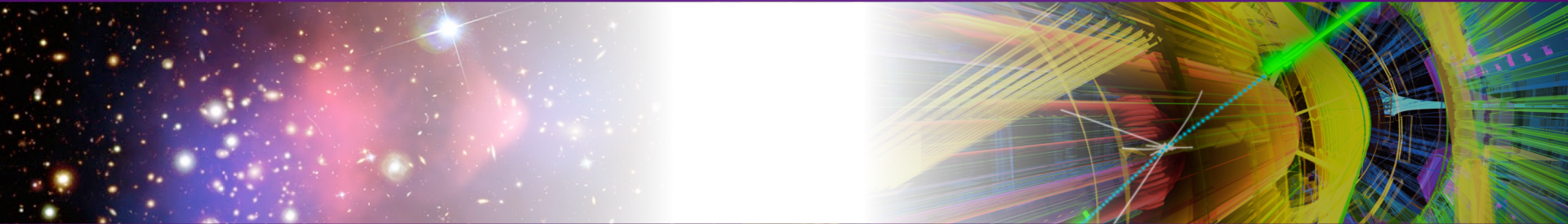




ATLAS dark matter searches and interpretation

.....



Darren Price, University of Manchester

on behalf of the ATLAS Collaboration

Rencontres du Vietnam, Quy Nhon, Vietnam, August 8th '18



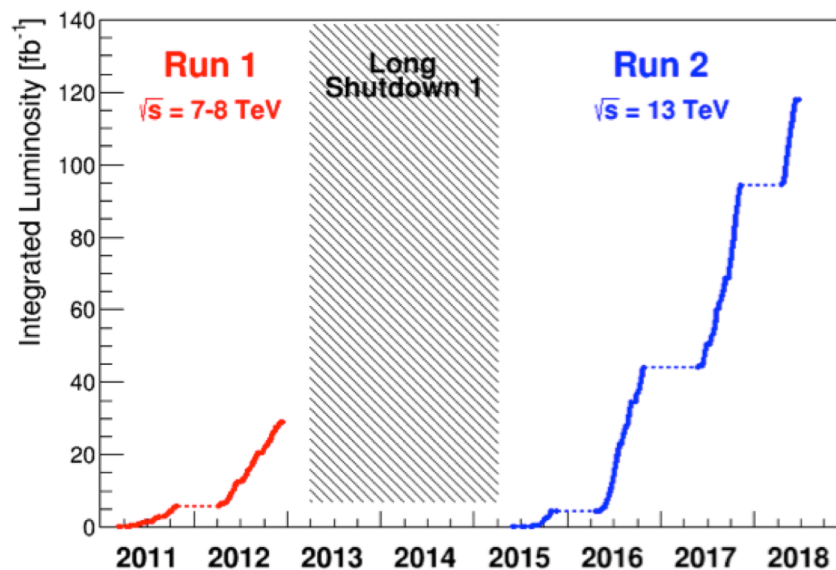
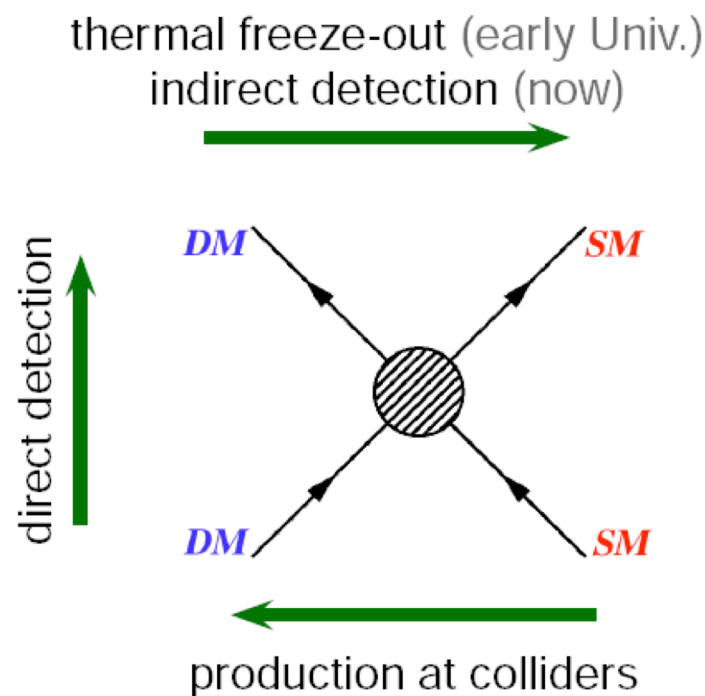
@darrenprice



darren.price@cern.ch

Why search for and study dark matter at colliders?

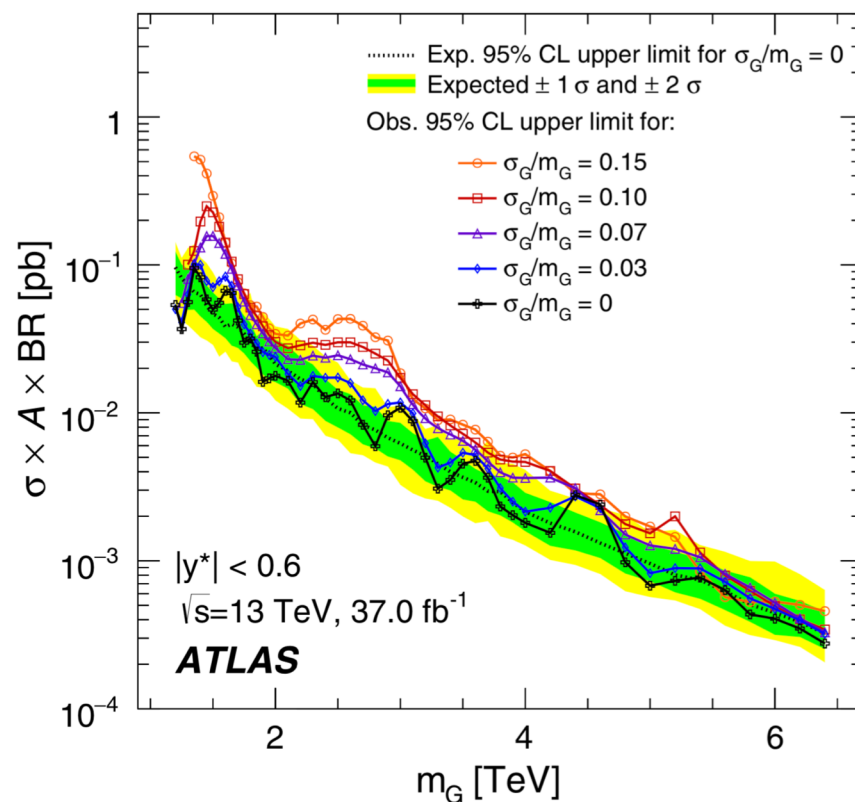
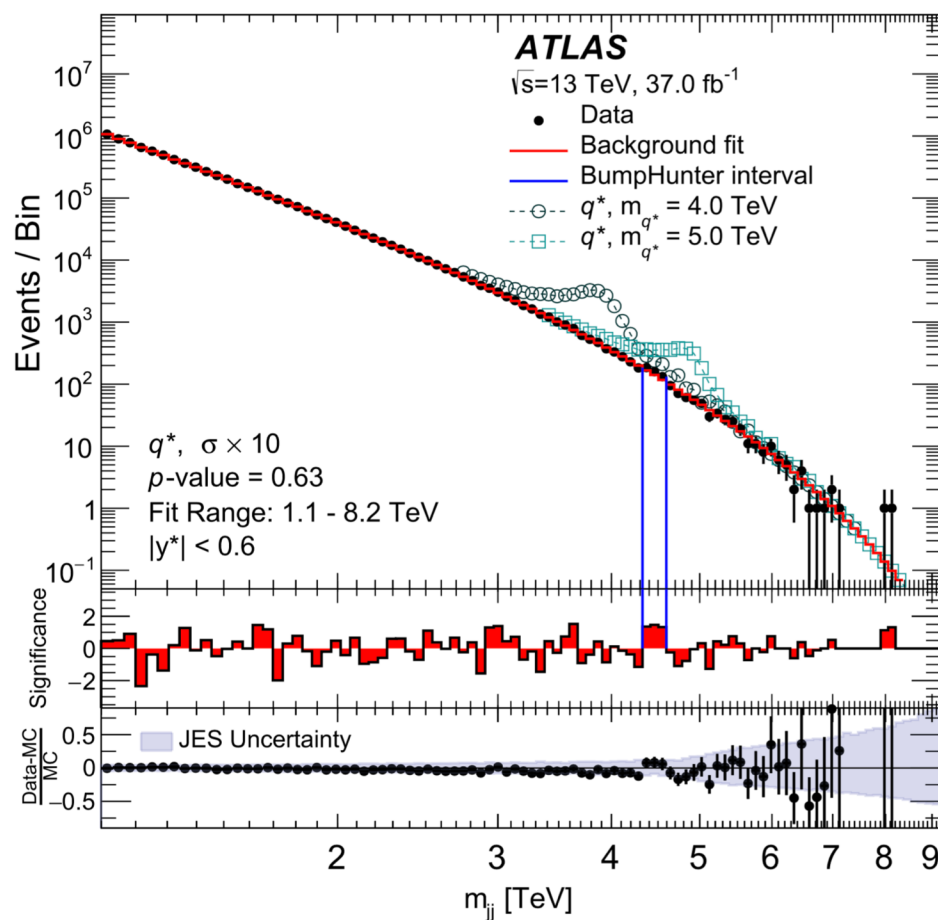
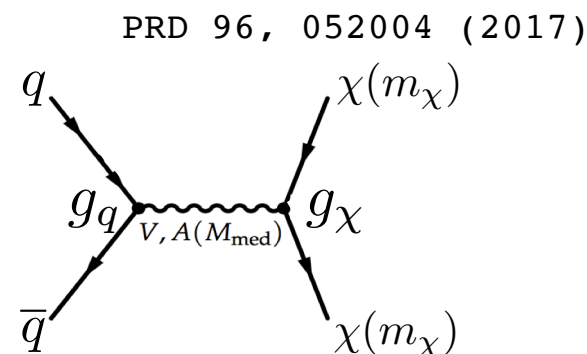
- Interactions, energy reach
- Complementarity sensitivity and properties measurement



- Search for mediator of the SM–DM
- Search for stable DM candidate(s) themselves

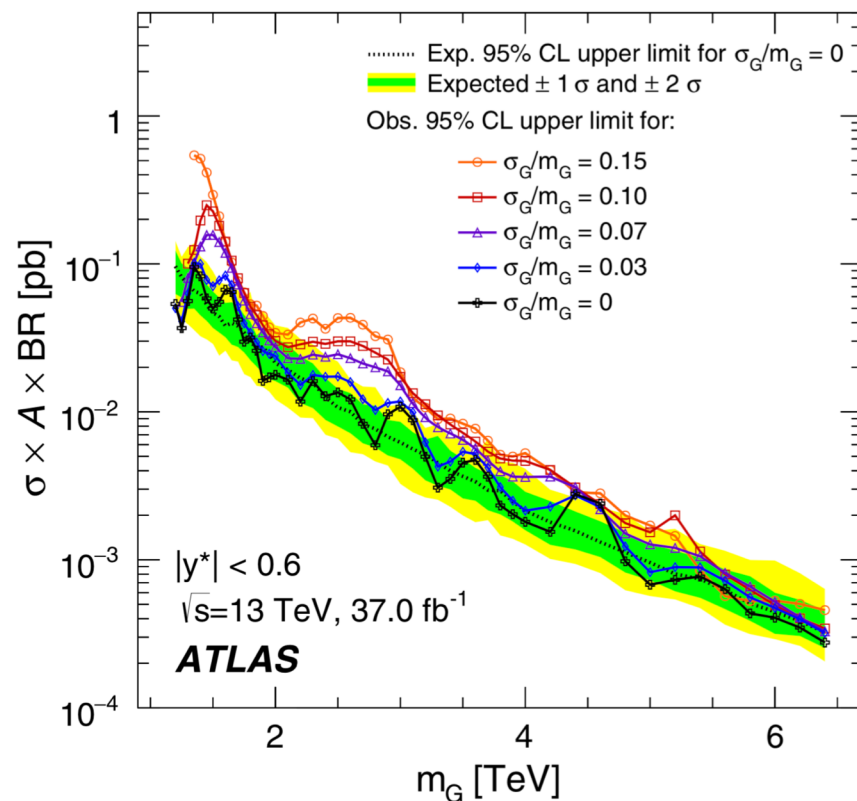
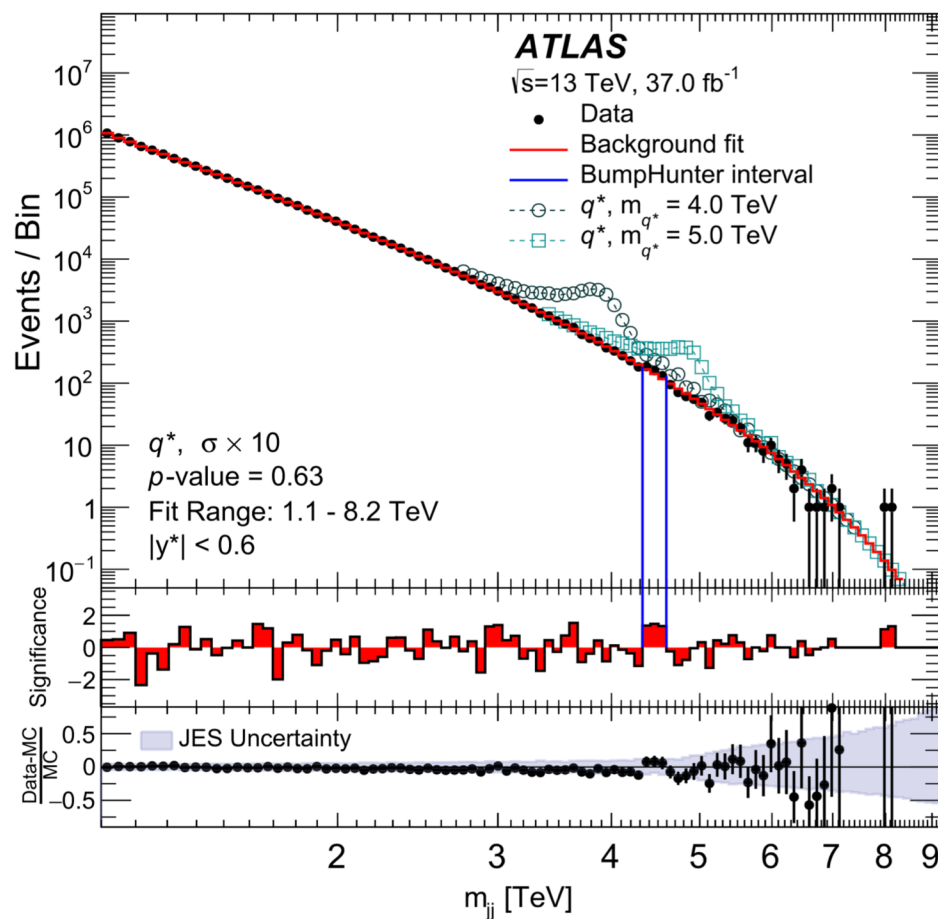
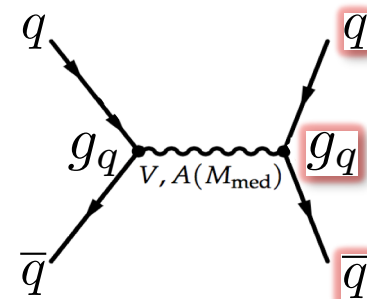
In high-energy pp collisions search for production of the DM—SM mediator (g_q^2)

Perform dijet resonance search



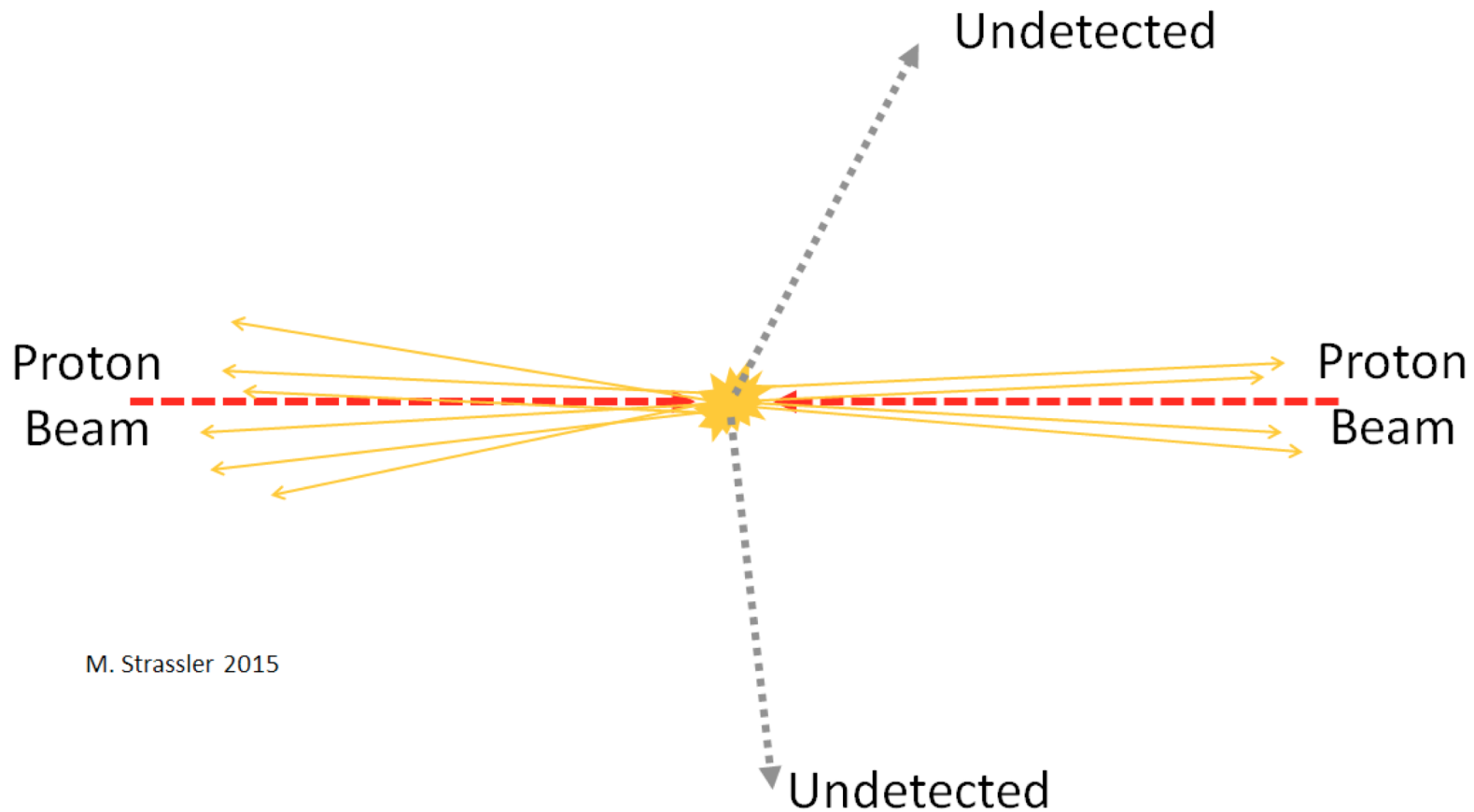
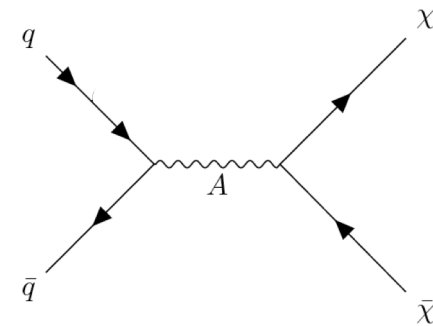
In high-energy pp collisions search for production of the DM—SM mediator (g_q^2)
Perform dijet resonance search

PRD 96, 052004 (2017)



How else can we search for dark matter at colliders?

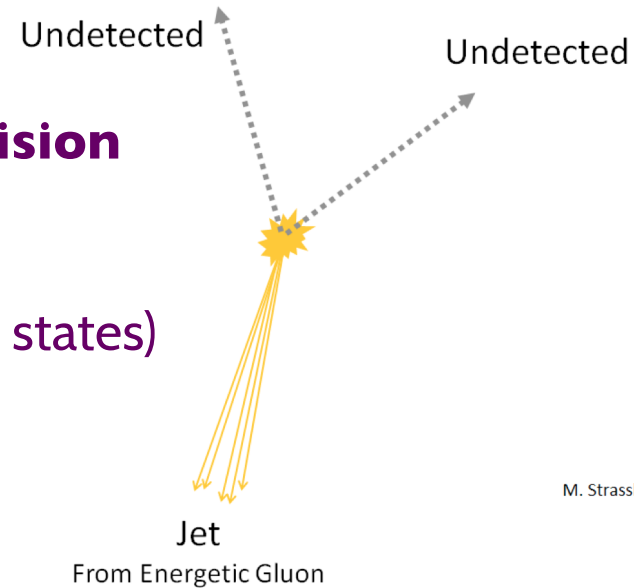
Inherently a missing energy signature
Issue of detectability



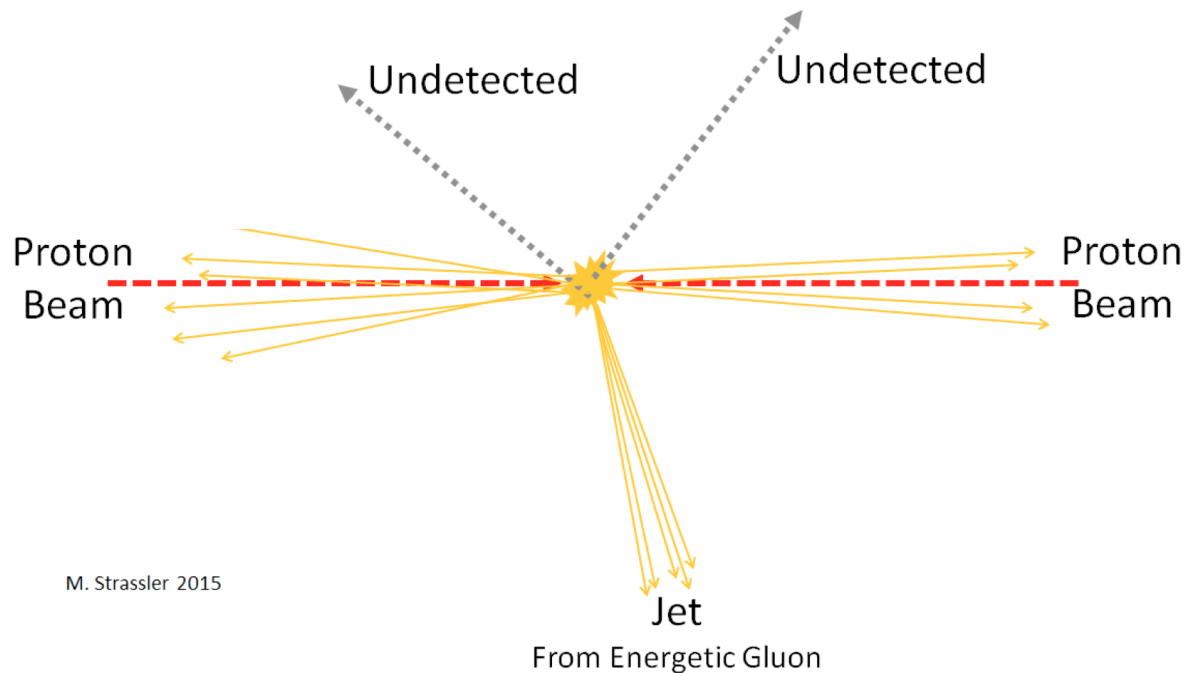
M. Strassler 2015

Need a visible object to identify collision

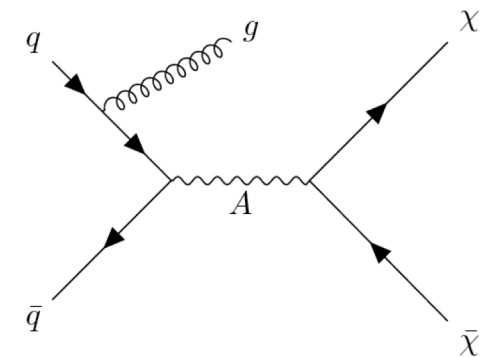
Maximise inclusivity of search (limited by experiment), and coverage (topologies, final states)



