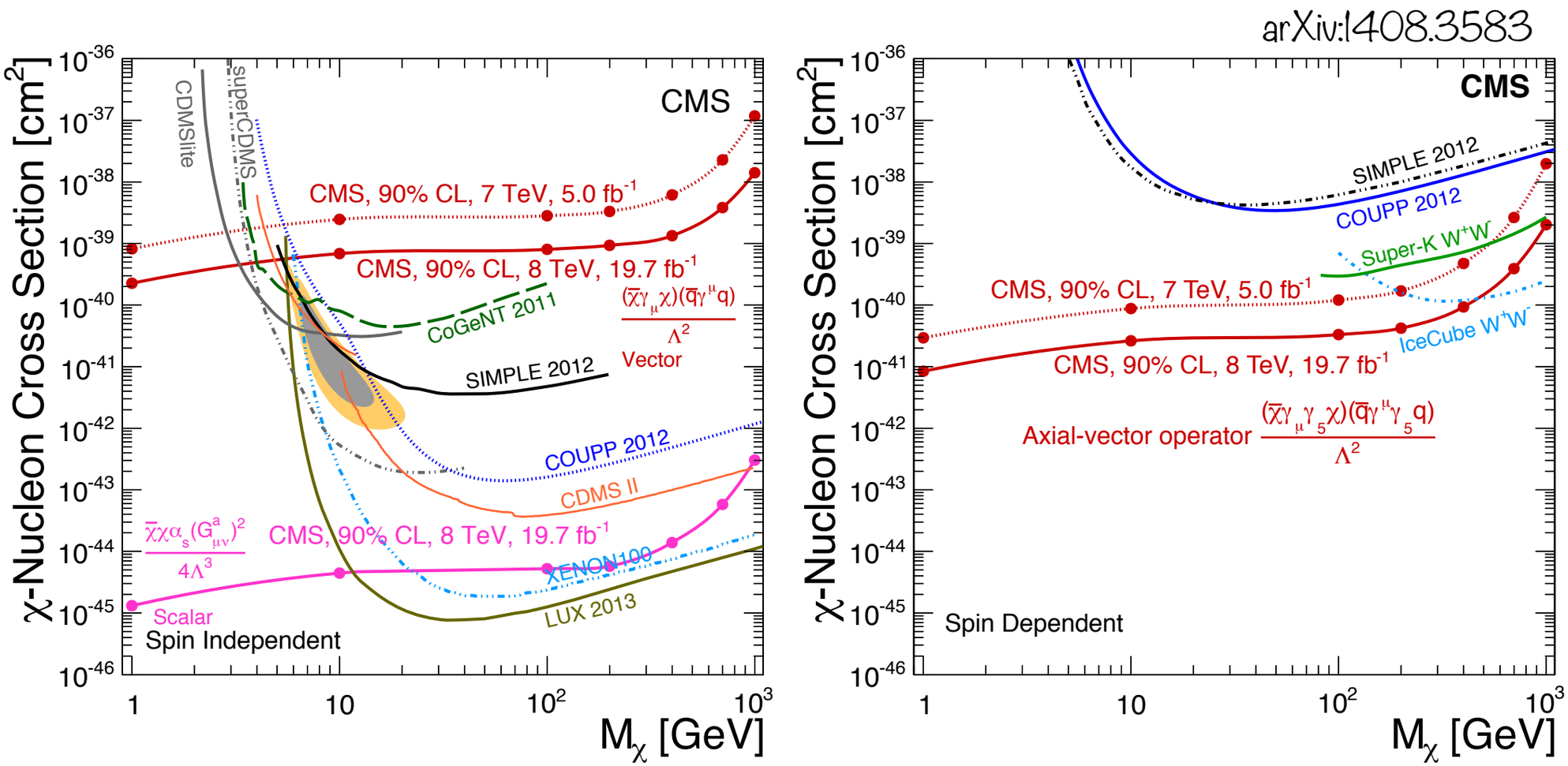

Cooley et al, arXiv:1410.4960
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
DAMIC
CDMSlite (2013)
(2012)
PICO250-C3F8
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011)
CDMS II Ge (2009)
Xenon100 (2012)
LUX (2013)
LUX 300day
DarkSide 50
SuperCDMS SNOLAB
PICO250-CF3I
Xenon1T
DEAP3600
DarkSide G2
LZ
SuperCDMS SNOLAB
COHERENT NEUTRINO SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
COHERENT NEUTRINO SCATTERING
COHERENT NEUTRINO SCATTERING
Atmospheric and DSNB Neutrinos

Why LHC?



- Both the LHC and direct detection experiments look for qq > DM DM interactions
- Given the stringent direct detection limits, what chance does LHC have to detect dark matter?

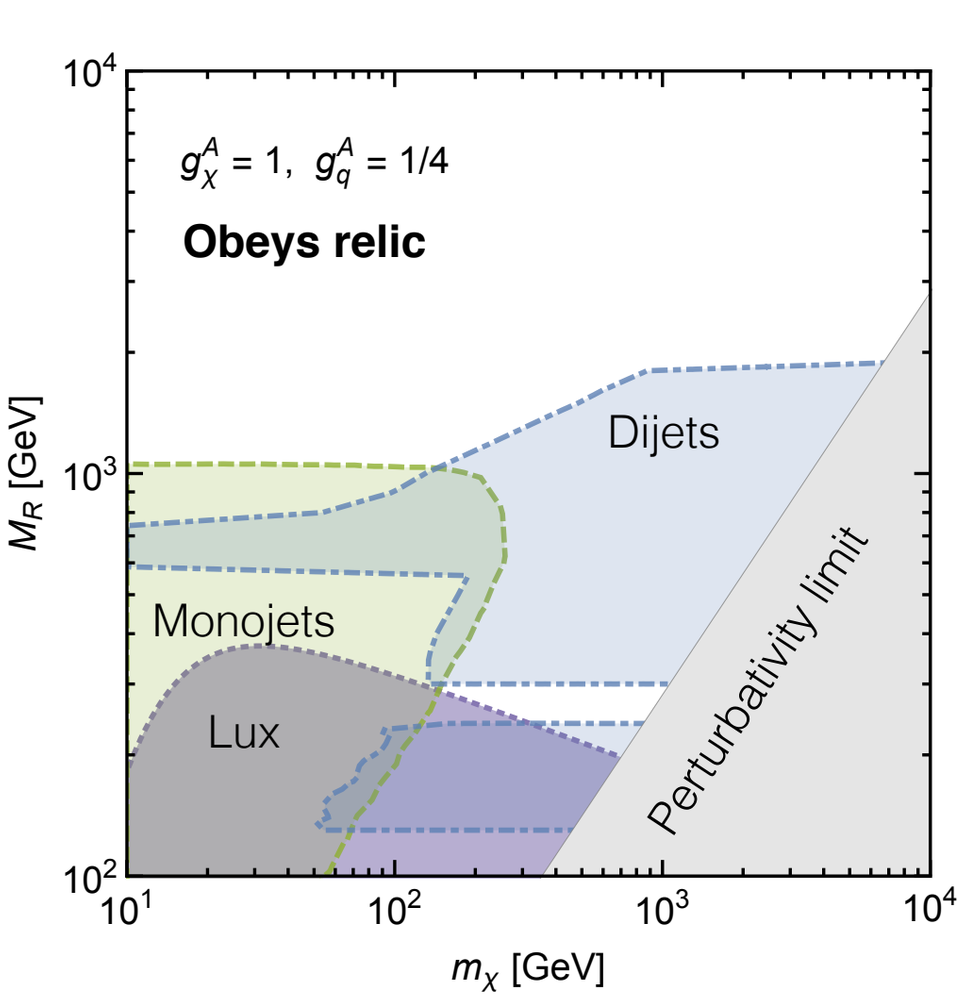
Why LHC?



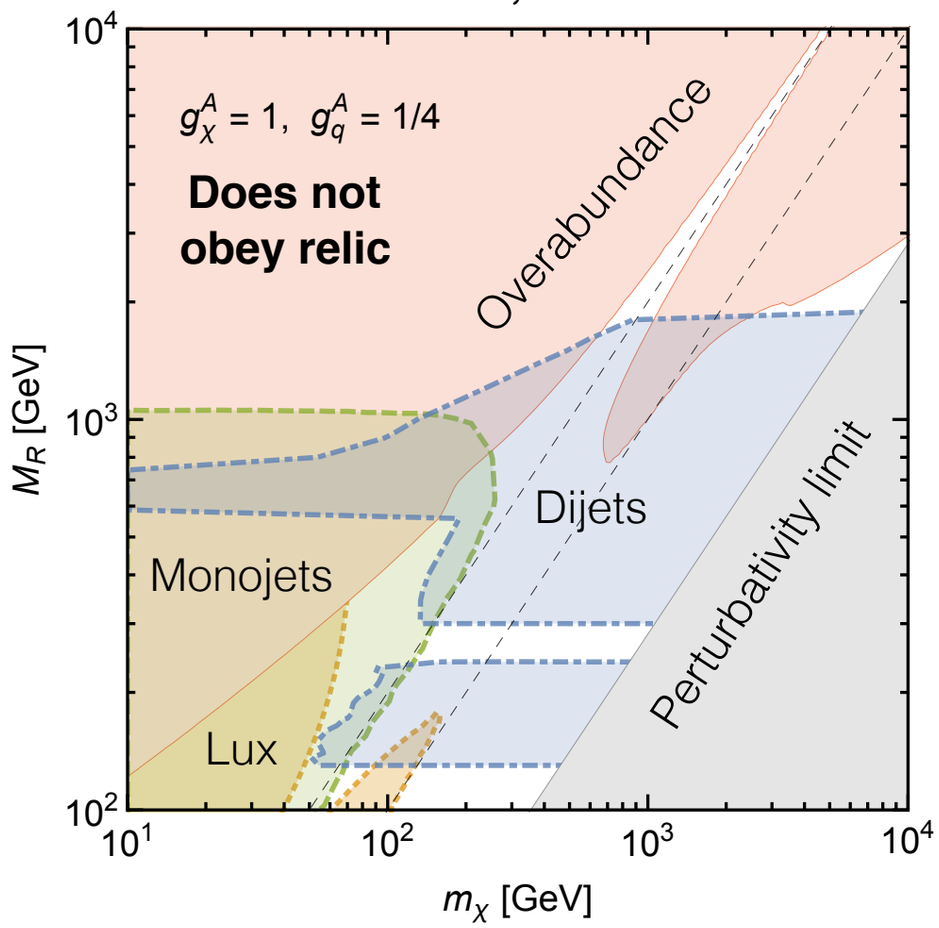
- Direct detection: spin independent limits are much stronger than spin dependent limits
- LHC: sets comparable limits for spin dependent and spin independent operators

NB: Effective operator description at the LHC is a dangerous way to set limits, interpret plots carefully

Why LHC?

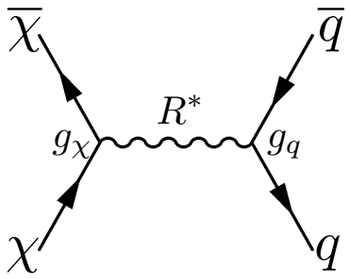


Chala et al, arXiv:1503.05916

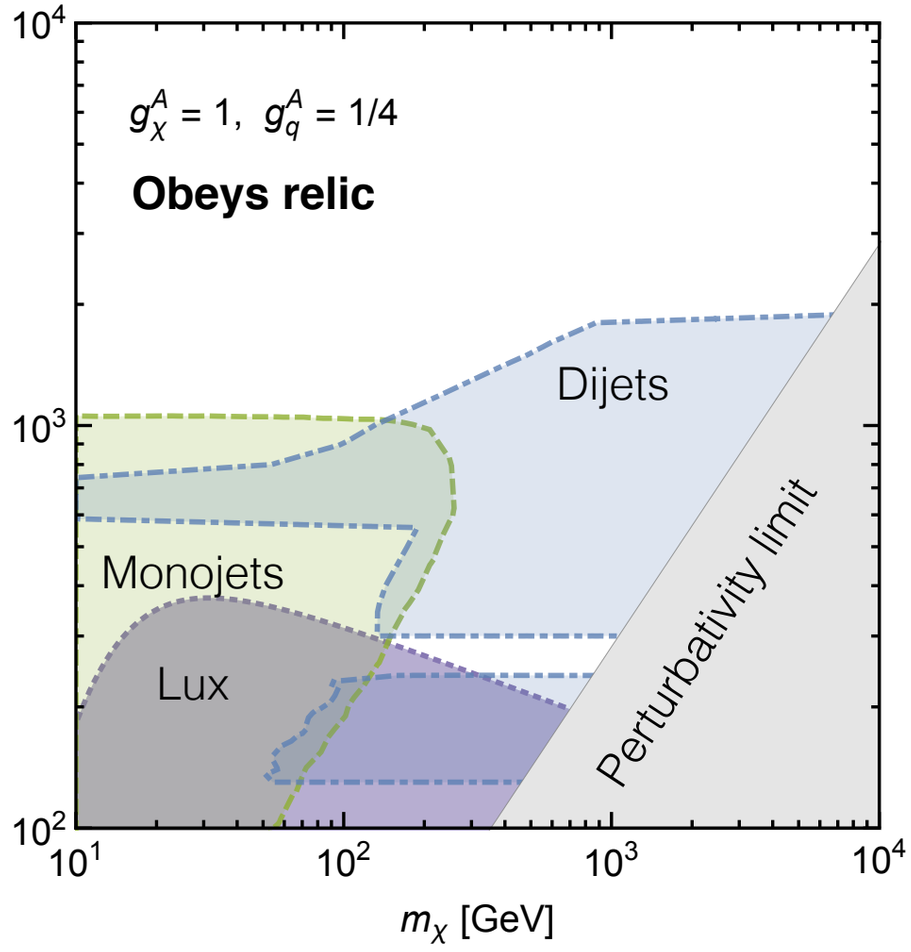


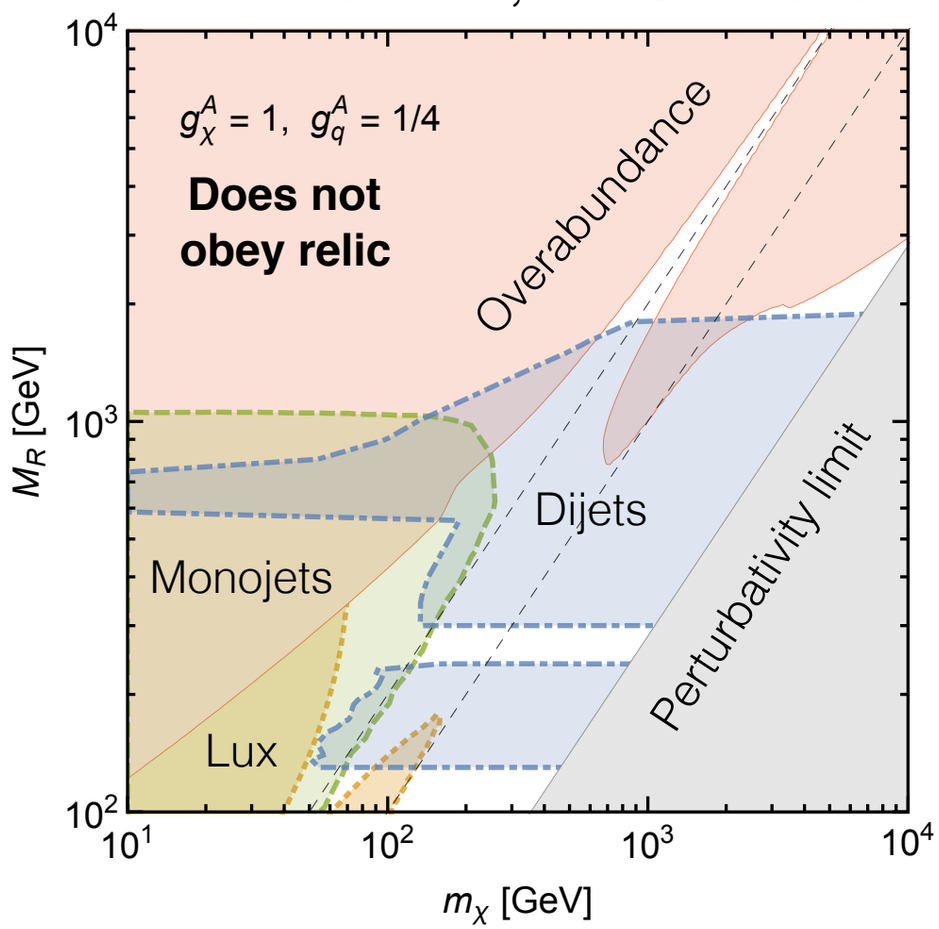
- Direct detection: Limits assume local dark matter density is the observed amount, limits get worse for under abundant dark matter
- LHC: Limits do not involve any assumption on the local dark matter density

Why LHC?



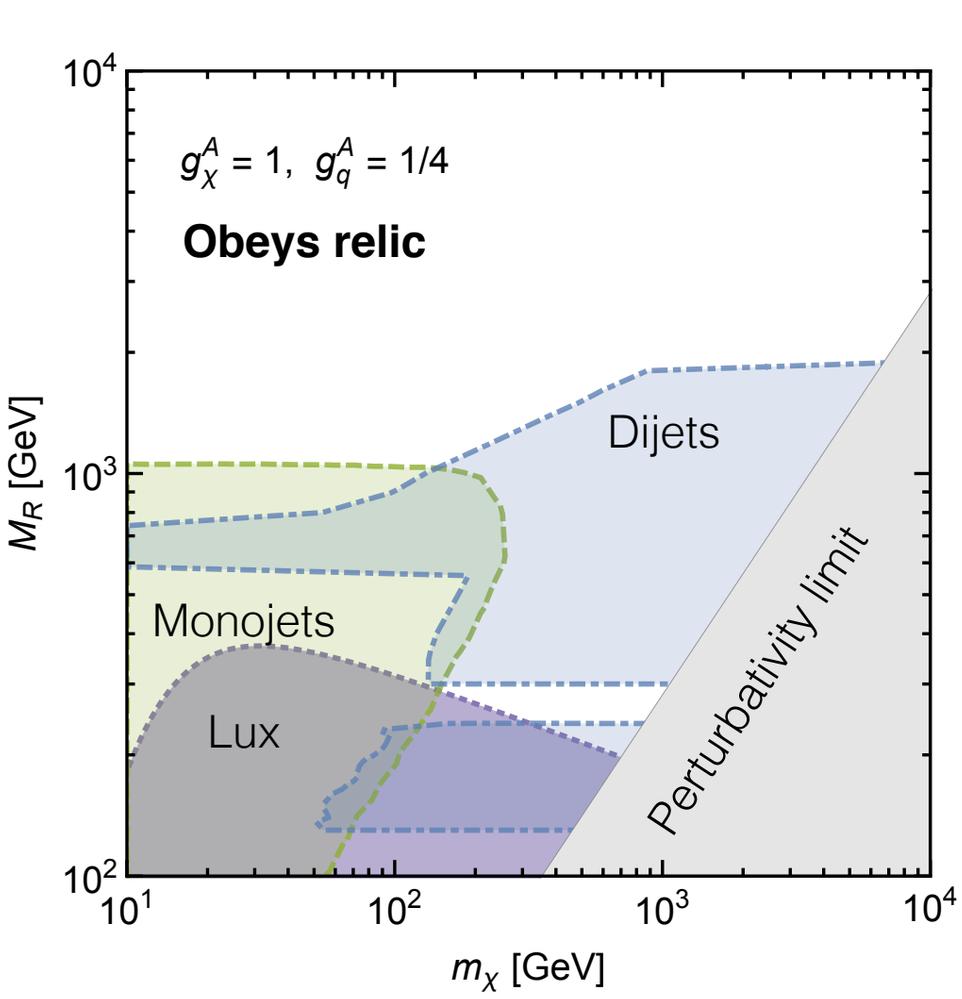
Chala et al, arXiv:1503.05916



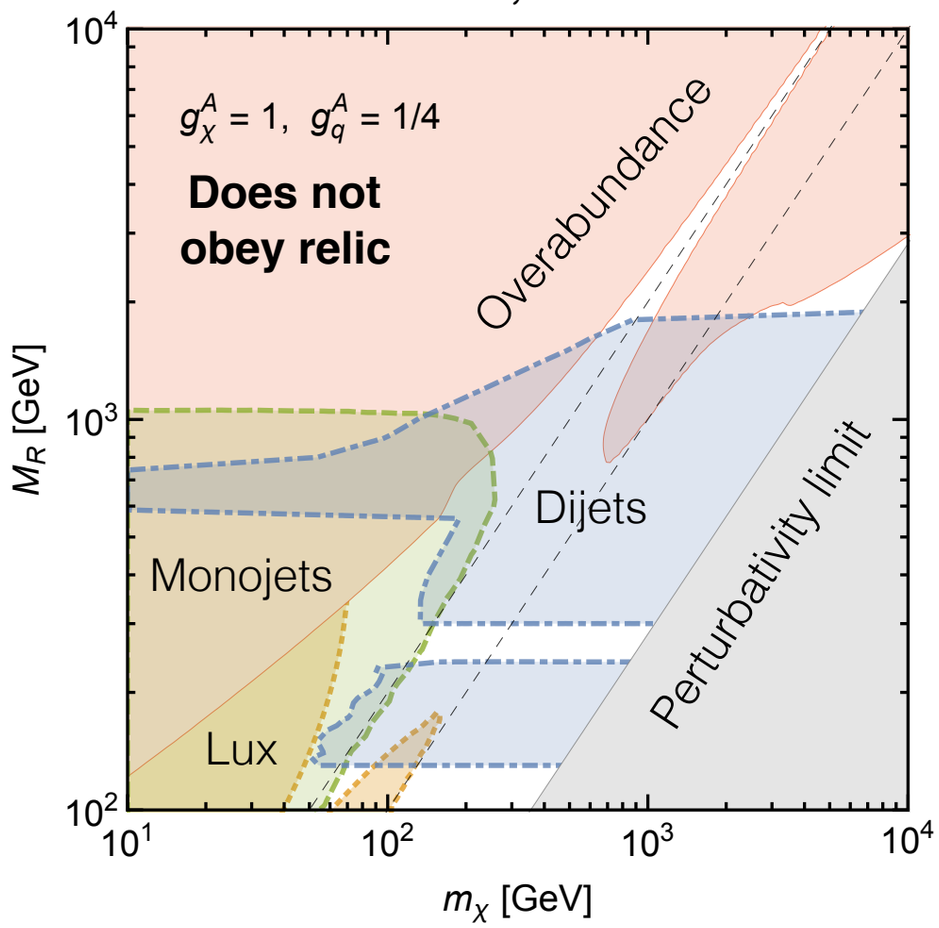


- Direct detection: Limits assume local dark matter density is the observed amount, limits get worse for under abundant dark matter
- LHC: Limits do not involve any assumption on the local dark matter density

Why LHC?

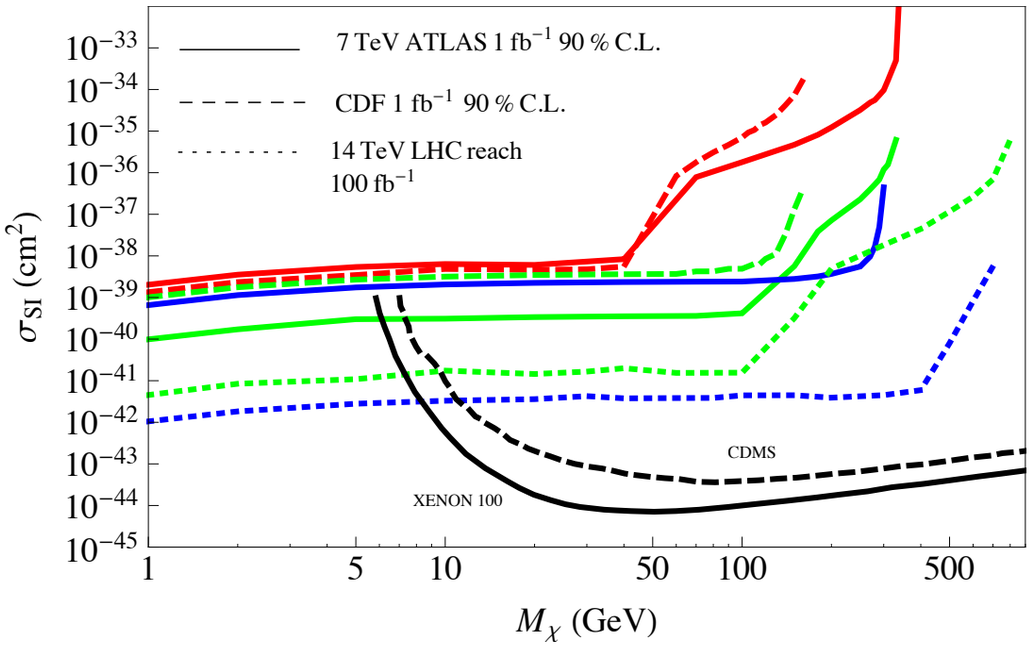


Chala et al, arXiv:1503.05916

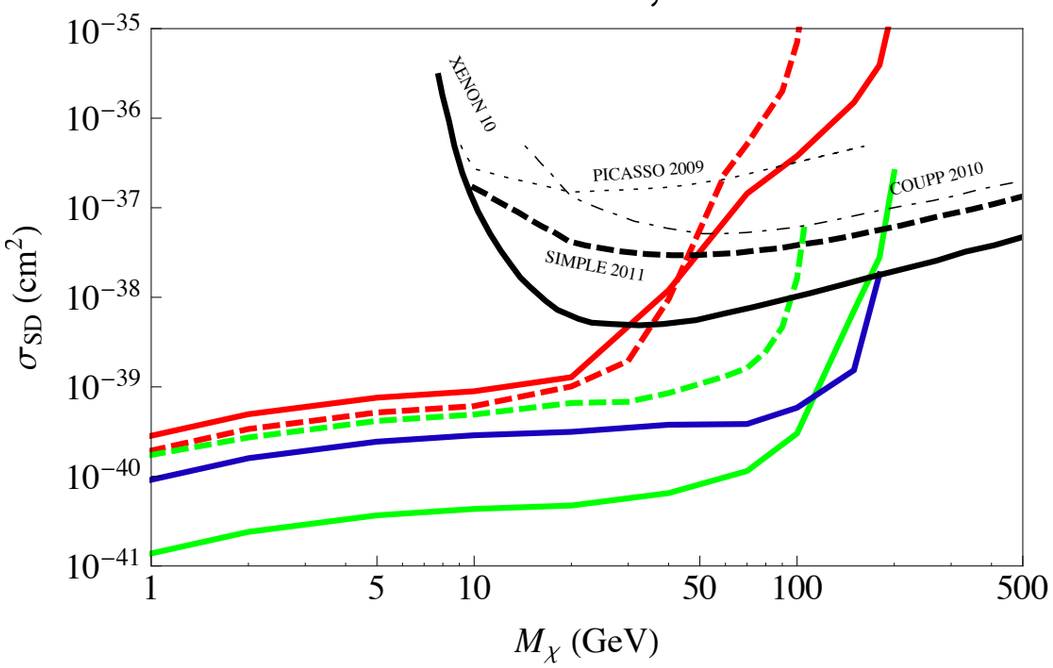


- Direct detection: Limits assume local dark matter density is the observed amount, limits get worse for under abundant dark matter
- LHC: Limits do not involve any assumption on the local dark matter density

Why LHC?

