# Dark Matter Searches with the ATLAS Detector

Othmane Rifki
On Behalf of the ATLAS Collaboration

*EPS 2019 - Ghent*

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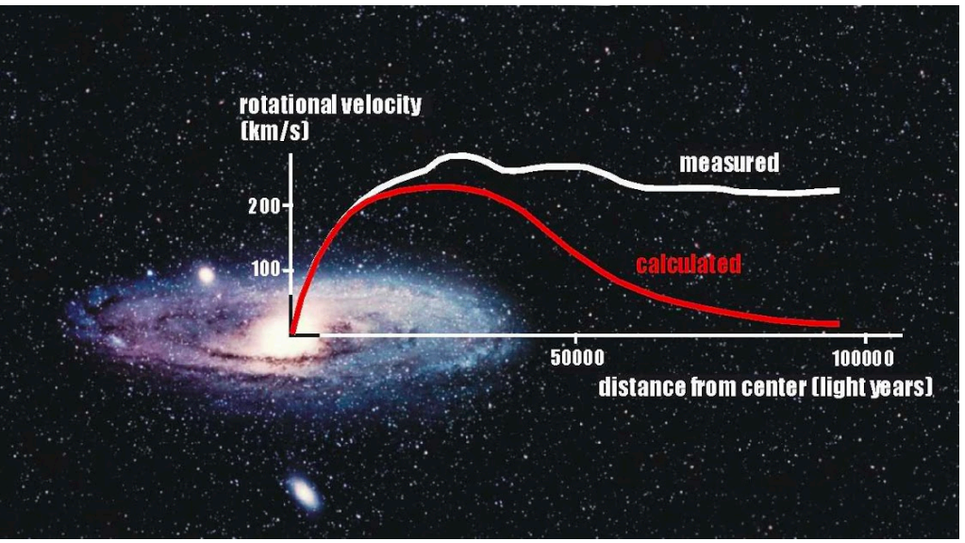
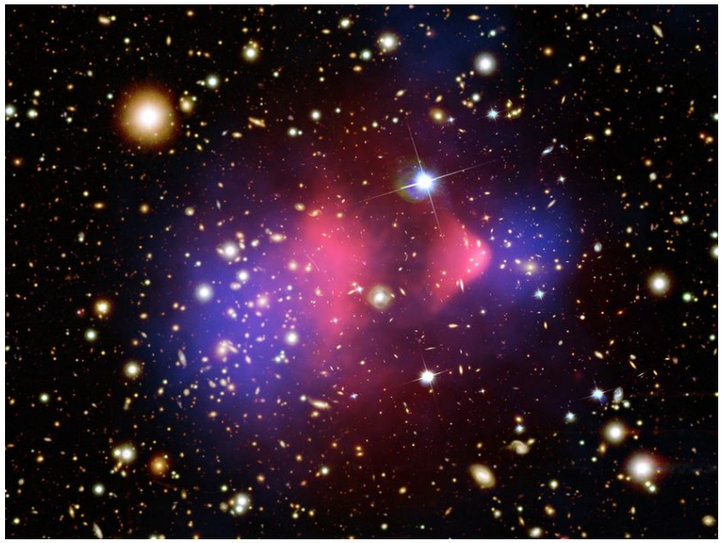
# Why Dark Matter?

Cosmological data suggests presence of **dark matter** (**DM, $\chi$**)

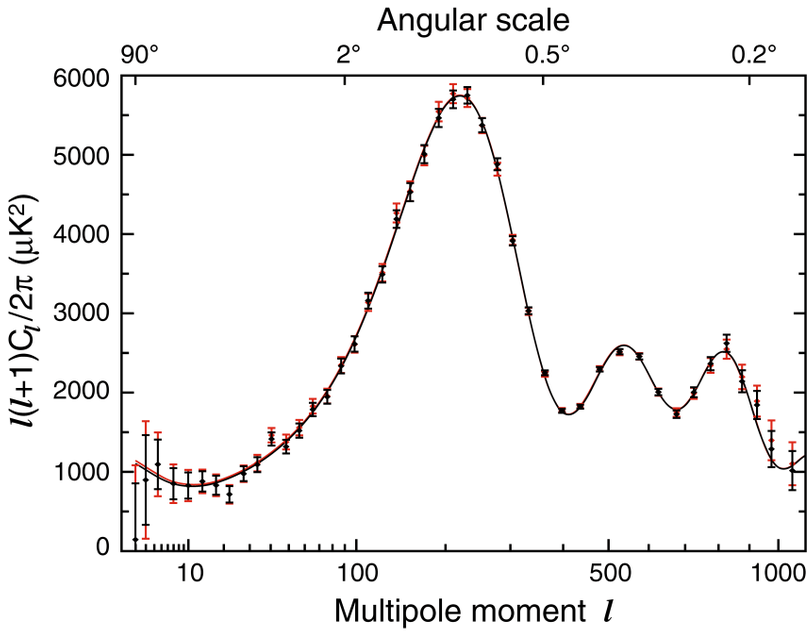
**Galactic rotation**




**Weak lensing**

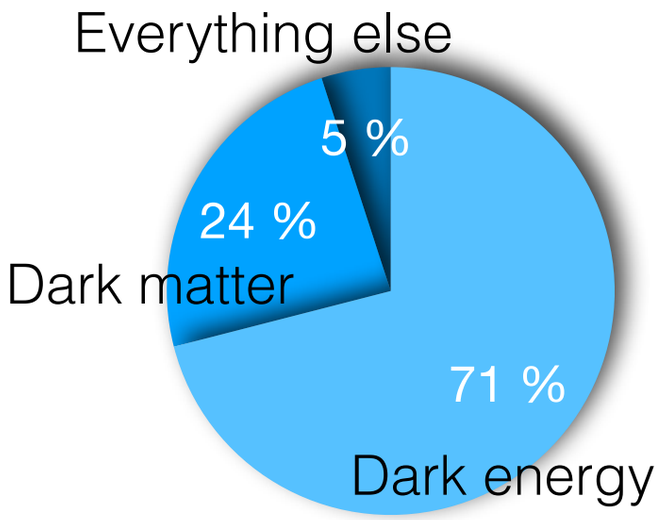


**CMB**



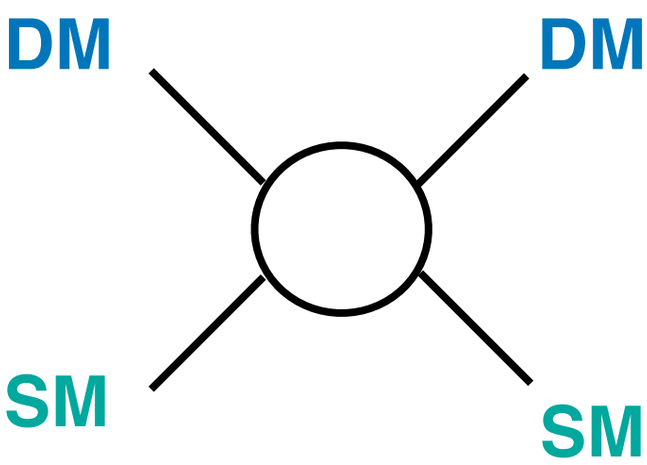

**Expect to produce DM at the LHC for DM mass below ~TeV**

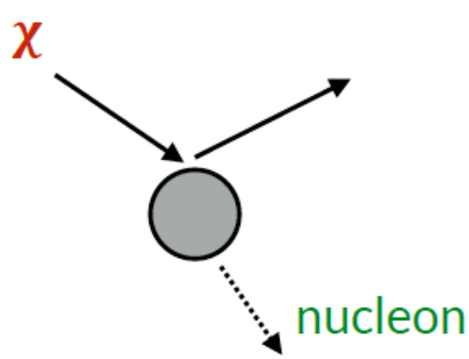
- Several extensions but will focus on weakly interacting particles (WIMP)
- Complements other methods at low DM masses