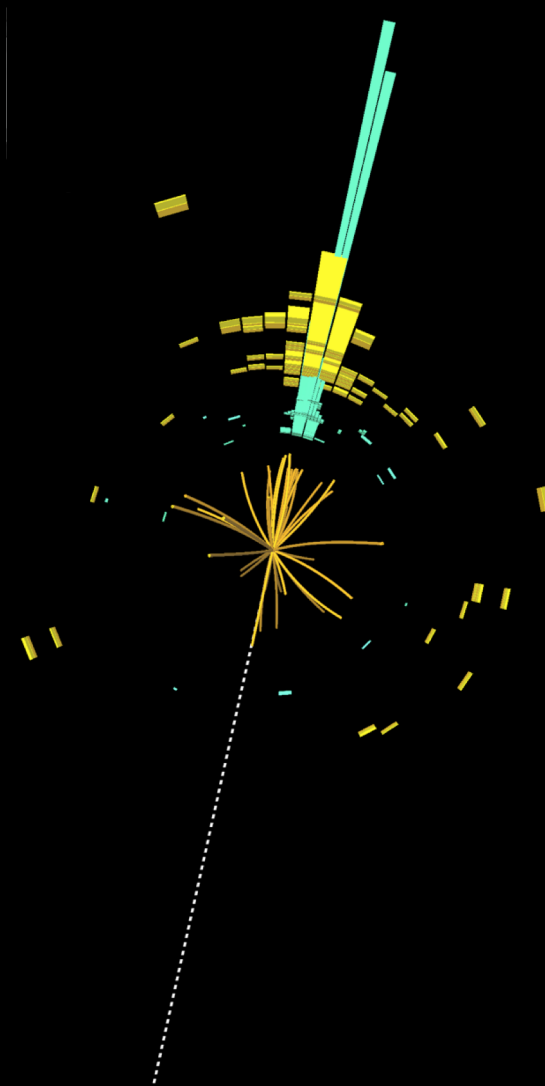
M. Strassler 2015



M. Strassler 2015

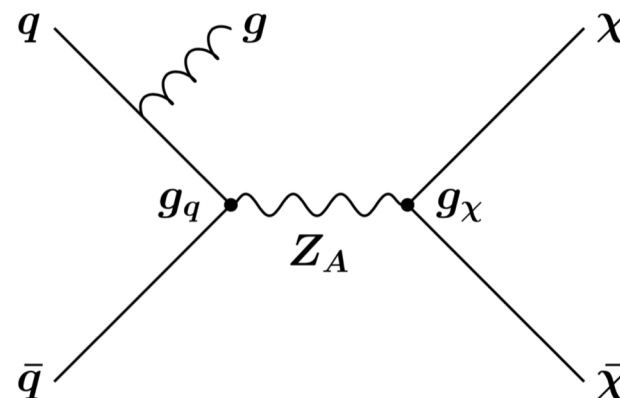
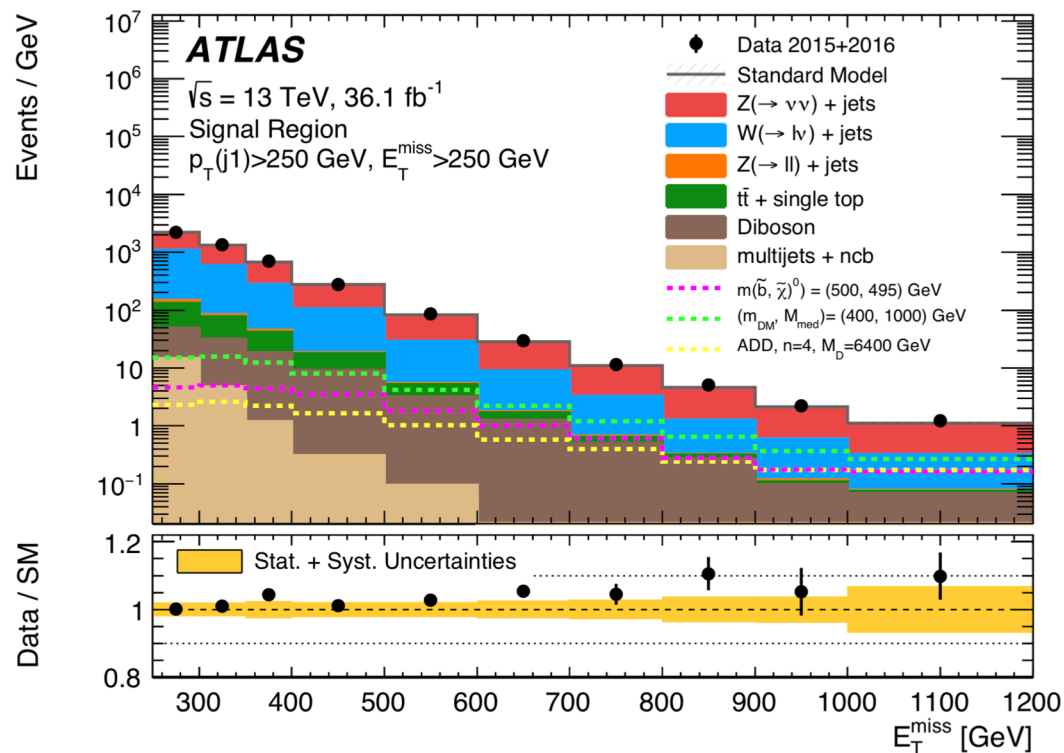


Mono-X signatures



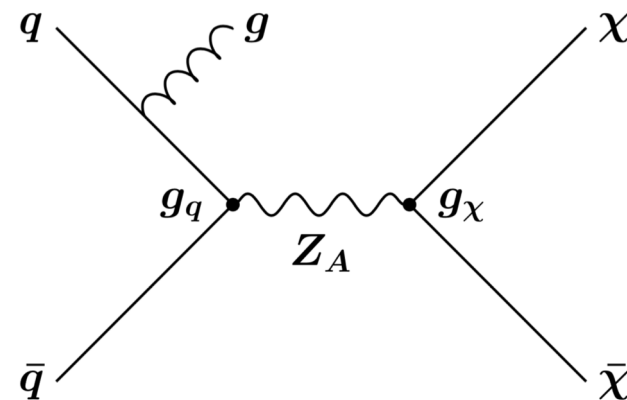
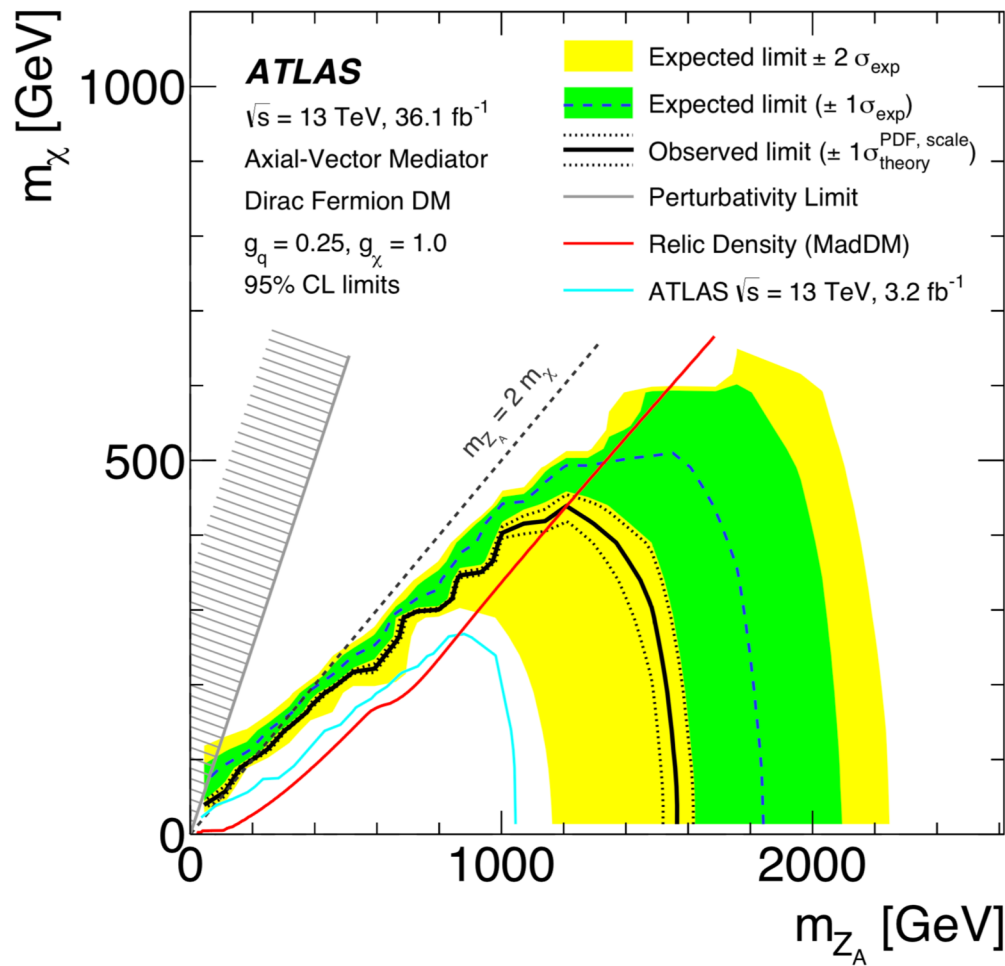
Monojet searches often most sensitive

Quark couplings restricted by dijet searches



Monojet searches often most sensitive

Exclusion region (95% C.L) in mediator–DM mass plane:

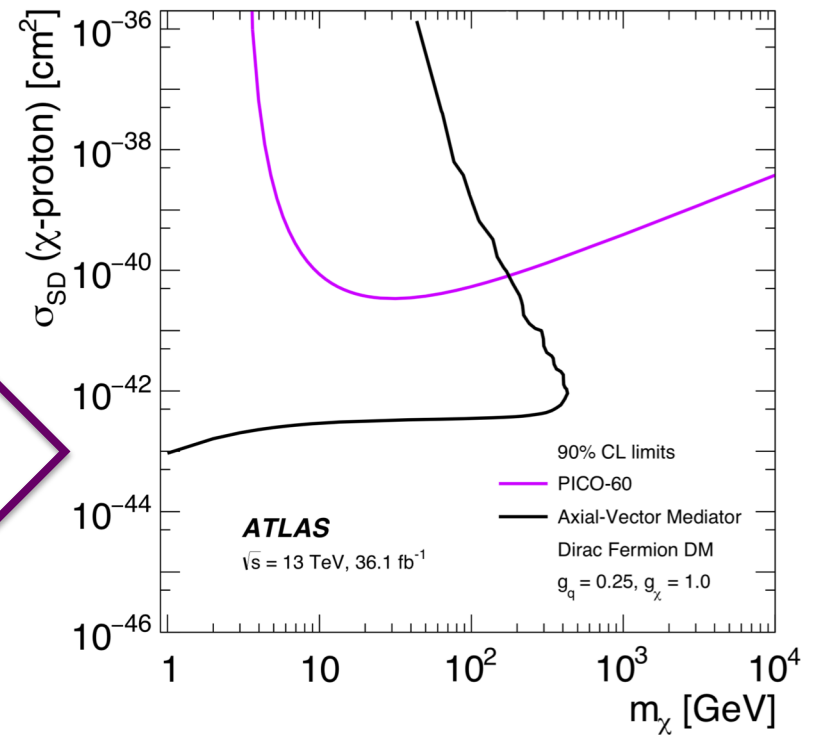
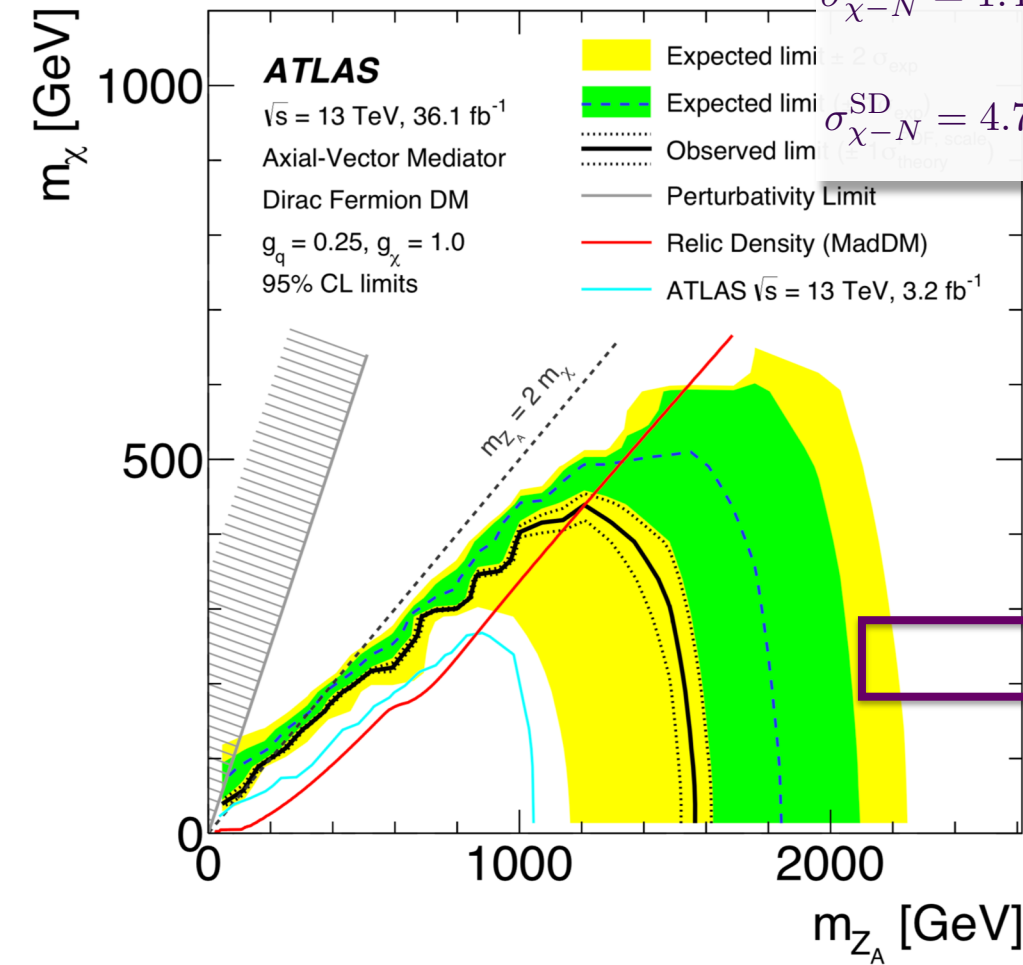


Monojet searches often most sensitive

Convert from collider rate to WIMP-nucleon cross-section exclusion:

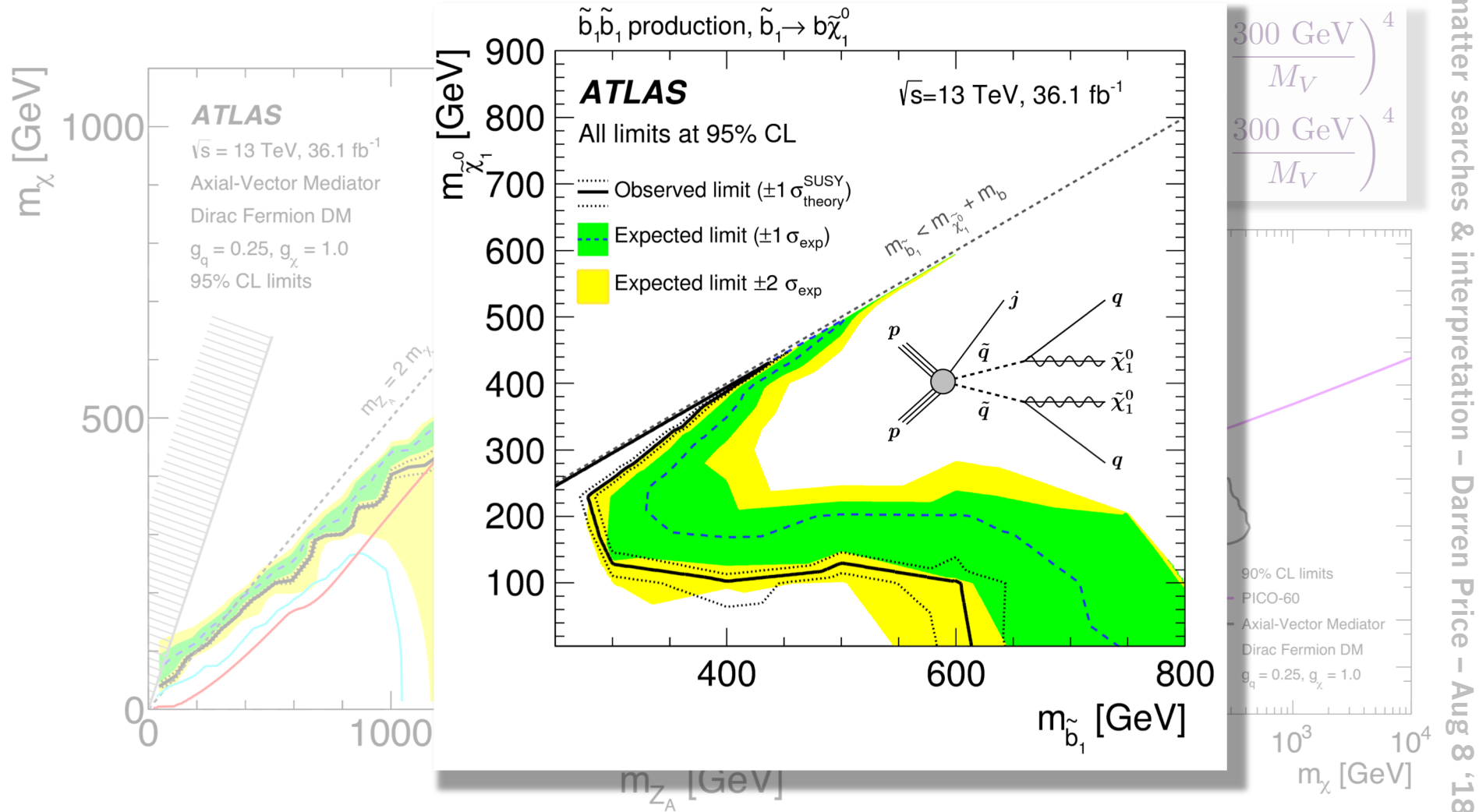
$$\sigma_{\chi-N}^{\text{SI}} = 1.4 \times 10^{-37} \text{cm}^2 g_{\chi}^V g_q^V \left(\frac{\mu_{\chi-N}}{1 \text{ GeV}} \right)^2 \left(\frac{300 \text{ GeV}}{M_V} \right)^4$$

$$\sigma_{\chi-N}^{\text{SD}} = 4.7 \times 10^{-39} \text{cm}^2 g_{\chi}^A g_q^A \left(\frac{\mu_{\chi-N}}{1 \text{ GeV}} \right)^2 \left(\frac{300 \text{ GeV}}{M_V} \right)^4$$

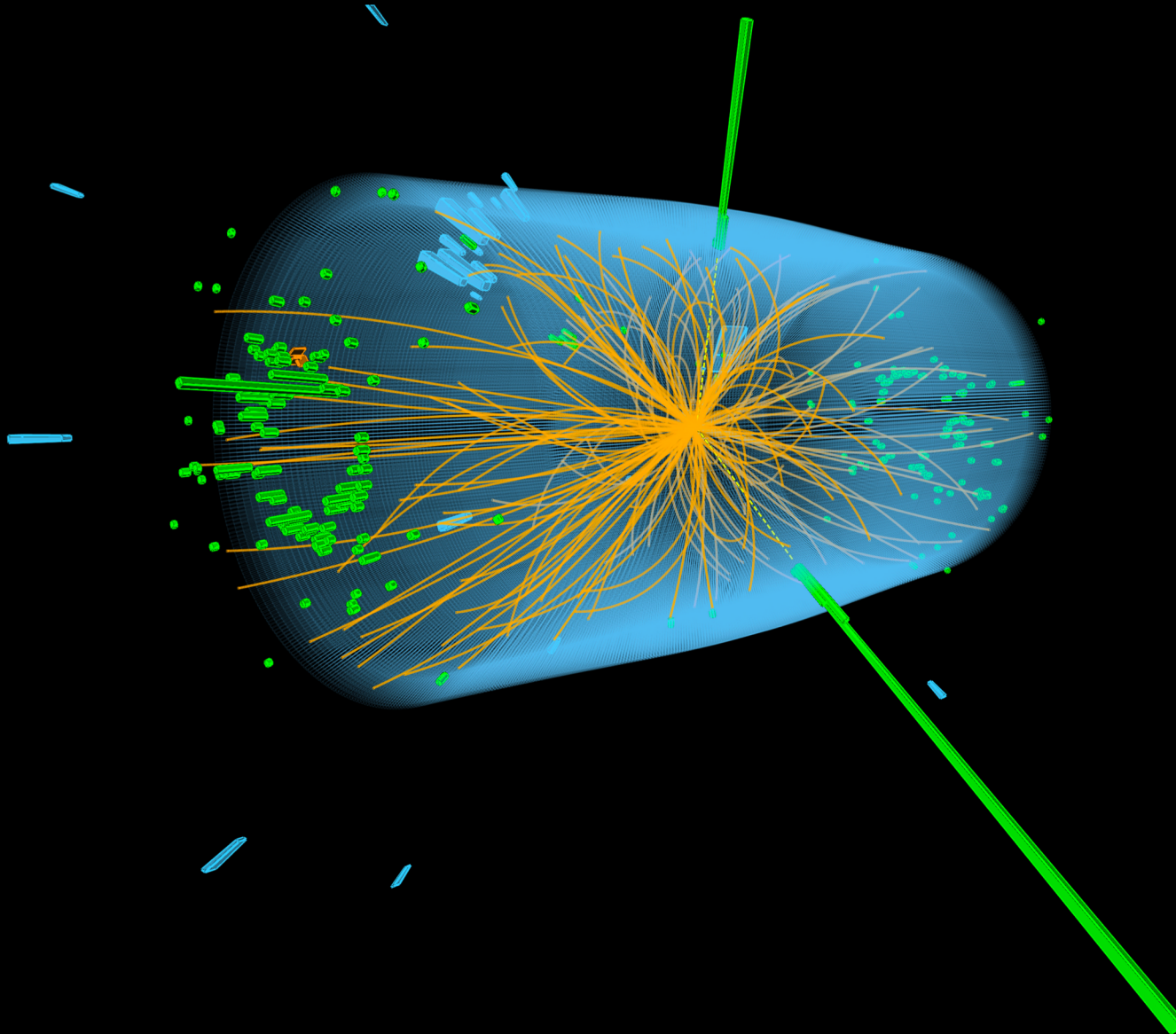


Monojet searches often most sensitive

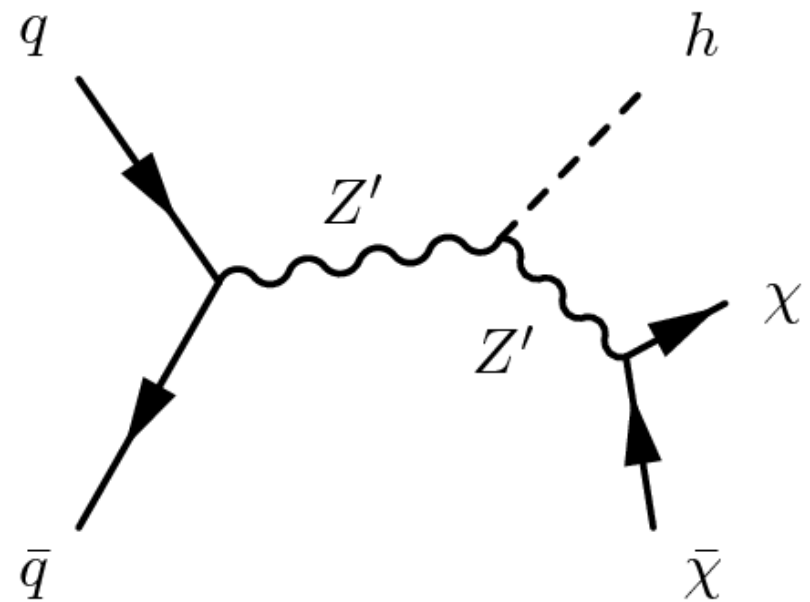
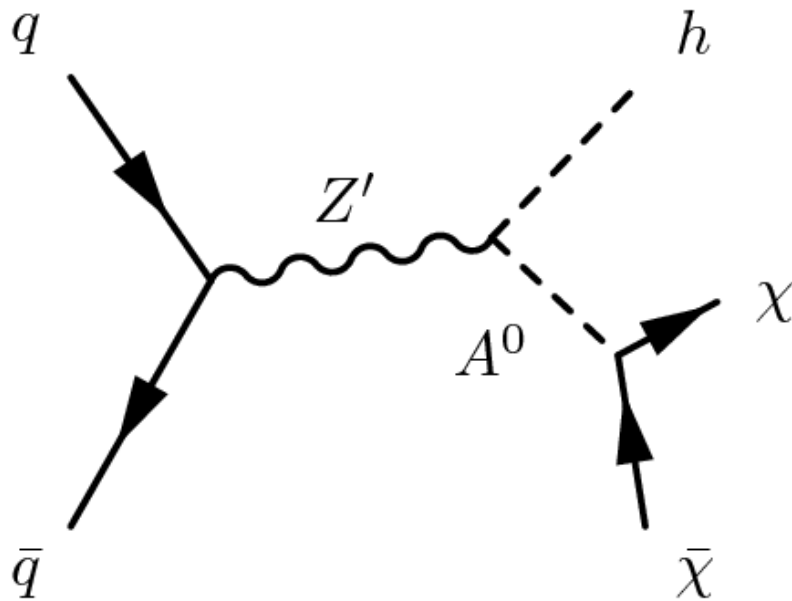
Very general search, so can be recast in terms of various models

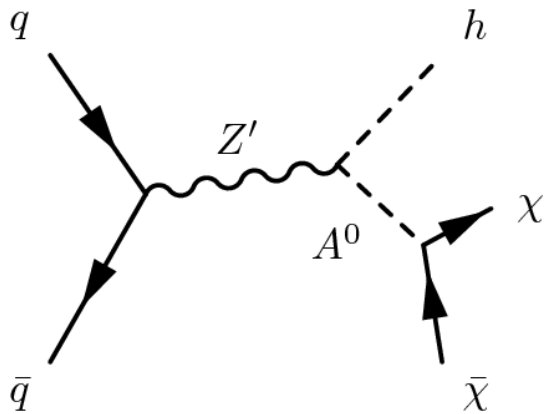


The Higgs boson as a window into dark matter

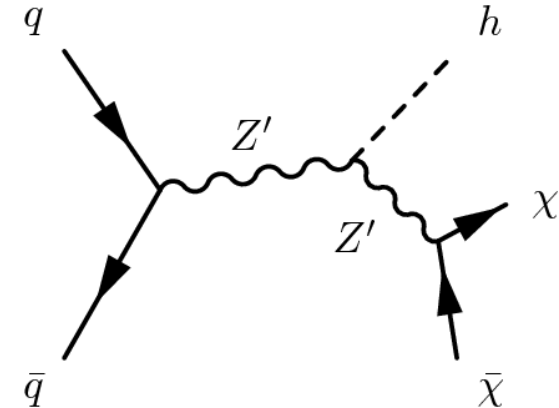


Search for Higgs in various decay modes (di-photon, di-b) alongside large missing transverse energy

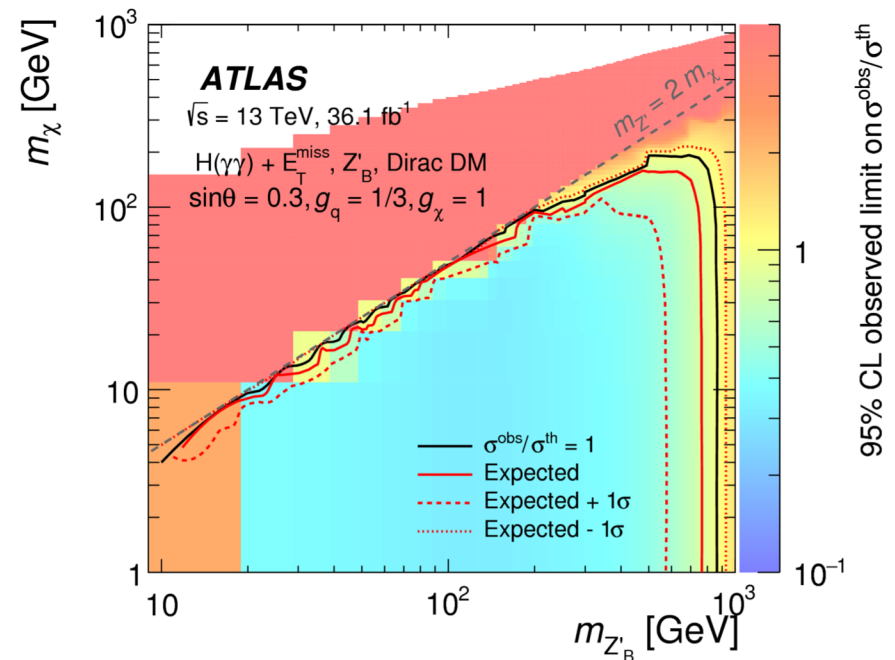
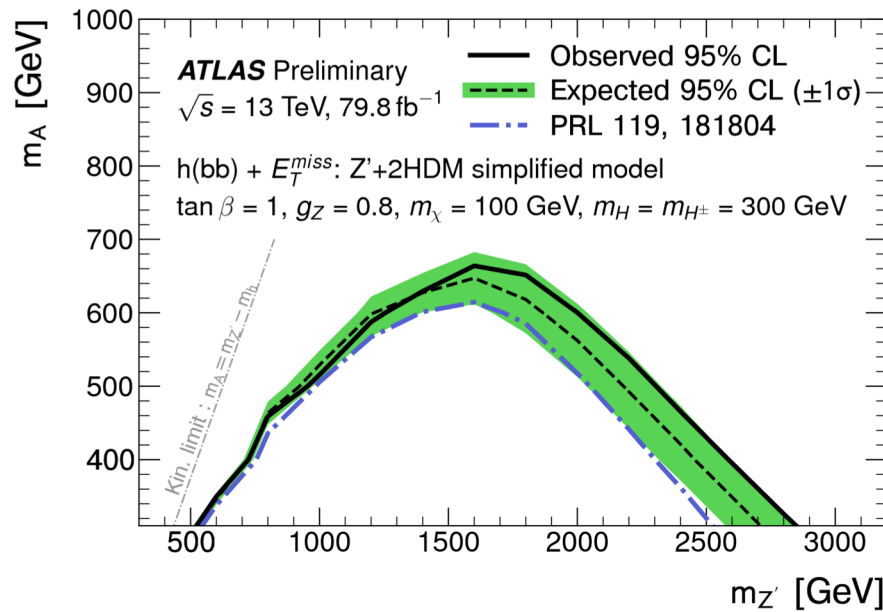


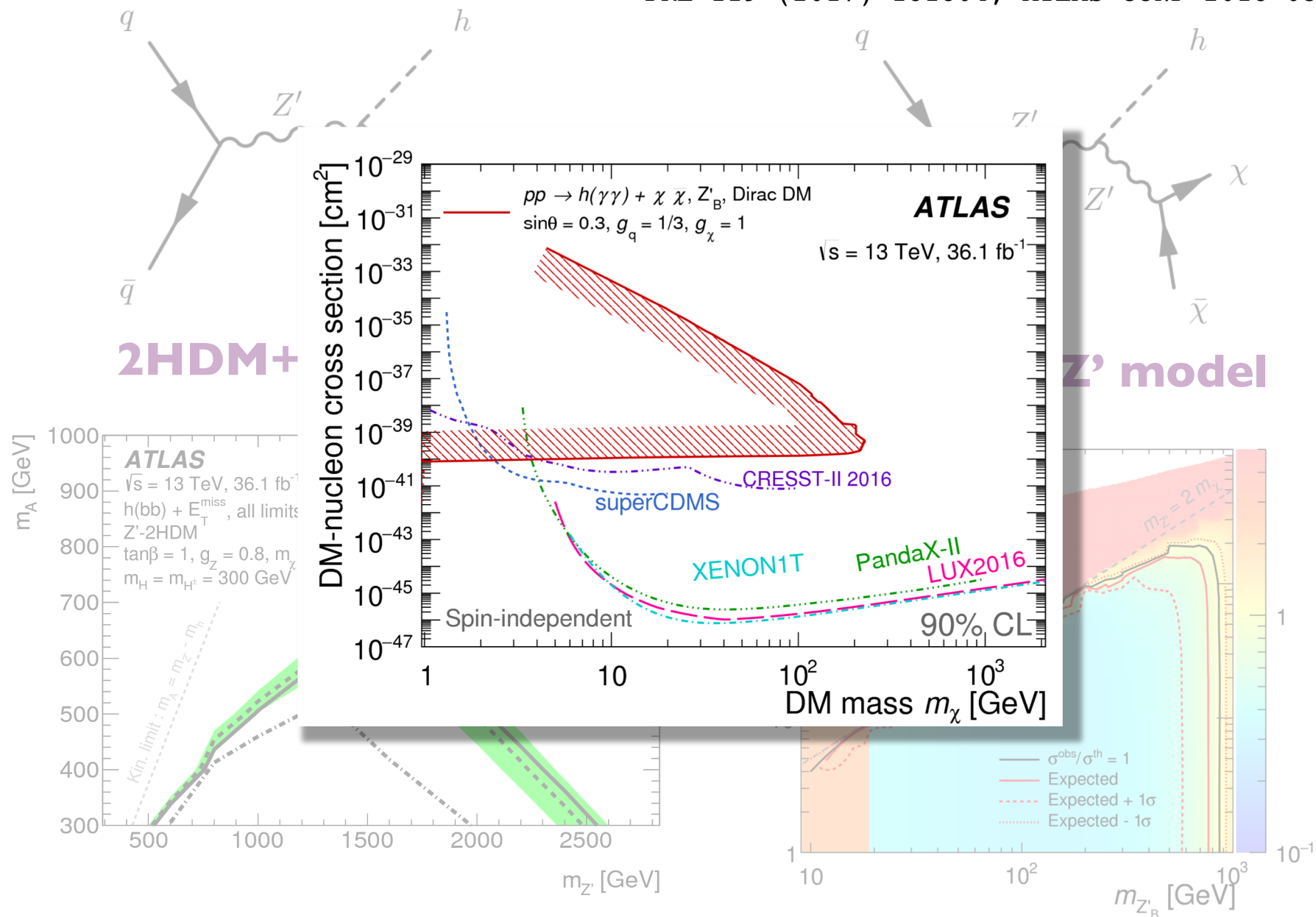


2HDM+Z' model



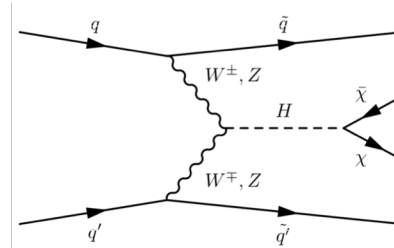
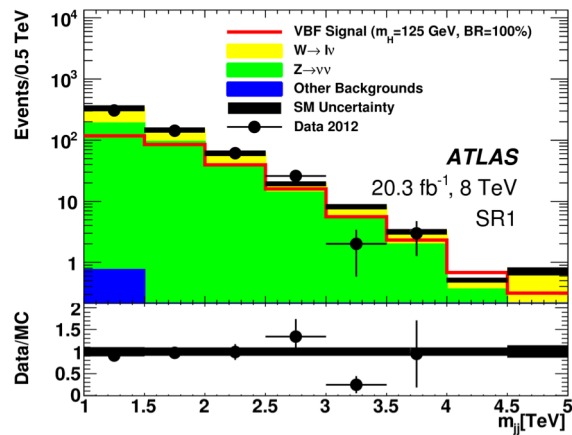
Baryonic Z' model



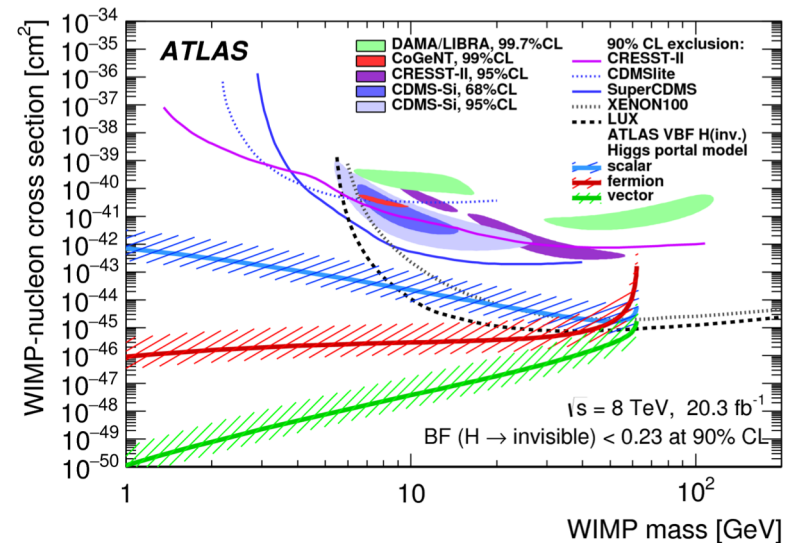
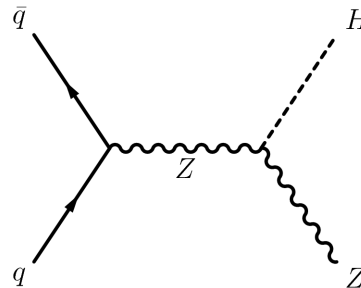
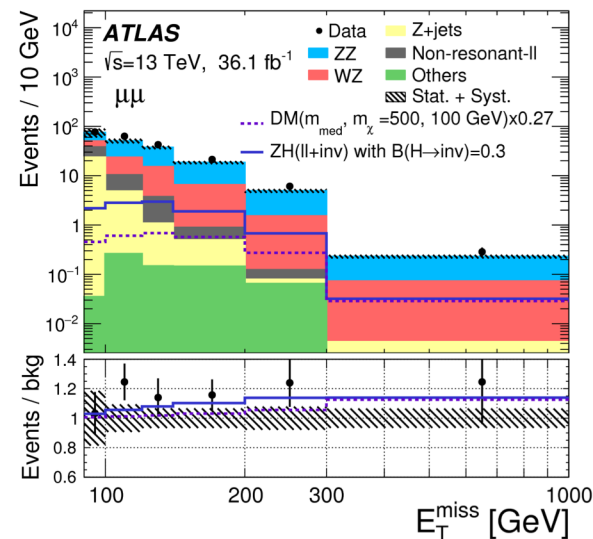


The Higgs can act as a direct mediator for dark matter

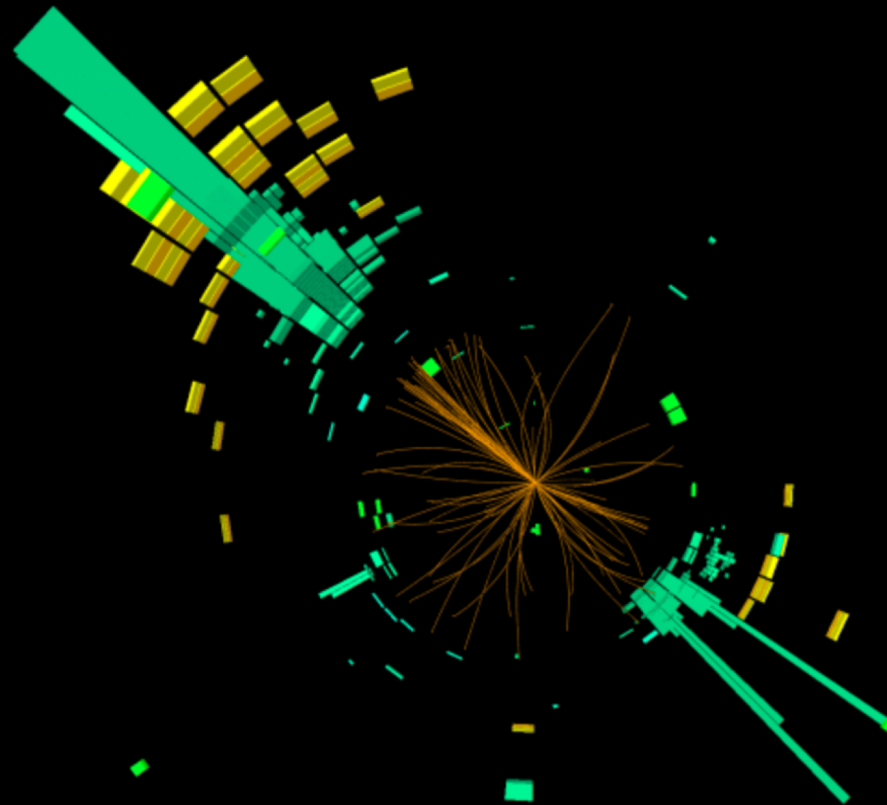
Most sensitive channel: vector boson fusion



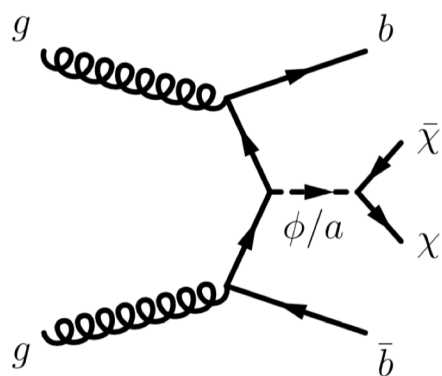
SR1	Expected	+1 σ	-1 σ	+2 σ	-2 σ	Observed
Fiducial cross section [fb]	4.78	6.32	3.51	8.43	2.53	3.93



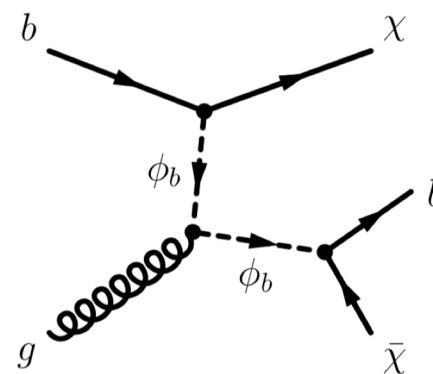
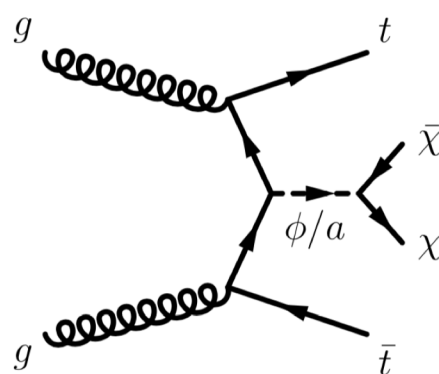
Flavourful dark matter



Interaction of dark matter and flavour unknown: searches for dark matter produced in association with $t\bar{t}/b\bar{b}$

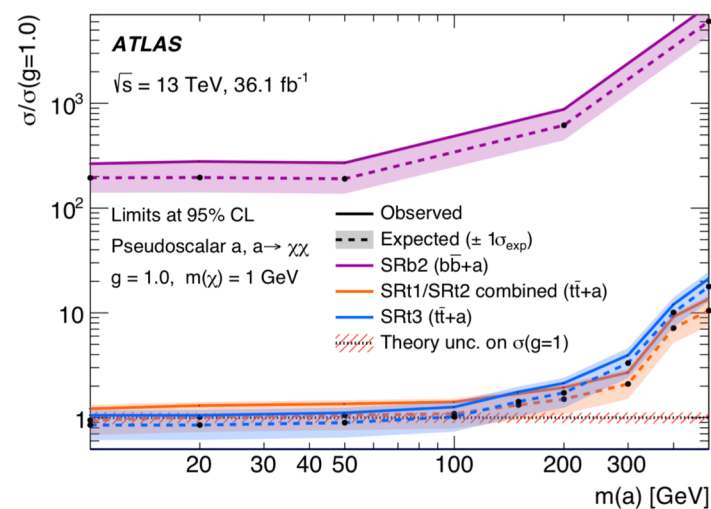
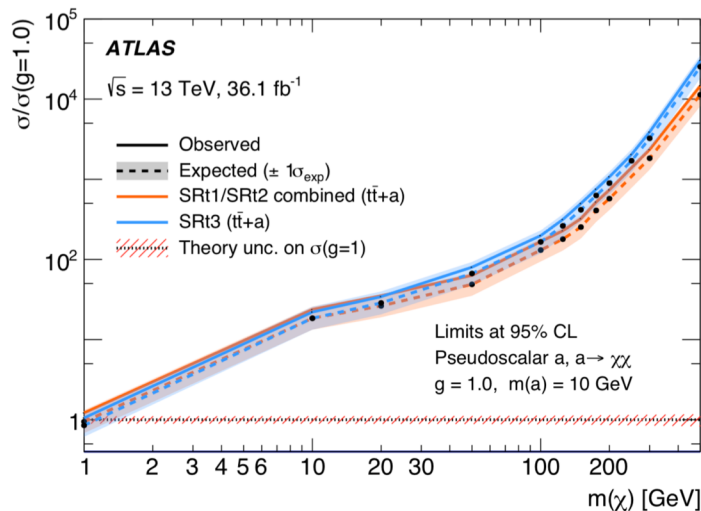
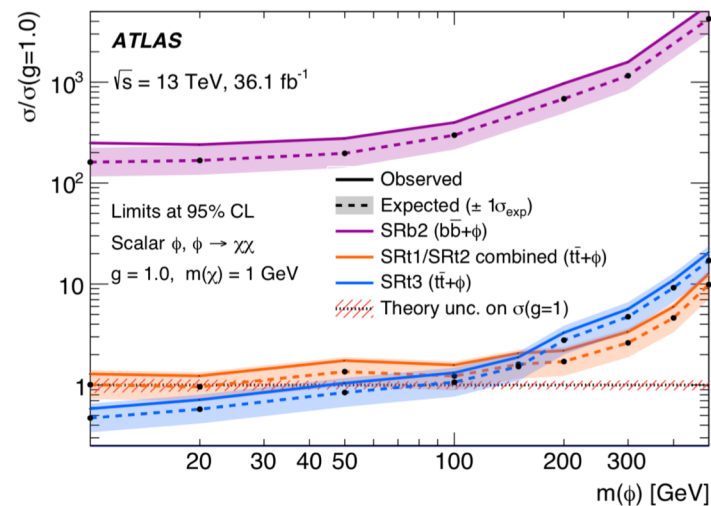
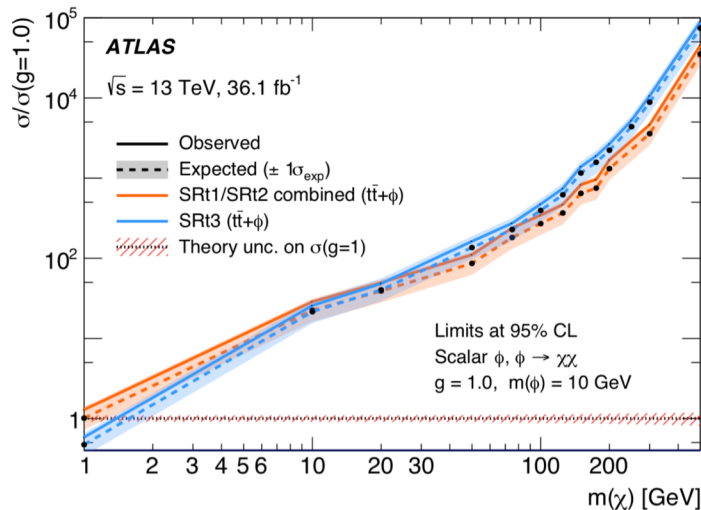


Colour neutral scalar/pseudoscalar models

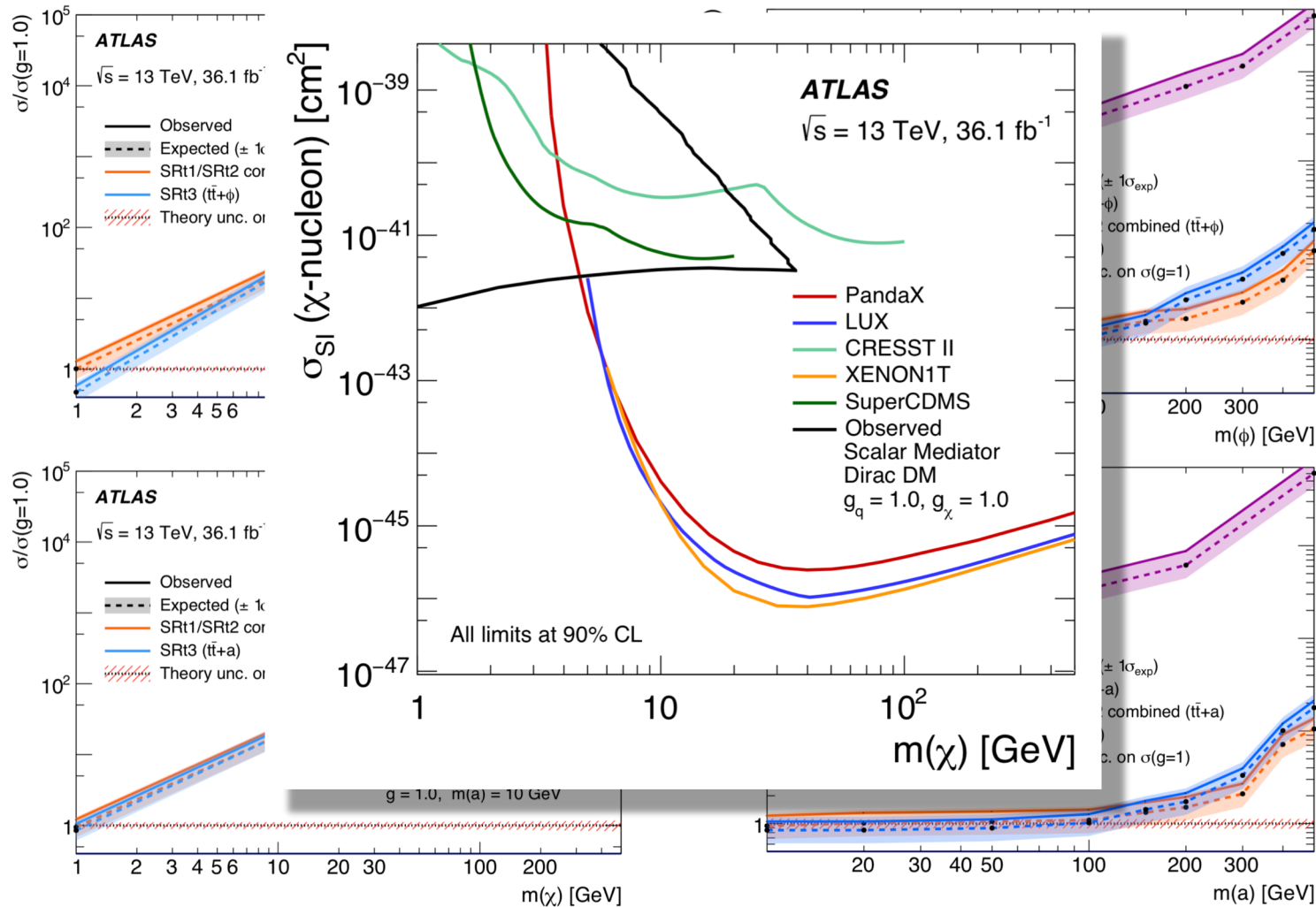


Colour-charged scalar mediator model

Bottom searches not yet able to exclude nominal values, exclusions in top searches:

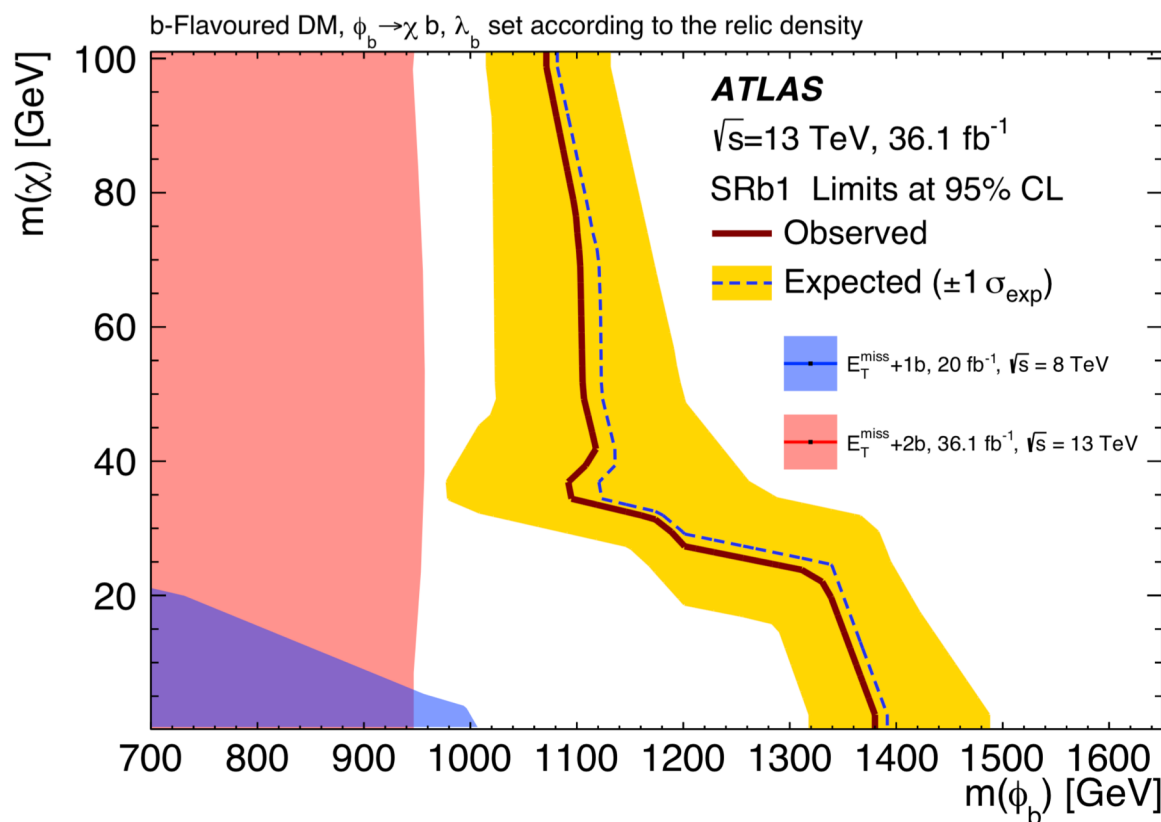
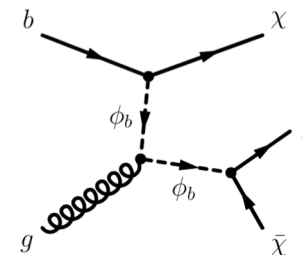


Translate results into spin-independent nucleon cross-sections:



Colour-charged mediator searches can constrain models relevant to explain Fermi-LAT excess:

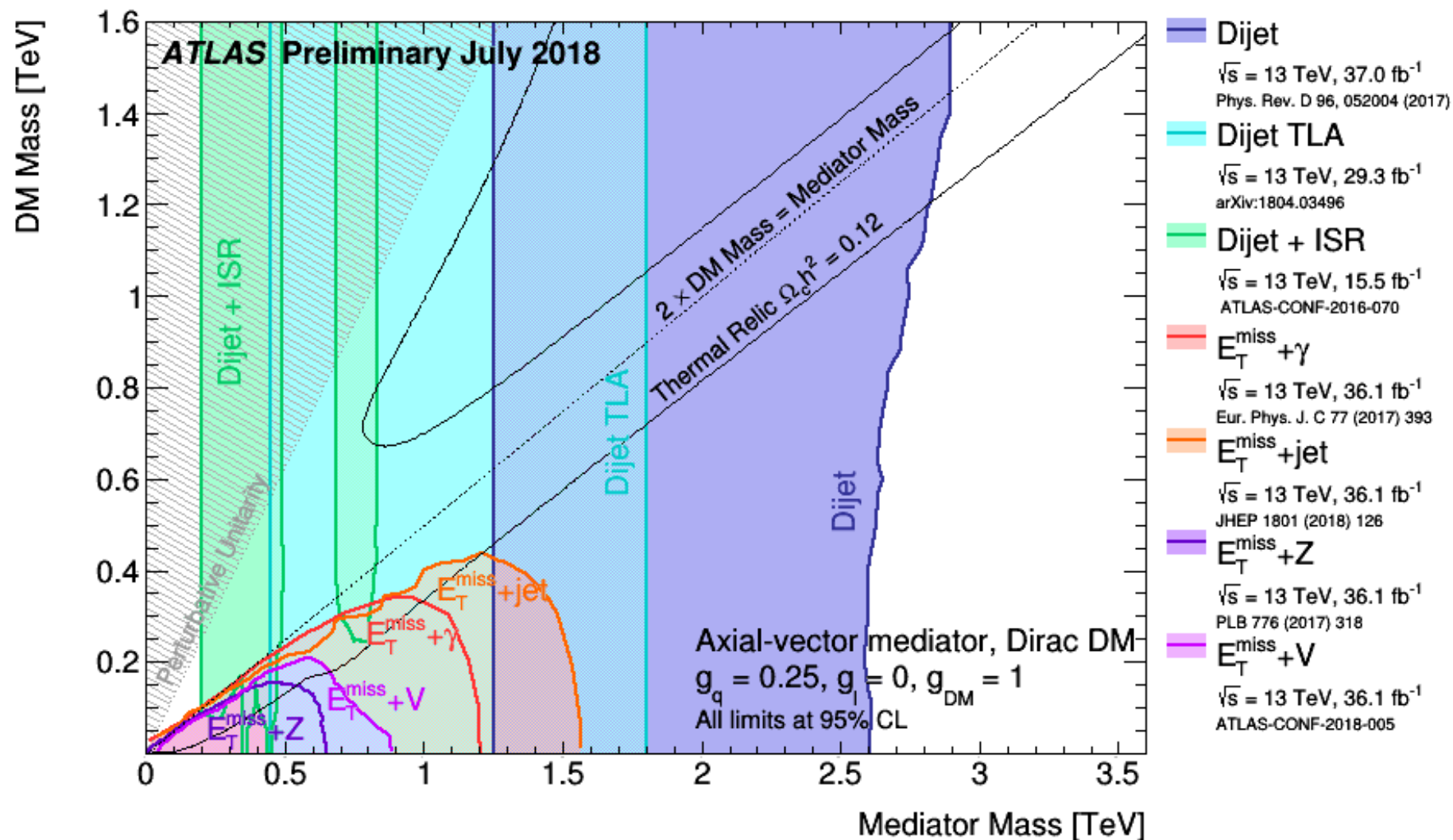
Mediators excluded below 1.1 TeV for $m_{DM} \sim 35$ GeV



A global view

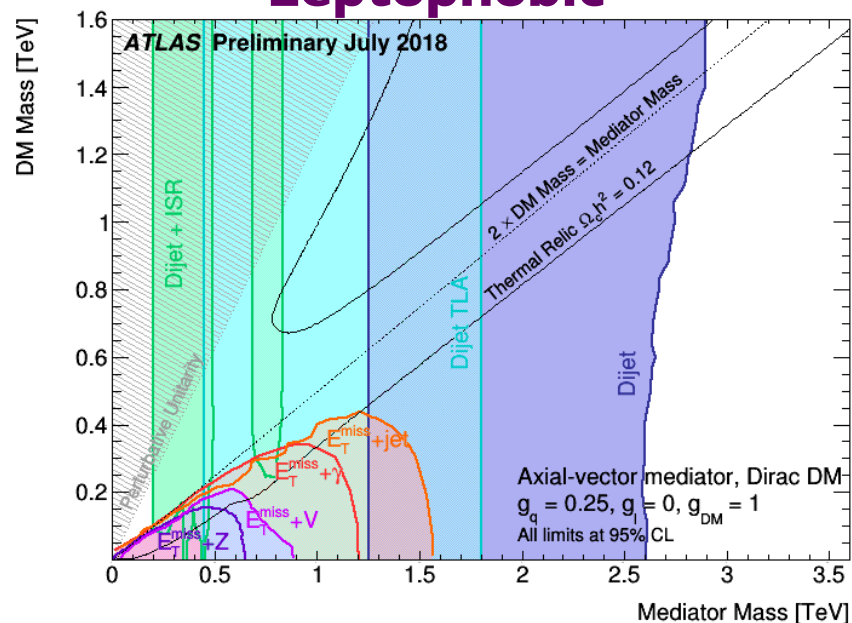


Can connect various searches with simplified model interpretation to provide global picture of sensitivity

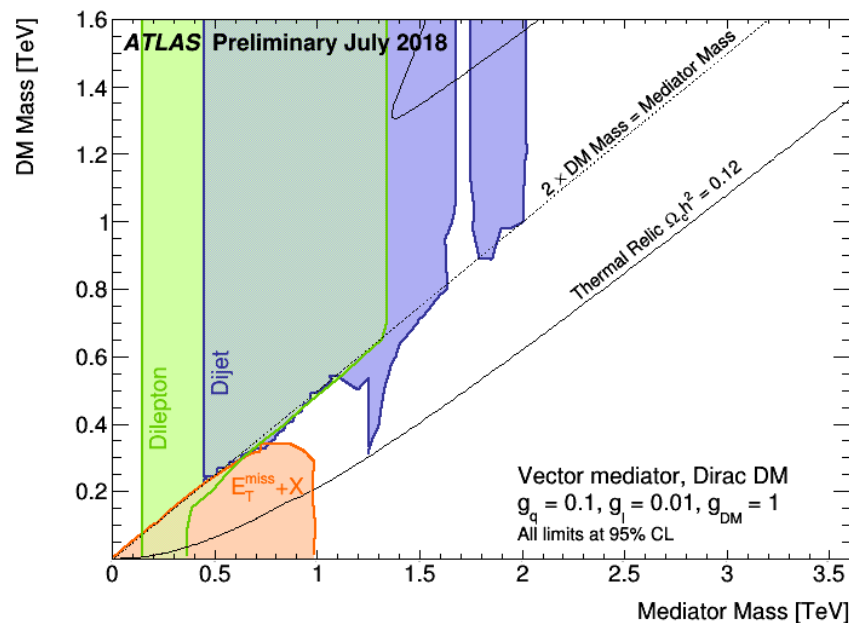
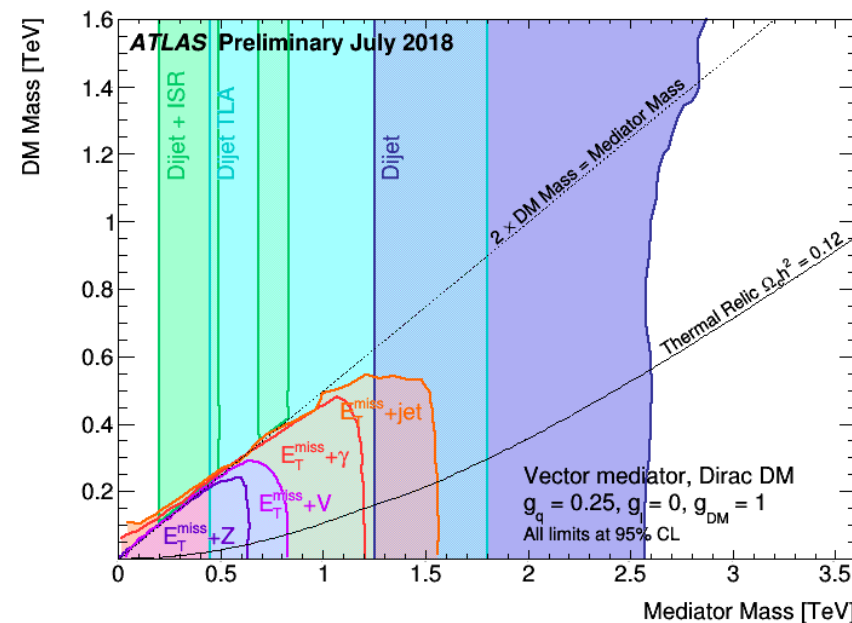
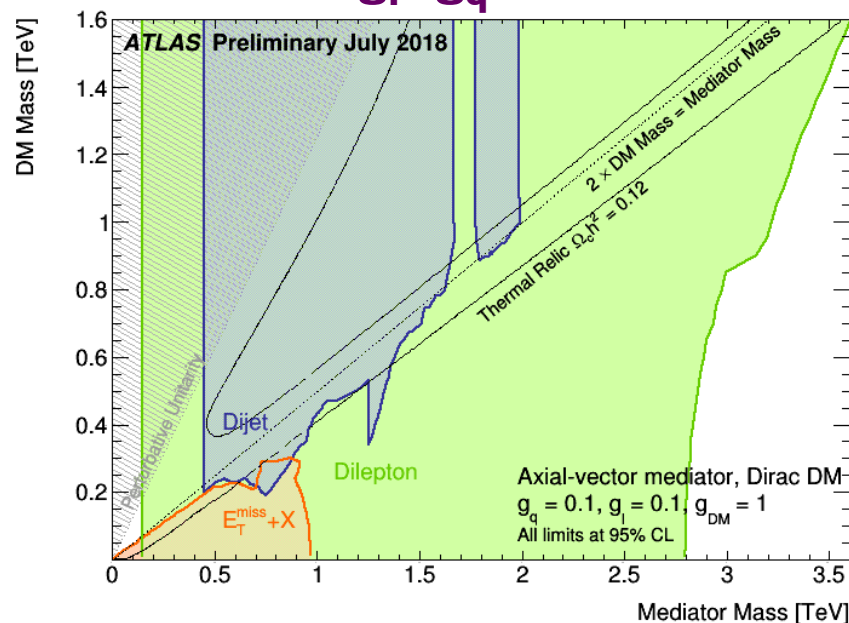


The

Leptophobic



$g_l = g_q = 0.1$

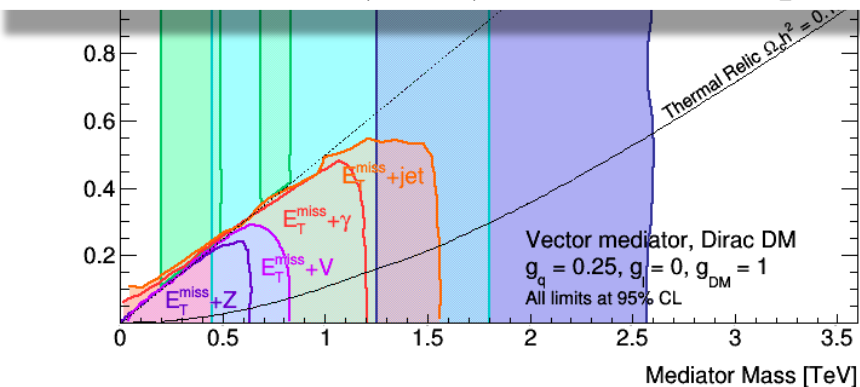
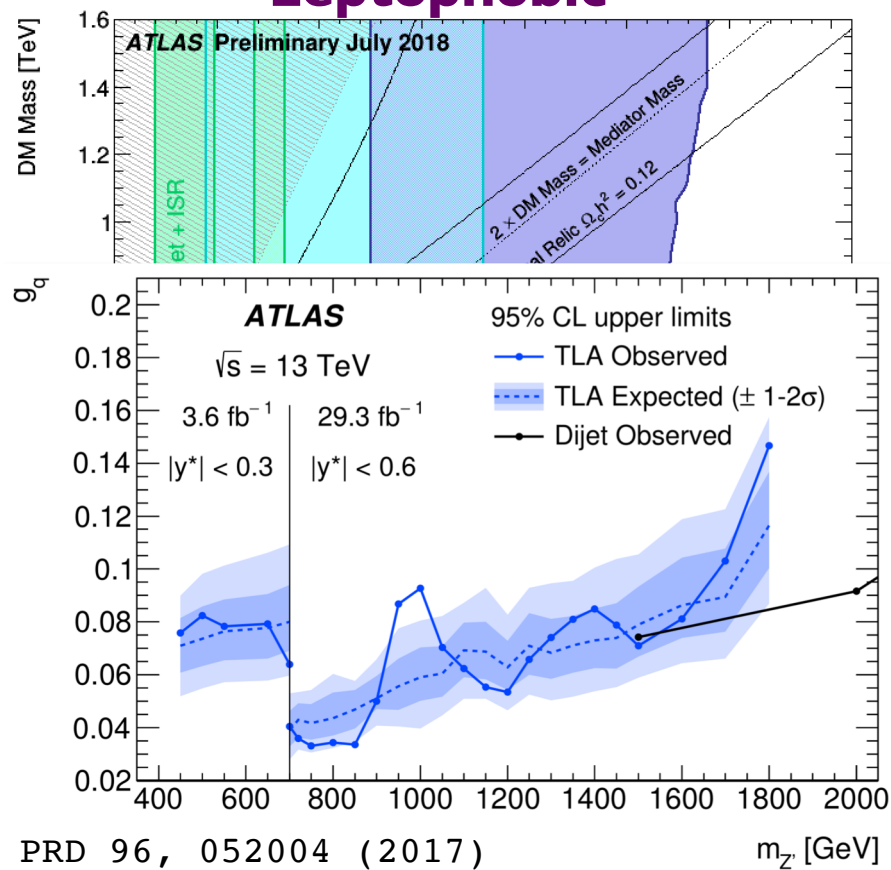


Axial vector mediator

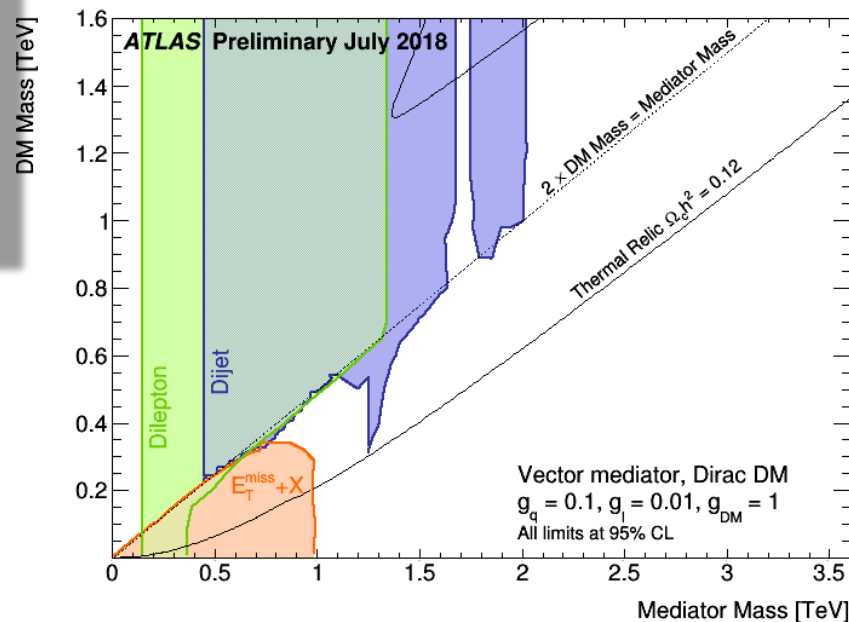
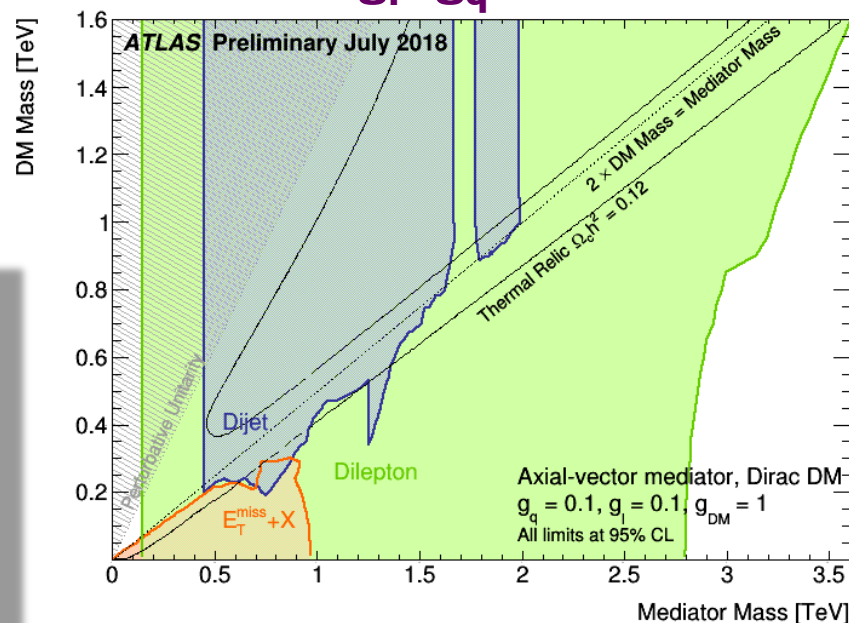
Vector mediator

The

Leptophobic



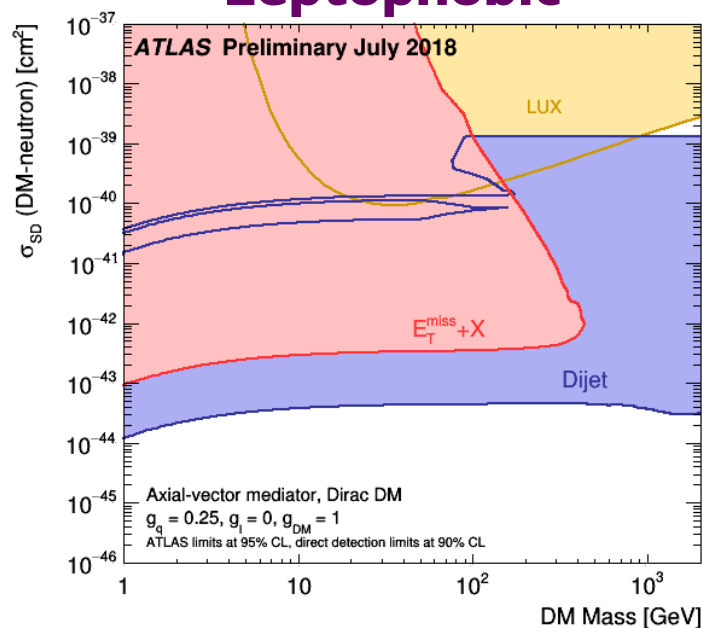
$g_l = g_q = 0.1$



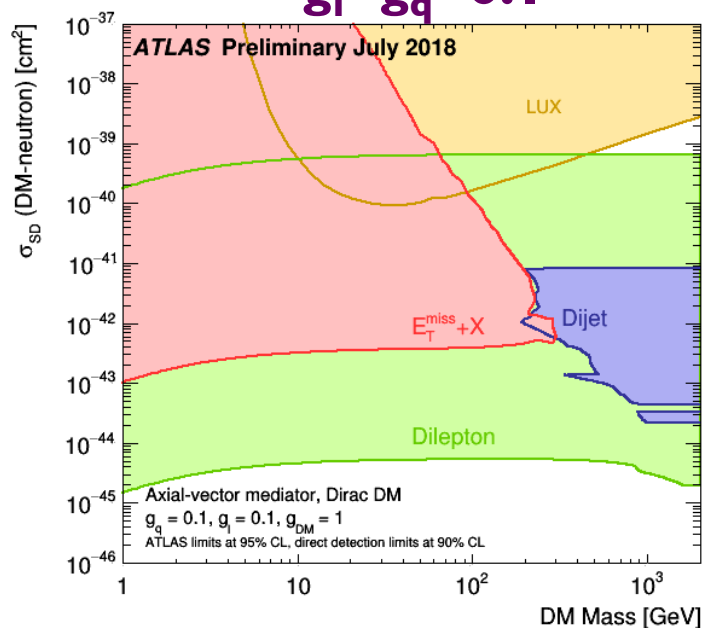
Axial vector mediator

Vector mediator

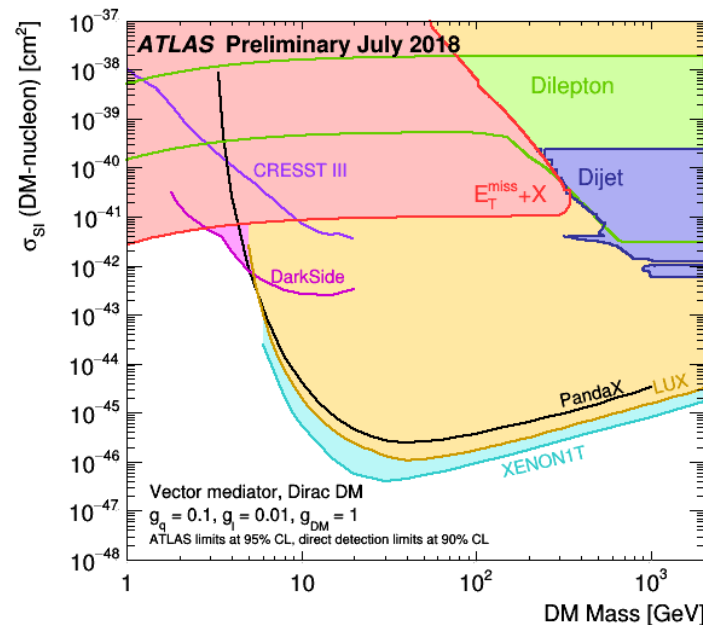
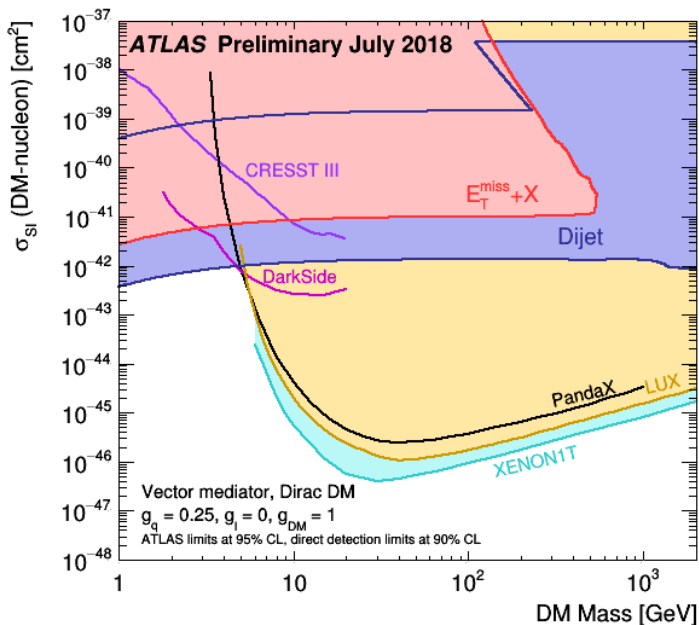
Leptophobic



$$g_l = g_q = 0.1$$

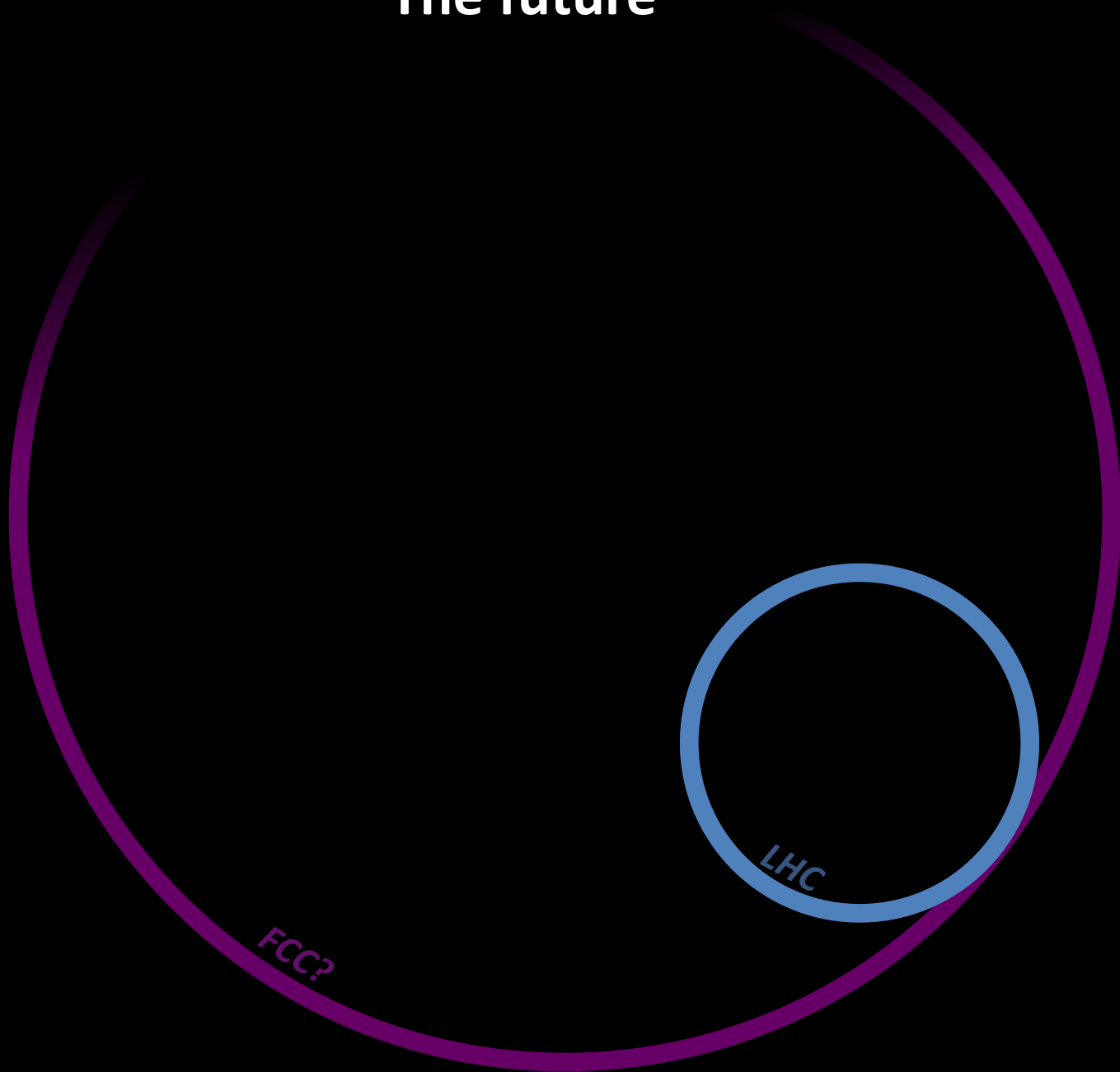


Spin-dependent



Spin-independent

The future

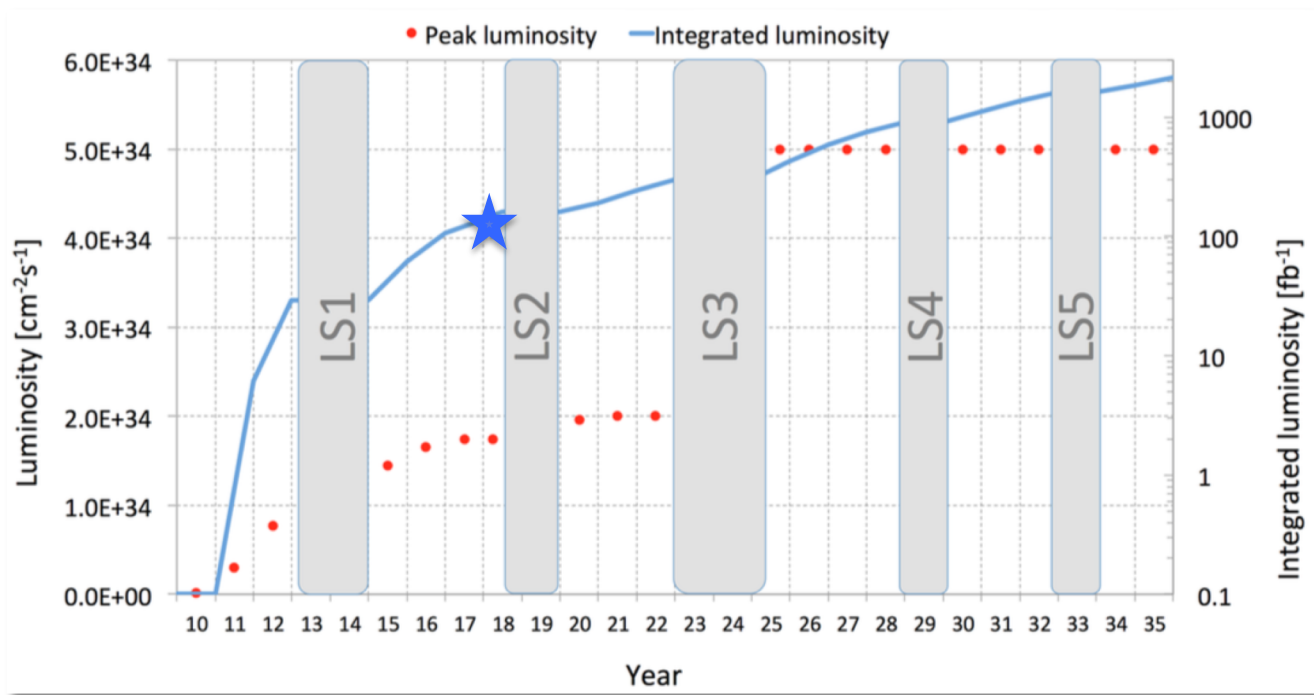


Key considerations

New dark matter theory in future?
Looking for the wrong things?
Improvements in SM modelling?
A global view on searches?

Reinterpretation.
Over-optimisation.
Recalculation of limits.
Maximising sensitivity.

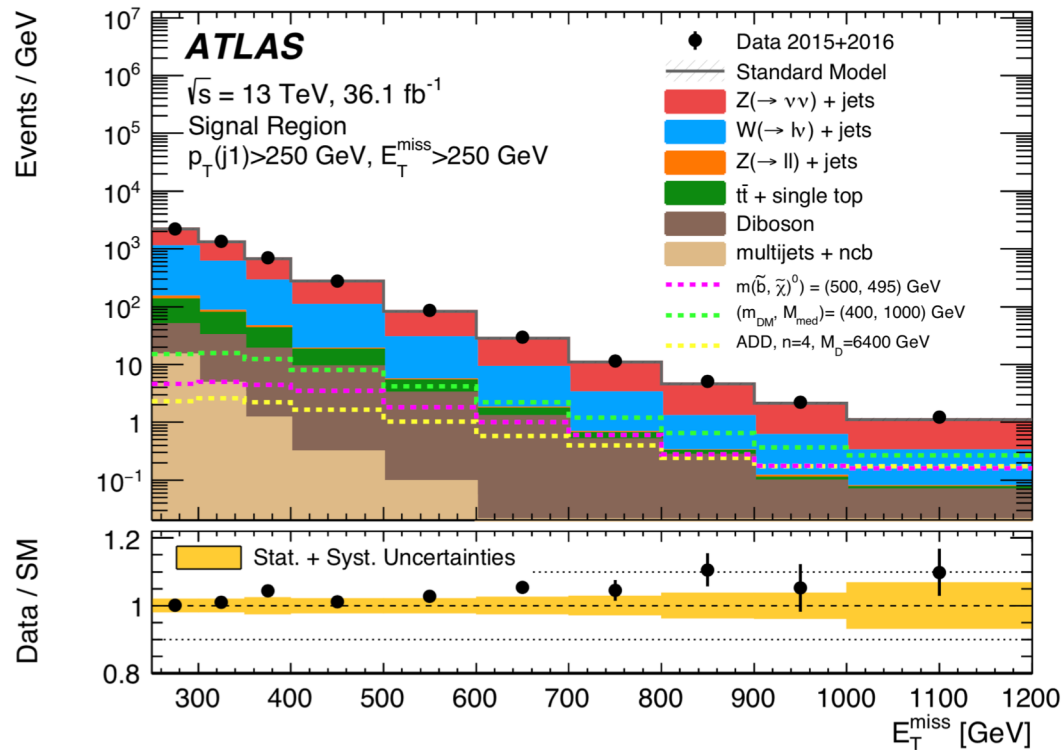
LHC luminosity evolution places increasing importance of making most of data we have!



Currently on the market:

Fit of models to 'detector-level' data

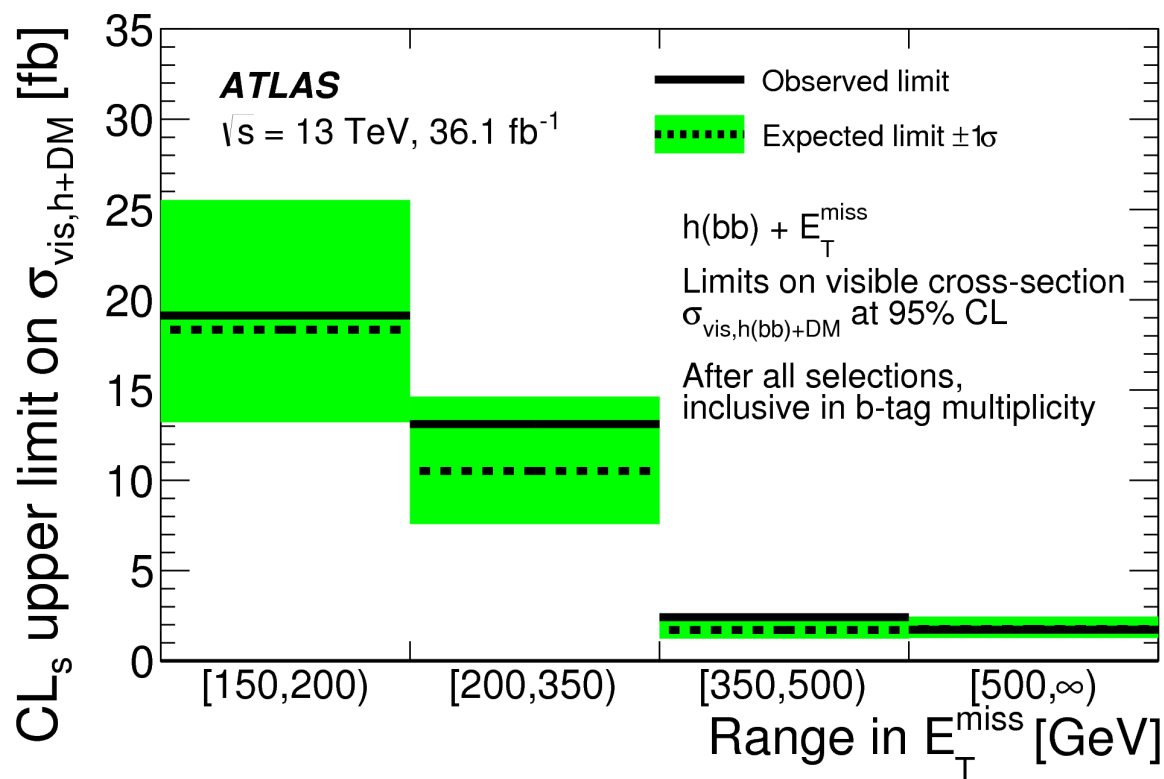
Needs signal generation, trustworthy detector simulation, implementation of (sometimes complex) detector-specific event selections.



Currently on the market:

Comparison to model-independent limits

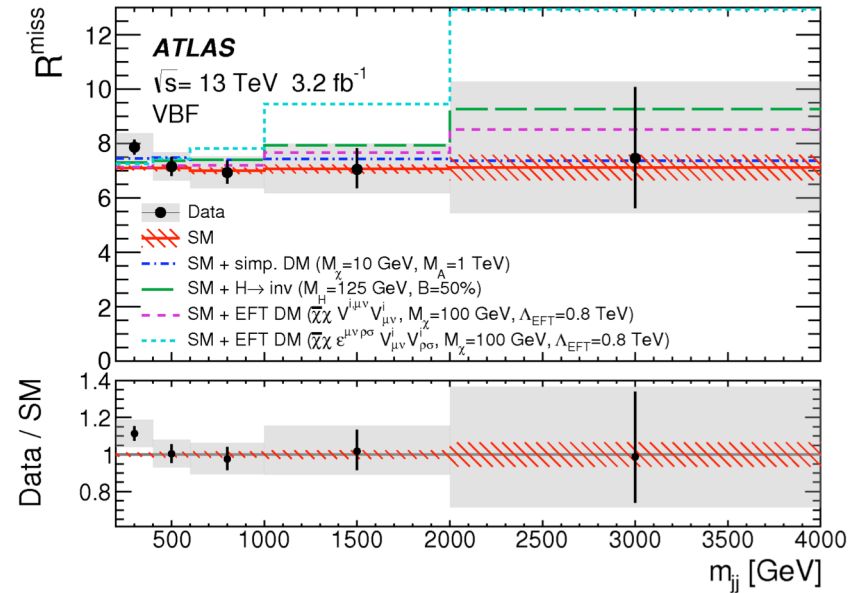
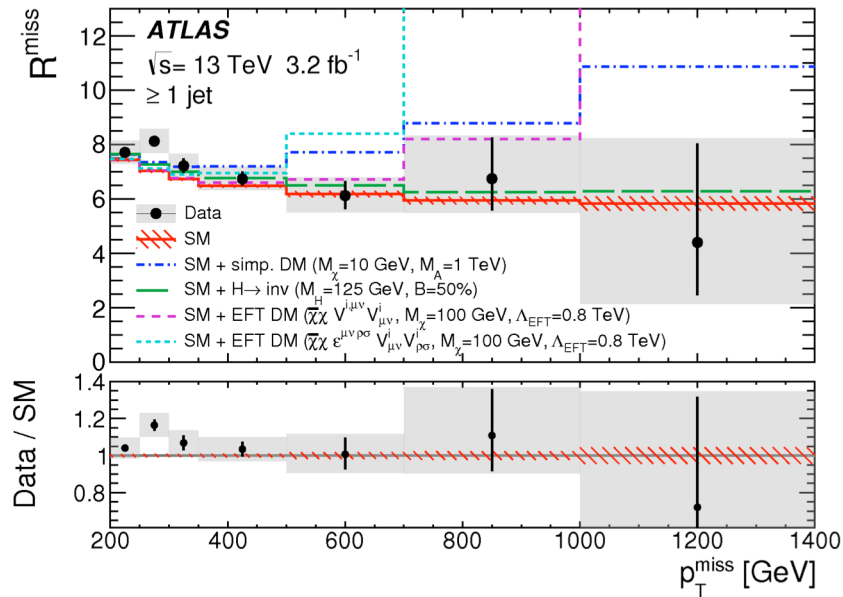
Needs signal generation, implementation of (sometimes complex) detector-specific event selections. Has imposed detector efficiency! – limitation



Currently on the market:

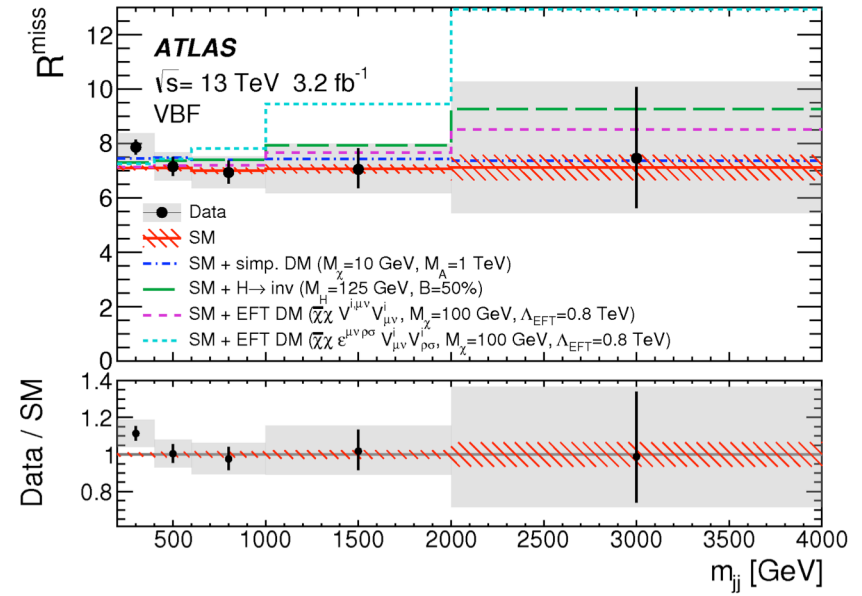
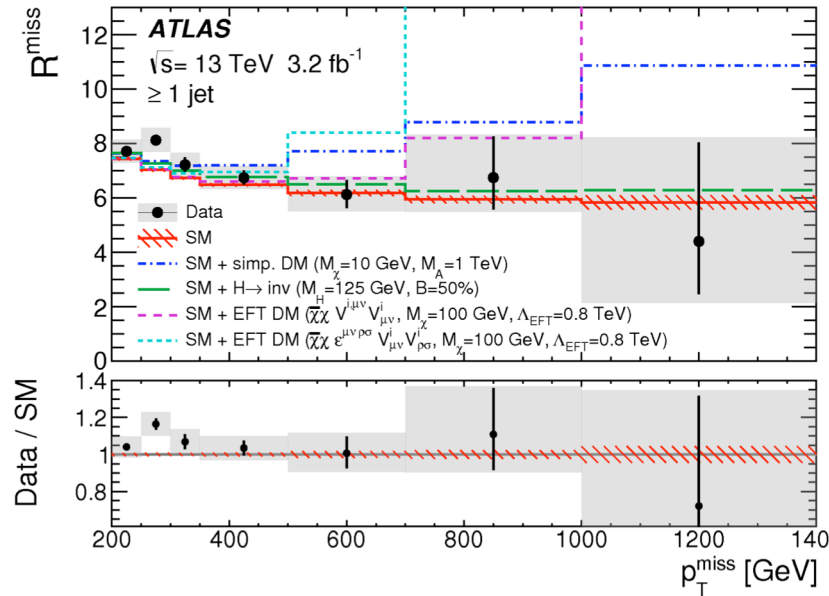
First ‘particle-level’ production cross-sections sensitive to DM

Needs signal generation. Event selections in public code, model and detector-independent. No loss of sensitivity in reinterpretation.

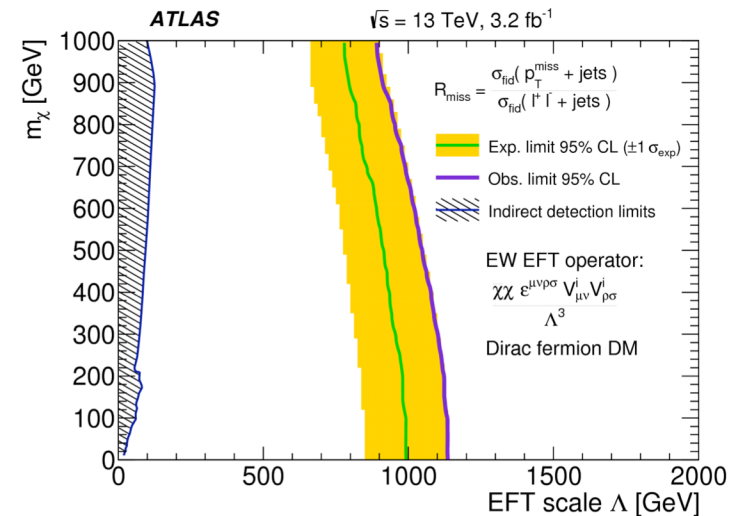
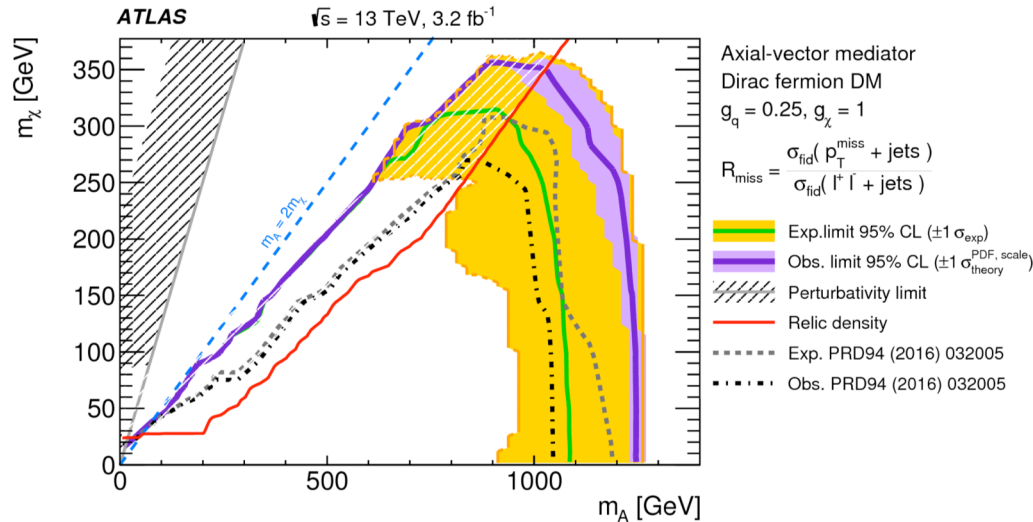


Rivet analysis code: https://rivet.hepforge.org/analyses/ATLAS_2017_I1609448.html

HEPDATA record: <https://hepdata.net/record/ins1609448>



Since published used to set limits on ALPs, asymmetric DM, EFTs...



Dark matter collider search programme is a large endeavour

- *But: are there any signatures/topologies not being explored?*

Dark matter collider search programme is a large endeavour

- *But: are there any signatures/topologies not being explored?*

Despite non-observation should remember we are still discovering SM processes!

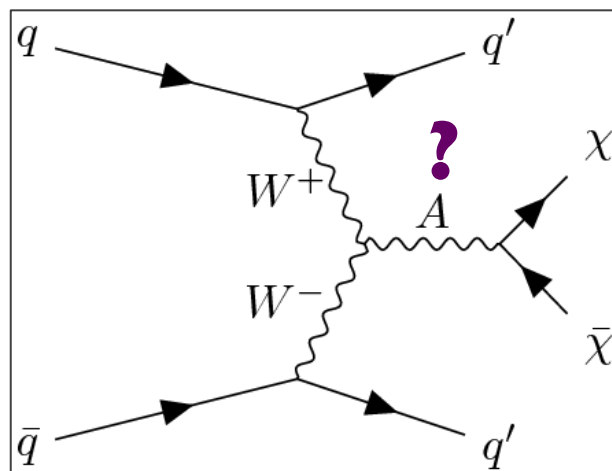
- *If DM very exclusive in production we have hard work ahead of us even with data++ and all existing analyses!*

Dark matter collider search programme is a large endeavour

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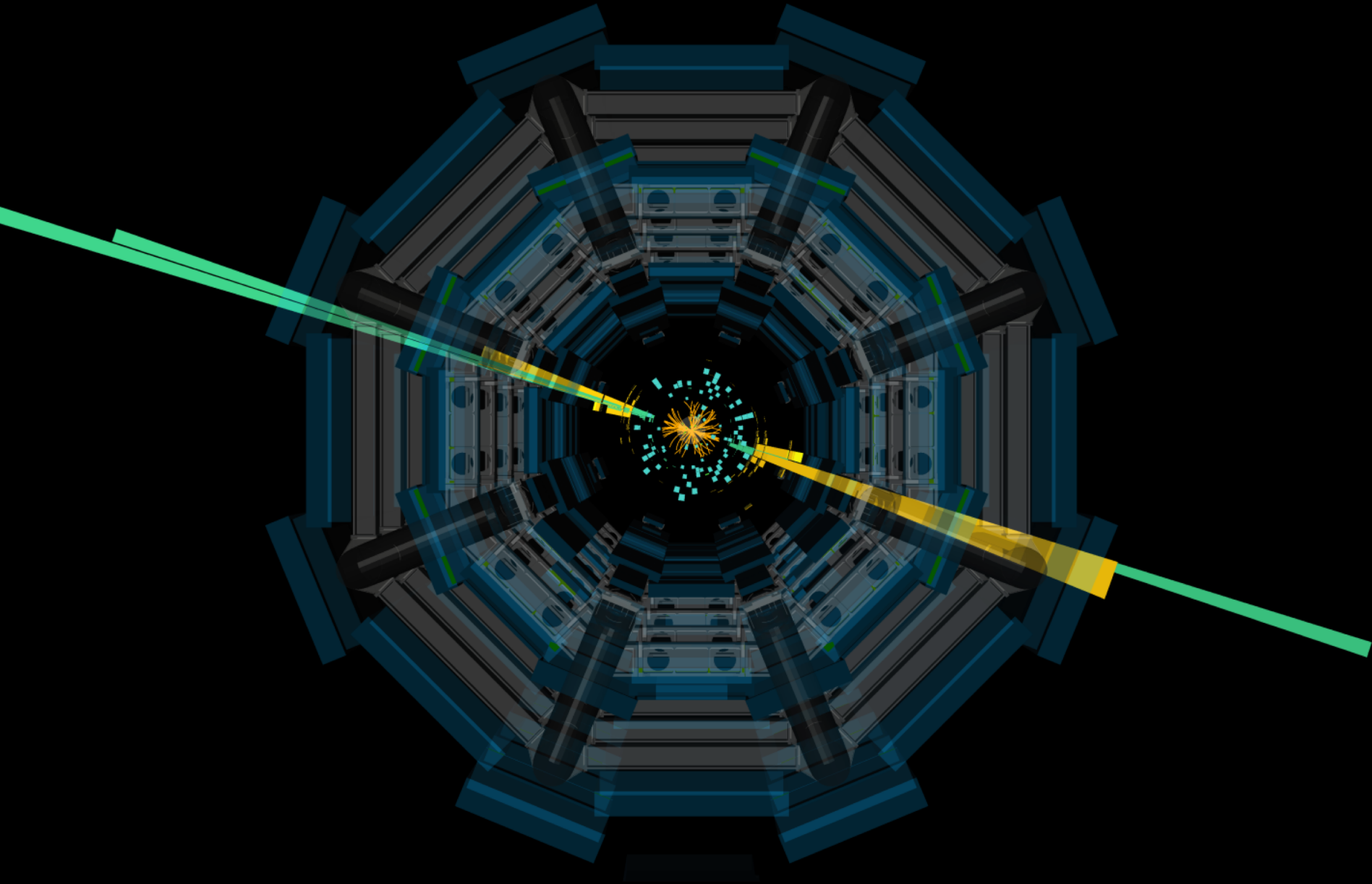
How best present/use data for reinterpretation/combination?

- *How to make best use of data from the LHC for reinterpretation with wider community (and vice-versa!)?*
- *Fully joined-up thinking between direct detection and collider communities? Can we do more?*

*Still far to go in the exploration of the dark sector:
how do we make the most of what we do?*

Backup

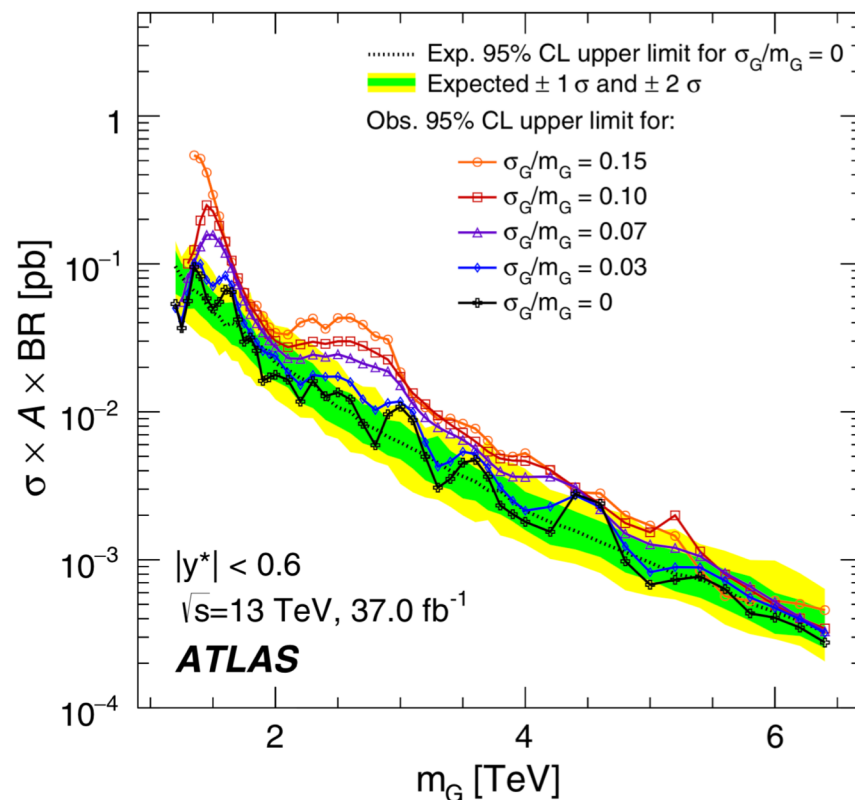
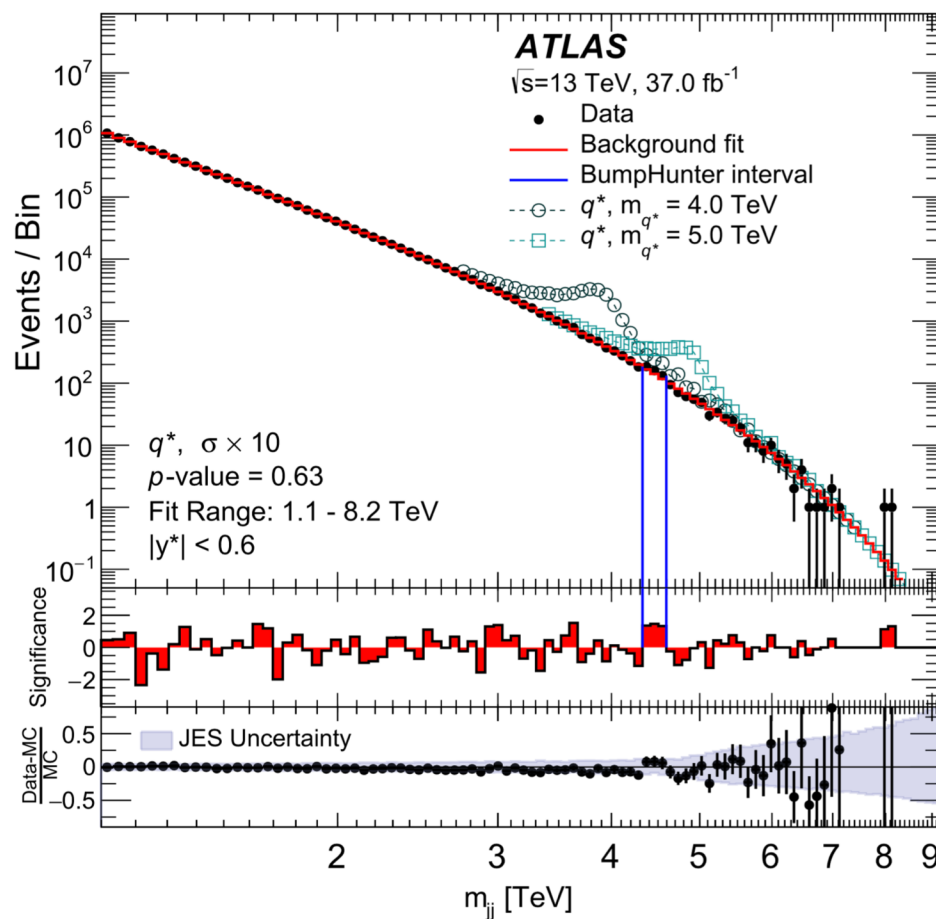
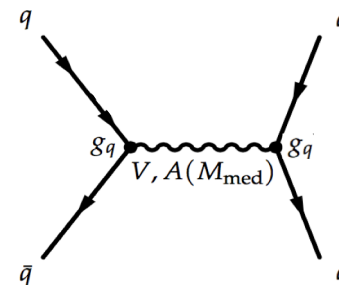
Dijet searches



In high-energy pp collisions search for production of the DM—SM mediator (g_q^2)

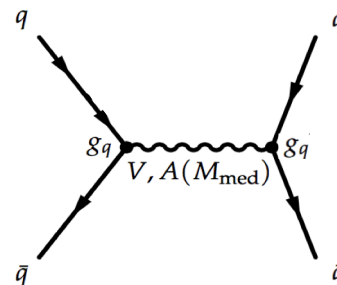
Perform dijet resonance search

PRD 96, 052004 (2017)

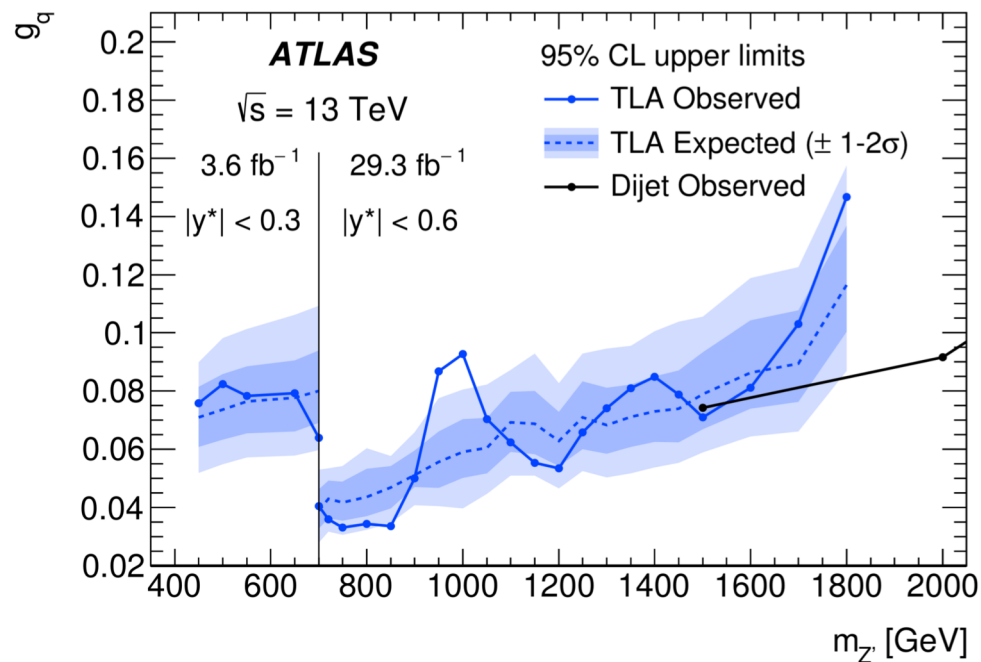
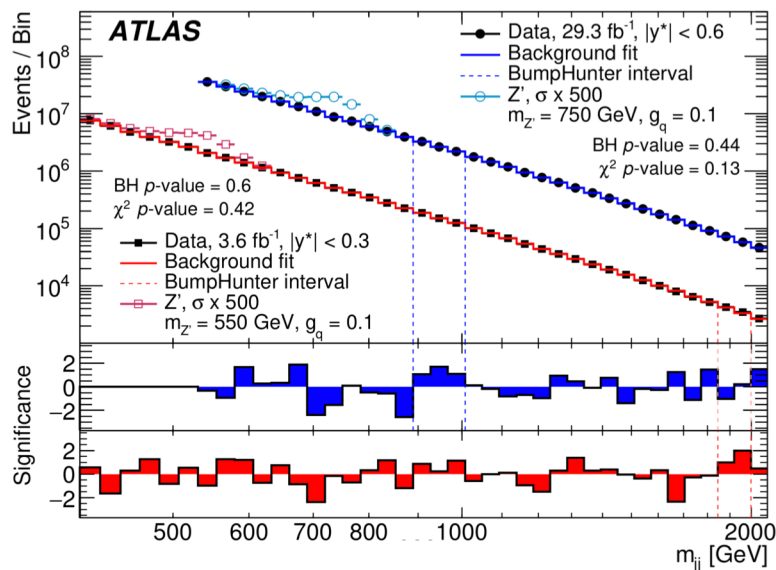


Sensitivity to low mass mediators is a challenge of data rate: *new techniques!*

PRD 96, 052004 (2017)

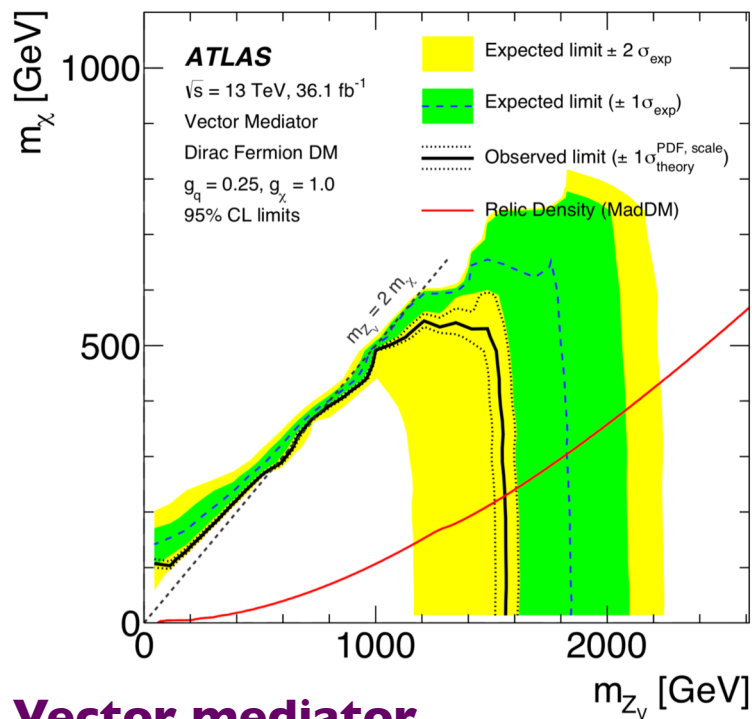
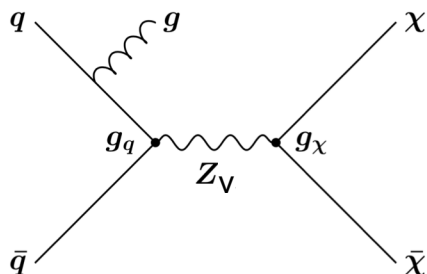


- Sensitivity to the coupling to quarks, g_q , improved by a factor of two
- Gaussian signals limited to cross-section times acceptance of:
6.5 pb at 450 GeV, to 0.4 pb at 700 GeV, to 0.05 pb at 1800 GeV.

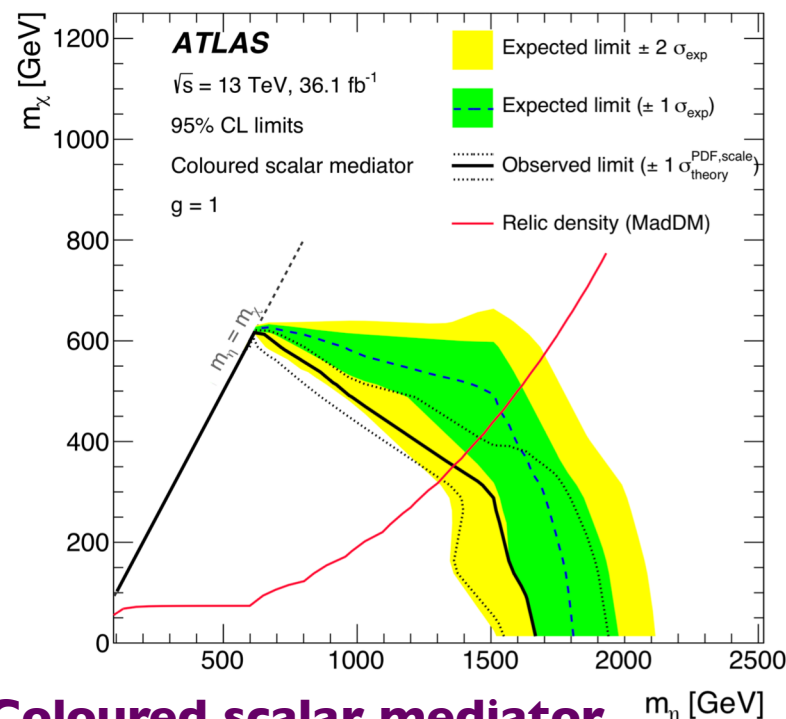
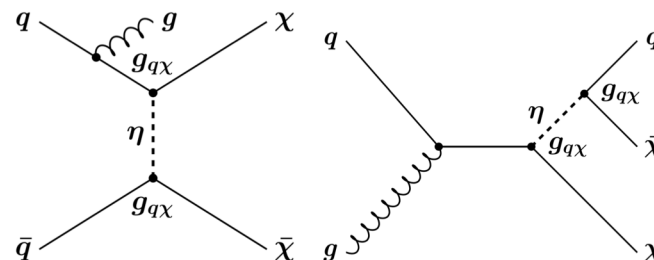


Monojet searches often most sensitive

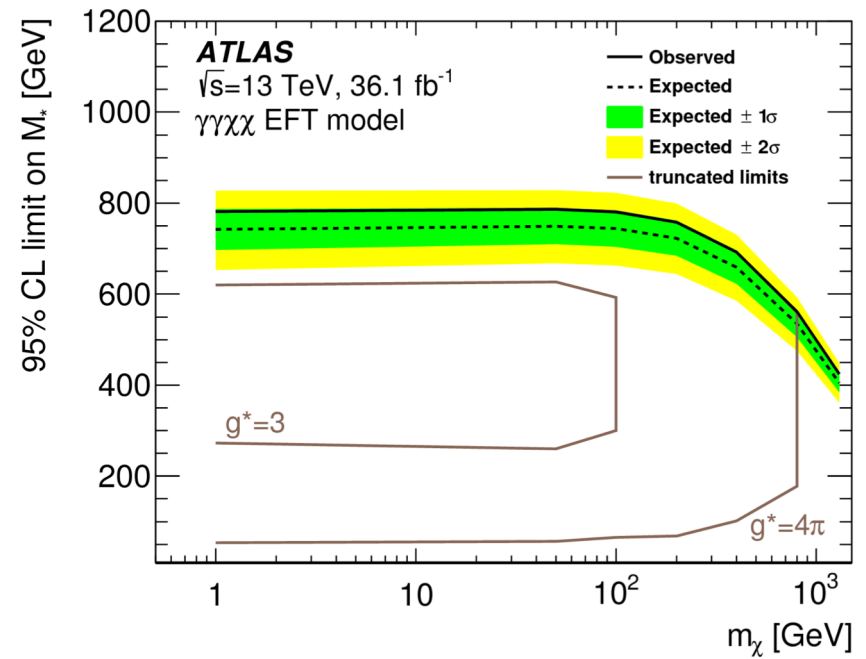
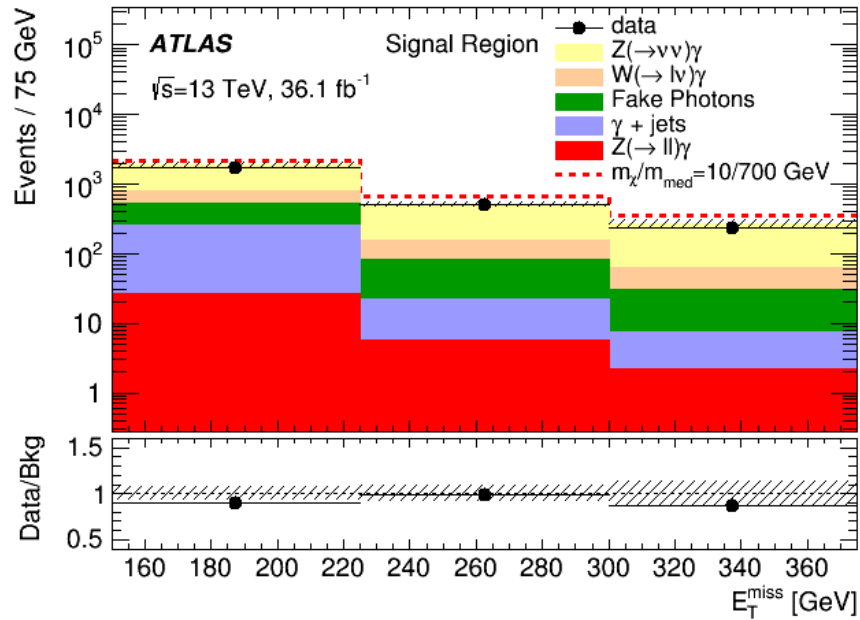
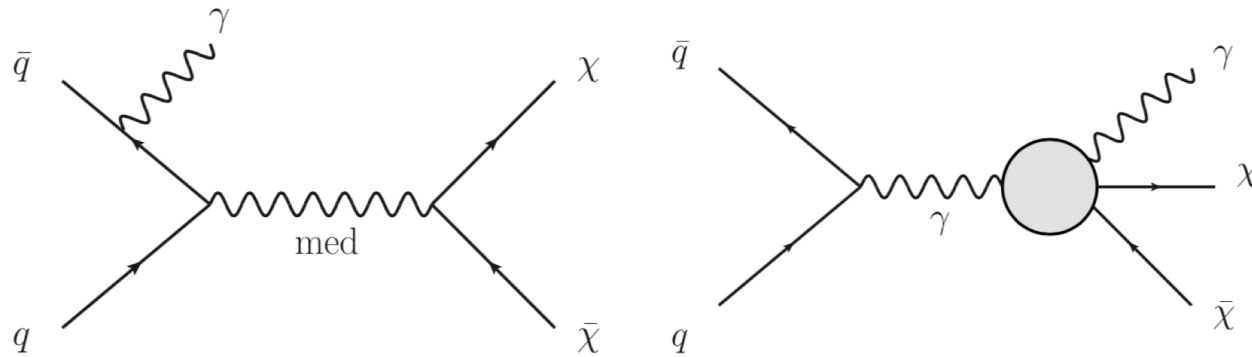
Very general, so can be recast in terms of various models

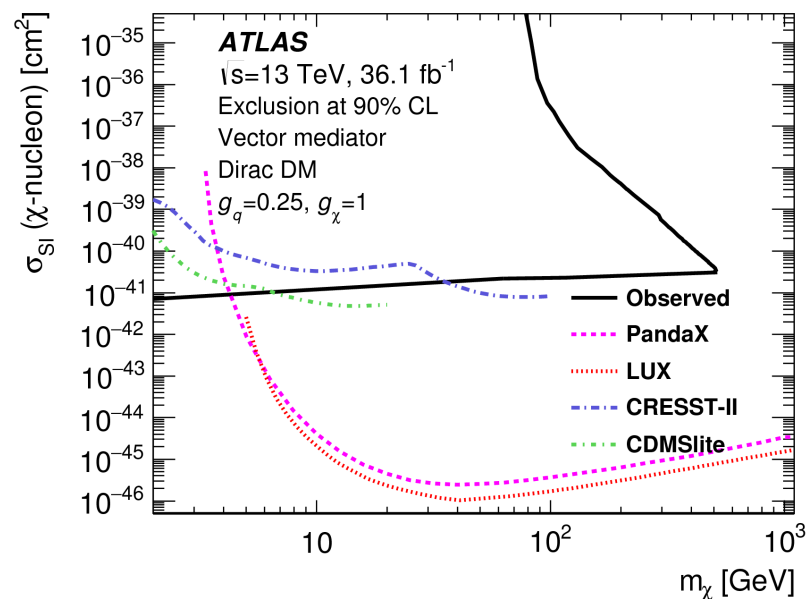
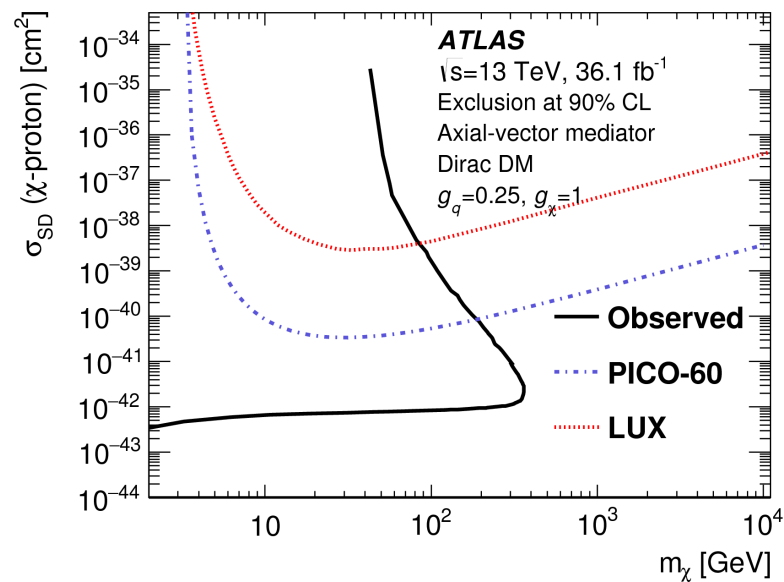
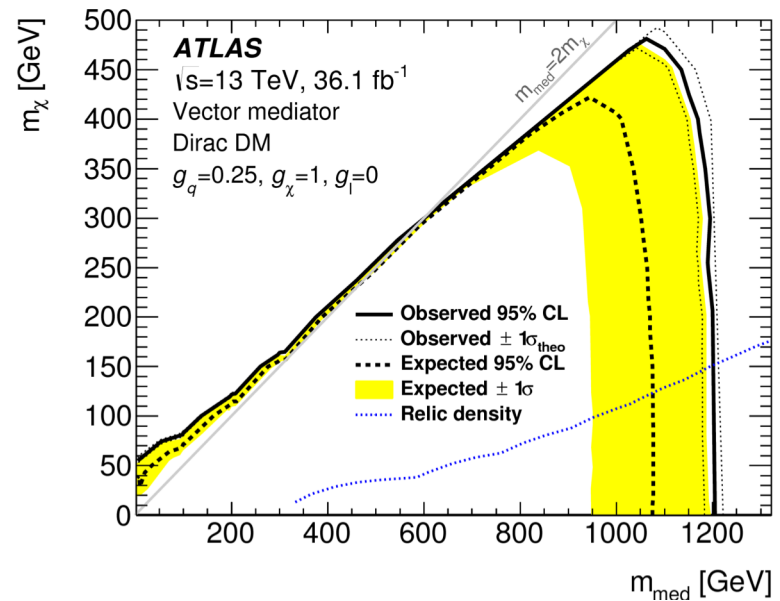
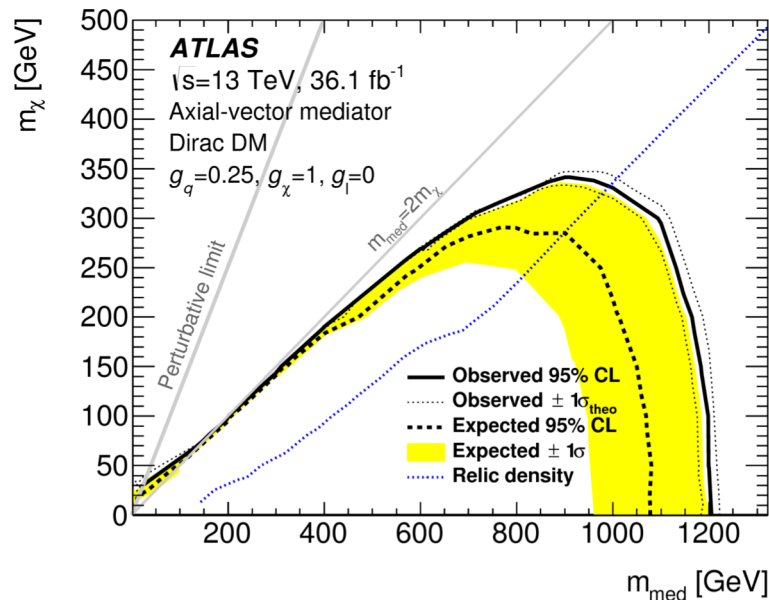


Vector mediator

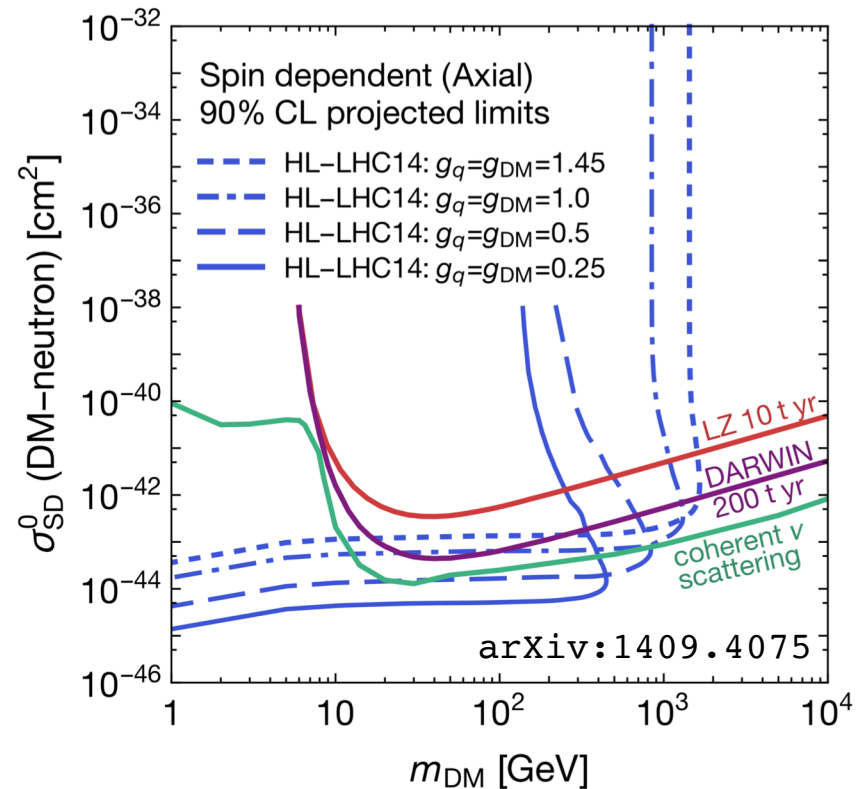
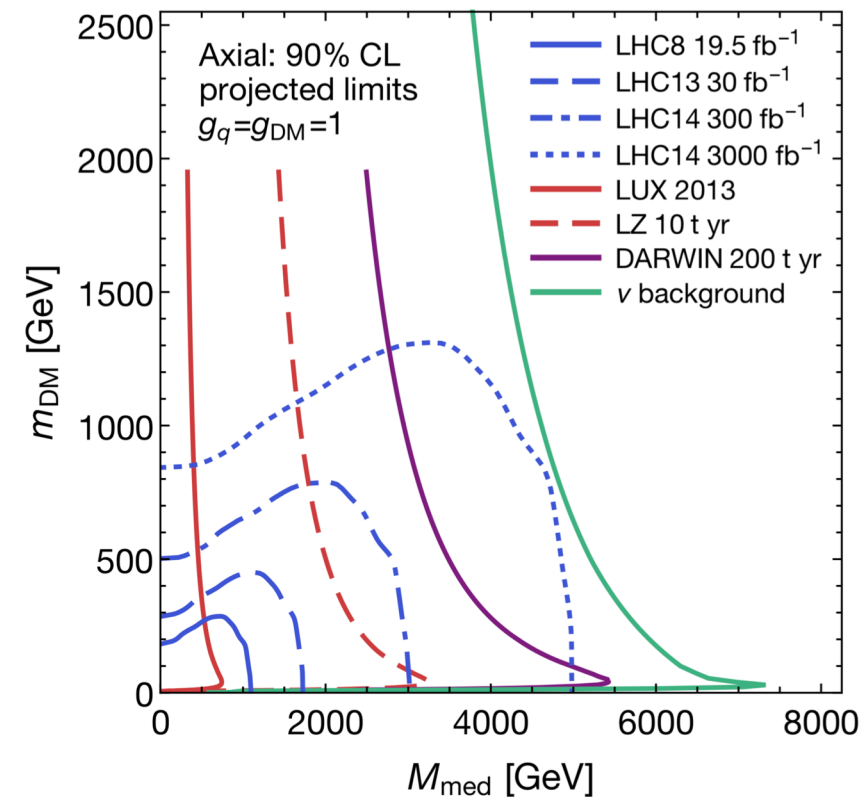


Coloured scalar mediator

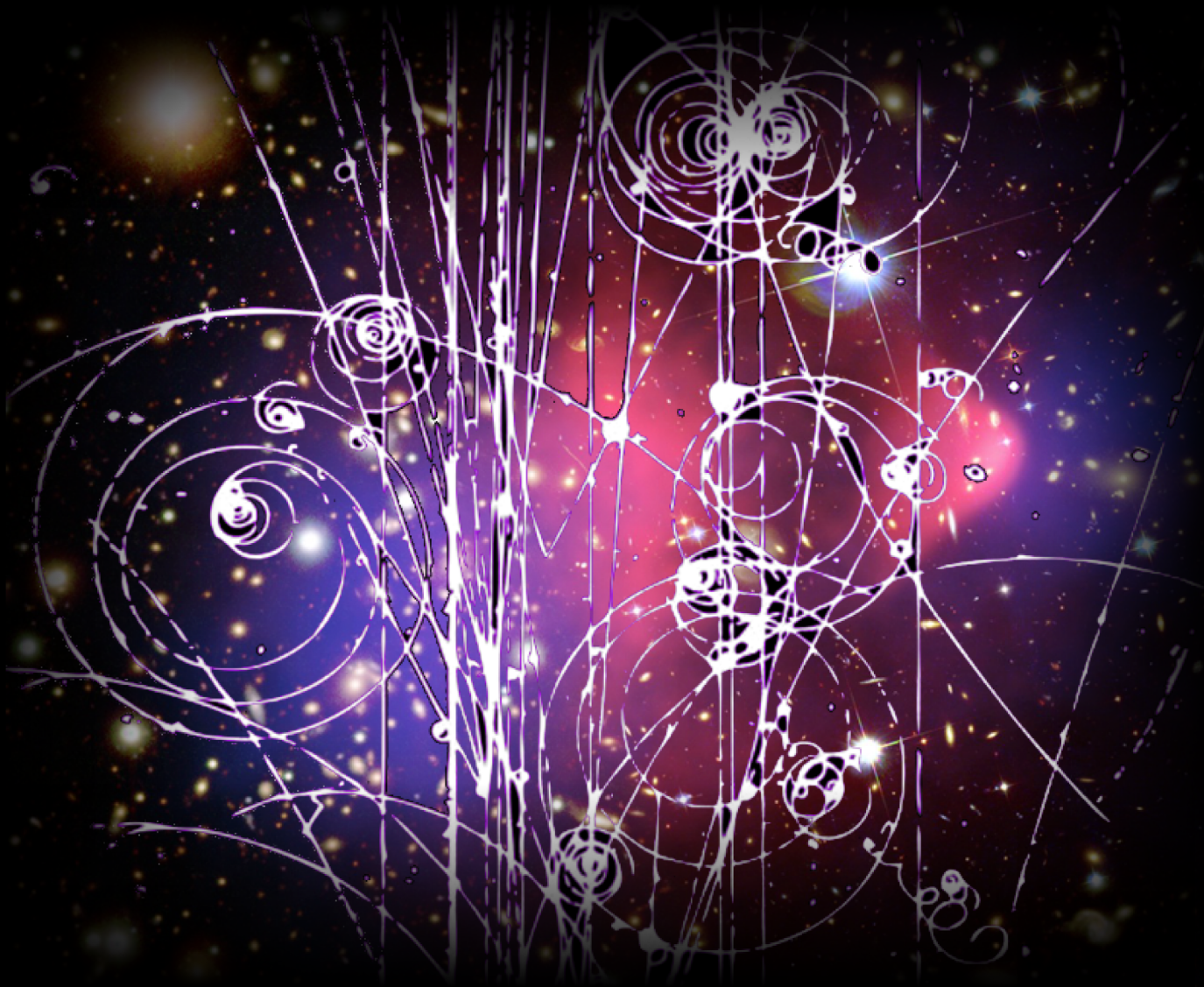




Excellent complementarity of direct and collider sensitivity as we move into the 2020s:



Detector-independent collider searches



Construct measurable quantity sensitive to dark matter that:

- Can be corrected for detector effects
- Has minimal model dependence

Benefit: if anomaly discovered, already measuring properties!

New observable:

Measure differential detector-corrected production cross-section ratio sensitive to new phenomena producing anomalous MET+jets rate:

$$R_{\text{miss}} = \frac{\sigma(\cancel{p}_T + \text{jets})}{\sigma(Z \rightarrow \ell^+ \ell^- + \text{jets})}$$

Detector-corrected observable R_{miss} :

(measure differentially versus event kinematics)

$$R_{\text{miss}} = \frac{\sigma(\cancel{p}_T + \text{jets})}{\sigma(Z(\rightarrow \ell^+ \ell^-) + \text{jets})} = \frac{1}{C_Z} \frac{N(\cancel{p}_T + \text{jets})}{N(Z(\rightarrow \ell^+ \ell^-) + \text{jets})}$$

Number of background-subtracted events in MET+jets signal region

Correction factor accounting for detector resolution and efficiency

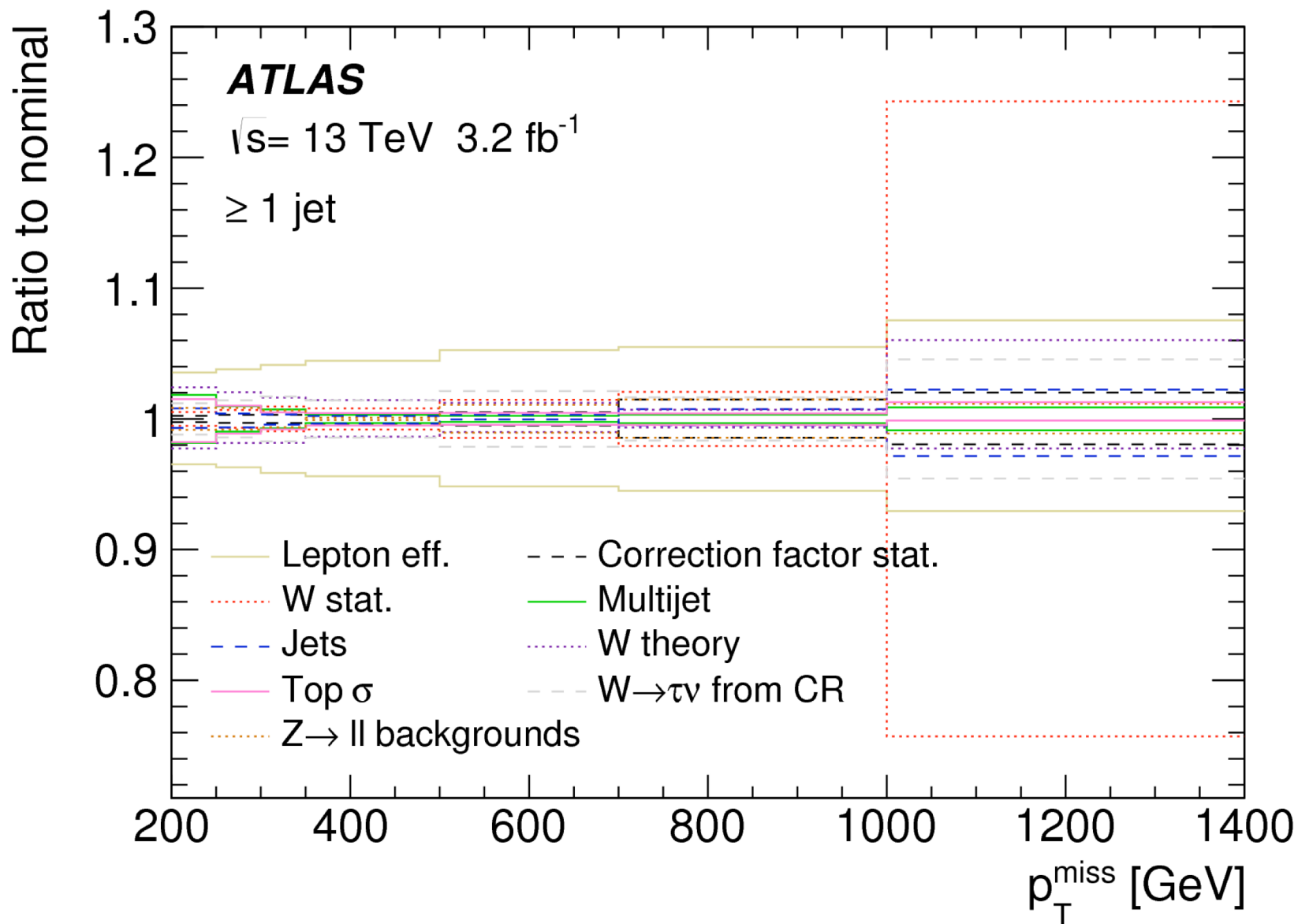
Number of background-subtracted events in $\ell^+ \ell^-$ + jets signal region

Detector-corrected observable R_{miss} :