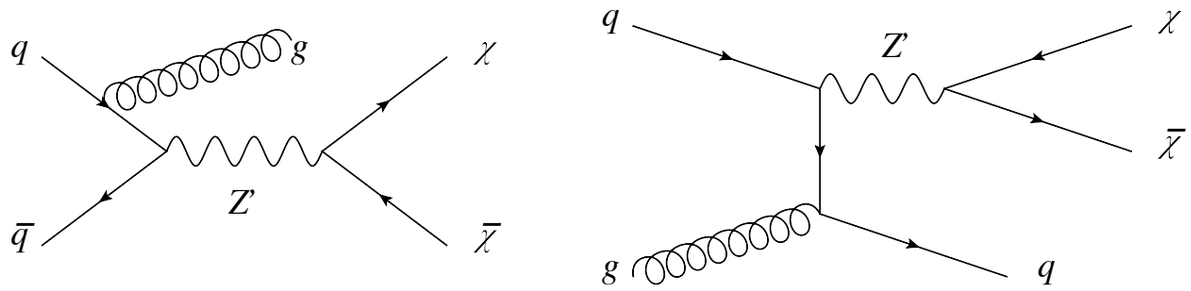


An et al, arXiv:1202.2894

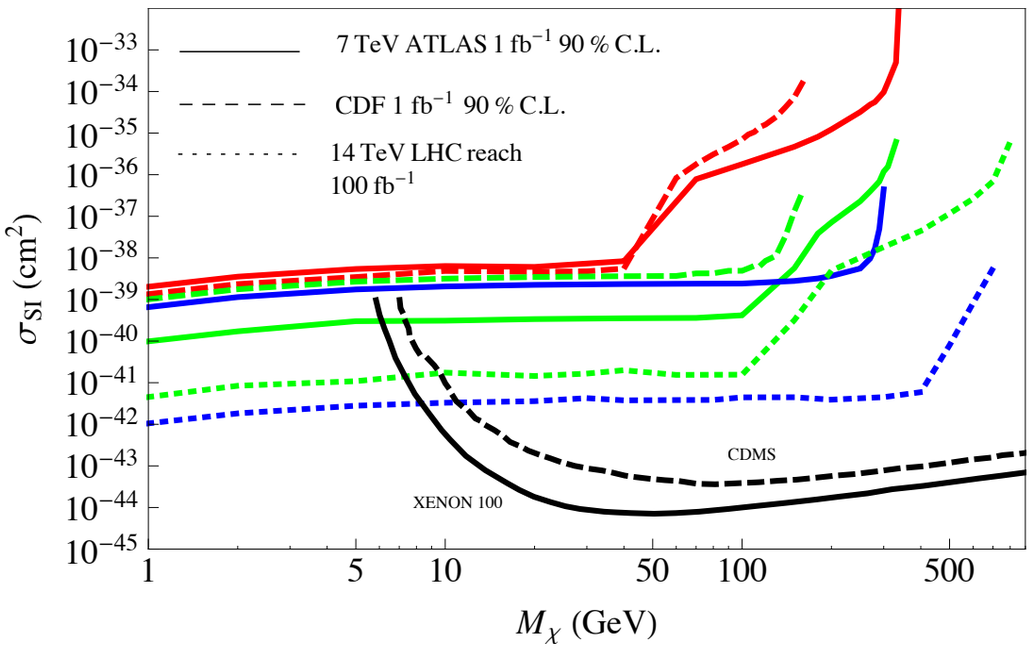


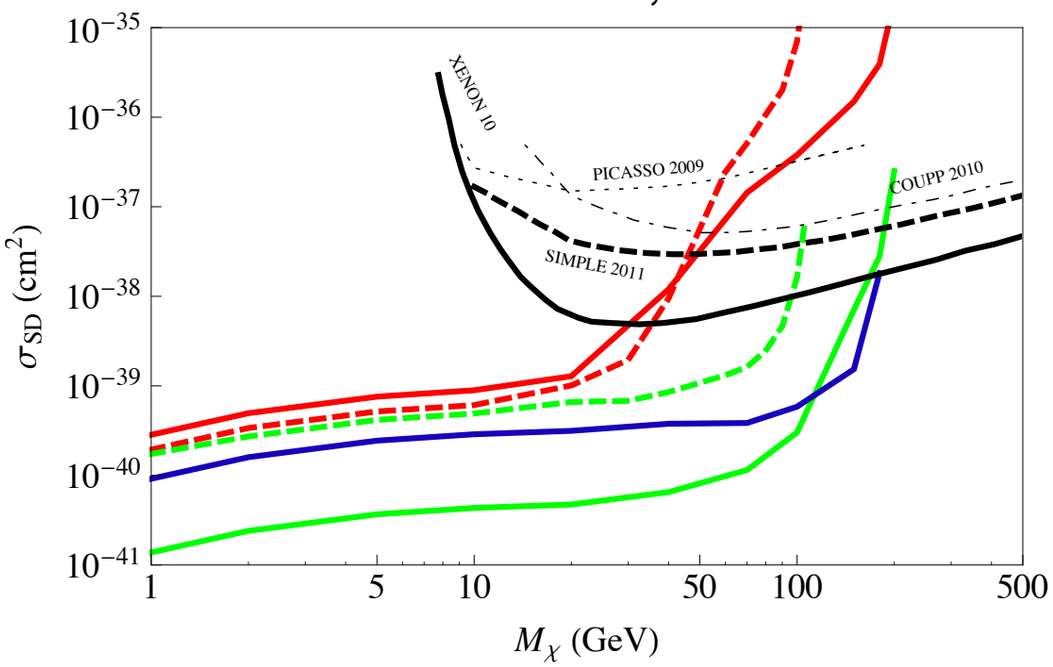
- Direct detection: Limits quickly get worse for light dark matter (CRESST not featured on the plots)
- LHC: Limits are reasonably strong even for very light dark matter

Why LHC?



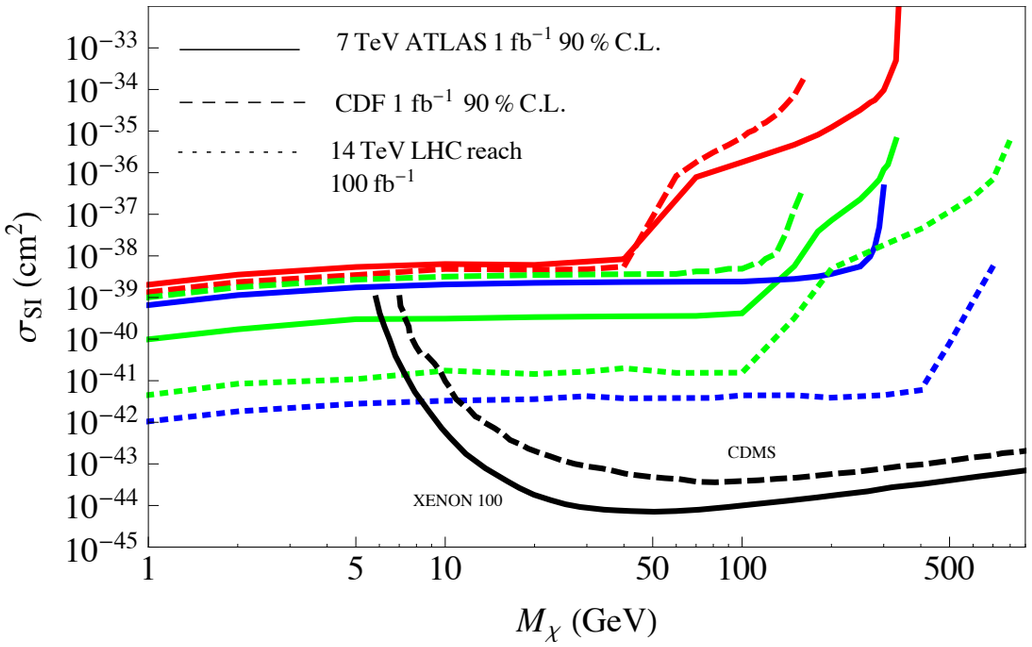
An et al, arXiv:1202.2894



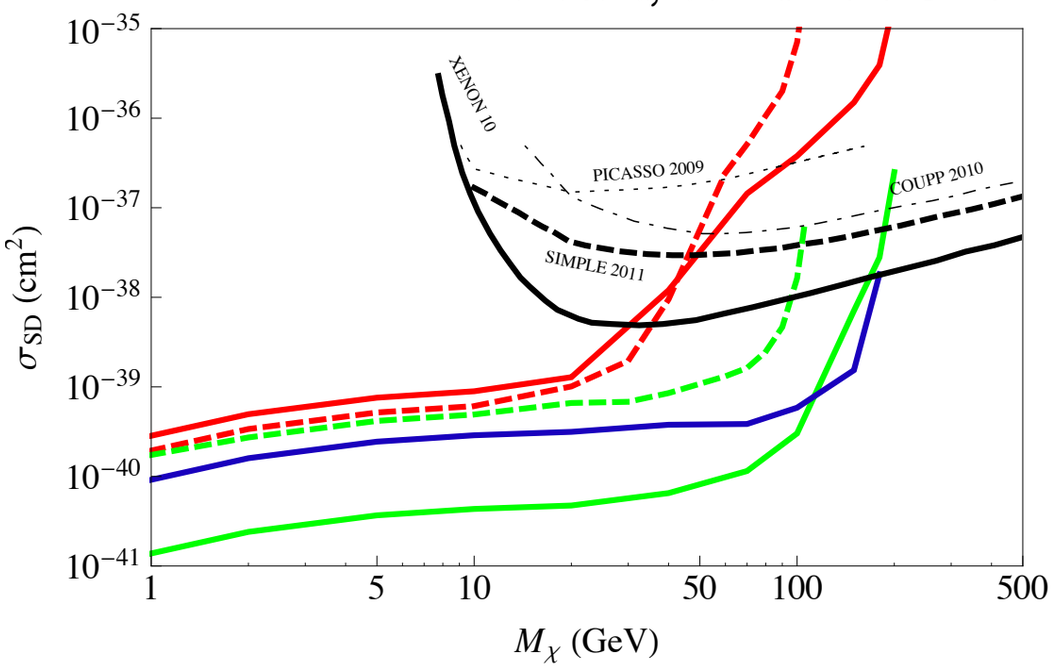


- Direct detection: Limits quickly get worse for light dark matter (CRESST not featured on the plots)
- LHC: Limits are reasonably strong even for very light dark matter

Why LHC?

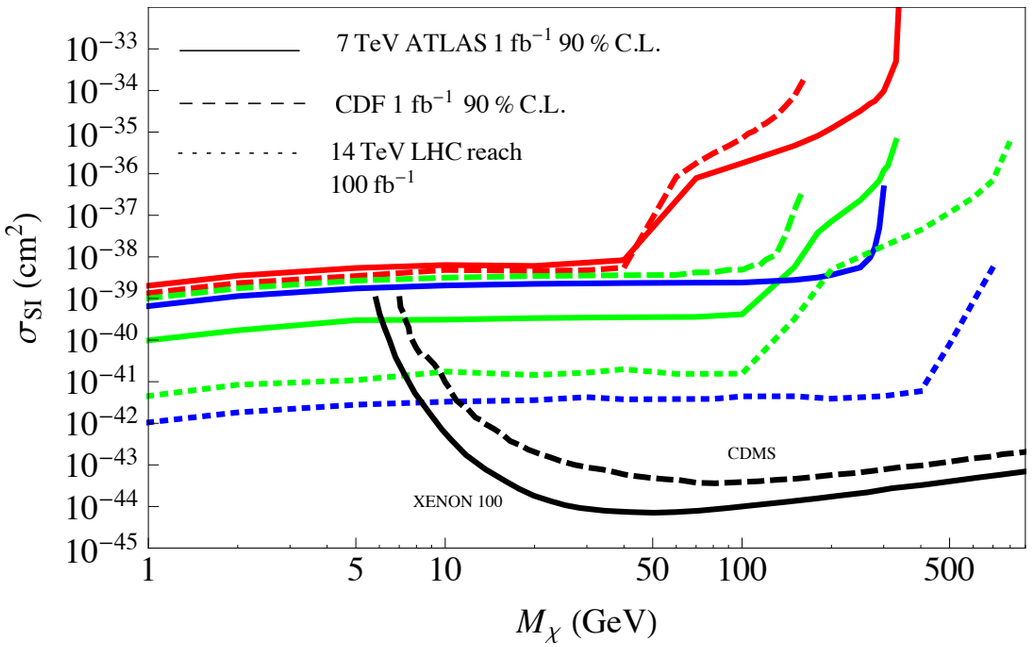


An et al, arXiv:1202.2894

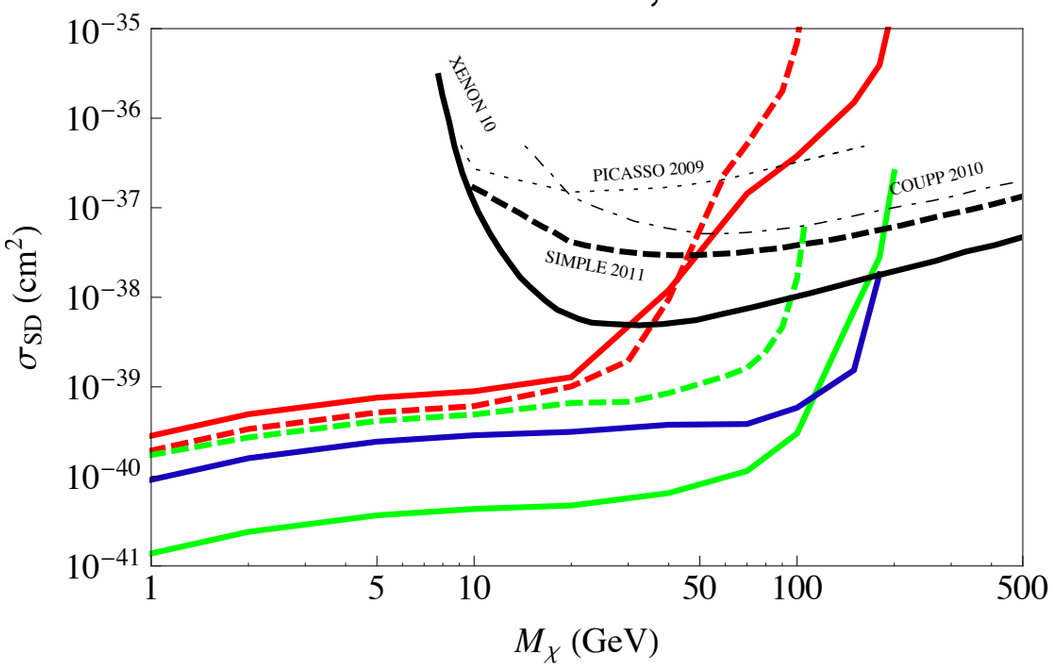


- Direct detection: Limits quickly get worse for light dark matter (CRESST not featured on the plots)
- LHC: Limits are reasonably strong even for very light dark matter

Why LHC?



An et al, arXiv:1202.2894



- Direct detection: Limits do well even for an off-shell mediator
- LHC: Limits get worse quickly once mediator goes off-shell

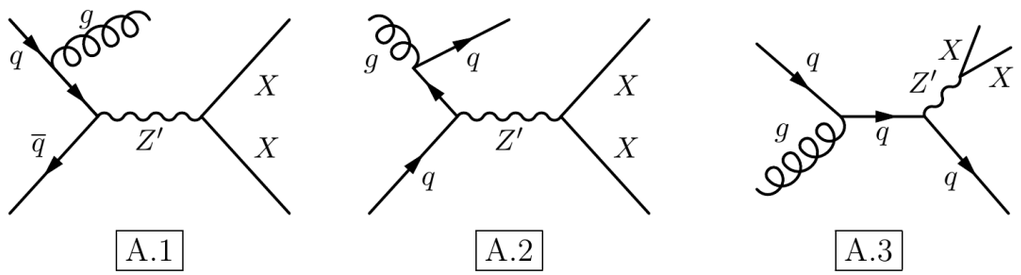
It does not have to be…

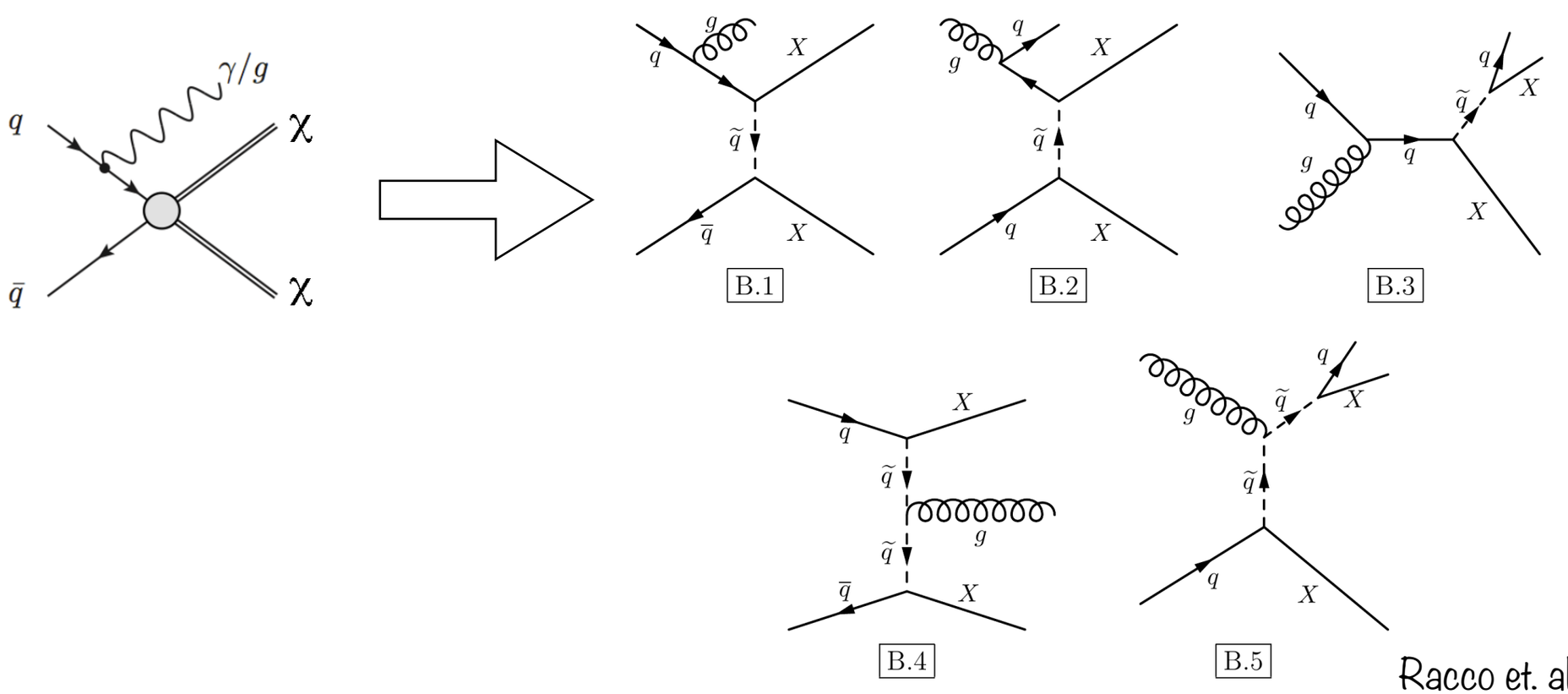
- If dark matter relic is driven by co-annihilations, then q q > DM DM interactions can be negligible, both dark matter searches at the LHC and direct detection experiments can loose
- WIMP is one of the many possible dark matter candidates, q q > DM DM one of the many possible dark matter interactions
- We are exploring a tiny but important part of landscape

NB: I have been unfair to indirect detection searches, the arguments I gave can also be extended to include indirect detection searches

Monojet searches

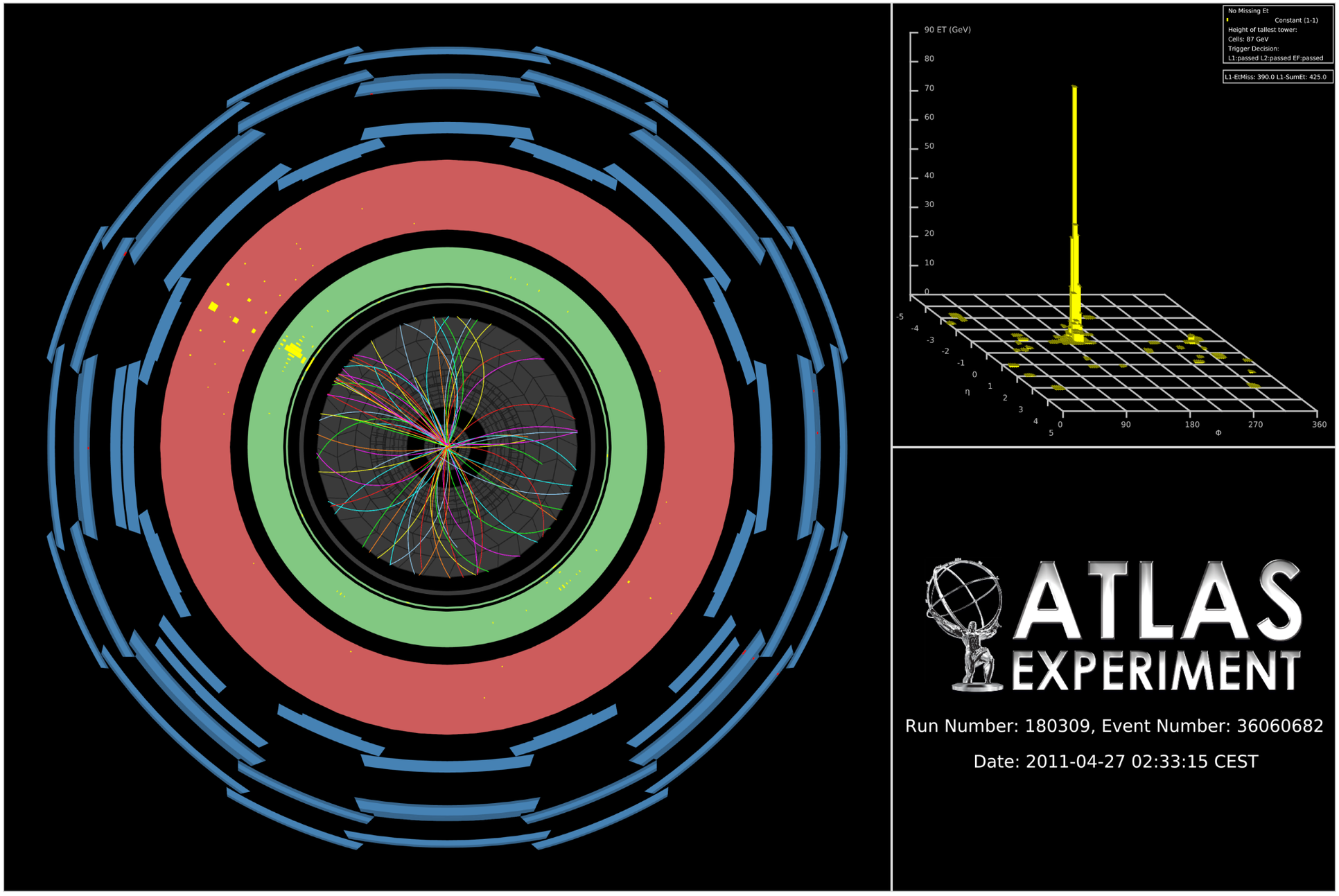
- Emission of a jet from initial state quarks, propagator or vertex e.g. from particles running in the loop
- NB: dark matter itself does not emit a jet





Racco et. al.arXiv: 1502.04701

Monojet searches



- Typical signature of monojet events: a high pT jet recoiling off MET

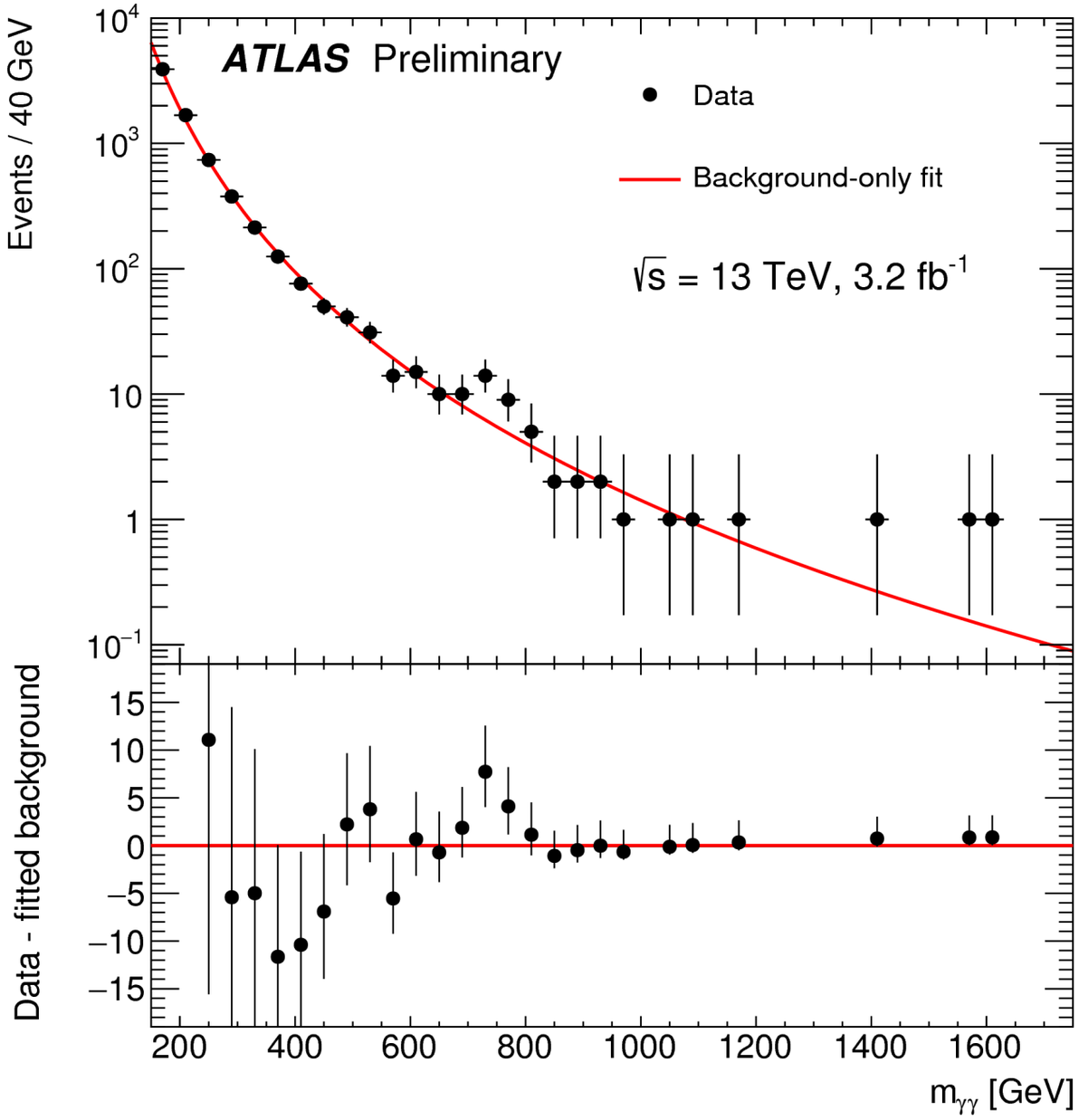
Test cases

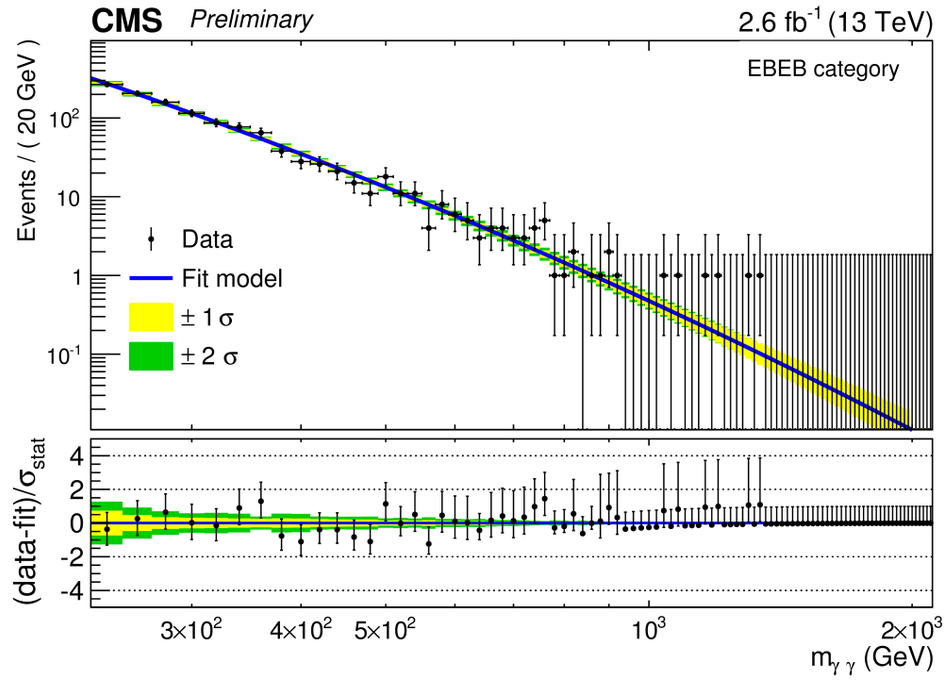
- What do the monojet searches tell us about the dark matter motivated explanations of 750 GeV diphoton excess?
- How well do these searches constrain momentum dependent couplings of dark matter?

