Hi!

Impact of LHC monojet searches on new physics scenarios

Suchita Kulkarni
HEPHY, Vienna

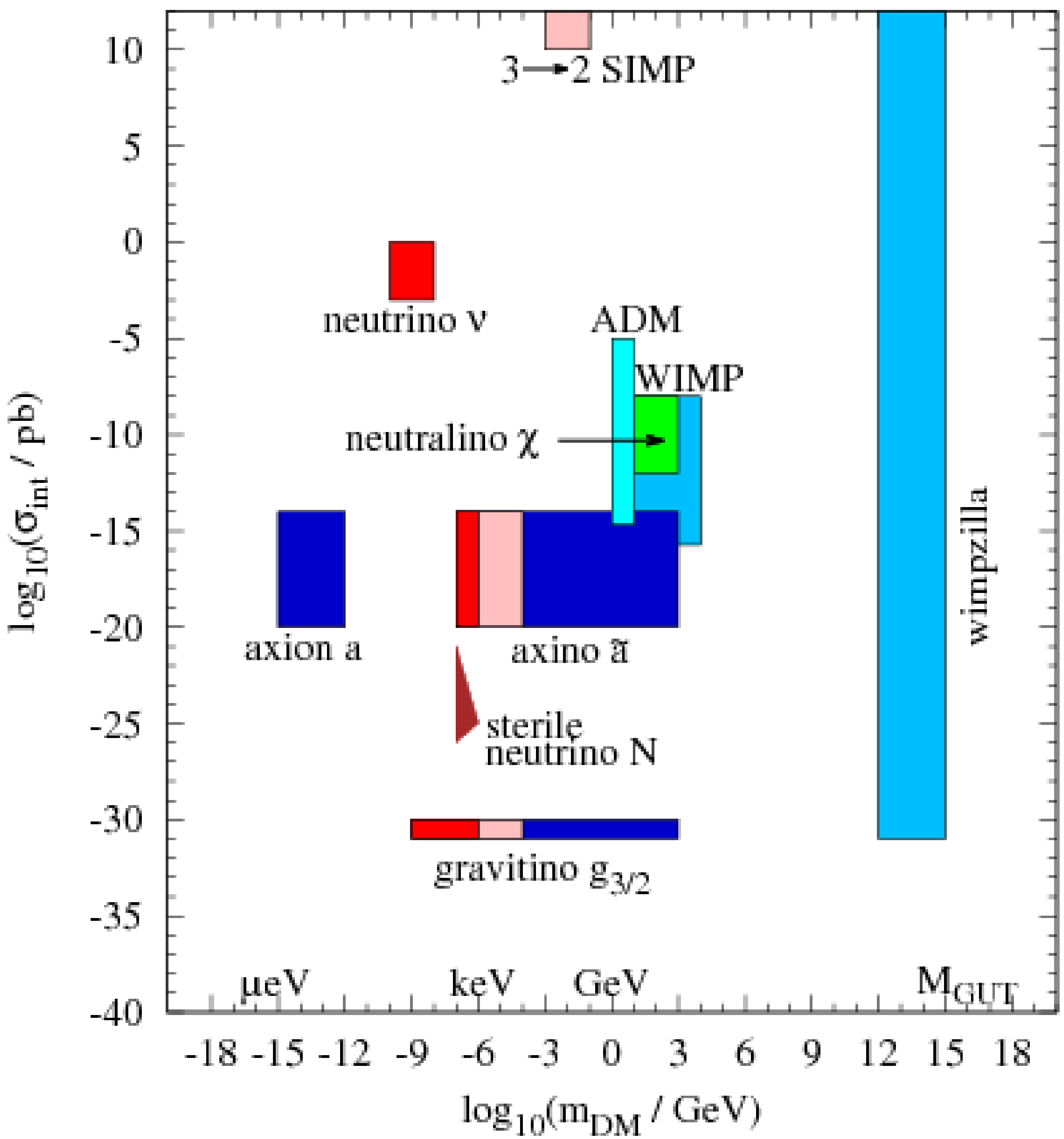
Based on:

1) arXiv:1512.06842 (D. Barducci, A. Goudelis, D. Sengupta) [JHEP 1605 (2016) 154]
2) arXiv:1605.07962 (M. Backovic, A. Mariotti, E. Maria Sessolo, M. Spannowsky)
3) arXiv:1605.02684 (D. Barducci, A. Bharucha, N. Desai, M. Frigerio, B. Fuks, A. Goudelis, S. Lacroix, G. Polesello, D. Sengupta) [Les Houches Proceedings]

10 June 2016, UCL, London, UK

Dark matter landscape

Baer et al, arXiv:1407.0017



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

Dark matter landscape

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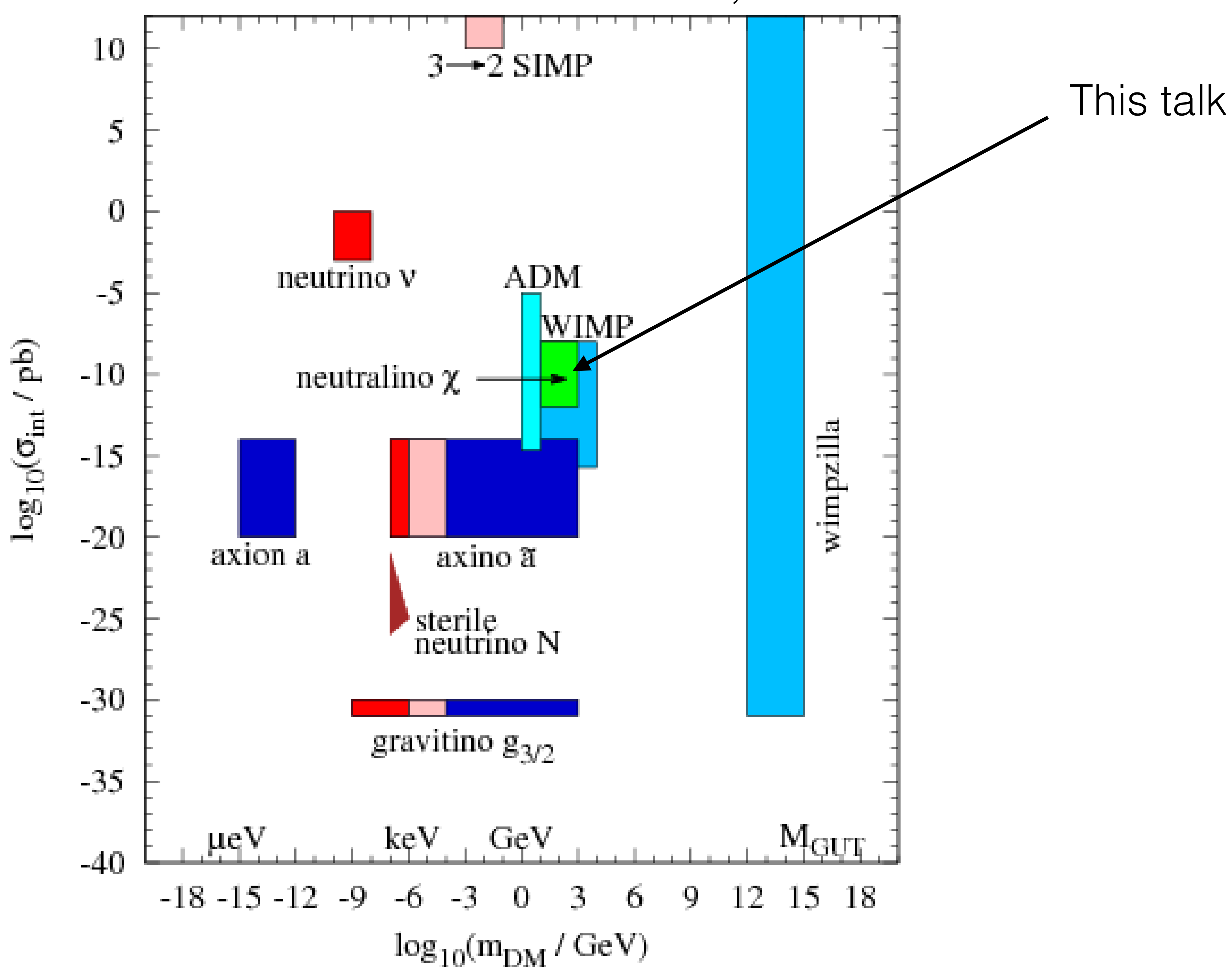

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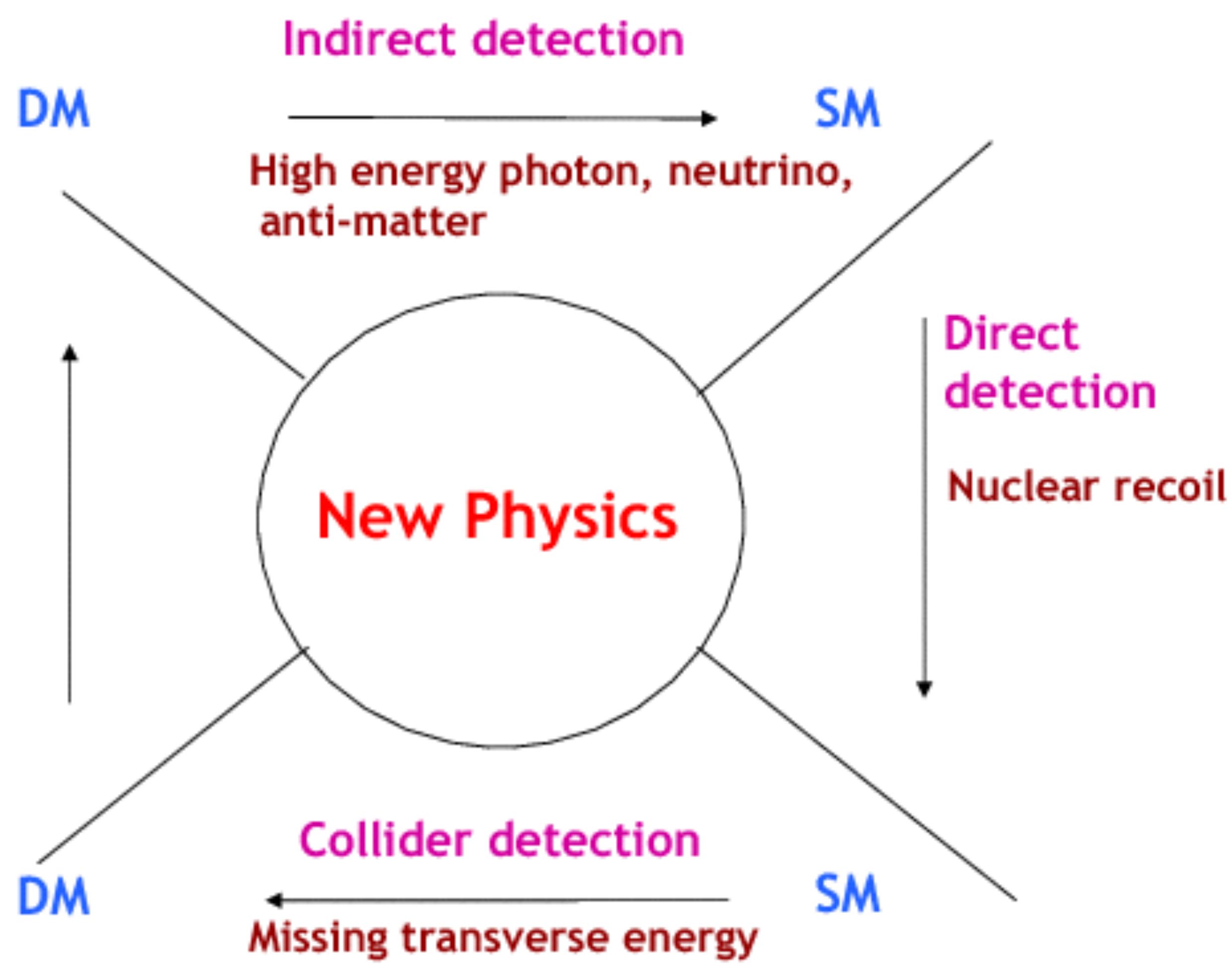
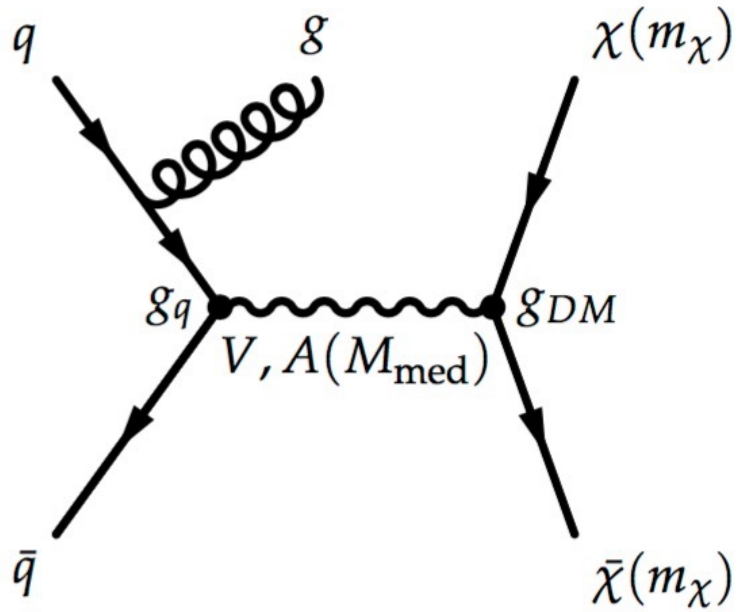
WIMP



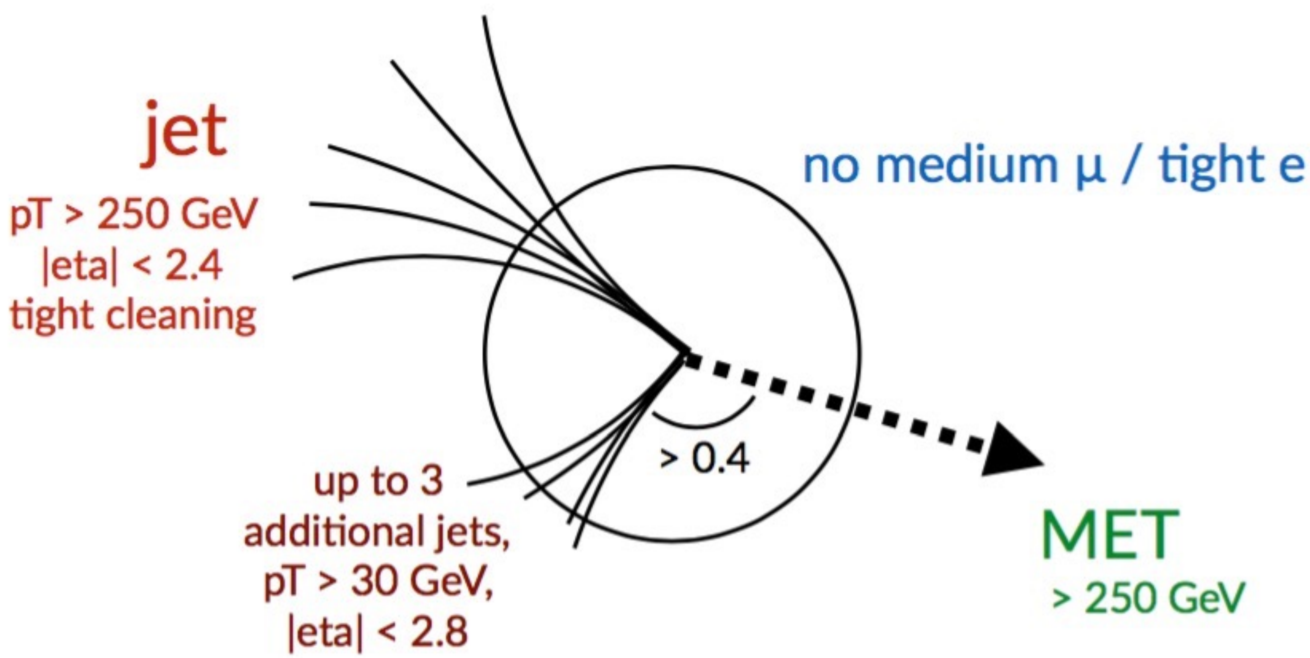
Indirect detection
DM
SM
High energy photon, neutrino, anti-matter
Direct detection
Nuclear recoil
New Physics
Collider detection
DM
SM
Missing transverse energy

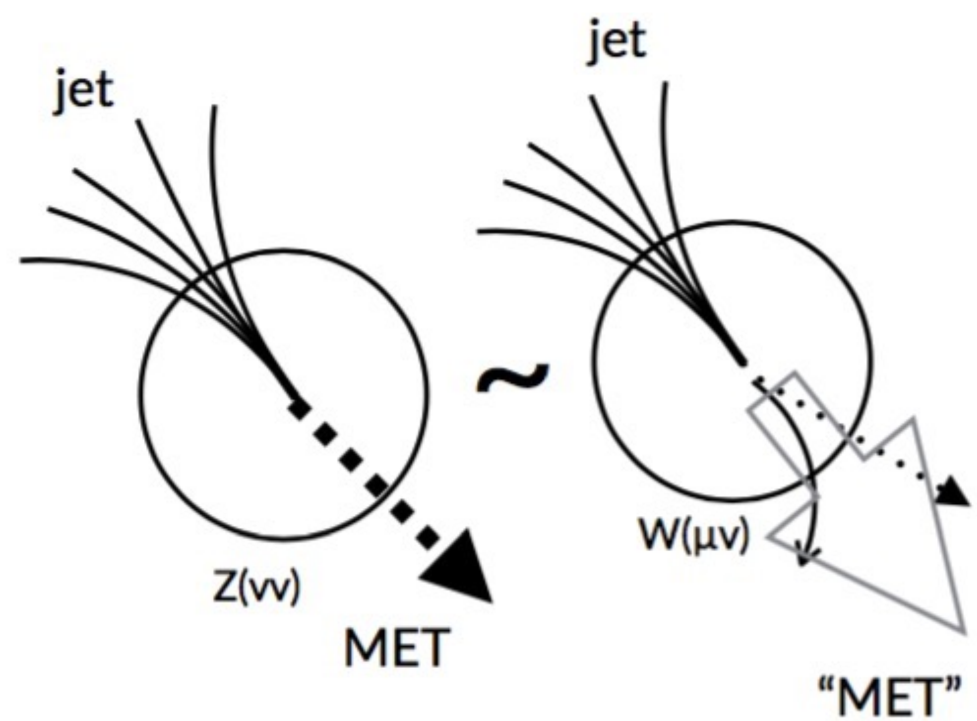
WIMPs @ LHC

Figures curtesy A. Boveia's talk

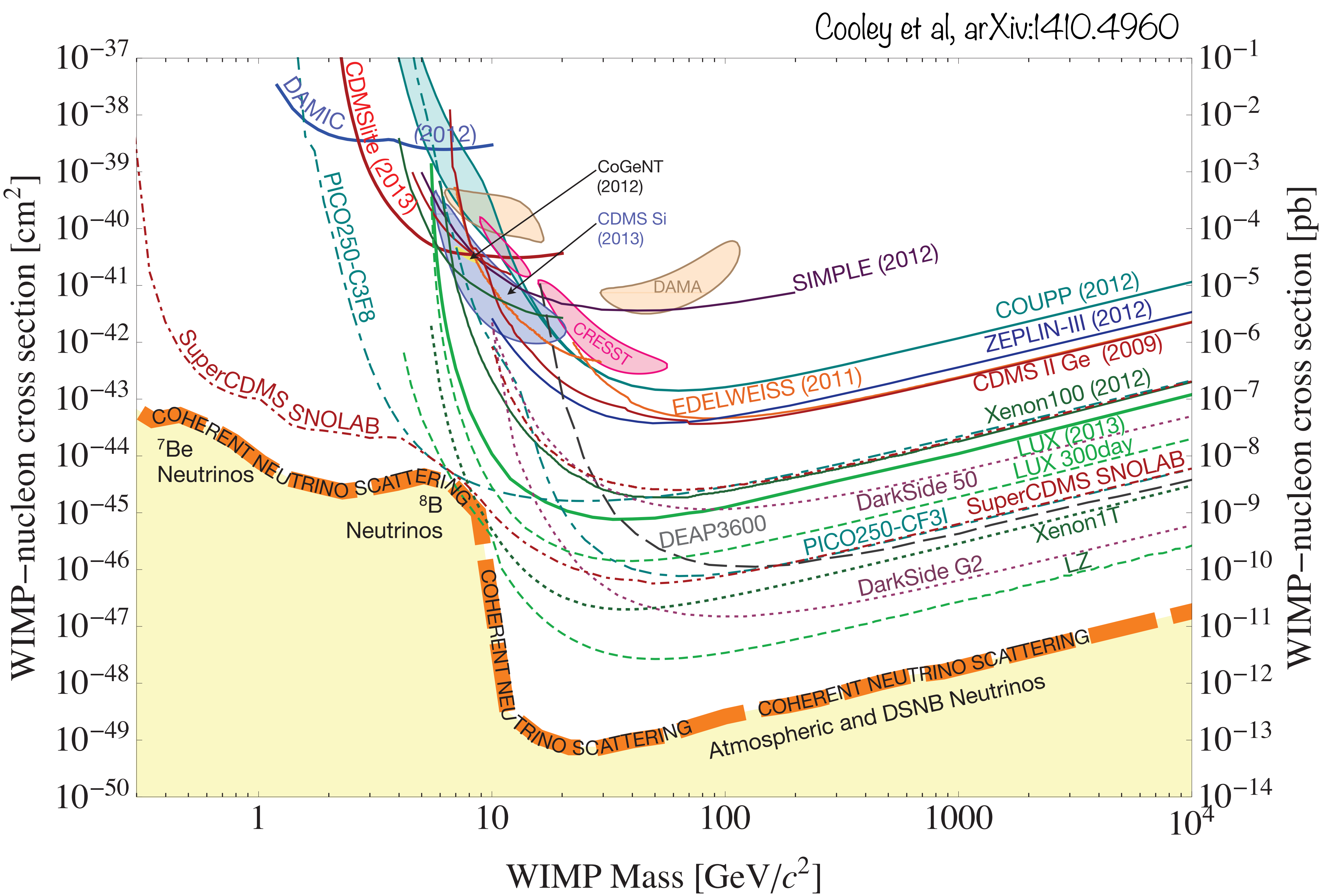


- Signal regions with successively larger MET requirement



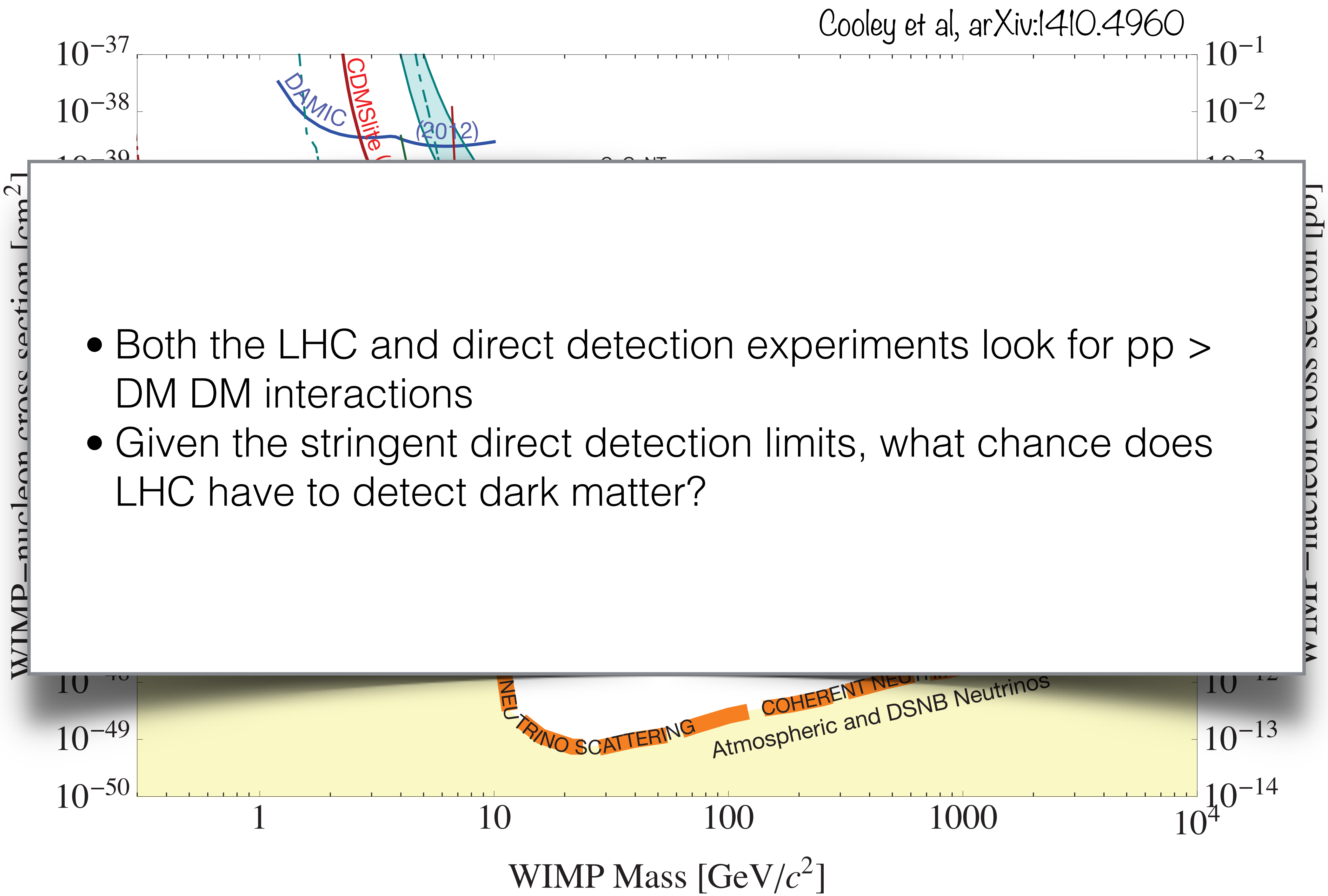


Why LHC?