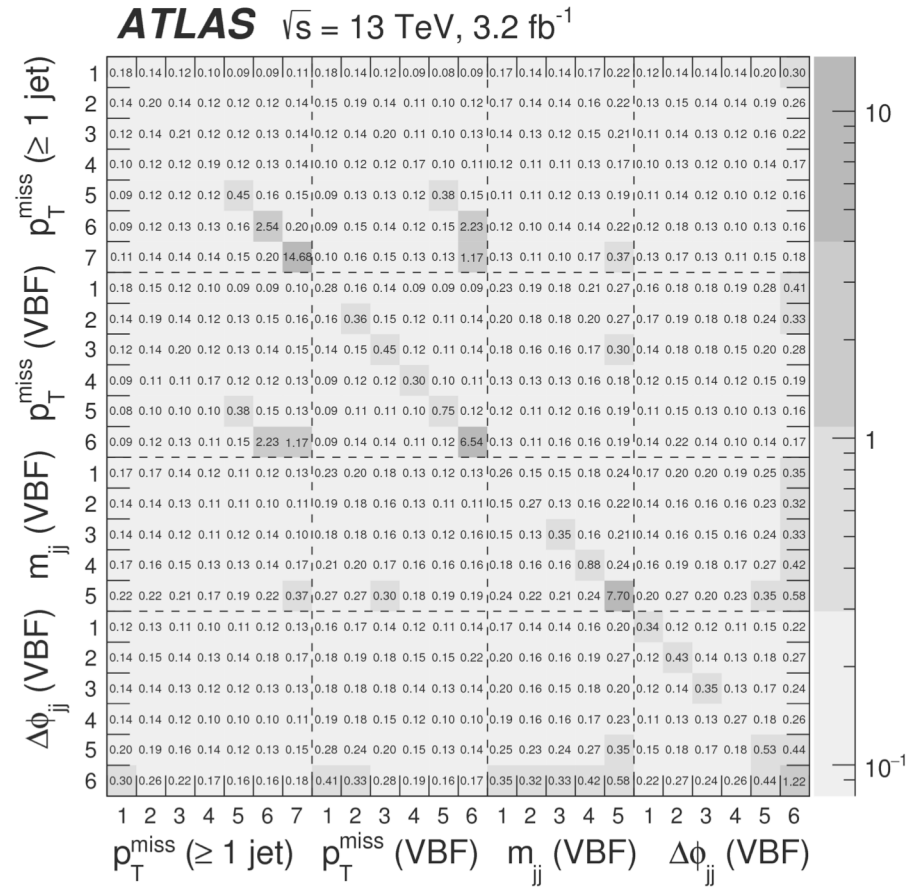
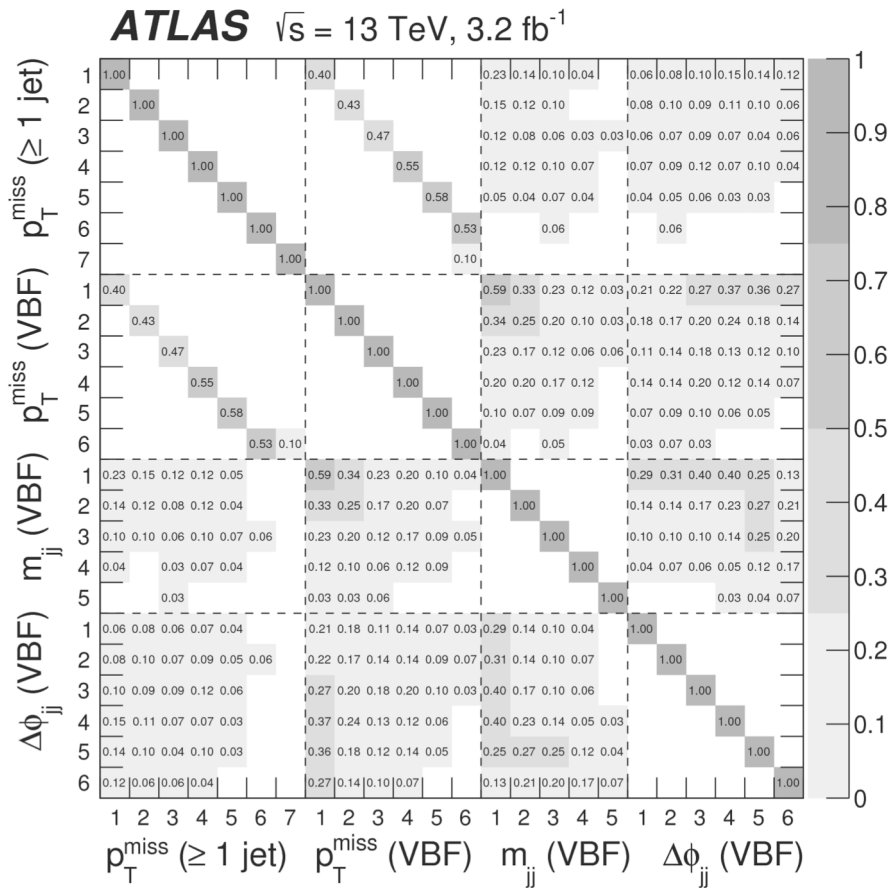
(measure differentially versus event kinematics)

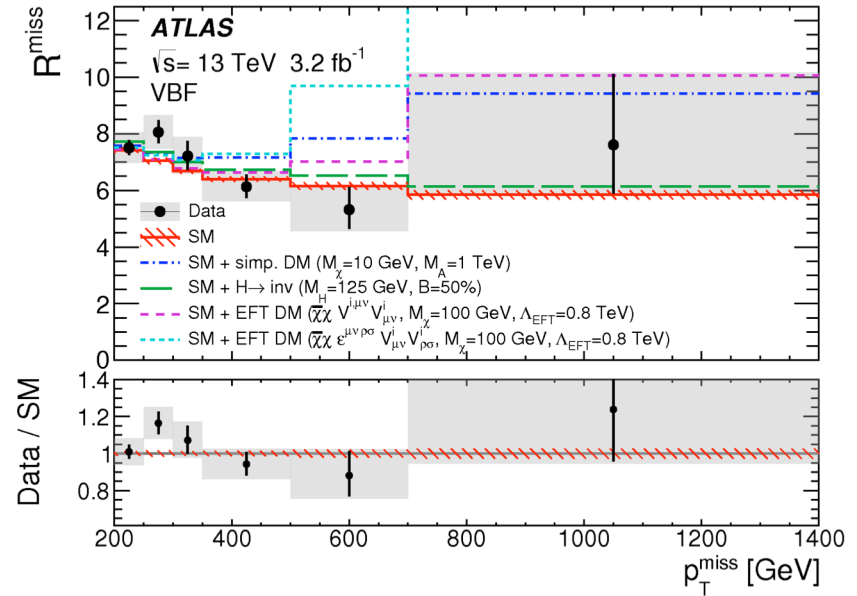
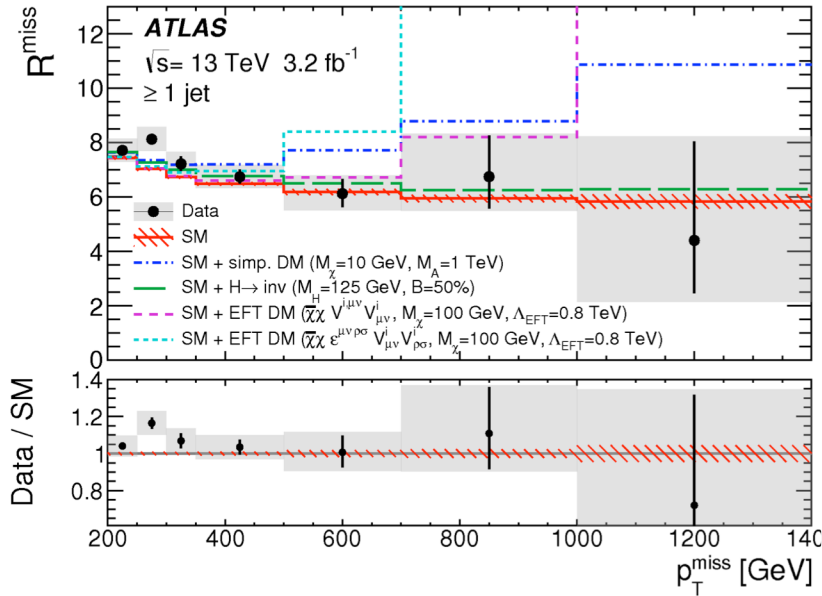
$$R_{\text{miss}} = \frac{\sigma(\cancel{p}_T + \text{jets})}{\sigma(Z(\rightarrow \ell^+ \ell^-) + \text{jets})} = \frac{\sigma(Z(\rightarrow \nu \bar{\nu}) + \text{jets}) + \sigma(\text{BSM})}{\sigma(Z(\rightarrow \ell^+ \ell^-) + \text{jets})}$$

In Standard Model, only contributions to numerator come from $Z \rightarrow \nu \bar{\nu}$ decays

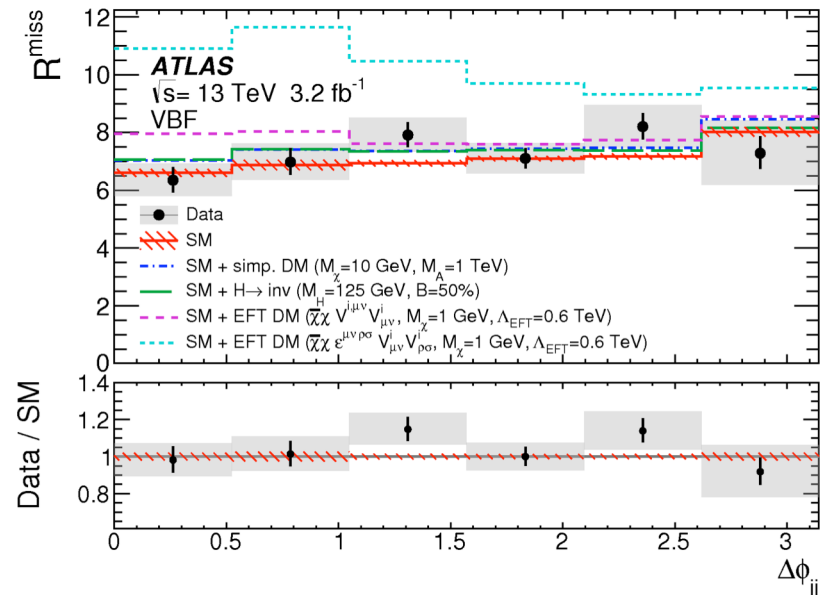
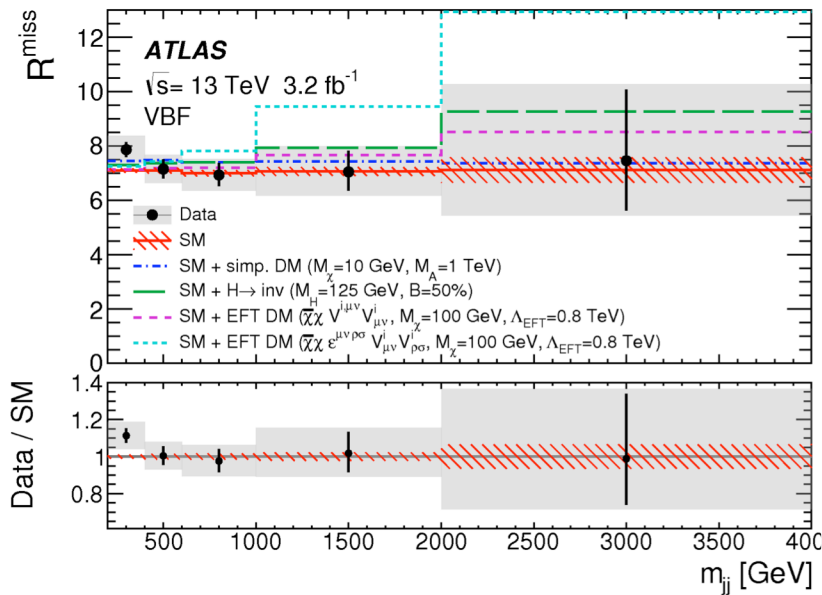


Determine statistical and systematic covariance between bins and between distributions by bootstrapping data





p-value compatibility of the data and the SM across all four distributions is 78%



Alongside paper ([arXiv:1707.03263](https://arxiv.org/abs/1707.03263)) released supporting material:

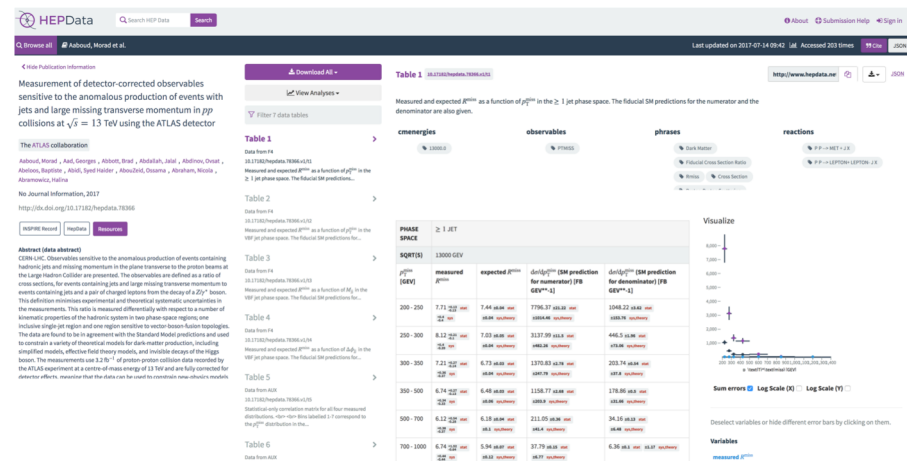
Rivet analysis code:

https://rivet.hepforge.org/analyses/ATLAS_2017_I1609448.html

HEPDATA record: <https://hepdata.net/record/ins1609448>

Containing:

- Measured R_{miss} ,
- SM R_{miss} ,
- SM numerator and denominator,
- Covariance matrices



Everything necessary to perform reinterpretation of this data in terms of any BSM prediction resulting in jets plus missing transverse energy!

Use detector-corrected data to probe three benchmark dark matter models using publicly-released resources:

- *Dark matter coupling to quarks*
- *Dark matter coupling to EW bosons*
- *Dark matter coupling to Higgs bosons*

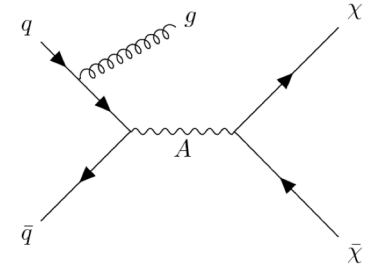
Approach:

Construct χ^2 compatibility between model under test and data across all bins of all corrected distributions simultaneously:

$$\chi^2 = \sum_{i,j}^n (x_i - t_i)(C^{-1})_{ij}(x_j - t_j)$$

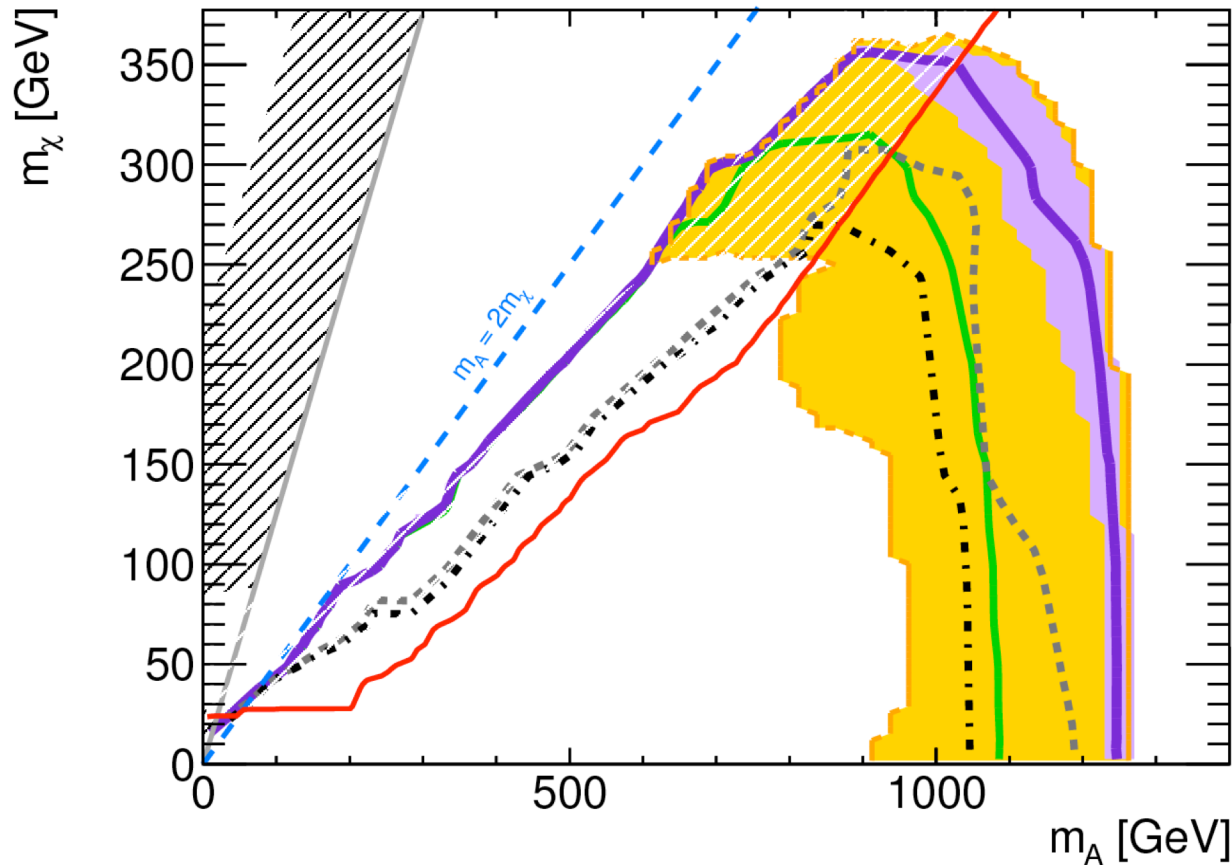
The CLs technique evaluated using the asymptotic approximation is used to derive 95% CL limits.

Exclusion contours (at 95 % CL) in the WIMP–mediator mass plane for a simplified model with an axial-vector mediator



ATLAS

$\sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1}$



Axial-vector mediator

Dirac fermion DM

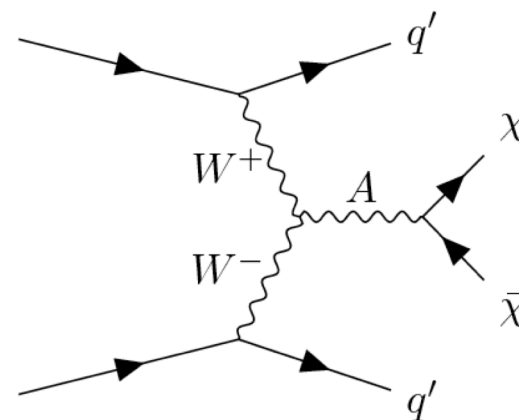
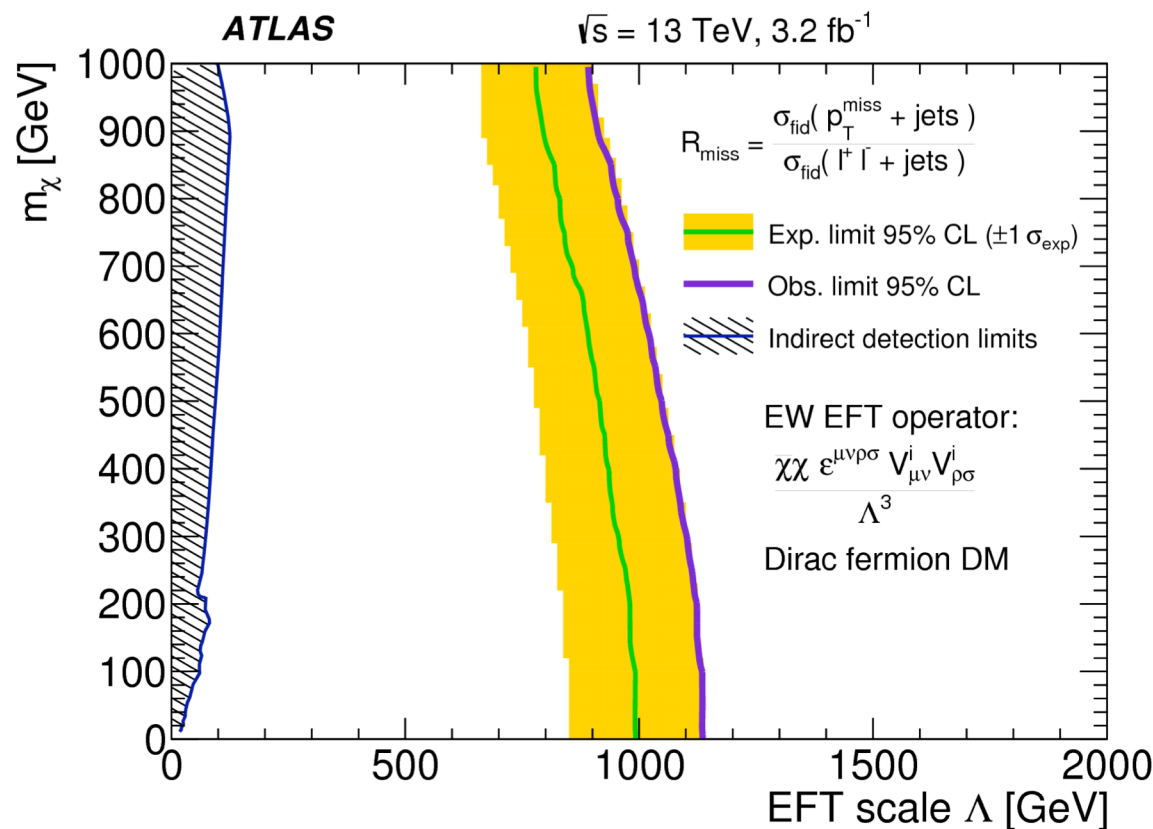
$g_q = 0.25, g_\chi = 1$

$$R_{\text{miss}} = \frac{\sigma_{\text{fid}}(p_T^{\text{miss}} + \text{jets})}{\sigma_{\text{fid}}(l^+ l^- + \text{jets})}$$

- Exp. limit 95% CL ($\pm 1 \sigma_{\text{exp}}$)
- Obs. limit 95% CL ($\pm 1 \sigma_{\text{theory}}^{\text{PDF, scale}}$)
- Perturbativity limit
- Relic density
- Exp. PRD94 (2016) 032005
- Obs. PRD94 (2016) 032005

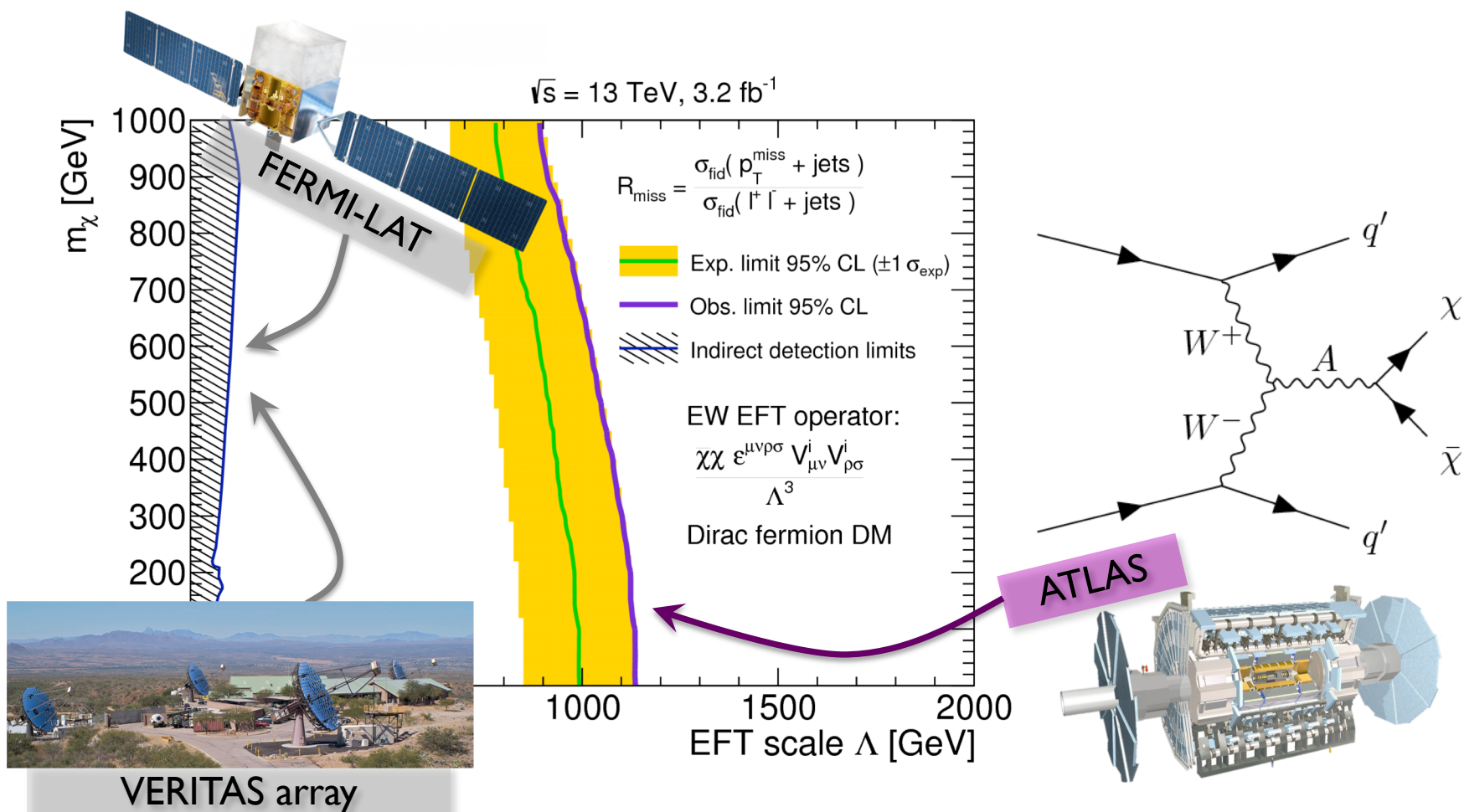
New approach competitive with standard collider searches!

Exclusion contours (at 95 % CL) for Dirac-fermion dark matter produced via a contact interaction with two electroweak bosons with a dimension-seven EFT operator.



Most stringent constraints to-date on such interactions!

Exclusion contours (at 95 % CL) for Dirac-fermion dark matter produced via a contact interaction with two electroweak bosons with a dimension-seven EFT operator.



Most stringent constraints to-date on such interactions!