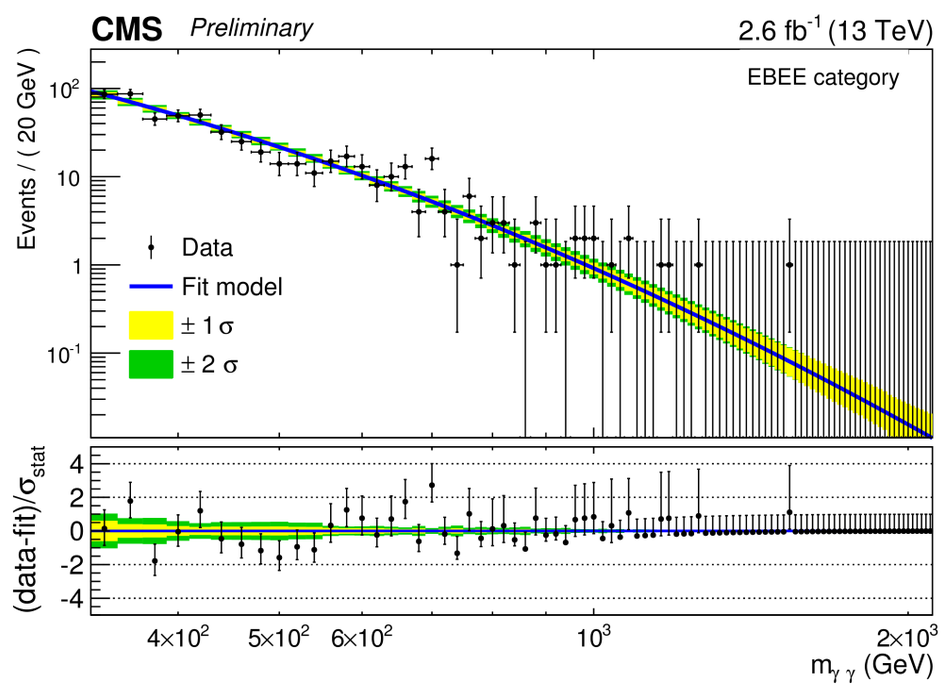
Test case: I

Explaining the 750 GeV diphoton excess with dark matter

The excess







ATLAS-CONF-2015-081,

CMS-PAS-EXO-15-004

The excess

ATLAS

$$\mathcal{L} = 3.2\,\mathrm{fb}^{-1}$$

$M \simeq 750\mathrm{GeV}$ $\Gamma \sim 45\mathrm{GeV}$

$\sim 14\,\mathrm{events}$ $3.9\sigma\,\mathrm{local}$ $2.3\sigma\,\mathrm{including\,LEE}$

CMS

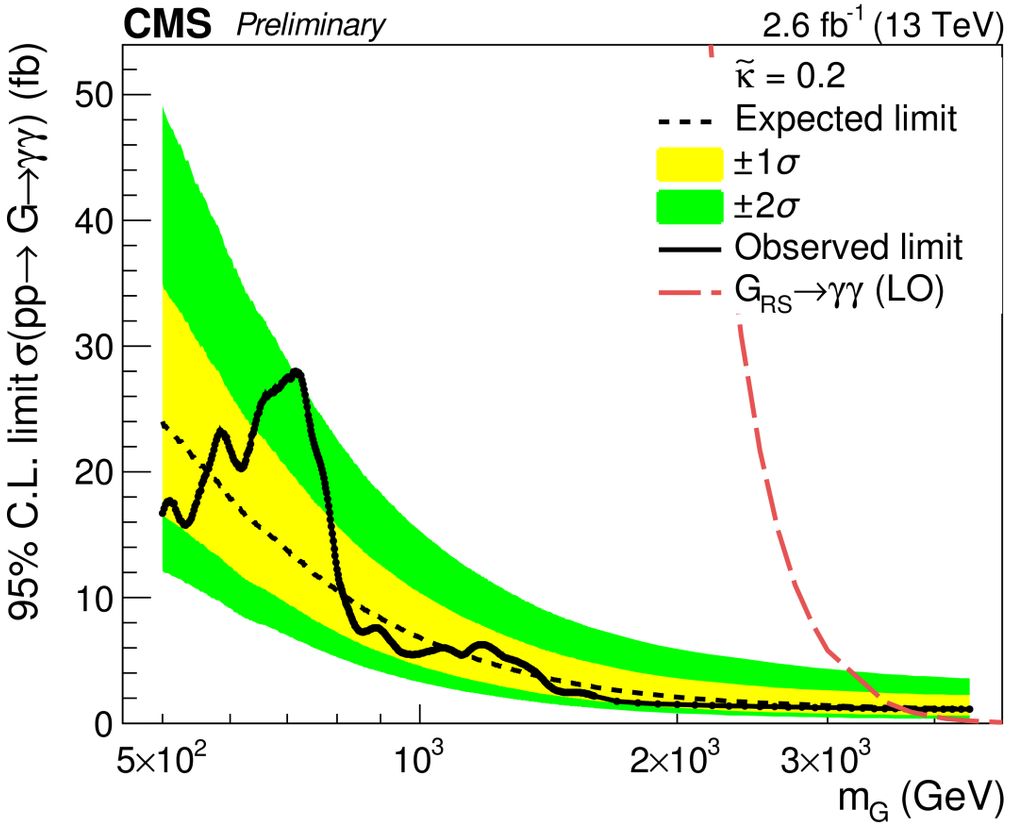
$$\mathcal{L} = 2.6\,\mathrm{fb}^{-1}$$

$M \simeq 760\,\mathrm{GeV}$ $\mathrm{narrow\,width\,favored}$

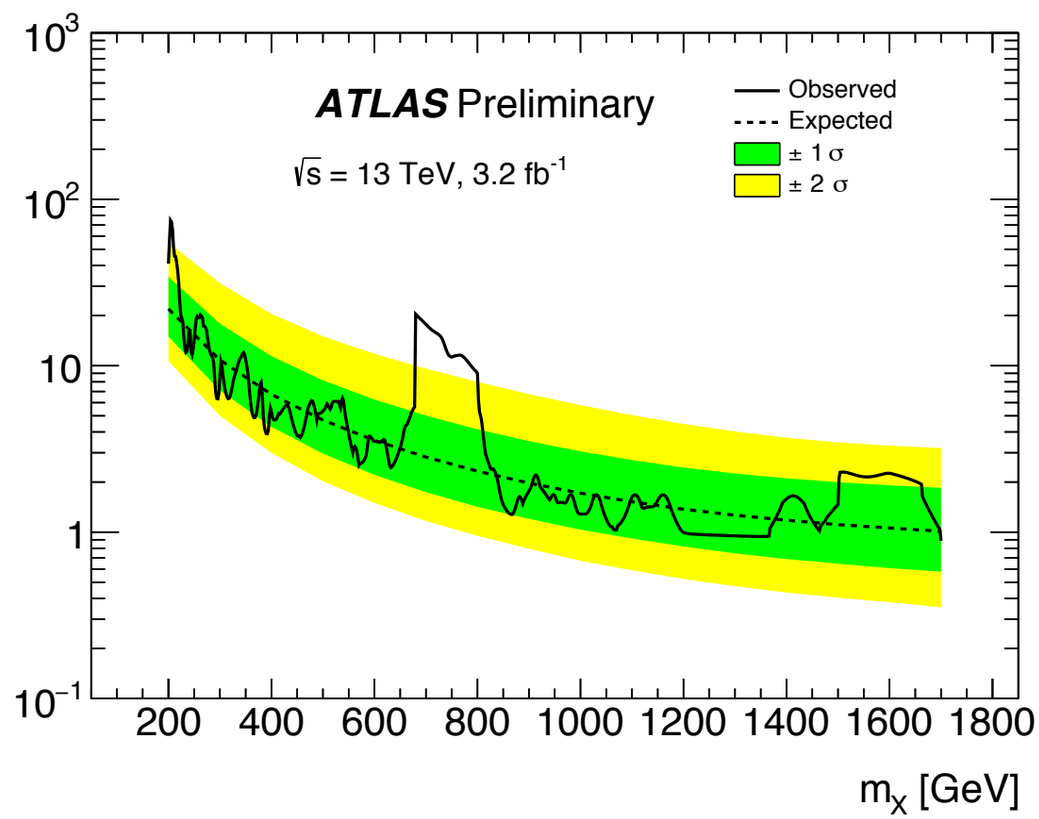
$\sim 10\,\mathrm{events}$ $2.6\sigma\,\mathrm{local}$ $1.2\sigma\,\mathrm{including\,LEE}$

The searches

CMS-PAS-EXO-15-004

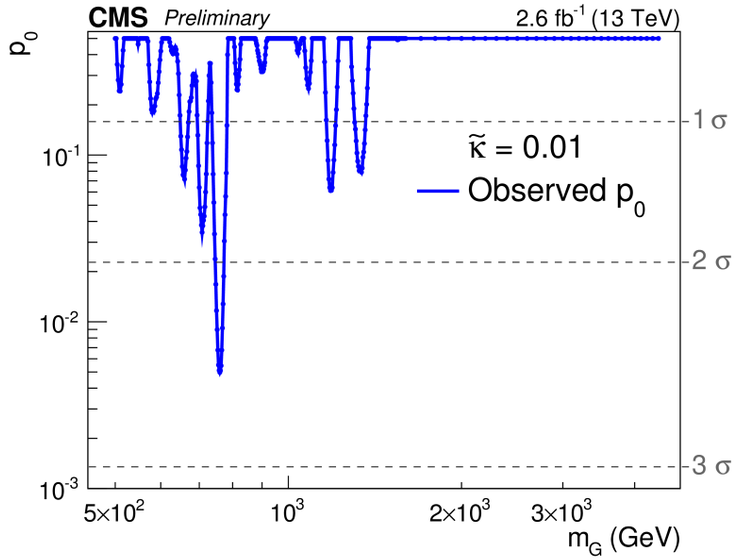


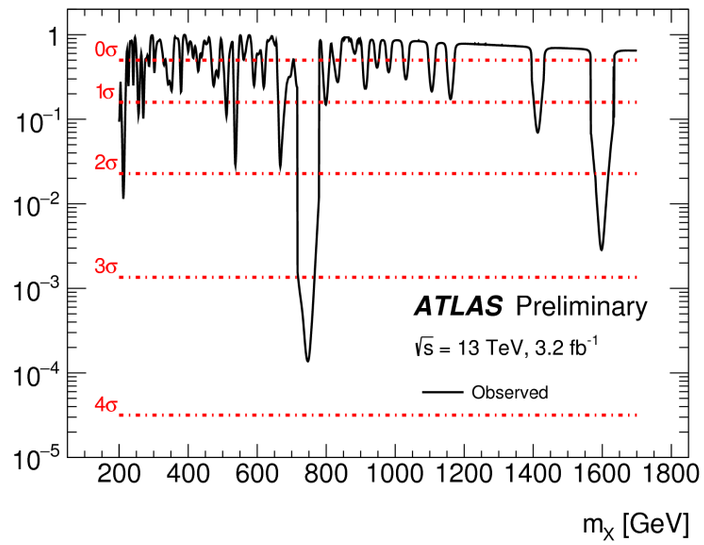
ATLAS-CONF-2015-081



- Upper limits on spin -2 resonance up to 4.5 TeV from CMS data
- Upper limits on spin - 0 resonance up to 1.8 TeV from ATLAS
- … and the observed diphoton excess around 750 GeV
- ATLAS and CMS data and interpretations are not exactly on the same footing

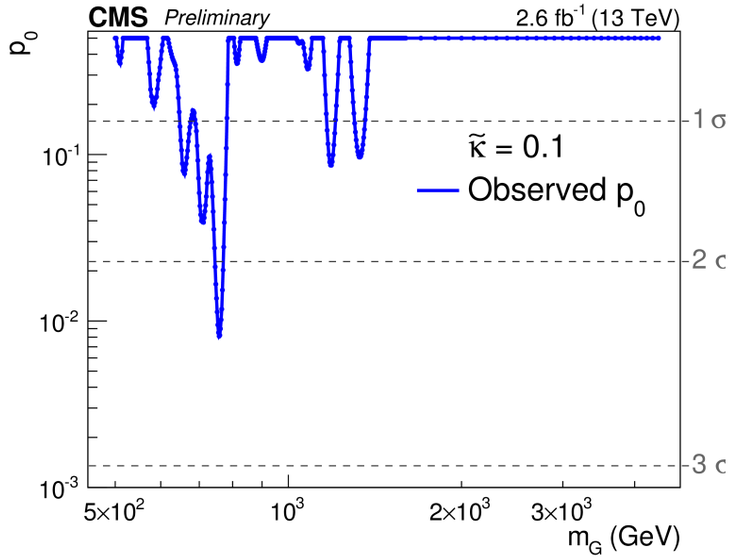
Current status

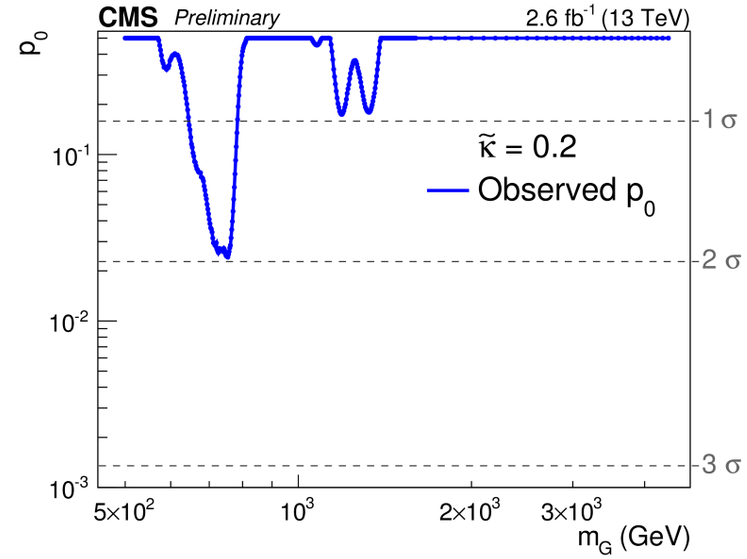




ATLAS-CONF-2015-081,

CMS-PAS-EXO-15-004





- ATLAS resonance compatible with a large width, CMS prefers narrow width
- Multiple dips in p-value plot, not impossible to have a ‘fluctuation’ in both CMS and ATLAS data around the same value

Current status

Franceschini et al, arXiv:1512.04933

$$\sigma(pp \to \gamma\gamma) \approx \begin{cases} (0.5 \pm 0.6)\,\text{fb} & \text{CMS [2]} & \sqrt{s} = 8\,\text{TeV}, \\ (0.4 \pm 0.8)\,\text{fb} & \text{ATLAS [3]} & \sqrt{s} = 8\,\text{TeV}, \\ (6 \pm 3)\,\text{fb} & \text{CMS [1]} & \sqrt{s} = 13\,\text{TeV}, \\ (10 \pm 3)\,\text{fb} & \text{ATLAS [1]} & \sqrt{s} = 13\,\text{TeV}. \end{cases}$$

$$\frac{\sigma(pp \to \gamma\gamma)_{13\,\text{TeV}}}{\sigma(pp \to \gamma\gamma)_{8\,\text{TeV}}} \approx 16$$

- Assume a production of scalar resonance S

$$\sigma(pp \to S \to \gamma\gamma) = \frac{2J+1}{M\Gamma s}\left[C_{gg}\Gamma(S \to gg) + \sum_q C_{q\bar{q}}\Gamma(S \to q\bar{q})\right]\Gamma(S \to \gamma\gamma)$$

$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}
8 TeV	1.07	2.7	7.2	89	158	174
13 TeV	15.3	36	83	627	1054	2137

$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}
5.4	5.1	4.3	2.7	2.5	4.7

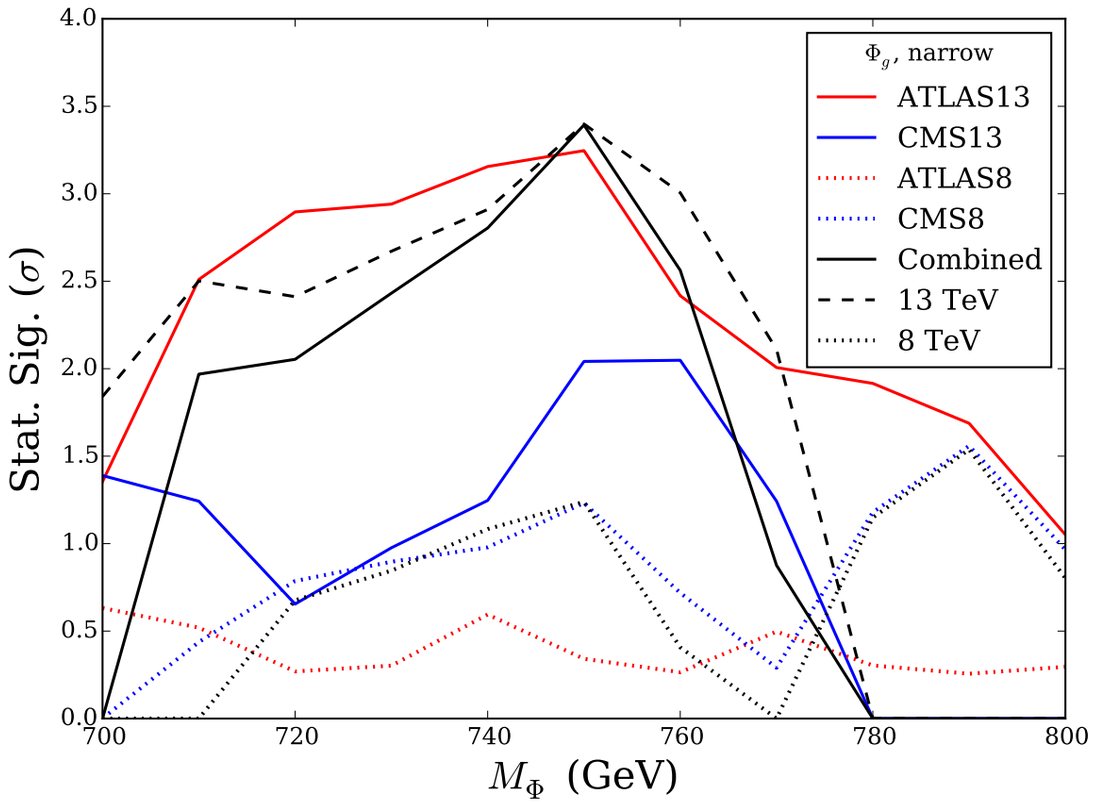
$$r = \sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}} = [C_{gg}/s]_{13\,\text{TeV}}/[C_{gg}/s]_{8\,\text{TeV}}$$

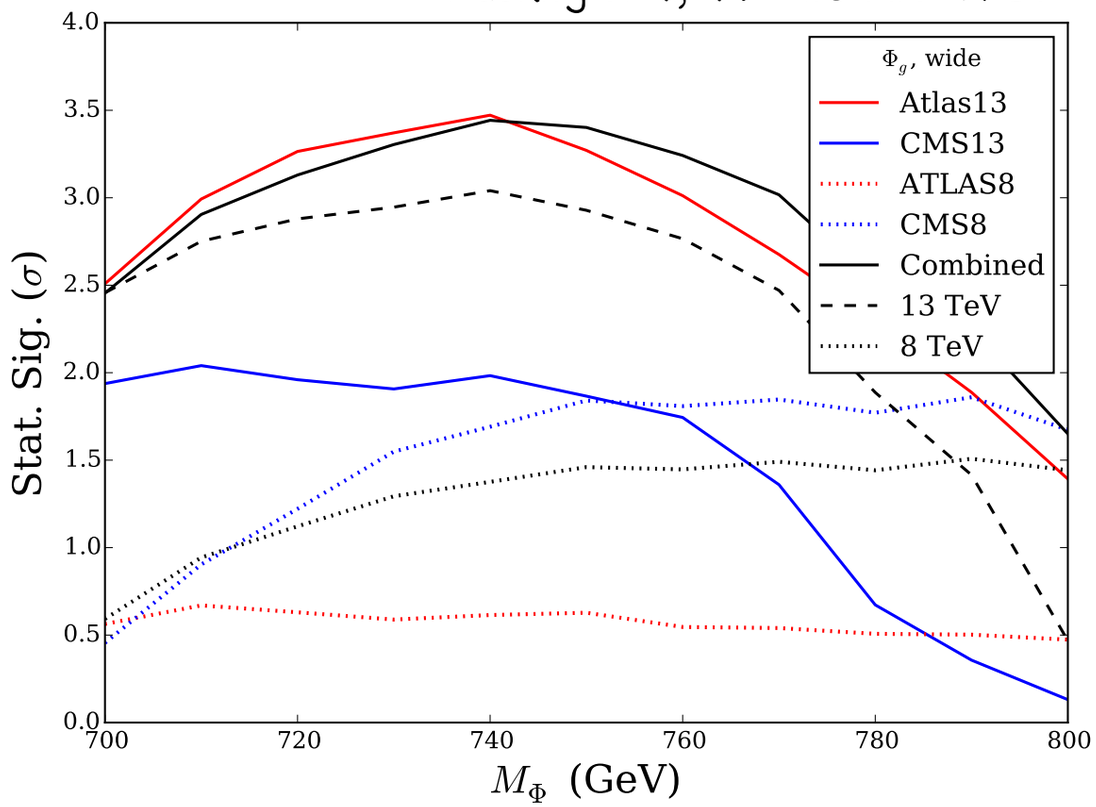
- Maximum increase in cross section due to PDF ~ 5, not exactly enough to explain the 8 ad 13 TeV data

Combining datasets

- Theorists exercises

Buckley et al, arXiv:1601.04751



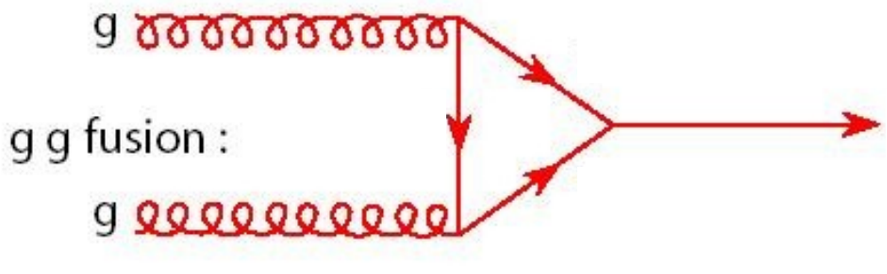


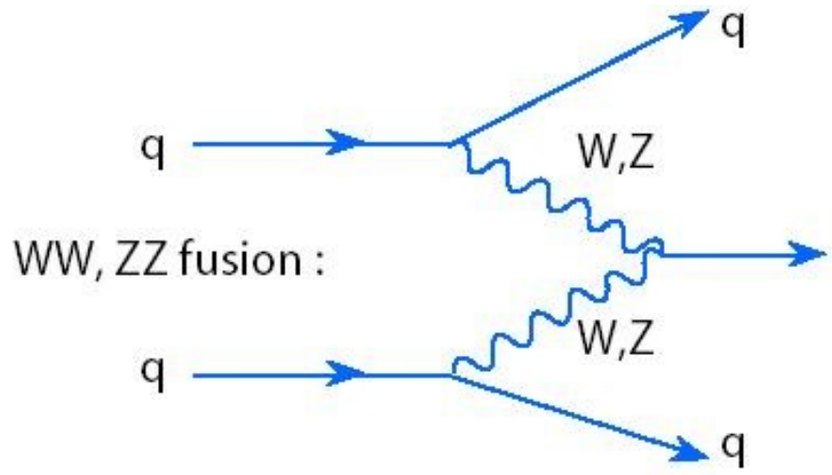
- Significance goes up for narrow width when 13 TeV data is combined
- Significance goes up for wide width if combined with 8TeV data
- 8 TeV limits and 13 TeV excess can live in harmony with each other

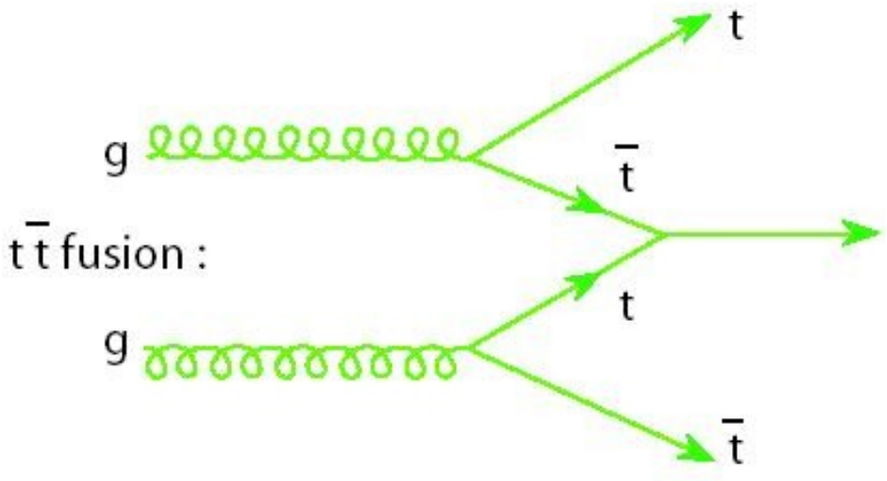
See also: arXiv:1512.05332, arXiv:1512.04928, arXiv:1512.05777, arXiv:1601.04751
http://www.physicsmatt.com/blog/2016/1/18/recent-paper-narrow-or-wide-the-phenomenology-of-750-gev-diphotons

Production modes

- If it is a resonance, it should be a spin - 0 or 2 particle (Landau-Yang theorem)
- The excess may not be a resonance arXiv:1512.06113, arXiv:1512.06833 both consider 3-body decays



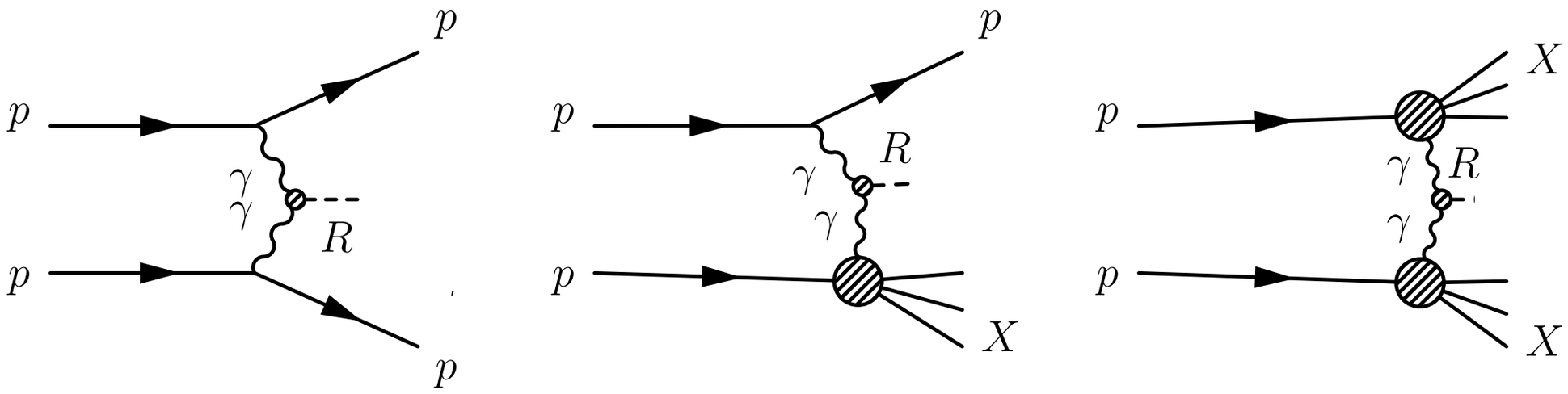




- VBF and tt fusion correspond to additional observable decay products
- ggF the most promising channel

