ATLAS EXPERIMENT

Lake Louise Winter Institute 2016

Dark Matter Searches at ATLAS

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for the ATLAS Collaboration

10.02.2016

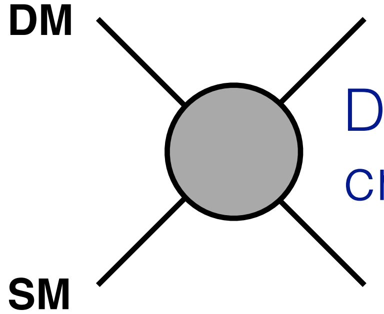
Looking for dark matter…

Much astrophysical evidence for the existence of dark matter (DM) but its nature remains unknown

- All we know: **relic density** (stable), **interacts gravitationally** (if otherwise, very weakly)
- Many scenarios possible, WIMP miracle: matches observed relic density for mass and coupling around EW scale

→ **could be produced at the LHC!**

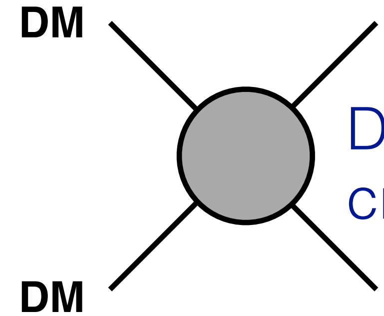
1: direct detection (DD): recoil from DM-nucleus scattering



DM-nucleon cross-section*

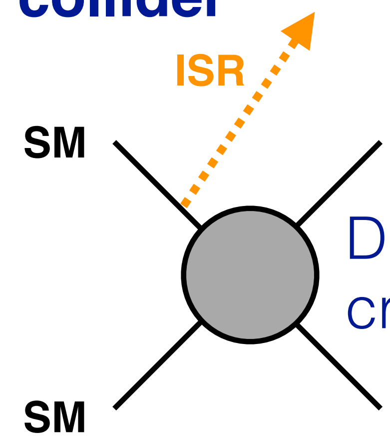
*(need to assume local DM density)

2: indirect detection (ID): DM-DM annihilation products



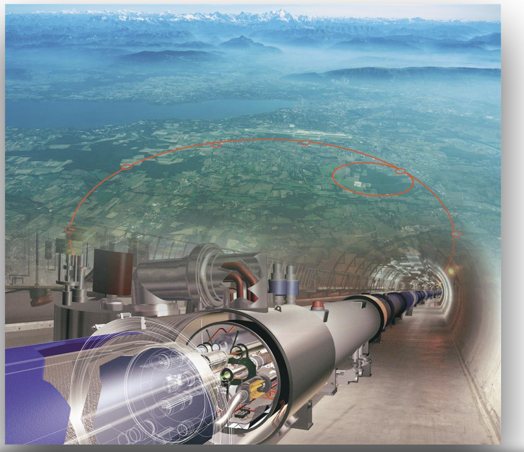
DM annihilation cross-section

3. DM production at a collider



DM production cross-section

… at the LHC



- No DM interaction with the detector → missing E_T signatures
- Initial-state radiation (ISR) to detect it * (can be **jets, photons, W, Z, …**)

* or direct coupling to DM (e.g. mono-Higgs)

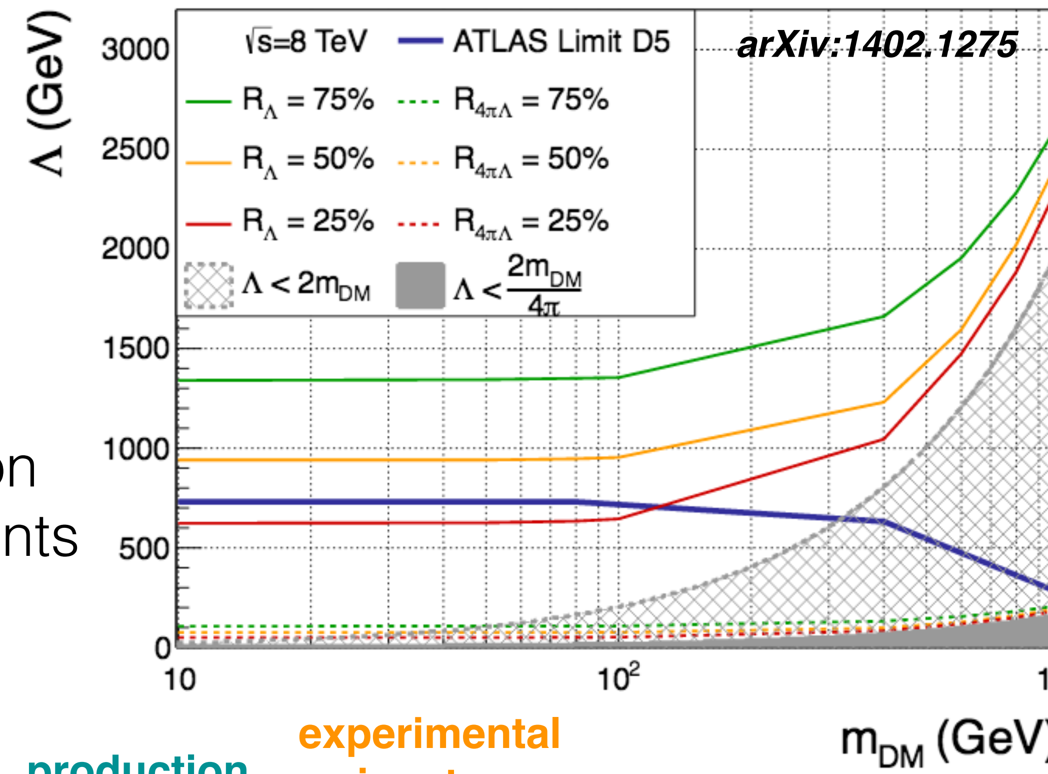
Making Comparisons

Completely different experimental techniques → different systematic effects enter

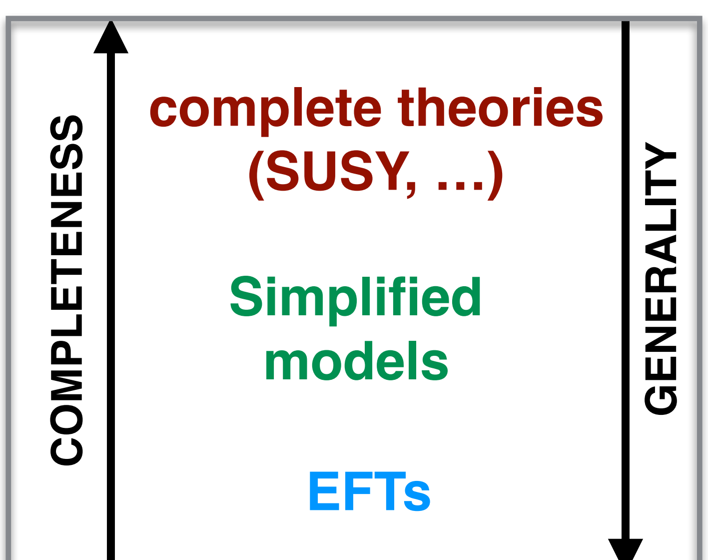
Fair comparisons require disclaimers stating assumptions made on the different sides

LHC results "traditionally" interpreted in effective field theory (EFT) models → easy comparisons

- Justified, if energy scale well below new physics ($Q_{trans} \ll m_{Med}$) → questionable at LHC!
- **Truncation procedure:** assume simplest interaction and correct cross-section, regarding only valid events
  - No "way out", but feeling for how problematic EFT is

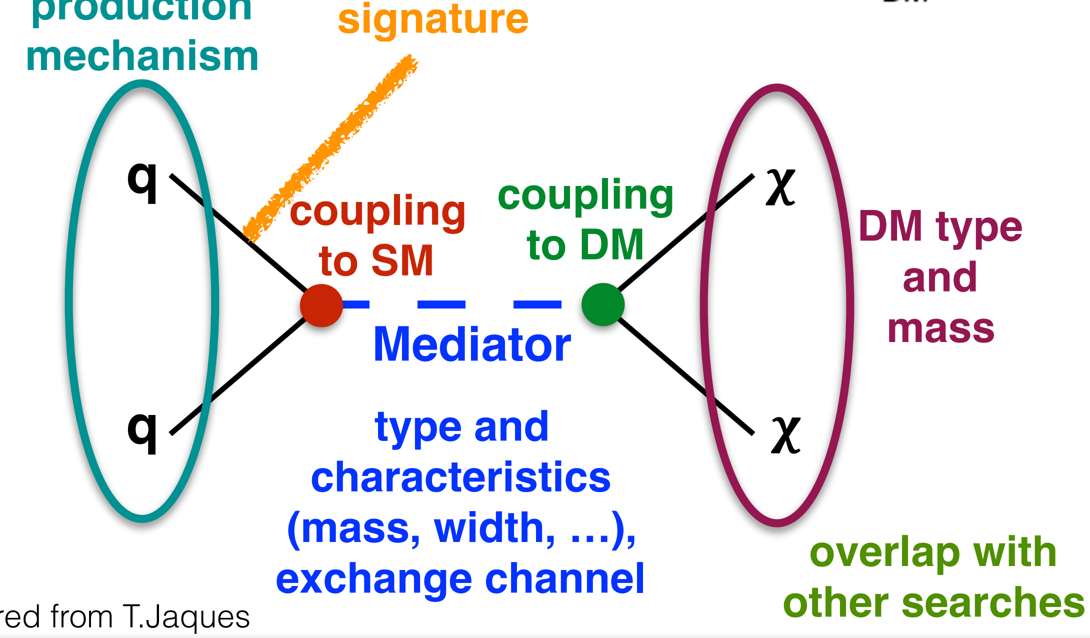


Need to move to simplified models



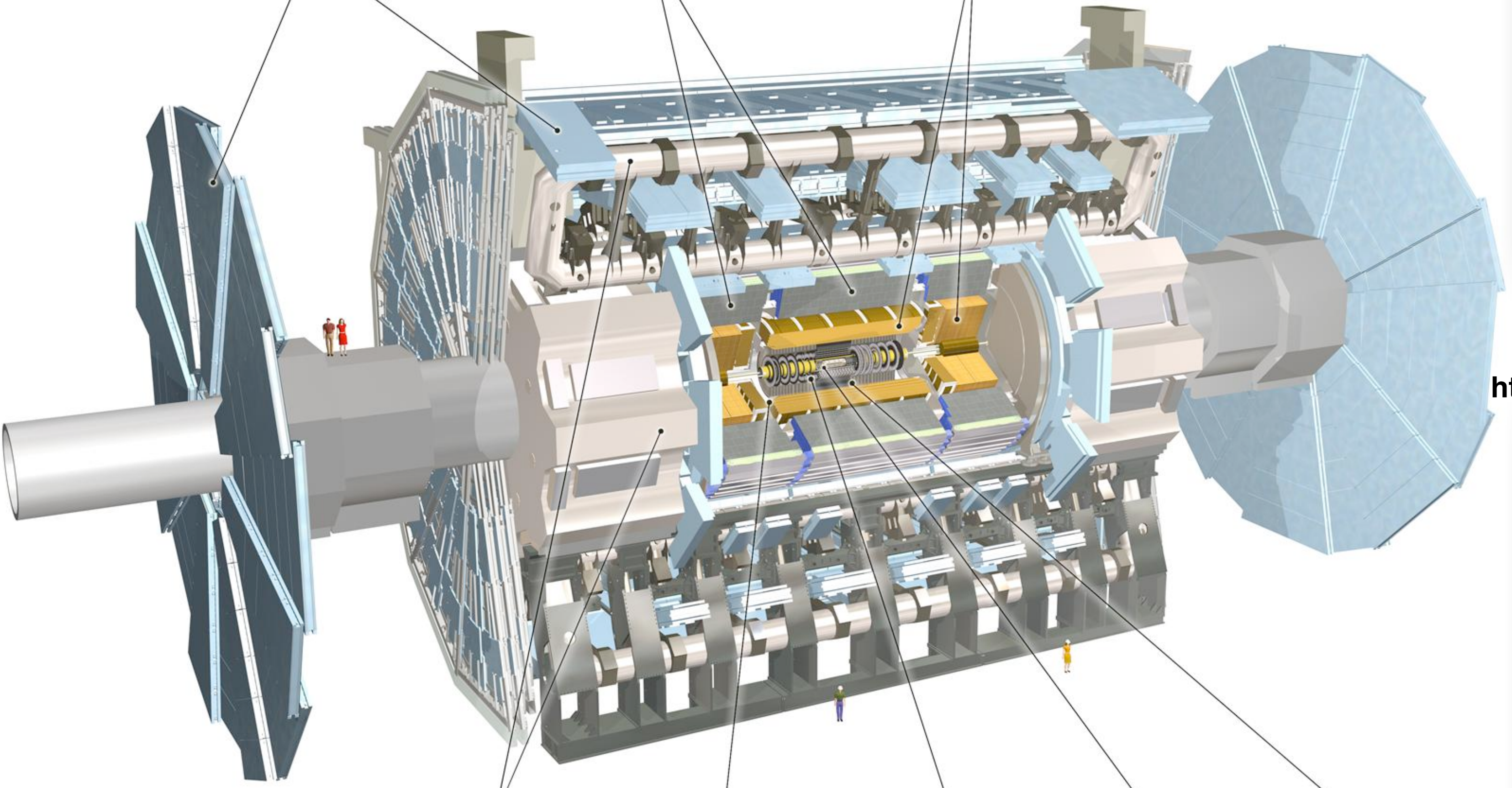
inspired from P.Pani

- Reduce whatever full theory to a simple model with DM, a mediator and one interaction