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)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
LUX 300day
SuperCDMS SNOLAB
DarkSide 50
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
COHERENT NEUTRINO SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos

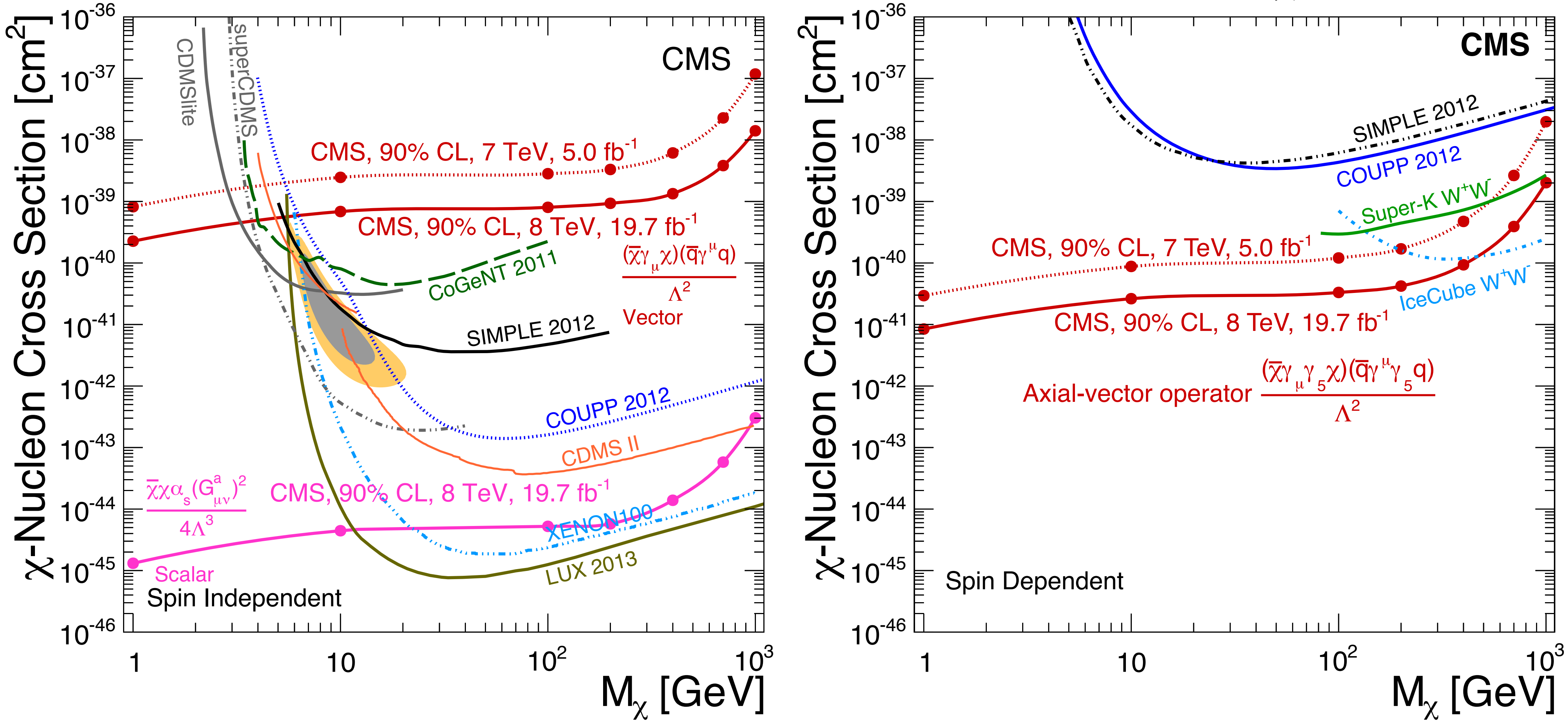
Why LHC?



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

Why LHC?

arXiv:1408.3583



- 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?

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

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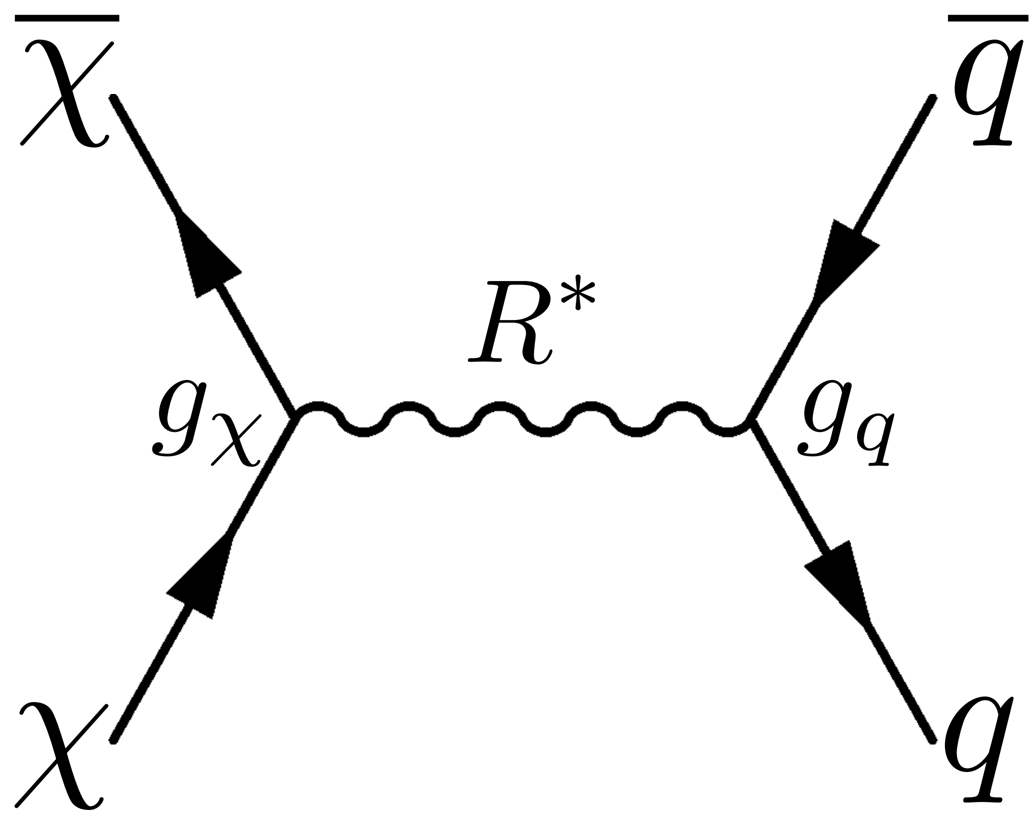

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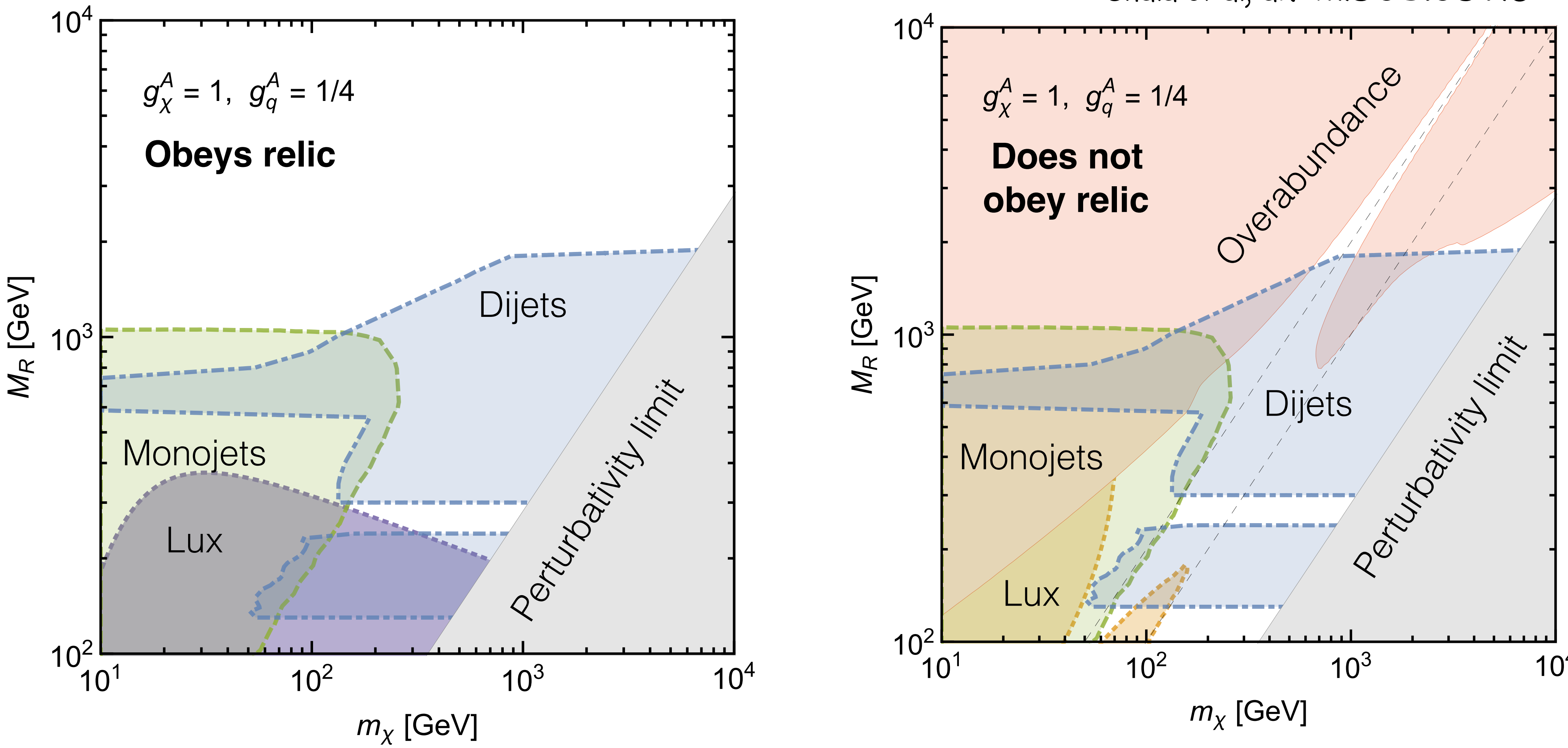
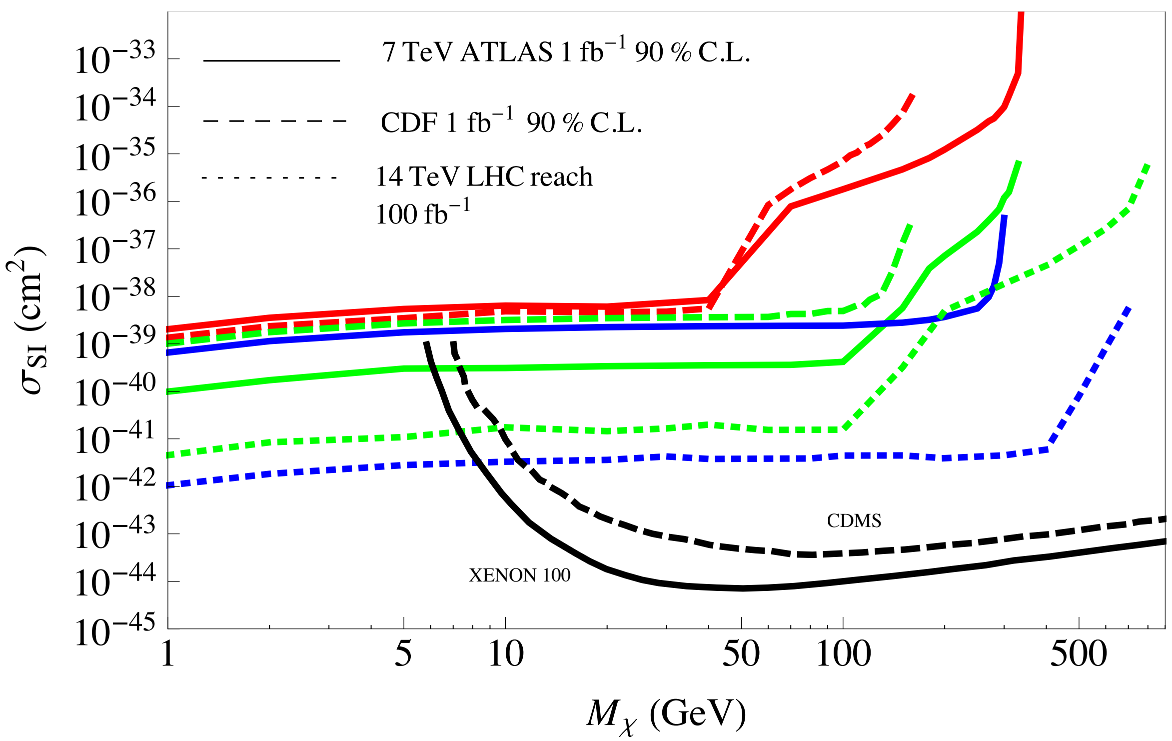
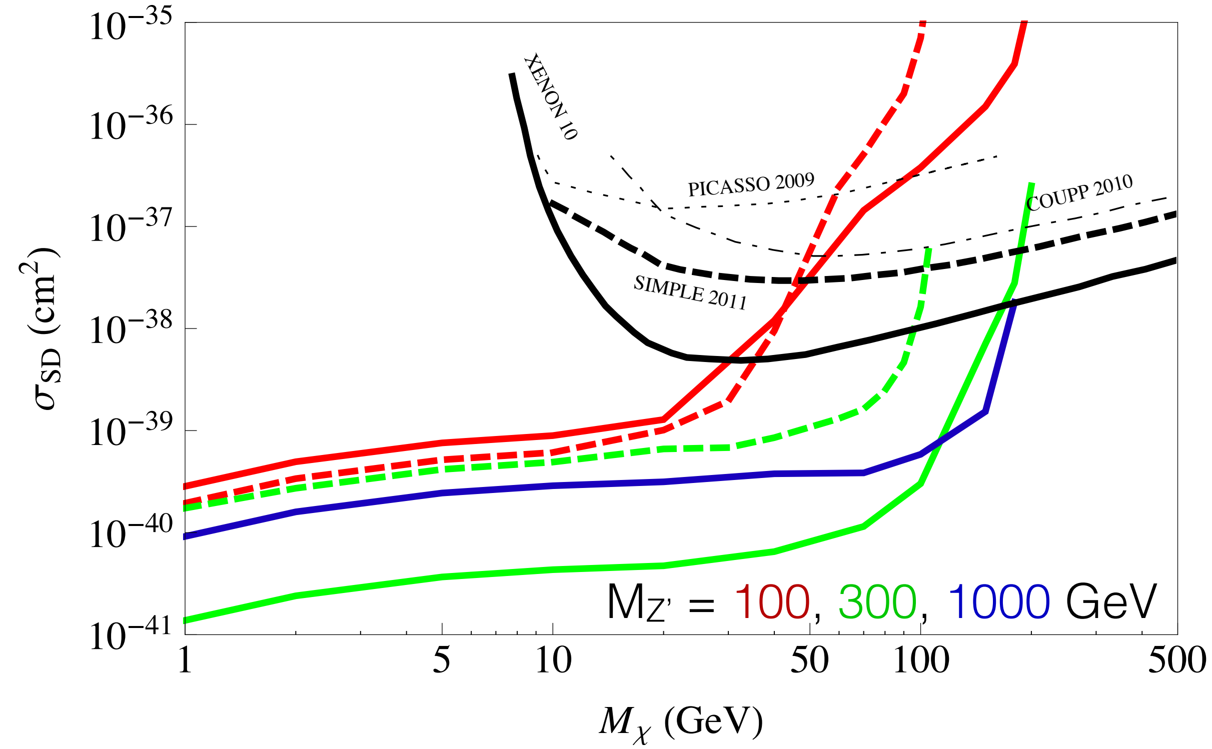
Chala et al, arXiv:1503.05916



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

NB: CRESST limits not included on the plots

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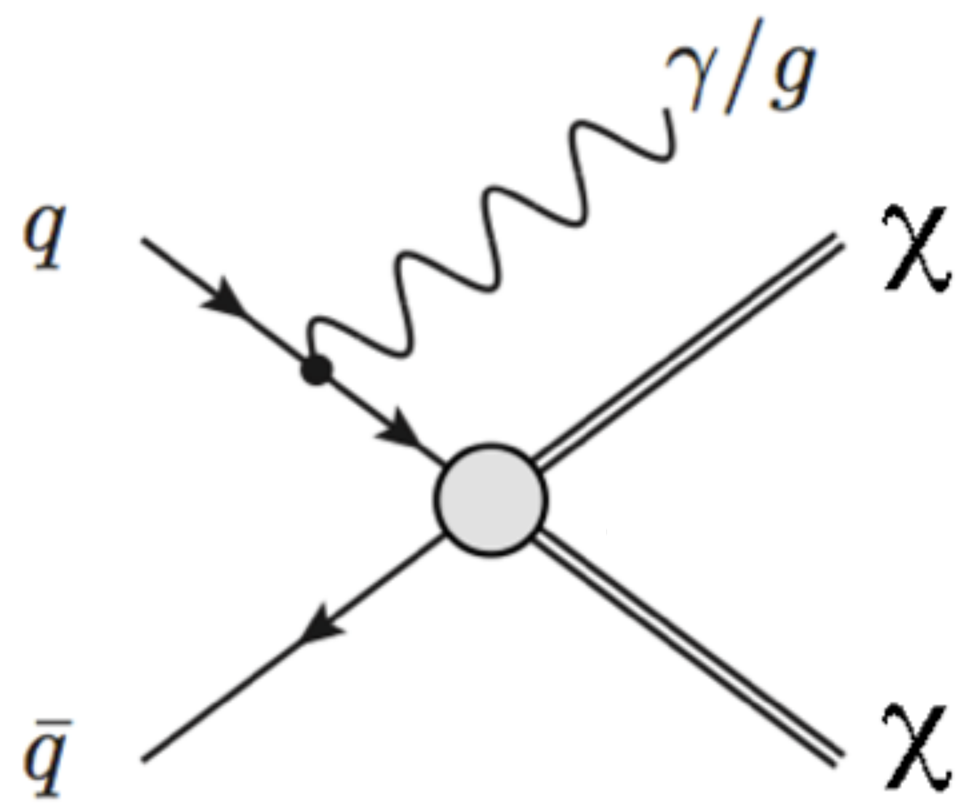
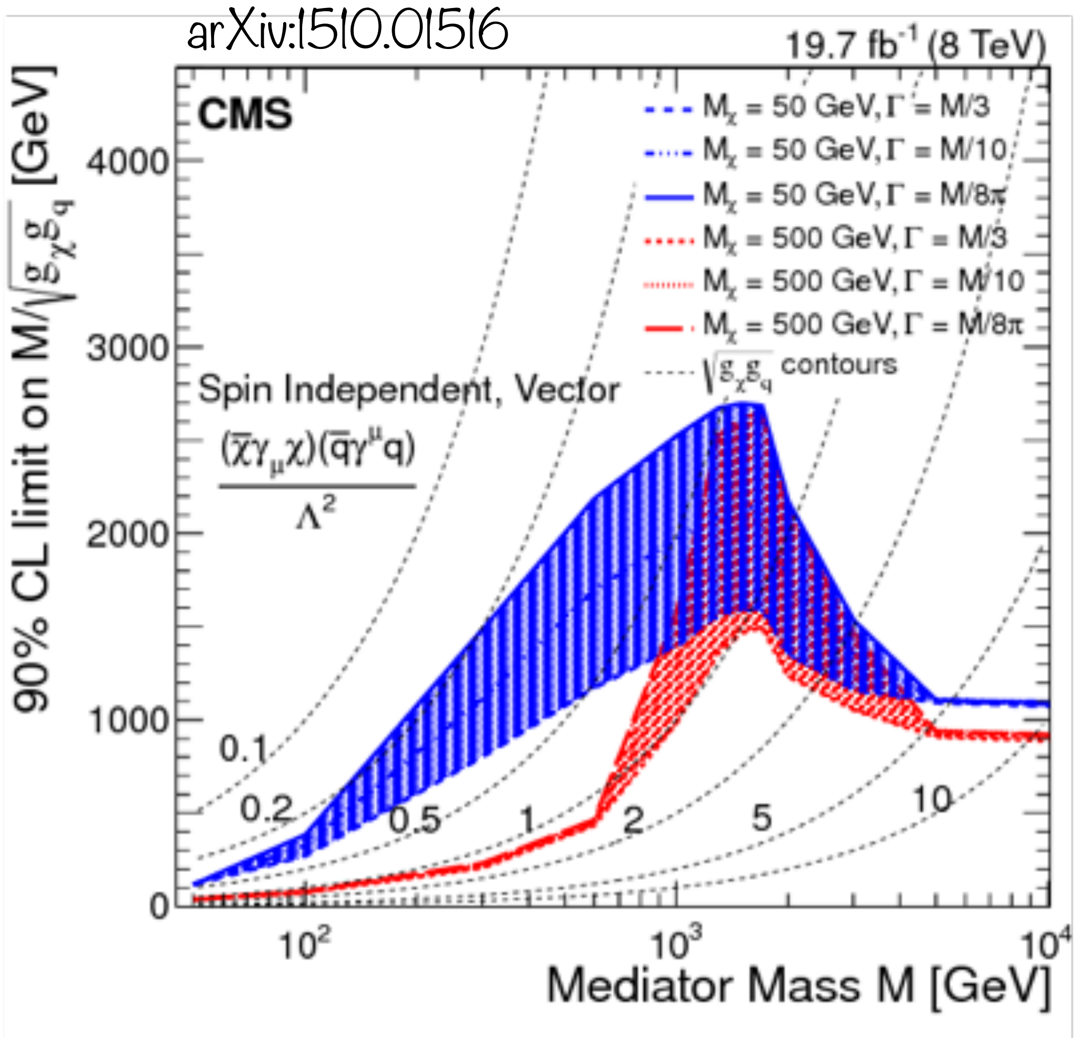
It does not have to be…

- If dark matter relic is driven by co-annihilations, then p p > DM DM interactions can be negligible, both dark matter searches at the LHC and direct detection experiments can loose
- WIMPs can be heavy
- WIMP is one of the many possible dark matter candidates
- p p > DM DM one of the many possible dark matter interactions
- Important to remember, 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

DM @ LHC





- Derived limits often depend on exact theoretical scenario, mediator width, couplings and masses
- Necessary to reinterpret mono jet limits within a given theoretical scenario

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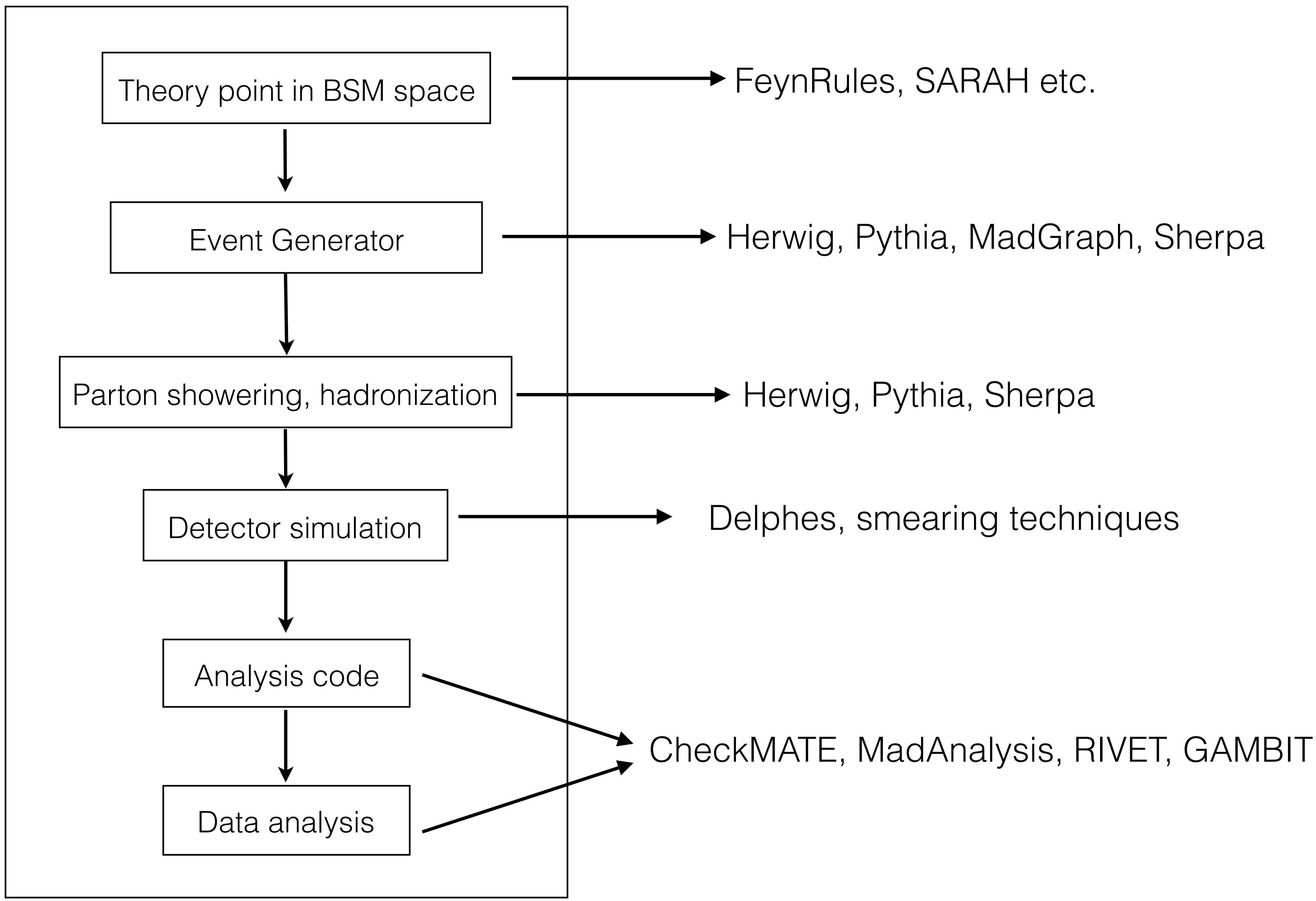
Analysis reinterpretation

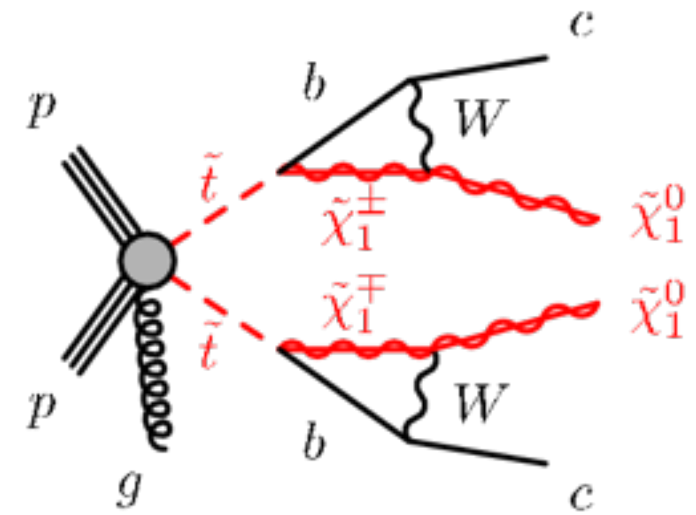


MadAnalysis5

- Public framework for analysing Monte-Carlo events
- Has different levels of sophistication — partonic, hadronic, detector reconstructed
- Input formats: StdHEP, HepMC, LHE, LHCO, Delphes ROOT files
- Normal mode: Initiative commends typed in python interface
- Expert mode: C++/ROOT programmes

http://madanalysis.irmp.ucl.ac.be/,
Conte et al Eur. Phys. J. C74 (2014), no. 10 3103 ,
Dumont et al. Eur. Phys. J. C75 (2015), no. 2 56

ATLAS-SUSY-2013-21



- Analysis designed to search for compressed stops
- Considers monojet (ISR) and c-tagging
- Only monojet analysis implemented in MA5
- Monojet analysis: three signal regions of different pT and missing ET ((pT, ET)= (280, 220), (340,340),(450,450))

ATLAS-SUSY-2013-21

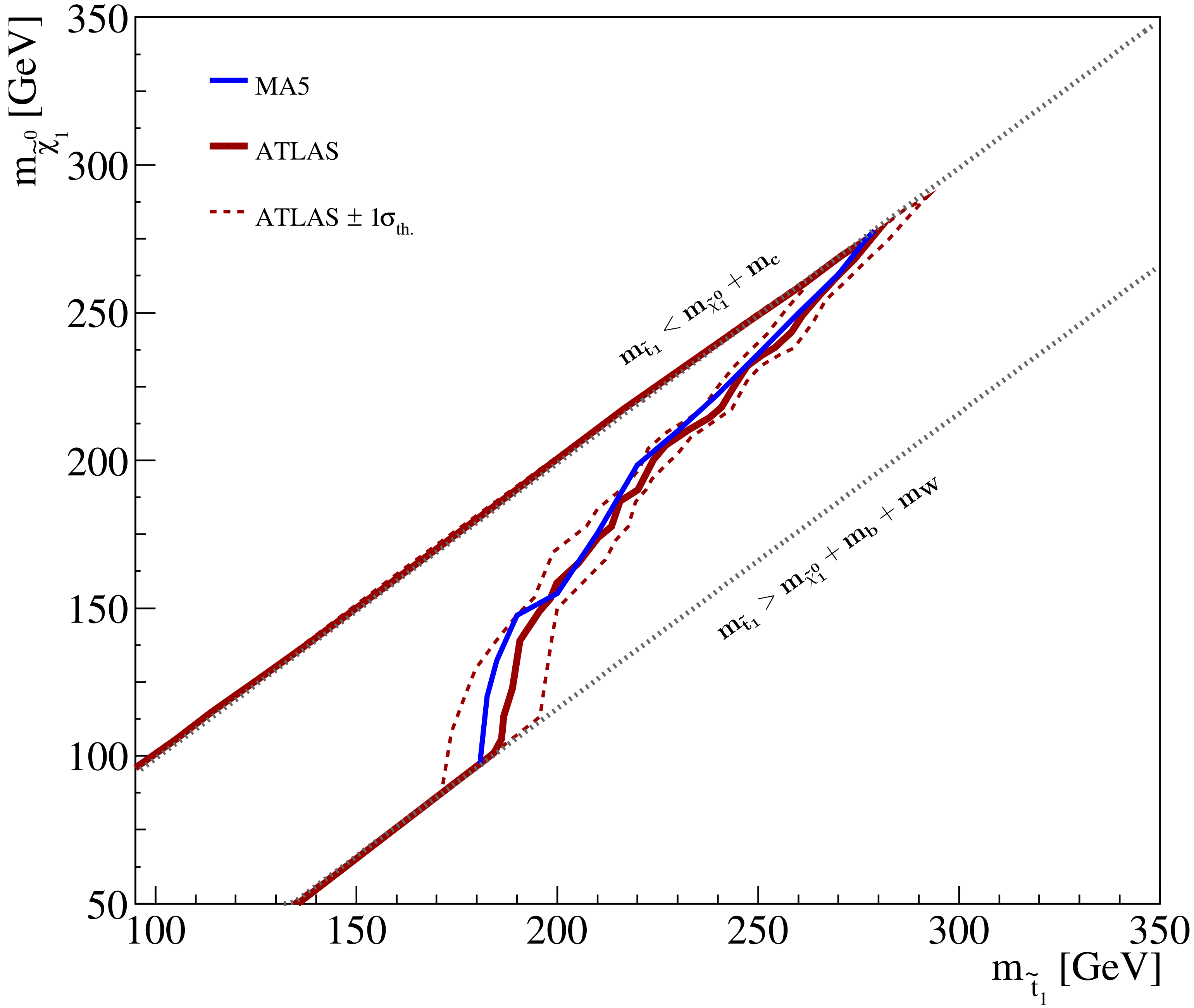
Sengupta et. al. https://inspirehep.net/record/1388797

$\tilde{t} \to c\tilde{\chi}_1^0$ (200/125) cutflow

cut	# events (scaled to σ and $\mathcal{L}$)	relative change	# events (official)	relative change (official)
Initial number of events	376047.3	376047.3		
$E_T^{\text{miss}} > 80$ GeV Filter	192812.8	-48.7%	181902.0	181902.0
$E_T^{\text{miss}} > 100$ GeV	136257.1	-29.3%	97217.0	-46.6%
Trigger, Event cleaning...	-	-	82131.0	
Lepton veto	134894.2	-1.0%	81855.0	-15.8%
$N_{\text{jets}} \leq 3$	101653.7	-24.6%	59315.0	-27.5%
$\Delta\phi(E_T^{\text{miss}}, \text{jets}) > 0.4$	95568.8	-2.1%	54295.0	-8.5%
Leading jet $p_T > 150$ GeV	17282.8	-81.9%	14220.0	-73.8%
$E_T^{\text{miss}} > 150$ GeV	10987.8	-36.4%	9468.0	-33.4%
M1 Signal Region				
Leading jet $p_T > 280$ GeV	2031.2	-81.5%	1627.0	-82.8%
$E_T^{\text{miss}} > 220$ GeV	1517.6	-25.3%	1276.0	-21.6%
M2 Signal Region				
Leading jet $p_T > 340$ GeV	858.0	-92.2%	721.0	-92.4%
$E_T^{\text{miss}} > 340$ GeV	344.4	-59.9%	282.0	-60.9%
M3 Signal Region				
Leading jet $p_T > 450$ GeV	204.3	-98.1%	169.0	-98.2%
$E_T^{\text{miss}} > 450$ GeV	61.3	-70.0%	64.0	-62.1%

ATLAS-SUSY-2013-21

Sengupta et. al. https://inspirehep.net/record/1388797



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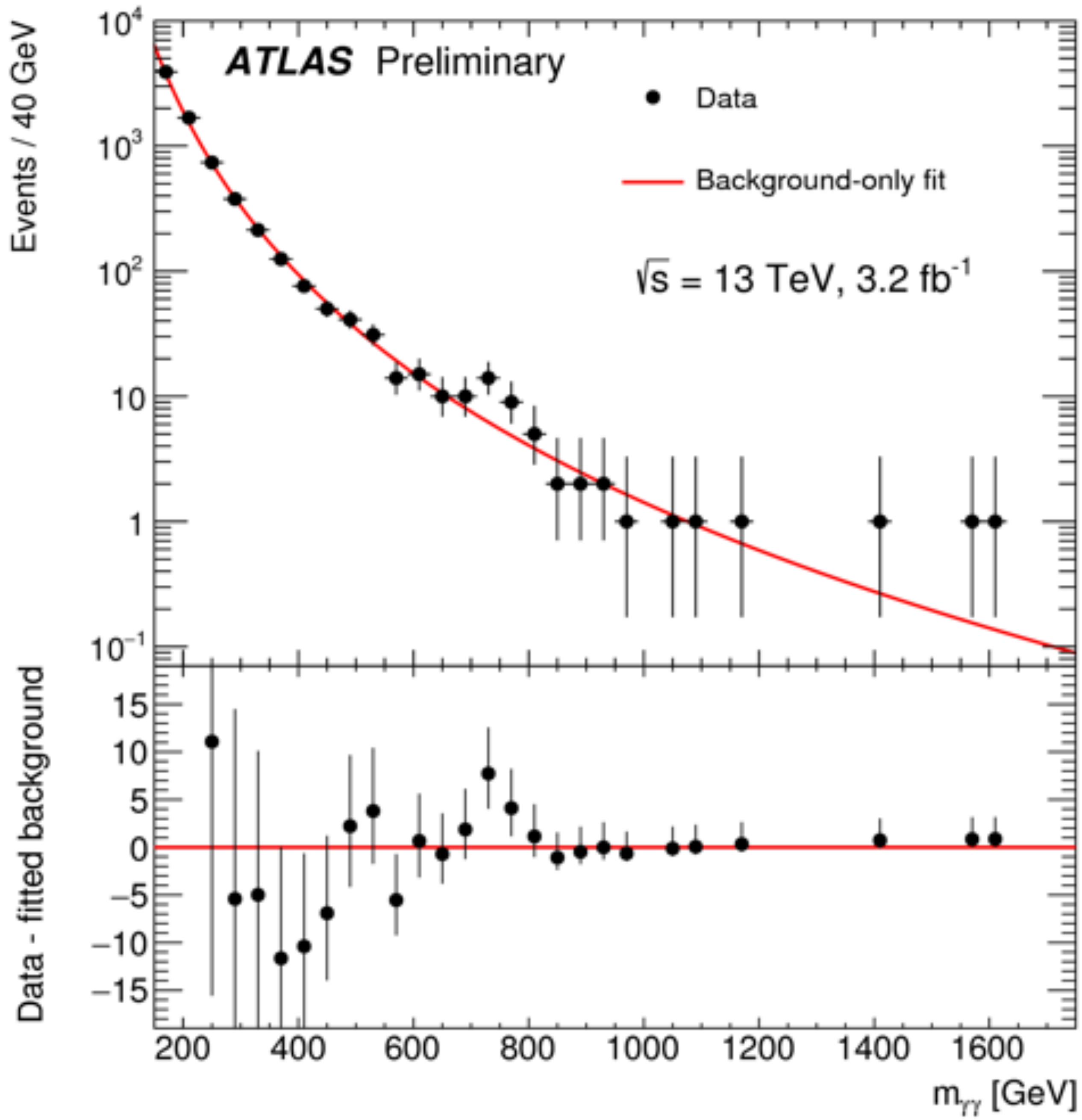
Test cases

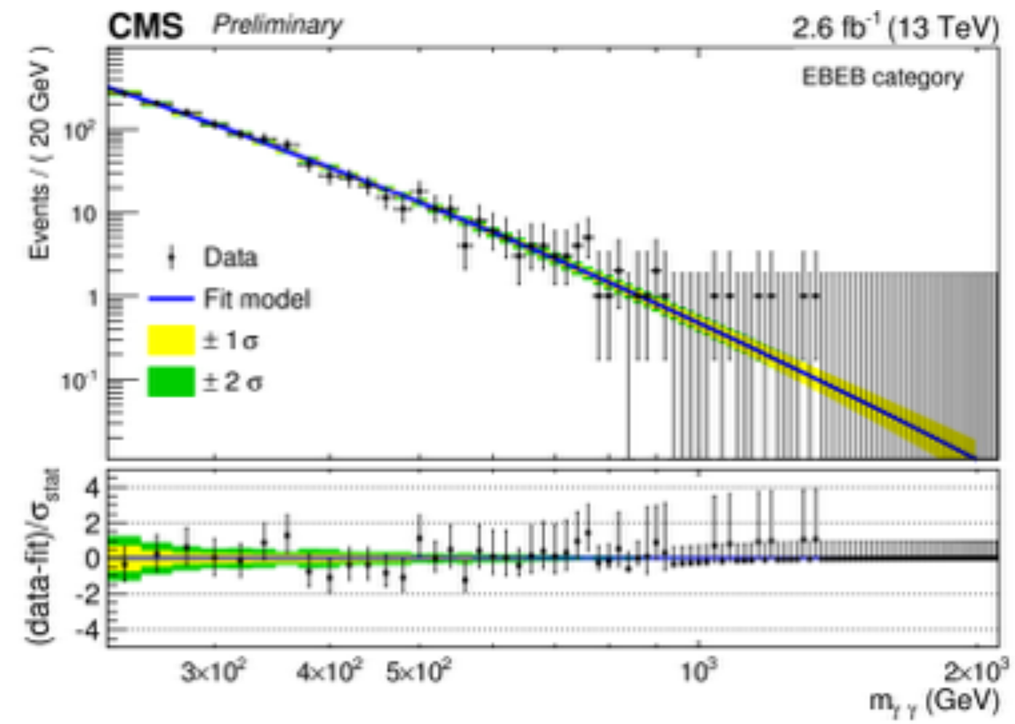
- What do the monojet searches tell us about the dark matter motivated explanations of 750 GeV diphoton excess?
- How well do these searches constrain momentum dependent couplings of dark matter?

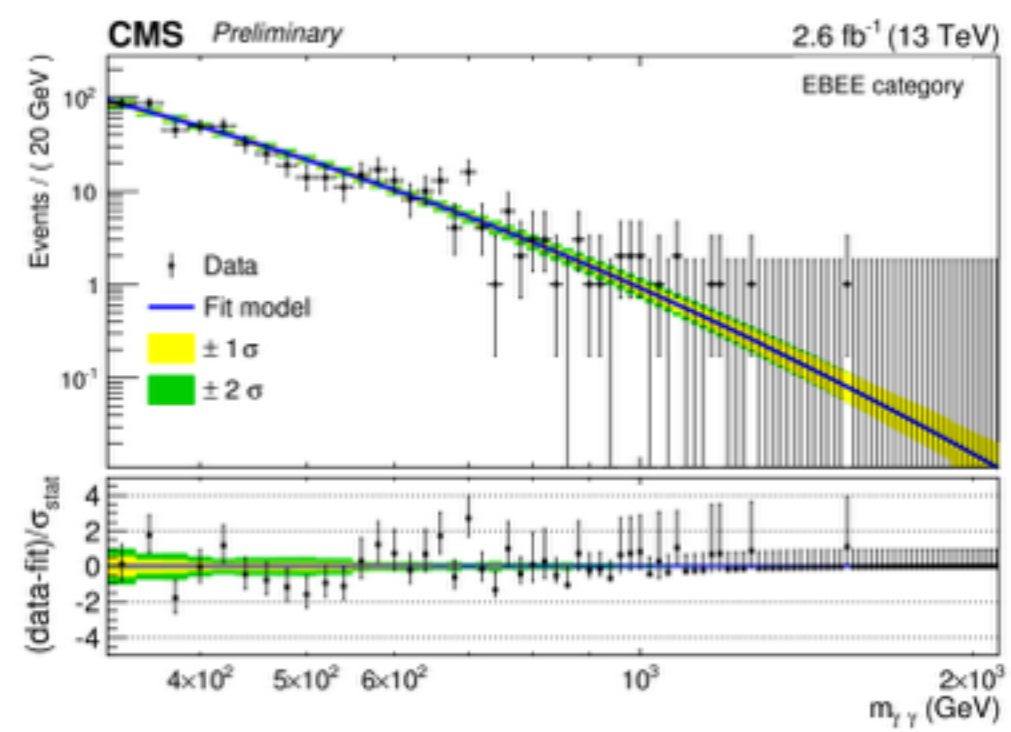
Test case: I

Exploring the 750 GeV diphoton excess portal to dark matter

The excess (as of 15 Dec)







ATLAS-CONF-2015-081,

CMS-PAS-EXO-15-004

The excess (as of 15 Dec)

ATLAS

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

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

~ 14 events 3.9σ local 2.3σ including LEE

CMS

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

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

~ 10 events 2.6σ local 1.2σ including LEE

The excess (post-moriond)

Stolen from talk by M. Bosman (Planck 2016)

Compatibility with $\sqrt{s}$ = 8 TeV data

Spin0	Spin 2

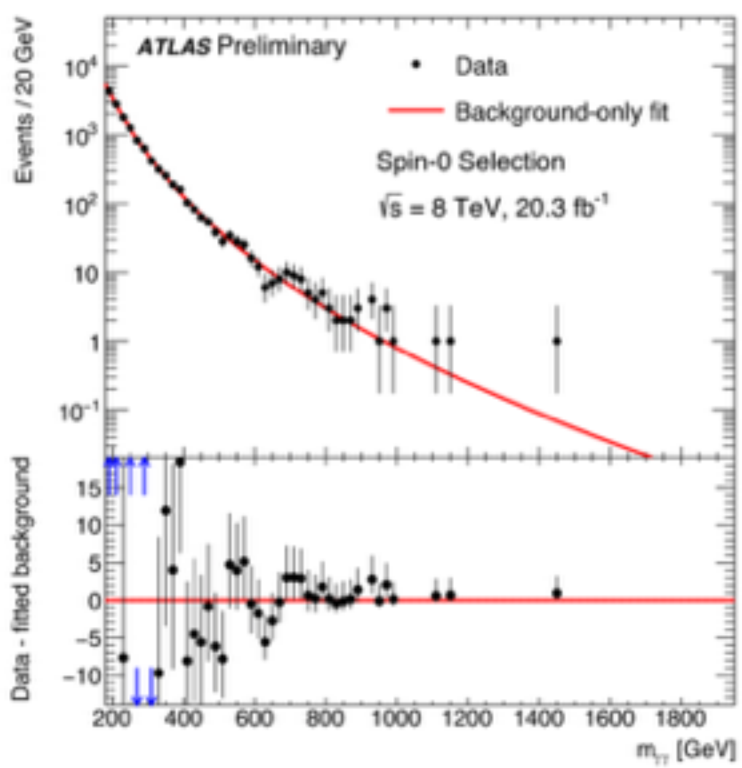
Spin0

- 8 TeV data: 1.9 σ deviation from bkg-only hypothesis at m_X = 750 GeV, Γ_X/m_X = 6%
- Assuming common signal model; production X-sec scales like Parton luminosities

  gg s-channel = 4.7; qq s-channel = 2.7

Compatibility 8 TeV ↔ 13 TeV (gg hypothesis): 1.2 σ

Compatibility 8 TeV ↔ 13 TeV (qq hypothesis): 2.1 σ

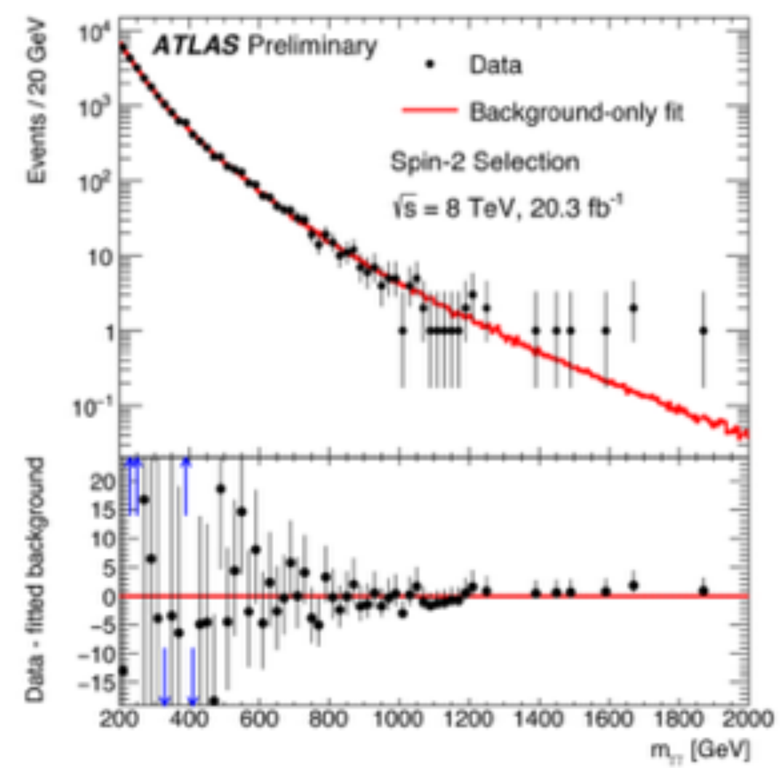


Spin 2

- 8 TeV data: no excess in the region of interest

Compatibility 8 TeV ↔ 13 TeV (gg hypothesis): 2.7 σ

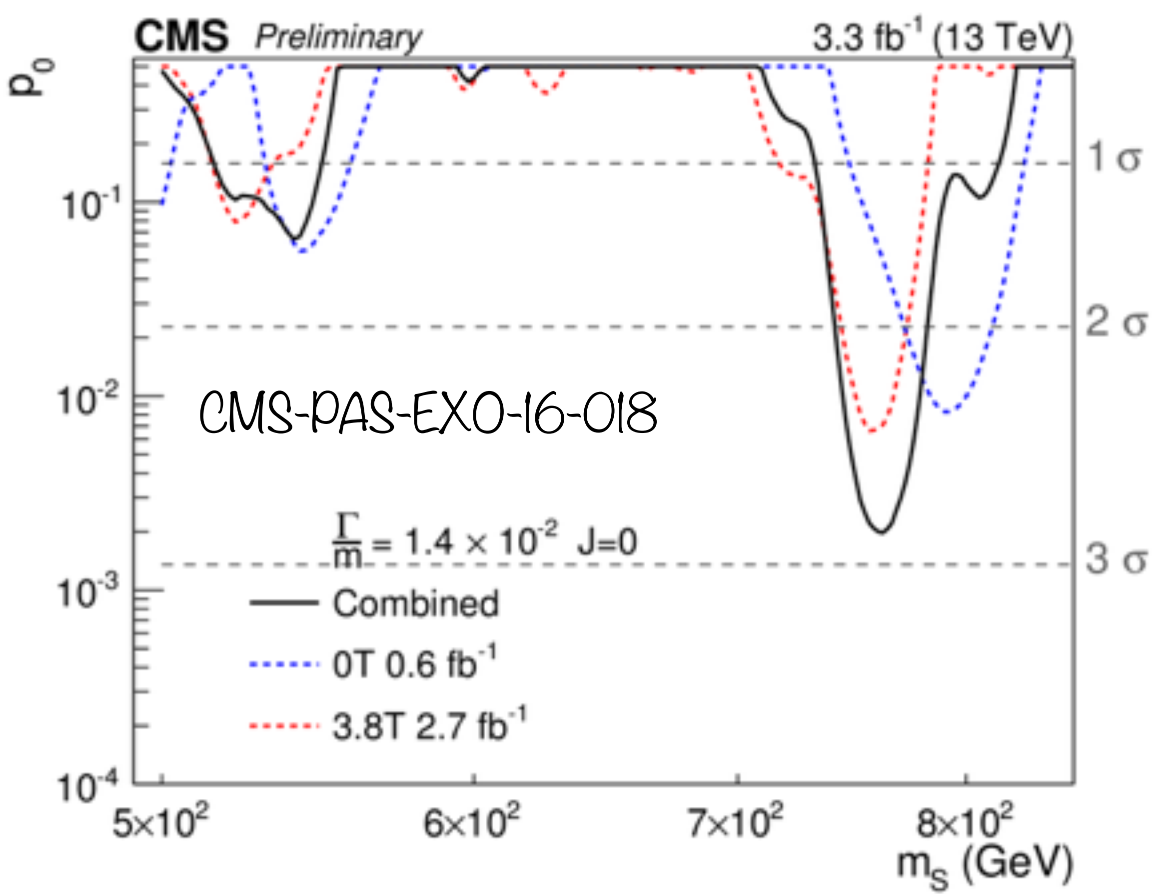
Compatibility 8 TeV ↔ 13 TeV (qq hypothesis): 3.6 σ

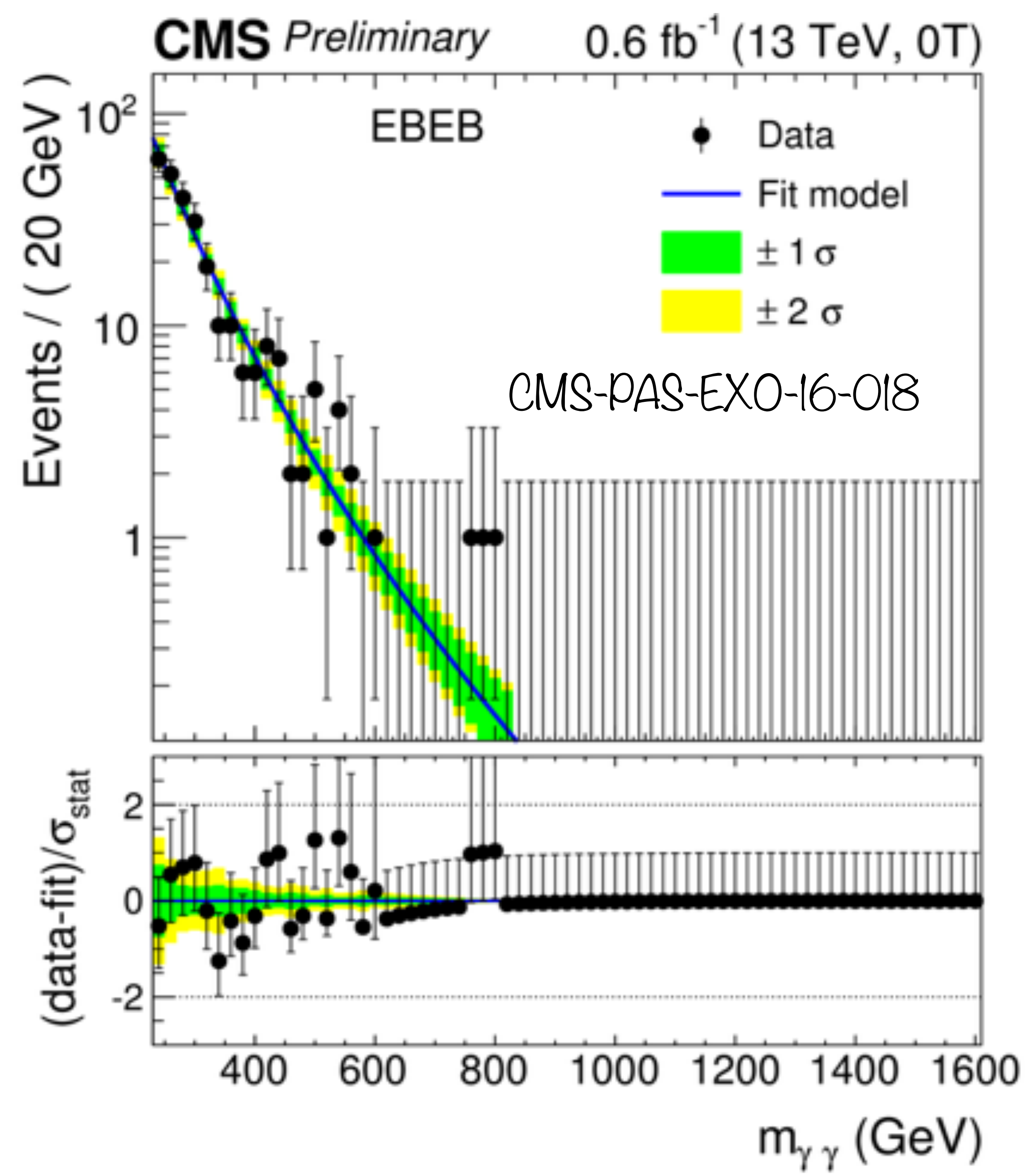


ATLAS-CONF-2016-018

The excess (post-moriond)