Production modes

- If it is a resonance, it should be a spin - 0 or 2 particle (Landau-Yang theorem)
- The excess may not be a resonance arXiv:1512.06113, arXiv:1512.06833 both consider 3-body decays



- For photon fusion, three possibilities: Elastic-elastic, elastic-inelastic and inelastic-inelastic

see e.g.
arXiv:1601.00638,
arXiv:1512.05751,
arXiv:1512.05776

Run - 1 results

- Multiple searches already done at Run - 1

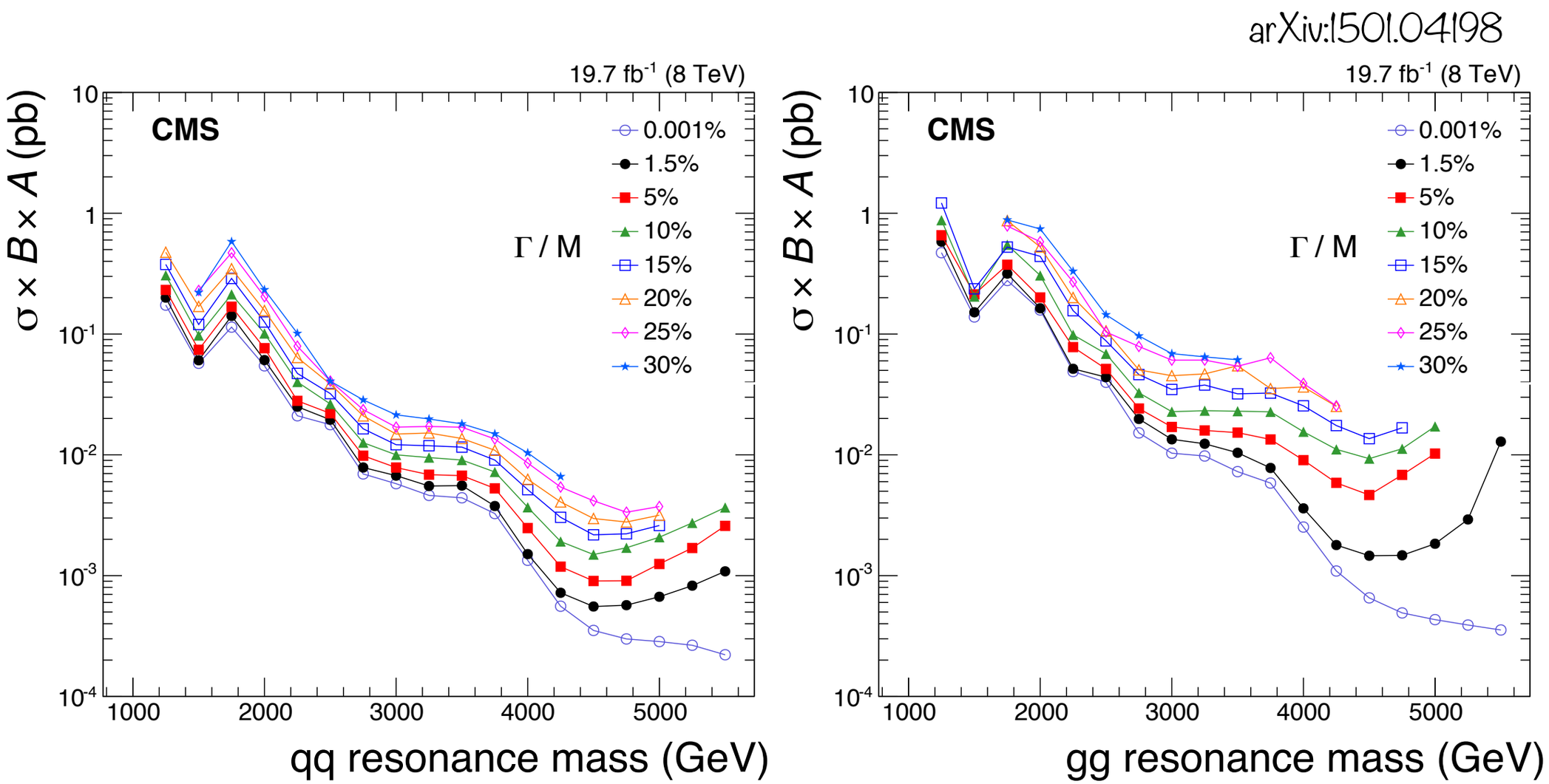
Franceschini et al, arXiv:1512.04933

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[6, 7]	$< 0.8\ (r/5)$
$e^+e^- + \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[8]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	15 fb	[9]	$< 6\ (r/5)$
$Z\gamma$	< 4.0 fb	< 3.4 fb	[10]	$< 2\ (r/5)$
ZZ	< 12 fb	< 20 fb	[11]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[12]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[13]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[14, 15]	$< 20\ (r/5)$
$t\bar{t}$	< 550 fb	-	[16]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[17]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1\,\text{pb}$	$\lesssim 1\,\text{pb}$	[18]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[5]	$< 1300\ (r/5)$

- Limits depend on width of the resonance, limits should be taken with care
- Dijet limits are some of the weakest (controlling QCD background at lower masses harder)

Run - 1 results

- Multiple searches already done at Run - 1



- Dijet limits are some of the weakest (controlling QCD background at lower masses harder)

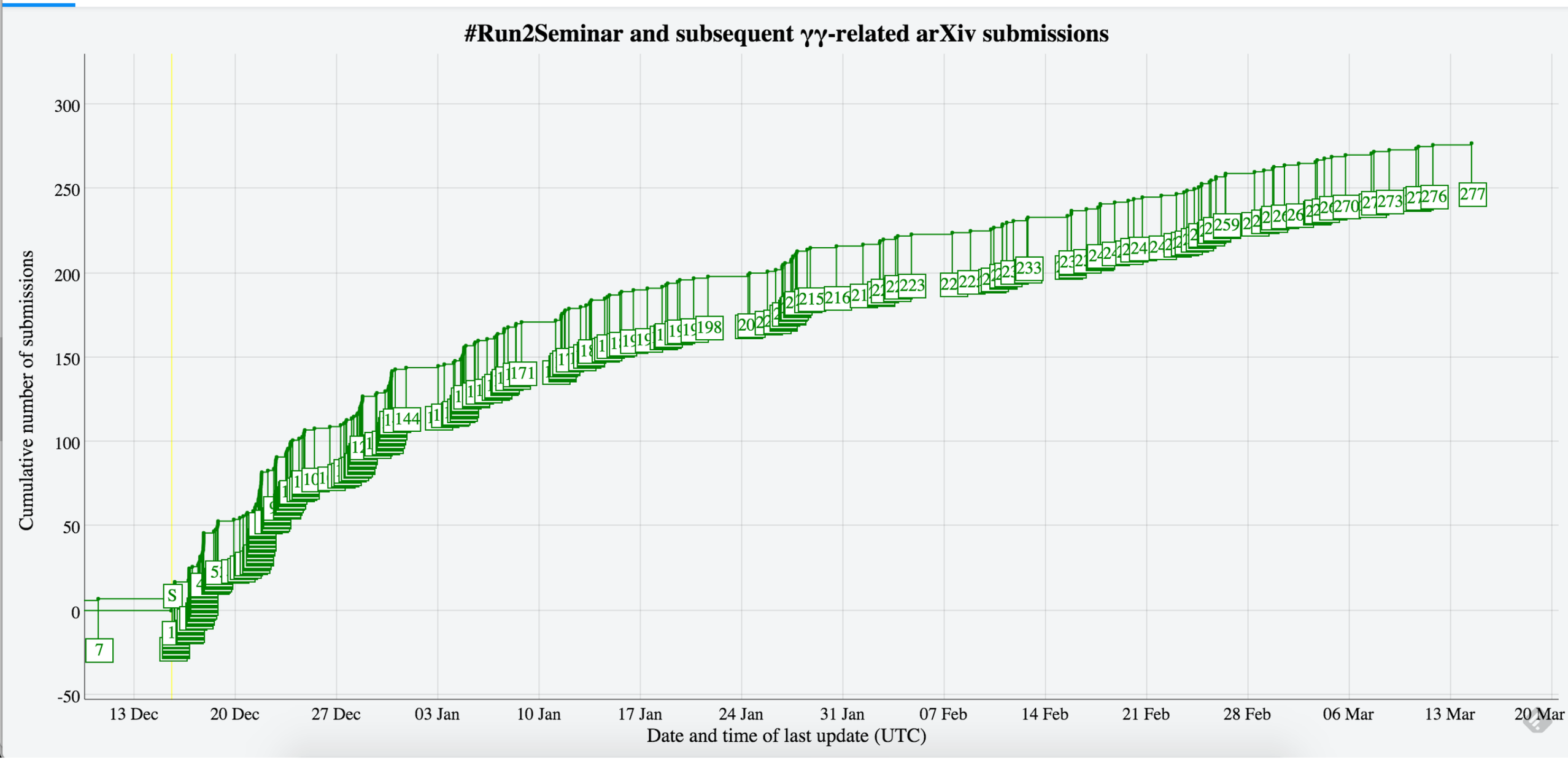
Is the excess a thing or a nothing?



“Little bit” of excitement

Result

Edit in JSFiddle



http://jsfiddle.net/adavid/bk2tmc2m/show/

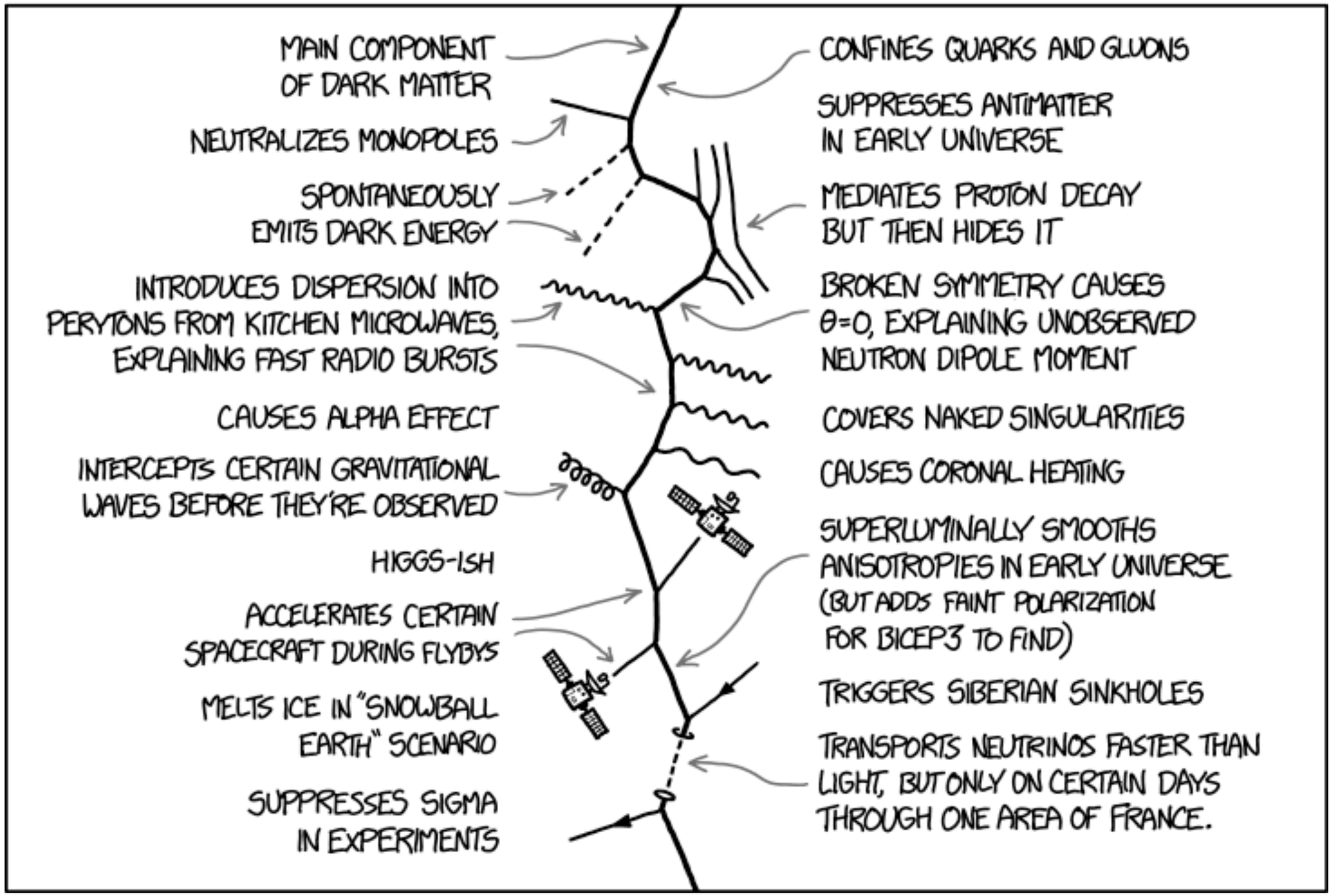
We also have a prediction for the total number of papers!

Backović et. al. arXiv:1603.01204

A CHRISTMAS GIFT FOR PHYSICISTS:

THE FIXION

A NEW PARTICLE THAT EXPLAINS EVERYTHING



HTTP://XKCD.COM/1621/

The model

- Coupling of a 750 scalar resonance to gluon, photon and Majorana dark matter particle

$$\mathcal{L}_{\rm NP,CPE} = \frac{1}{2}(\partial_\mu s)^2 - \frac{\mu_s^2}{2}s^2 + \frac{1}{2}\bar{\psi}(i\not{\partial}_\mu - m_\psi)\psi - \frac{y_\psi}{2}s\bar{\psi}\psi$$
$$- \frac{g_1^2}{4\pi}\frac{1}{4\Lambda_1}s\ B_{\mu\nu}B^{\mu\nu} - \frac{g_2^2}{4\pi}\frac{1}{4\Lambda_2}s\ W_{\mu\nu}W^{\mu\nu} - \frac{g_3^2}{4\pi}\frac{1}{4\Lambda_3}s\ G_{\mu\nu}G^{\mu\nu}$$

$$\mathcal{L}_{\rm NP,CPO} = \frac{1}{2}(\partial_\mu s)^2 - \frac{\mu_s^2}{2}s^2 + \frac{1}{2}\bar{\psi}(i\not{\partial}_\mu - m_\psi)\psi - i\frac{y_\psi}{2}s\bar{\psi}\gamma^5\psi$$
$$- \frac{g_1^2}{4\pi}\frac{1}{4\Lambda_1}s\ B_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{g_2^2}{4\pi}\frac{1}{4\Lambda_2}s\ W_{\mu\nu}\tilde{W}^{\mu\nu} - \frac{g_3^2}{4\pi}\frac{1}{4\Lambda_3}s\ G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Mambrini et al, arXiv:1512.04913,

Backovic et al, arXiv:1512.04917,

Barducci et al, arXiv: 1512.06842

The model

- Coupling of a 750 scalar resonance to gluon, photon and dark matter particle
- d = 5 effective Lagrangian, Majorana fermion dark matter

$$\mathcal{L}_{\mathrm{NP,CPE}} = \frac{1}{2}(\partial_\mu s)^2 - \frac{\mu_s^2}{2}s^2 + \frac{1}{2}\bar{\psi}(i\partial\!\!\!/_\mu - m_\psi)\psi - \frac{y_\psi}{2}s\bar{\psi}\psi$$
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Gauge boson couplings

The model

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Gluon couplings

The model

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Mass term 750 GeV

Coupling to DM
(controls width of s)

The model

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SM gauge couplings

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Mass scales for effective couplings

The model

- Coupling of a 750 scalar resonance to gluon, photon and dark matter particle
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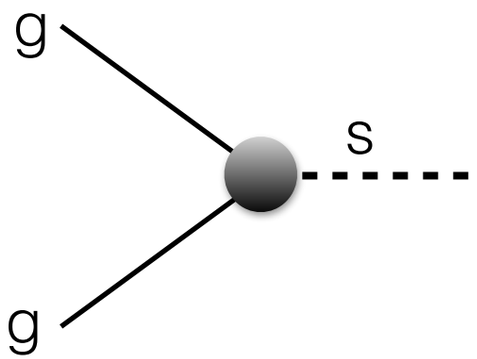
$$\mathcal{L}_{\mathrm{NP,CPE}} = \frac{1}{2}(\partial_\mu s)^2 - \frac{\mu_s^2}{2}s^2 + \frac{1}{2}\bar{\psi}(i\partial\!\!\!/_\mu - m_\psi)\psi - \frac{y_\psi}{2}s\bar{\psi}\psi$$
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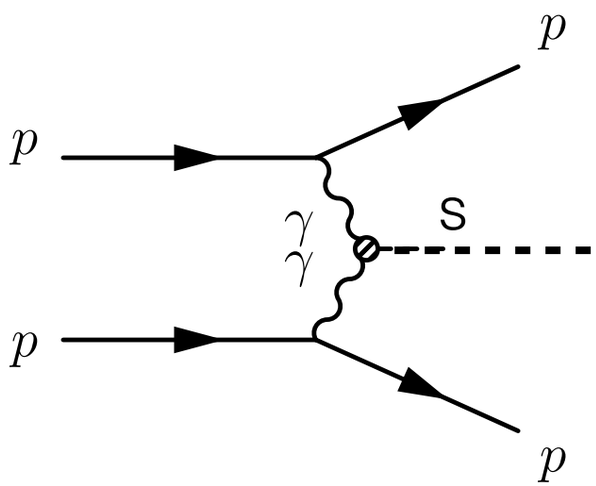
UV completion

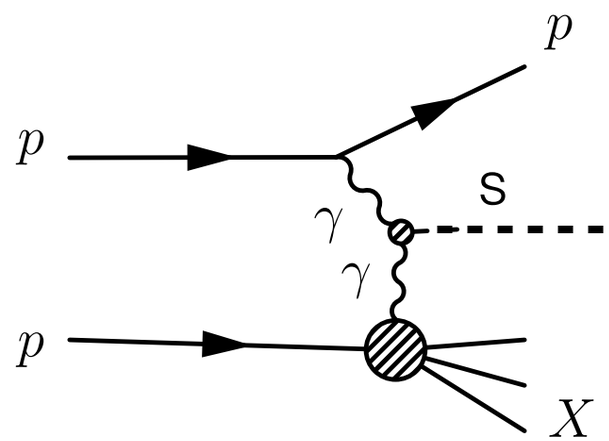


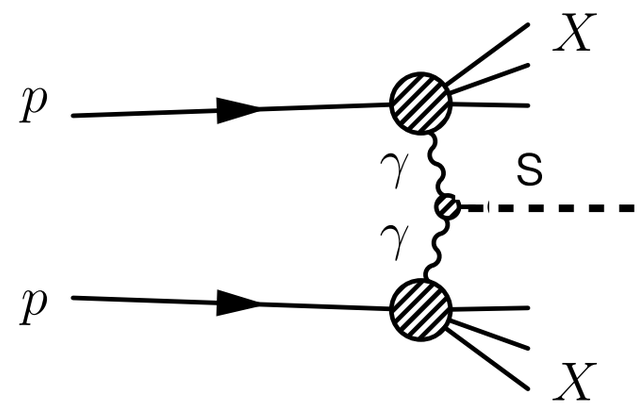
- I don’t care about the UV completion of the model at the moment
- It is known that such kinds of scales and/or couplings need large charge/ multiplicity for the vector-like matter and/or sizeable couplings of the singlet
- Such large couplings might cause problems for perturbativity at UV scale
- Aim at this point is to assess the viability of the parameter space rather than worrying about the UV completion