# How to detect DM?

## Direct Detection

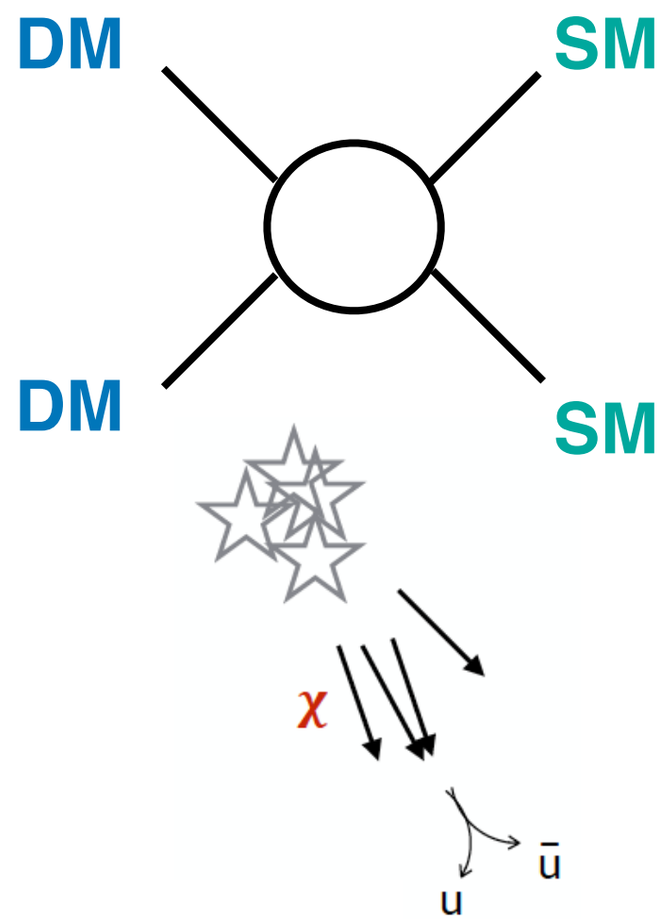



*Elastic scattering on detector nuclei in the lab*

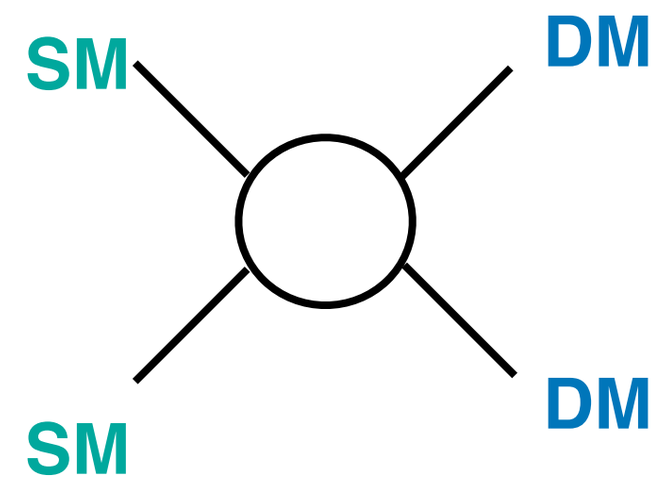
$\chi + N \rightarrow \chi + N$

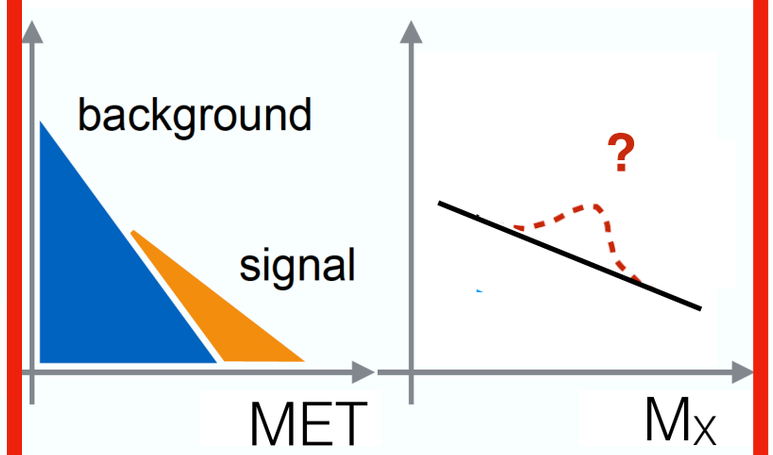
## Indirect Detection




*Annihilation products from gamma-rays and anti-matter (i.e. galactic center)*

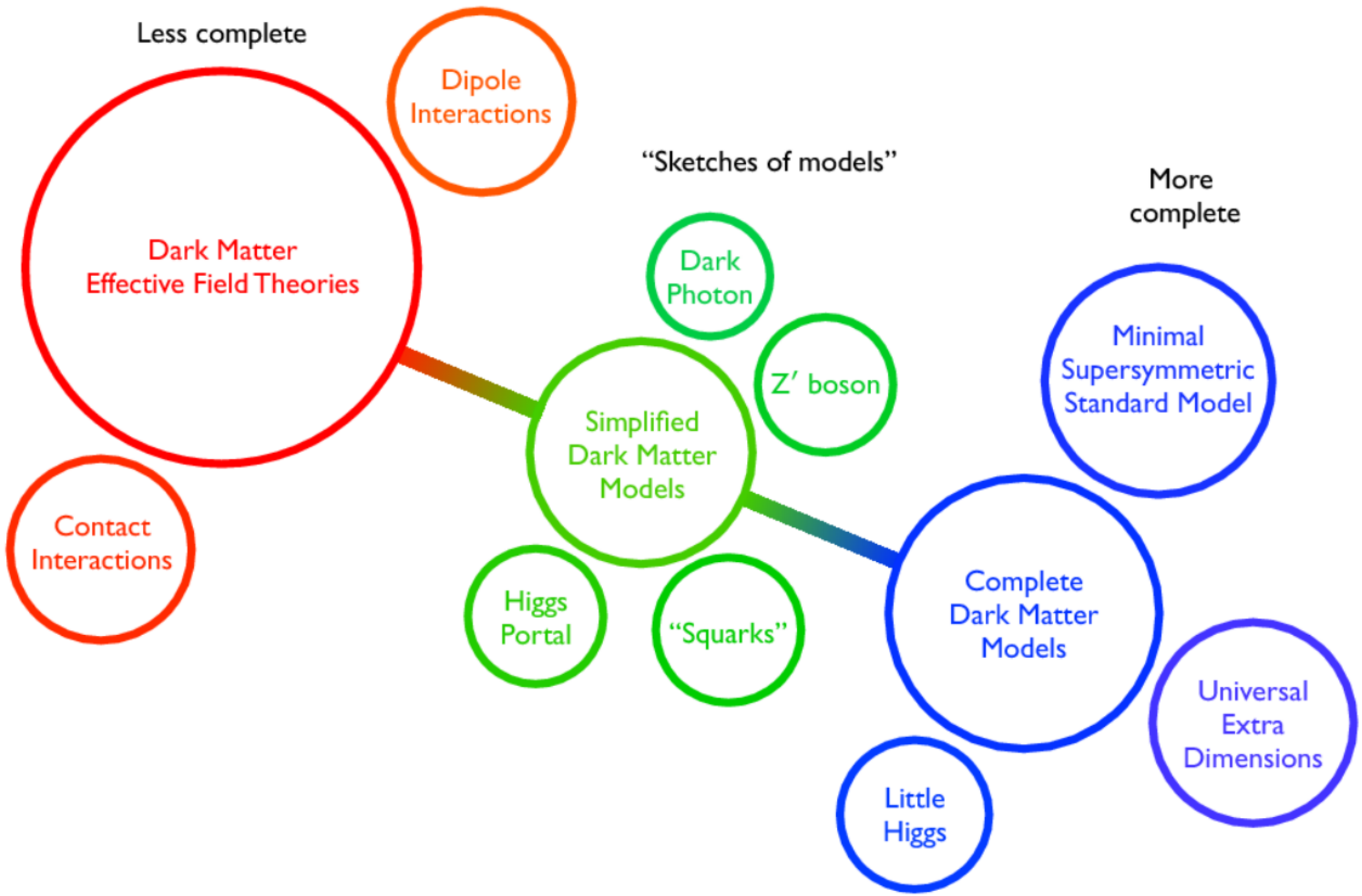
## Colliders




**Topic of this talk**

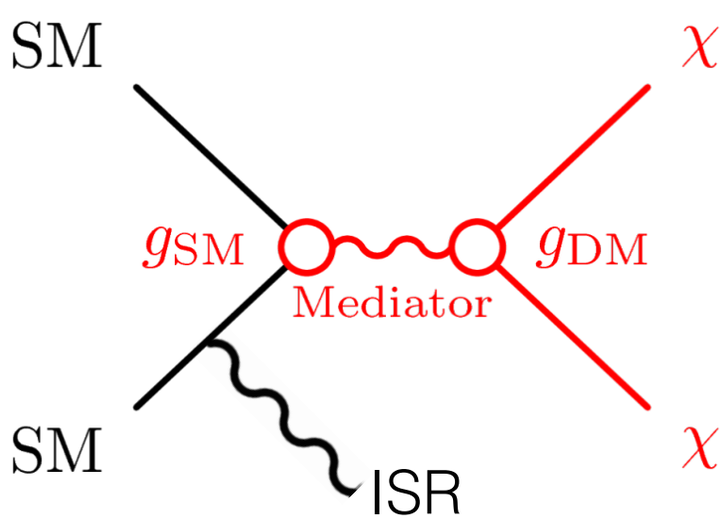
# Models for DM



# Simplified Models

## X + MET

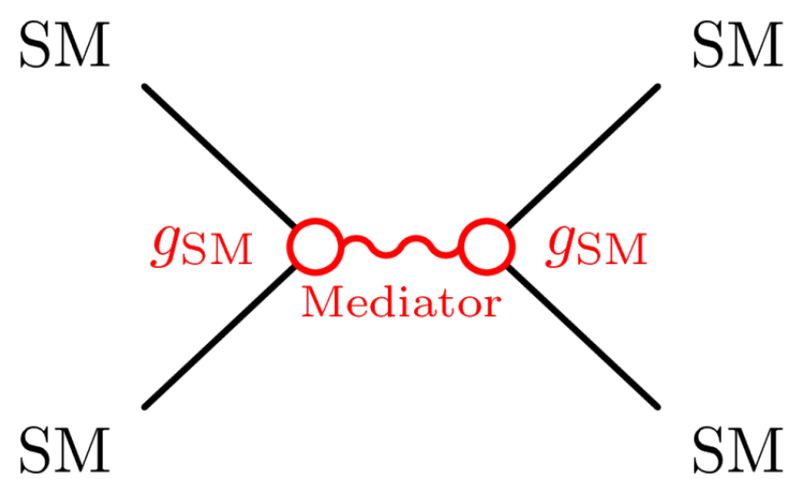
"Direct" searches
using ISR or associated production




Look for **deviation** from standard model background

## Resonances

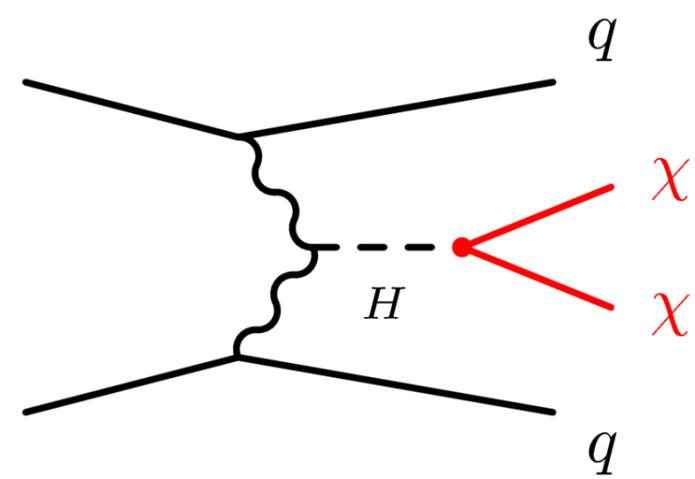
Mediator searches
bump hunt for mediator decays to fermions




Look for mass **peak** above background continuum

## Higgs as mediator

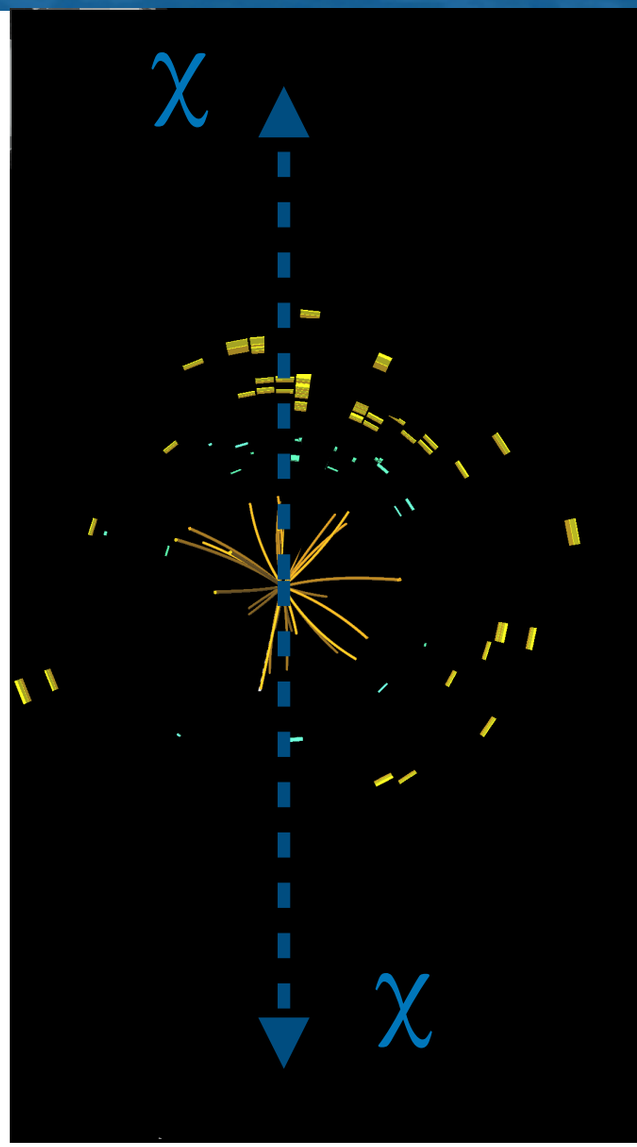
*Higgs to invisible*
0.1% branching ratio in SM




Look for **enhancement** of higgs decay to invisible

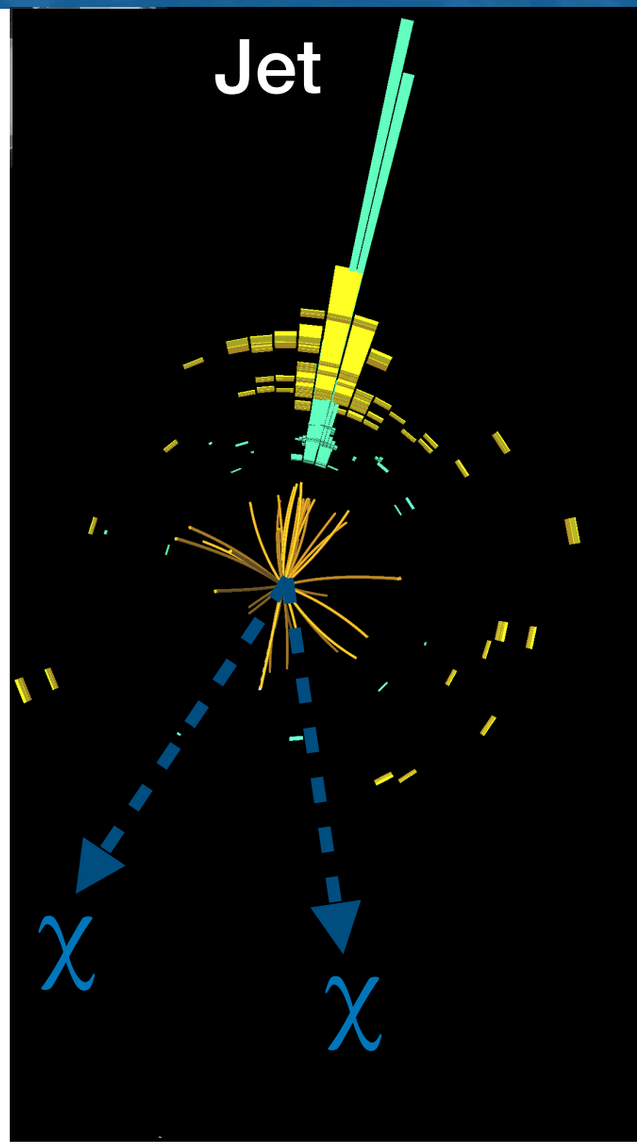
# X+MET searches

Invisible final state requires additional particles from **initial state radiation** or **associated production**



# X+MET searches

Invisible final state requires additional particles from **initial state radiation** or **associated production**

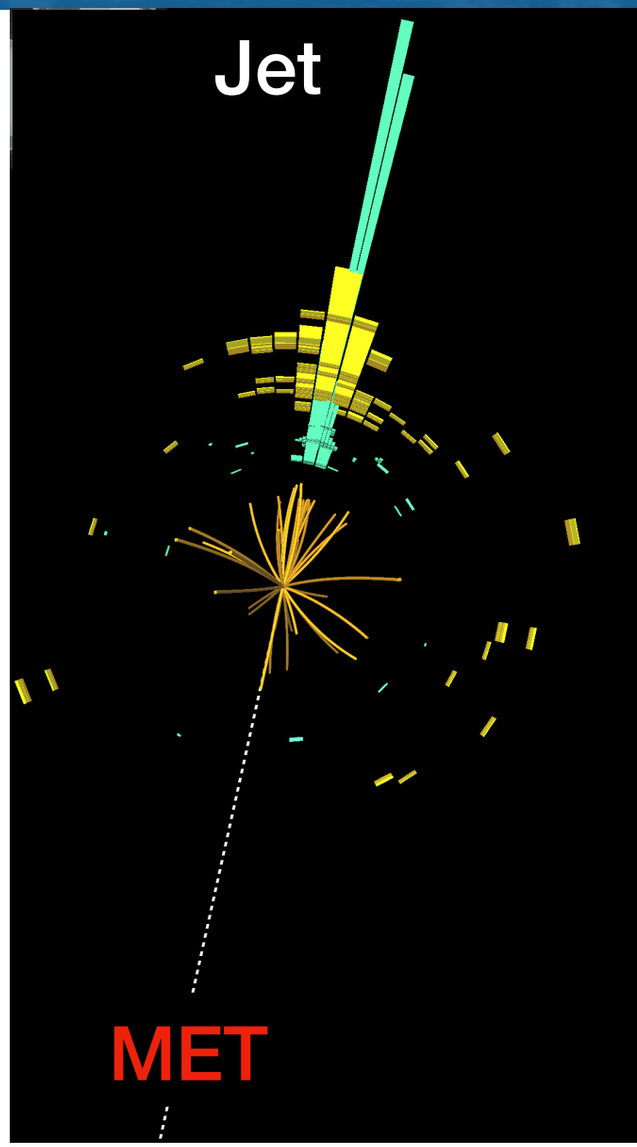



# X+MET searches

Invisible final state requires additional particles from **initial state radiation** or **associated production**