- 0.6 fb^{-1} dataset with B=0T is included (2.7 to 3.3fb^{-1} total)
- 4 different categories:(EB-EB,EB-EE)x(3.8T,0T)
- Spin 0,2 interpretation

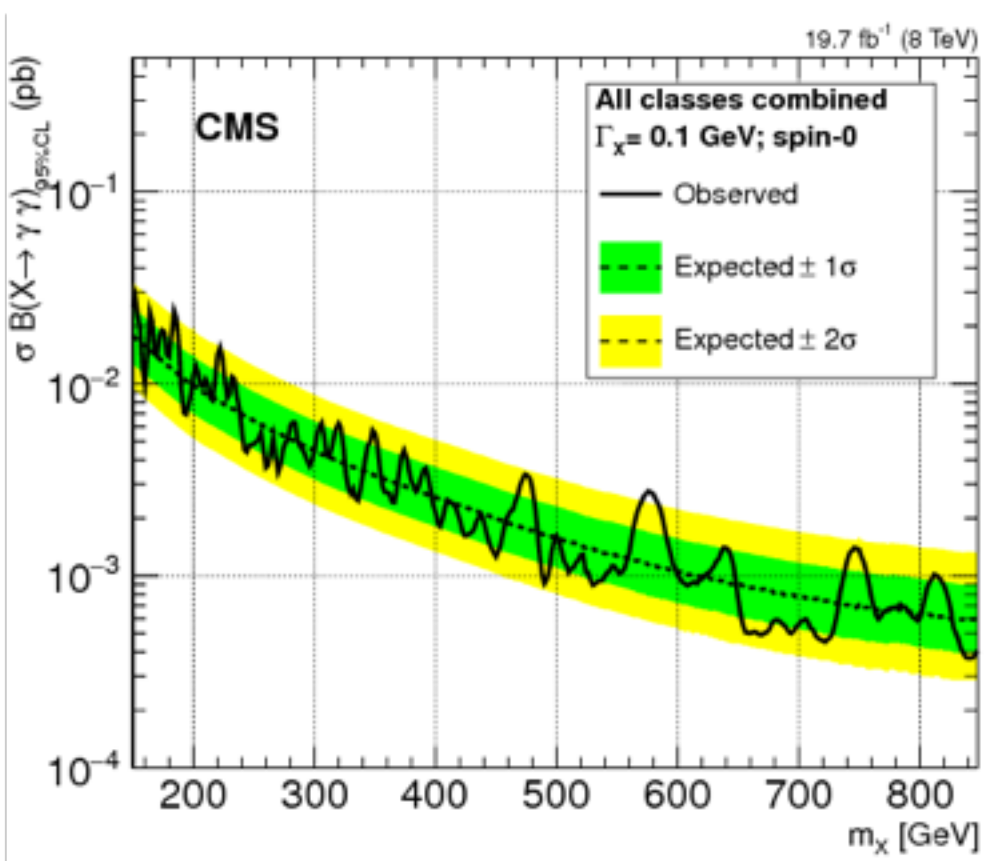




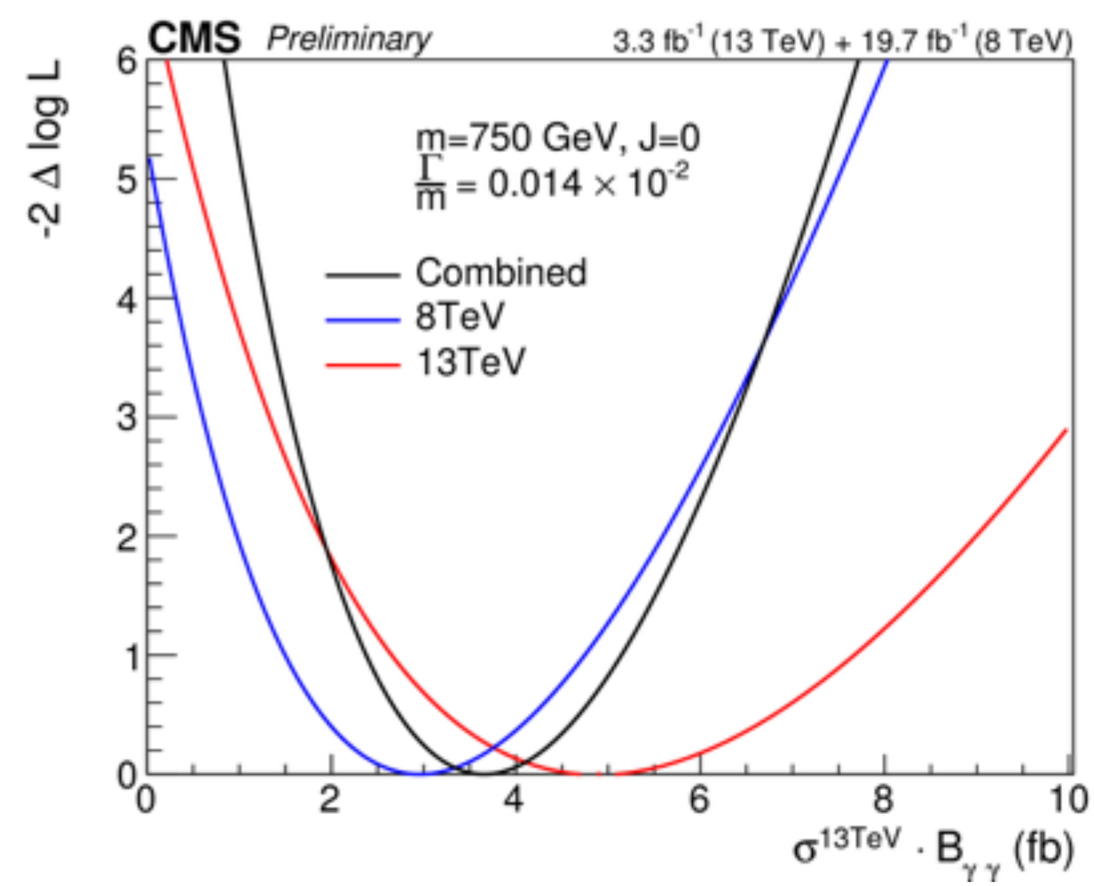
The excess (post-moriond)

- 13 TeV excess compatible with 8 TeV analysis

arXiv:1506.02301



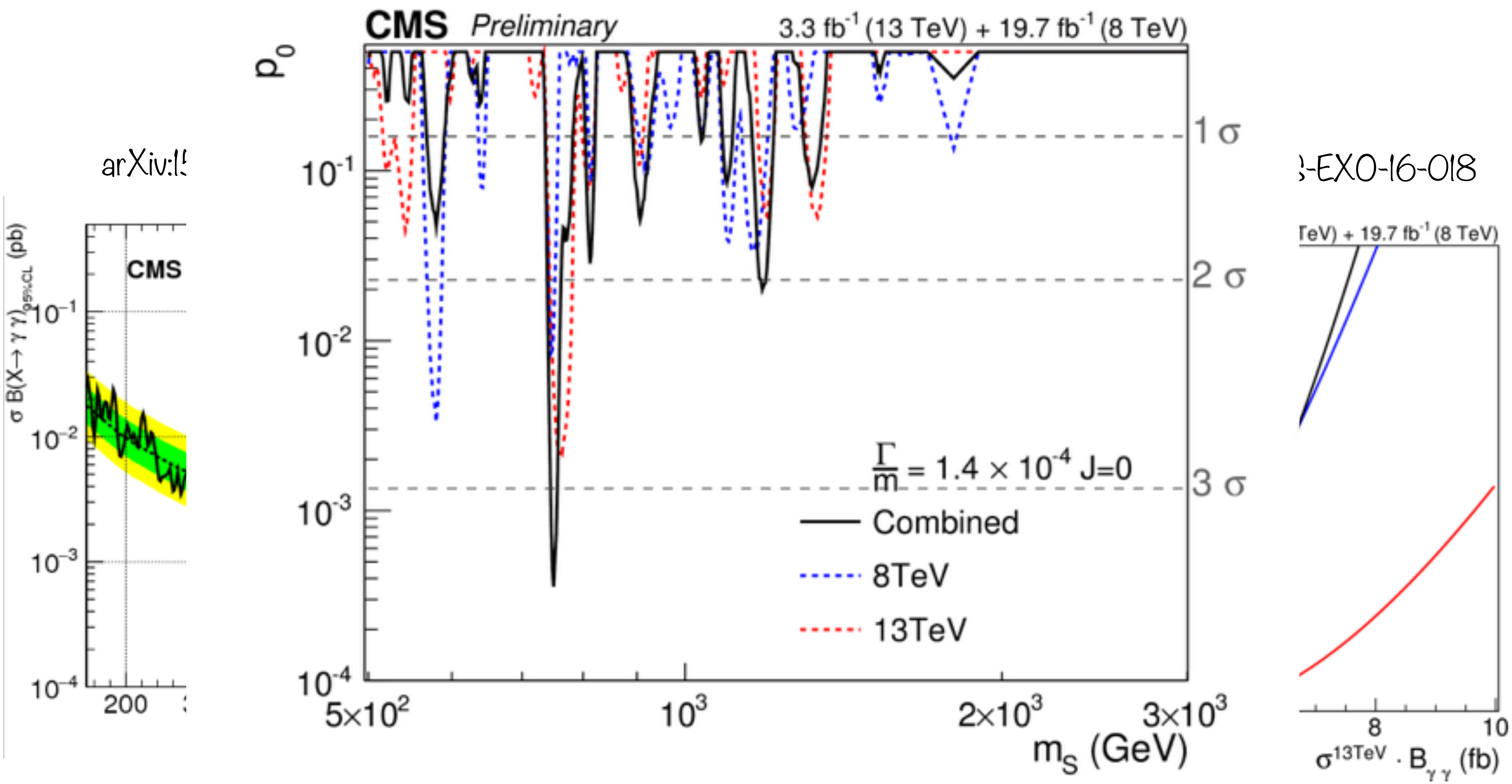
CMS-PAS-EXO-16-018



- 8 + 13 TeV excess: 3.4σ local and 1.4σ global significance

The excess (post-moriond)

- 13 TeV excess compatible with 8 TeV analysis



- 8 + 13 TeV excess: 3.4σ local and 1.4σ global significance

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Visitor VISA for 750 GeV

Strumia et al, arXiv:1605.09401

Citation: Particle Data Group, 2016 update

F (750$_{000}$)

$I(J^P) = ?(0^?)$
J needs confirmation

OMITTED FROM SUMMARY TABLE
Needs confirmation.

F MASS

VALUE (GeV)	EVTS	DOCUMENT ID	TECN	COMMENT
750 ± 30 OUR AVERAGE		ATLAS, CMS		$pp \to F$

• • • We do not use the following data for average, fits, limits, etc. • • •

F WIDTH

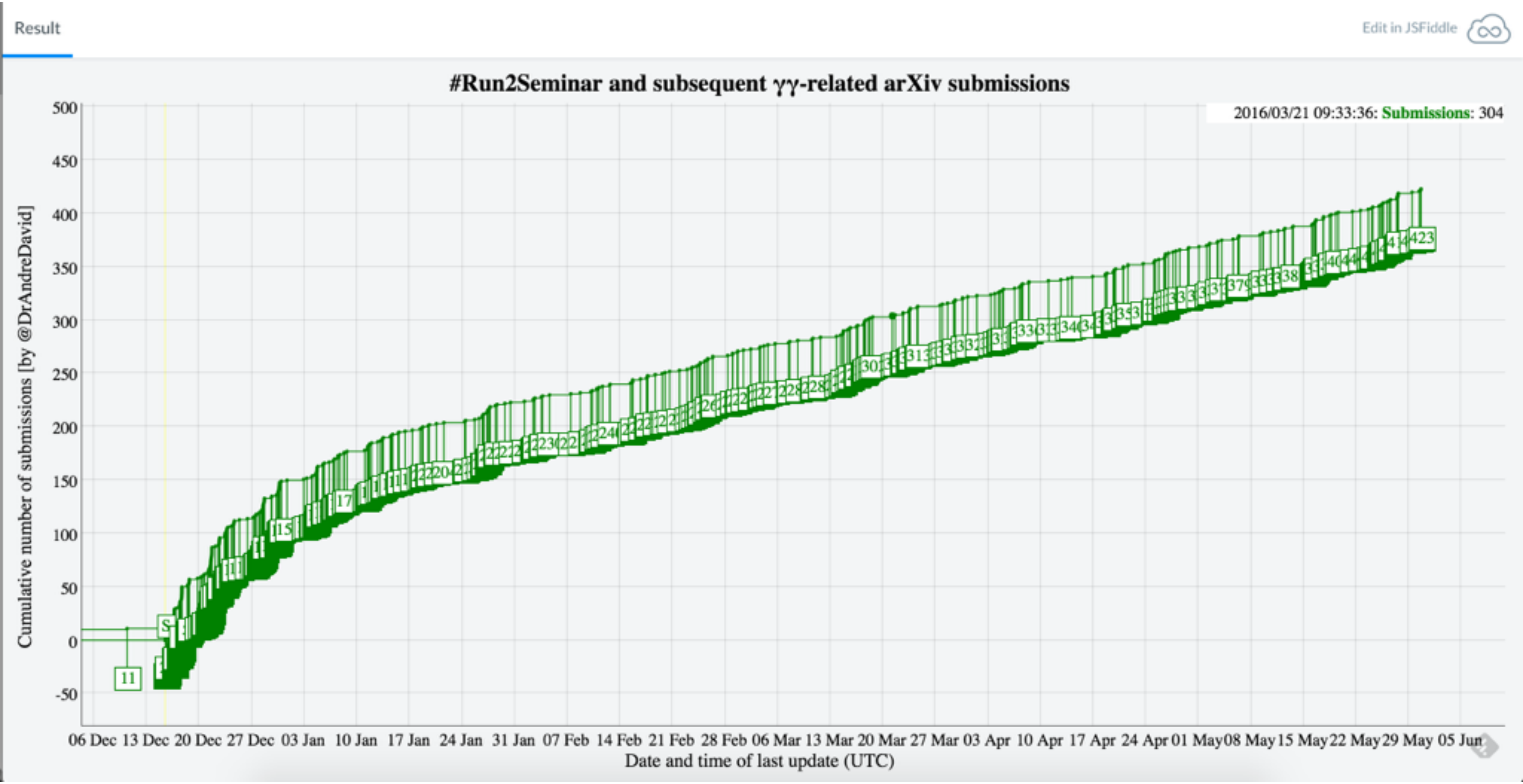
VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
$<$**100**	95	ATLAS, CMS		$pp \to F$

• • • We do not use the following data for average, fits, limits, etc. • • •

F DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\gamma$	seen
Γ_2	$\gamma Z, ZZ, jj$	expected

“Little bit” of excitement



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

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

Backović et. al. arXiv:1603.01204

PDF enhancements

Franceschini et al, arXiv:1512.04933

- 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

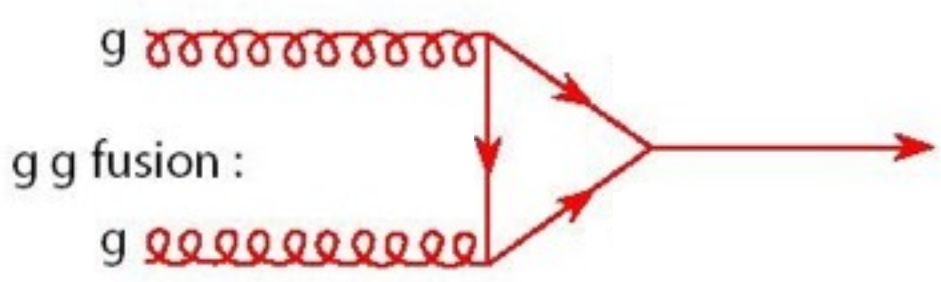
$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}
5.4	5.1	4.3	2.7	2.5	4.7

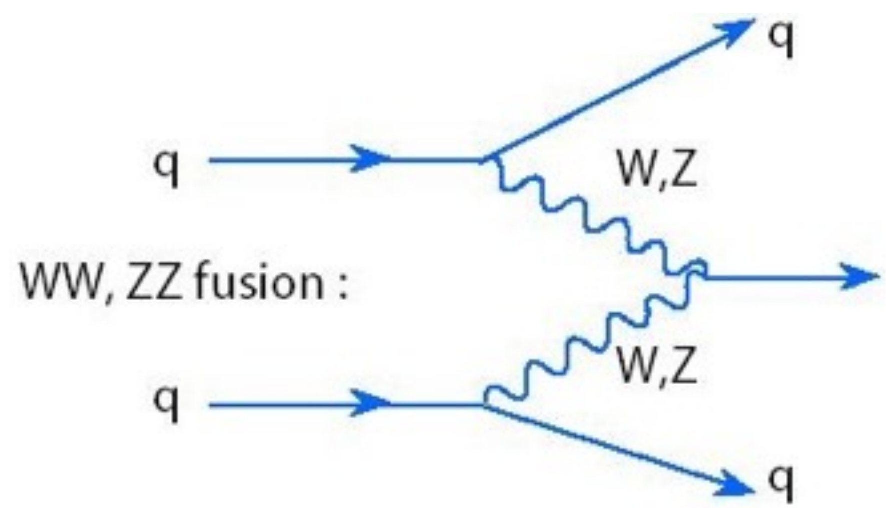
$$r = \sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}} = [C_{gg}/s]_{13\,\text{TeV}}/[C_{gg}/s]_{8\,\text{TeV}}$$

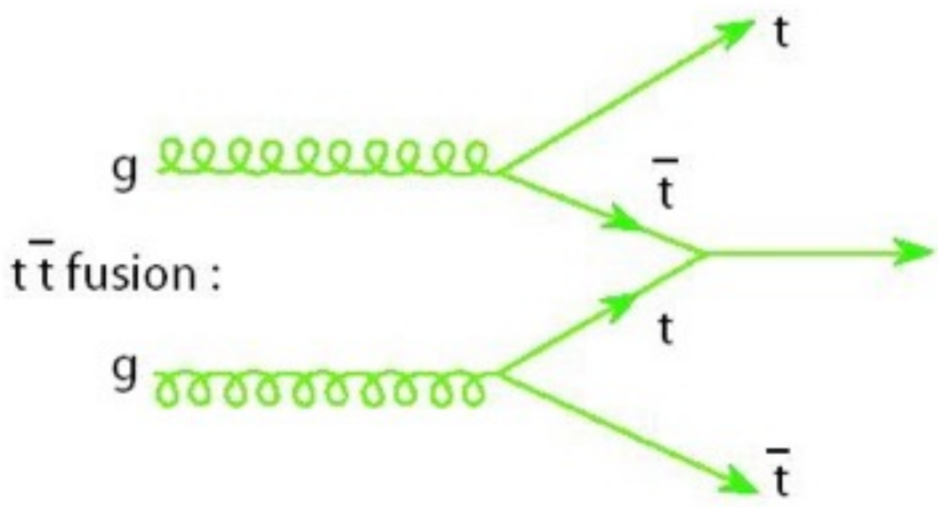
- MSTW2008NLO PDF estimates (typical K factors from higher order K_{gg} = 1.5 and $K_{q\bar{q}}$ = 1.2 can modify these estimates)
- Gluon gluon initial state gets more attention due to large gain in PDFs

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

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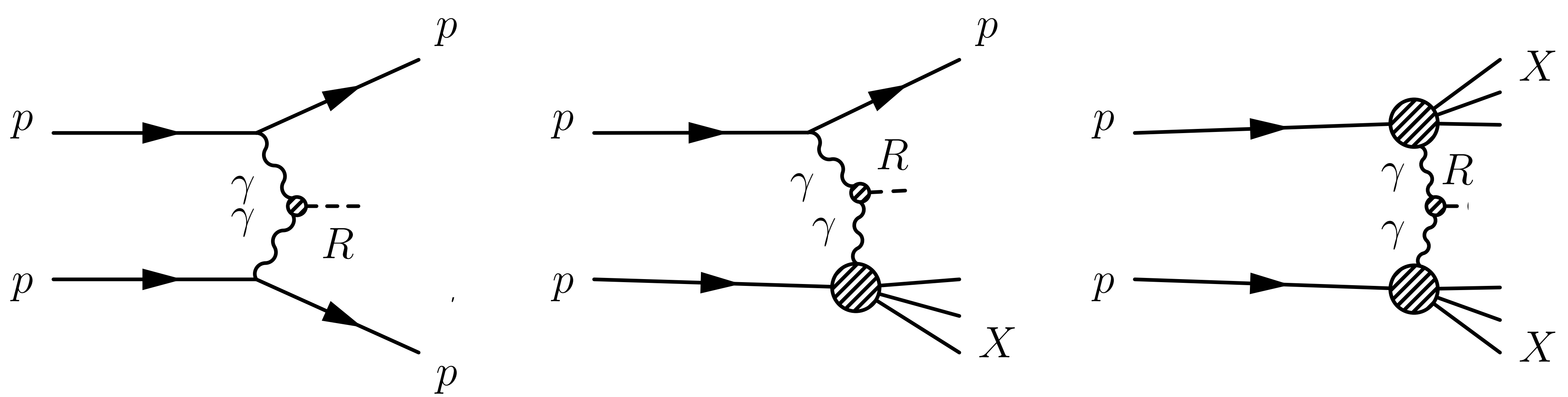


- For photon fusion, three possibilities: Elastic-elastic, elastic-inelastic and inelastic-inelastic

see e.g.

Csaki et al, arXiv:1601.00638,
Fichet et. al, arXiv:1512.05751,
Harland-Lang et al, arXiv:1601.07187

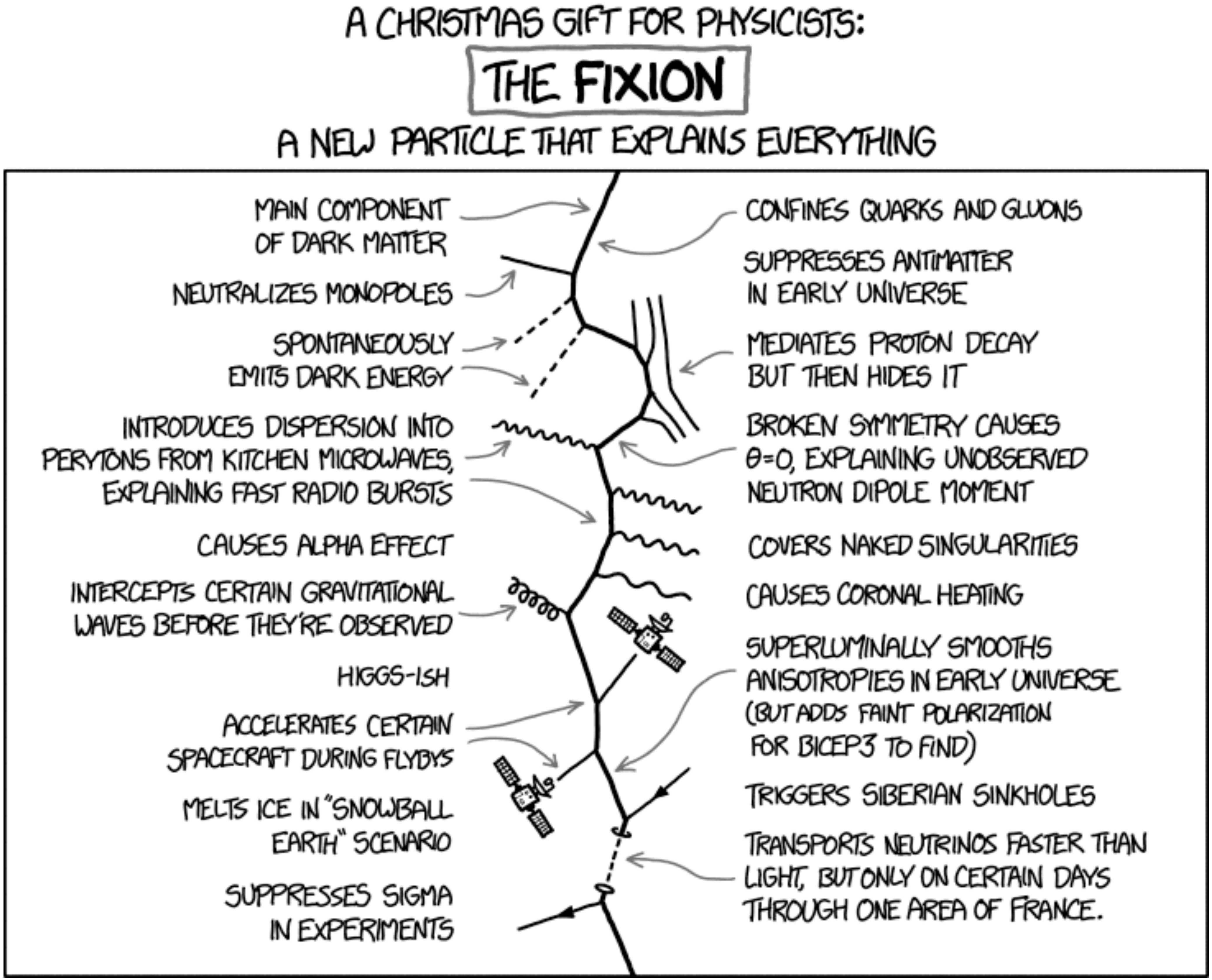
Run - 1 results

- 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]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ 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)


A CHRISTMAS GIFT FOR PHYSICISTS:
THE FIXION
A NEW PARTICLE THAT EXPLAINS EVERYTHING
MAIN COMPONENT OF DARK MATTER
NEUTRALIZES MONOPOLES
SPONTANEOUSLY EMITS DARK ENERGY
INTRODUCES DISPERSION INTO PERYTONS FROM KITCHEN MICROWAVES, EXPLAINING FAST RADIO BURSTS
CAUSES ALPHA EFFECT
INTERCEPTS CERTAIN GRAVITATIONAL WAVES BEFORE THEY'RE OBSERVED
HIGGS-ISH
ACCELERATES CERTAIN SPACECRAFT DURING FLYBYS
MELTS ICE IN "SNOWBALL EARTH" SCENARIO
SUPPRESSES SIGMA IN EXPERIMENTS
CONFINES QUARKS AND GLUONS
SUPPRESSES ANTIMATTER IN EARLY UNIVERSE
MEDIATES PROTON DECAY BUT THEN HIDES IT
BROKEN SYMMETRY CAUSES θ=0, EXPLAINING UNOBSERVED NEUTRON DIPOLE MOMENT
COVERS NAKED SINGULARITIES
CAUSES CORONAL HEATING
SUPERLUMINALLY SMOOTHS ANISOTROPIES IN EARLY UNIVERSE (BUT ADDS FAINT POLARIZATION FOR BICEP3 TO FIND)
TRIGGERS SIBERIAN SINKHOLES
TRANSPORTS NEUTRINOS FASTER THAN LIGHT, BUT ONLY ON CERTAIN DAYS THROUGH ONE AREA OF FRANCE.

750 GeV portal to DM

- Coupling of a 750 scalar resonance to gauge bosons and Majorana dark matter particle

$$\mathcal{L}_{\rm NP,CPE} = \frac{1}{2}(\partial_\mu s)^2 - \frac{\mu_s^2}{2}s^2 + \frac{1}{2}\bar{\psi}(i\partial\!\!\!/_\mu - m_\psi)\psi - \frac{y_\psi}{2}s\bar{\psi}\psi$$
$$- \frac{g_1^2}{4\pi}\frac{1}{4\Lambda_1}s\ B_{\mu\nu}B^{\mu\nu} - \frac{g_2^2}{4\pi}\frac{1}{4\Lambda_2}s\ W_{\mu\nu}W^{\mu\nu} - \frac{g_3^2}{4\pi}\frac{1}{4\Lambda_3}s\ G_{\mu\nu}G^{\mu\nu}$$

$$\mathcal{L}_{\rm NP,CPO} = \frac{1}{2}(\partial_\mu s)^2 - \frac{\mu_s^2}{2}s^2 + \frac{1}{2}\bar{\psi}(i\partial\!\!\!/_\mu - m_\psi)\psi - i\frac{y_\psi}{2}s\bar{\psi}\gamma^5\psi$$
$$- \frac{g_1^2}{4\pi}\frac{1}{4\Lambda_1}s\ B_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{g_2^2}{4\pi}\frac{1}{4\Lambda_2}s\ W_{\mu\nu}\tilde{W}^{\mu\nu} - \frac{g_3^2}{4\pi}\frac{1}{4\Lambda_3}s\ G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Mambrini et al, arXiv:1512.04913,

Backovic et al, arXiv:1512.04917,

Barducci et al, arXiv: 1512.06842

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750 GeV portal to DM

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Effective couplings to gauge bosons

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750 GeV portal to DM

$$\mathcal{L}_{\mathrm{NP,CPE}} = \frac{1}{2}(\partial_\mu s)^2 - \frac{\mu_s^2}{2}s^2 + \frac{1}{2}\bar{\psi}(i\partial\!\!\!/_\mu - m_\psi)\psi - \frac{y_\psi}{2}s\bar{\psi}\psi$$
$$- \frac{g_1^2}{4\pi}\frac{1}{4\Lambda_1}s\, B_{\mu\nu}B^{\mu\nu} - \frac{g_2^2}{4\pi}\frac{1}{4\Lambda_2}s\, W_{\mu\nu}W^{\mu\nu} - \frac{g_3^2}{4\pi}\frac{1}{4\Lambda_3}s\, G_{\mu\nu}G^{\mu\nu}$$

Mass scales for effective couplings

750 GeV portal to DM

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

750 GeV portal to DM

$$\mathcal{L}_{\mathrm{NP,CPE}} = \frac{1}{2}(\partial_\mu s)^2 - \frac{\mu_s^2}{2}s^2 + \frac{1}{2}\bar{\psi}(i\partial\!\!\!/_\mu - m_\psi)\psi - \frac{y_\psi}{2}s\bar{\psi}\psi$$
$$- \frac{g_1^2}{4\pi}\frac{1}{4\Lambda_1}s\, B_{\mu\nu}B^{\mu\nu} - \frac{g_2^2}{4\pi}\frac{1}{4\Lambda_2}s\, W_{\mu\nu}W^{\mu\nu} - \frac{g_3^2}{4\pi}\frac{1}{4\Lambda_3}s\, G_{\mu\nu}G^{\mu\nu}$$

Coupling to DM
(controls width of s)

750 GeV portal to DM

$$\mathcal{L}_{\text{NP,CPE}} = \frac{1}{2}(\partial_\mu s)^2 - \frac{\mu_s^2}{2}s^2 + \frac{1}{2}\bar{\psi}(i\partial\!\!\!/_\mu - m_\psi)\psi - \frac{y_\psi}{2}s\bar{\psi}\psi$$
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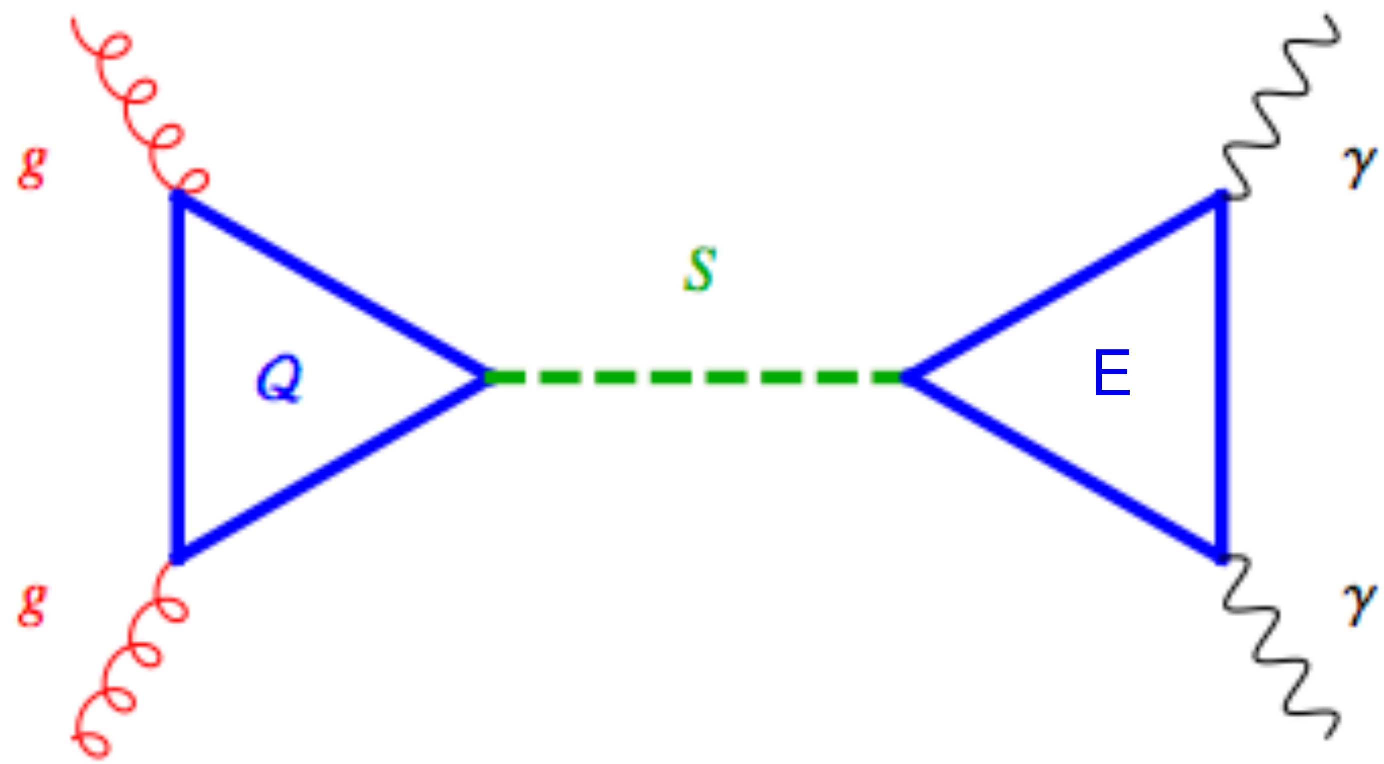
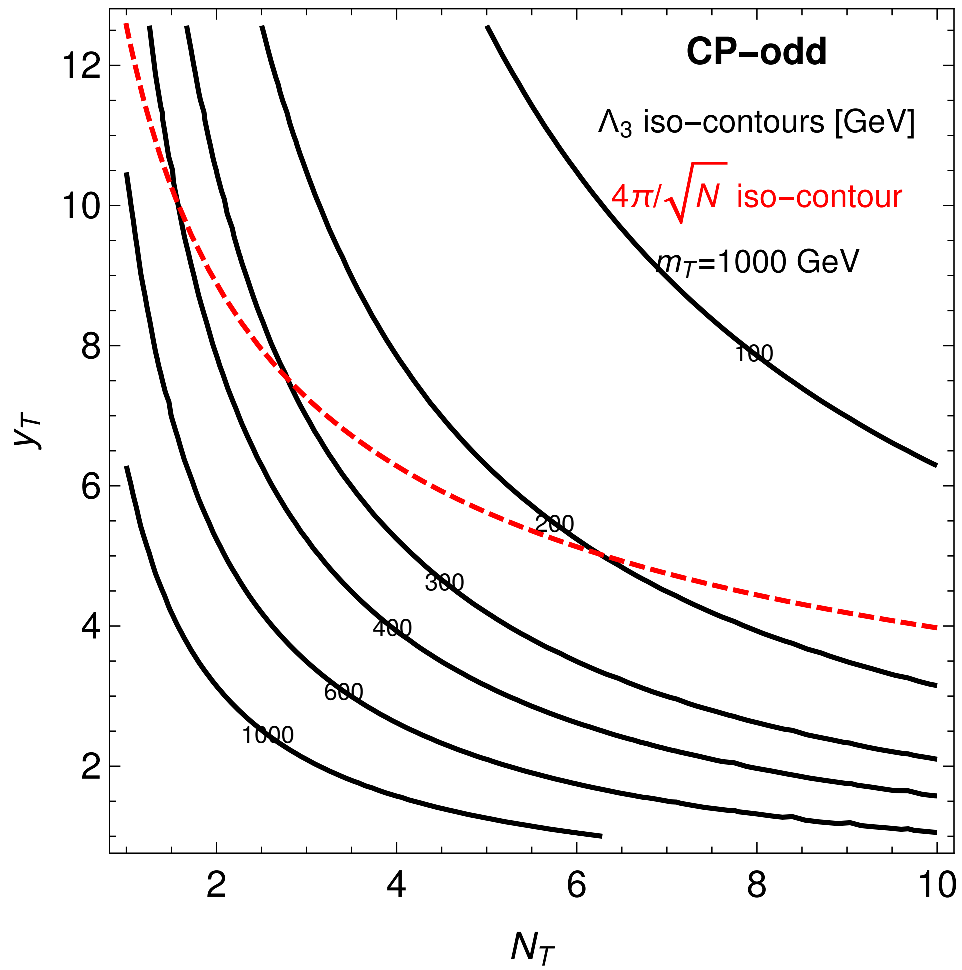
Mass term 750 GeV

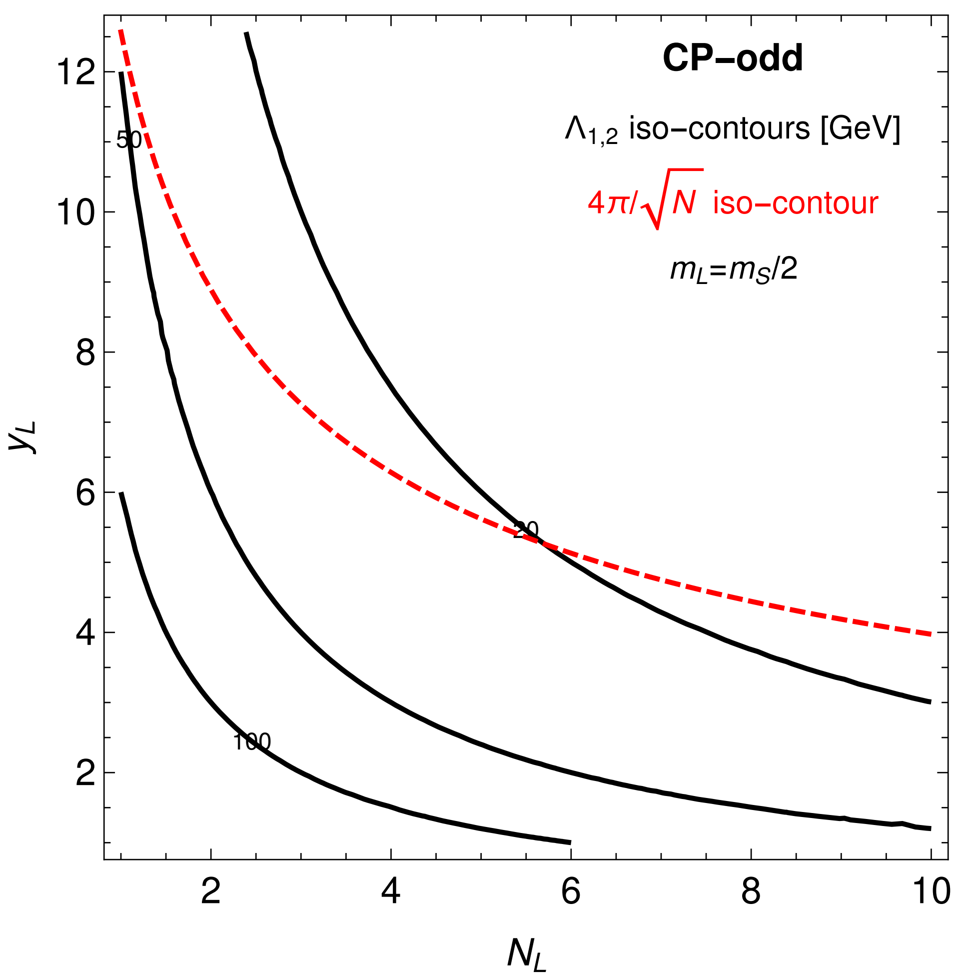
Generating effective couplings



Generating effective couplings

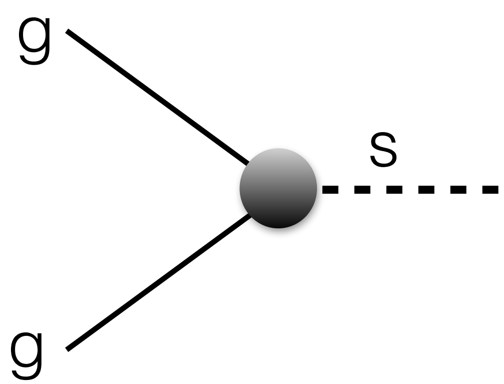
$$\Lambda_3 = \begin{cases} \dfrac{3\pi m_f}{N_f y_f} & \text{(scalar)} \\ \dfrac{2\pi m_f}{N_f y_f} & \text{(pseudoscalar)} \end{cases}$$

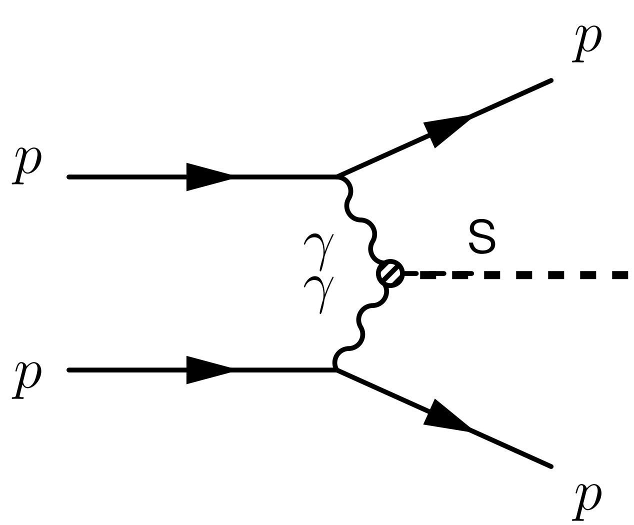


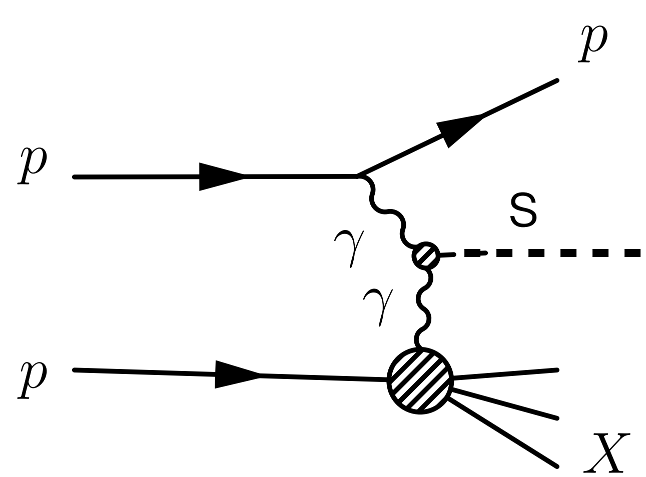


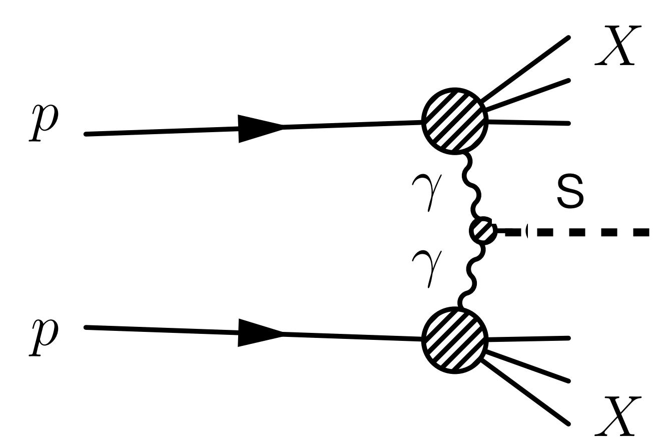
$$\Lambda_{1,2} \sim \begin{cases} \dfrac{2350\ \text{GeV}}{\left(N_f Q_f^2 y_f\right)} & \text{scalar.} \\ \dfrac{950\ \text{GeV}}{\left(N_f Q_f^2 y_f\right)} & \text{pseudoscalar.} \end{cases}$$

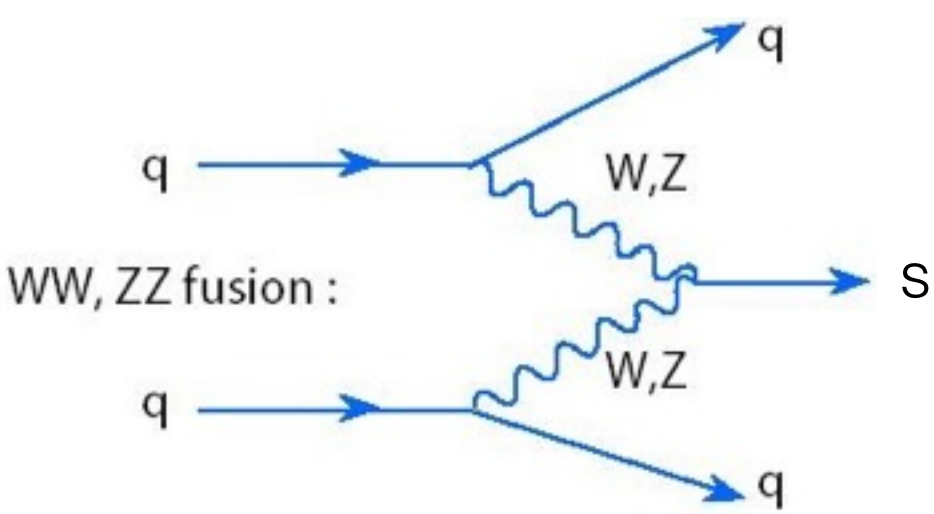
Production



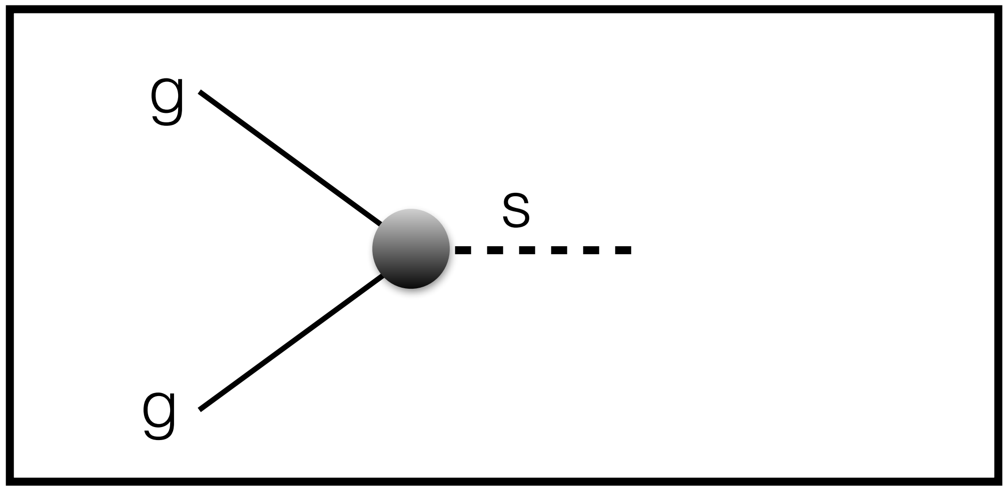


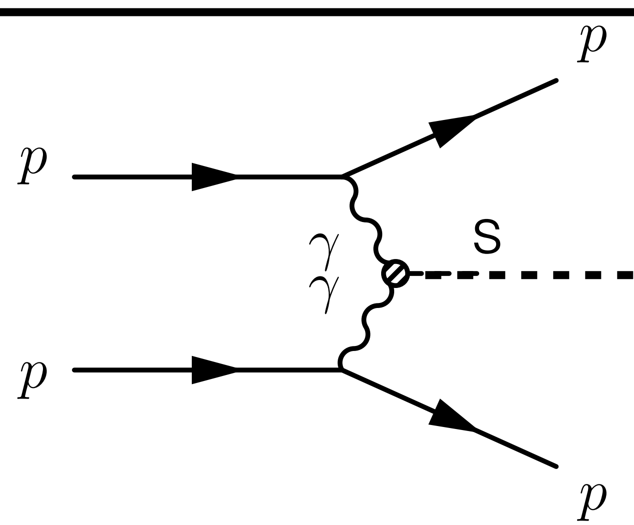


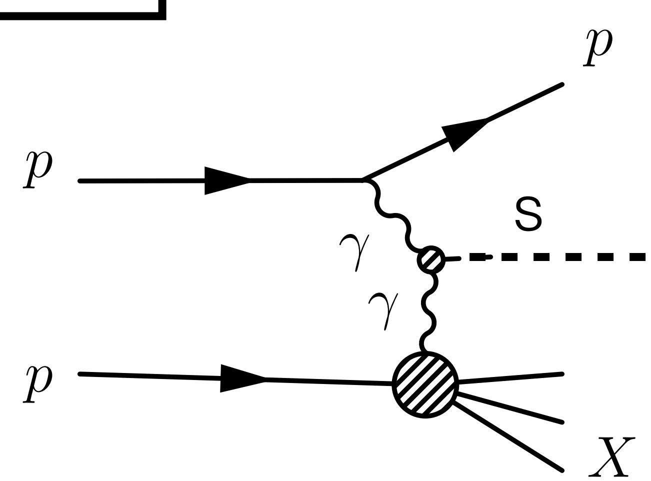


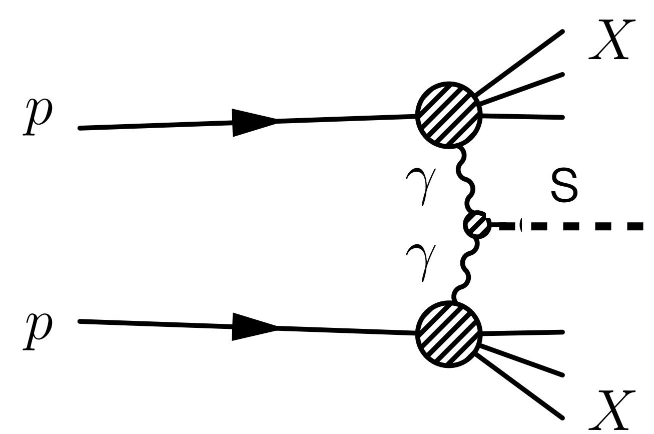


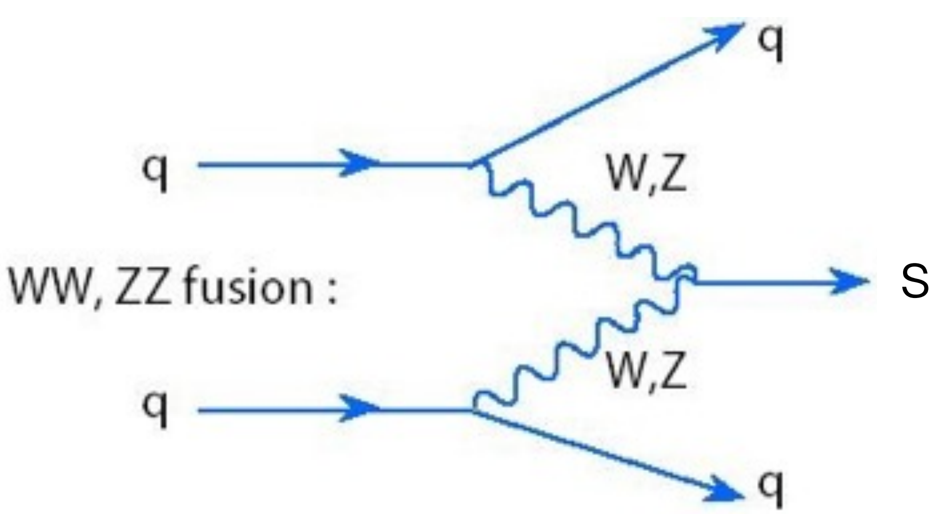
Production











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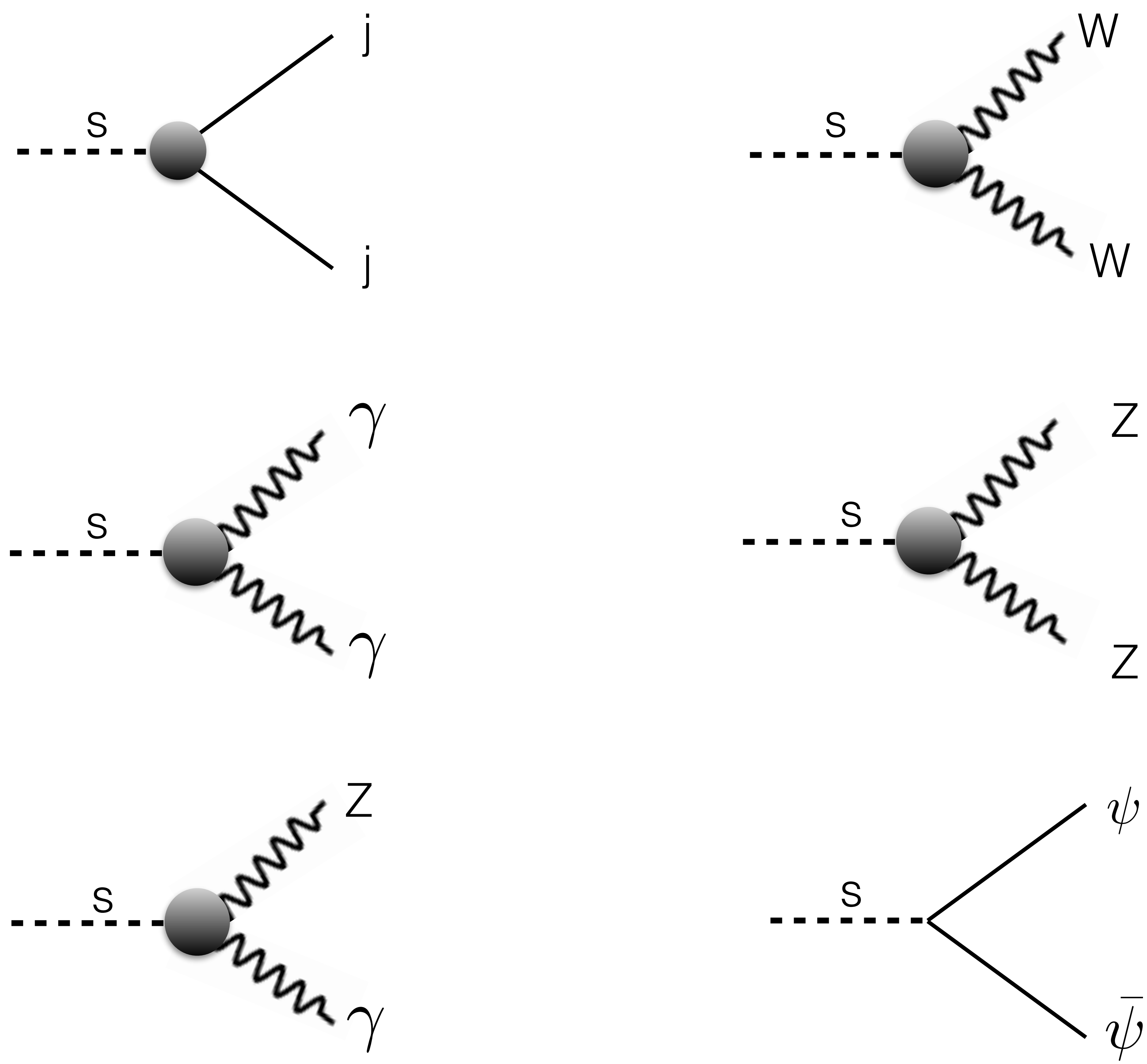
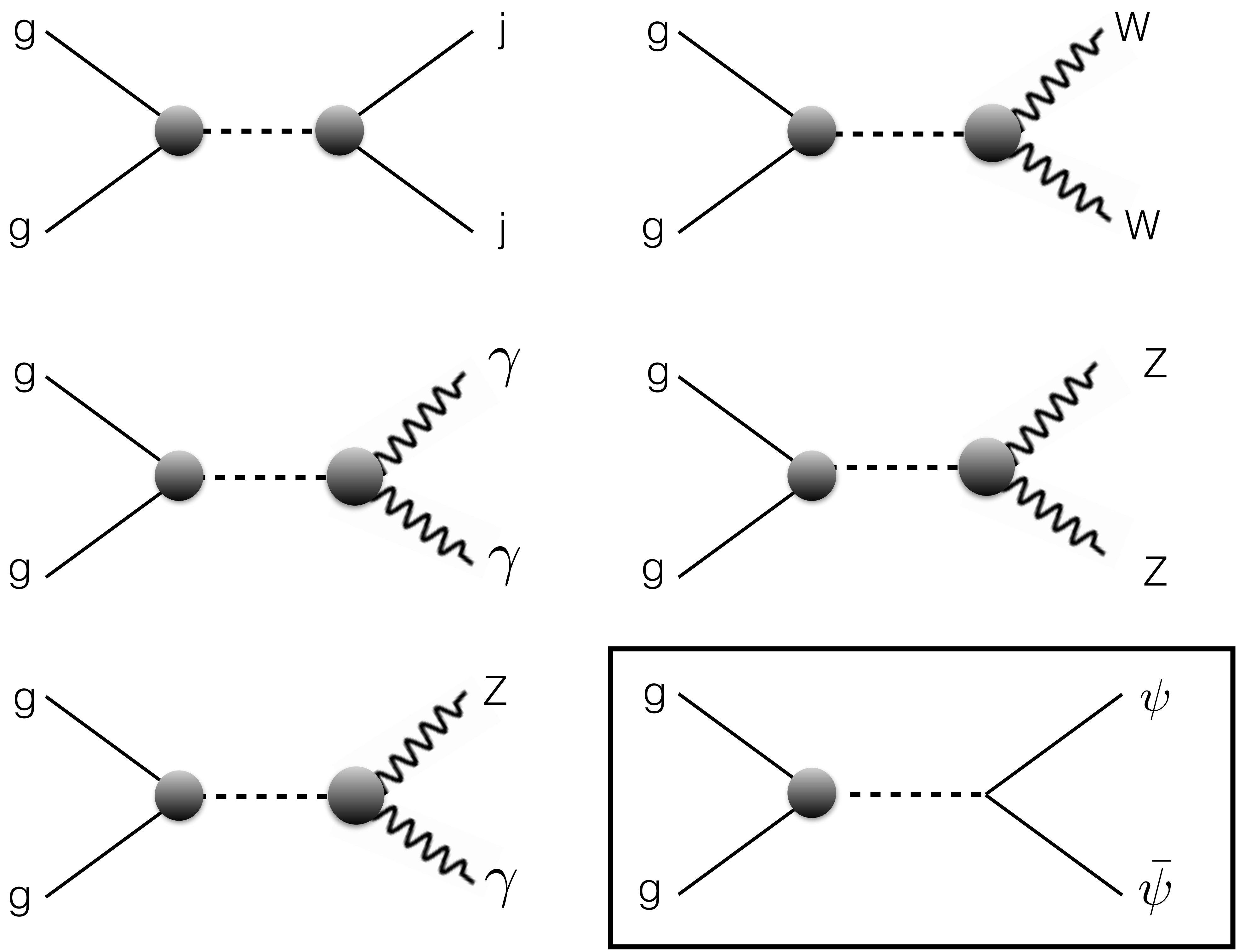
Decays



LHC phenomenology



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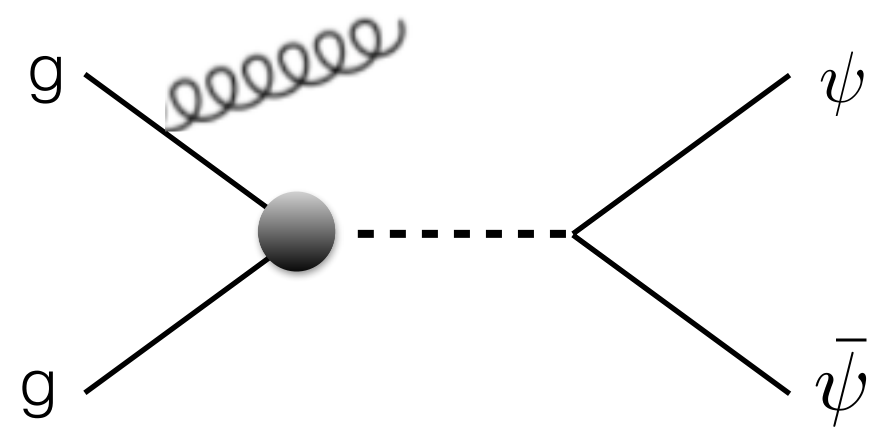
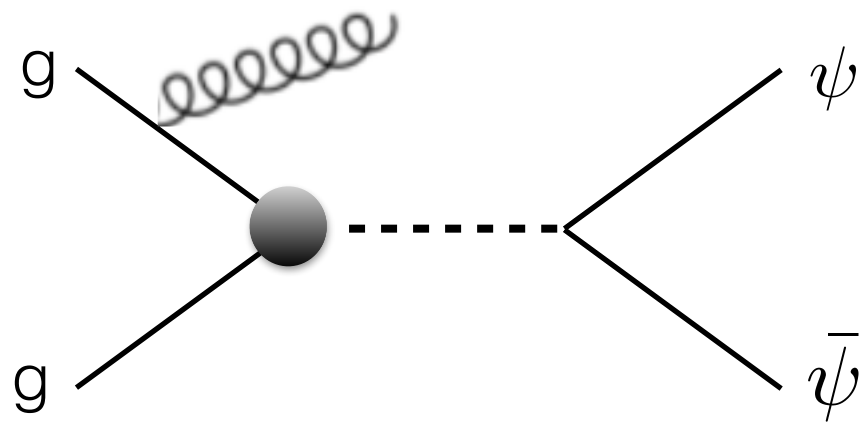
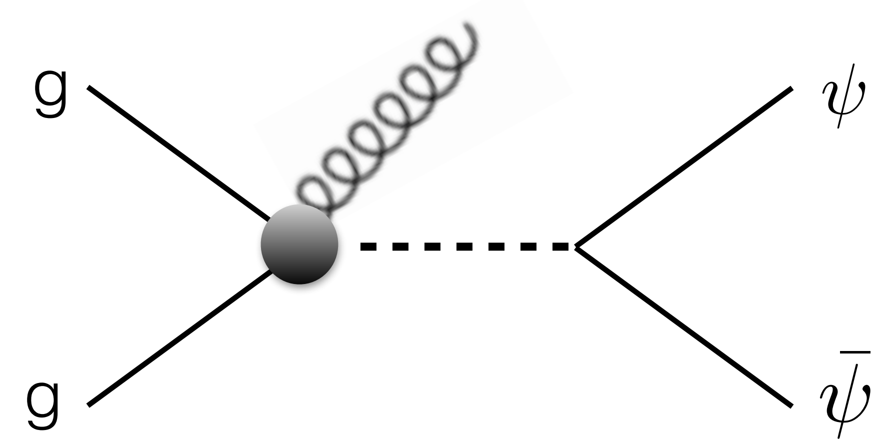


- Feynman diagram for monojet analysis

Emission from vertex



- Working assumption emission of a jet from vertex small probability



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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

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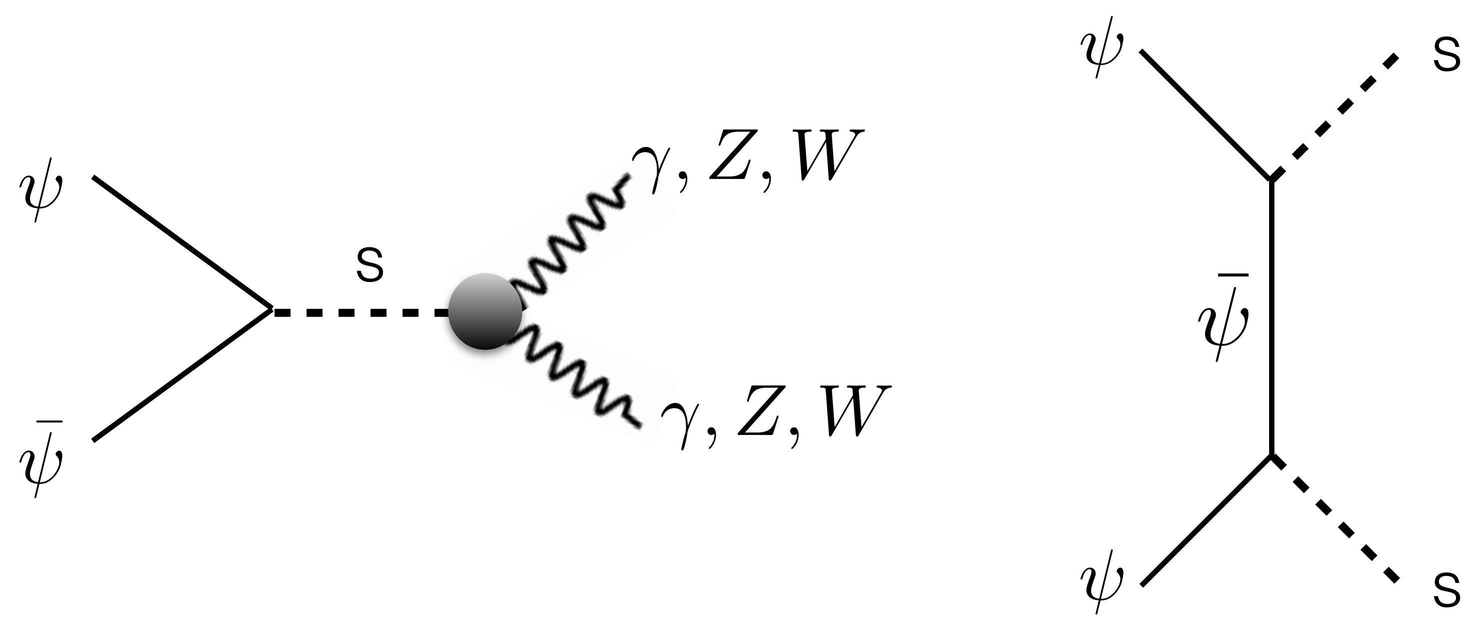
Dark matter relic

- 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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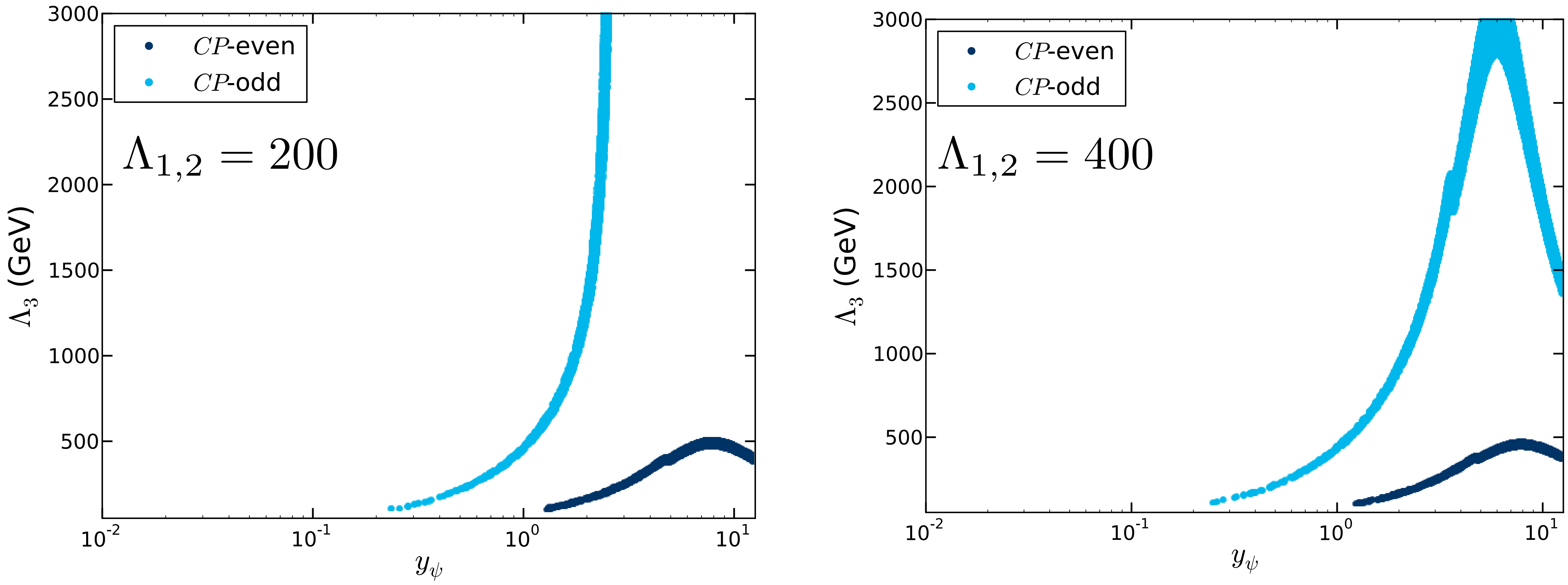
$$m_\psi = 250\,\text{GeV}$$



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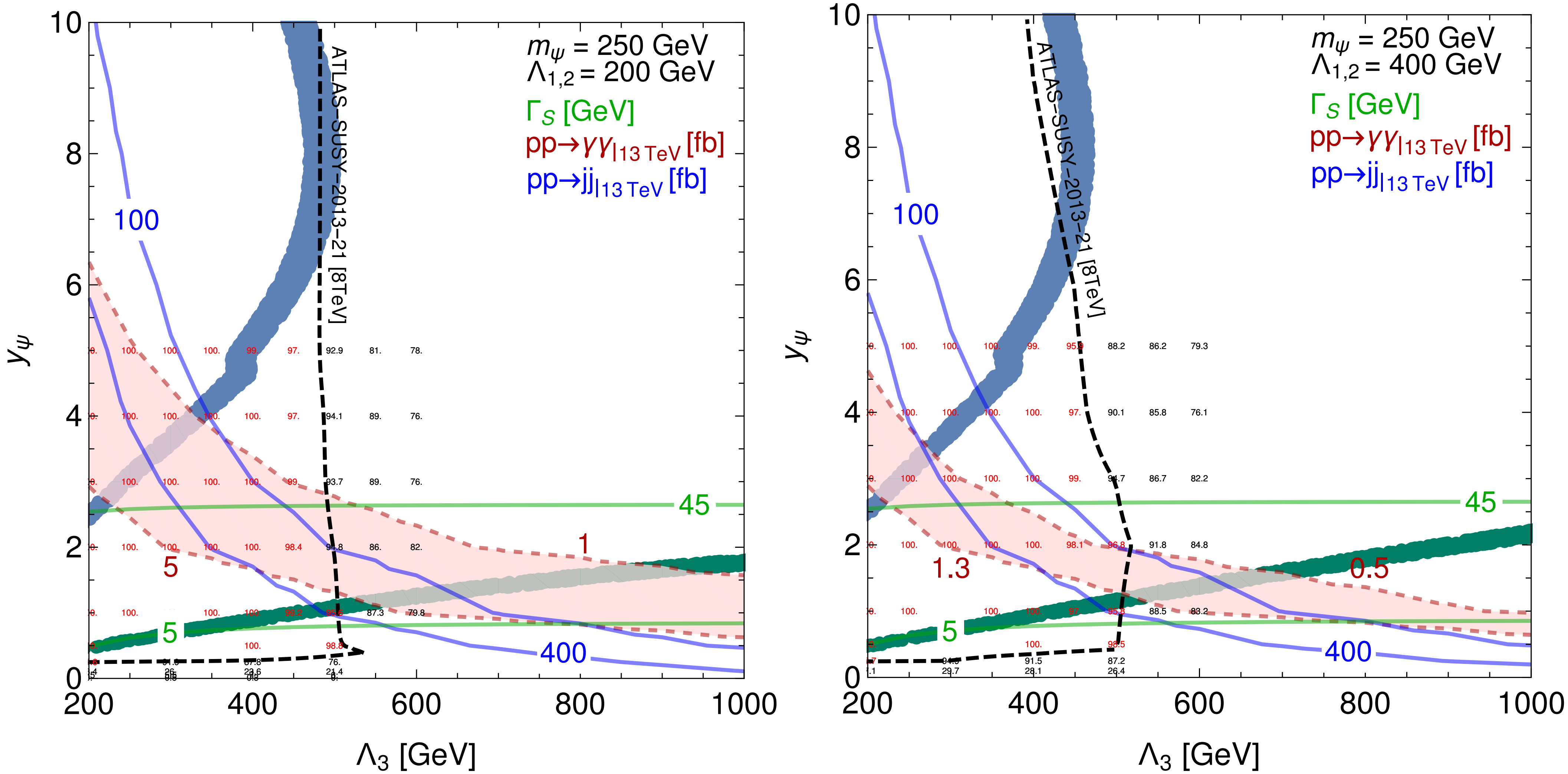
Melange des constraints

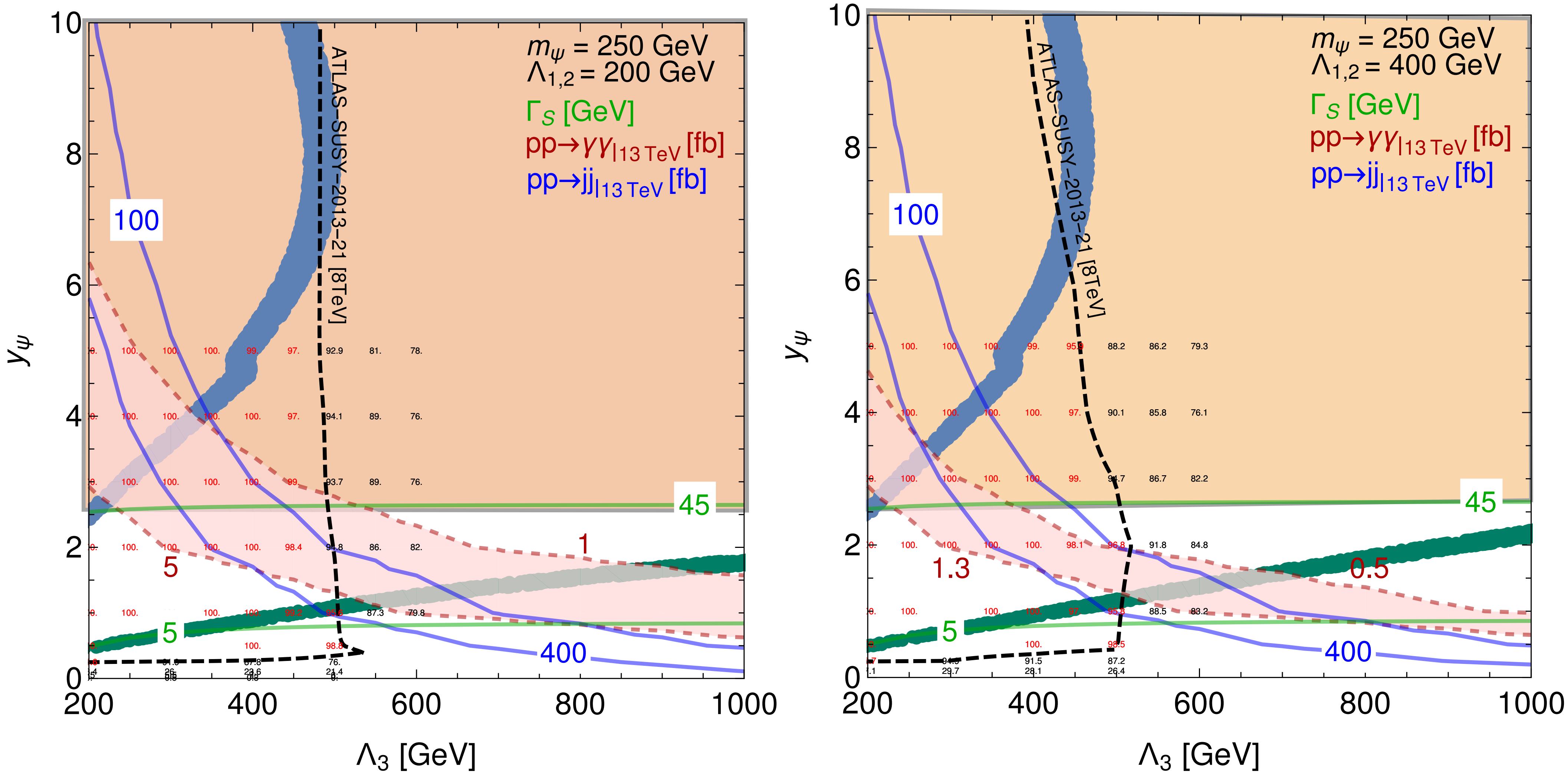
Barducci et al arXiv: 1512.06842



- 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)

Melange des constraints

Barducci et al arXiv: 1512.06842



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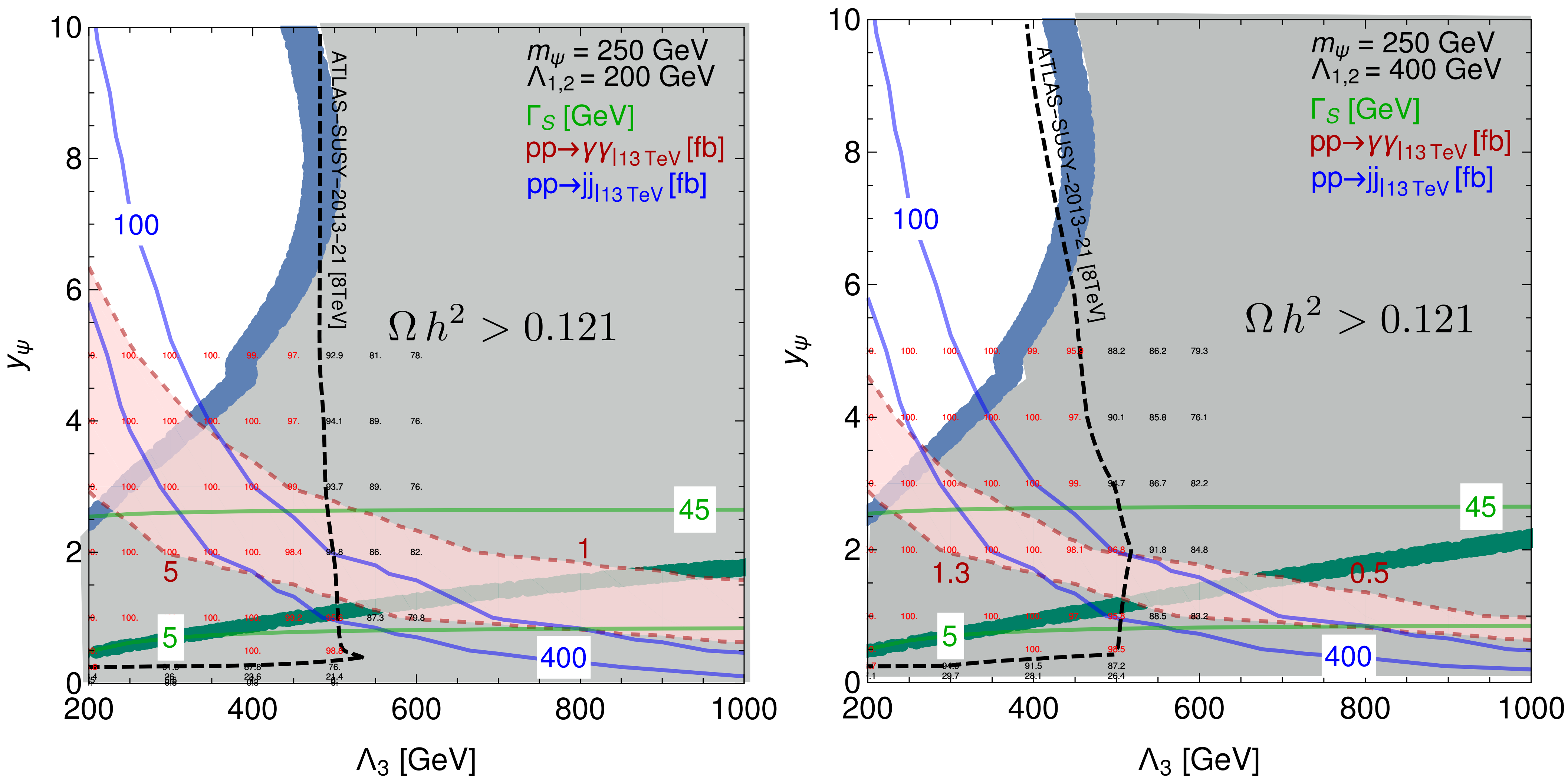

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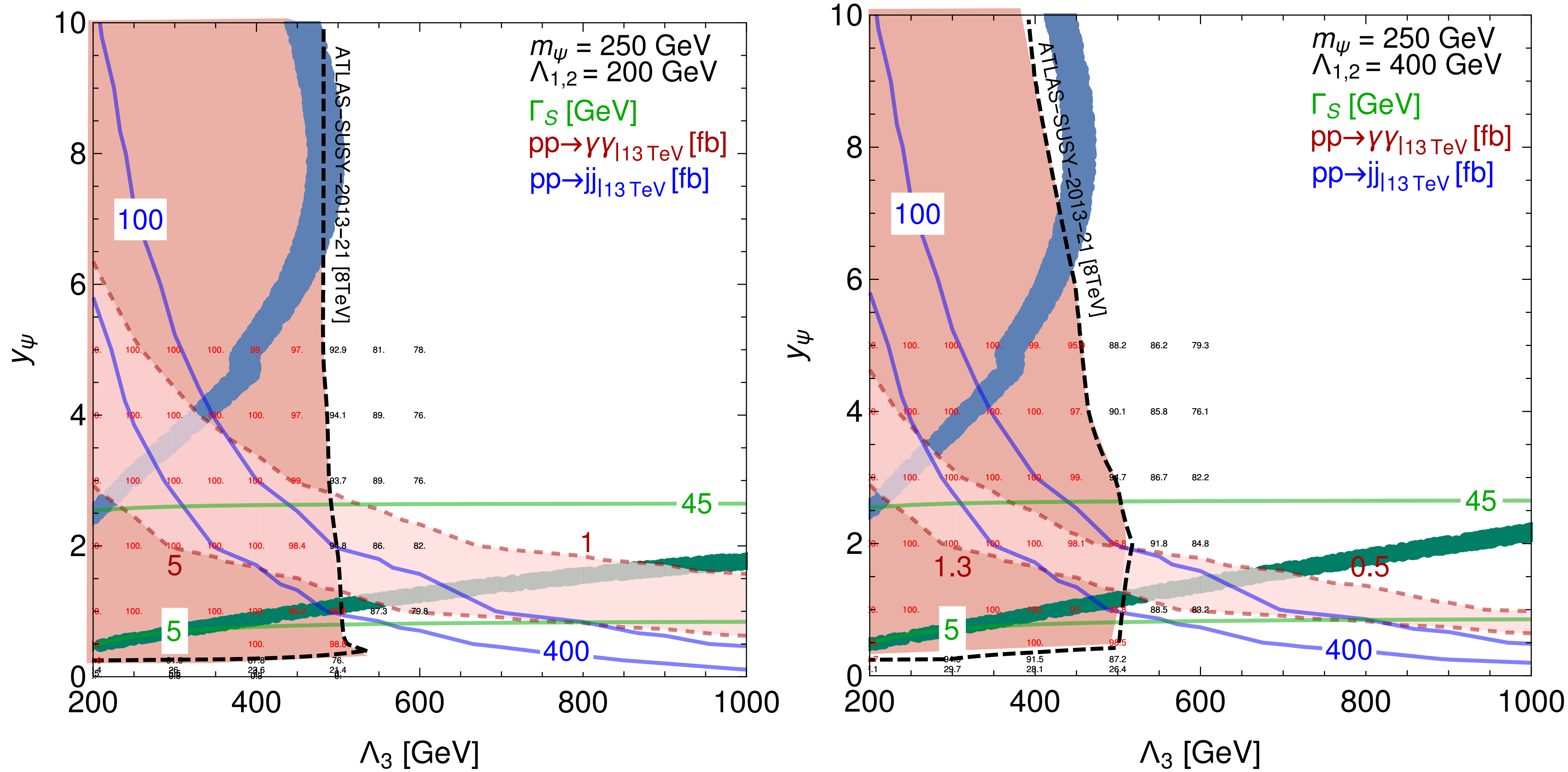

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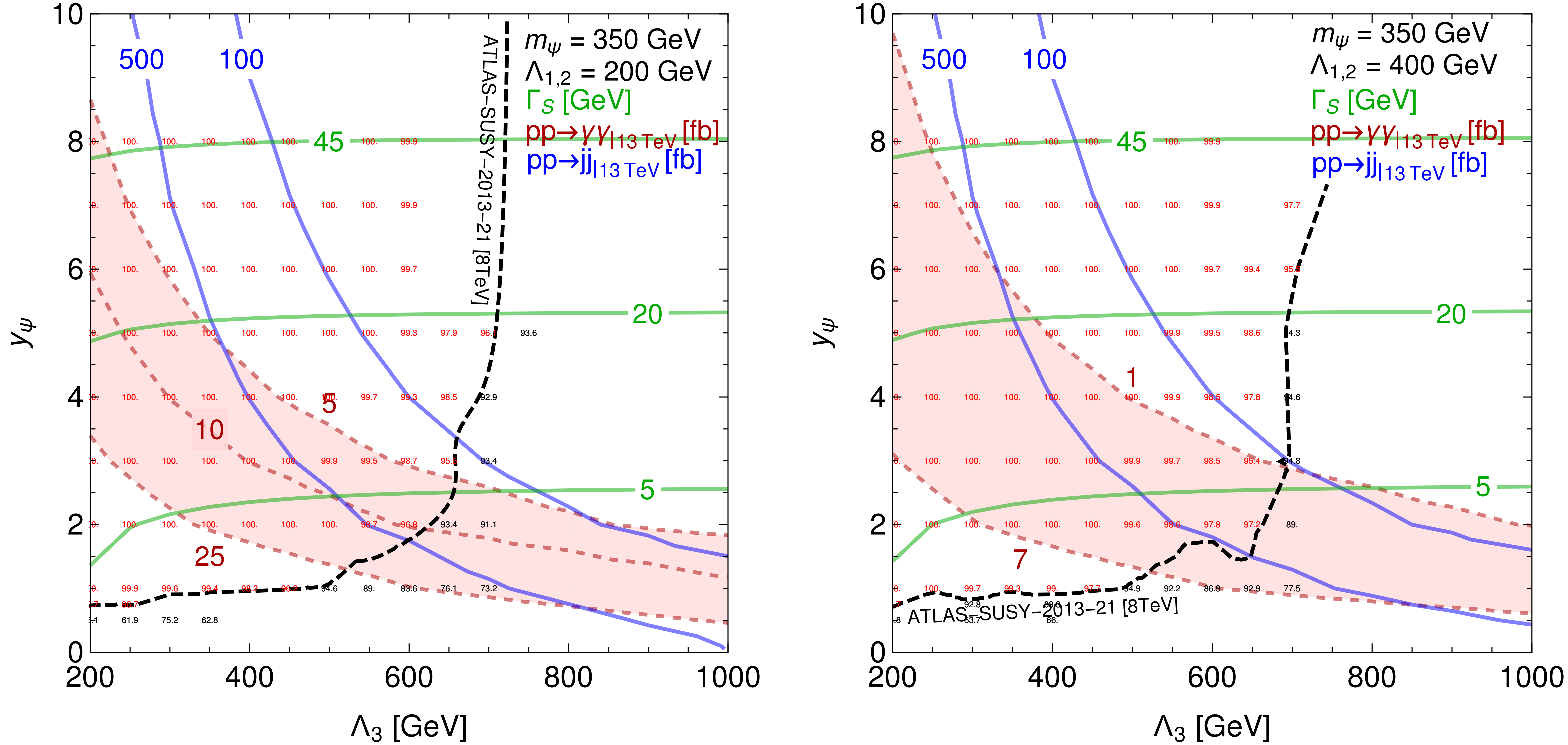
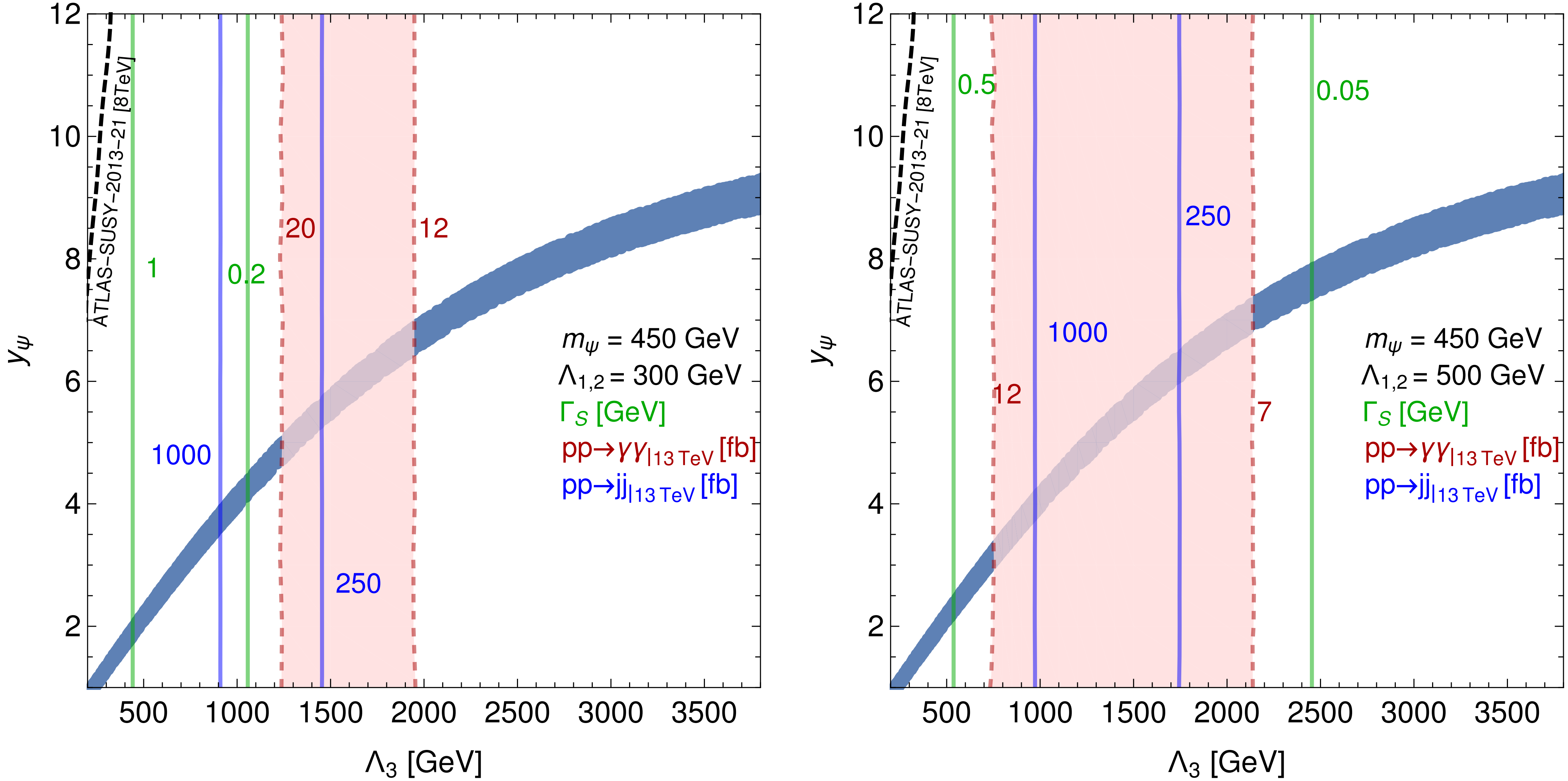


- Large part excluded by mono jet
- Relic density achieved for ypsi < 1
- Although monojet constraints and LHC diphoton excess can work, the width is very small

Melange des constraints

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 might do a better job
- Not possible to get the large width, the DM LHC constraints less interesting

Future prospects

Backovic et al arXiv:1605.07962

$$\mathcal{L} \supset \frac{c_G}{\Lambda} S G^{\mu\nu} G_{\mu\nu} + \frac{c_W}{\Lambda} S W^{\mu\nu} W_{\mu\nu} + \frac{c_B}{\Lambda} S B^{\mu\nu} B_{\mu\nu} + g_f \sum_q \frac{m_q}{\Lambda} S \bar{q} q + g_X S \bar{X} X$$

$$\begin{aligned}\mathcal{L}_{\rm NP,CPE} = & \frac{1}{2}(\partial_\mu s)^2 - \frac{\mu_s^2}{2} s^2 + \frac{1}{2}\bar{\psi}(i\partial\!\!\!/_\mu - m_\psi)\psi - \frac{y_\psi}{2} s\bar{\psi}\psi \\ & - \frac{g_1^2}{4\pi}\frac{1}{4\Lambda_1} s\ B_{\mu\nu}B^{\mu\nu} - \frac{g_2^2}{4\pi}\frac{1}{4\Lambda_2} s\ W_{\mu\nu}W^{\mu\nu} - \frac{g_3^2}{4\pi}\frac{1}{4\Lambda_3} s\ G_{\mu\nu}G^{\mu\nu}\end{aligned}$$

- Slightly different parametrisation of Lagrangian, however the same model

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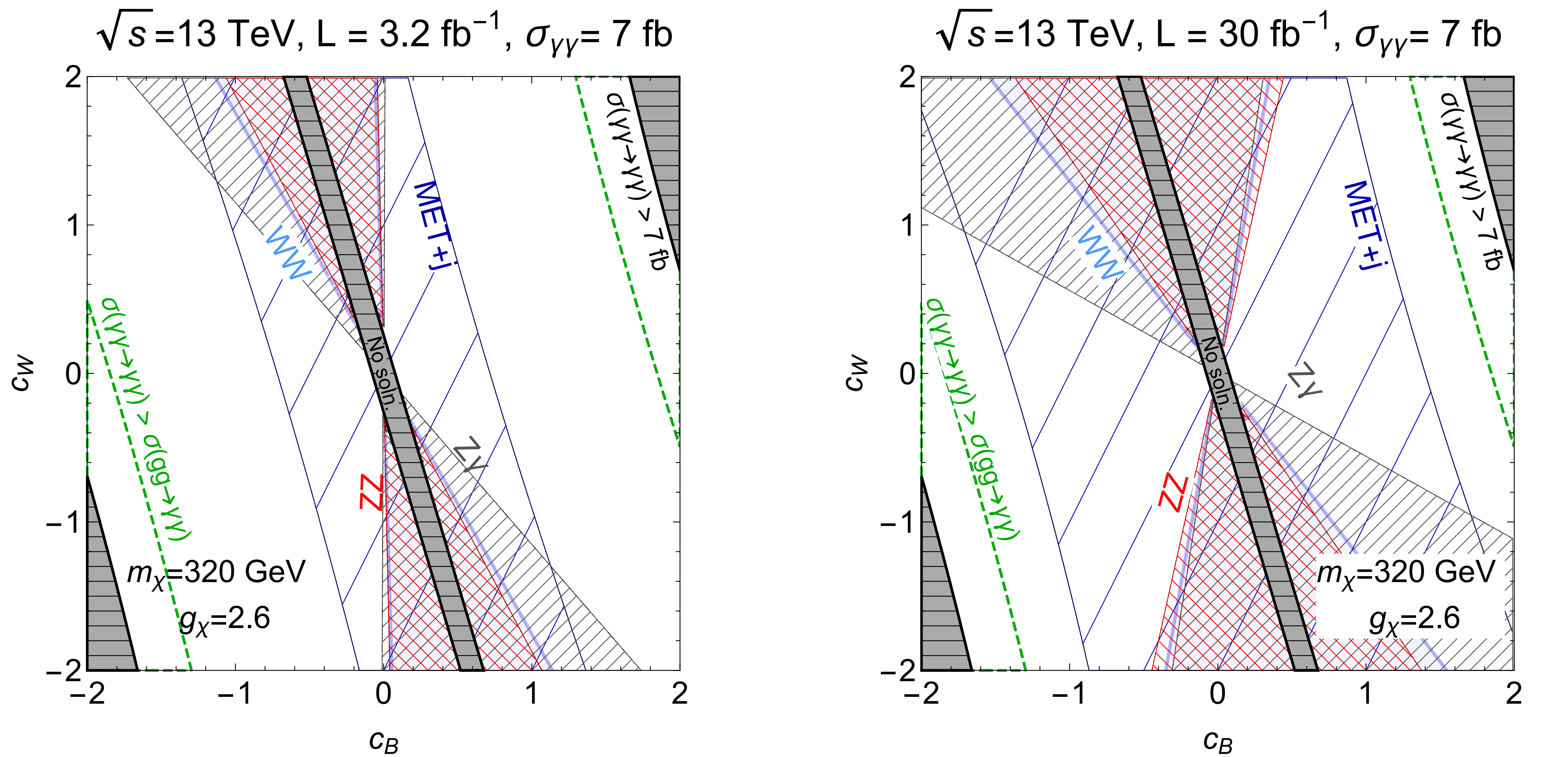
Future prospects

Backovic et al arXiv:1605.07962



- Extrapolated limits from LHC8 to LHC13
- Almost entire parameter space covered for 30 fb^{-1} luminosity

Test case: II

Exploring momentum dependent dark matter couplings

Barducci et al, arXiv:1605.02684 [LH proceedings]

Barducci et al, work in progress

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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?

Simple case

- 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

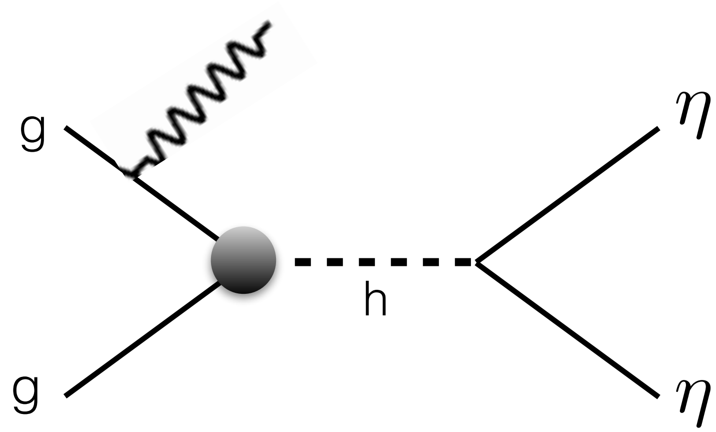
$$\mathcal{L}_\eta \supset -\frac{1}{4}(v+h)^2\left(\lambda\eta^2 + \frac{1}{f^2}\partial_\mu\partial^\mu\eta^2\right) \qquad m_\eta^2 = \mu_\eta^2 + \lambda v^2/2$$

scale of spontaneous symmetry breaking (f)

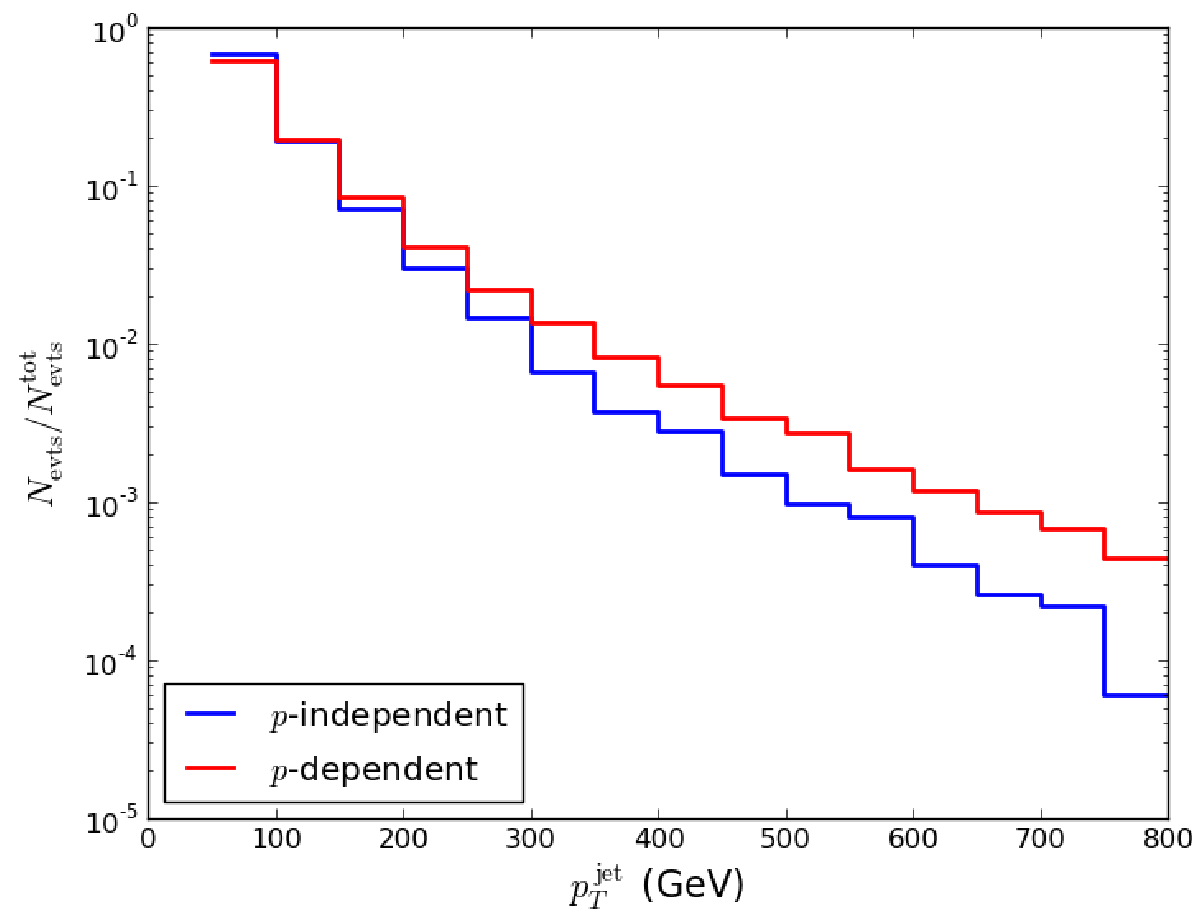
Momentum dependent coupling ($\partial_\mu\partial^\mu\eta^2$)

For mono-Higgs signature study of similar model see e.g. arXiv:1312.2592, arXiv:1412.0258

Impact on monojets

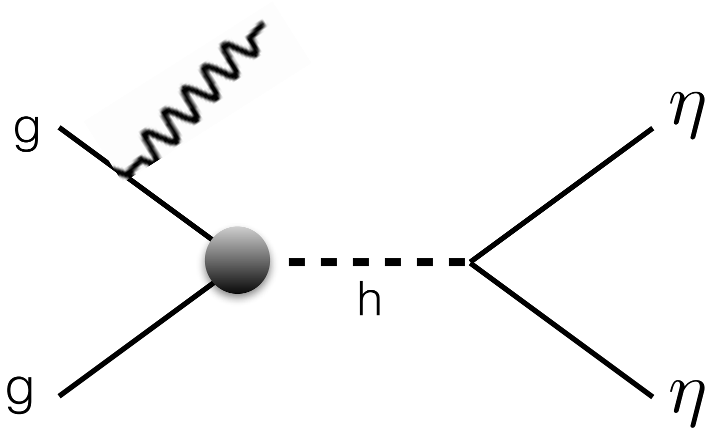


$$ig_{h\eta\eta} = 2iv\left[\lambda_{\rm mi} + \frac{p_h^2}{f^2}\right]$$



- Different integrated number of events after a fixed jet pT cut in momentum dependent or independent couplings

Impact on monojets



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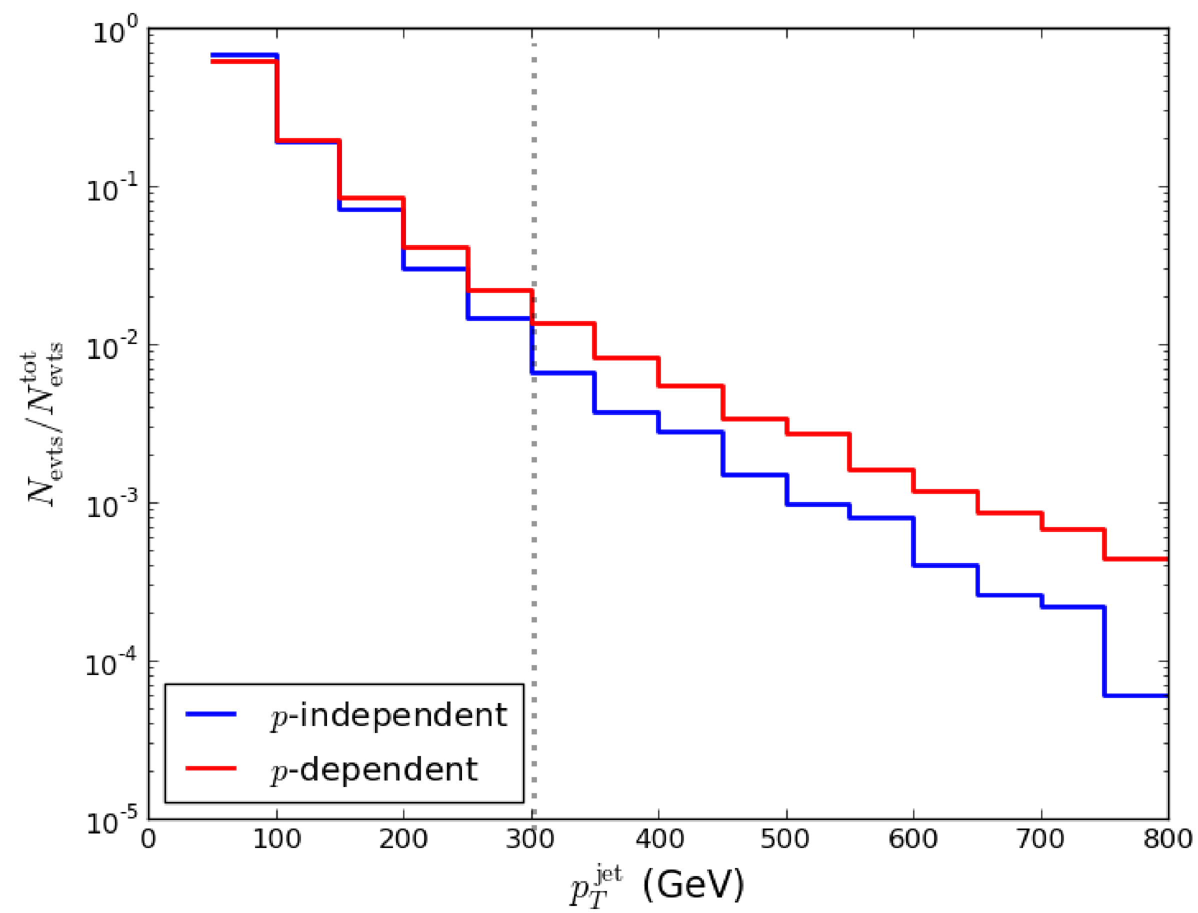


- Different integrated number of events after a fixed jet pT cut in momentum dependent or independent couplings

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

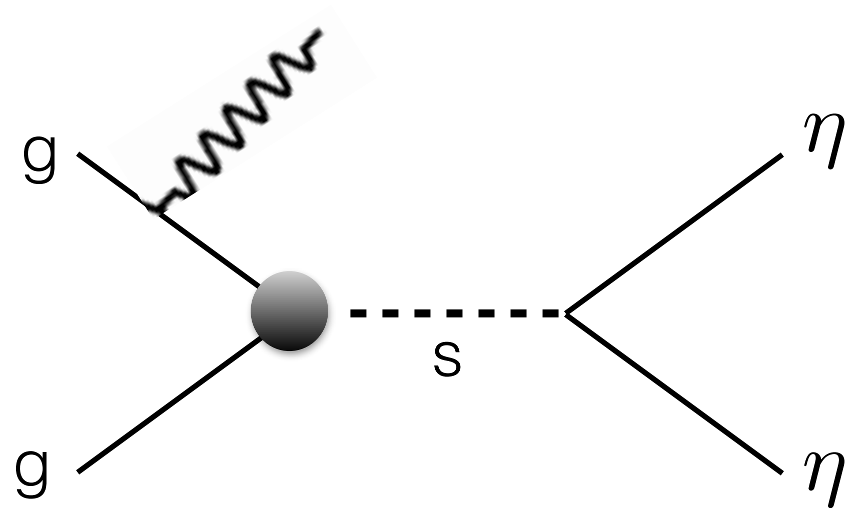
- Off-shell Higgs regime, leads to a very small cross section < 1 fb for momentum dependent and <0.5 fb for momentum independent couplings

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

Model

- Z_2 odd real singlet scalar dark matter particle couplings to the Standard Model with Z_2 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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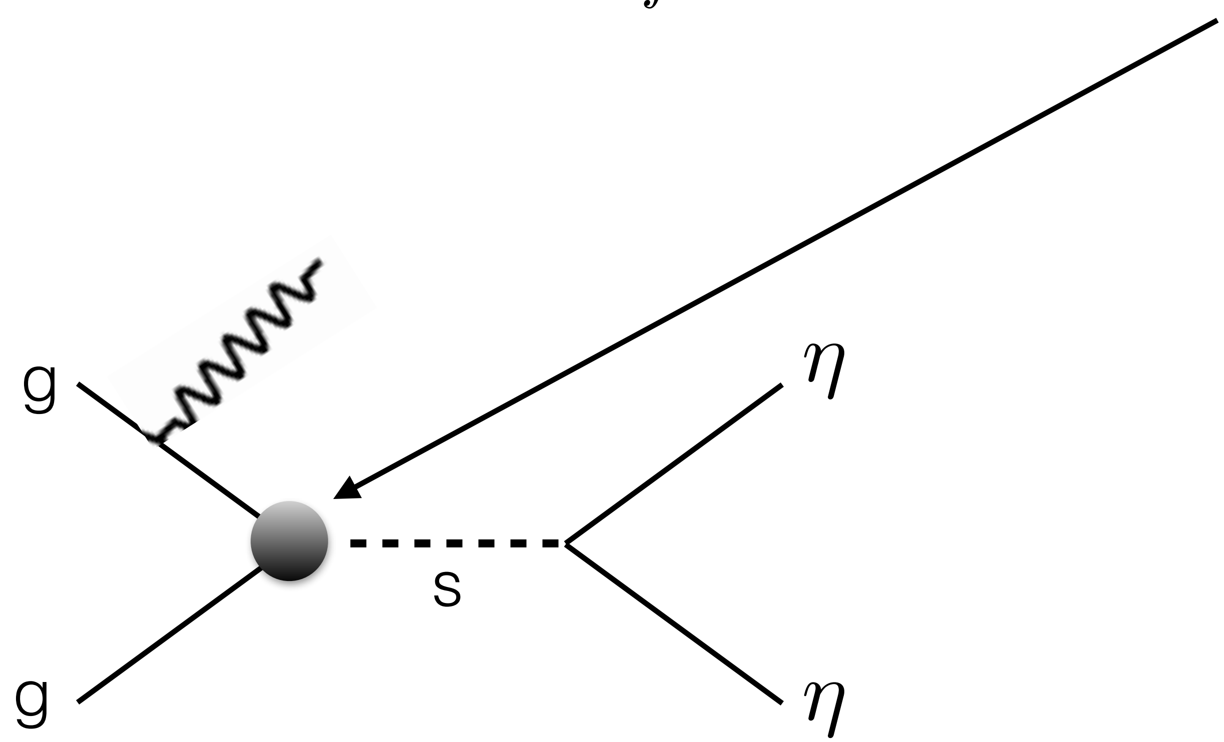

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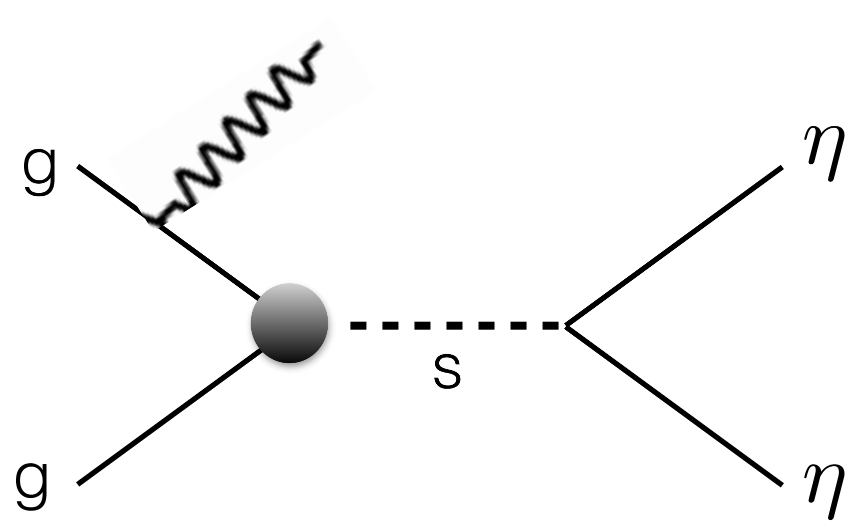
$$\mathcal{L}_{\eta,s} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}m_\eta^2\eta\eta + \frac{1}{2}\partial_\mu s\partial^\mu s - \frac{1}{2}m_s^2 ss$$
$$+ \frac{c_{s\eta}f}{2}s\eta\eta + \frac{c_{\partial s\eta}}{f}(\partial_\mu s)(\partial^\mu\eta)\eta + \frac{\alpha_s}{16\pi}\frac{c_{sg}}{f}sG^a_{\mu\nu}G^{a\mu\nu}$$



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

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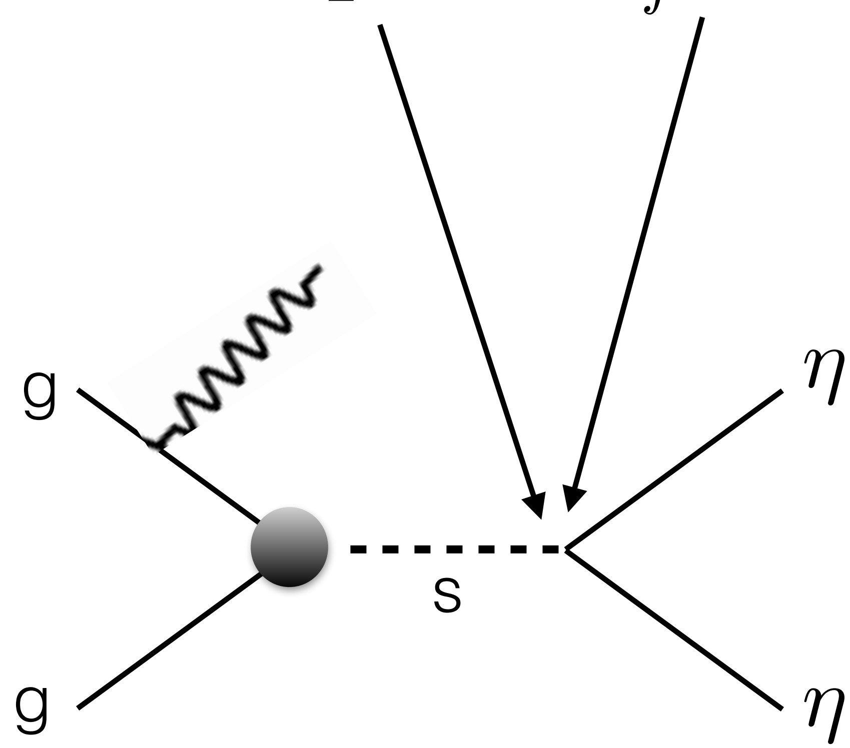

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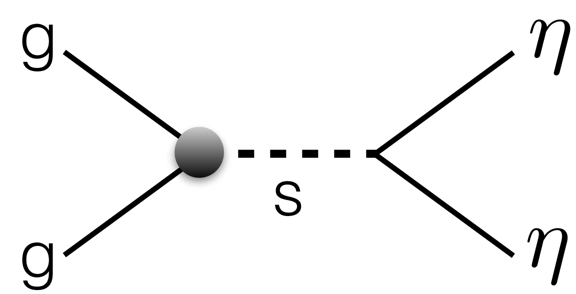
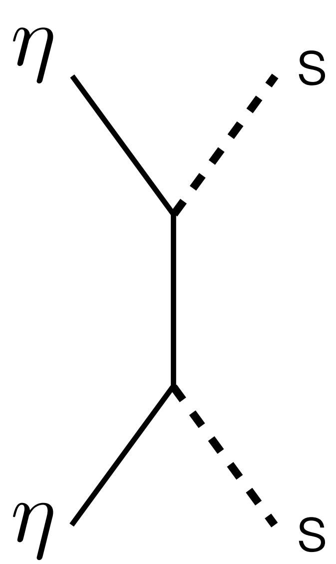
Relic density

- 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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Mostly drives relic

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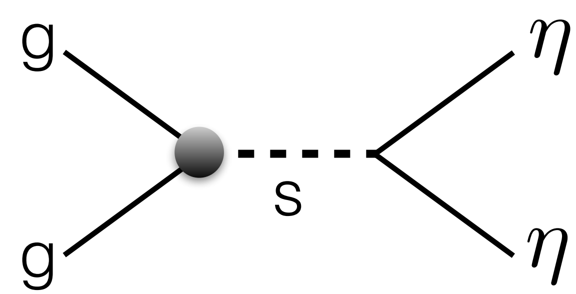

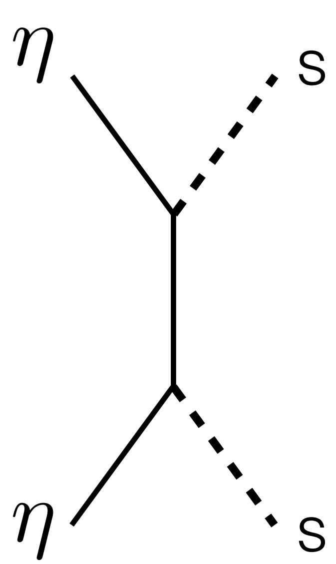

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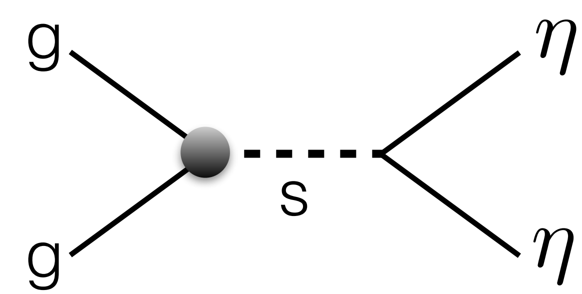
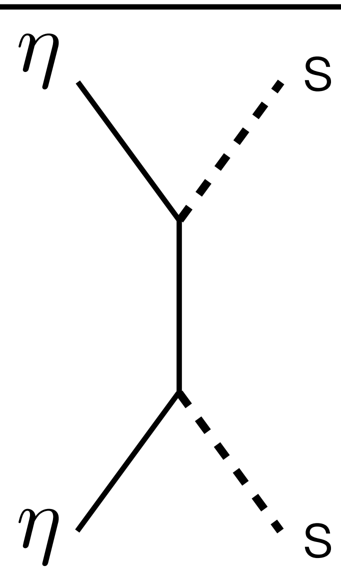


Contributes up to 15%



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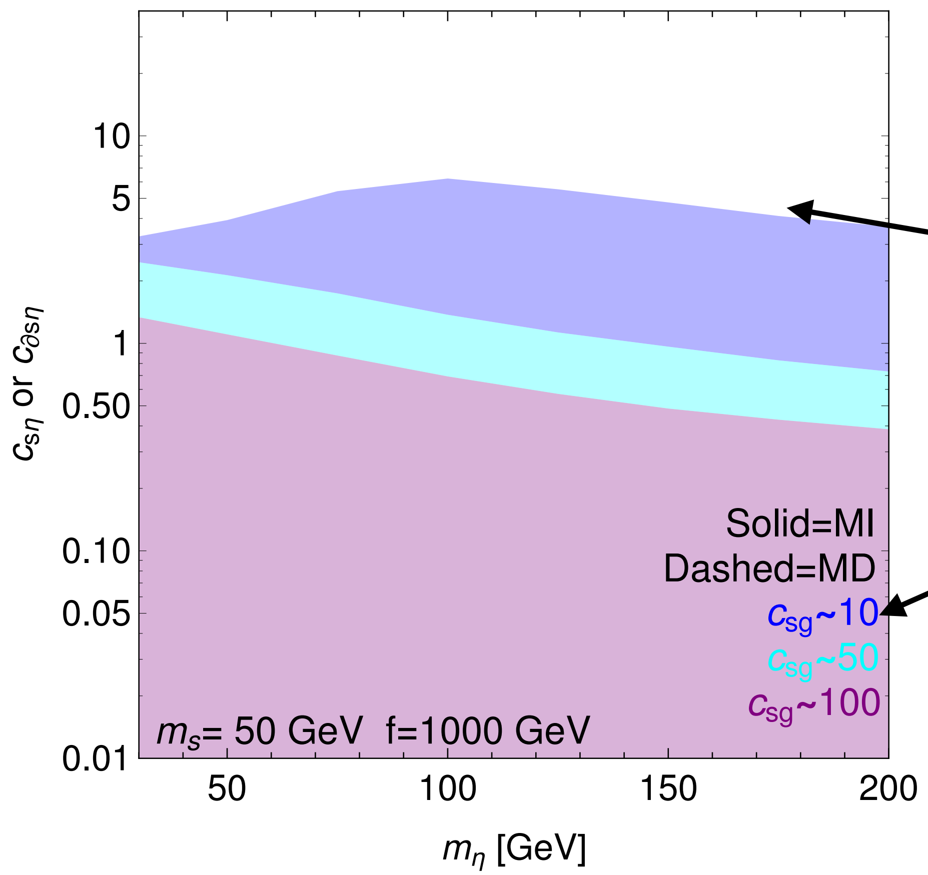
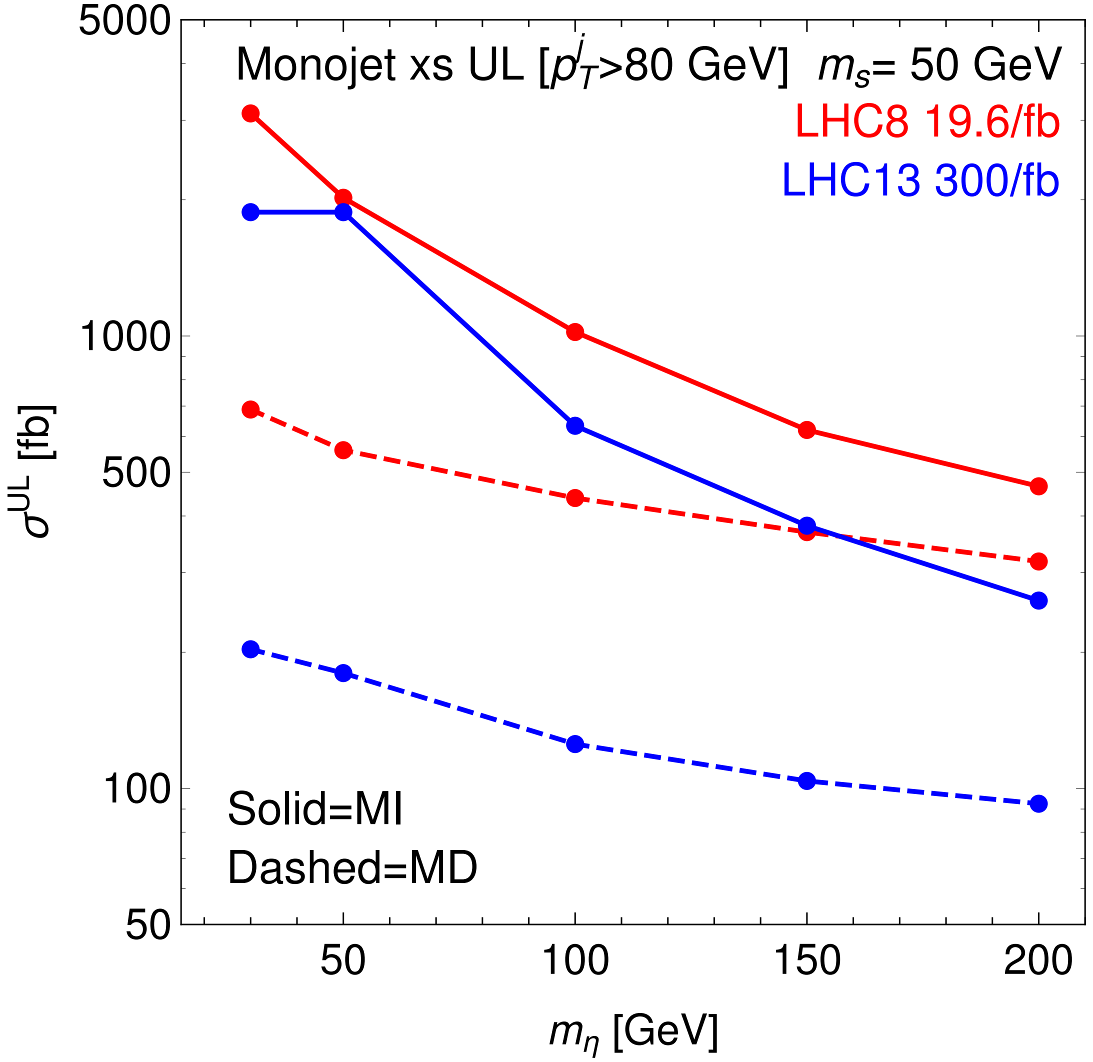
Relic density

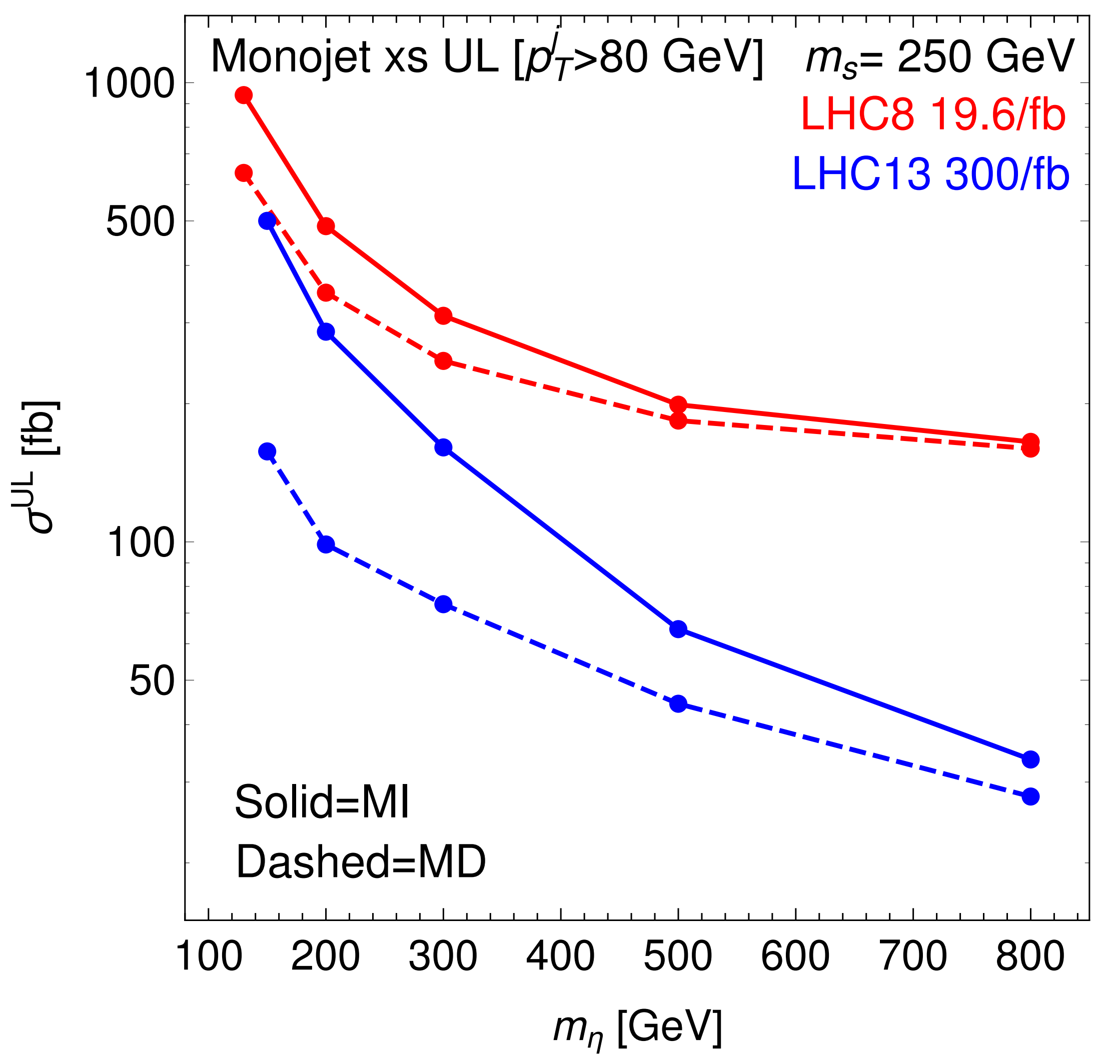


$$\langle \sigma v \rangle_{gg} \propto (c_{\partial s\eta} \times c_{sg})^2$$

Low C_{sg} requires large $C_{\partial s\eta}$

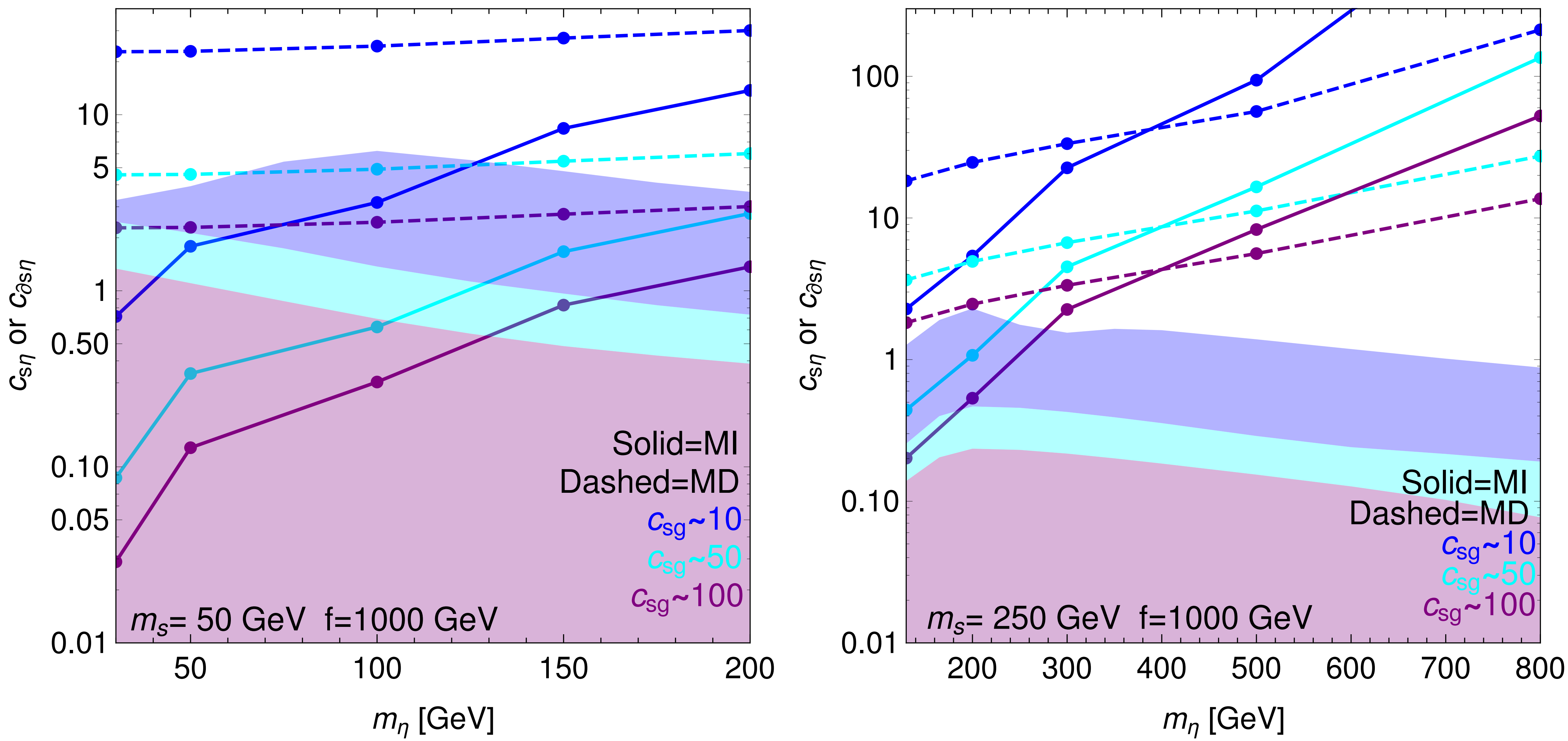
Limits





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

Does LHC probe the relic?



- 8TeV constraints projected, 13 TeV analysis ongoing

Conclusions

- 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
- 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

HEPHY
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Thank you!