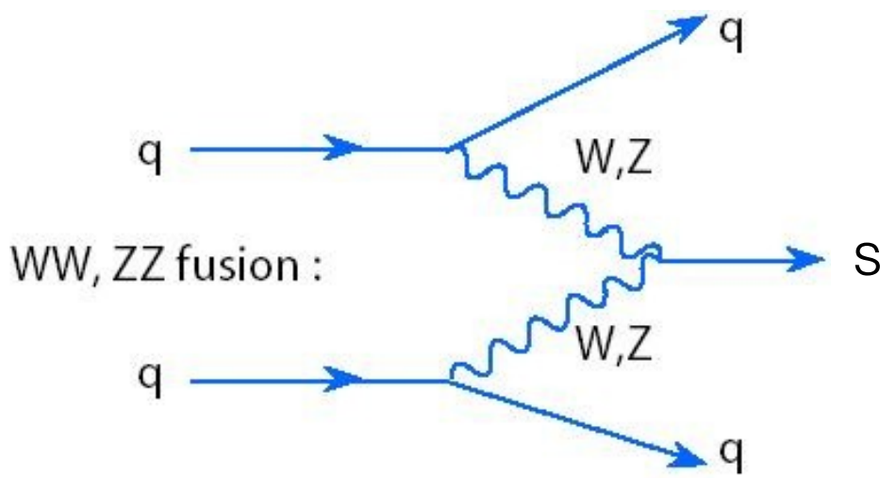
Production



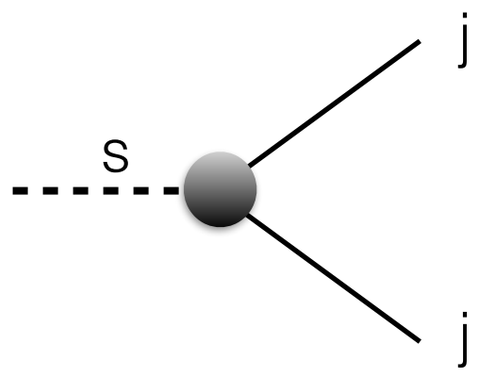


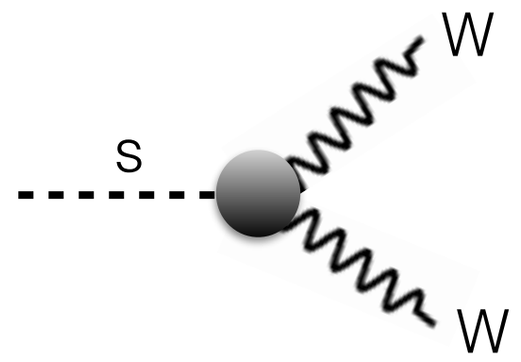


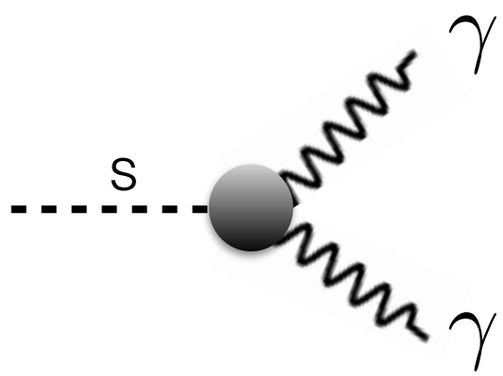


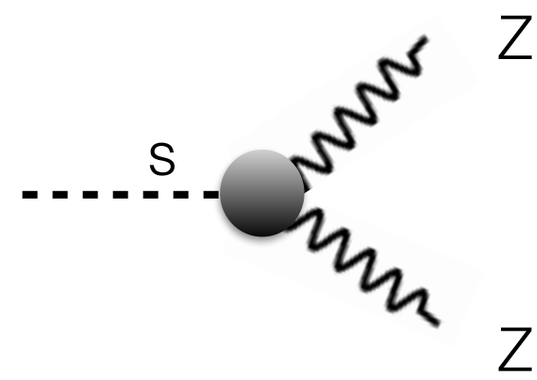


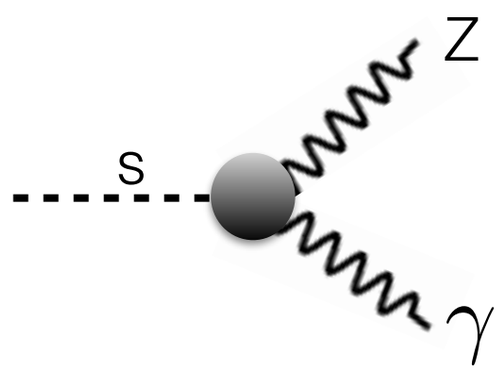
Decays

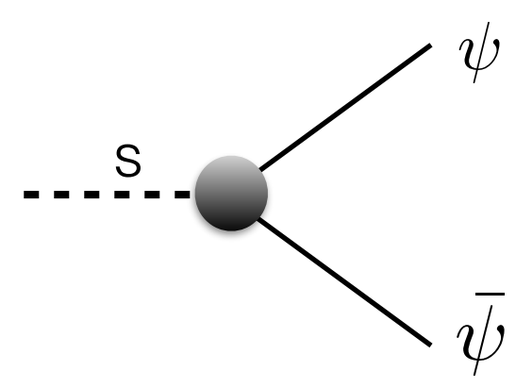




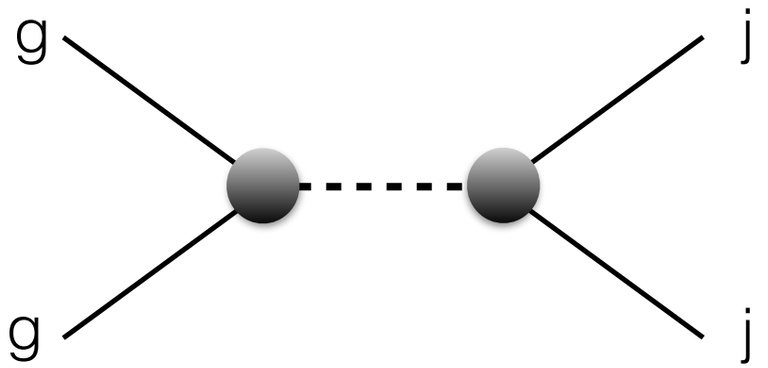


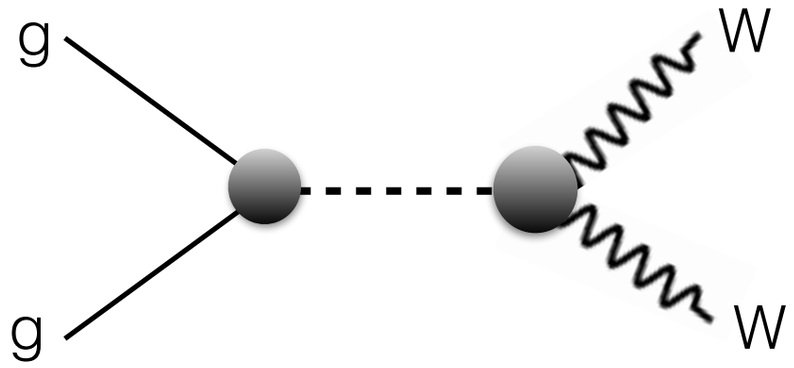


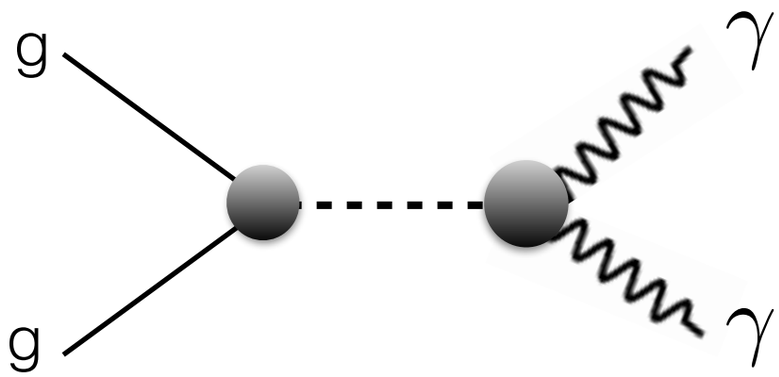


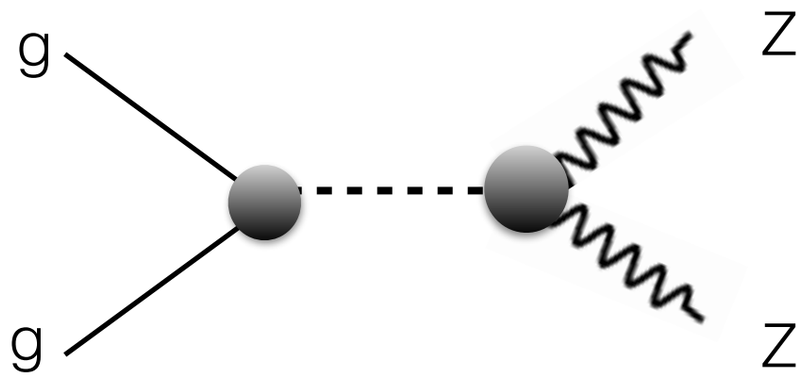


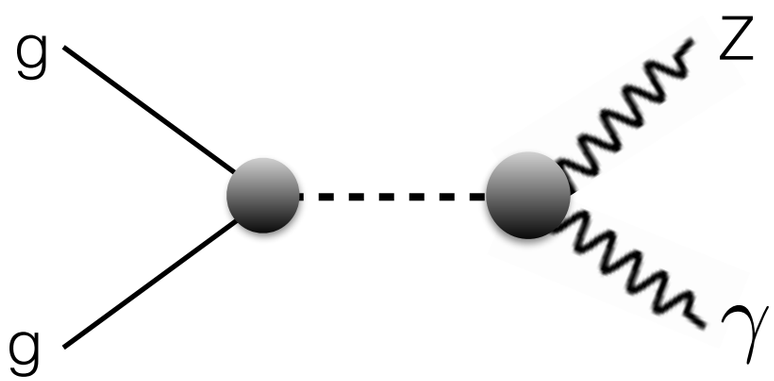
LHC phenomenology

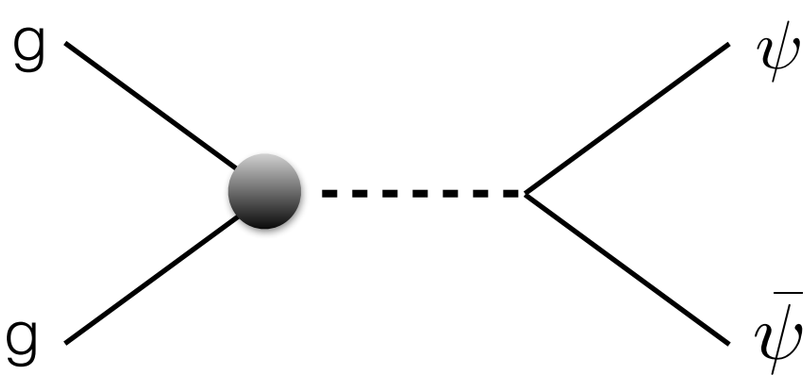




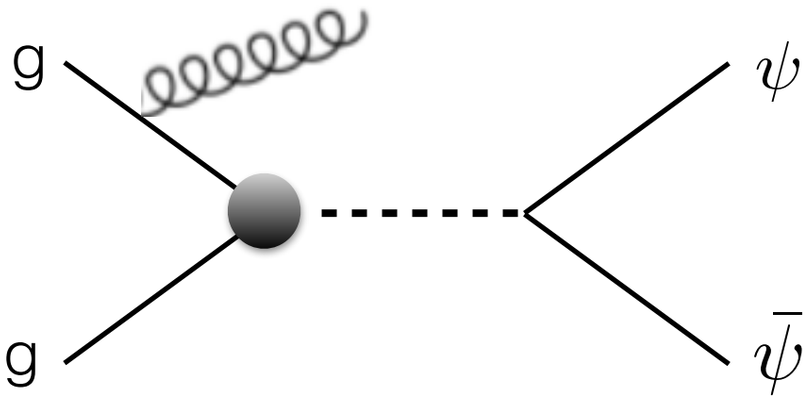








LHC phenomenology



CMS-EXO-12-048

$\mathrm{MET} > 250\ \mathrm{GeV}$

$\mathrm{MET} > 300\ \mathrm{GeV}$

$\mathrm{MET} > 350\ \mathrm{GeV}$

$\mathrm{MET} > 400\ \mathrm{GeV}$

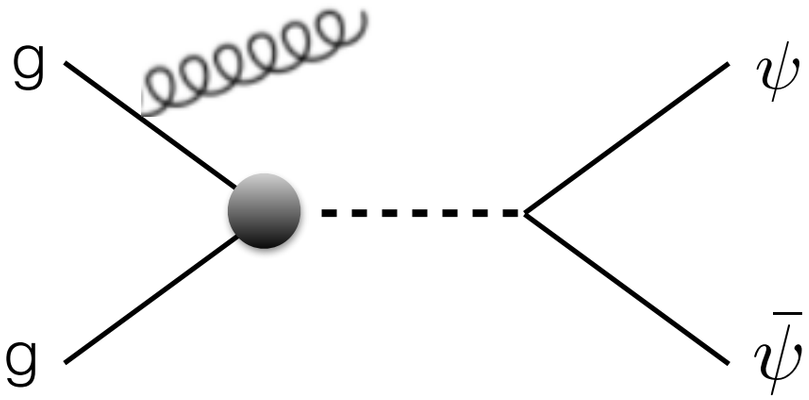
$\mathrm{MET} > 450\ \mathrm{GeV}$

$\mathrm{MET} > 500\ \mathrm{GeV}$

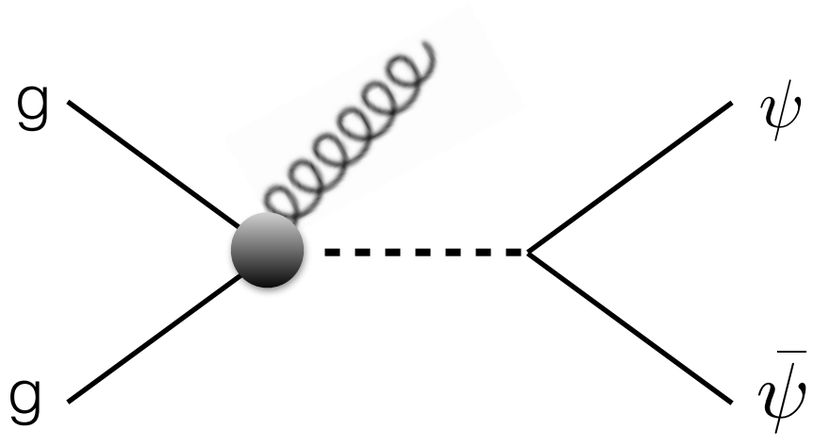
$\mathrm{MET} > 550\ \mathrm{GeV}$

- Jet recoils against the total MET production
- By requiring presence of MET and a high pT jet, such events can be detected

Monojet and resonance



- Working assumption emission of a jet from vertex small probability



LHC phenomenology

- Consider CP even couplings for LHC simulations
- Determine LHC predictions for dijet, diphoton rates, width of the resonance
- Determine current exclusion for the monojet analysis
- Determine current dark matter constraints

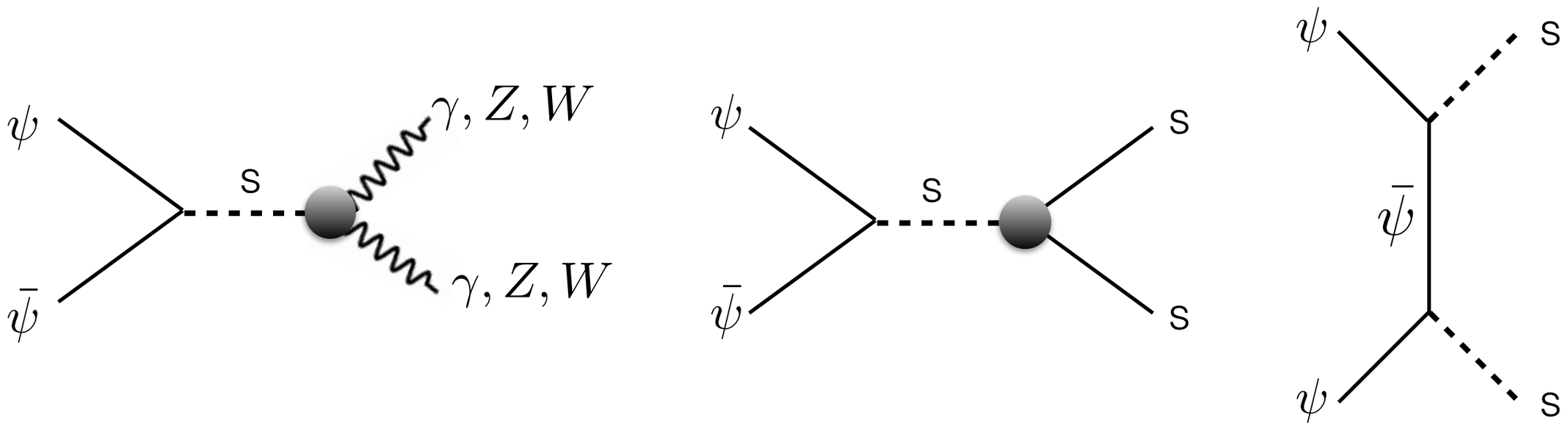
Constraint	Evaluation	Tool
Dijet	Parton level @ 13 TeV	MadGraph
Diphoton	Parton level @ 13 TeV	MadGraph
Monojet	Reco level @ 8 TeV	MadAnalysis
Relic		Micromegas
DD		Analytical
ID		Micromegas

Dark matter relic

- CP even and CP odd couplings make a big difference for relic density
- CP even case: p-wave suppression for annihilation cross section
  - Needs large values of Yukawa couplings to achieve relic
- CP odd case: No velocity suppression much smaller values of Yukawa couplings work

- No couplings to fermions present
- For dark matter mass less than 375 GeV, only gauge bosons, photons, and gg final states in s-channel present
- For dark matter mass greater than 750 GeV t-channel annihilation into scalar resonance possible
  - Contribution up to 20% of the first scenario

Dark matter relic

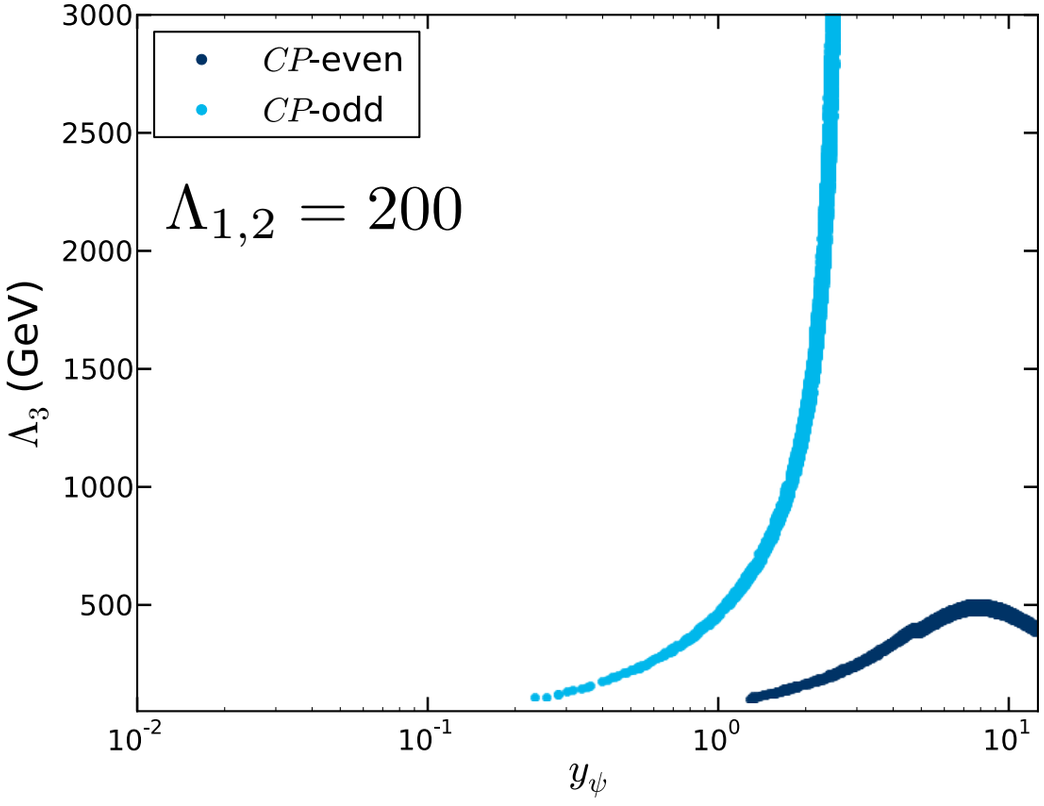


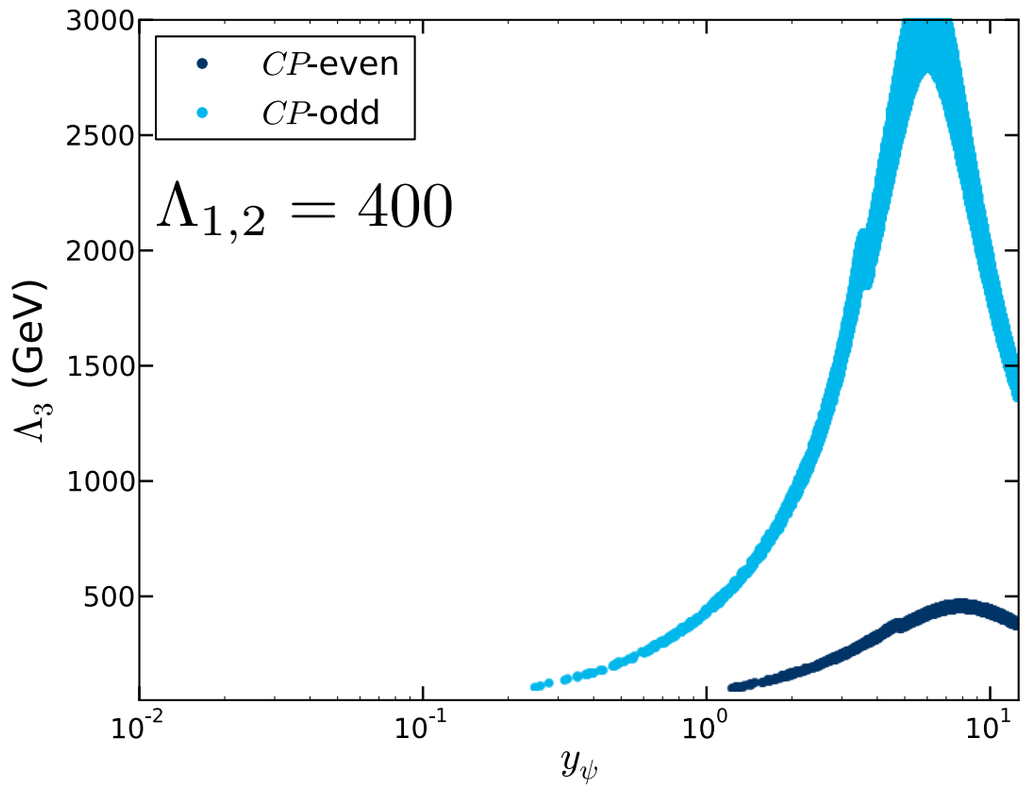
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$$m_\psi = 250\,\mathrm{GeV}$$

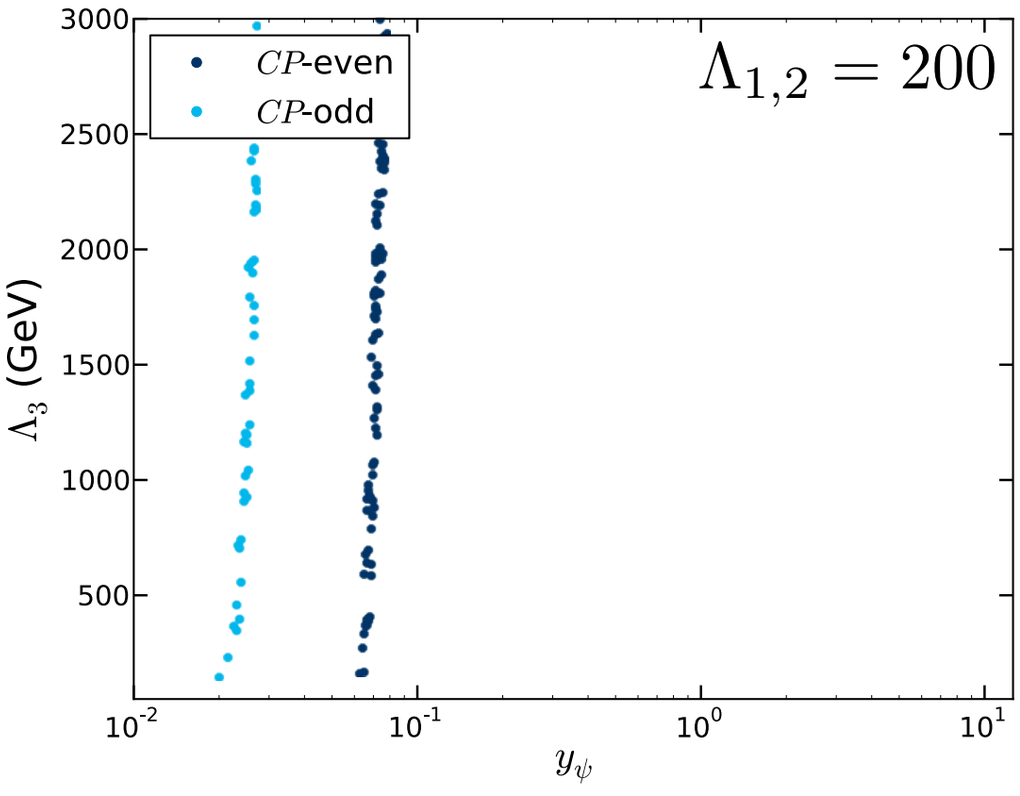


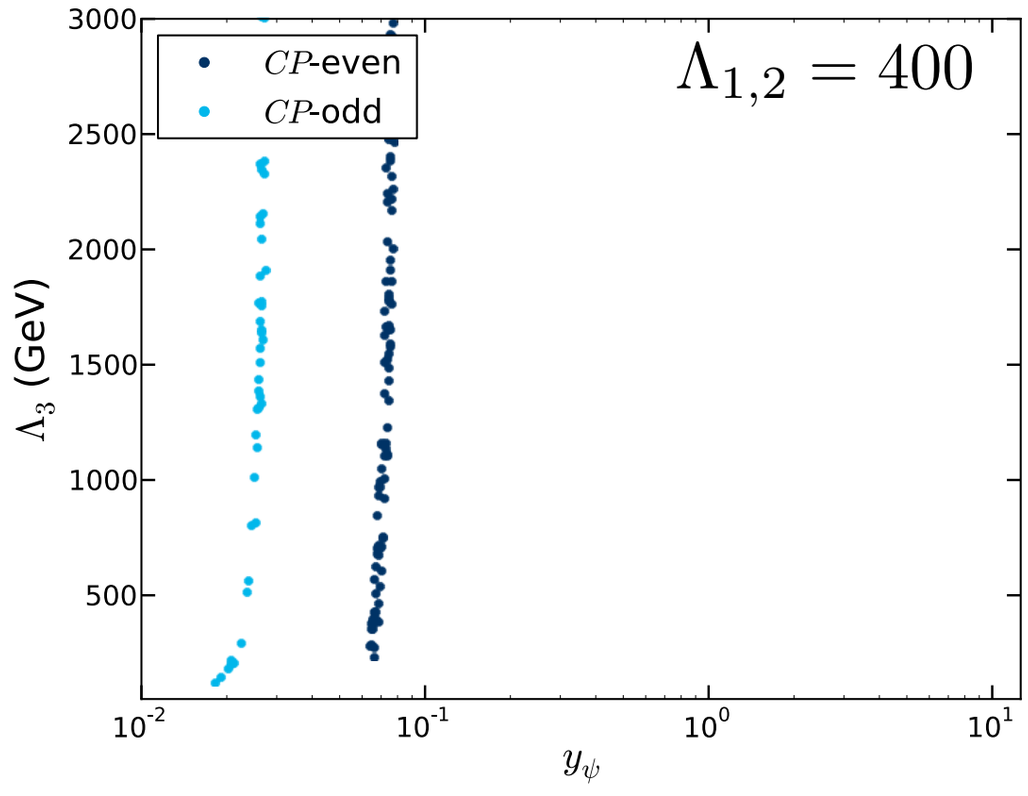


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  - Needs large values of Yukawa couplings to achieve relic
- CP odd case: No velocity suppression much smaller values of Yukawa couplings work