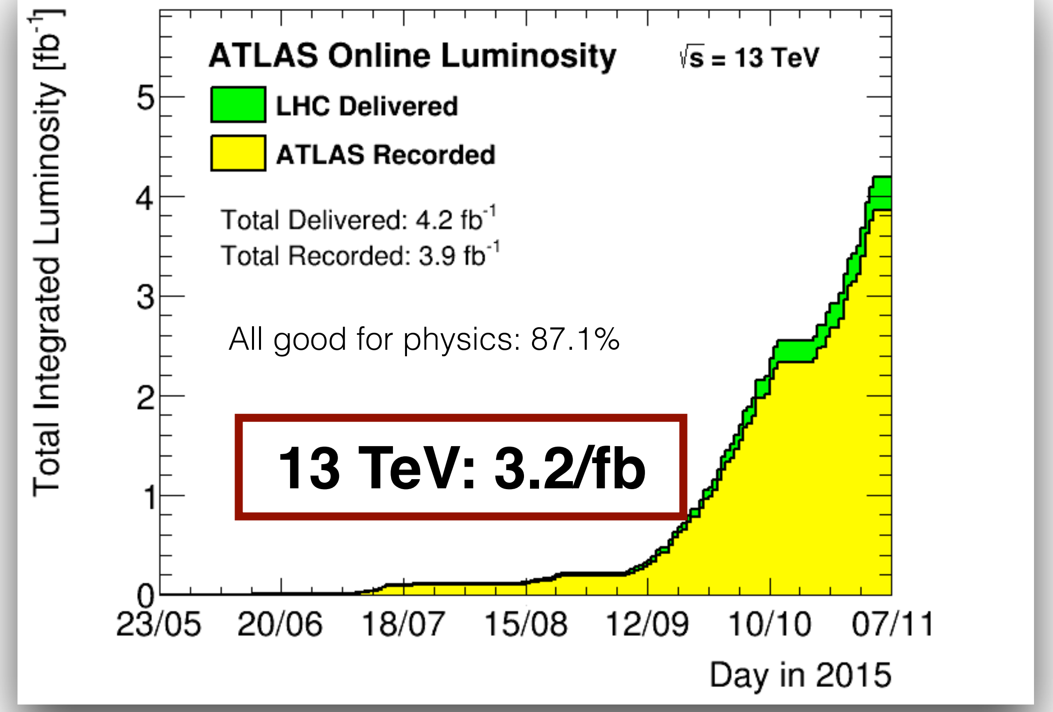


inspired from T.Jaques

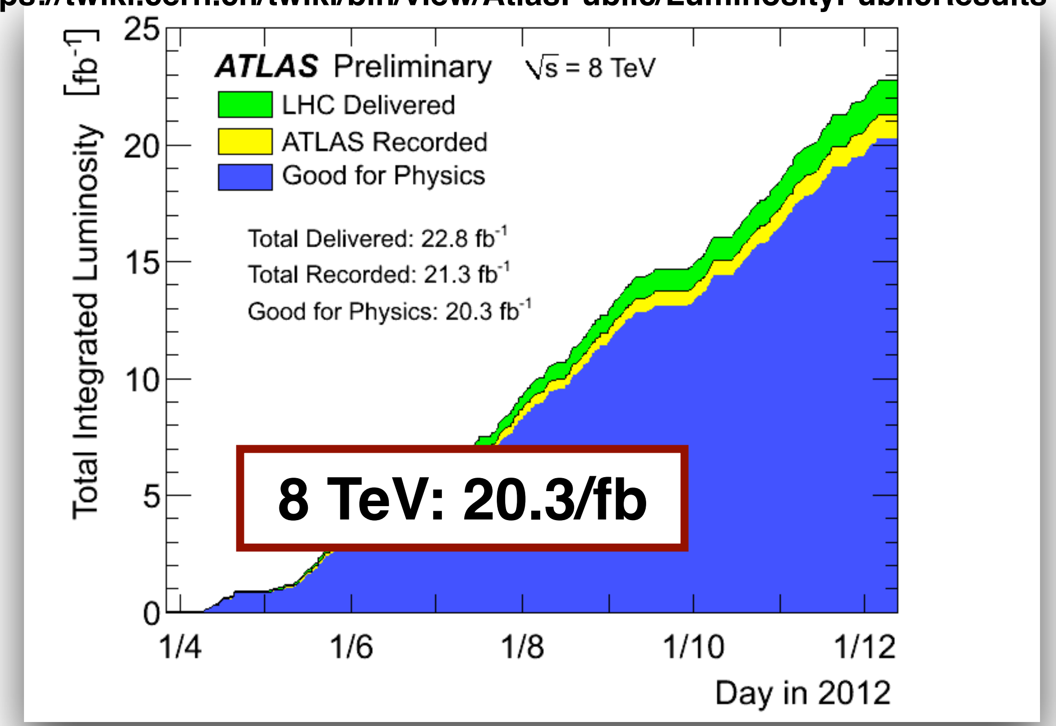
The ATLAS detector



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults

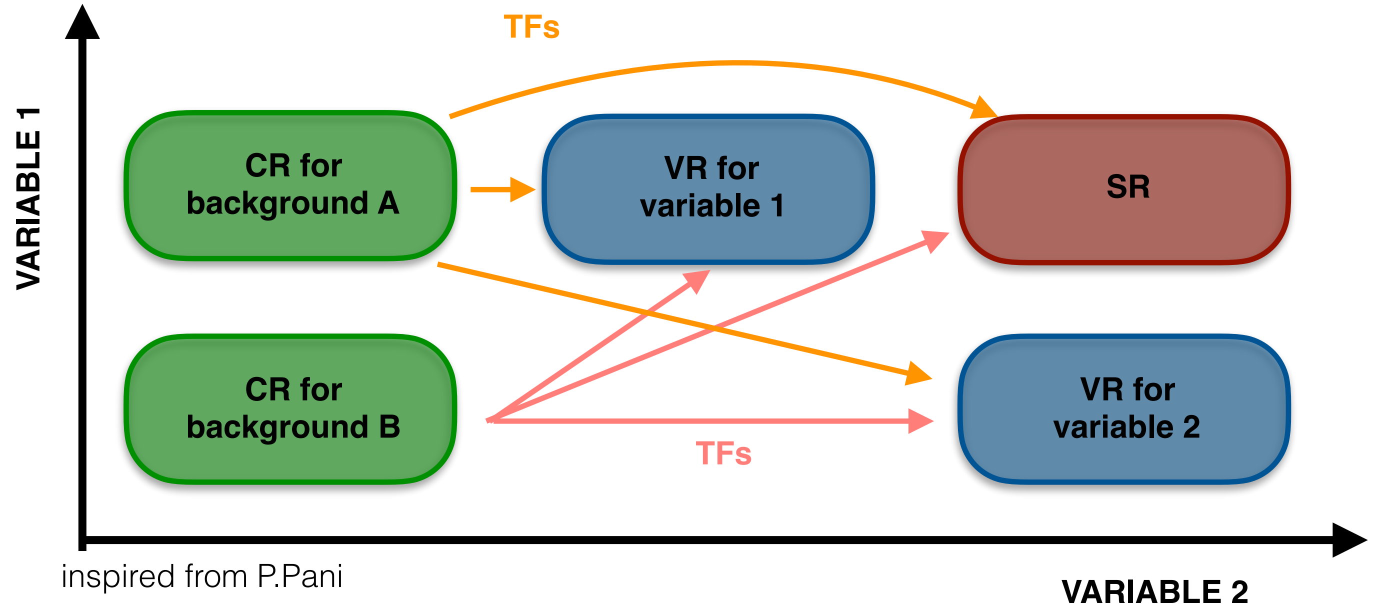


Search strategies

1: Define signal regions (SRs): as much signal and as little background as possible

2: Define control regions (CRs): similar to SR, but background-enriched

- Typically, one CR for each major background, normalise MC processes to data and extrapolate to SR via **“transfer factors” (TFs) ***



inspired from P.Pani

3: Validate TF in validation region (in between SR and CR)

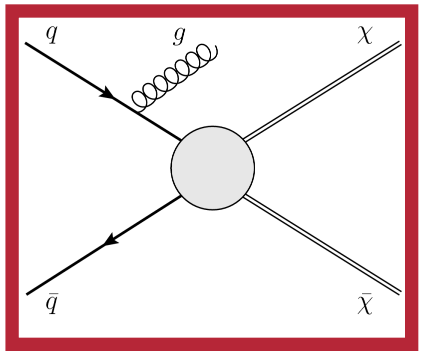
4: Look at data in SR (“unblind”)

5: Interpretation of results: signal measurements and/or limits…

* Often much more complicated in practice: CRs and corresponding SRs are fitted simultaneously in a likelihood fit or shape fits can be used

Results: Monojets

Eur. Phys. J. C (2015) 75:299



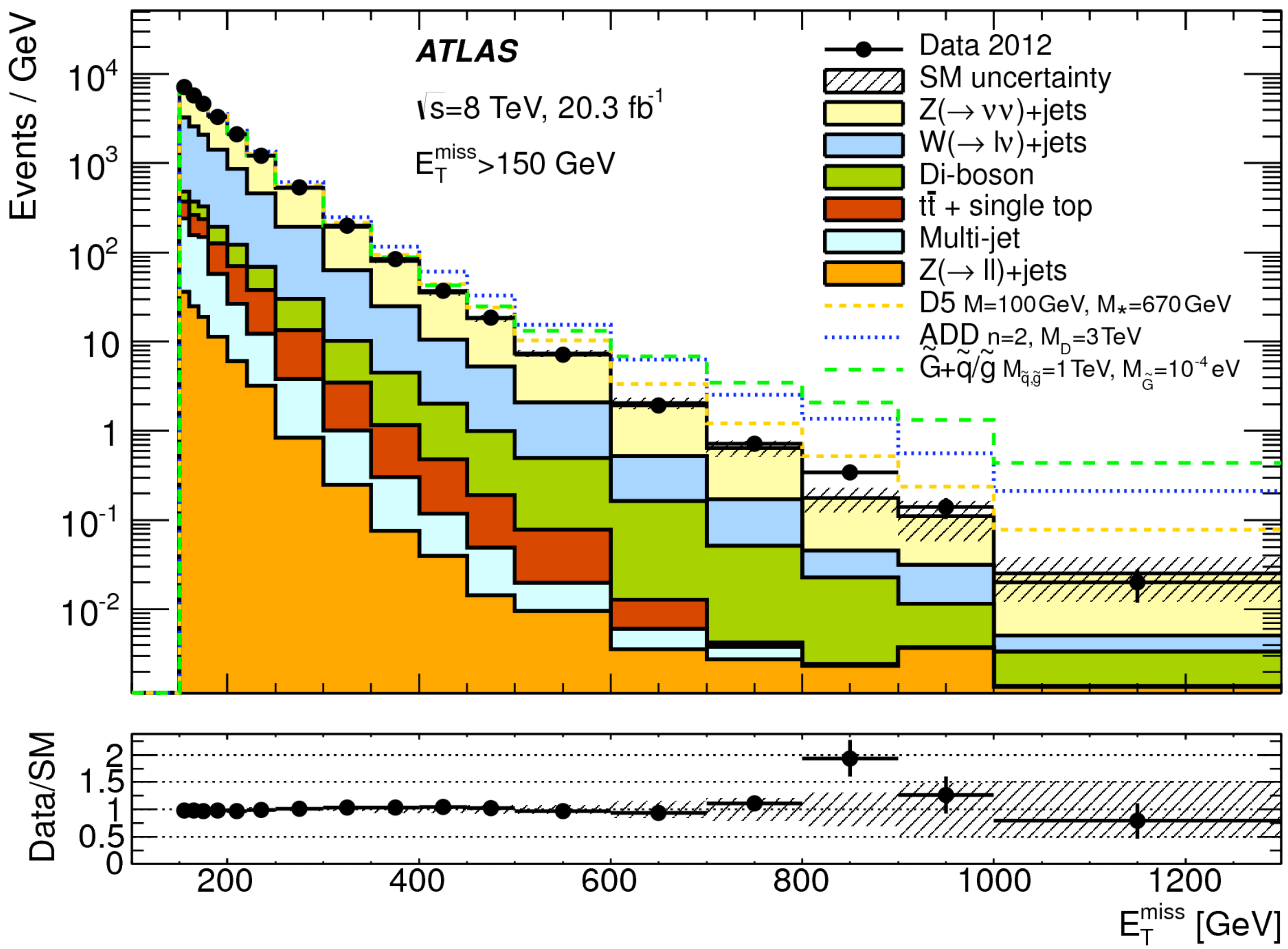
Generally most sensitive channel (highest cross-section) *

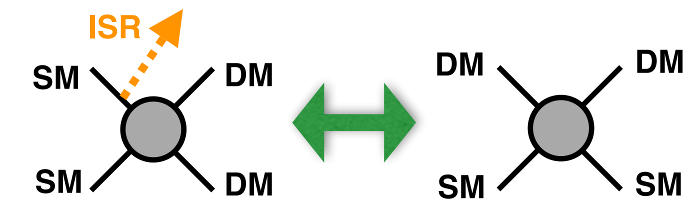
- Main irreducible background from $Z \to \nu\nu$ + jets (estimated from $W \to l\nu$ + jets and $Z \to ll$ + jets CRs)
- Truncation procedure for EFT limits

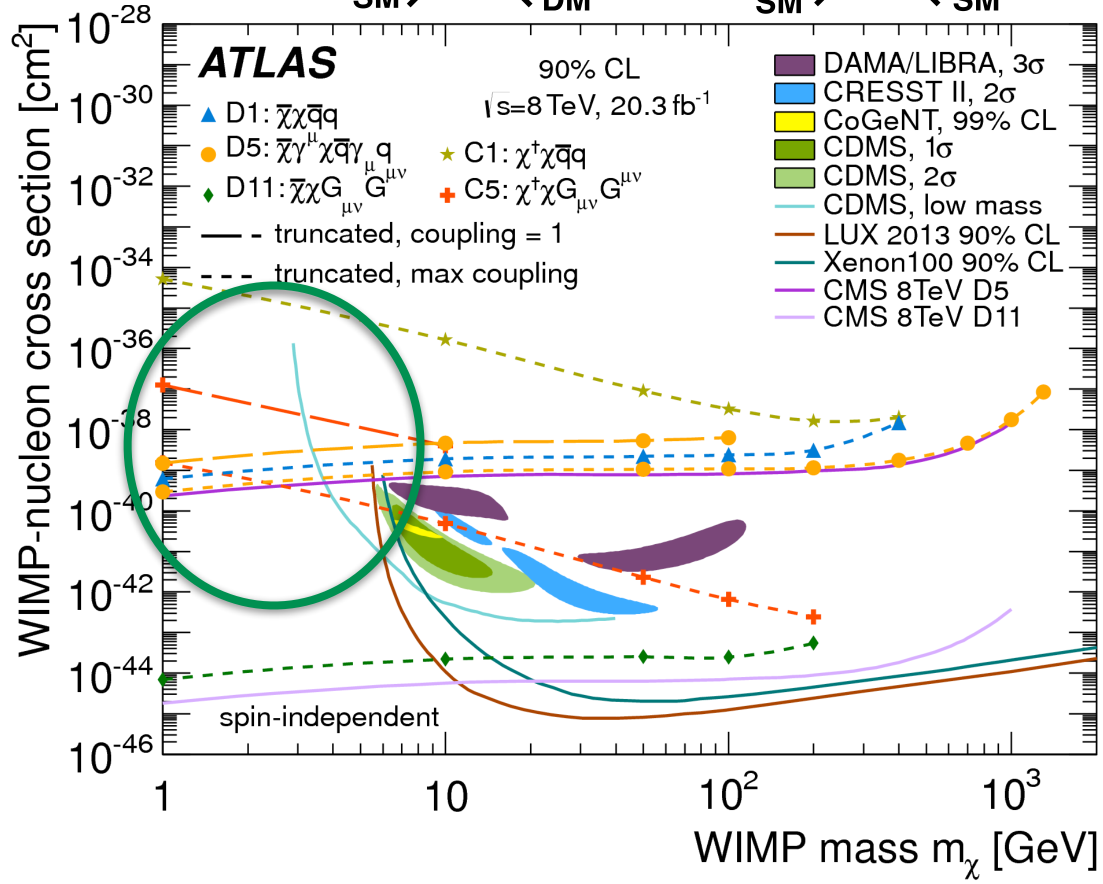
* strictly not always true, some special cases/operators

E_T^{miss} + jet(s)

- at least 1 central jet with $p_T > \max(120\ \text{GeV}, 0.5\ E_T^{miss})$
- $\Delta\phi$ (jets, E_T^{miss}) > 1
- veto leptons
- 9 E_T^{miss} bins

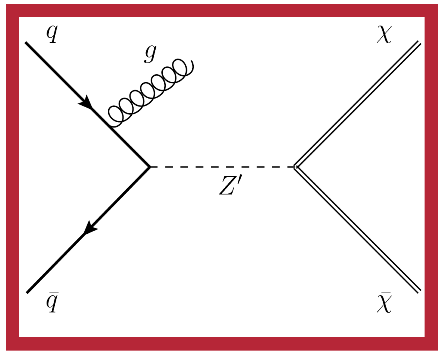






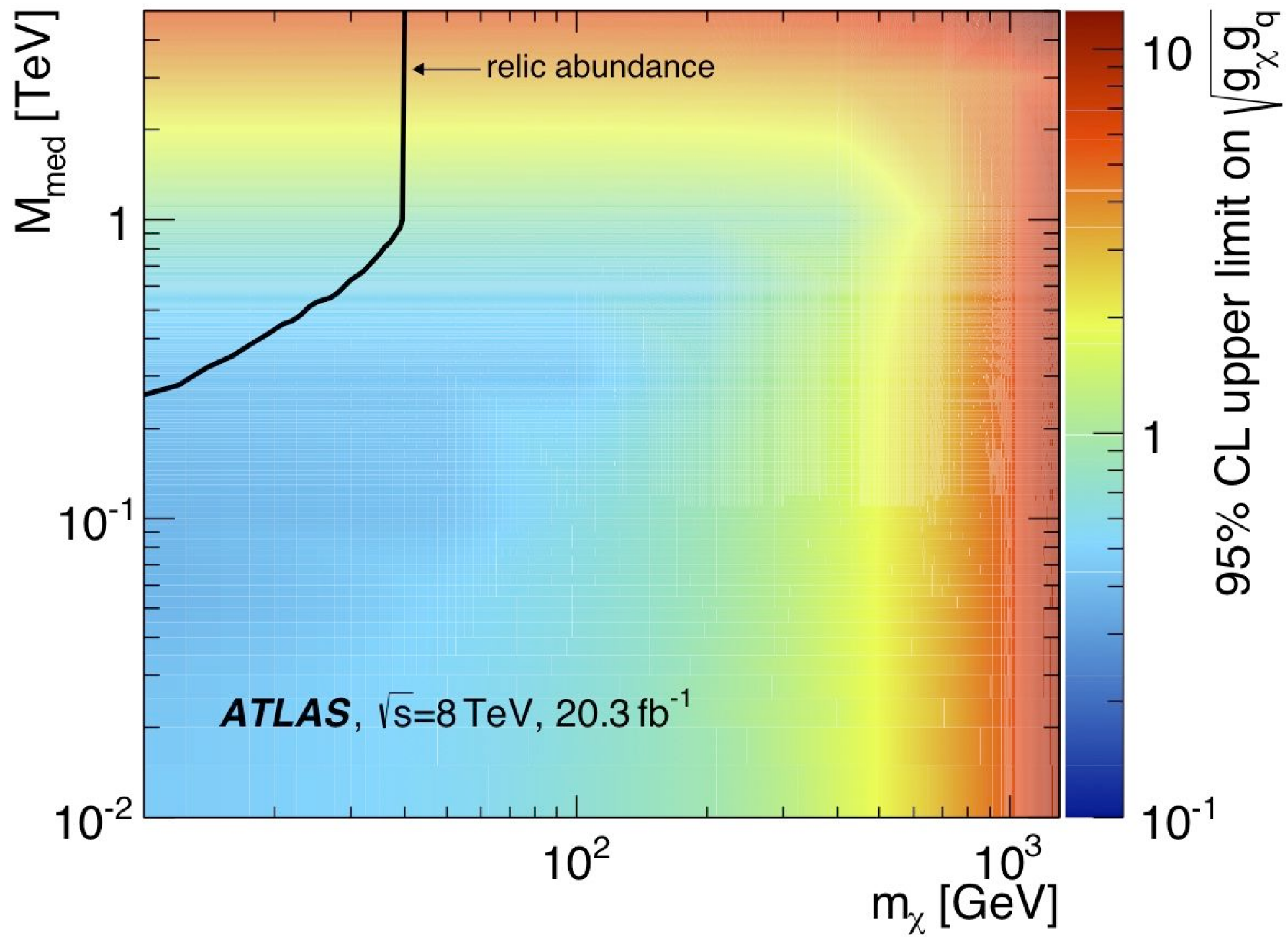
Results: Monojets

Eur. Phys. J. C (2015) 75:299



Interpretation in terms of Z'-like simplified models

- Mediator mass and width, DM mass are free parameters, set limit on couplings

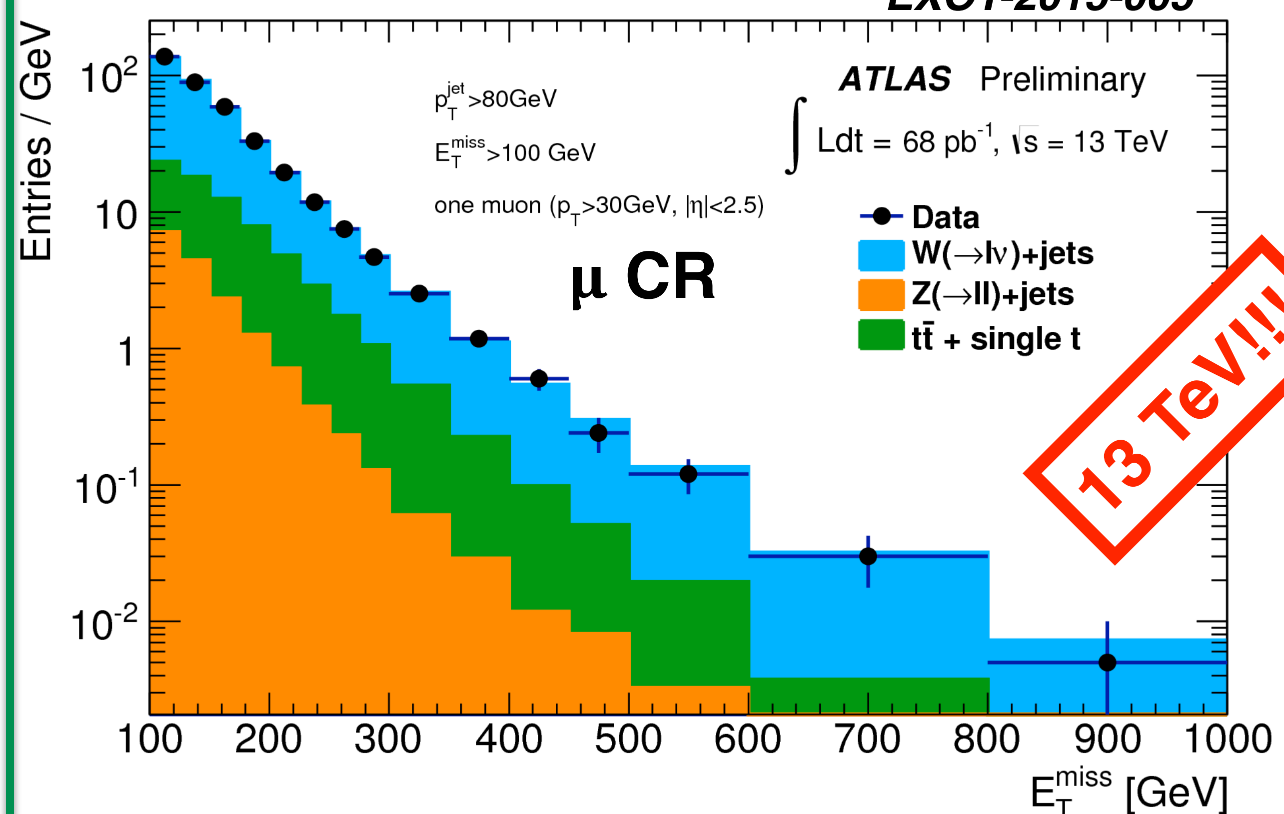


Preview

13 TeV CR distribution shows good MC modelling

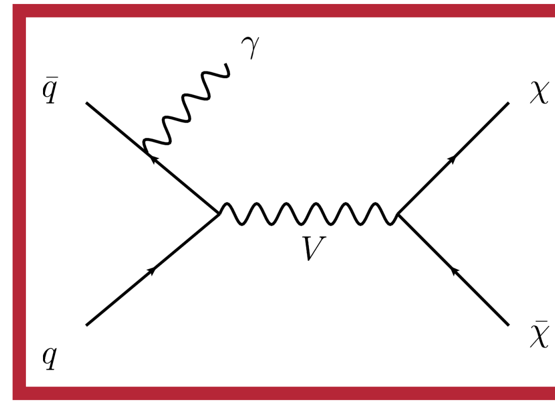
- apart from V+jets, ttbar is significant background

EXOT-2015-005



Results: Monophotons

Phys. Rev. D 91, 012008 (2015)



Generally most sensitive channel after monojets

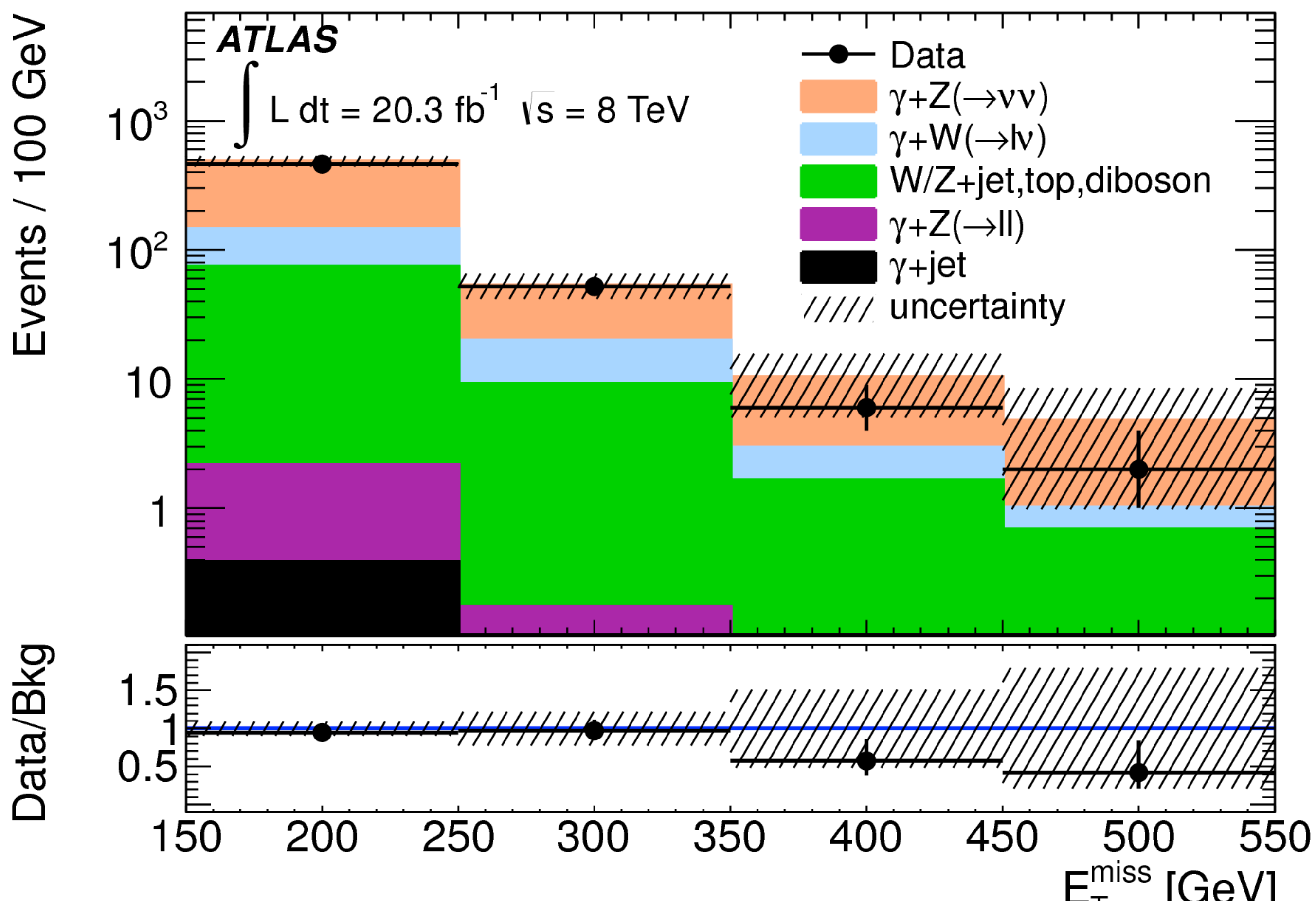
- Challenge: reject fake gammas
- Z → $\nu\nu$ also irreducible background

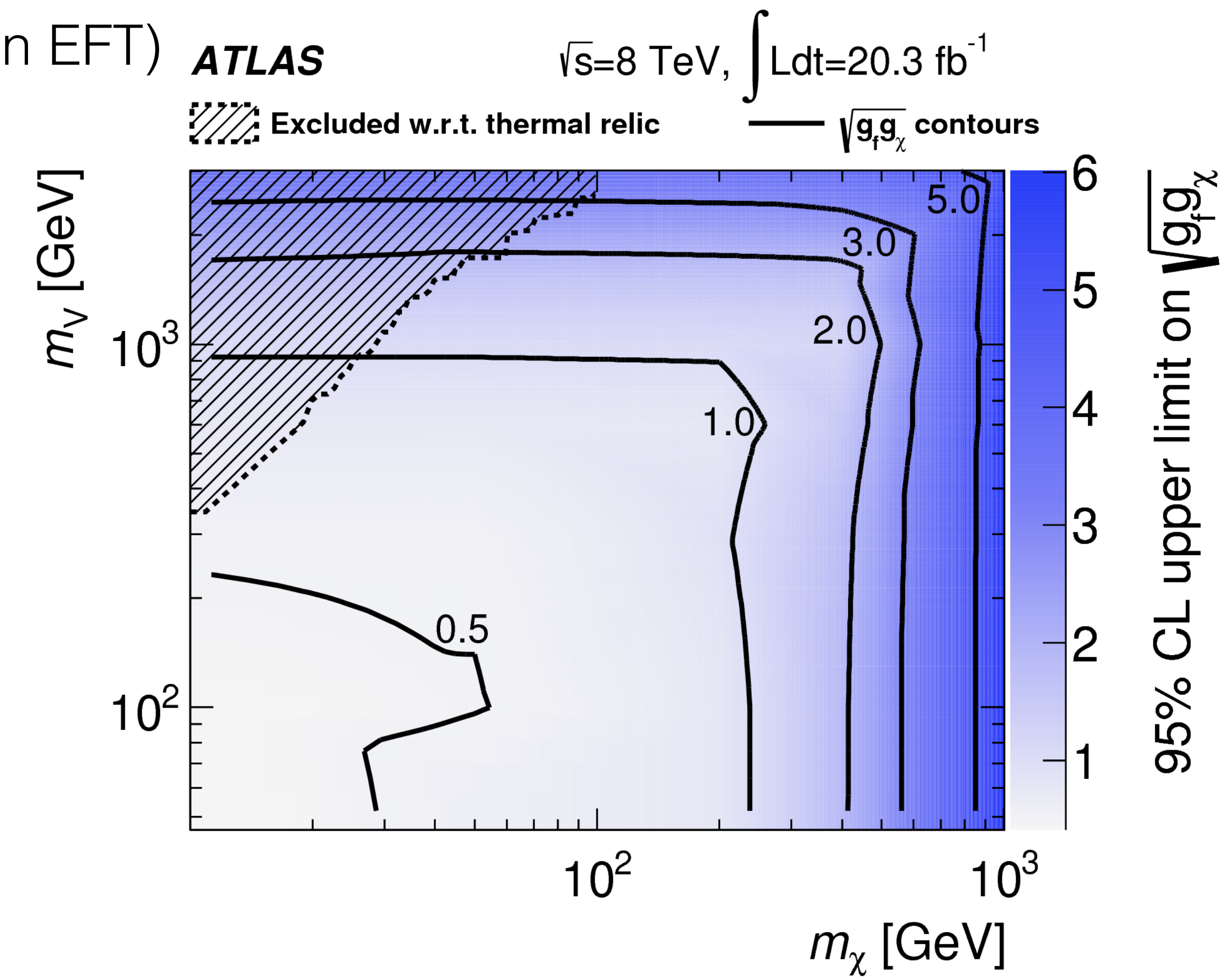
E_T^{miss} + photon(s)

- 1 central γ with p_T > 120 GeV
- E_T^{miss} > 150 GeV
- $\Delta\phi$ (γ, E_T^{miss}) > 0.4
- veto leptons

Interpretation in terms of simplified model, analogous to monojets

- Also possible: direct DM-photon coupling (in EFT)

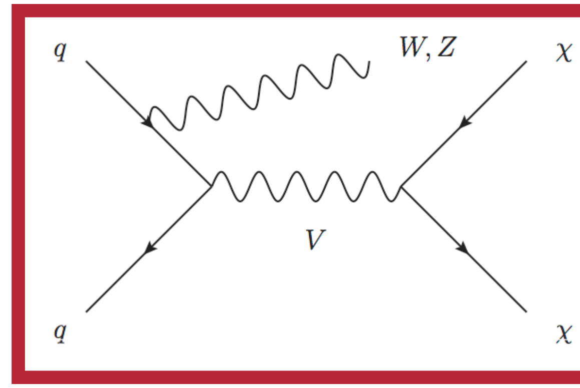




13 TeV!!!

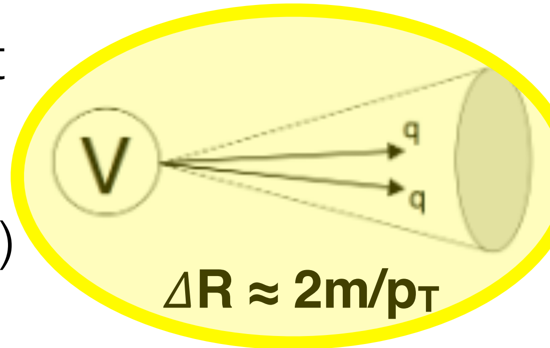
Results: Mono-V

ATLAS-CONF-2015-080



Mono-W/Z hadronic

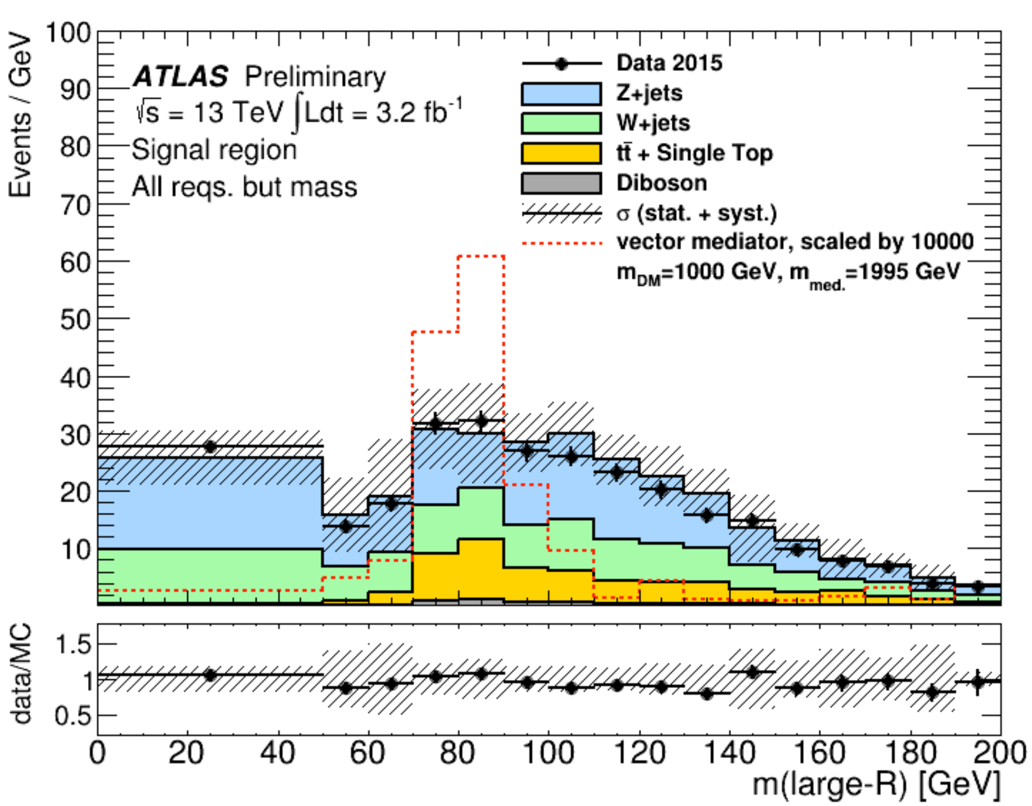
- Based on boson-tagged large-R jet
  - Largest systematic from modelling of its properties (< 10 %)
- W, Z and ttbar CRs

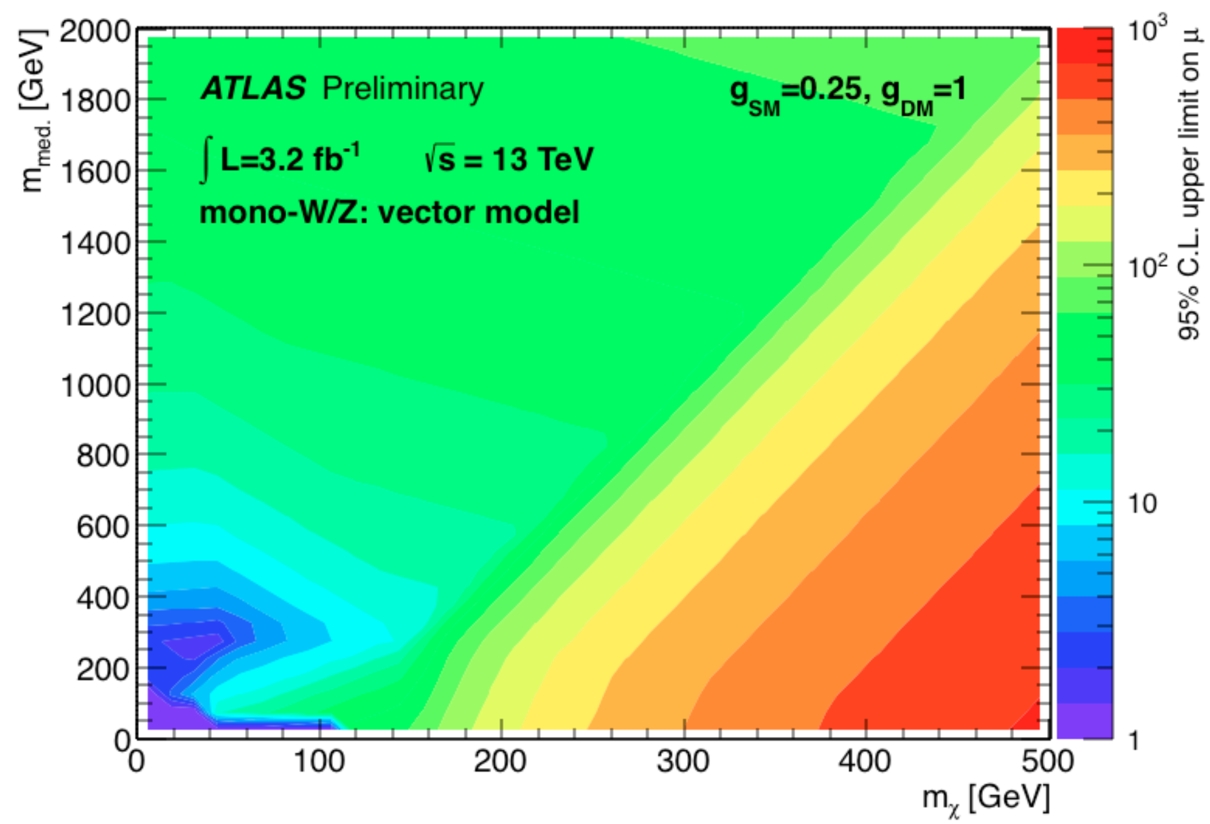


E_T^{miss} +boson-tagged jet
- lepton veto
- E_T^{miss} > 250 GeV
- at least 1 large-R jet (boson-tagged)
- $\Delta\phi$ (E_T^{miss},jet) > 0.6
- p_T^{miss} > 30 GeV
- $\Delta\phi$ (E_T^{miss}, p_T^{miss}) < $\pi/2$

Results from shape fit of E_T^{miss} distribution

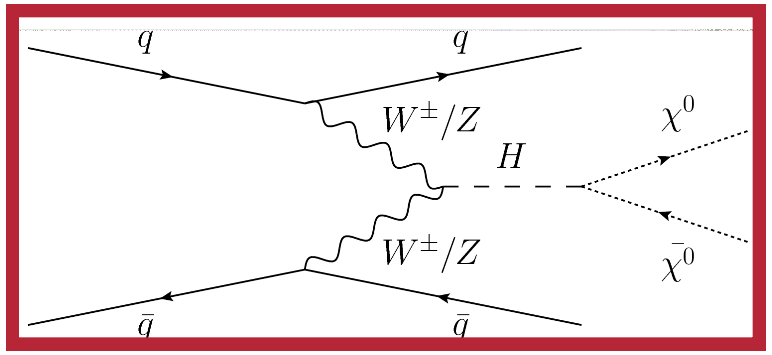
- Interpreted both in EFT and simplified models





Results: DM and Higgs

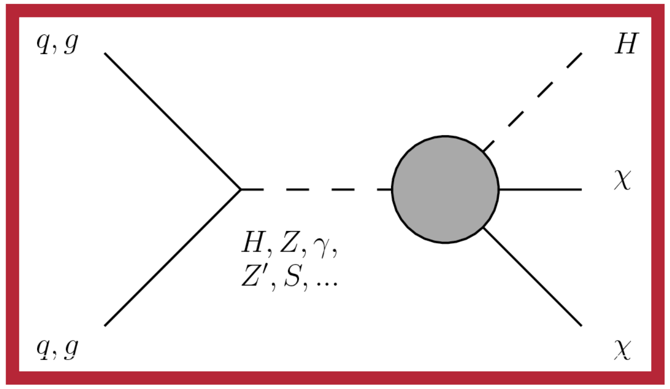
arXiv:1508.07869 , JHEP11(2015)206, Phys. Rev. Lett. 115, 131801 (2015)



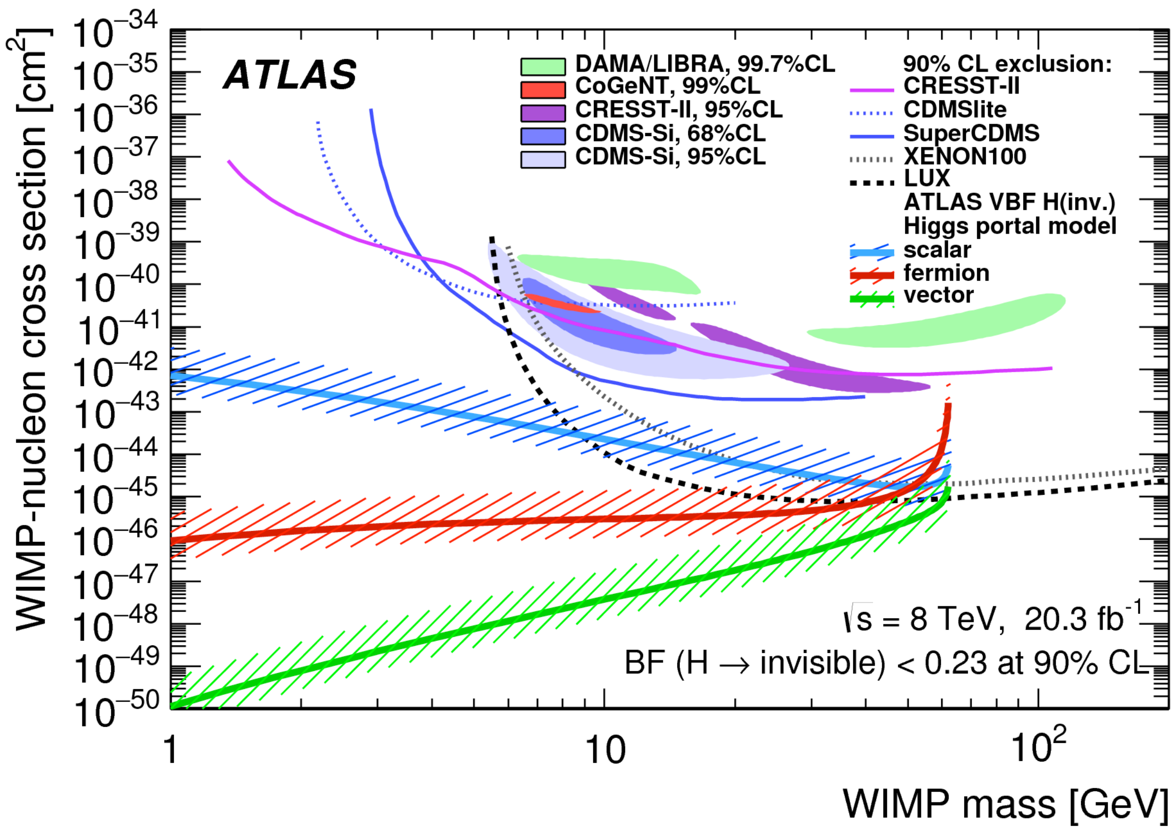
For $m_{DM} < m_H/2$: BR (H→inv.) relevant

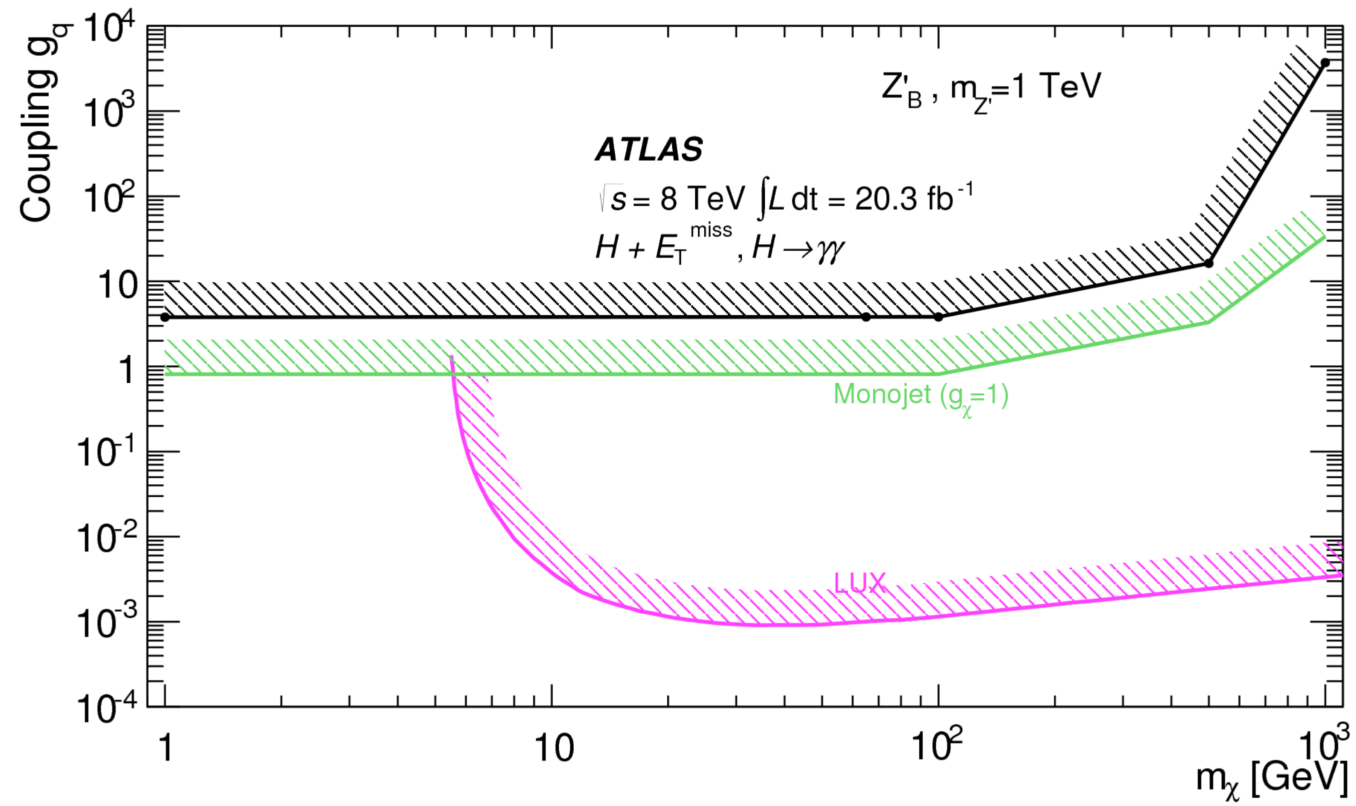
- **BR (H→inv.) < 28%** (31%) from VBF
  BR (H→inv.) < 25% (27%) from combination with WH/ZH

For $m_{DM} > m_H/2$: mono-Higgs relevant



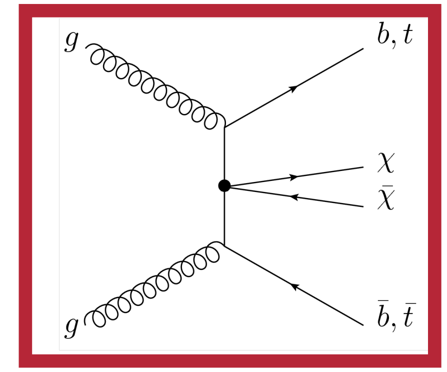
- Interesting, because probe cannot be ISR (as opposed to other mono-X signatures)
- decay channels H→$\gamma\gamma$ and H→bb (**poster by Jia Jian TEOH**) studied
- Interpretation done both for EFT and simplified model





Results: DM + heavy flavour

Eur. Phys. J. C (2015) 75:92



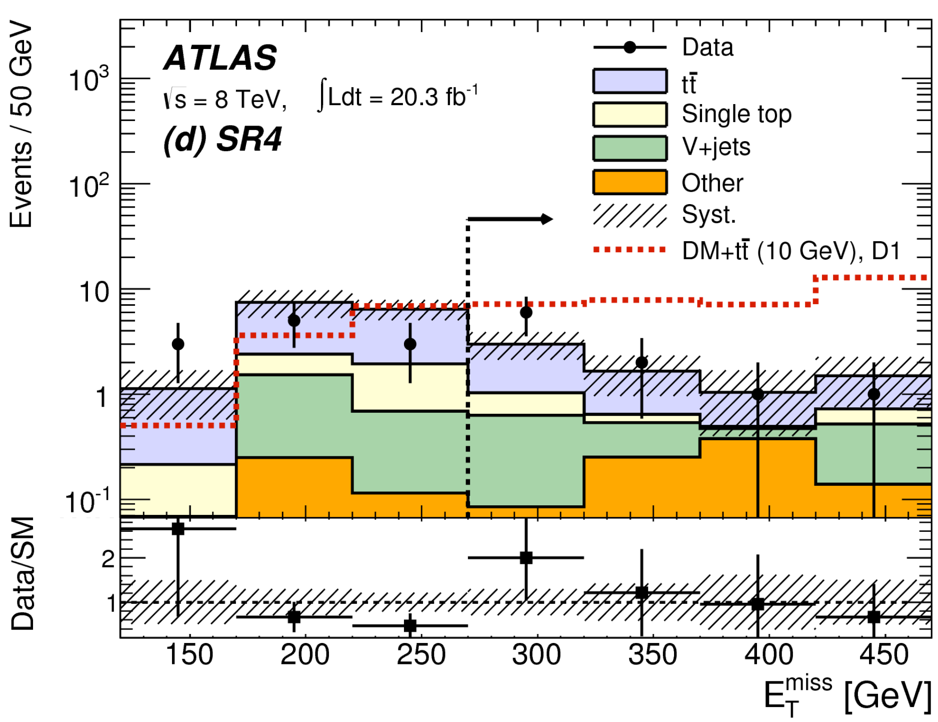
$$\mathcal{O}_{\text{scalar}} = \sum_q \frac{m_q}{M_*^N} \bar{q}q\bar{\chi}\chi$$

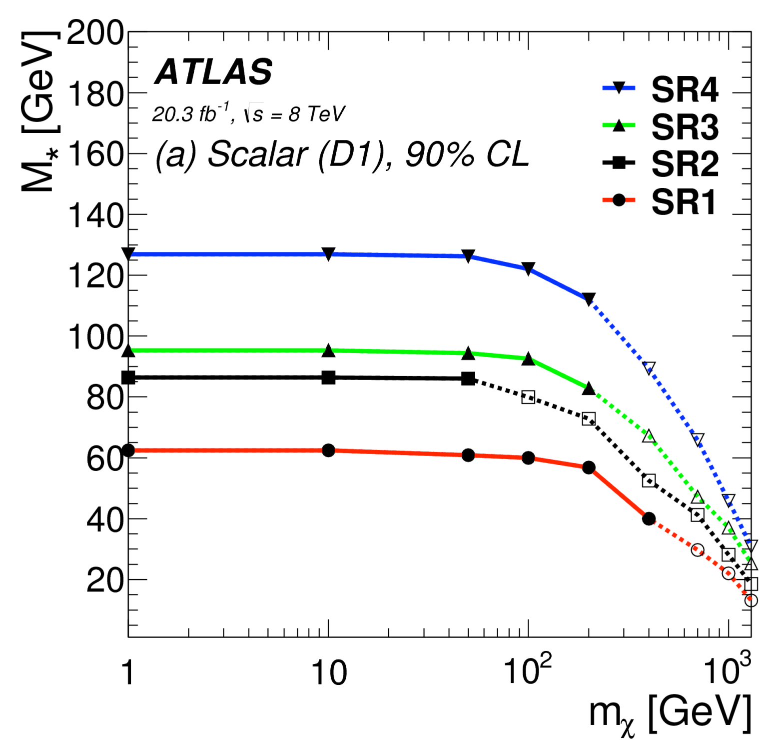
Scalar operators/mediators can have explicit dependence on quark mass

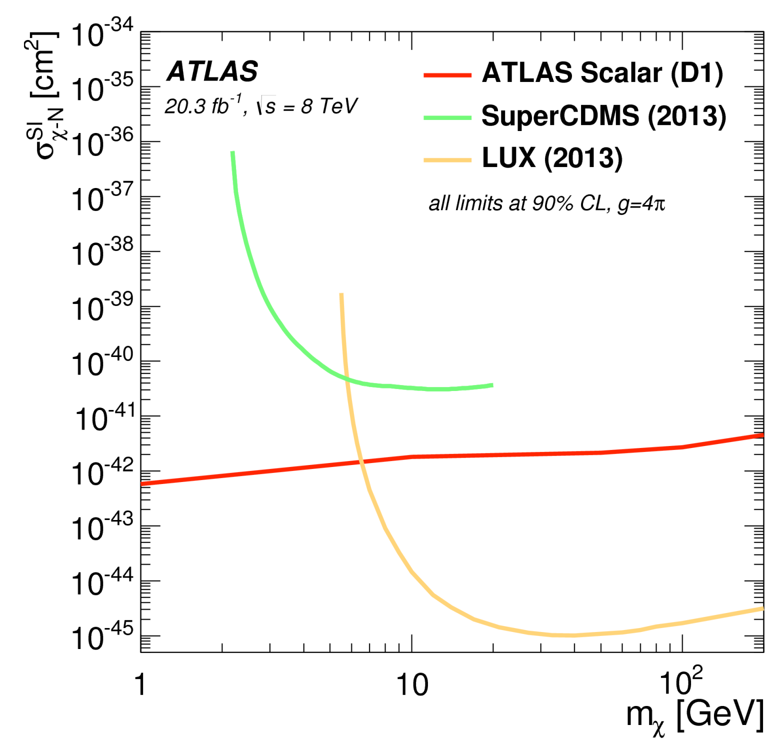
- Motivated by minimal flavour violation
- Couplings to top quarks interesting!
- Signature "ttbar + E_T^{miss}" similar to SUSY stop

ttbar + E_T^{miss}

- at least 1 b-jet
- E_T^{miss} > 270 GeV
- jet p_T > 80, 70, 50, 25 GeV
- b-jet p_T > 60 GeV
- $\Delta\phi$ (E_T^{miss}, $j_{1/2}$) > 0.6
- m_T > 130 GeV
- and other topological cuts







Summary

LHC is an excellent and exciting place to look for DM - especially now!

- Most searches profit enormously from increase of energy to 13 TeV

Many complementary searches have been performed at ATLAS

- No signal detected, limits placed
- Interpretation mostly within EFT, some simplified models examples

First results from Run II (13 TeV) presented

- No surprises up to now
- Interpretation and optimisation more and more focused on simplified models

Many more 13 TeV searches in preparation - stay tuned!

Web References

Monojets 8 TeV: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2013-13/

Monojets 13 TeV: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/EXOT-2015-005/

Monophotons: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2014-06/

Mono-V (hadronic, 13 TeV): https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-080/

Invisible Higgs: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-16/

Mono-Higgs (bb): https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2014-20/

Mono-Higgs ($\gamma\gamma$): https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2014-05/

DMHF: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2014-06/

bullet cluster: http://apod.nasa.gov/apod/image/0608/bulletcluster_comp_f2048.jpg

LHC image: http://cds.cern.ch/record/826521

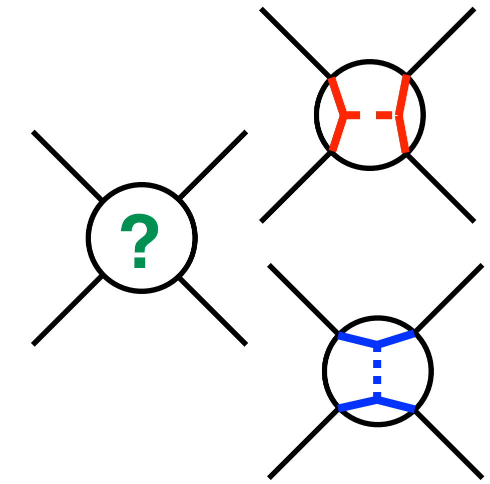
ATLAS sketch: http://www.atlas.ch/photos/full-detector-cgi.html

“dark matter” zoo particle: http://particlezoo.net/individual_pages/shop_dark_matter.html

Additional Material

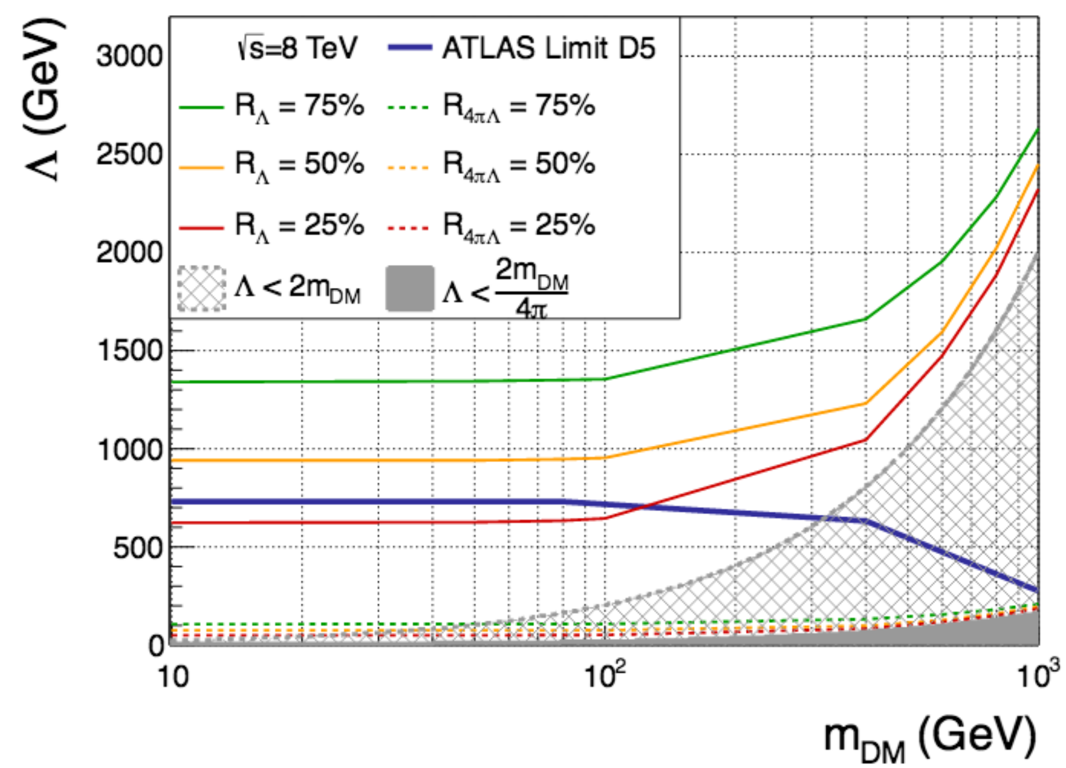
Problems with EFTs

arXiv:1402.1275



EFT idea: integrate out mediator - “ignore everything in the bubble”

- justified, if energy scale well below mediator mass/hidden physics ($Q_{trans} \ll m_{Med}$)
- advantage: as model-independent as possible, only 2 free parameters (m_{DM}, cut-off scale Lambda (dependent on mediator mass and couplings))
  → allows for easy comparisons between DD/ID/LHC



But: in significant fraction of events at LHC, EFT assumption is questionable

- Past LHC results always criticised for EFT approach from DD/ID sides

For EFT limits: truncation procedure

- assume simplest interaction and correct cross-section, regarding only valid events ($Q_{trans} < f(g_q g_\chi, \Lambda)$)
- cross-check with iterative procedure that scans through Lambda until convergence is found

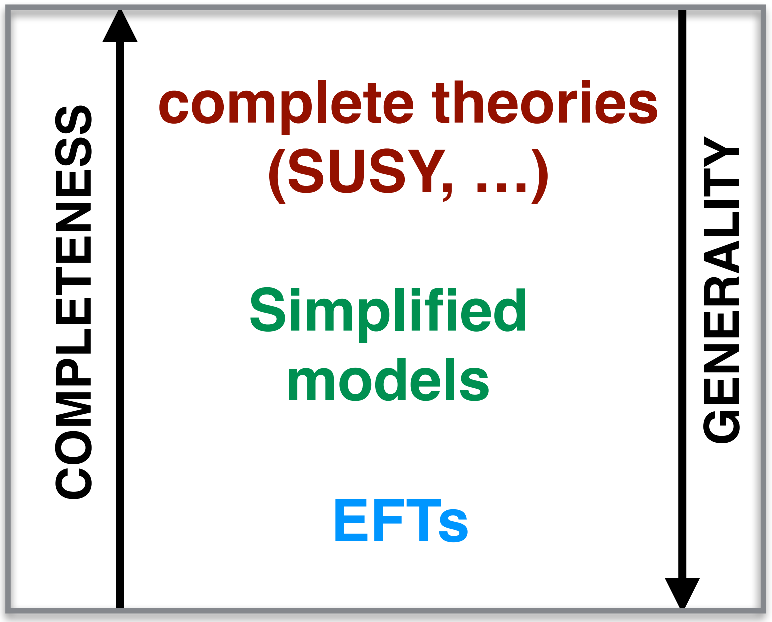
Truncation is no “way out”, but gives feeling for how problematic EFT is

Simplified models

arXiv:1507.00966

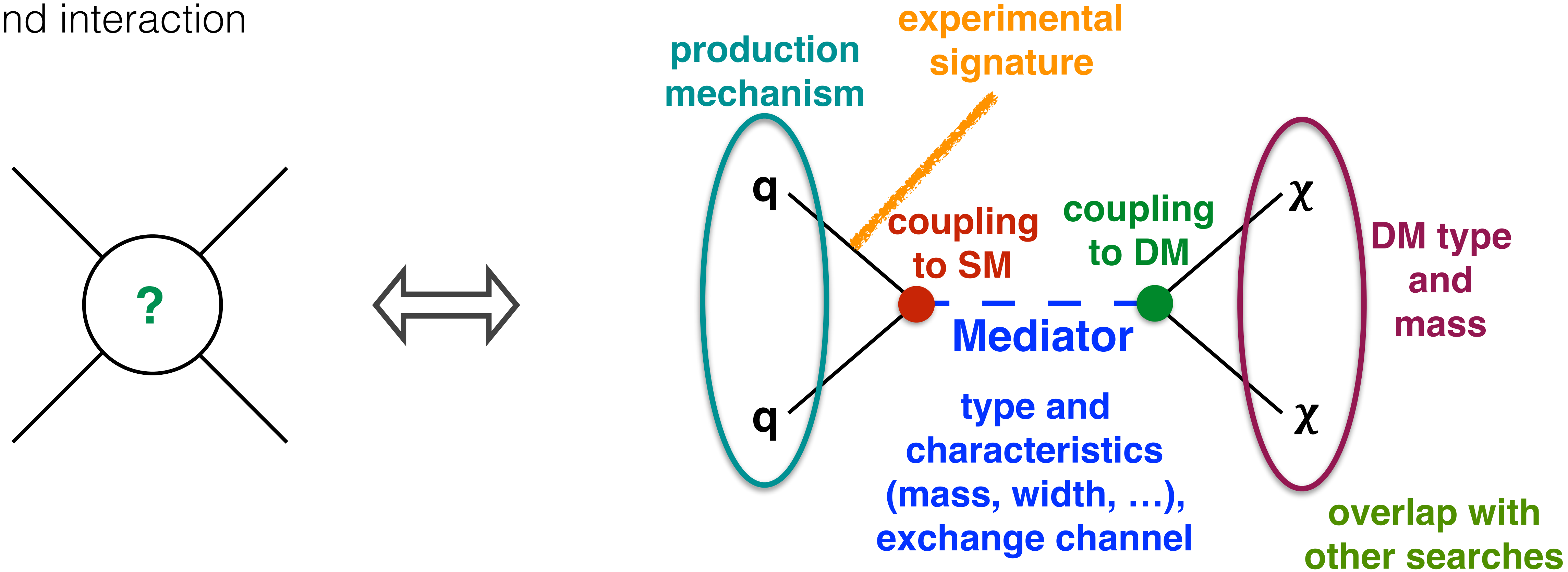
“Solution”: move to simplified models - always valid

- lots of work done within ATLAS/CMS DM forum to define benchmarks, grids, …



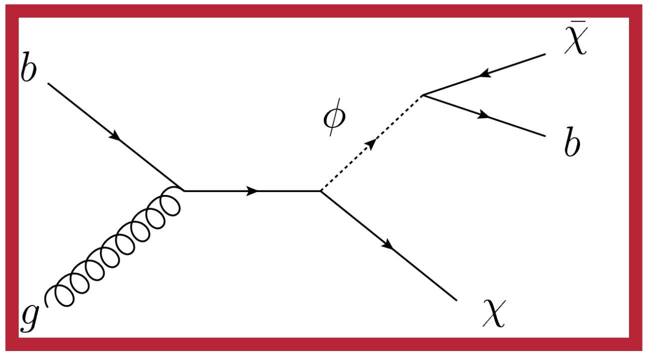
Reduce whatever complex full theory to a simple model with DM, a mediator between the SM and the Dark Sector, one interaction

- few free parameters: m_{DM}, m_{Med}, g_{SM}, g_{DM}, Γ_{Med}
  and mediator and DM type
  and interaction



Results: DM+HF

Phys. Rev. D 91, 012008 (2015)



Mono-b interesting, if scalar mediator coupling only to down-type quarks

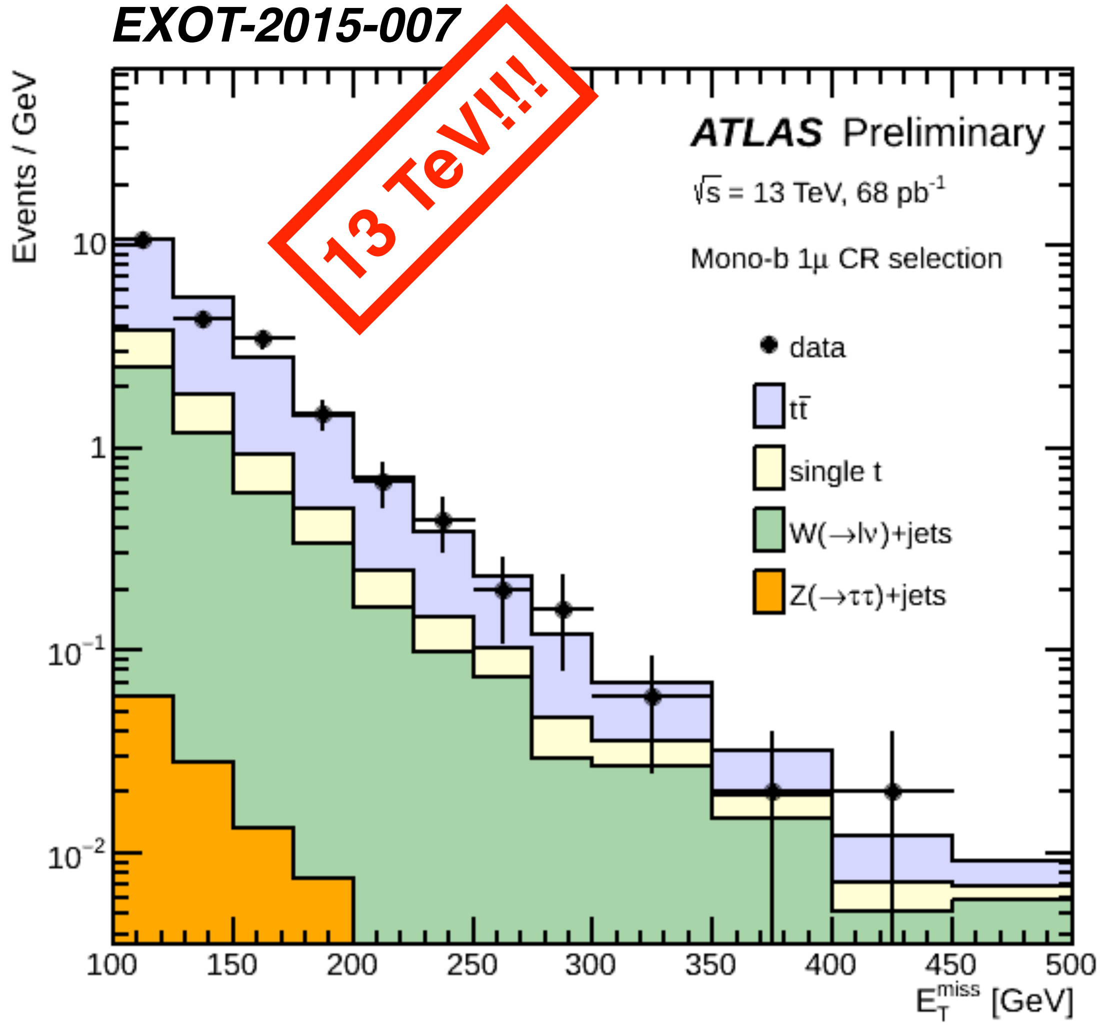
Interpretation in terms of EFT and simplified models

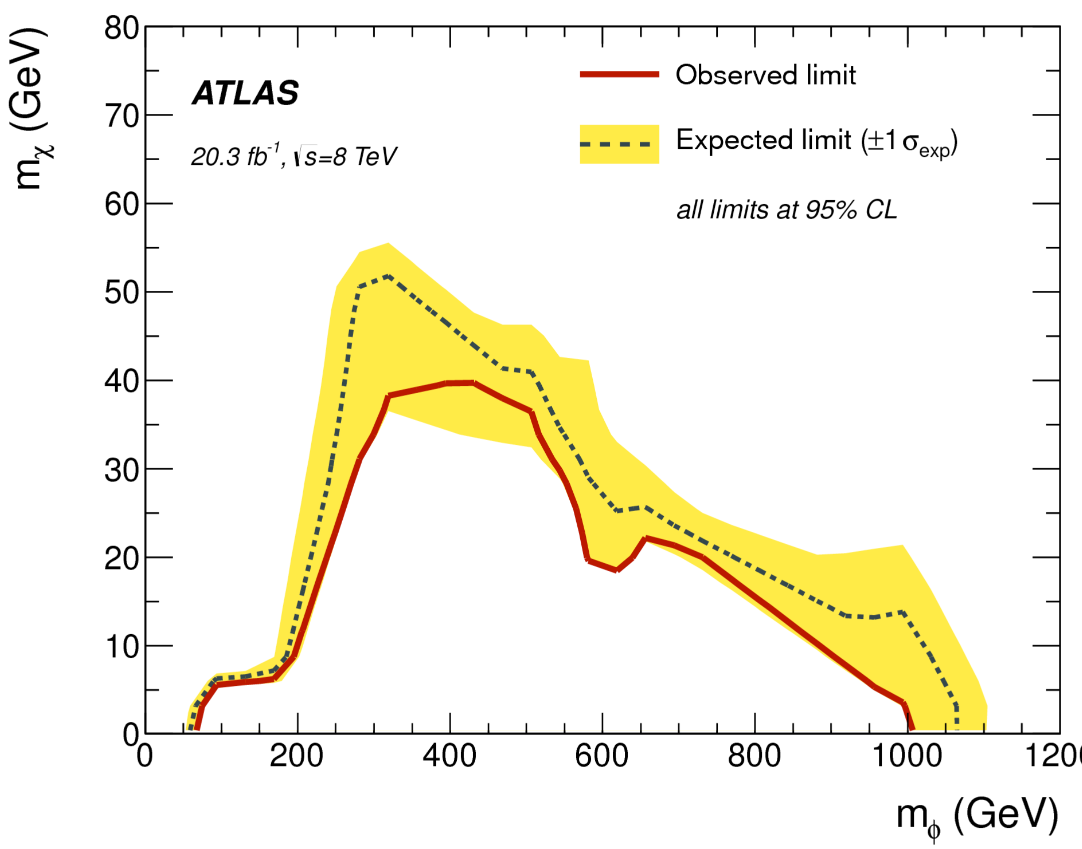
- simplified model motivated by FERMI gamma-ray excess

E_T^{miss} + b(b)

- 1-2 (3-4) jets
- at least one b jet
- lepton veto
- E_T^{miss} > 300 GeV
- b-jet p_T > 100 GeV
- $\Delta\phi$ (j, E_T^{miss}) > 1.0

EXOT-2015-007



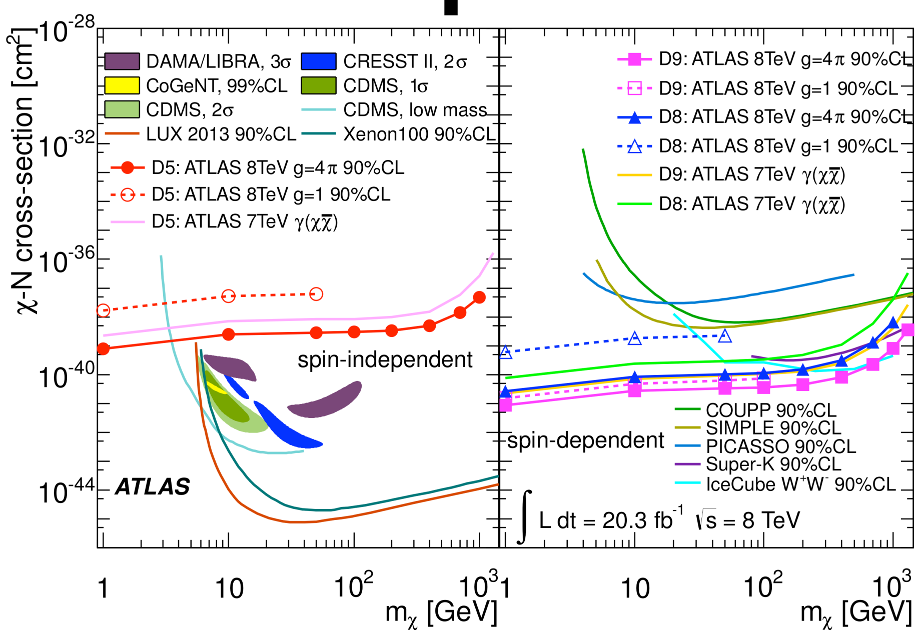


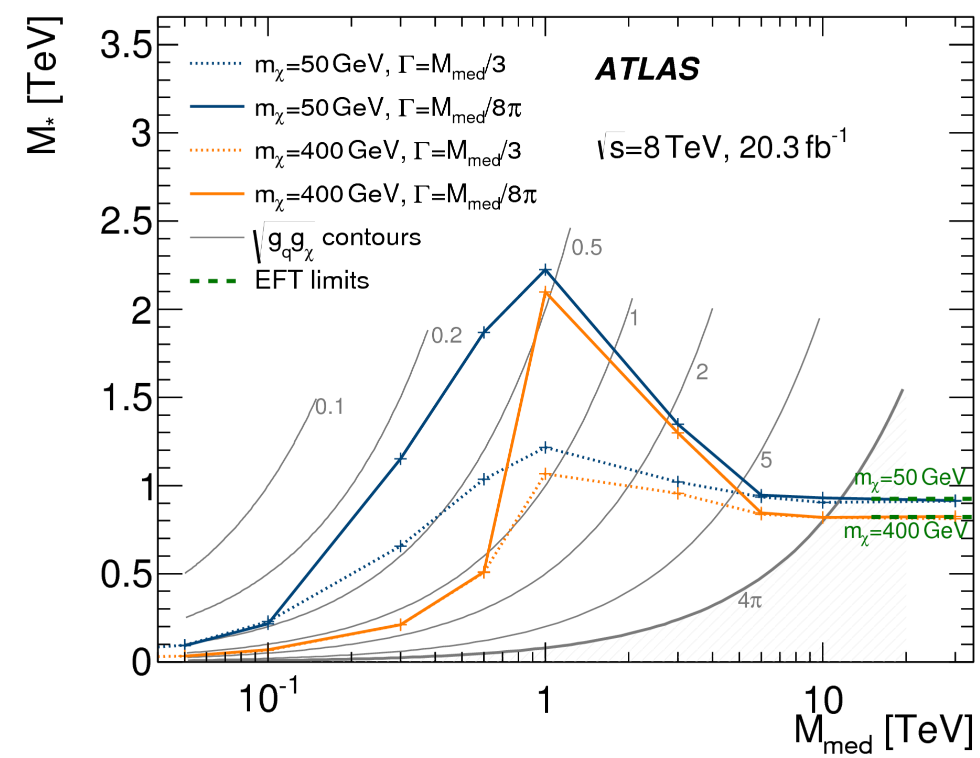
Backup: Monojet

Table 3 Summary of the methods and control samples used to constrain the different background contributions in the signal regions.

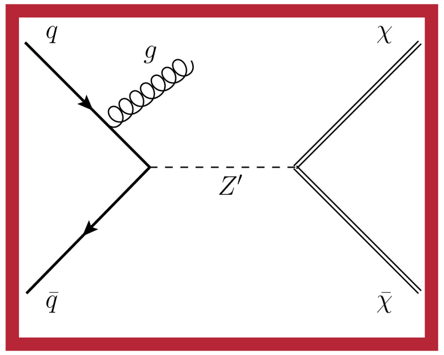
Background process	Method	Control sample
$Z(\to \nu\bar{\nu})$+jets	MC and control samples in data	$Z/\gamma^*(\to \ell^+\ell^-)$, $W(\to \ell\nu)$ $(\ell = e, \mu)$
$W(\to e\nu)$+jets	MC and control samples in data	$W(\to e\nu)$ (loose)
$W(\to \tau\nu)$+jets	MC and control samples in data	$W(\to e\nu)$ (loose)
$W(\to \mu\nu)$+jets	MC and control samples in data	$W(\to \mu\nu)$
$Z/\gamma^*(\to \ell^+\ell^-)$+jets $(\ell = e, \mu, \tau)$	MC-only	
$t\bar{t}$, single top	MC-only	
Diboson	MC-only	
Multijets	data-driven	
Non-collision	data-driven	

Monophotons





Monojets @ 13 TeV



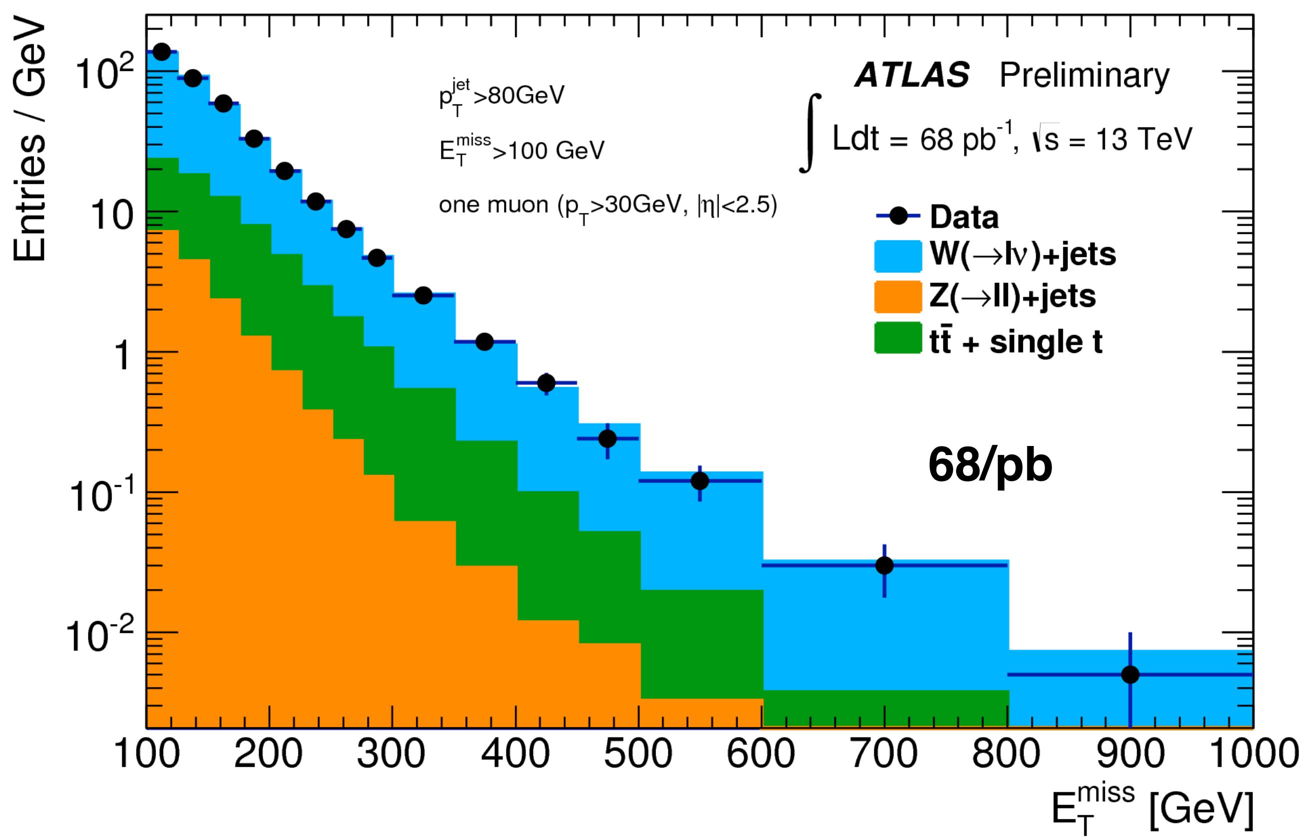
EXOT-2015-005

Non-collision background needs to be very well controlled

- first step after data-taking conditions change

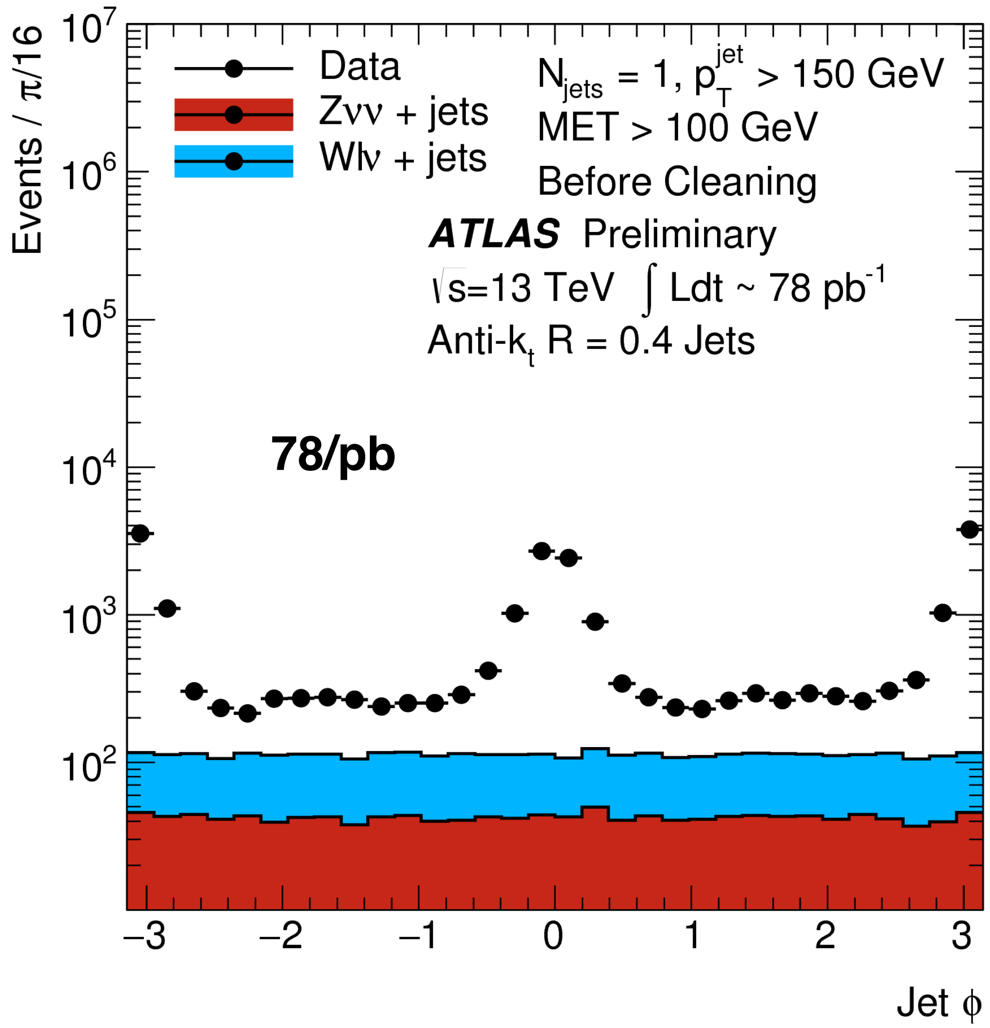
Control region distribution shows reasonable MC modelling

- apart from V+jets, ttbar is significant background

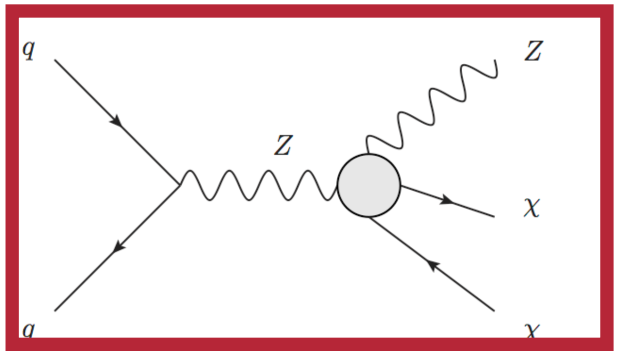


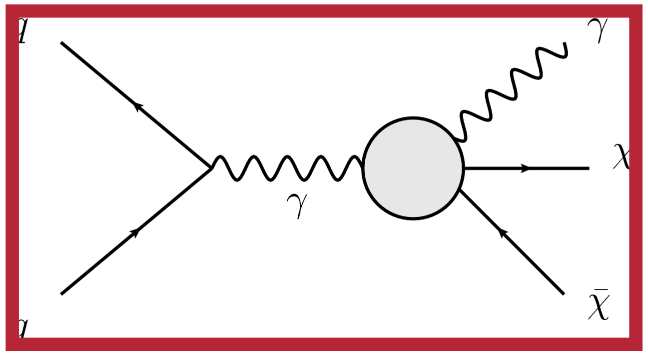
ETmiss + jet(s)

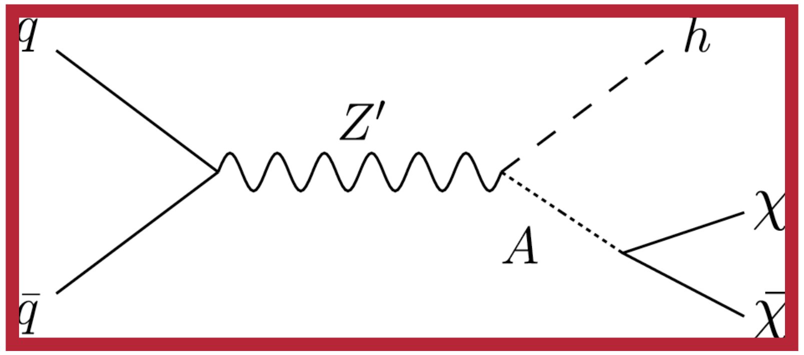
- 1 central jet with pT > min(120 GeV, 0.5 ETmiss)
- delta phi (jets, ETmiss) > 1
- veto leptons
- 9 ETmiss bins



Alternative models & EFT info





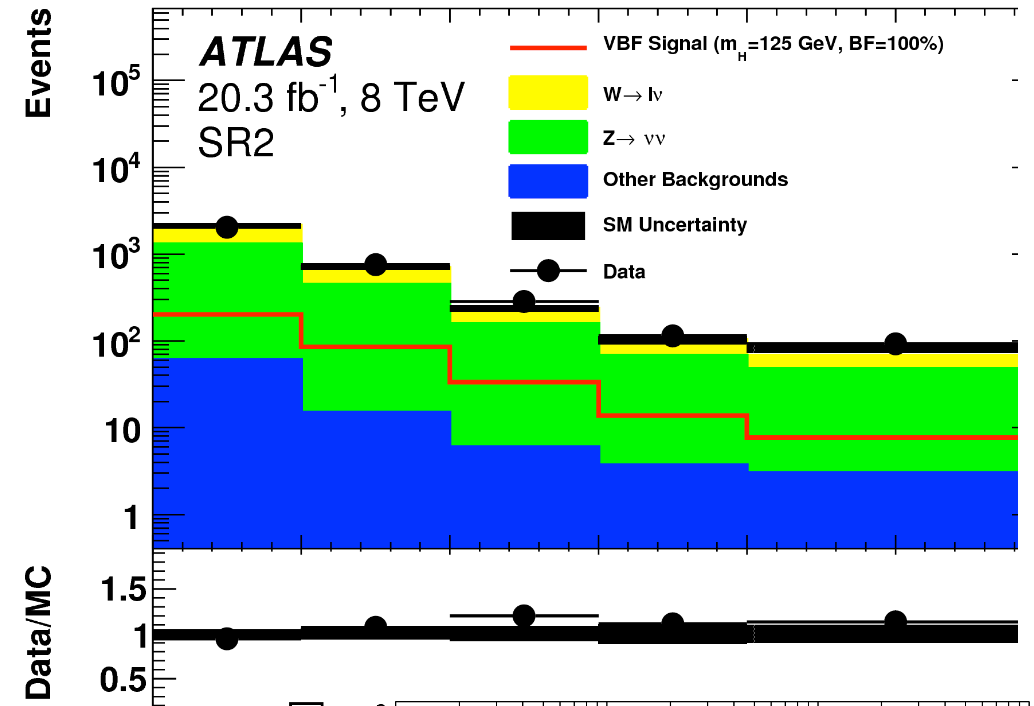


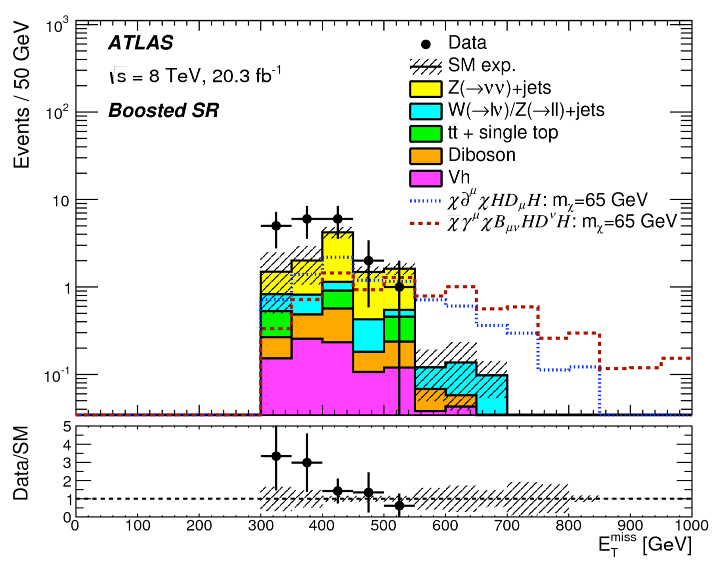
Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

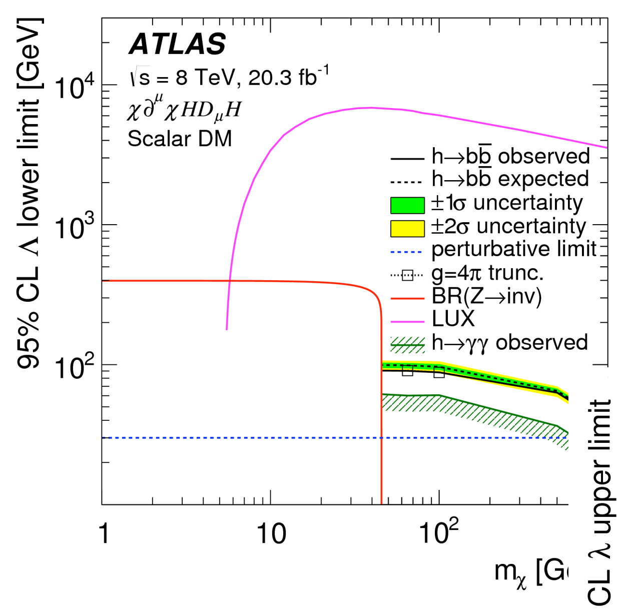
$$M_*^{limit} = M_*^{gen}\left(\frac{\sigma_{th}}{\sigma_{excl}}\right)^{1/y}$$

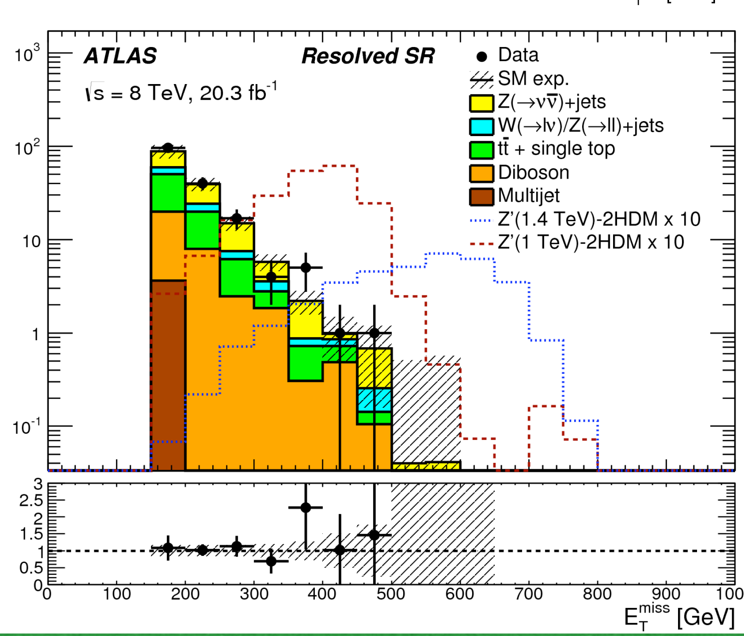
Higgs DM

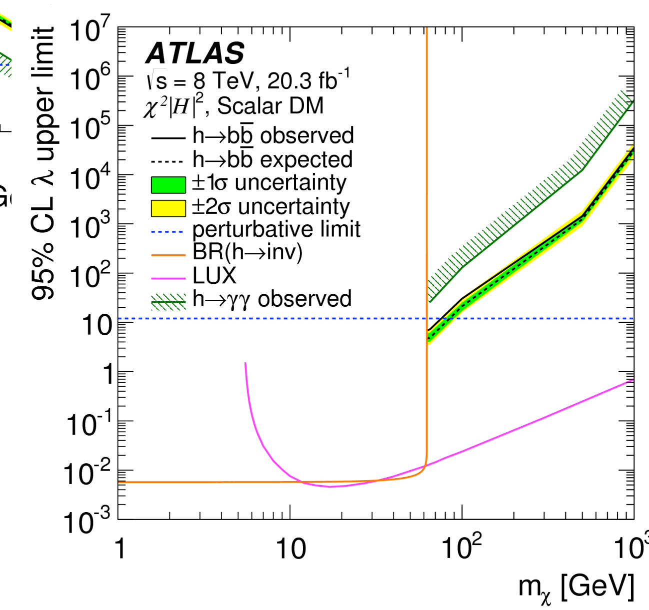
Requirement	SR1	SR2a	SR2b
Leading Jet p_T	>75 GeV	>120 GeV	>120 GeV
Leading Jet Charge Fraction	N/A	>10%	>10%
Second Jet p_T	>50 GeV	>35 GeV	>35 GeV
m_{jj}	>1 TeV	$0.5 < m_{jj} < 1$ TeV	> 1 TeV
$\eta_{j1} \times \eta_{j2}$	<0		
$\lvert\Delta\eta_{jj}\rvert$	>4.8	>3	$3 < \lvert\Delta\eta_{jj}\rvert < 4.8$
$\lvert\Delta\phi_{jj}\rvert$	<2.5	N/A	
Third Jet Veto p_T Threshold	30 GeV		
$\lvert\Delta\phi_{j,E_T^{miss}}\rvert$	>1.6 for j_1, >1 otherwise	>0.5	
E_T^{miss}	>150 GeV	>200 GeV	

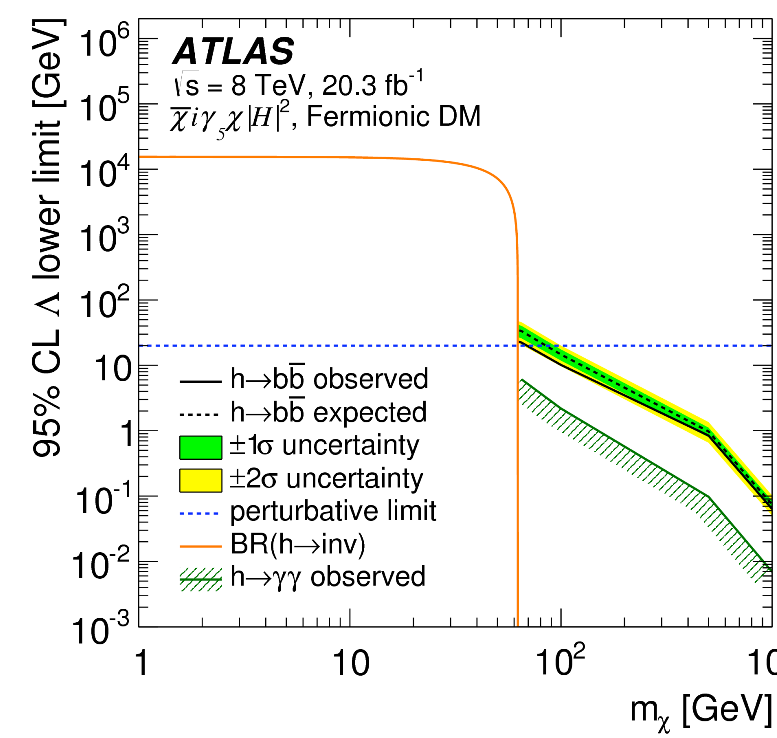








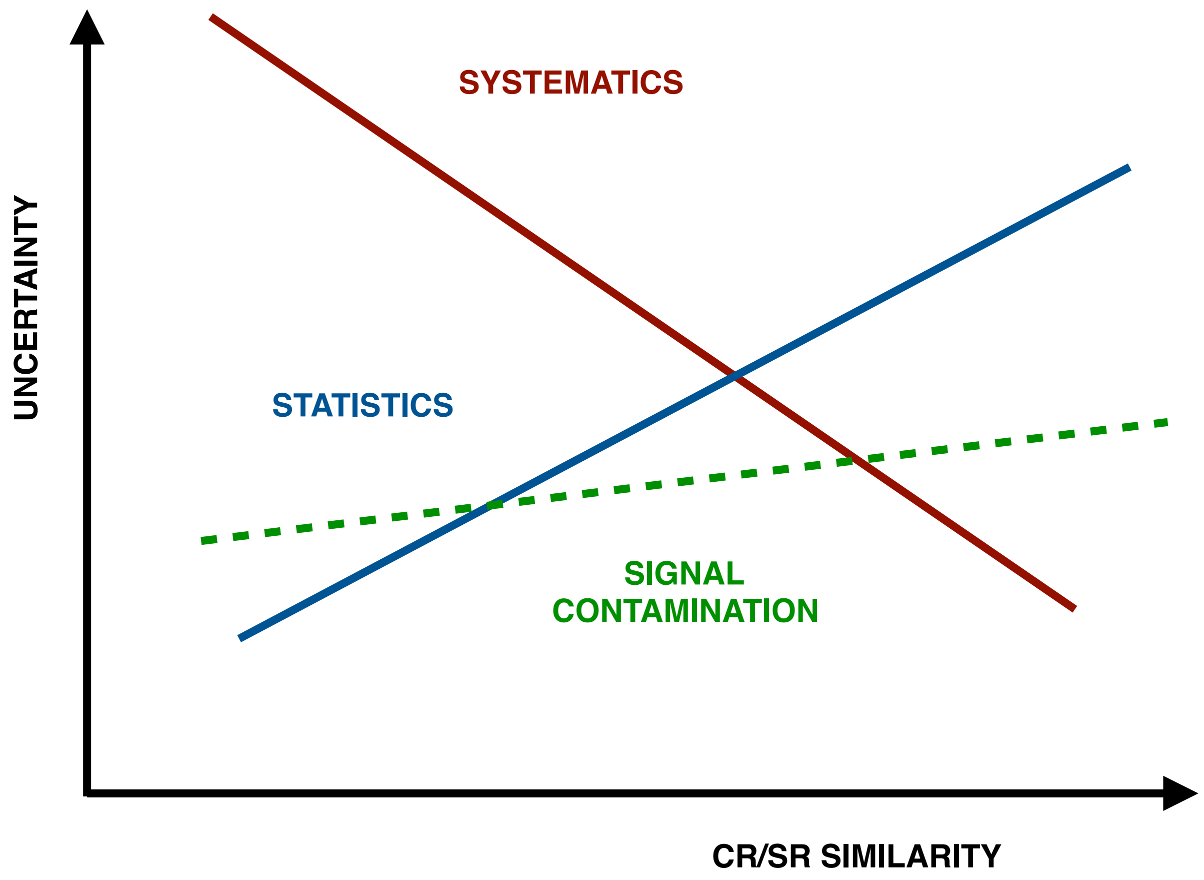




ATLAS EXPERIMENT

Backup: DMHF

	SR1	SR2	SR3	SR4
Trigger	E_T^{miss}	E_T^{miss}	5 jets || 4jets(1b)	E_T^{miss} || 1 lepton (no τ)
Jet multiplicity n_j	1–2	3–4	$\geq$5	$\geq$4
b-jet multiplicity n_b	>0 (60% eff.)	>0 (60% eff.)	>1 (70% eff.)	>0 (70% eff.)
Lepton multiplicity n_ℓ	0	0	0	1 ℓ ($\ell = e, \mu$)
E_T^{miss}	>300 GeV	>300 GeV	>200 GeV	>270 GeV
Jet kinematics	$p_T^{b_1} > 100$ GeV	$p_T^{b_1} > 100$ GeV $p_T^{j_2} > 100$ (60) GeV	$p_T^{j} > 25$ GeV	$p_T^{b_1} > 60$ GeV $p_T^{1\text{-}4} = 80, 70, 50, 25$ GeV
Three-jet invariant mass				$m_{jjj} < 360$ GeV
$\Delta\ \ i\left(j_i, E_T^{miss}\right)$	$> 1.0,\ i = 1, 2$	$> 1.0,\ i = 1 - 4$	-	$> 0.6,\ i = 1, 2$
Angular selections	-	-	$\Delta\ \ i\left(b_1, E_T^{miss}\right) \geq 1.6$	$\Delta\ \ i\left(\ell, E_T^{miss}\right) > 0.6$ $\Delta R\left(\ell, j_1\right) < 2.75$ $\Delta R\left(\ell, b\right) < 3.0$
Event shape	-	-	Razor R >0.75	*topness* >2
am_{T2}	-	-	-	>190 GeV
$m_T^{\ell + E_T^{miss}}$	-	-	-	>130 GeV
$E_T^{miss}/\sqrt{H_T^{4j}}$	-	-	-	>9 $\sqrt{\text{GeV}}$


SYSTEMATICS
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SIGNAL
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CR/SR SIMILARITY