RECOIL

**Invisible DM becomes visible as $E_T^{miss}$**



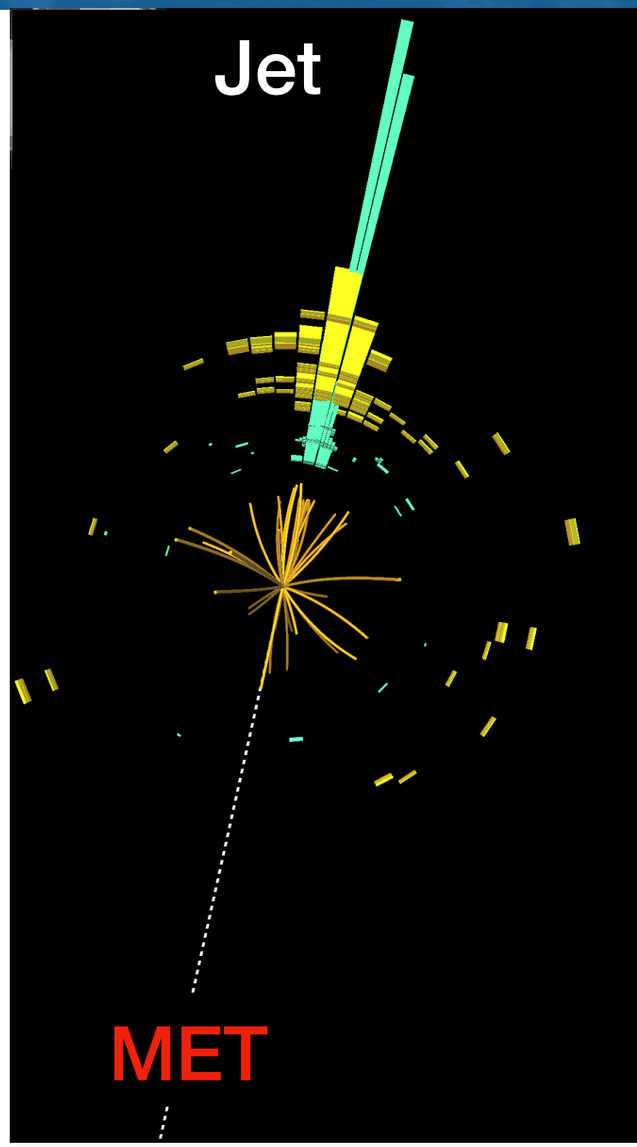
# X+MET searches

Invisible final state requires additional particles from **initial state radiation** or **associated production**

RECOIL

**Invisible DM becomes visible as $E_T^{miss}$**

- **Jet** + $E_T^{miss}$ (36 fb$^{-1}$): JHEP 01 (2018) 126 ★
- **Photon** + $E_T^{miss}$ (36 fb$^{-1}$): EPJC 77 (2017) 393
- **Z(ll)** + $E_T^{miss}$ (36 fb$^{-1}$): PLB 776 (2017) 318
- **V(qq)** + $E_T^{miss}$ (36 fb$^{-1}$): JHEP 10 (2018) 180
- **h(bb)** + $E_T^{miss}$ (80 fb$^{-1}$): ATLAS-CONF-2018-039 ★
- **h(γγ)** + $E_T^{miss}$ (36 fb$^{-1}$): PRD-96 (2017) 112004
- **top** + $E_T^{miss}$ (36 fb$^{-1}$): JHEP 05 (2019) 41
- **tt/bb** + $E_T^{miss}$ (36 fb$^{-1}$): EurPhys (2018) 78:18
- **tt** + $E_T^{miss}$ (36 fb$^{-1}$): JHEP 06 (2018) 108

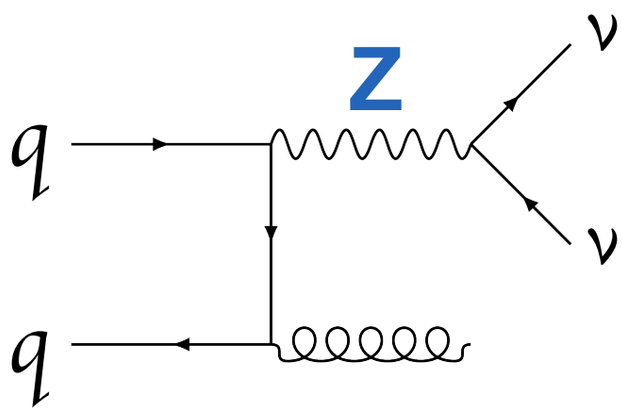


# Jet + $E_T^{miss}$

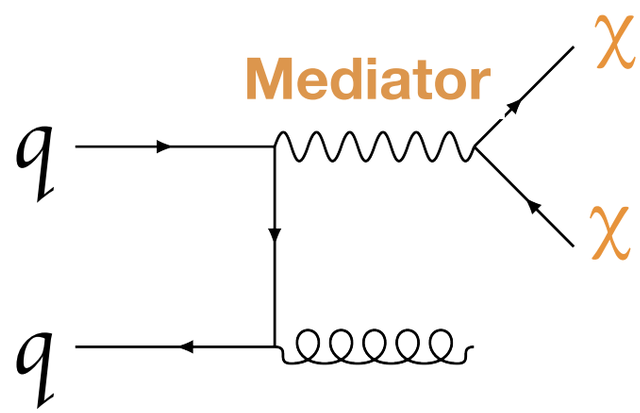
JHEP 01 (2018) 126

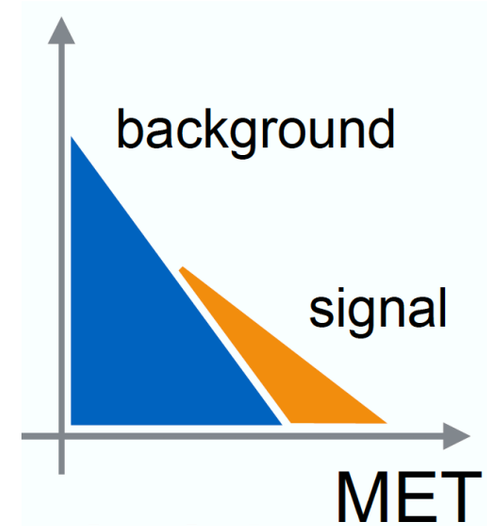
- **Initial State Radiation**: Jet required to boost the invisible system
- $E_T^{miss}$ > 250 GeV + jet pT > 250 GeV + up to 3 extra jets

**Background**




**Signal**

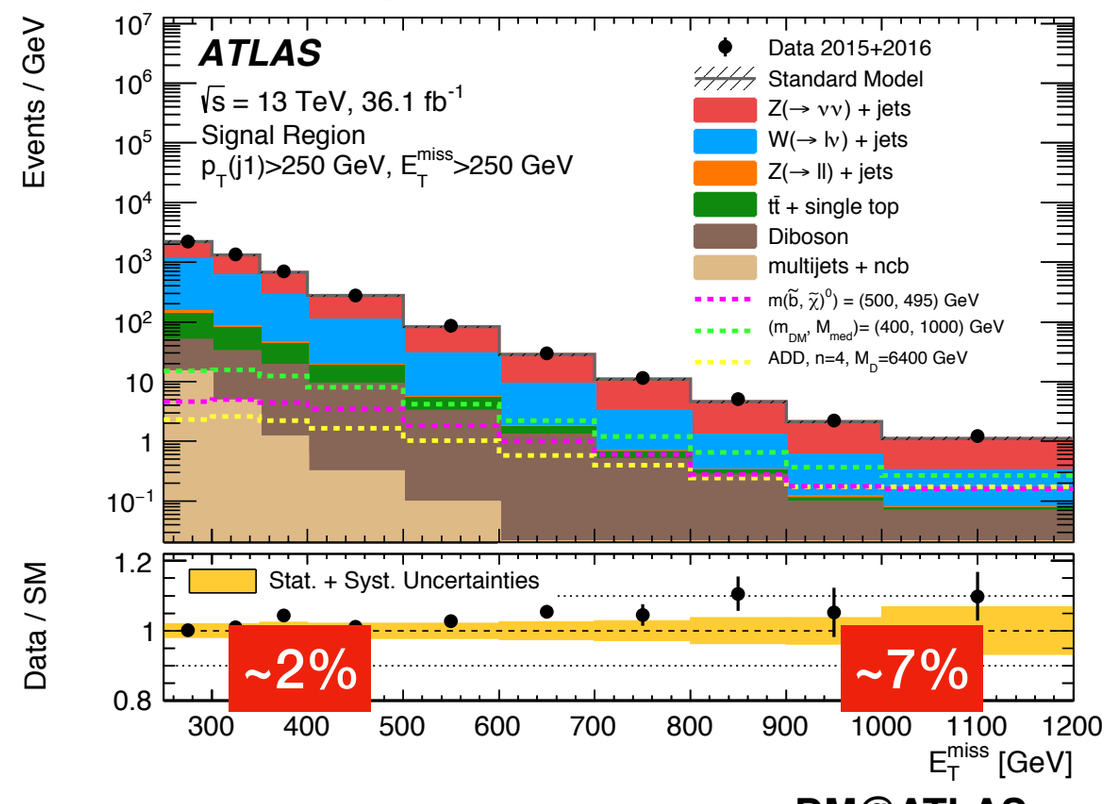



**Measure standard model background precisely!**

- Constrain W and Z backgrounds using lepton control regions
- High precision theoretical predictions of W/Z $p_T$ distributions

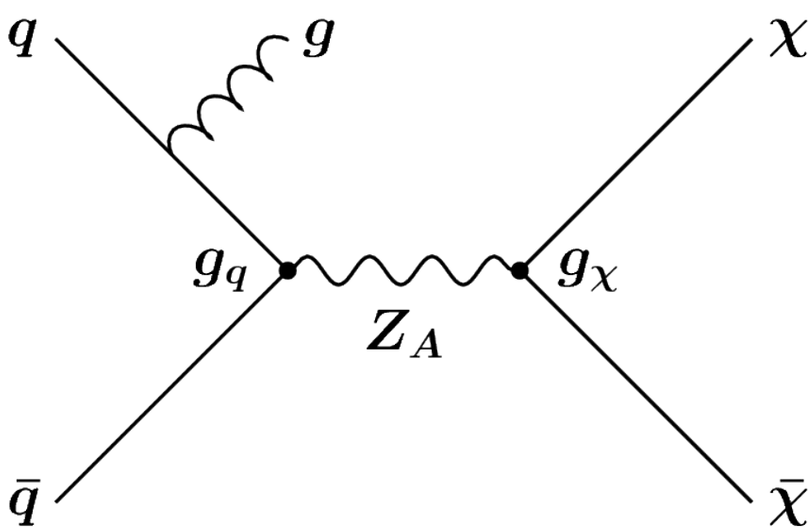
NNLO($\alpha_S$)+NNLL($\alpha_S$), NLO($\alpha_{EW}$)

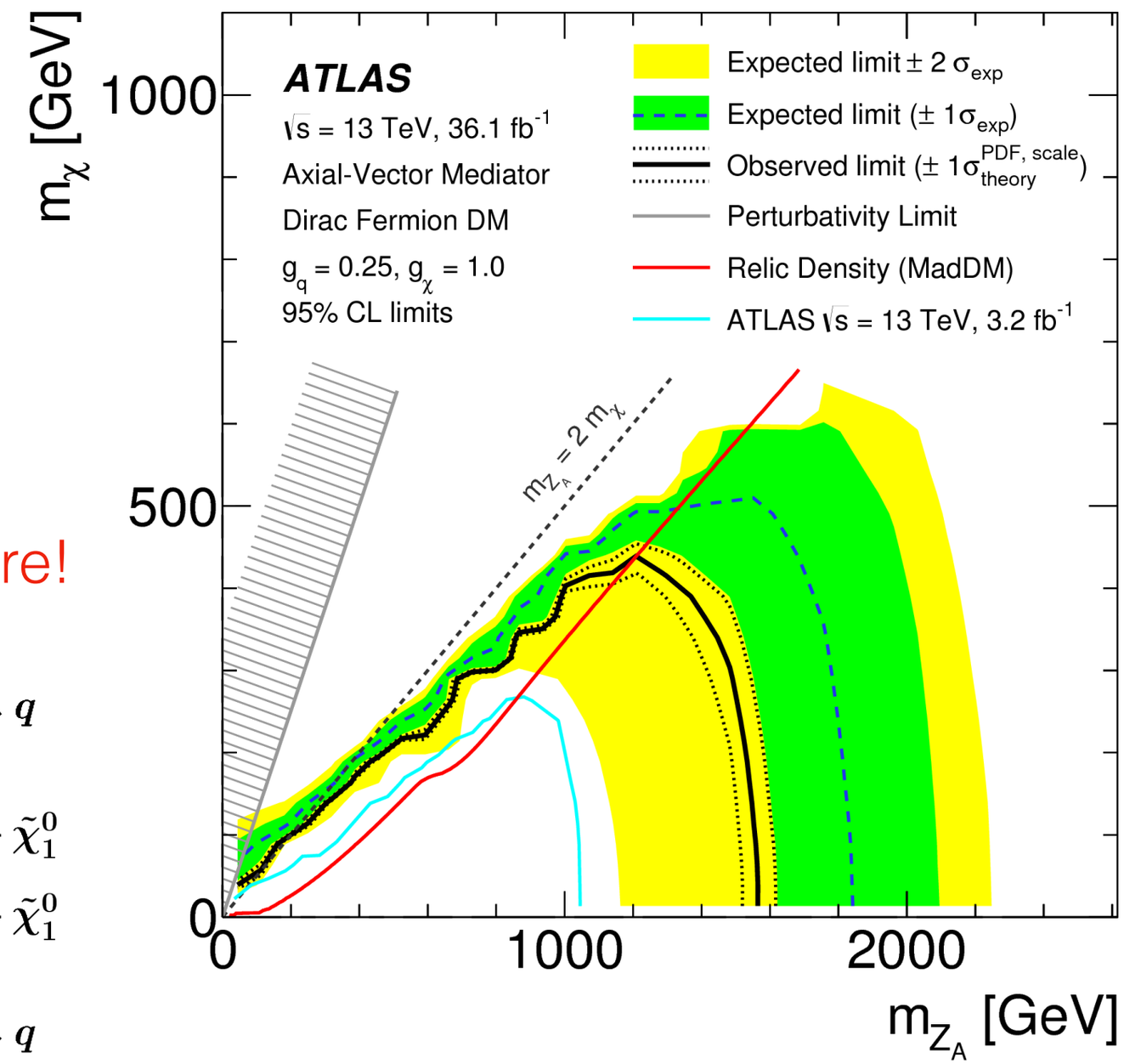


# Jet + $E_T^{miss}$

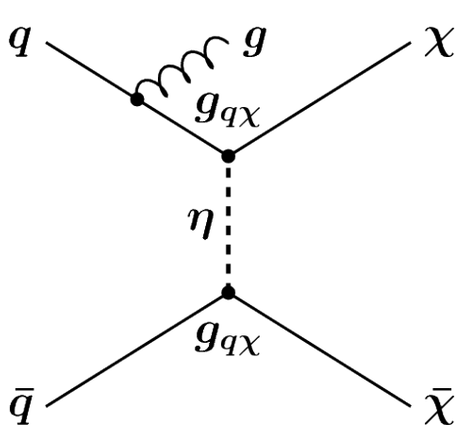
JHEP 01 (2018) 126

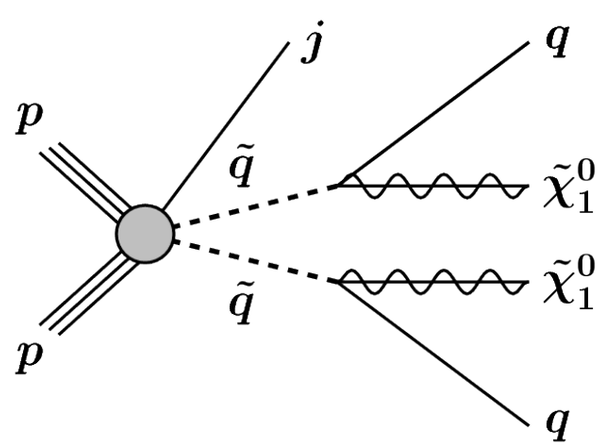
- Example interpretation in DM production via an axial-vector mediator



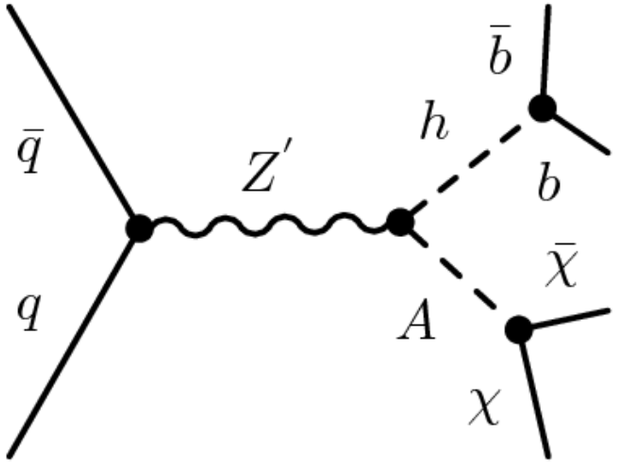

Many models produce this signature!



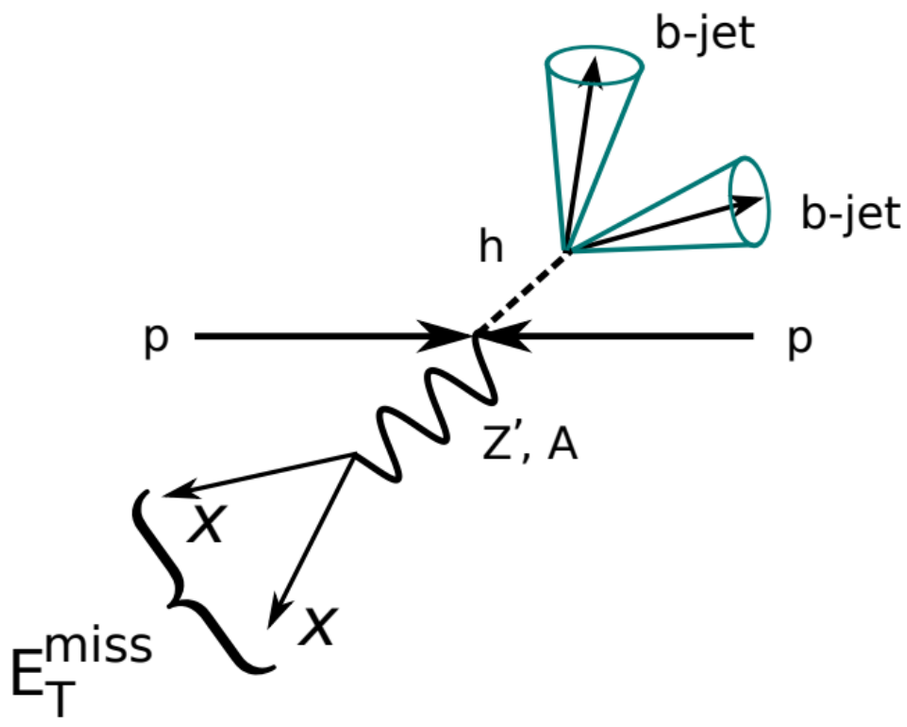



# h(bb) + $E_T^{miss}$ ATLAS-CONF-2018-039

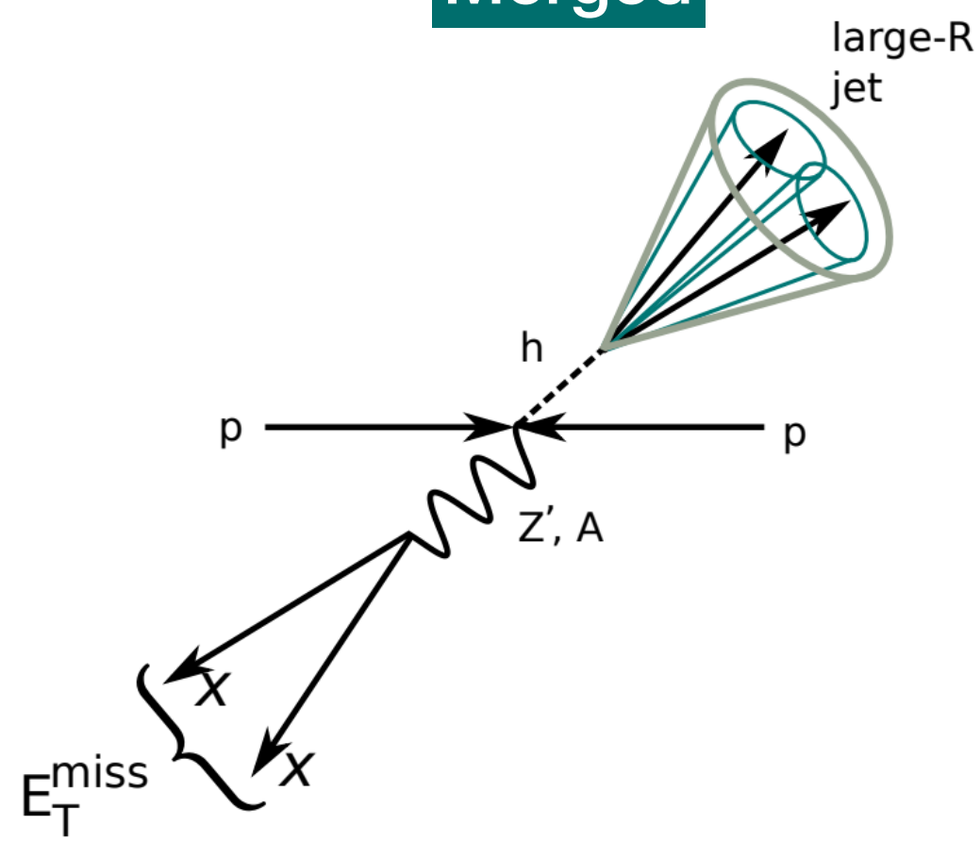
- **Associated production** of DM and a Higgs
- H(bb) has the largest branching ratio
- $E_T^{miss}$ > 150 GeV, leptons vetoed in SR
- 2 topologies depending on Higgs $p_T$




**Resolved**

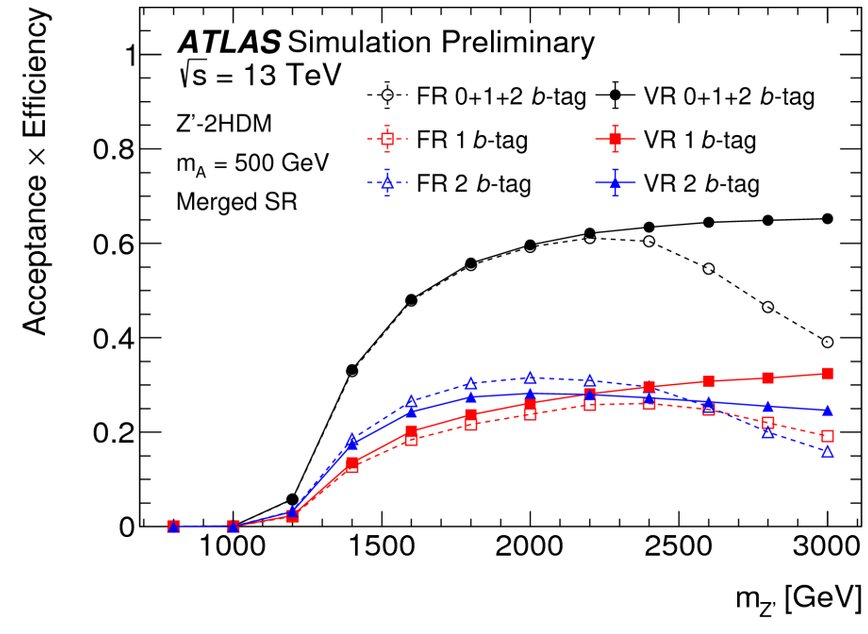


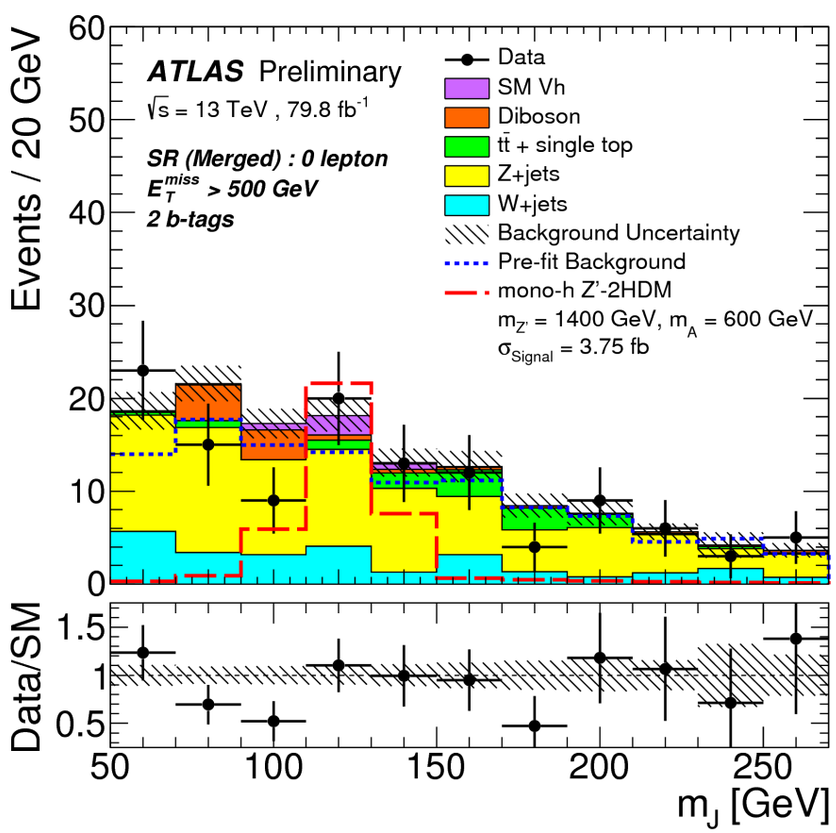

**Merged**

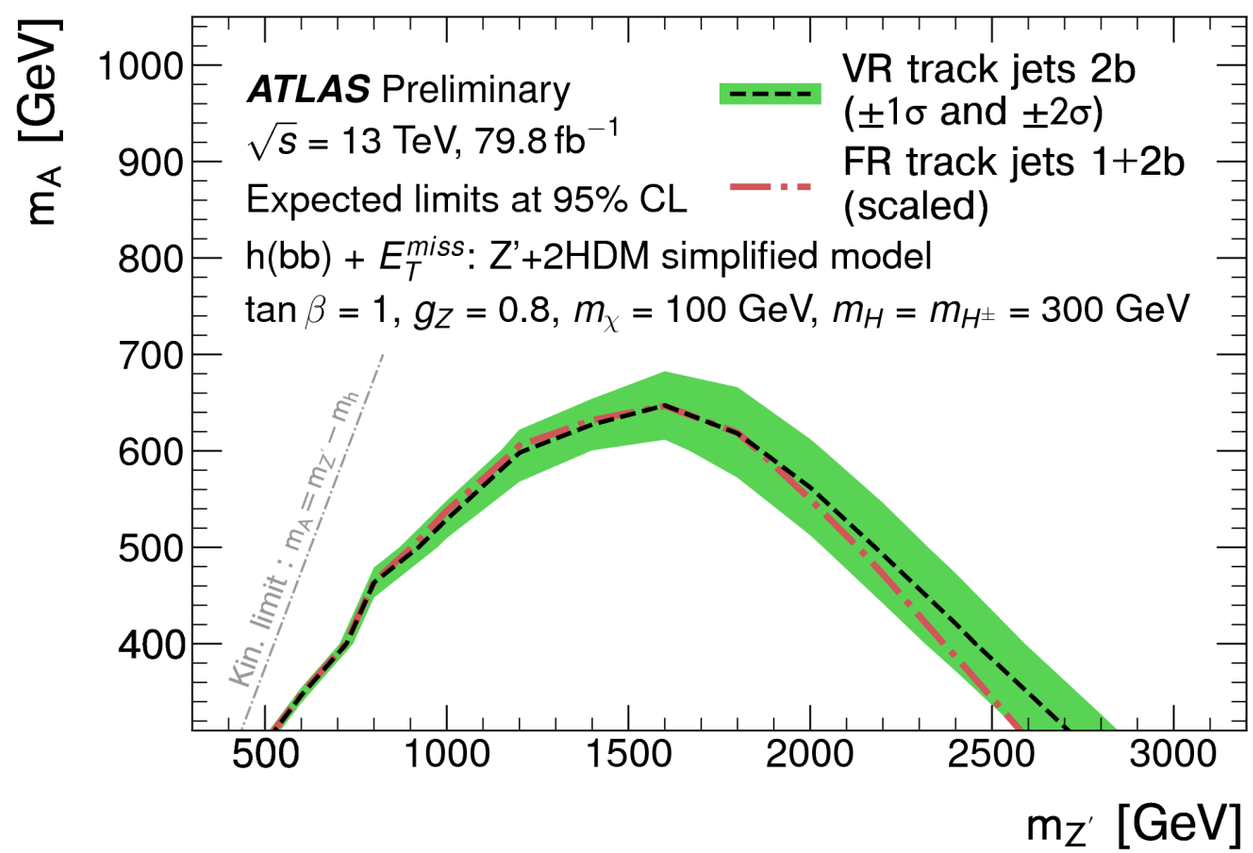


# h(bb) + $E_T^{miss}$ ATLAS-CONF-2018-039

- Use Variable-Radius (VR) track jets since Fixed-Radius (FR) track jets merge at large $p^h$
- Discriminating variables: dijet or large-R jet mass and $E_T^{miss}$
- Interpretation in terms of mass limits on new mediators

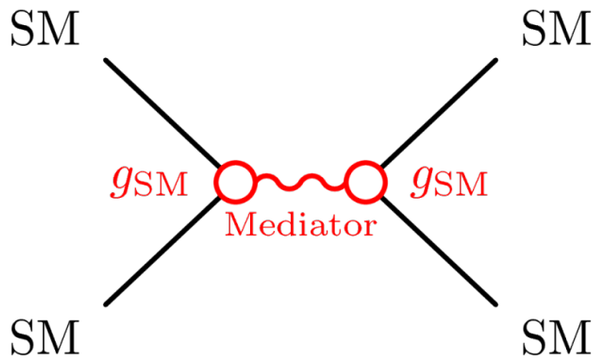


# Resonance searches

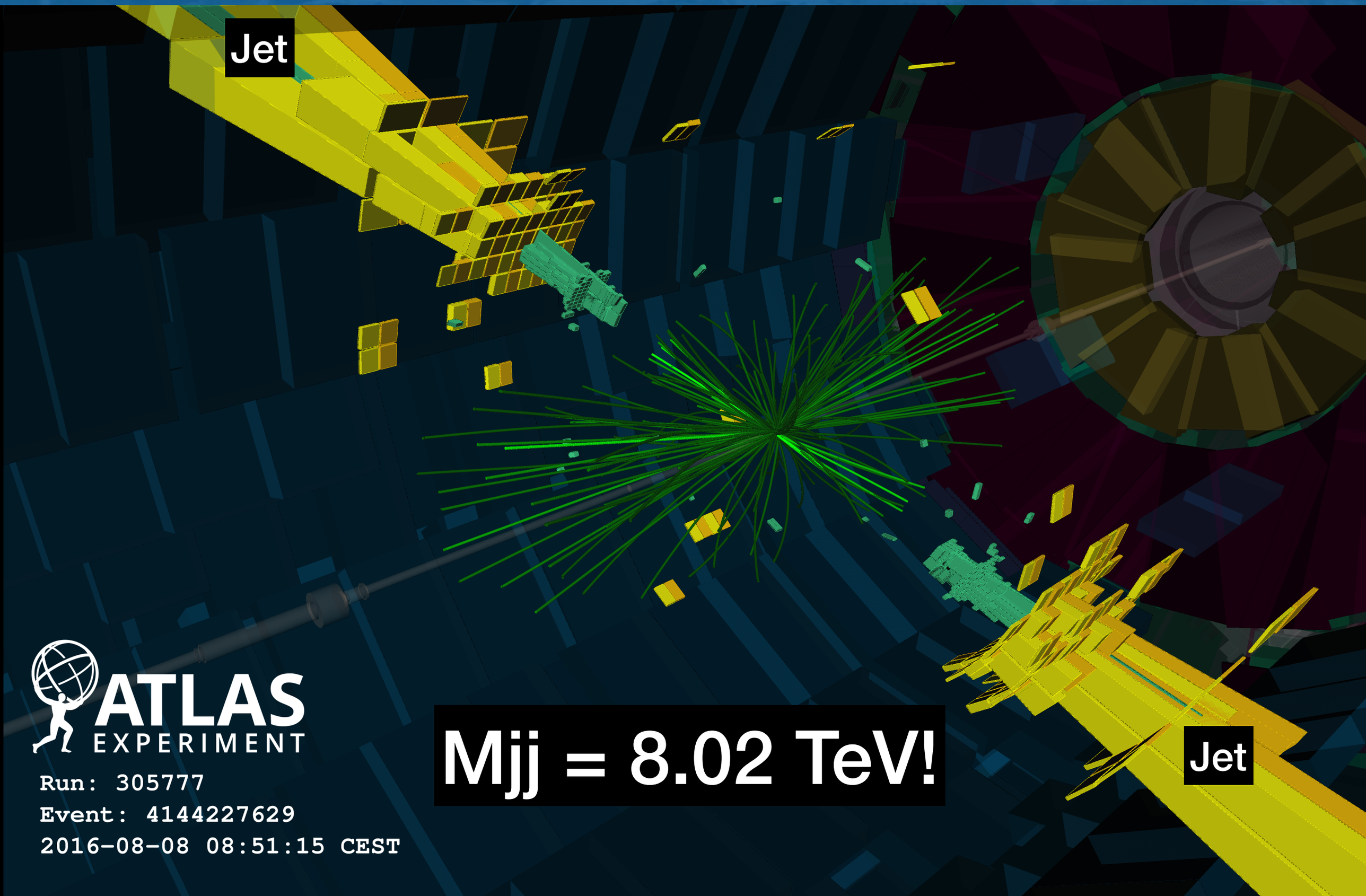
Visible final state with jets, leptons, and/or top quarks




- **Dijet** (139 fb$^{-1}$): ATLAS-CONF-2019-007 ★
- **Angular dijet** (37 fb$^{-1}$): PRD 96 (2017) 052004
- **Resolved dijet+ISR (+bjet)** (80 fb$^{-1}$): 1901.10917
- **Di-b-jet** (36 fb$^{-1}$): PRD 98 (2018) 032016
- **Dijet Trigger-Level Analysis** (29 fb$^{-1}$): PRL 121 (2018) 081801 ★
- **Boosted dijet+ISR** (36 fb$^{-1}$): PLB 788 (2019) 316 ★
- **Boosted di-b-jet+ISR** (81 fb$^{-1}$): ATLAS-CONF-2018-052
- **1lepton tt** (36 fb$^{-1}$): EPJC 78 (2018) 565
- **Hadronic tt** (36 fb$^{-1}$): EXOT-2016-24
- **Dilepton** (139 fb$^{-1}$): EXOT-2018-08

Y. Takubo talk

# Dijet


Jet
Jet
ATLAS
EXPERIMENT
Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST
Mjj = 8.02 TeV!

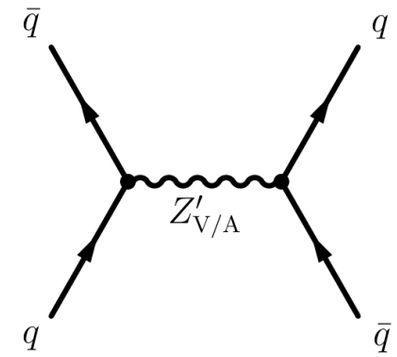
# Dijet

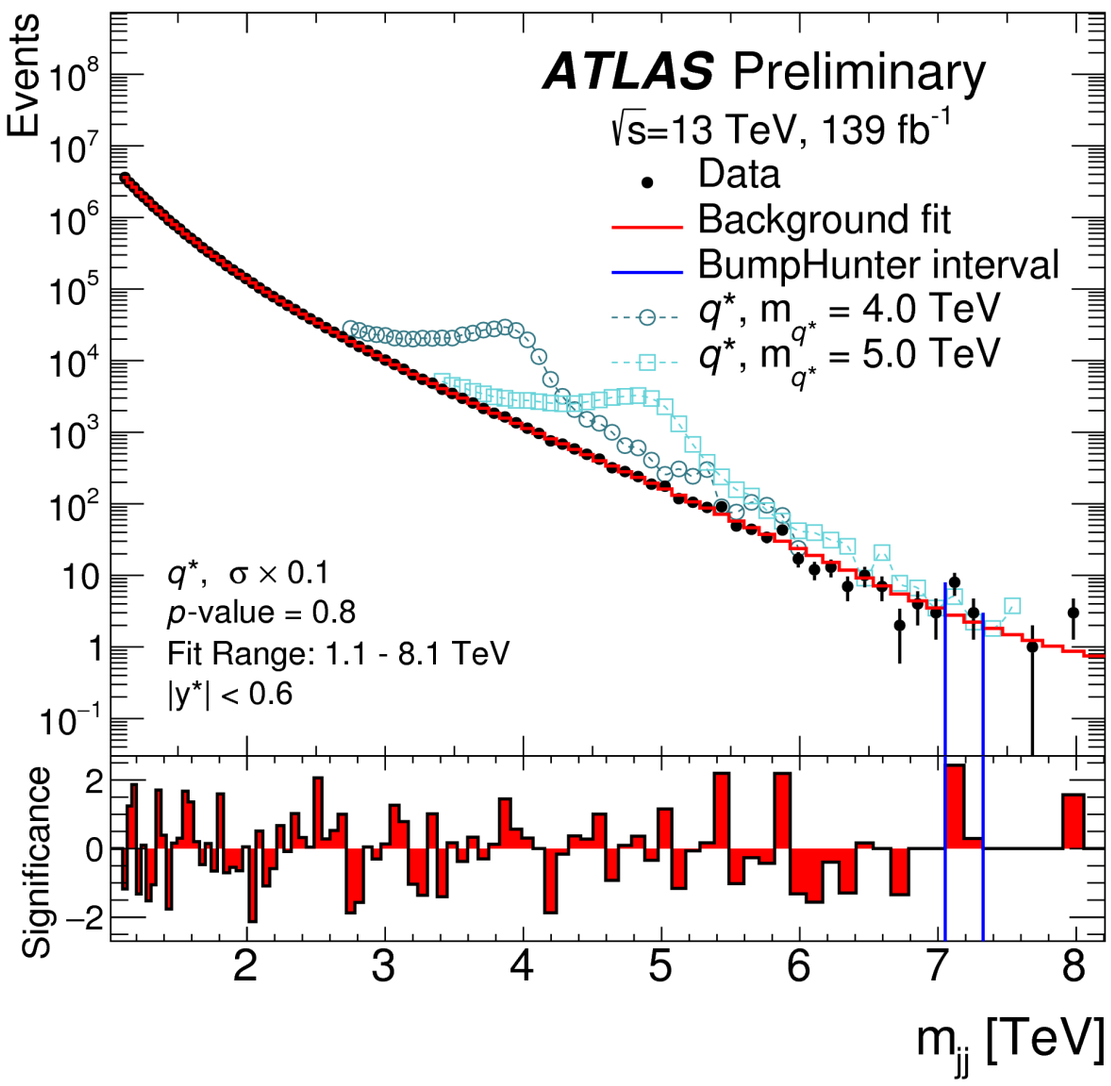
ATLAS-CONF-2019-007

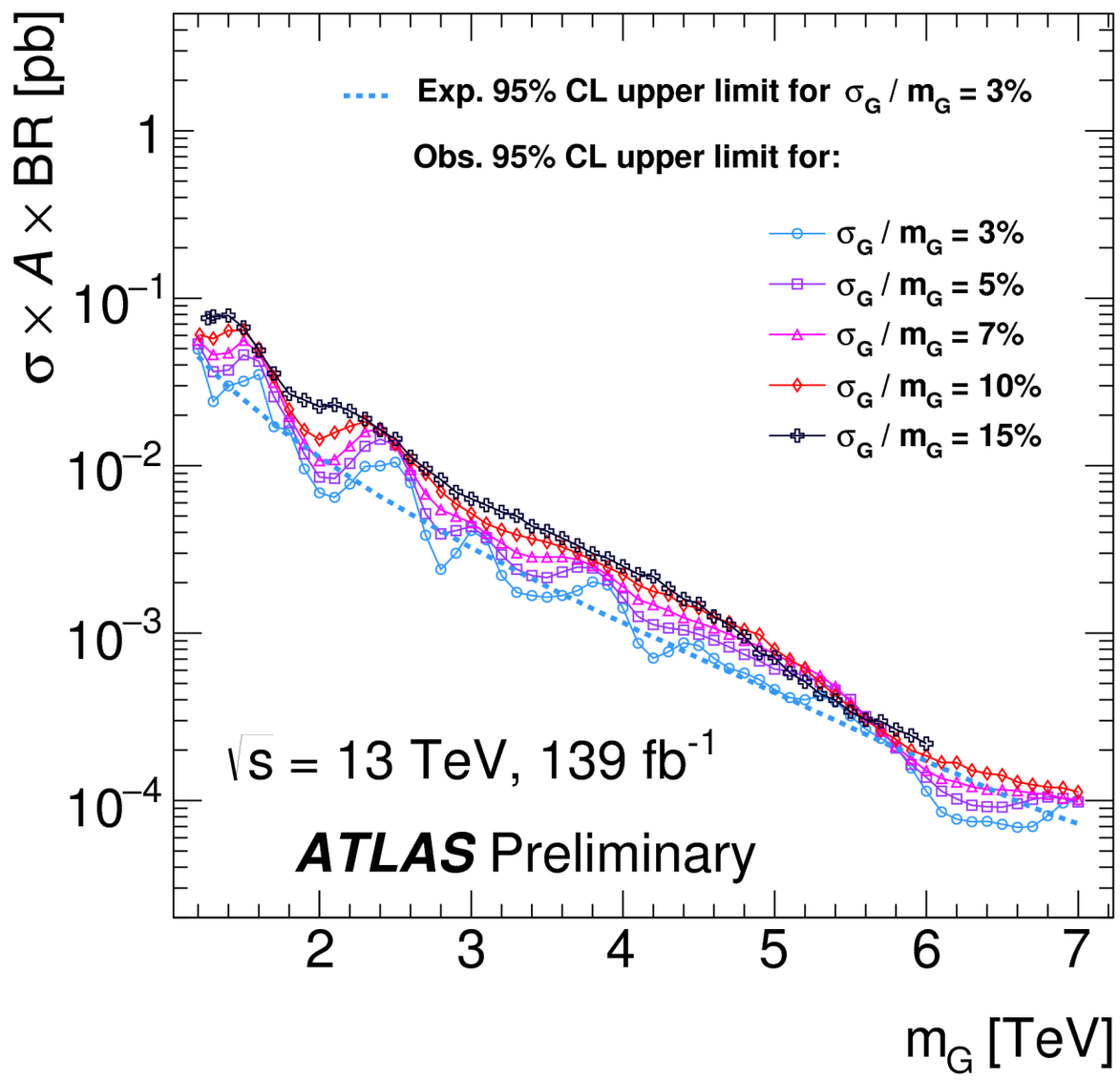
- Require >= 2 of jets with pT > 150 GeV, $M_{jj}$ > 1.1 TeV
- Sliding-window **bump** hunt along the $M_{jj}$ mass range

$$f(x) = p_1 (1-x)^{p_2} x^{p_3 + p_4 \ln x + p_5 (\ln x)^2}$$

$x \equiv m_{jj}/\sqrt{s}$ $p_5$=0 in nominal fit



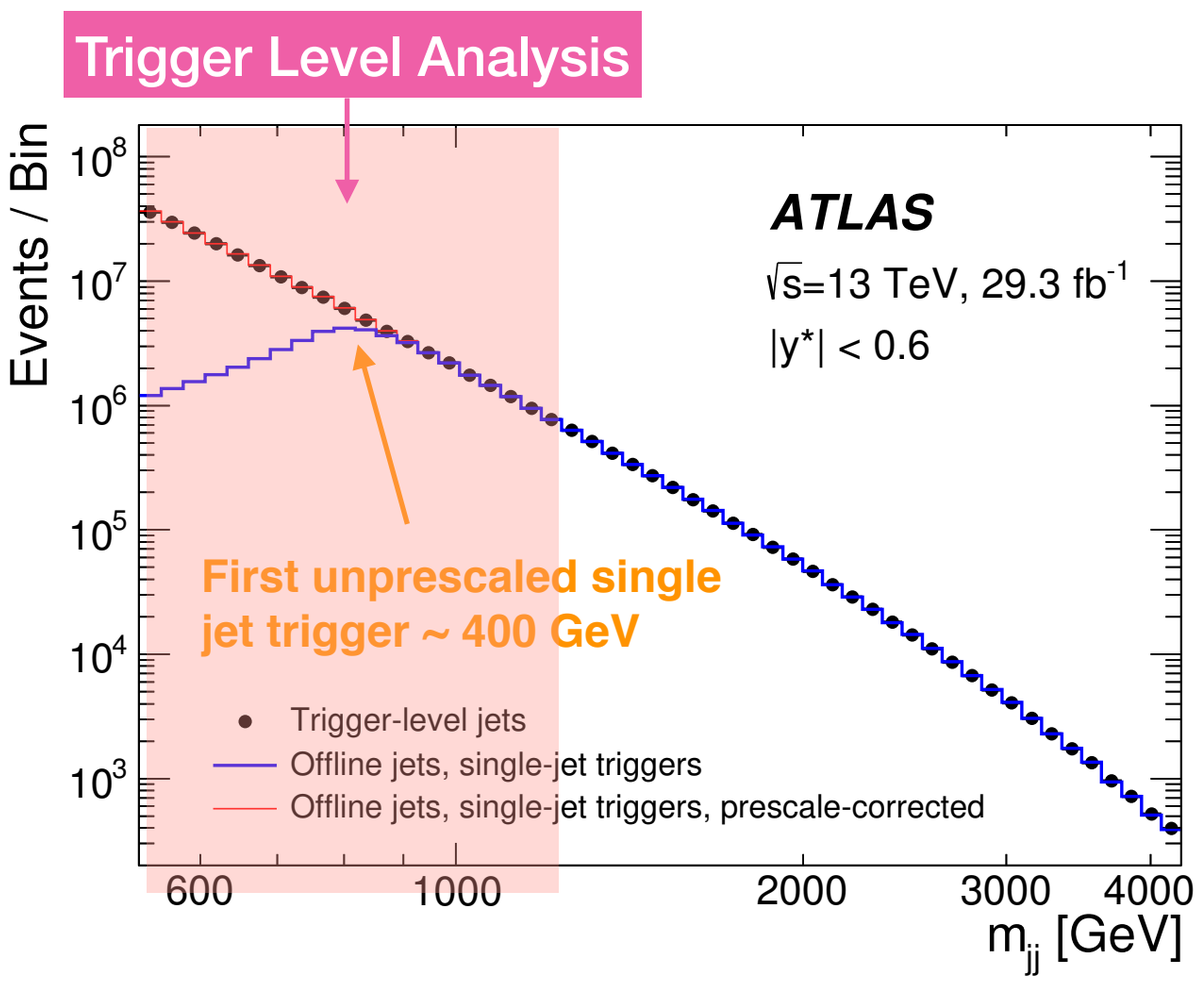



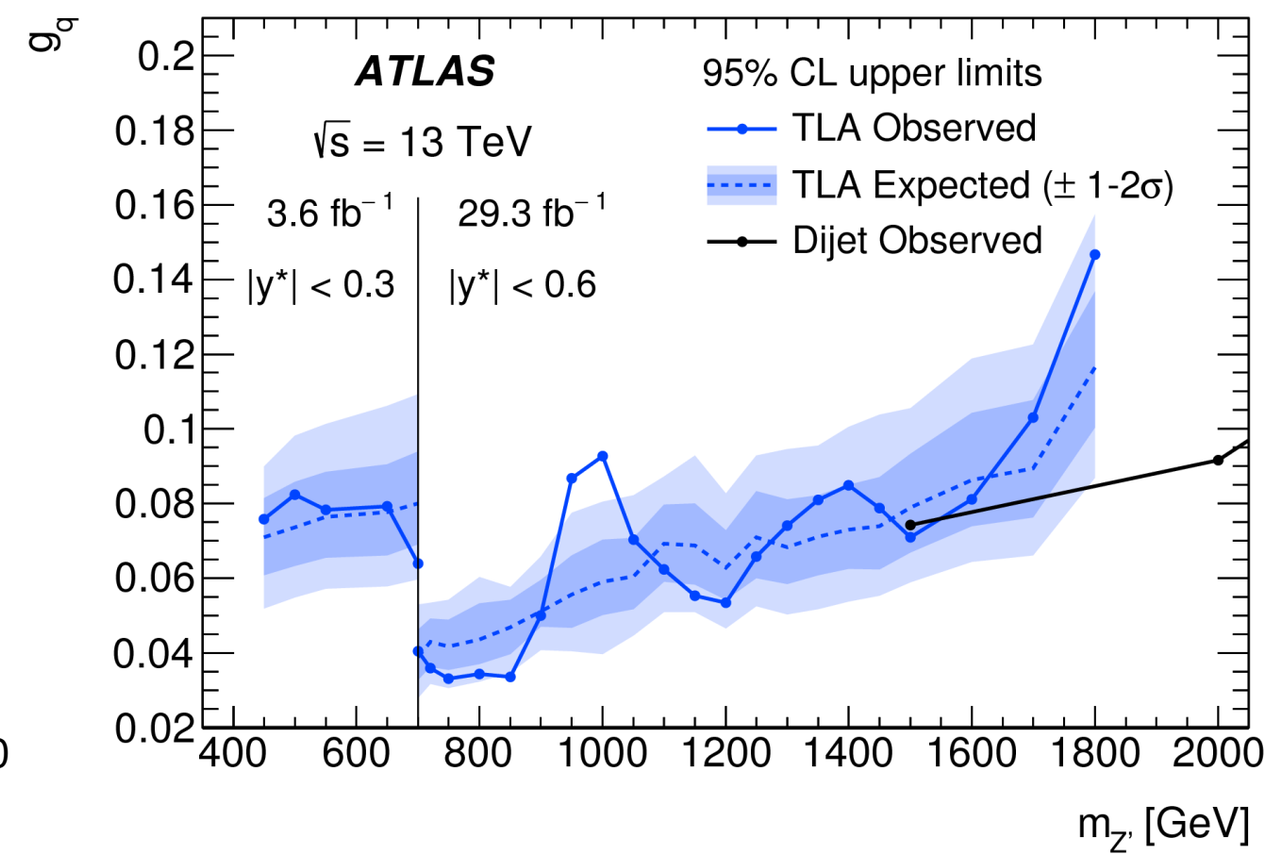



# Dijet - lower masses

**Standard dijet search limited by trigger threshold below 1 TeV**

- Use trigger level objects in a reduced event format (0.5%) to take data at much higher rates (20x)
- Jet reconstruction and calibration in High Level Trigger
- Go even lower using **boosted dijet system** with jet or photon ISRs (trigger)
  - ➡ Recoiling object is model independent

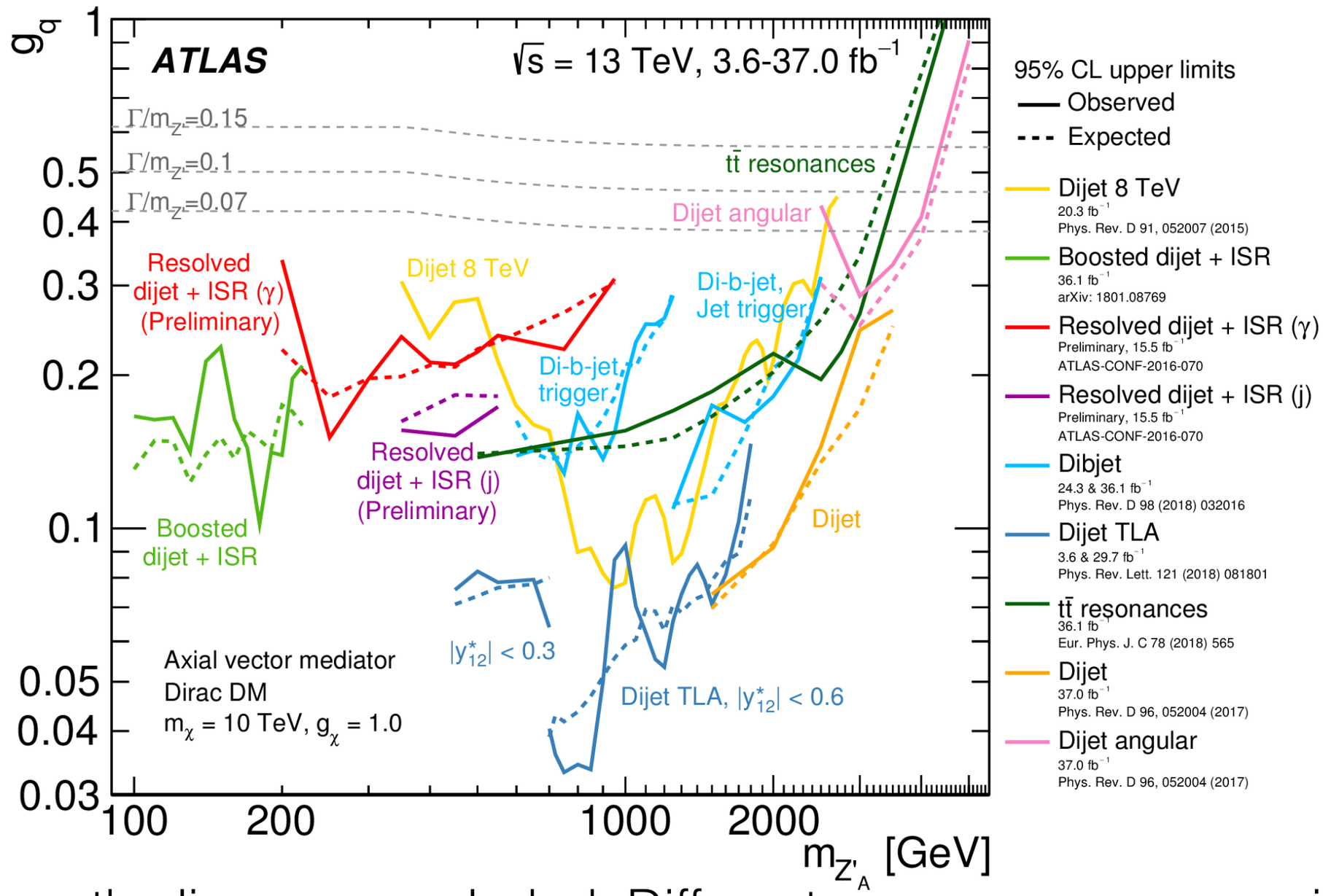


# Complementarity of dijet searches

For many coupling values of simplified models, resonance searches are more sensitive than X + $E_T^{miss}$ searches

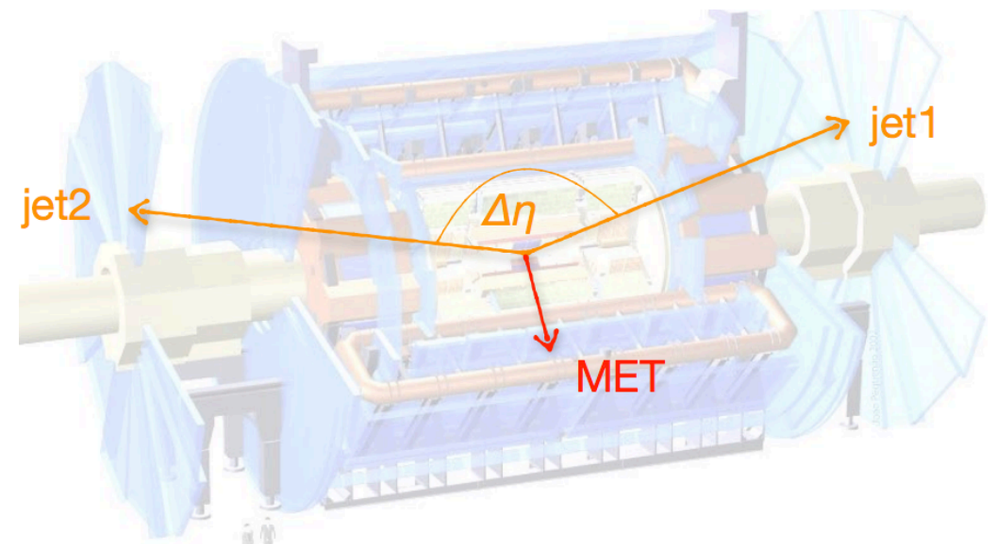
DM summary: 1903.01400




Couplings above the lines are excluded. Different resonances are sensitive to different regions of the coupling-mass parameter space

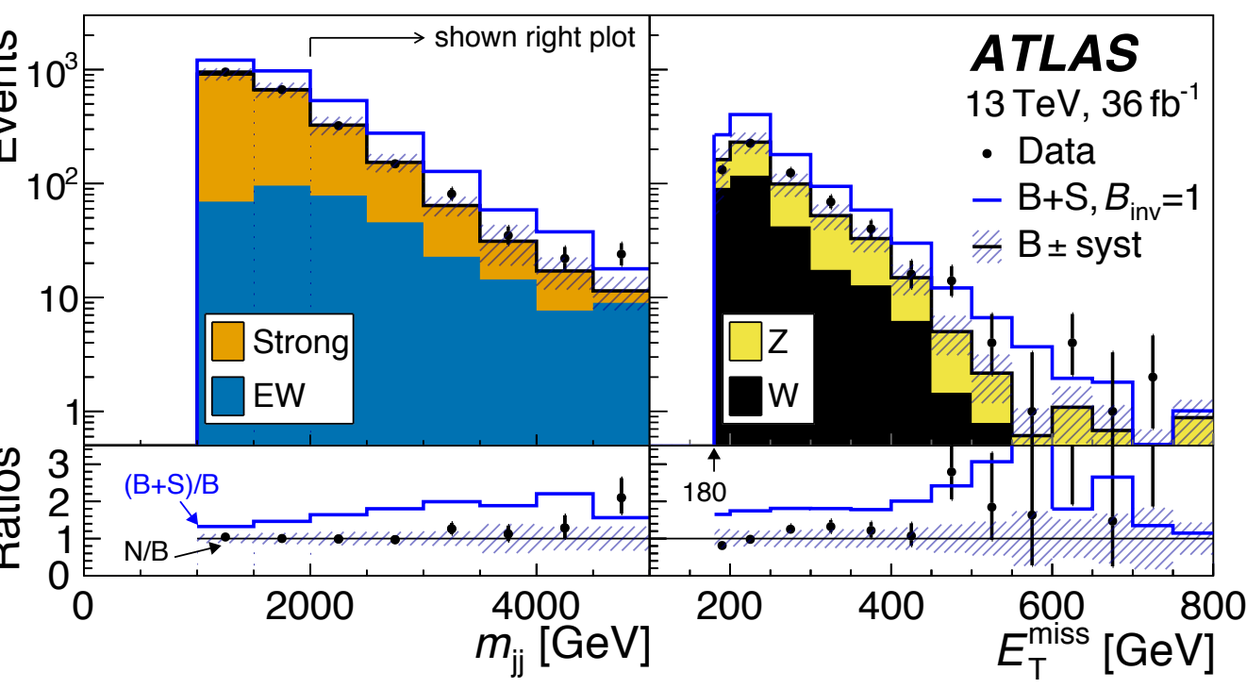
# Higgs as Mediator

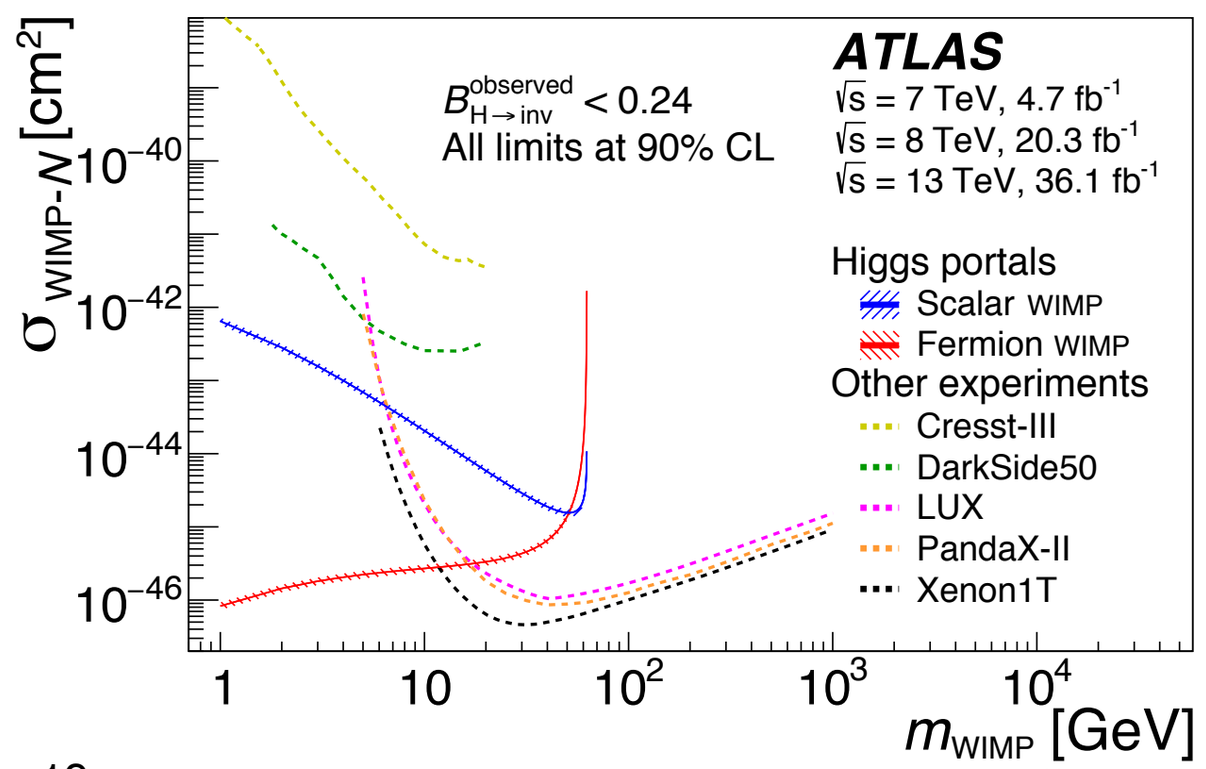
- Higgs to invisible will limit the potential Higgs coupling of candidate models with $m_{DM} \leq m_H/2$
- VBF is most sensitivity
- Uses VBF topology (forward jets) to discriminate against large SM backgrounds
- Also search using W/Z associated production




**BR(H → inv) < 26 % (17$^{+7}_{-5}$ % expected)**

PRL122,231801



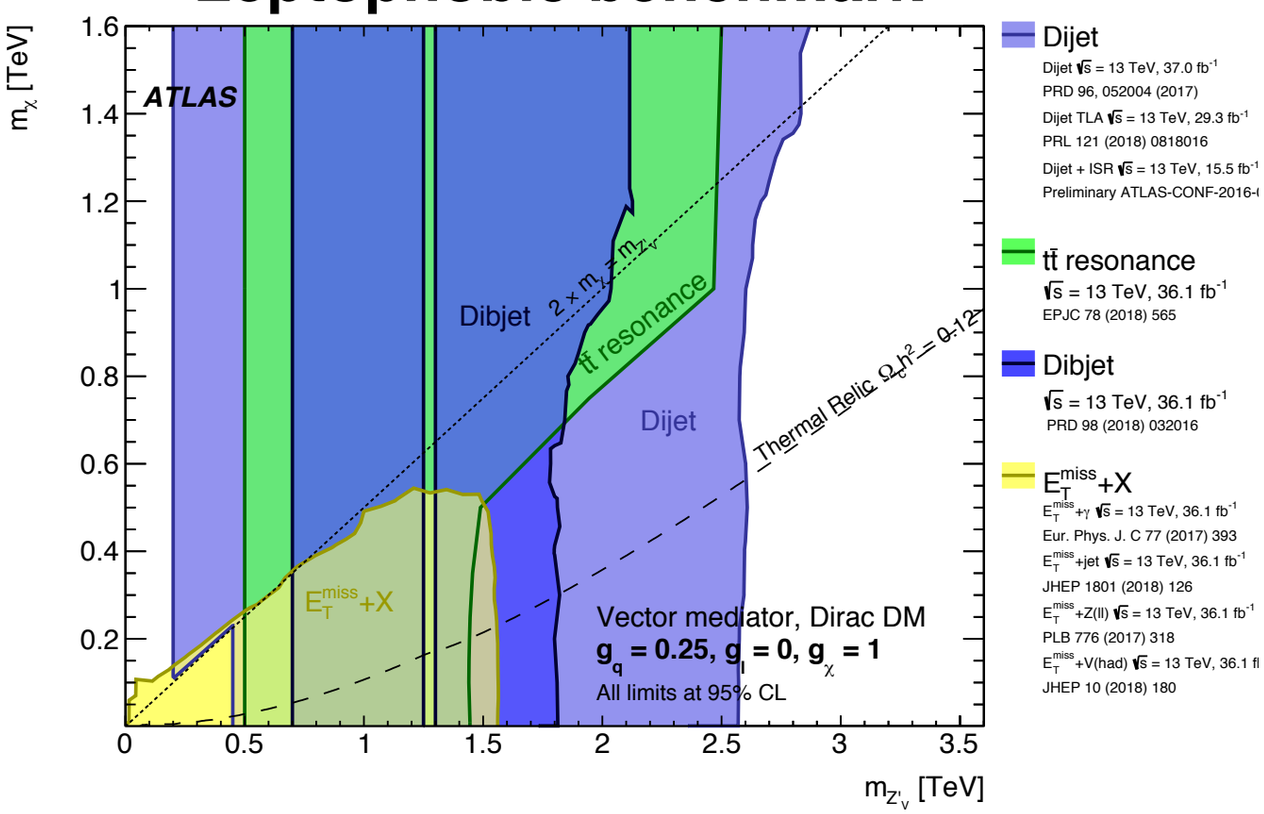



# Vector Models

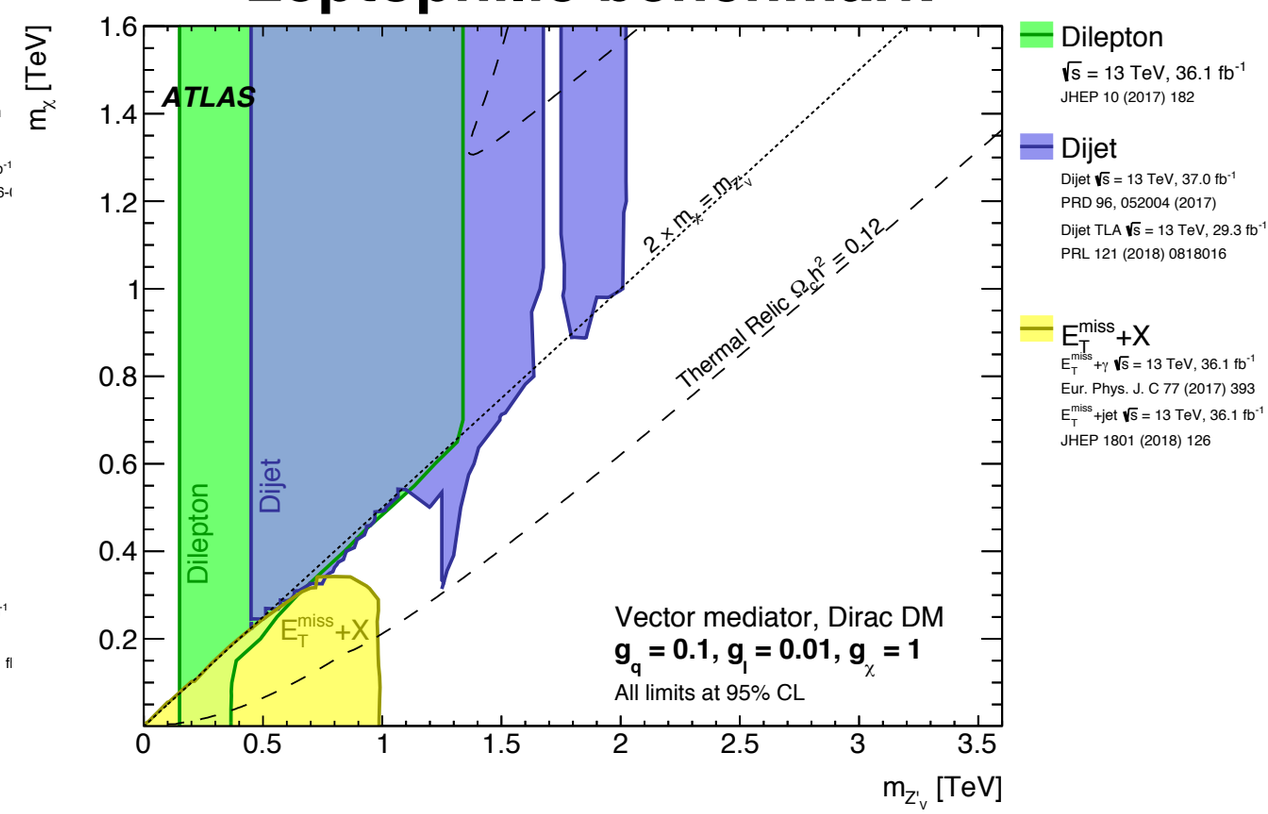
**DM Working Group Recommendations**: ATLAS and CMS use the same set of coupling values

- Set of leptophobic couplings for the AV and V models ($g_q$=0.25, $g_l$=0, $g_X$=1)
- Separate leptophilic couplings for AV ($g_q$=0.1 $g_l$=0.1, $g_X$=1) and V ($g_q$=0.1 $g_l$=0.01, $g_X$=1)
- Results shown as 2D exclusion plots in $M_{med}$ : $M_{DM}$

**Leptophobic benchmark**




**Leptophilic benchmark**

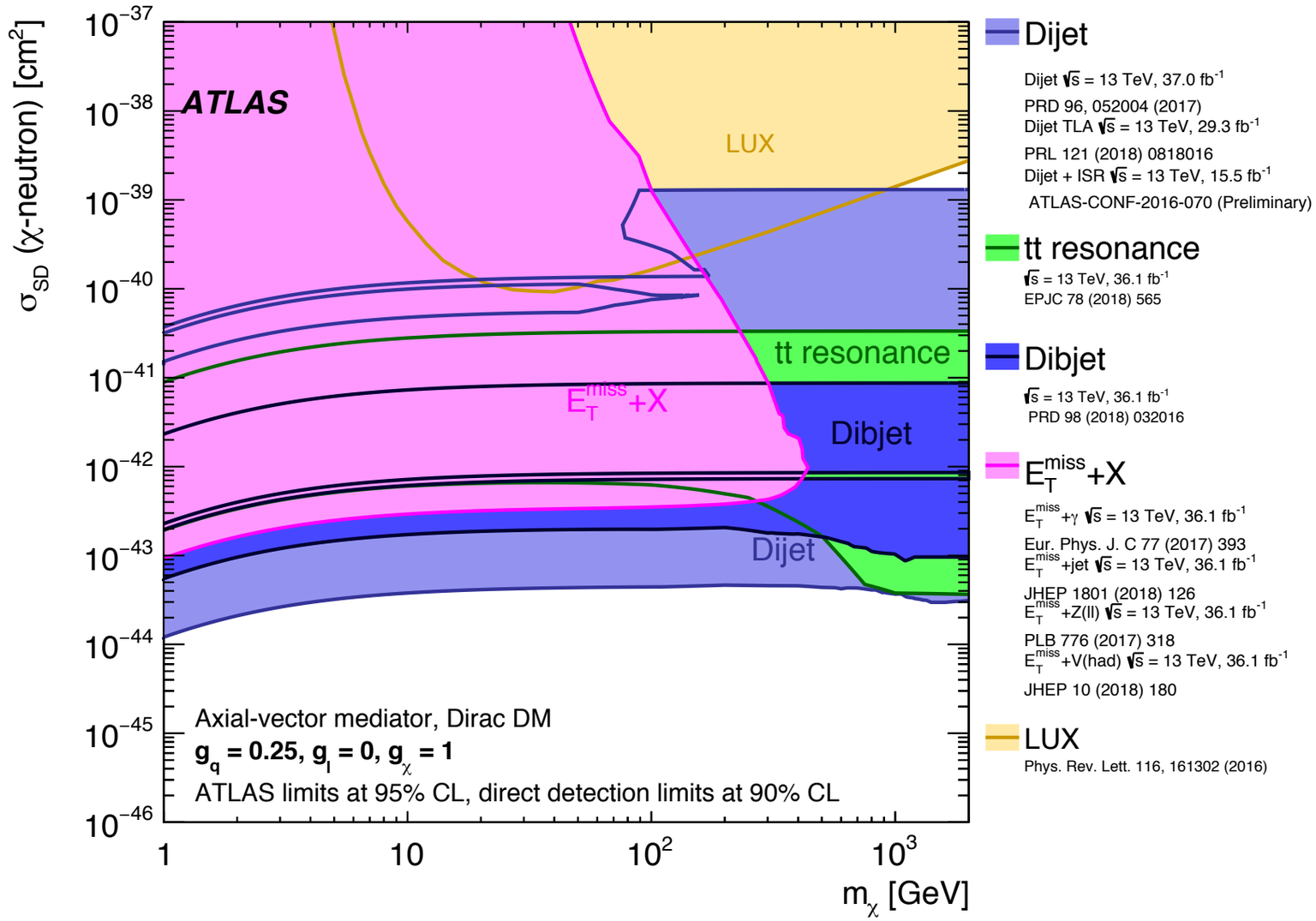



Recent summary paper: 1903.01400

# Comparison to Direct Detection

- Rates of DM production are used to calculate cross sections of other processes involving DM particles

**Leptophilic benchmark**
**Axial-vector model**




- Collider limits stronger than direct detection for spin-dependent interactions
  - ⋆ Model dependent, comparisons different for different coupling values!

# Summary

- LHC searches complementary to direct searches, providing improved sensitivity to low DM masses
- Diverse program of dark matter searches in ATLAS
  - **Complementarity** between different final states
  - No assumption on distribution and velocity profile of DM
  - Wide program of searches of Supersymmetry not discussed
- None of the DM searches have observed a significant excess over expected backgrounds
- ATLAS main reference for dark matter searches: 1903.01400
- Many more searches in progress with full Run 2
  **Stay tuned…**

# Backup

# Benchmark Models

- Broad ATLAS DM search program!
  - Interpret in terms of a few benchmark scenarios

**(Pseudo)scalar mediator**

- *Neutral interaction*
- *Baryon-charged interaction*
- *Flavor-changing interaction*

**(Axial) vector mediator**

- *Color-neutral interaction*
- *Color-charged*

**Extended Higgs sector**

- *2HDM + Vector*
- *2HDM + Pseudoscalar*

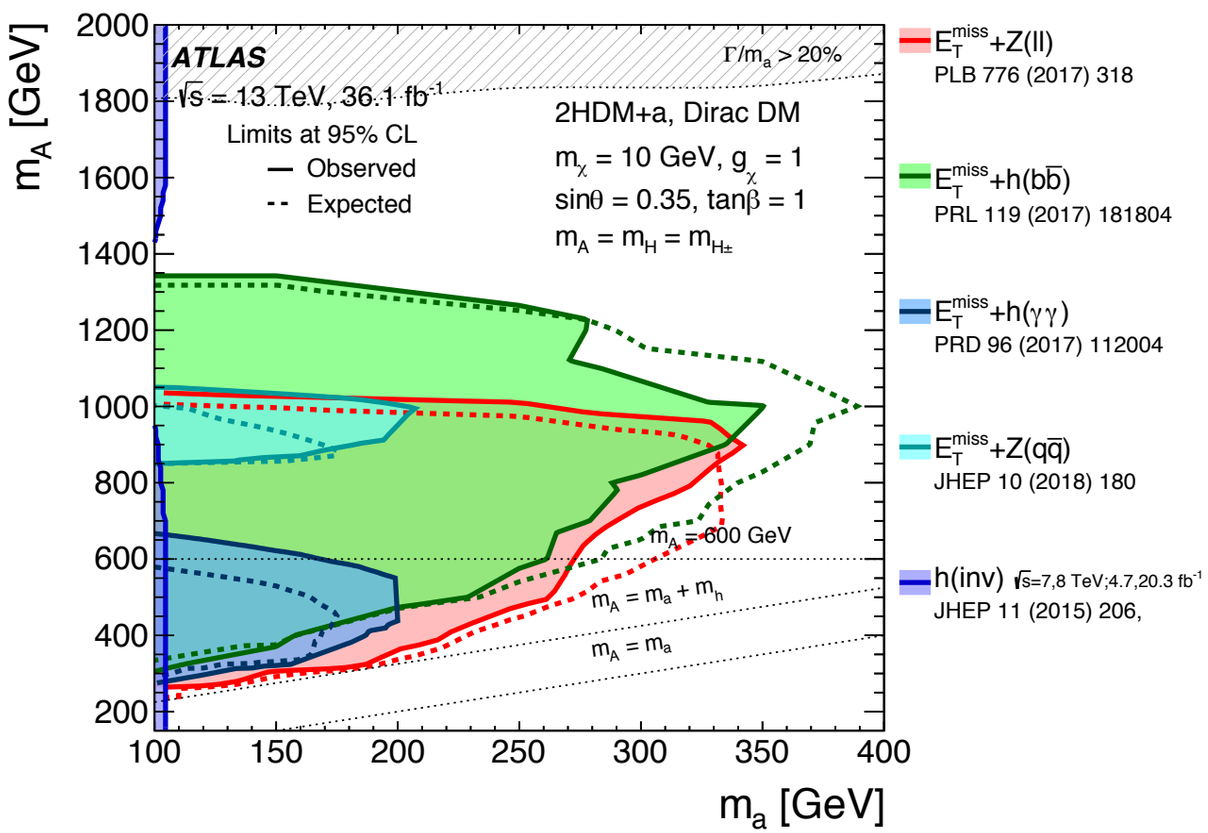
Recent summary paper: 1903.01400

# 2 Higgs-Doublet + Pseudoscalar Model

- Results in 3 new physical scalars ($H, H^+, H^-$) and 2 new pseudo scalars (a, A)

## $M_A$-$M_{\phi\rho}$ scan

($\sin\theta$ = 0.35, $\tan\beta$ = 1.0, $M_X$ = 10 GeV)




## $\tan\beta$-$M_{\phi\rho}$ scan

($\sin\theta$ = 0.35, $M_H$ = 600 GeV), $M_X$ = 10 GeV)