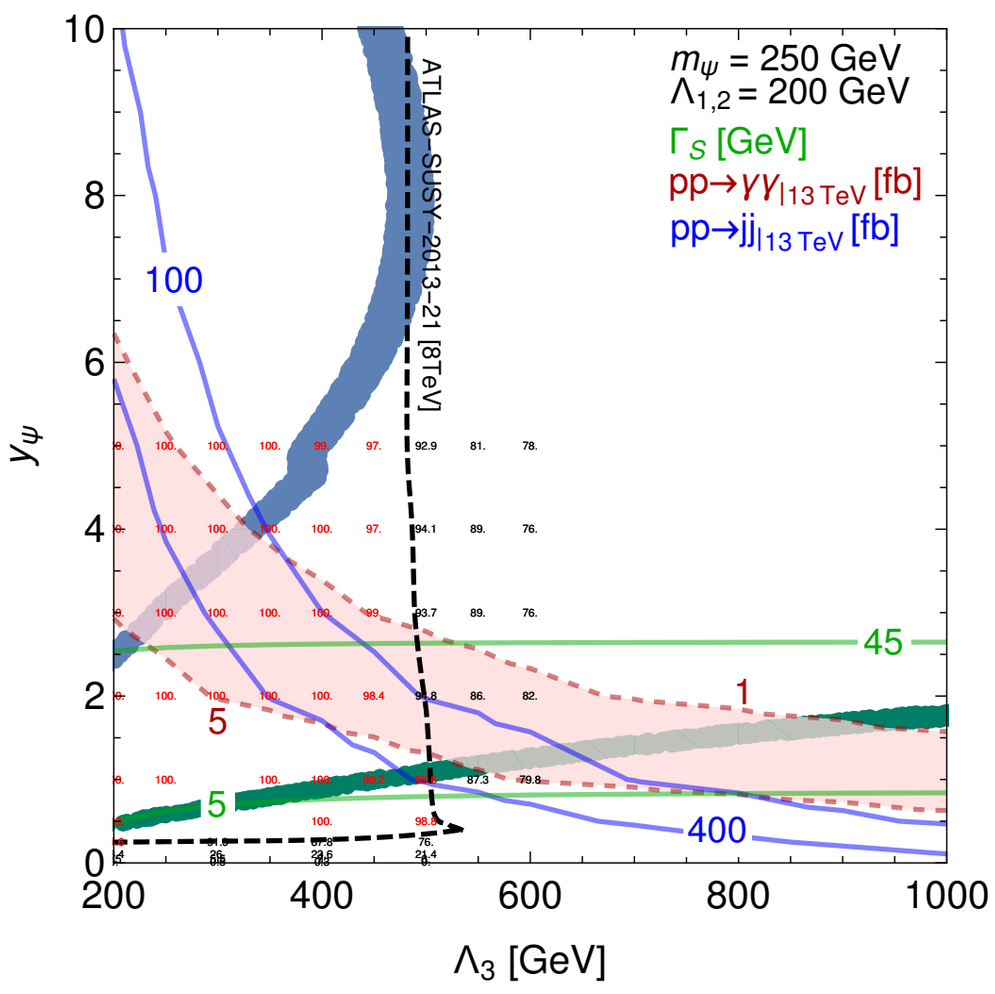
$$m_\psi = 350\,\mathrm{GeV}$$

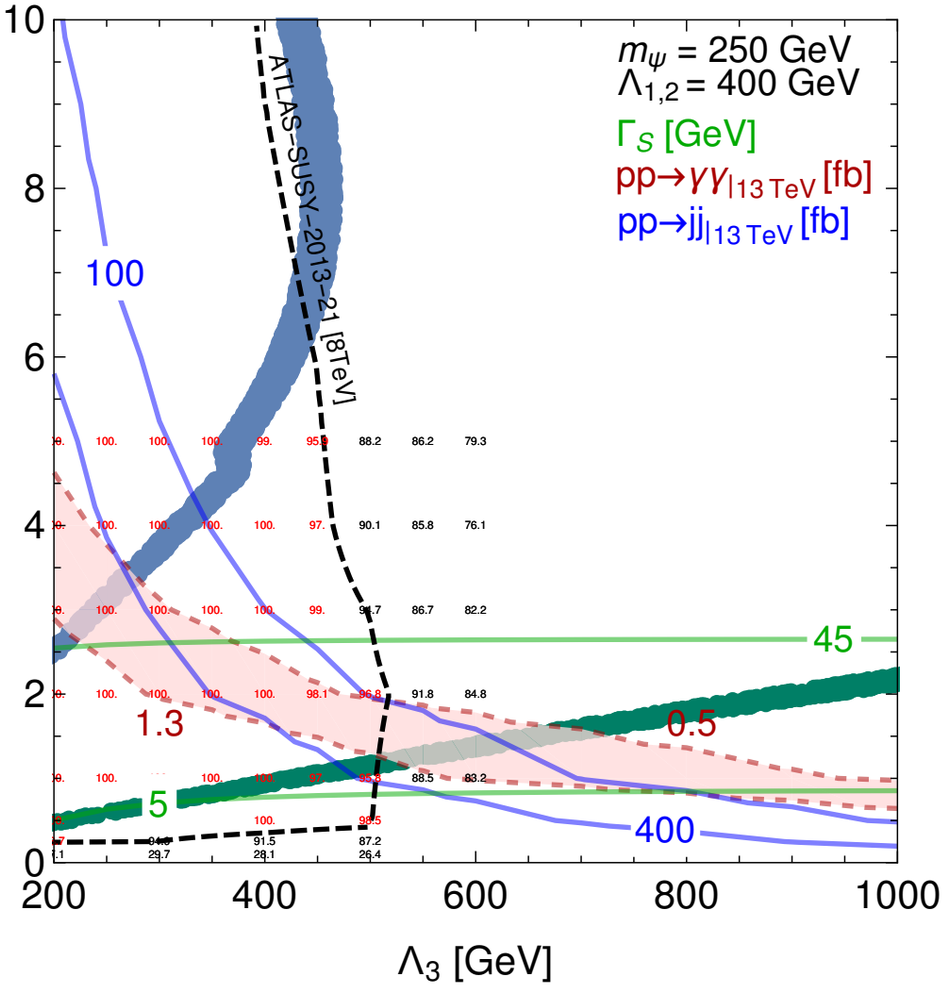




Results

Barducci et al arXiv: 1512.06842

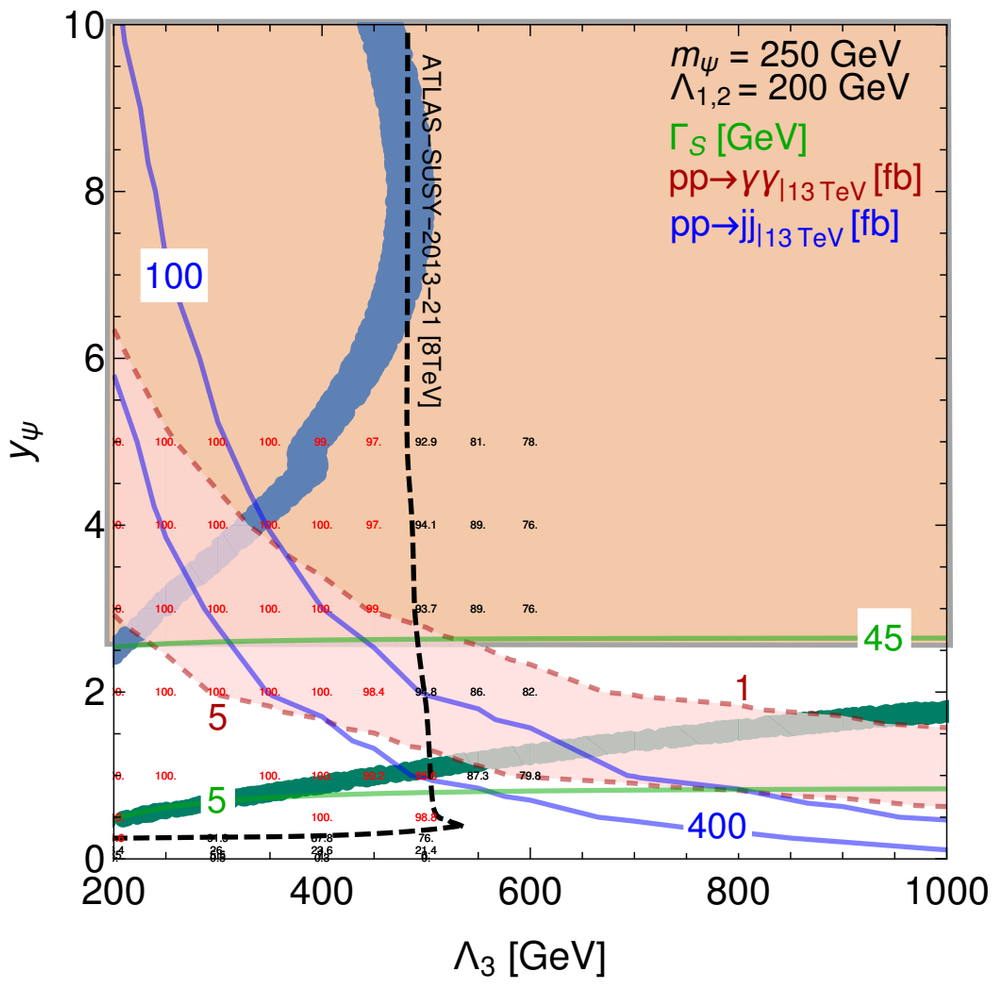


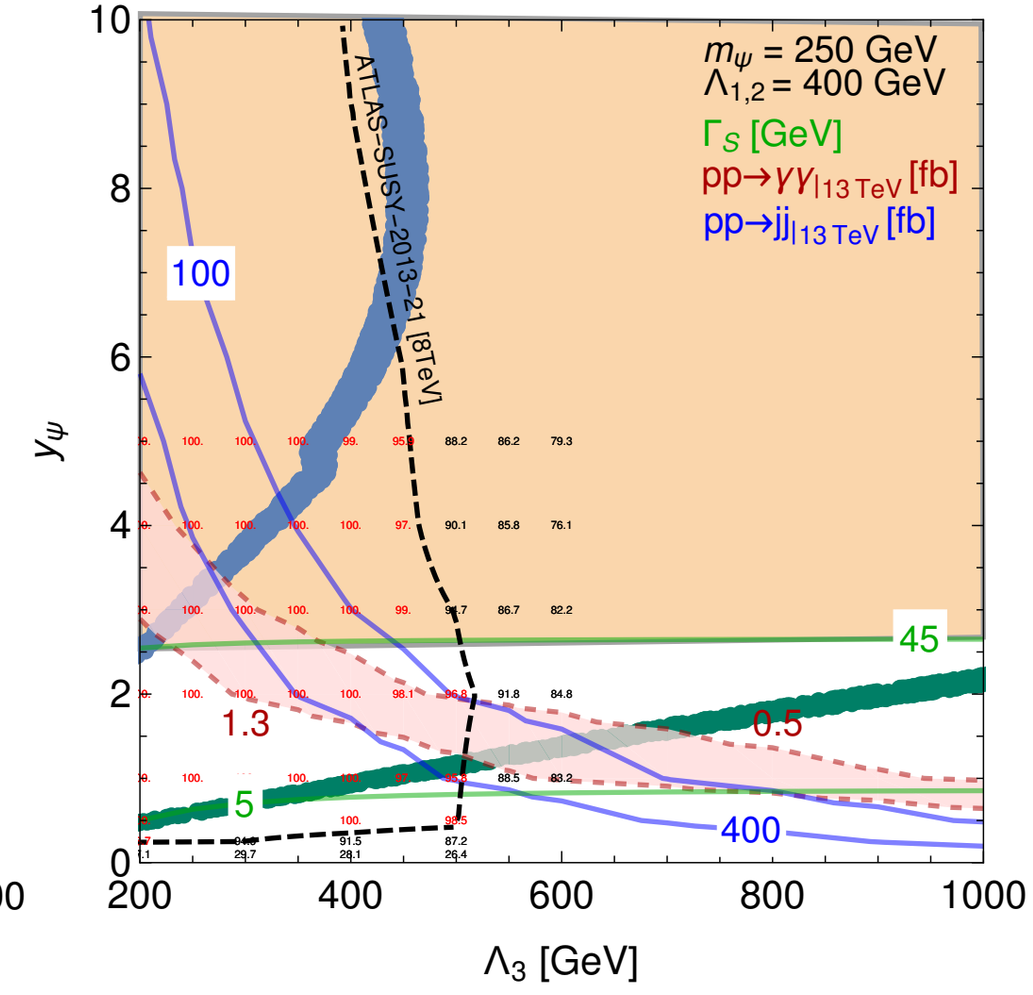


- Large part excluded by very large width
- Reconciling everything together not possible in CP even case within the ranges on the plot
- Possibility of reconciling everything for Lambda1,2 = 20 GeV (see backup)

Results

Barducci et al arXiv: 1512.06842

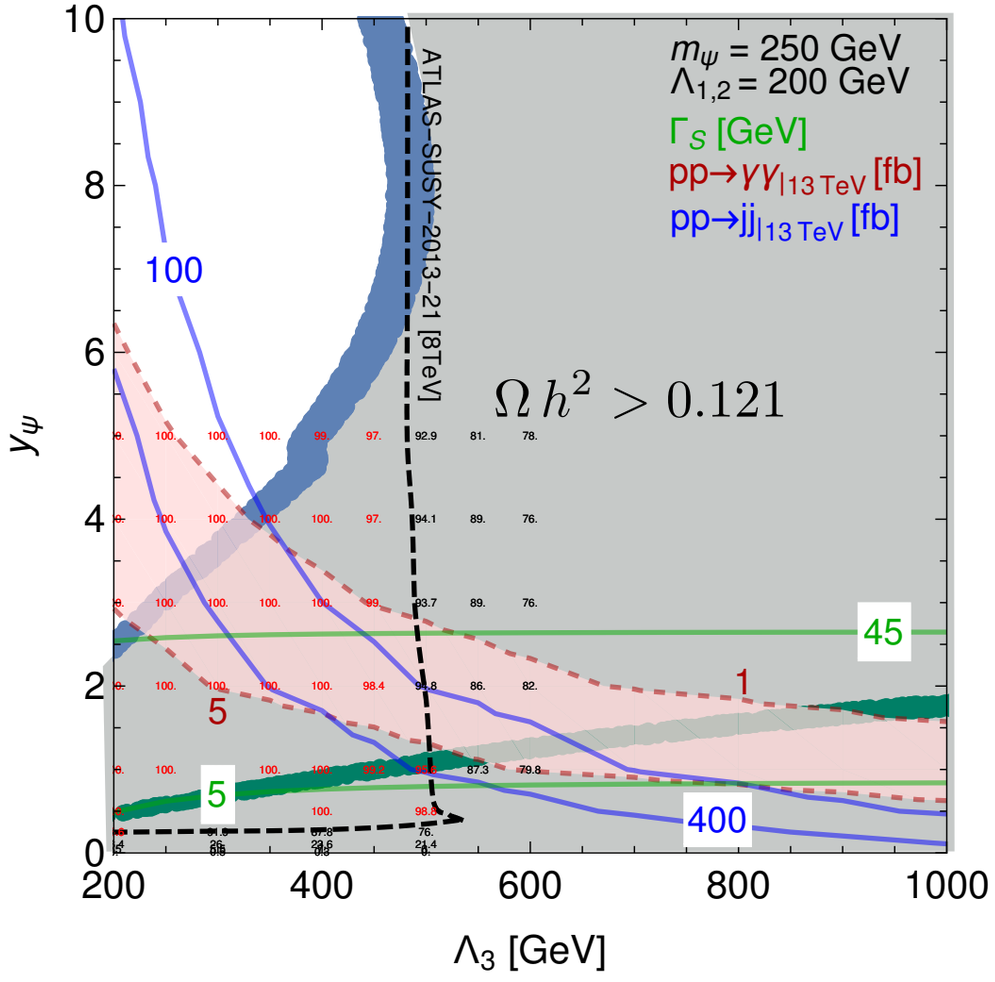


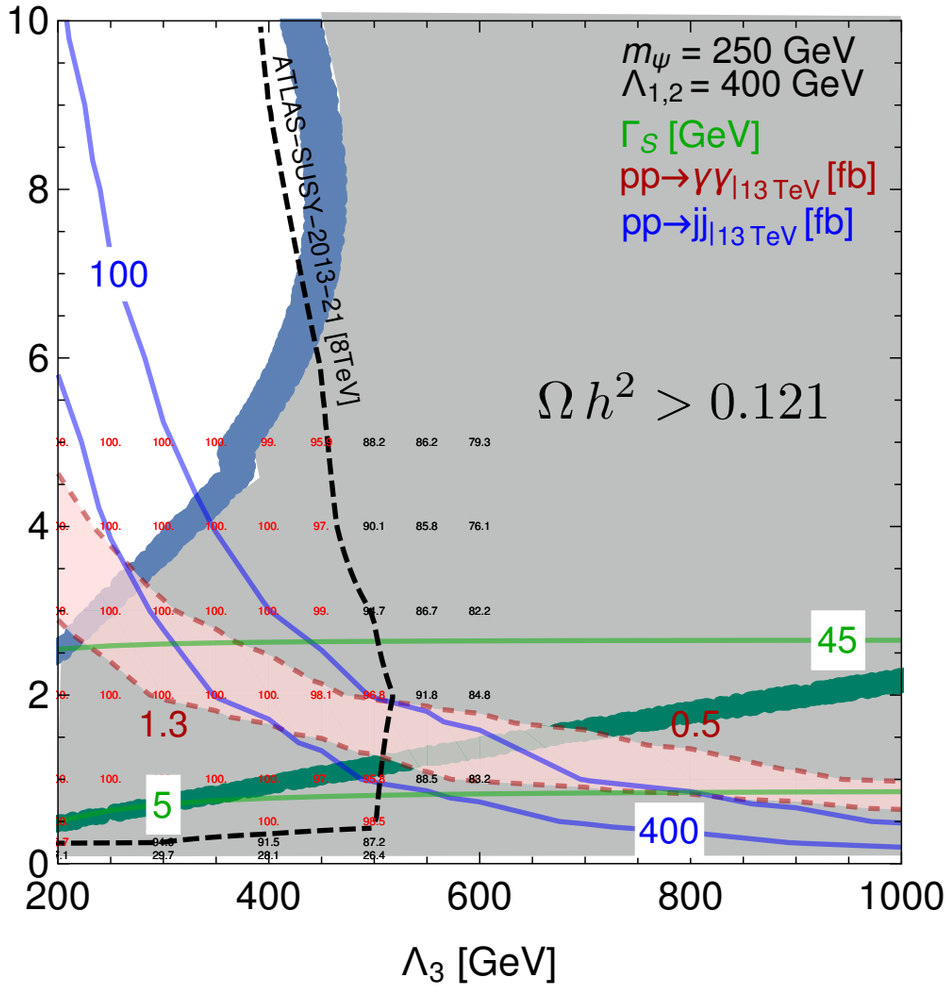


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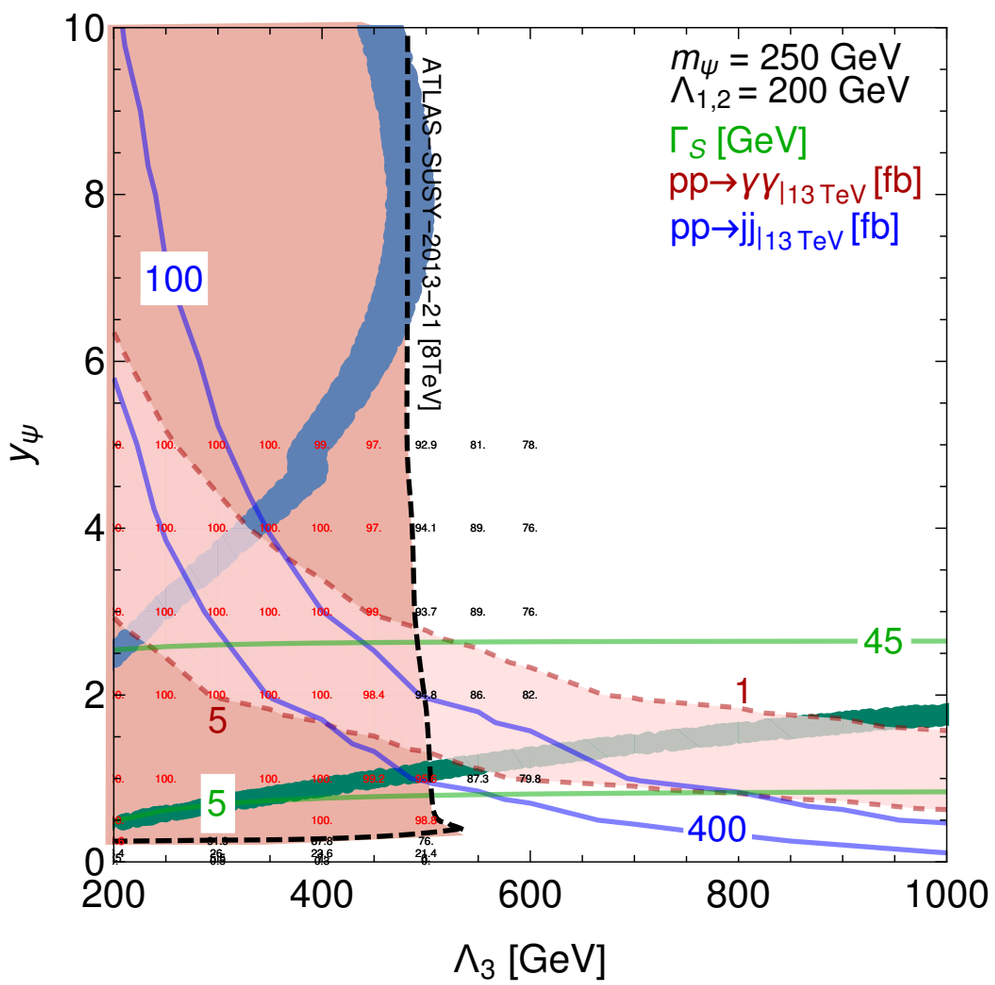


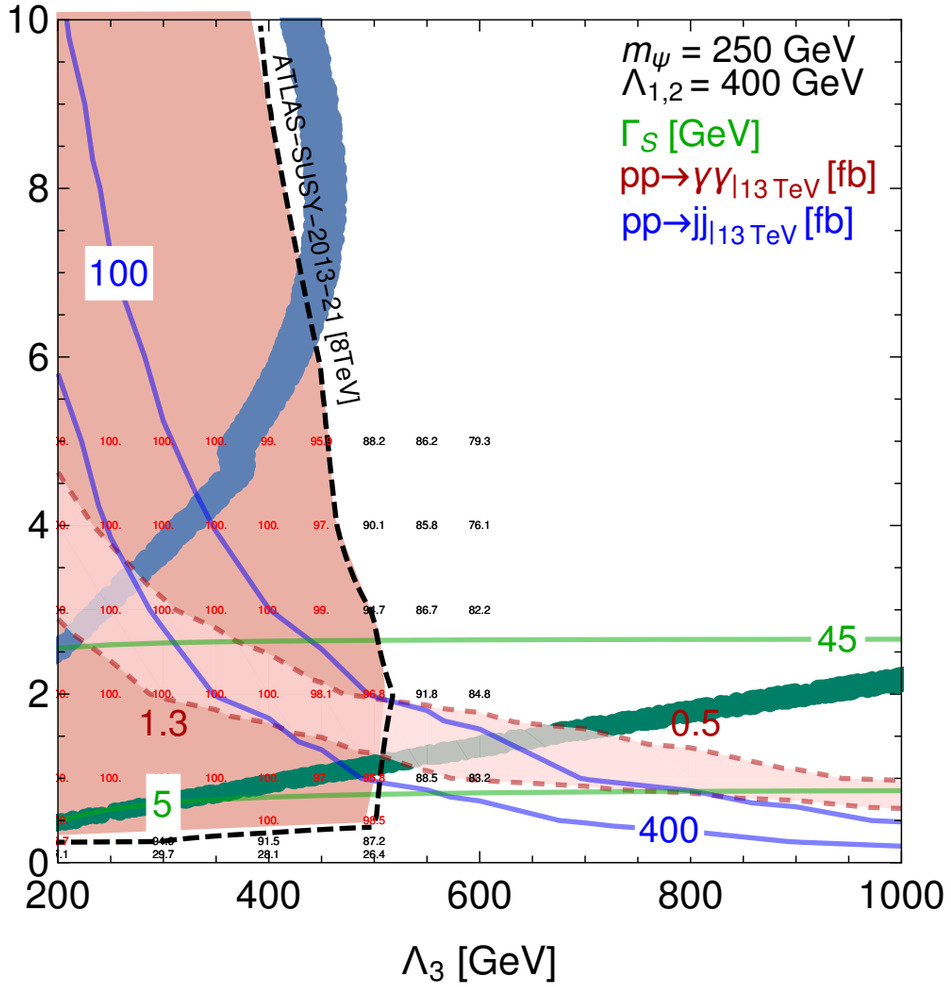


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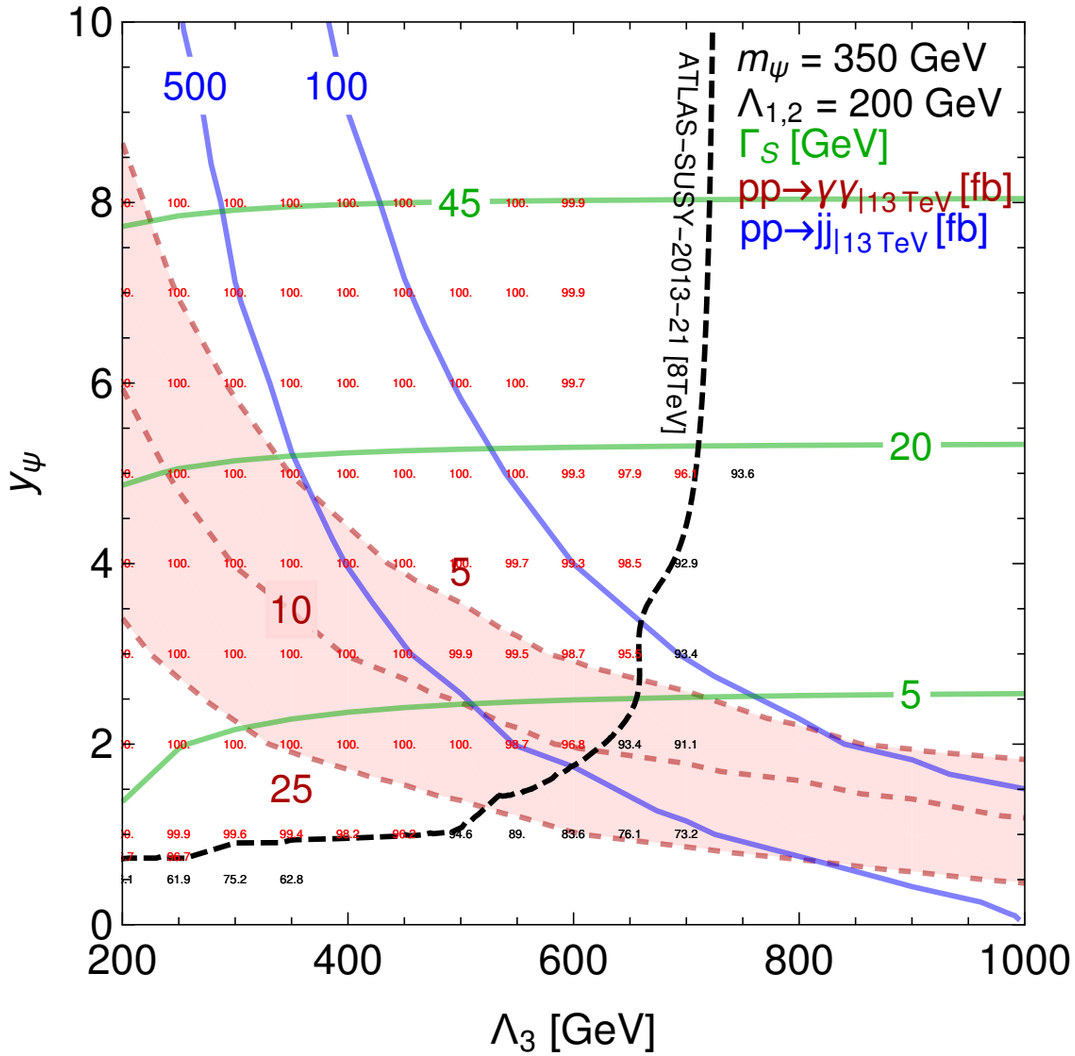


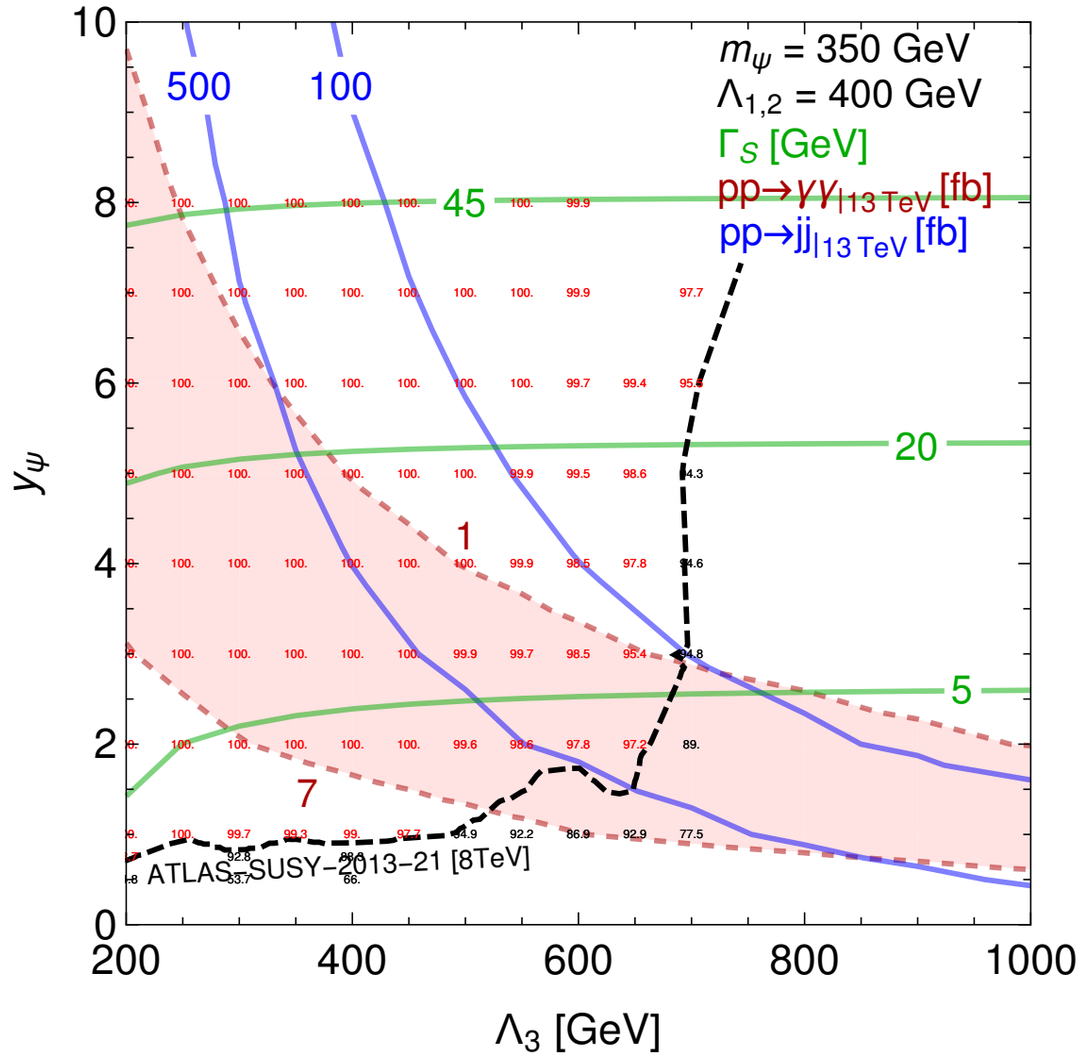


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Results

Barducci et al arXiv: 1512.06842

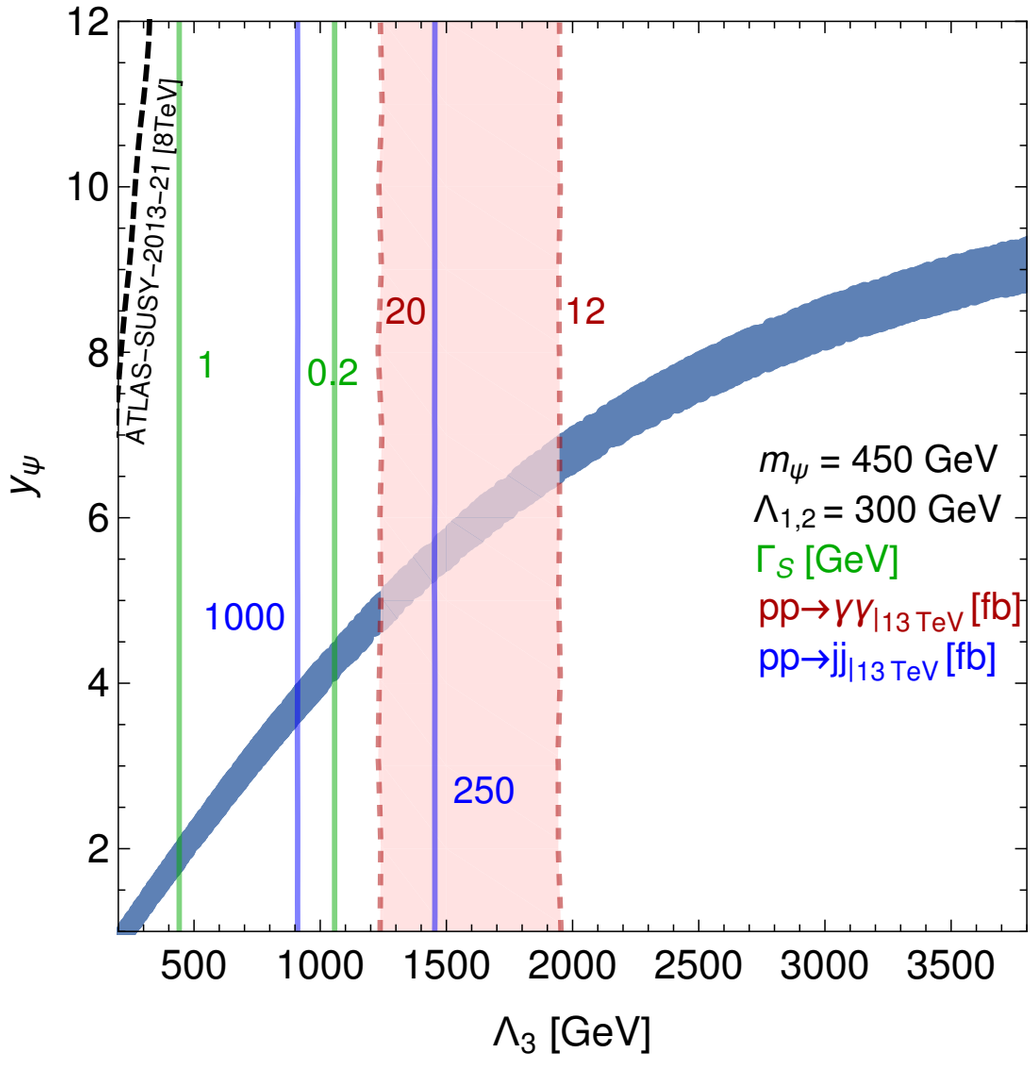


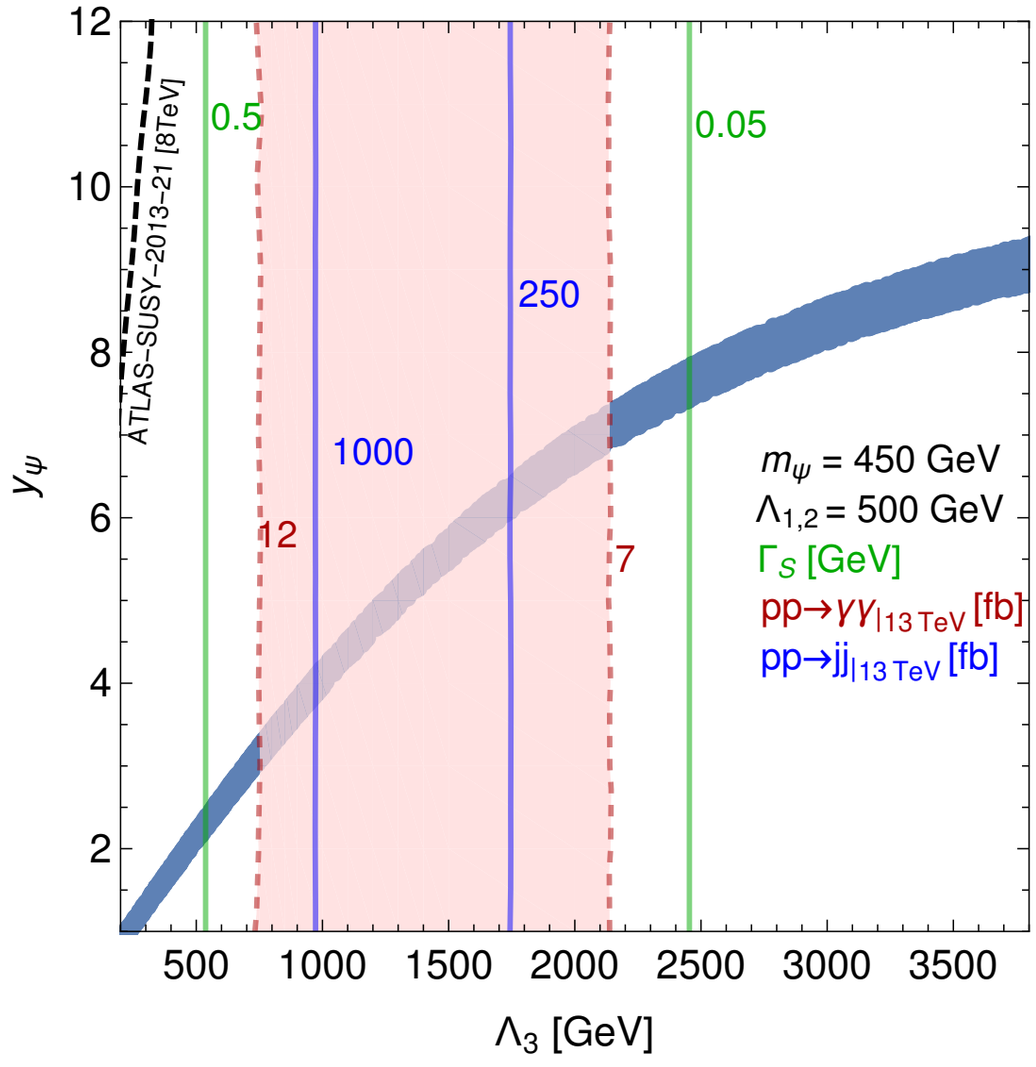


- Large part excluded by mono jet
- Relic density achieved for ypsi < 1
- Although monojet constraints and LHC diphoton excess can work, the width is very small

Results

Barducci et al arXiv: 1512.06842





- Production of DM particles via off-shell propagator
- Small width of the resonance
- Monojet constraints are weak, multijet analysis will do a better job
- Not possible to get the large width, the DM LHC constraints less interesting

Sweet spot for the model

- Three potentially independent couplings
- Reduce coupling to gluons and increase couplings to diphoton
- Can have a large coupling to dark matter since the couplings to gluons are small
- Demands a hierarchy in the coupling structure or the mass scale of the couplings

benchmark	(g_{GG}, g_{BB})	g_{DM}	M_ψ (GeV)	Γ_{tot}(GeV)	$\sigma_{\gamma\gamma}$(fb) at 13TeV	Ωh^2
p_1	(0.25,1)	2.7	322	30	6.2	0.10
p_2	(0.25,2)	2.2	307	29	25	0.12
p_3	(0.14,1)	2.7	323	29	2.1	0.12
p_4	(0.14,2)	2.3	308	31	7.8	0.12

Backovic et al arXiv:1512.0491

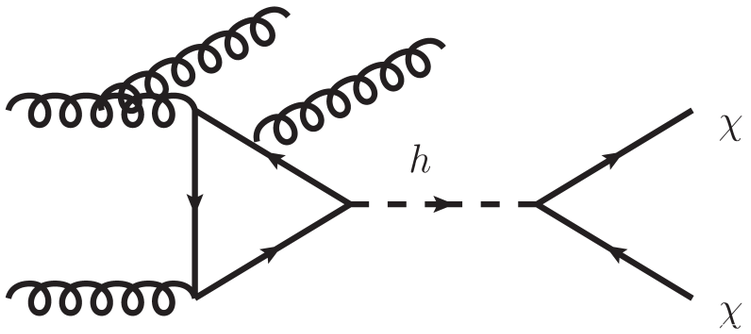
Test case: II

Exploring momentum dependent dark matter couplings

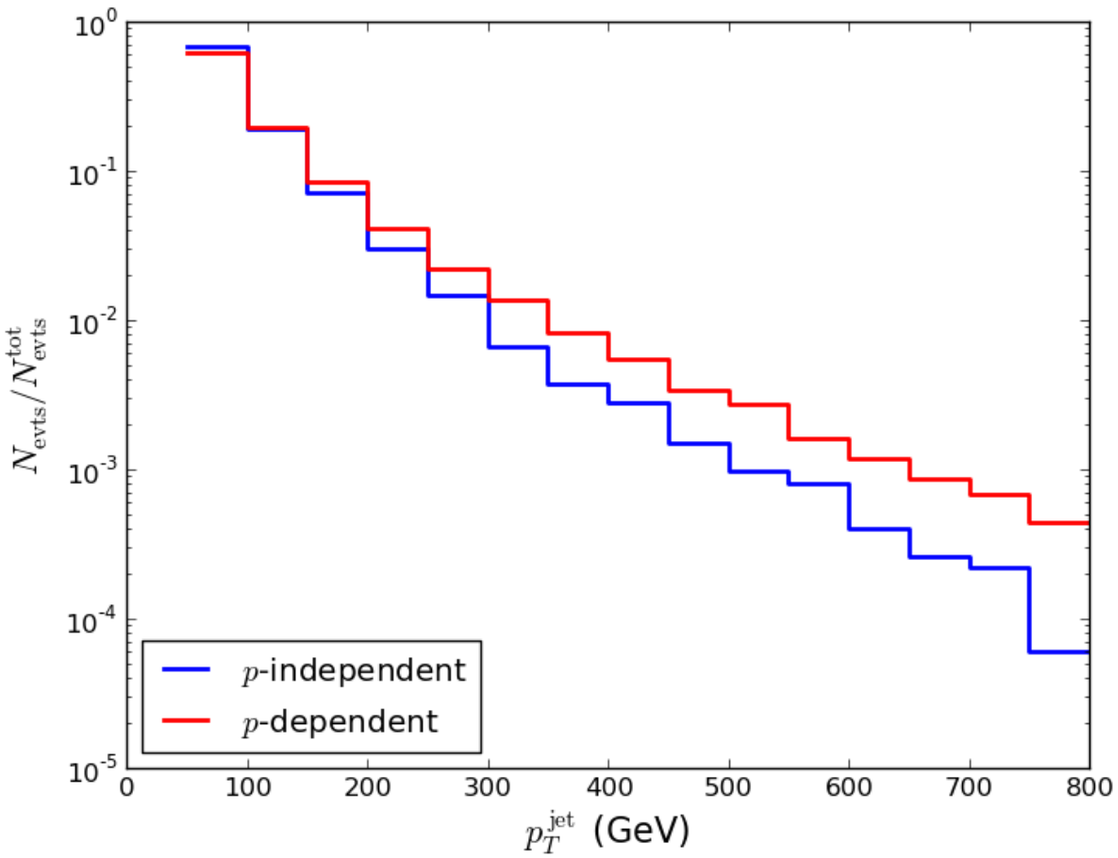
Theoretical motivation

- Dark matter could be a pseudo Nambu Goldstone Boson appearing in the low energy theory as a result of the spontaneous breaking of a global symmetry by a new strong sector dynamics
- Strong sector dynamics can appear in the context of a new strongly-coupled sector above the TeV scale
- The analogy is the pion in QCD, the pions appear as Goldstone bosons of qqbar condensate breaking the chiral symmetry
- The shift symmetry of Goldstone bosons imply that their interactions are derivative (in the exact symmetry limit)
- What kind on phenomenological limits can be placed on such dark matter scenarios and what is the sensitivity of the LHC for these couplings?

Impact on monojets

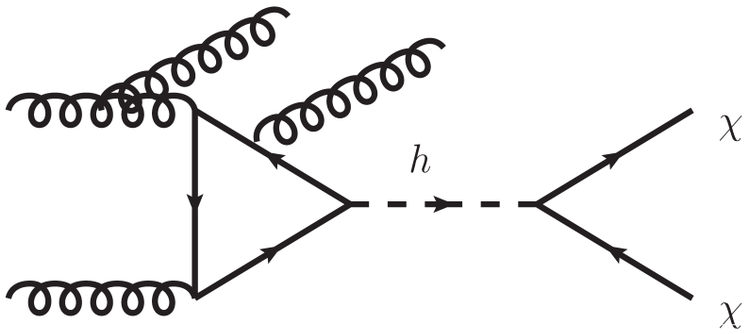


$$ig_{h\eta\eta} = 2iv\left[\lambda_{\rm mi} + \frac{p_h^2}{f^2}\right]$$

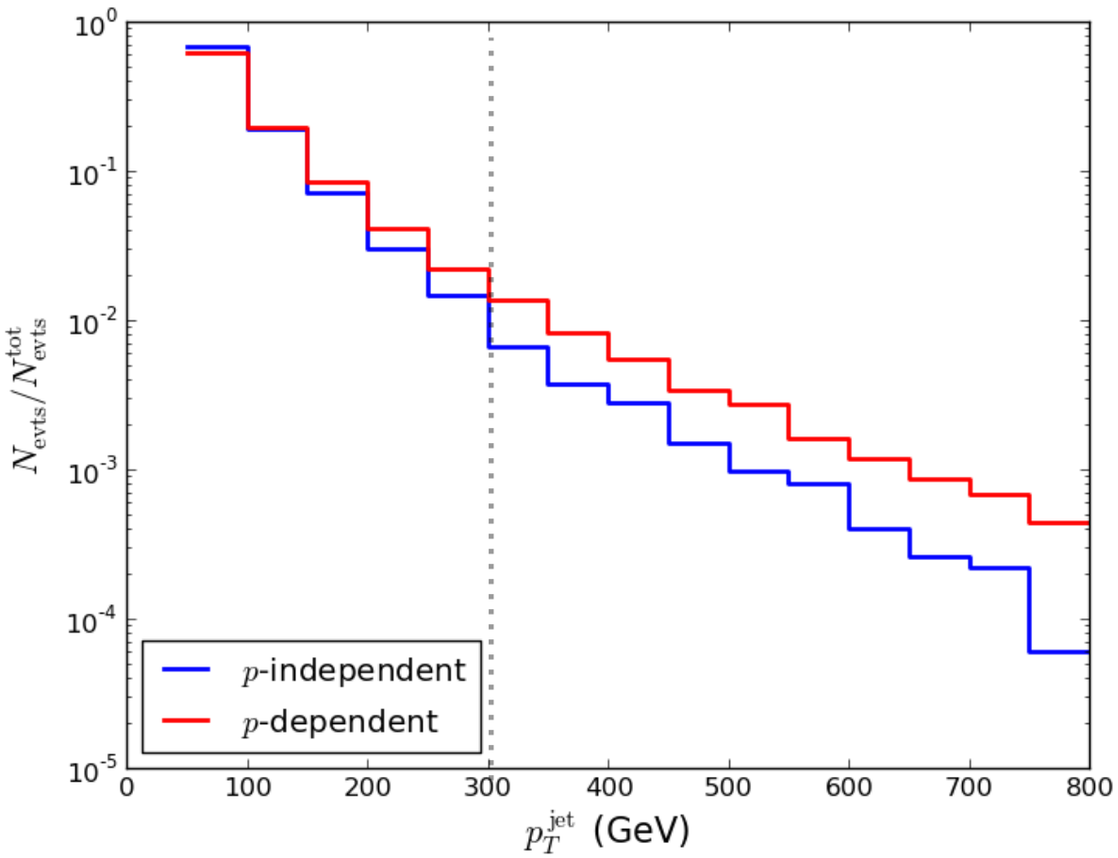


- Dark matter could be a pseudo Nambu Goldstone Boson appearing in the low energy theory as a result of the spontaneous breaking of a global symmetry by a new strong sector dynamics

Impact on monojets



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- Dark matter could be a pseudo Nambu Goldstone Boson appearing in the low energy theory as a result of the spontaneous breaking of a global symmetry by a new strong sector dynamics

Simple case

Barducci et al, to appear

- Extension of the Standard Model by gauge singlet real scalar field

$$\mathcal{L}_\eta = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}\mu_\eta^2\eta^2 - \frac{1}{4}\lambda_\eta\eta^4 - \frac{1}{2}\lambda\eta^2 H^\dagger H + \frac{1}{2f^2}(\partial_\mu\eta^2)\partial^\mu(H^\dagger H)$$

- After electroweak symmetry breaking

$$\mathcal{L}_\eta \supset -\frac{1}{4}(v+h)^2\left(\lambda\eta^2 + \frac{1}{f^2}\partial_\mu\partial^\mu\eta^2\right) \qquad m_\eta^2 = \mu_\eta^2 + \lambda v^2/2$$

scale of spontaneous symmetry breaking

Momentum dependent coupling

For mono-Higgs signature study of similar model see e.g. arXiv:1312.2592

Simple case

- Monojet production cross section

$$\hat{\sigma}(gg \to gh^* \to g\eta\eta) \propto \frac{\theta(p_h^2 - 4m_\eta^2)}{(p_h^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \left(\frac{p_h^2}{f^2} - \lambda\right)^2 \sqrt{1 - \frac{4m_\eta^2}{p_h^2}}$$

- For the onshell regime the momentum dependence vanishes

- Off-shell Higgs regime, leads to a very small cross section < 1 fb for momentum dependent and <0.5 fb for momentum independent couplings

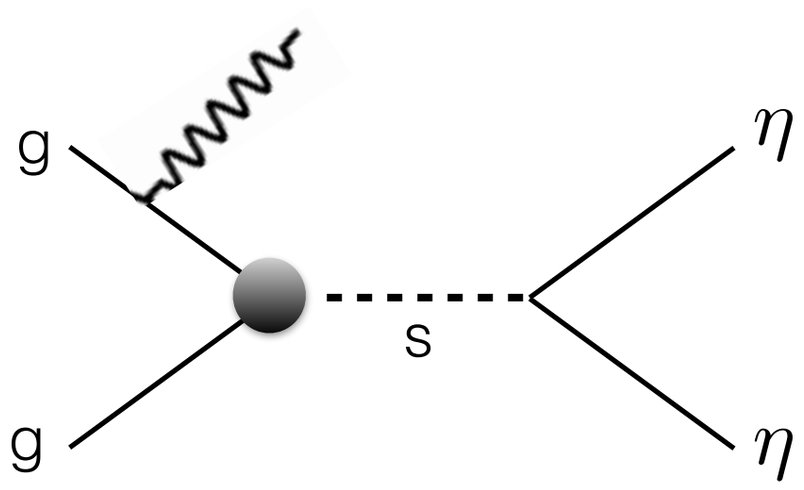
- Good measurements of Higgs production cross sections limit ggh couplings, decreasing the total cross section for monojet production

Model

Barducci et al, to appear

- Z2 odd real singlet scalar dark matter particle couplings to the Standard Model with Z2 even scalar singlet

$$\mathcal{L}_{\eta,s} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}m_\eta^2\eta\eta + \frac{1}{2}\partial_\mu s\partial^\mu s - \frac{1}{2}m_s^2 ss$$
$$+ \frac{c_{s\eta} f}{2} s\eta\eta + \frac{c_{\partial s\eta}}{f}(\partial_\mu s)(\partial^\mu\eta)\eta + \frac{\alpha_s}{16\pi}\frac{c_{sg}}{f} sG^a_{\mu\nu}G^{a\mu\nu}$$



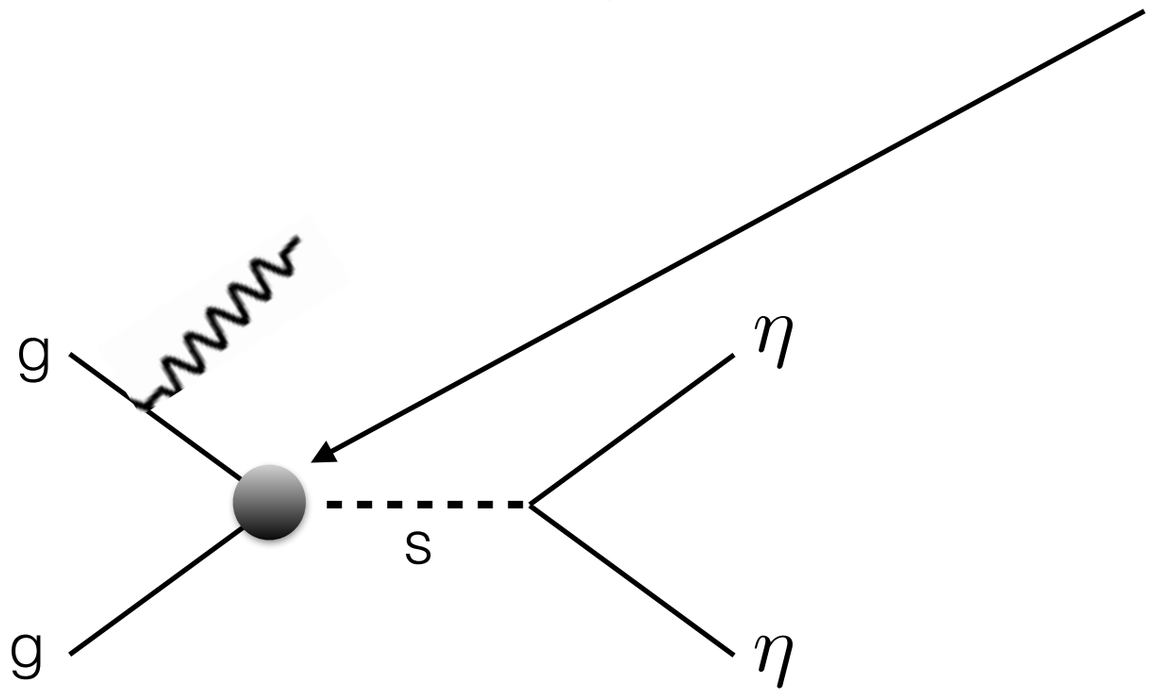
For consistent model constructions and detailed dark matter phenomenology see arXiv:1501.05957

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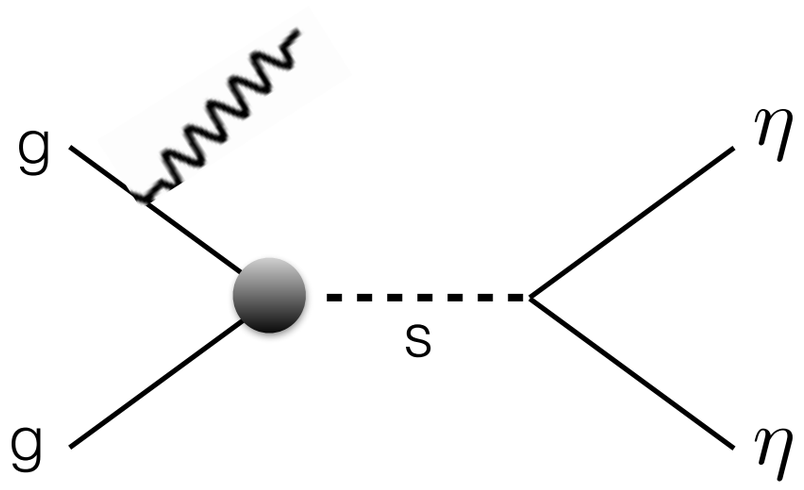
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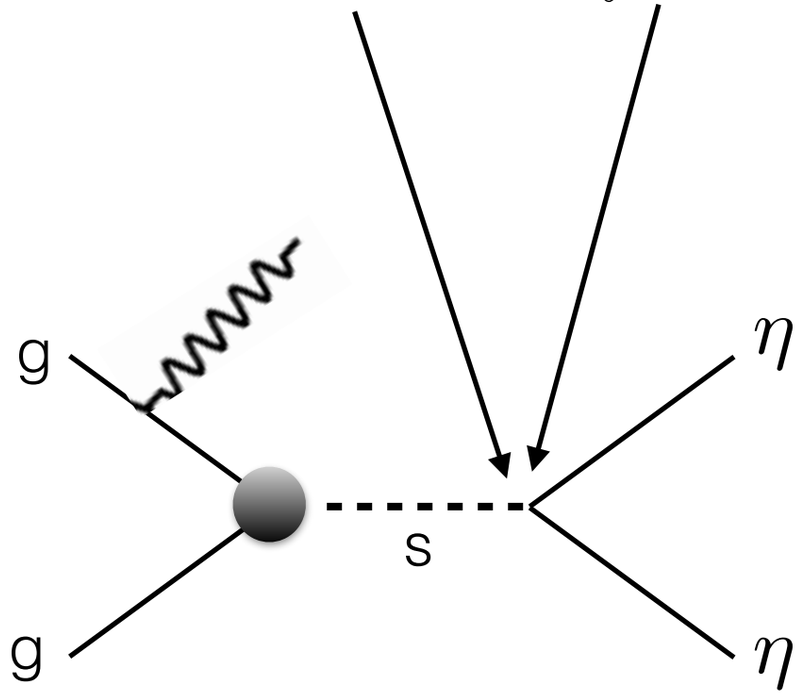
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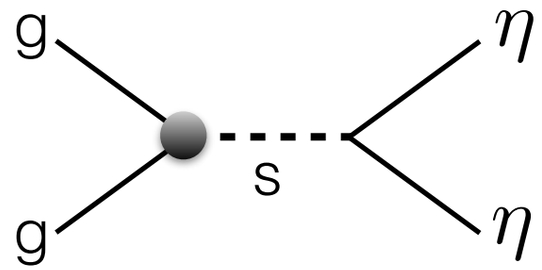


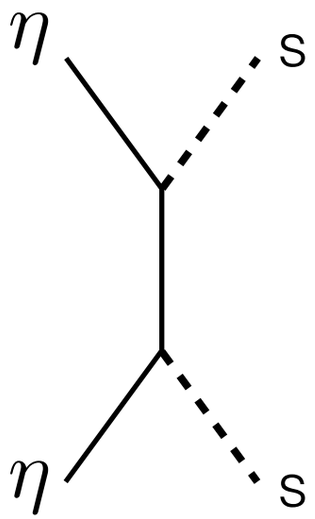
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Relic density

- Unlike LHC constraints, relic density depends on the propagator mass
- Two annihilation channels

$$\langle \sigma v \rangle_{gg} \simeq \frac{\alpha_s^2 c_{sg}^2 \left(c_{s\eta} f^2 + 4 c_{\partial s\eta} m_s^2 \right)^2}{256 \pi^3 f^4 \left(m_s^2 - 4 m_\eta^2 \right)^2}$$





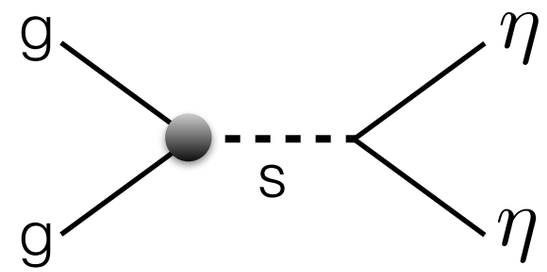
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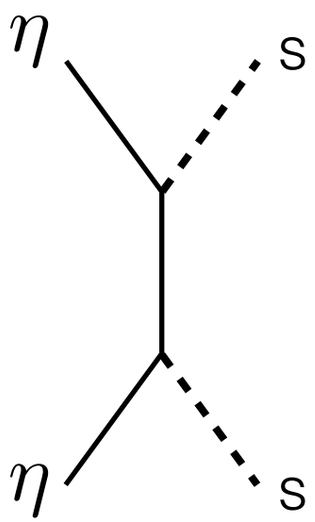
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Mostly drives relic

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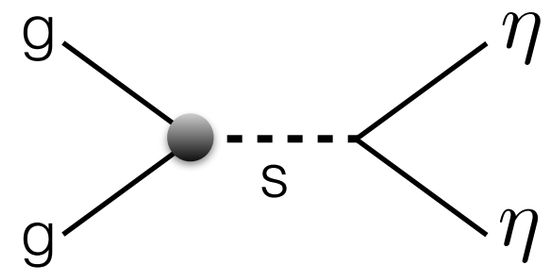
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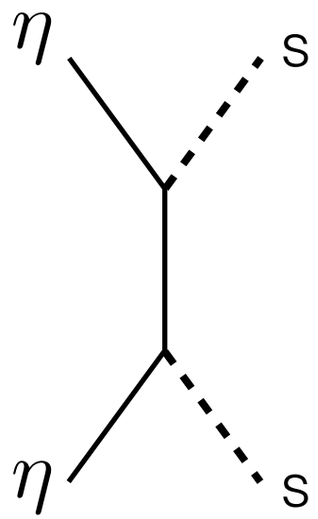
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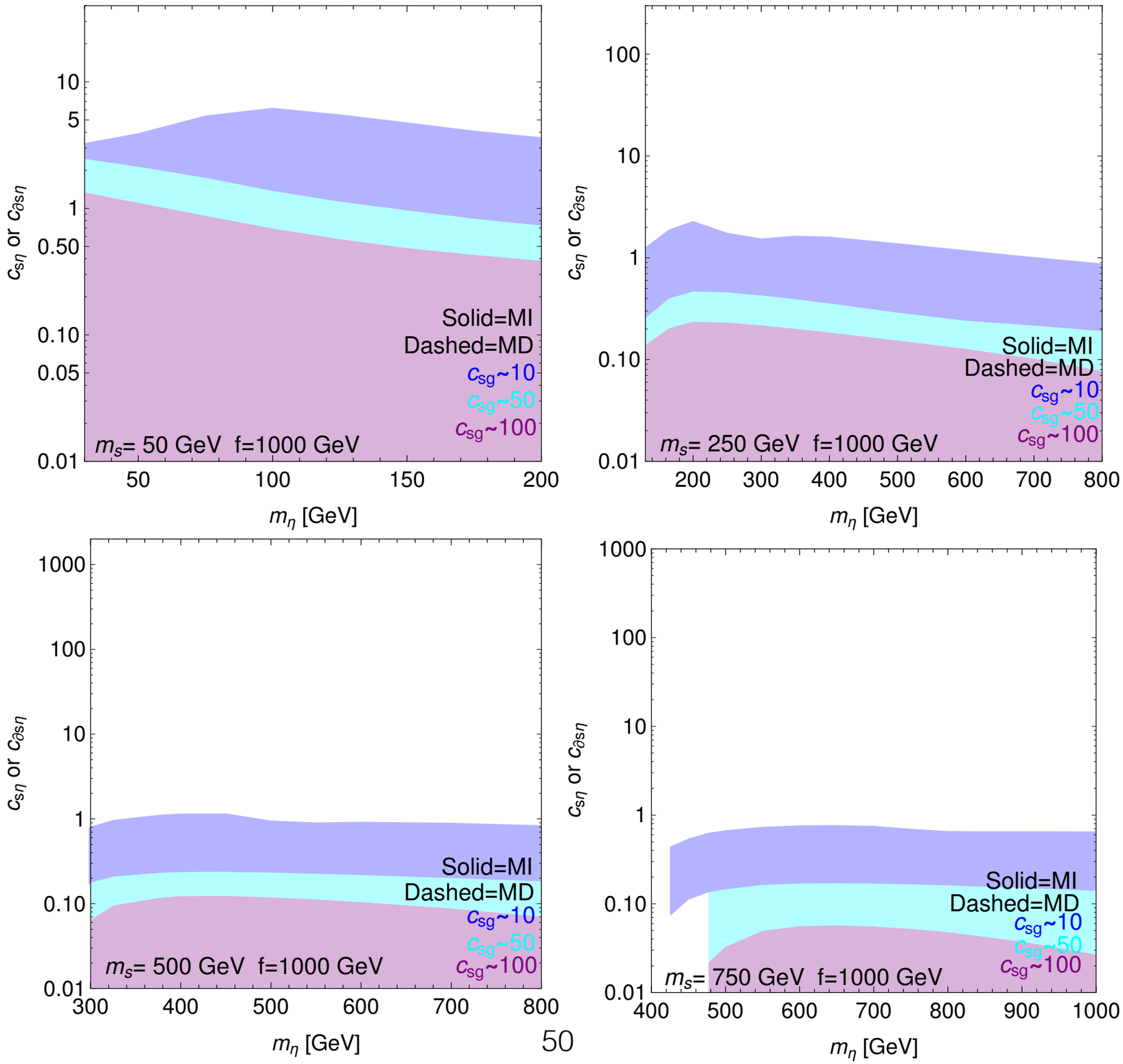


Contributes up to 15%

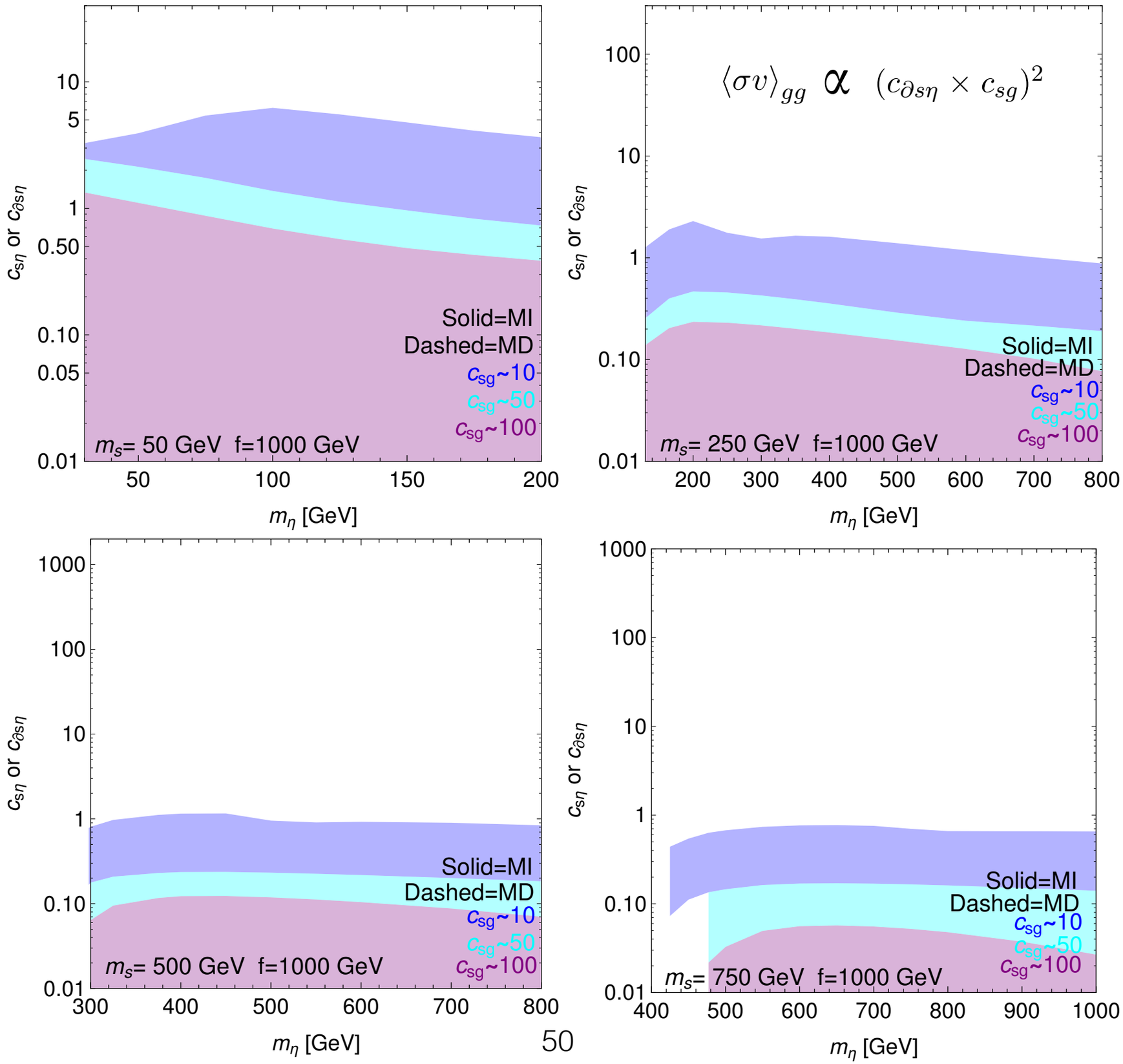


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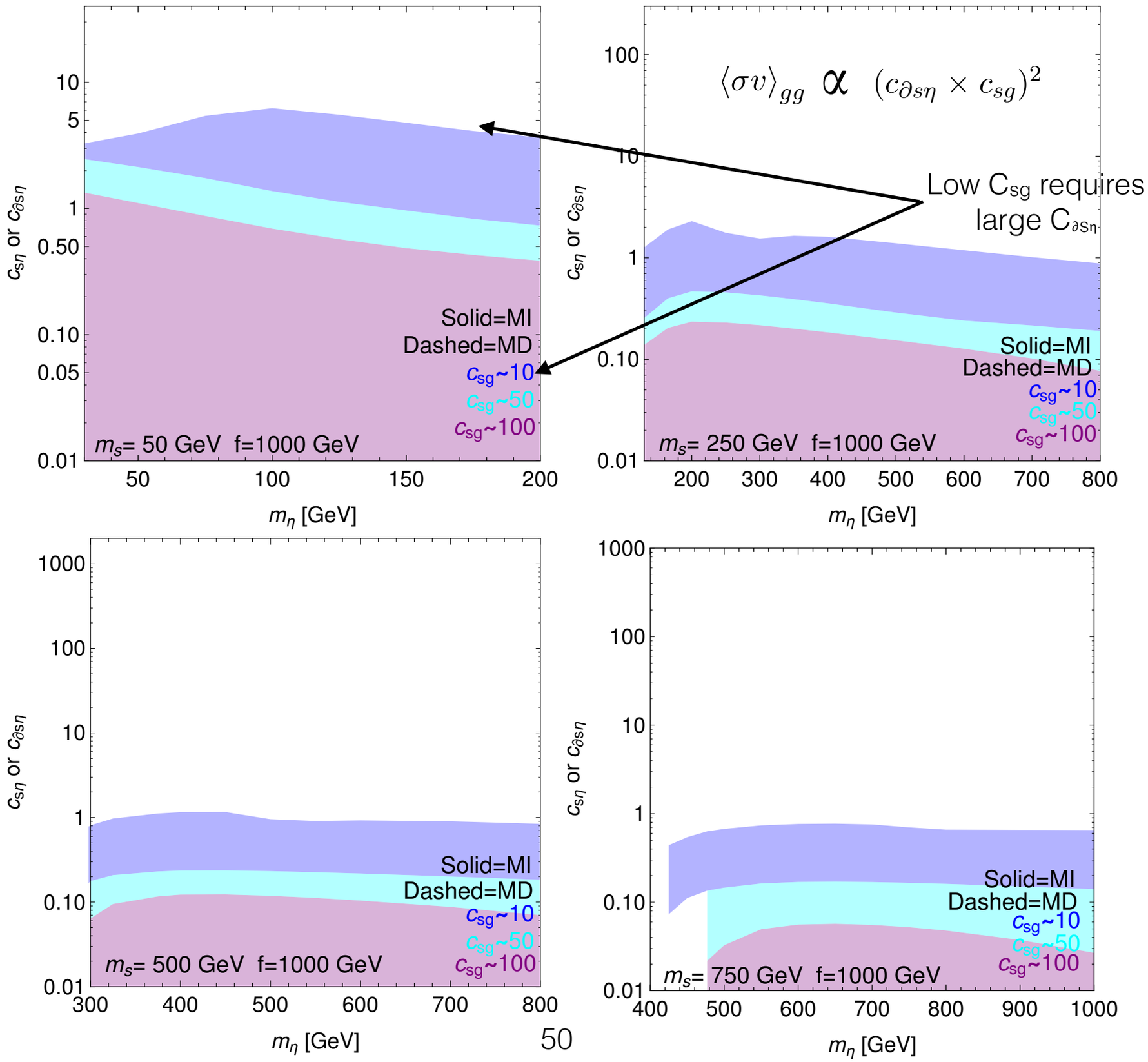
Relic density



Relic density

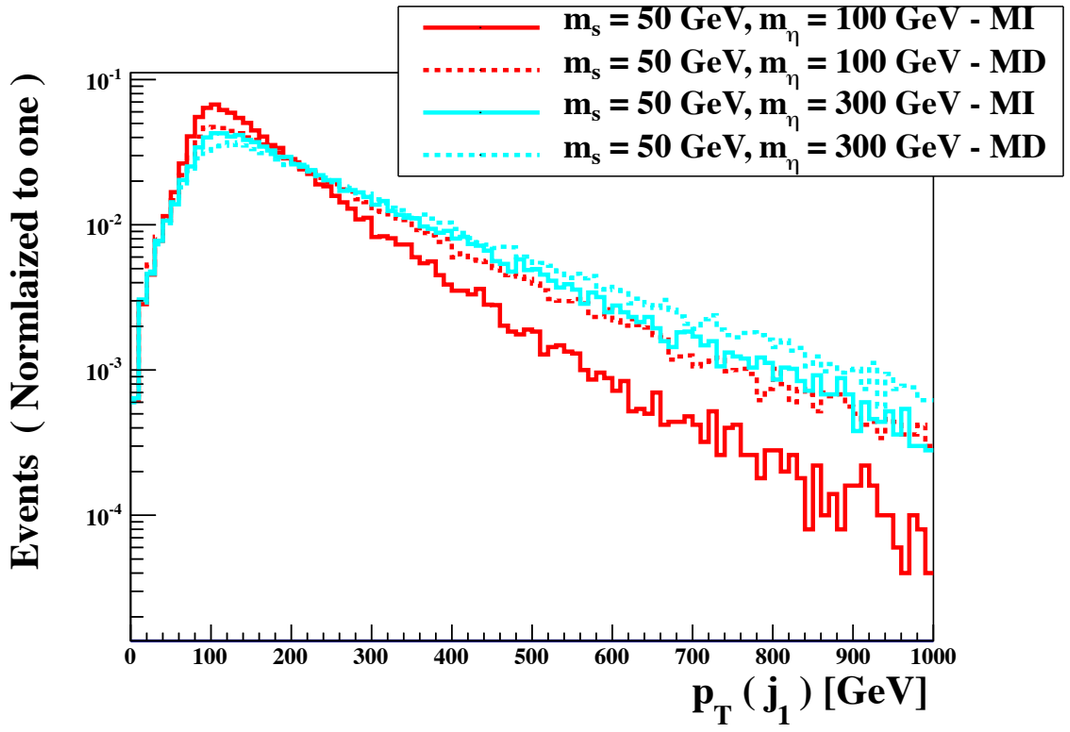


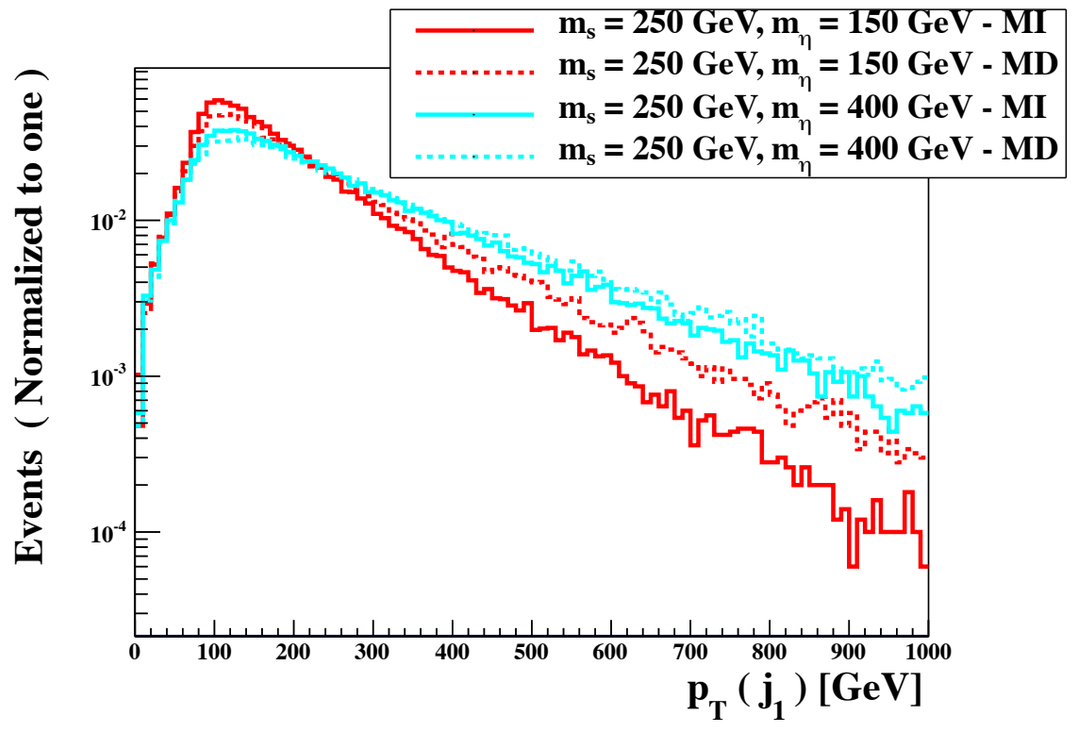
Relic density



Effect of momentum dependence

Barducci et al, to appear





$$c_{gs} = 100 \quad f = 1\ \text{TeV} \quad c_{\partial s\eta} = 2.5 \quad c_{s\eta} = 0.5$$

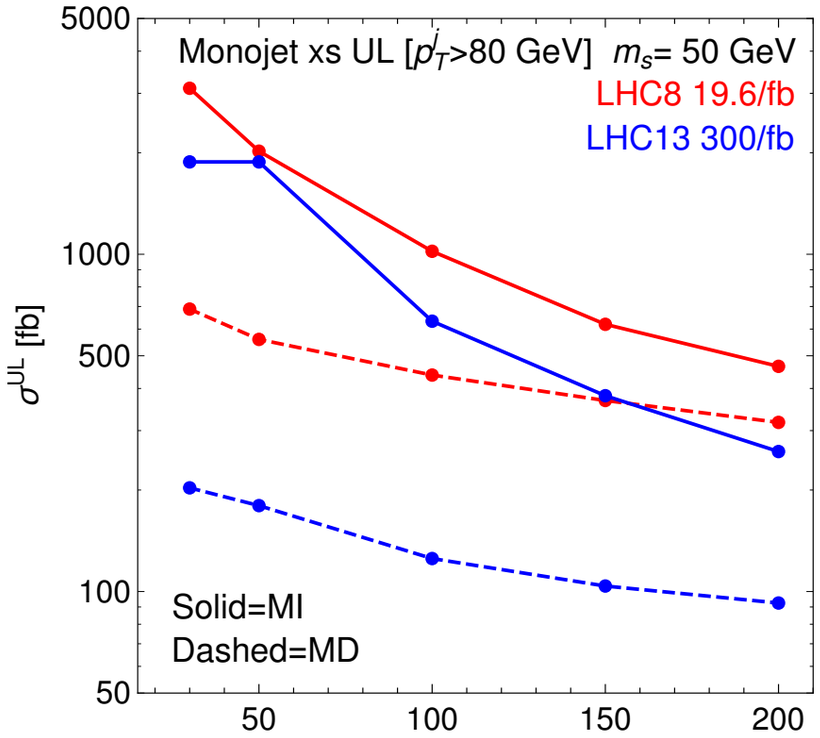
Production cross section of 2.9 pb after generator cut of jet pT > 80 GeV

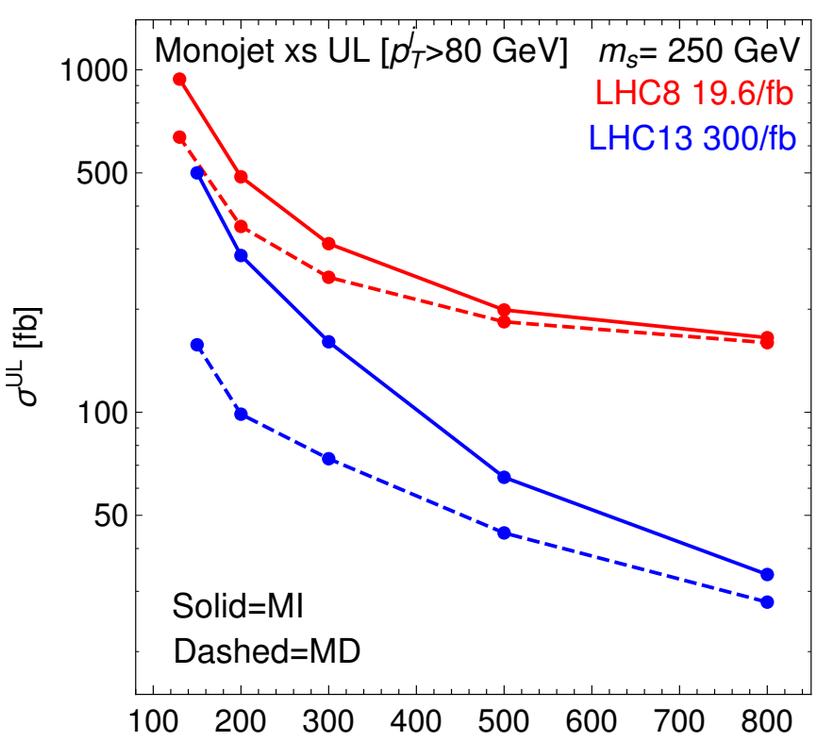
For $p_T > 300\ \text{GeV}$, Luminosity $300\ \text{fb}^{-1}$

#events MI	#events MD
131300	196533

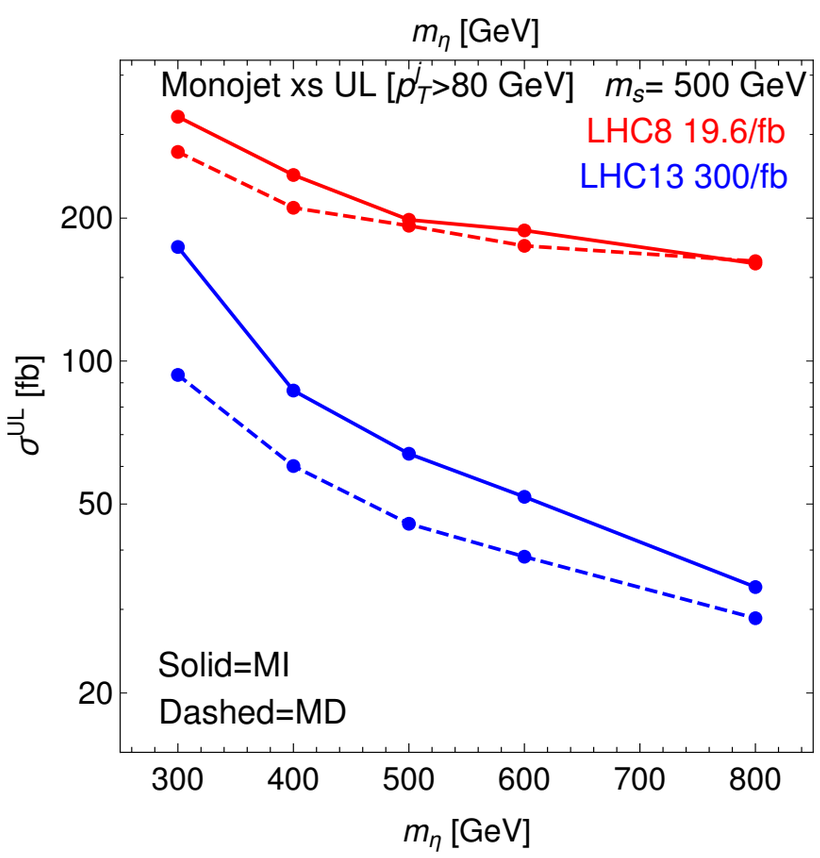
Momentum dependent expected to yield 50% better sensitivity

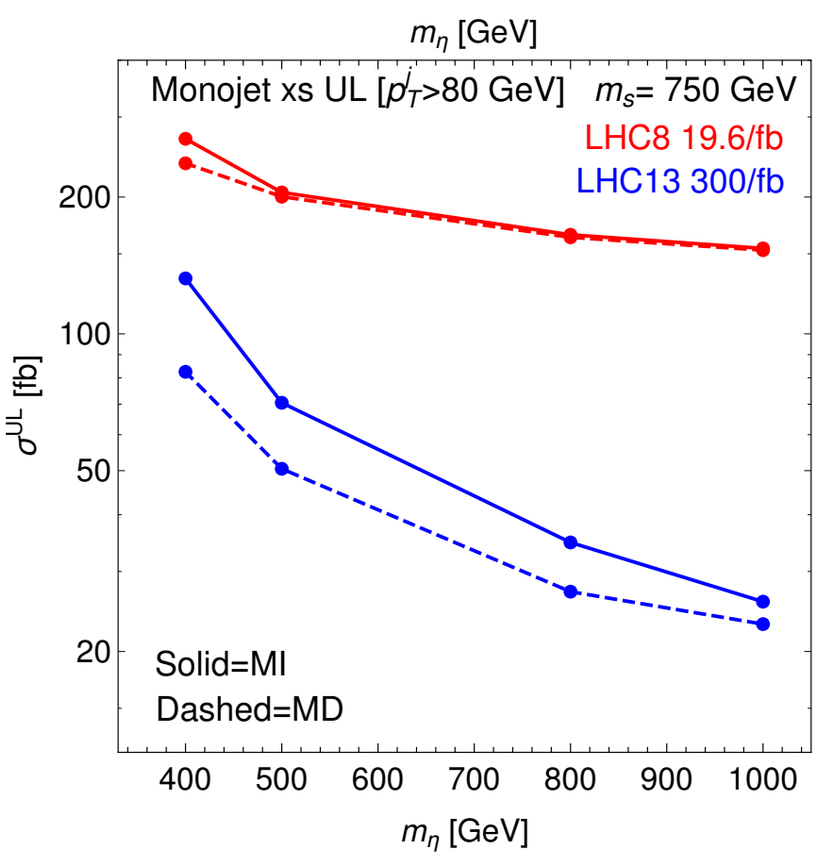
Limits



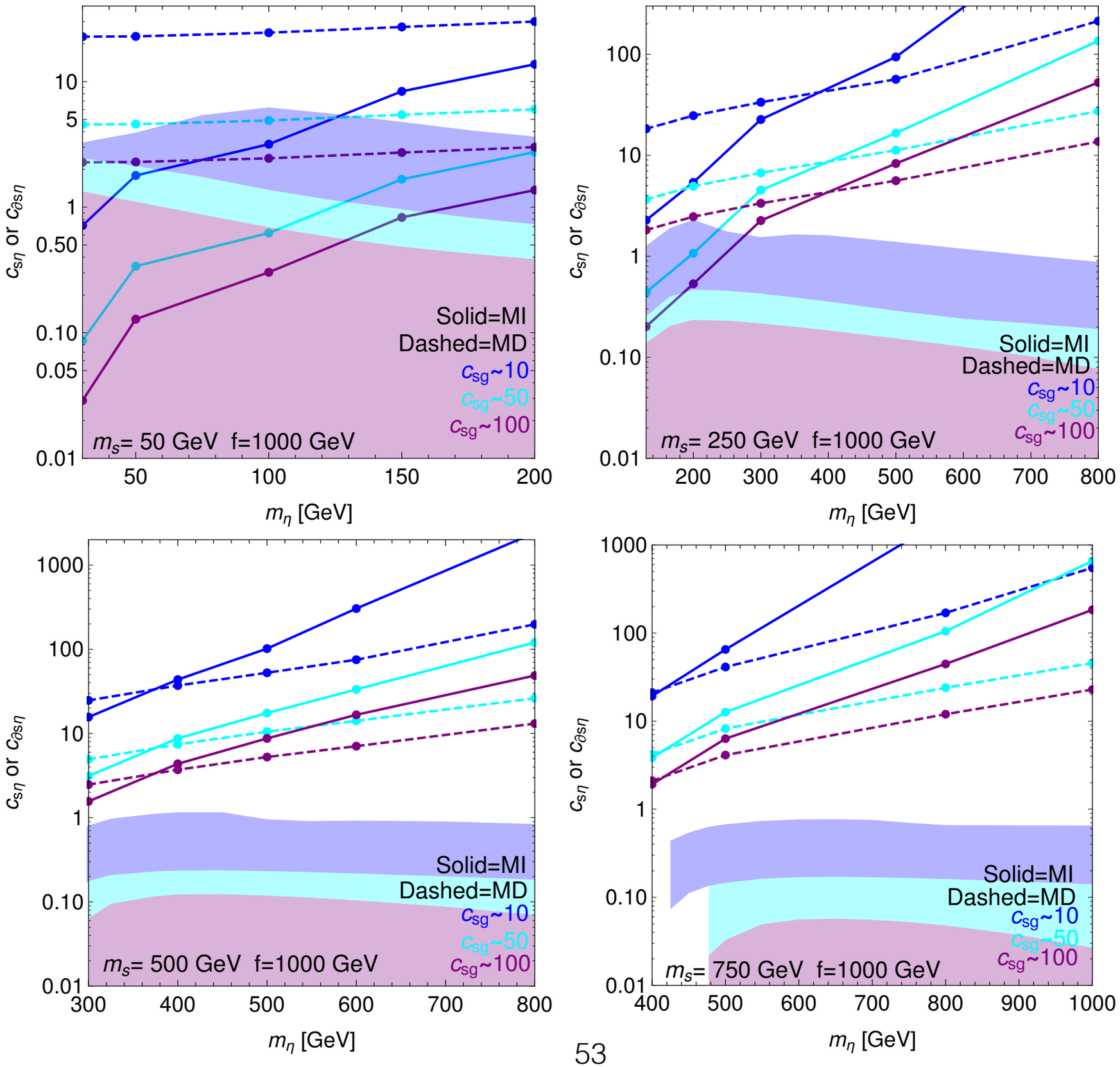


- 95% confidence level monojet cross section upper limits for momentum dependent and independent couplings





Does LHC probe the relic?



Conclusions

- Hunt for dark matter at the LHC and direct detection experiments is in full swing
- There is a strong complementarity between the direct detection and LHC searches
- Although, direct dark matter searches at the LHC probe a very tiny region of dark matter parameter it is an important channel to look at
- Monojet searches play an important role in exploring the dark matter parameter space at the LHC (and in most cases, yield the strongest constraints out of all mono-X searches)
- The dark matter motivated explanations 750 GeV diphoton excess are well constrained by the monojet searches
- Reconciling the monojet searches, the diphoton excess and other LHC searches demand a hierarchy in the resonance couplings
- Dark matter can also have momentum dependent couplings e..g. if dark matter is pNGB boson
- The momentum dependent and independent couplings yield genuine differences in the pT distributions of the jets and hence in the limits derived from monojet searches

Conclusions

- As long as diphoton excess is concerned:

