# Dark Matter Searches with the ATLAS Detector

Othmane Rifki

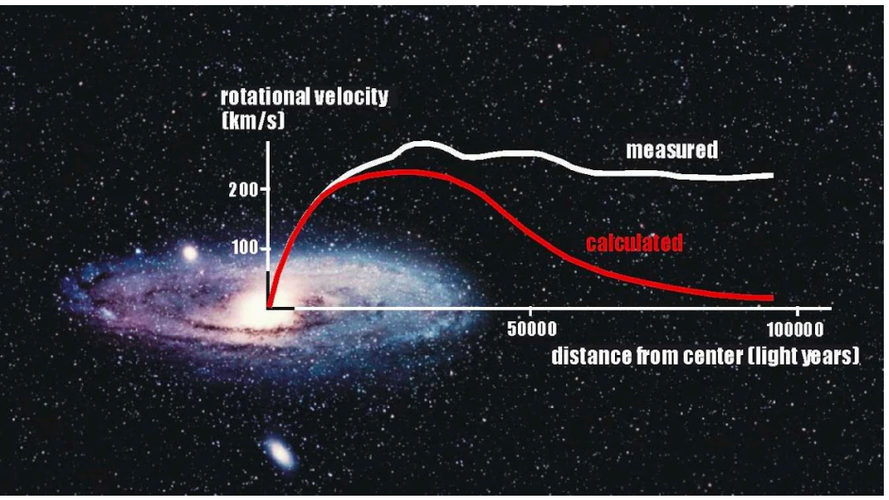
*ACP 2018*

Monday, July 2nd, 2018

# Why Dark Matter?

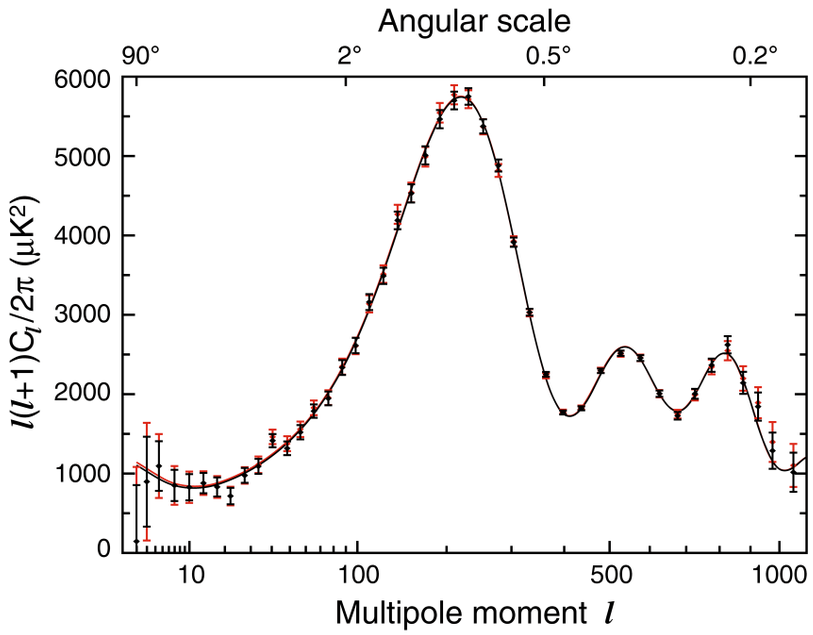
Cosmological data suggests presence of **dark matter** (**DM**)

## Galactic rotation



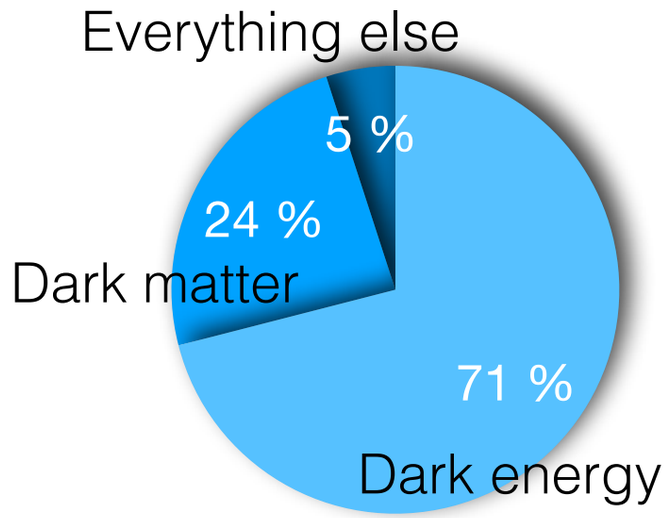

## Weak lensing

## CMB



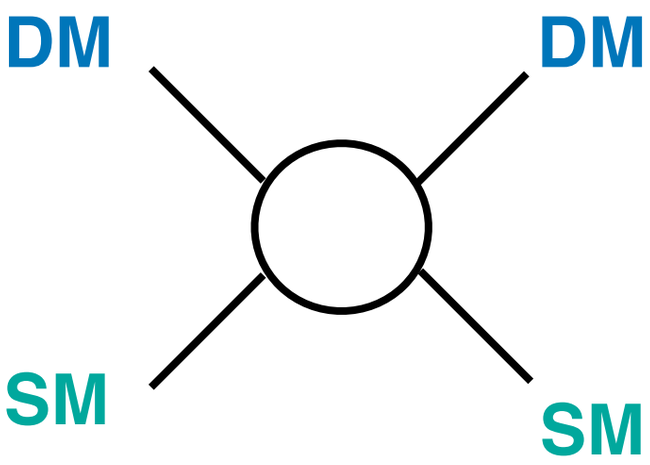

**No explanation within the standard model and the underlying nature of DM remains unknown**

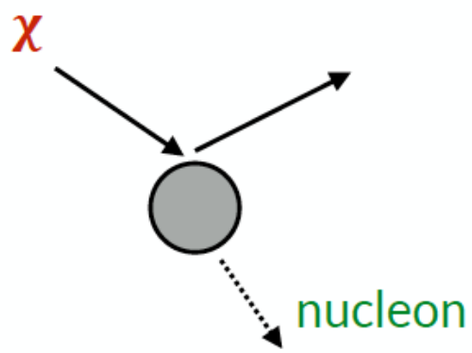
Several extensions but will focus on weakly interacting particles (WIMP)



# How to detect DM?

## Direct Detection

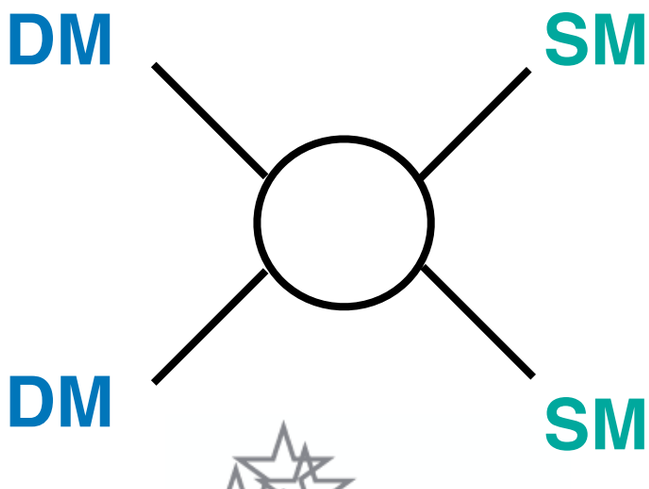


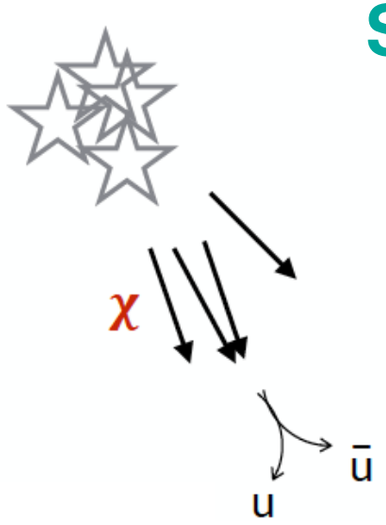




*Elastic scattering on detector nuclei in the lab*

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

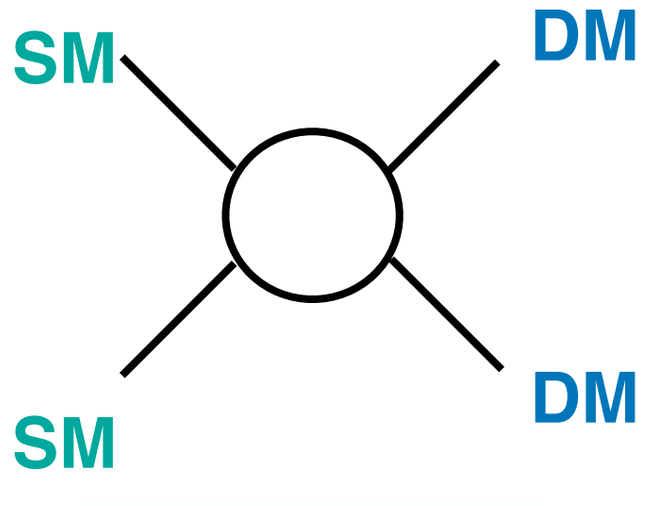
## Indirect Detection

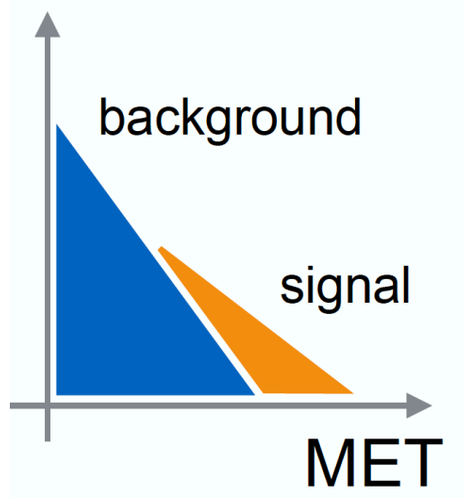



*Annihilation products from gamma-rays and anti-matter (i.e. galactic center)*

## Colliders




*Sufficient accuracy in background sensitive to distortions in tails*

# How to detect DM?

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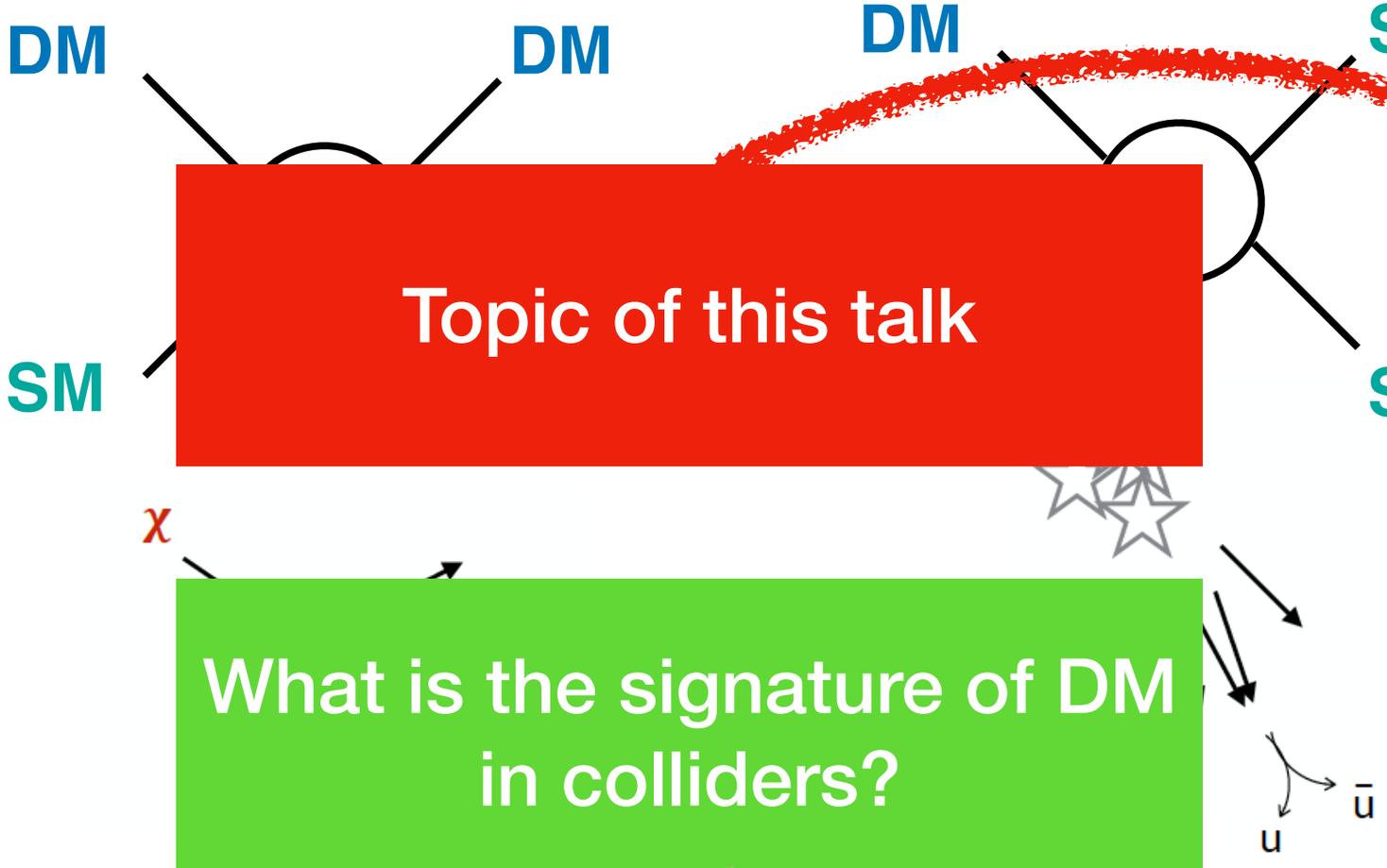


*Elastic scattering on detector nuclei in the lab*

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## Indirect Detection




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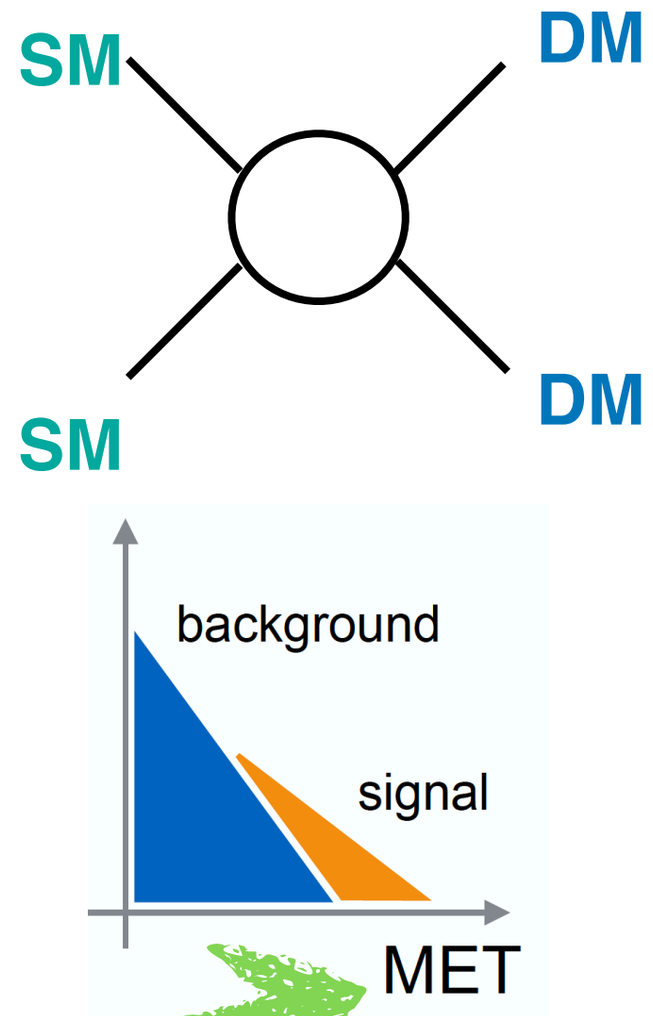
## Colliders




*Sufficient accuracy in background sensitive to distortions in tails*

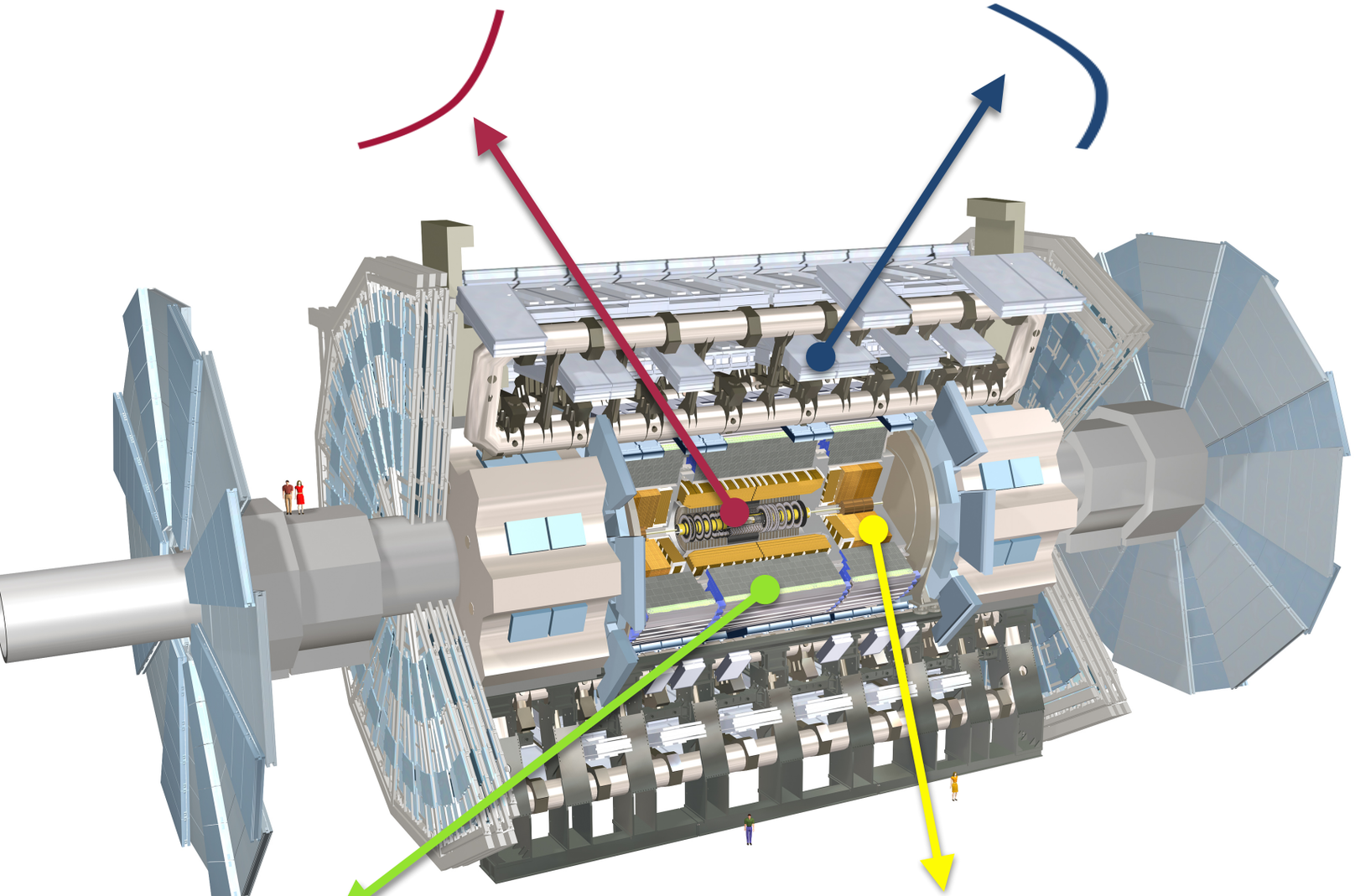
**Topic of this talk**

**What is the signature of DM in colliders?**

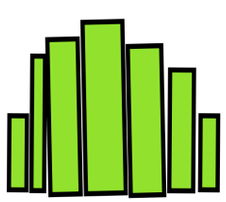
# ATLAS Detector

Inner Detector Tracks

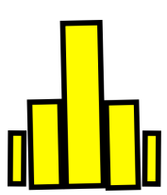
Muon Tracks



Hadronic Clusters



Electromagnetic Clusters



**Trigger**

40 million beam crossing/s

1 billion p-p/s

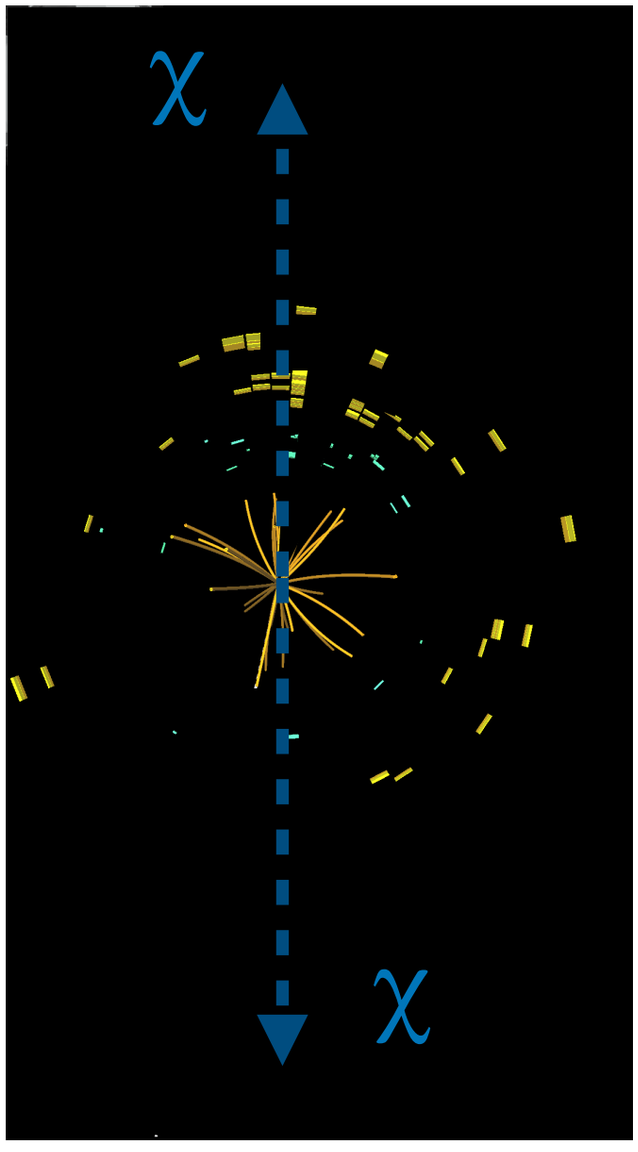
1000 p-p/s

**Rejection $10^6$**

Higgs to 4l 1 in $10^{12}$ p-p

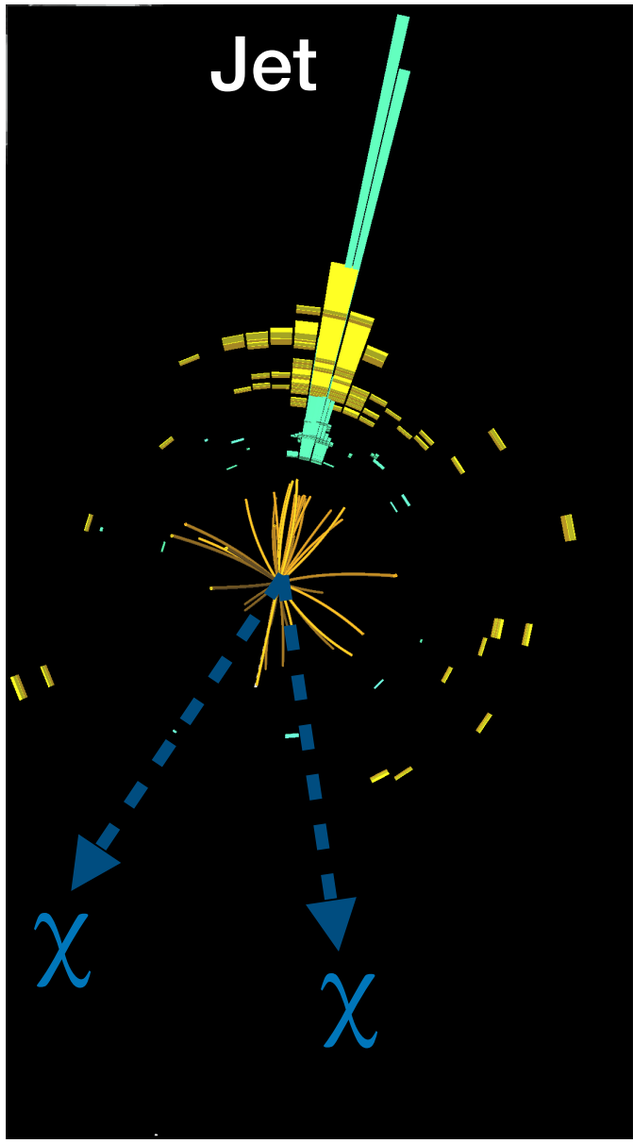
# Signature of DM

- DM is assumed to be **weakly interacting**: **No signature in the detector**



# Signature of DM

- DM is assumed to be **weakly interacting**: **No signature in the detector**
  - Events with **DM particles in the final state** can be recorded if produced in association to an **initial state radiation**




- Initial transverse momentum is **zero**
  - ➡ Total transverse momentum must be balanced

# Signature of DM

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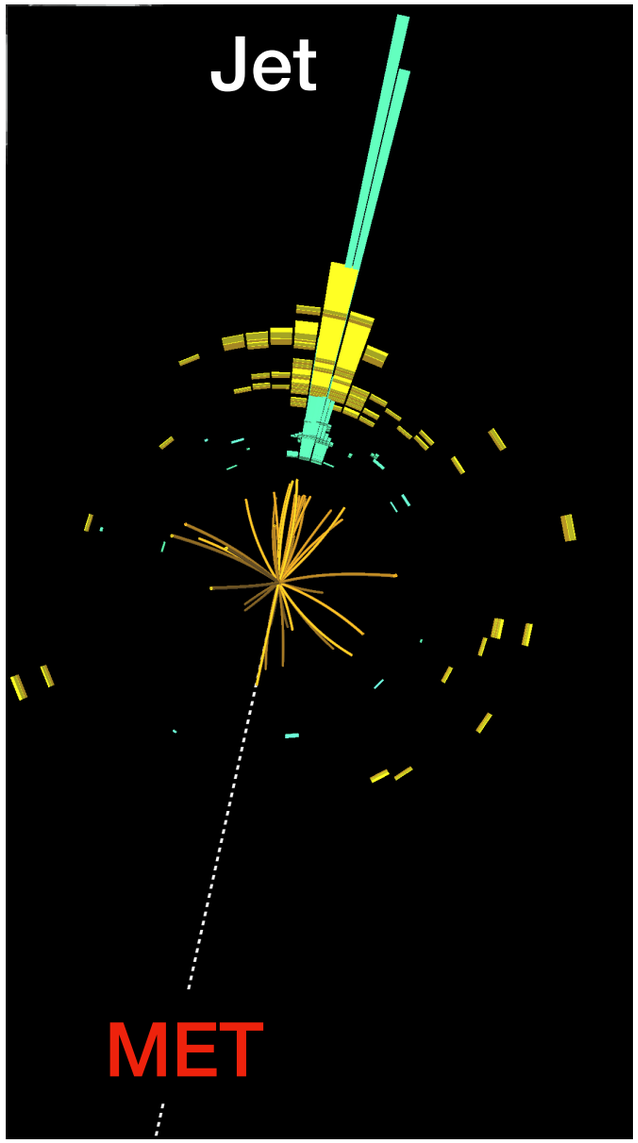



- Initial transverse momentum is **zero**
  - ➡ Total transverse momentum must be balanced

- Measure imbalance in the transverse momentum of all visible particles to the detector
  - ➡ **Missing transverse momentum** (colloquially **MET**)

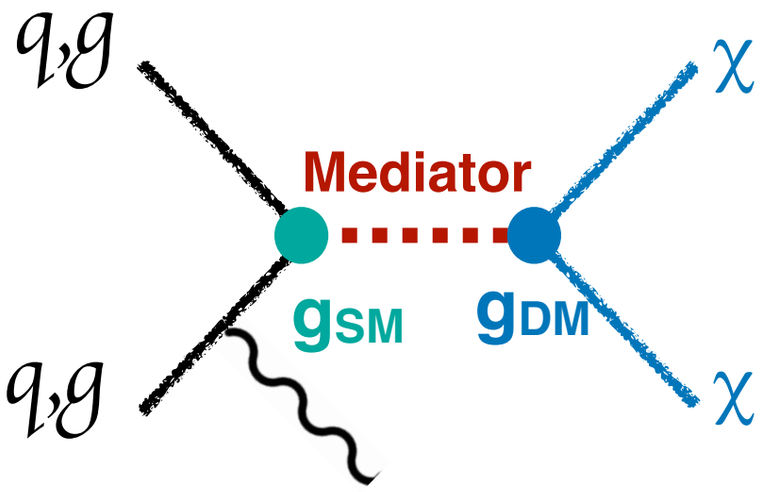
**MET in the event may be due to DM!**

# DM Searches in ATLAS

Cover **simplified models**: Mediator is light enough to be produced at the LHC

## Direct Production

*Mono-X* searches
use initial state radiation
recoiling against DM

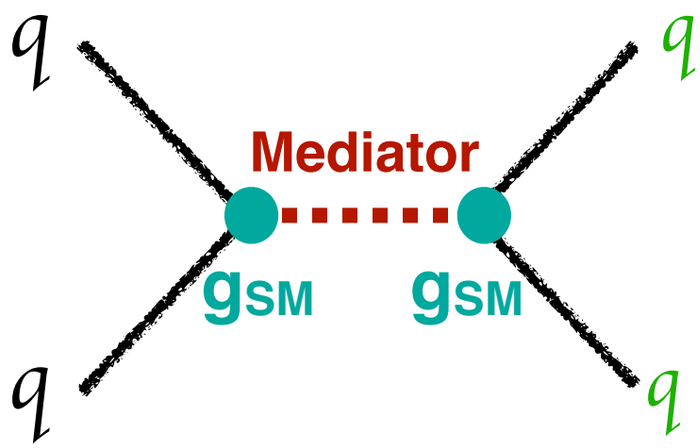



Look for **deviation**
from standard model
background

**Mono-jet**

## Mediator Search

*Di-X* searches
bump hunt for mediator
decays to jets

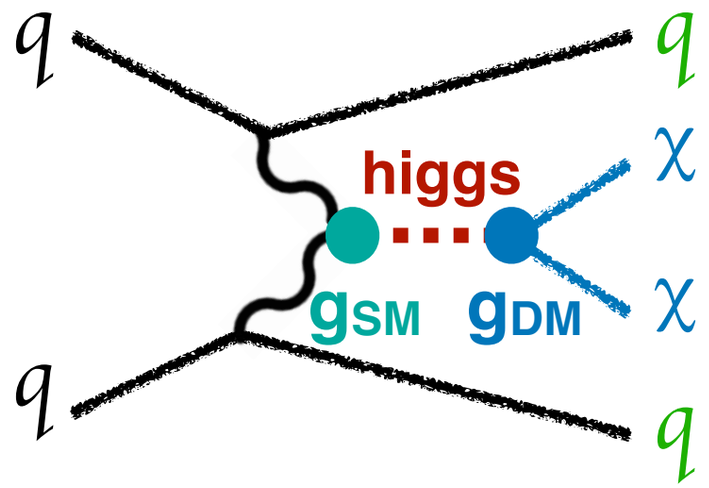



Look for mass **peak**
above background
continuum

**Di-jet Search**

## Higgs Portal

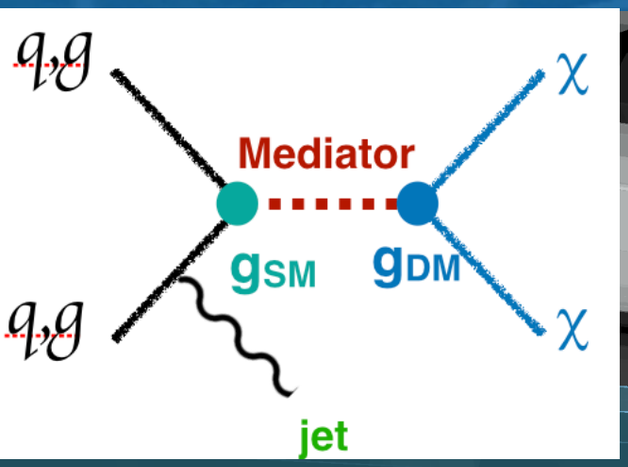
*Higgs to invisible*
0.1% branching ratio in
SM




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

**VBF**

# Mono-Jet

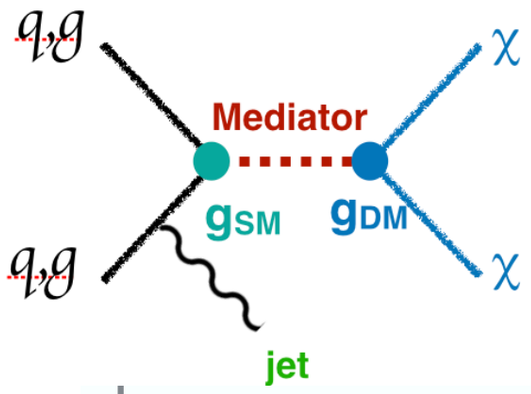

q,g
q,g
Mediator
$g_{SM}$
$g_{DM}$
χ
χ
jet


Jet
ATLAS
EXPERIMENT
Jet
1.7 TeV
MET
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

# Mono-Jet

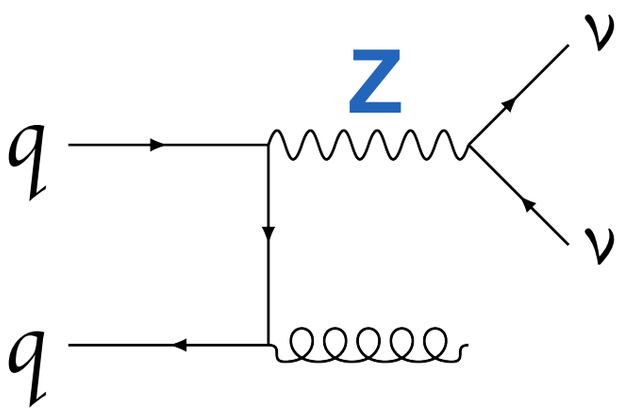
arXiv:1711.03301

- Dark matter is invisible to the detector
  - Events produced in **association** with a **jet**
  - **Missing transverse momentum** (**MET**) as a measure of the recoil system transverse momentum

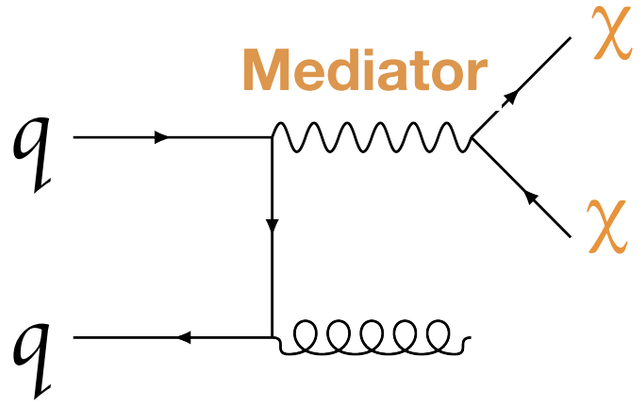



- Estimate known **standard model** processes
  - look for deviations consistent with **DM signal**

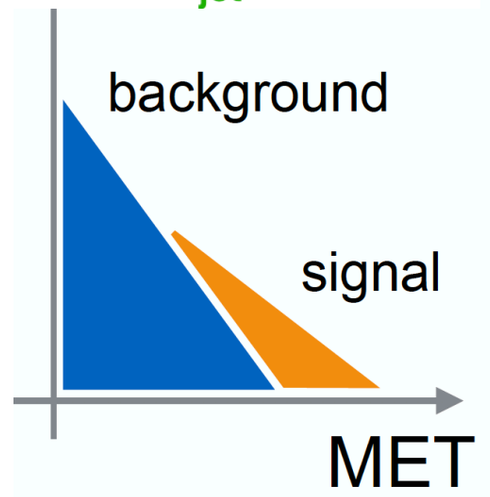
**Background**



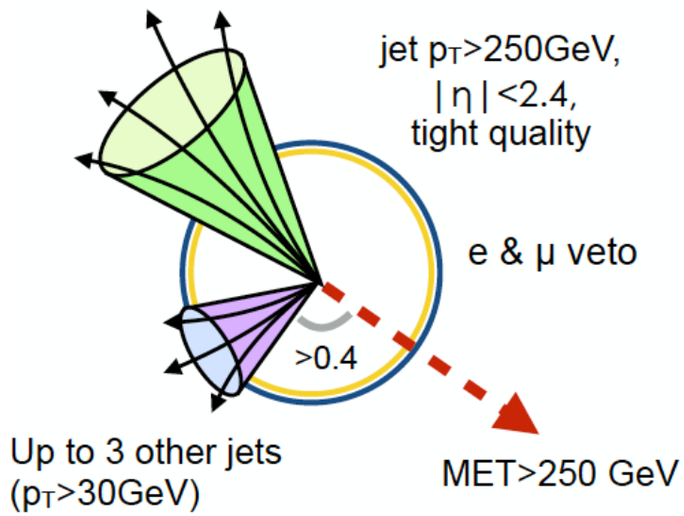

**Signal**




**Identical Signature**

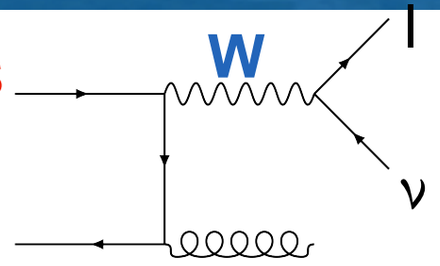



**Measure standard model background precisely!**

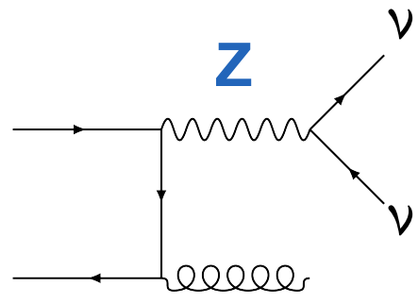


# Mono-Jet

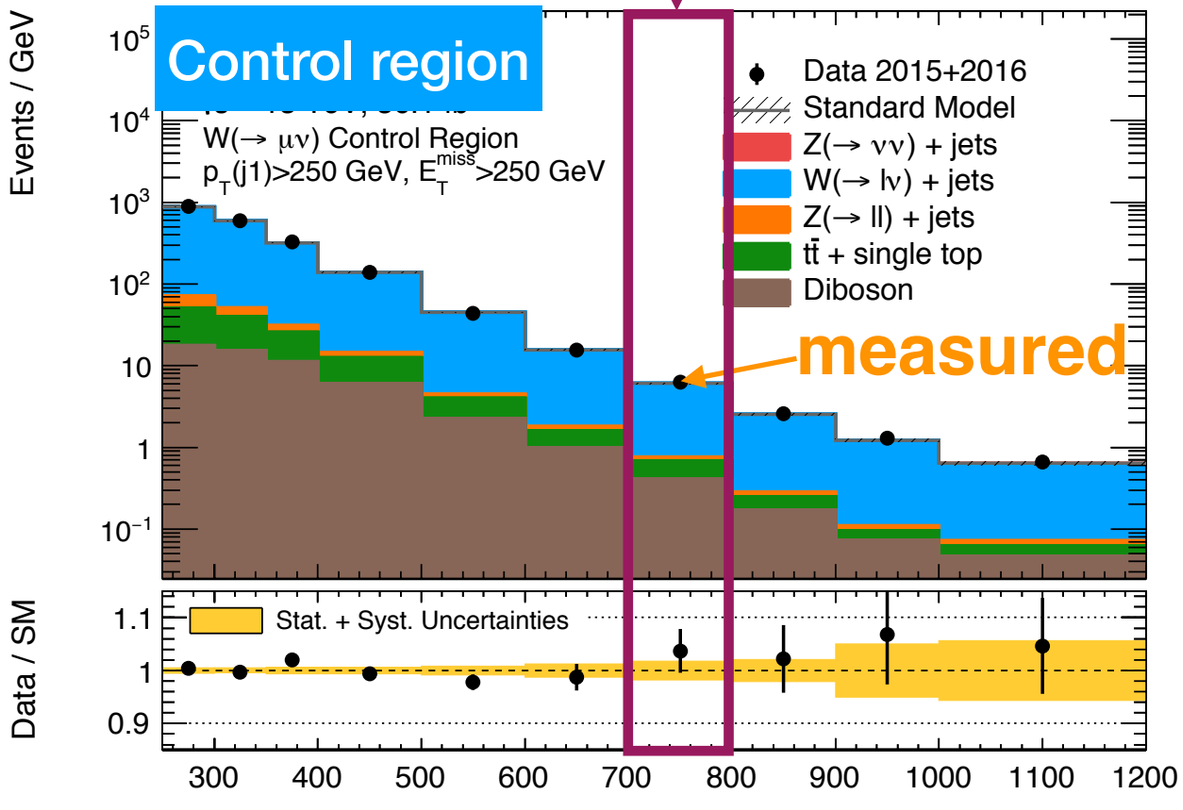
- **Control regions** for Z(ll)+jets and W+jets to estimate Z(νν)+jets
- Treat **leptons as invisible** to mimic Z(νν) event
- Similar uncertainties between Z(νν)+jets and W+jets **cancel**

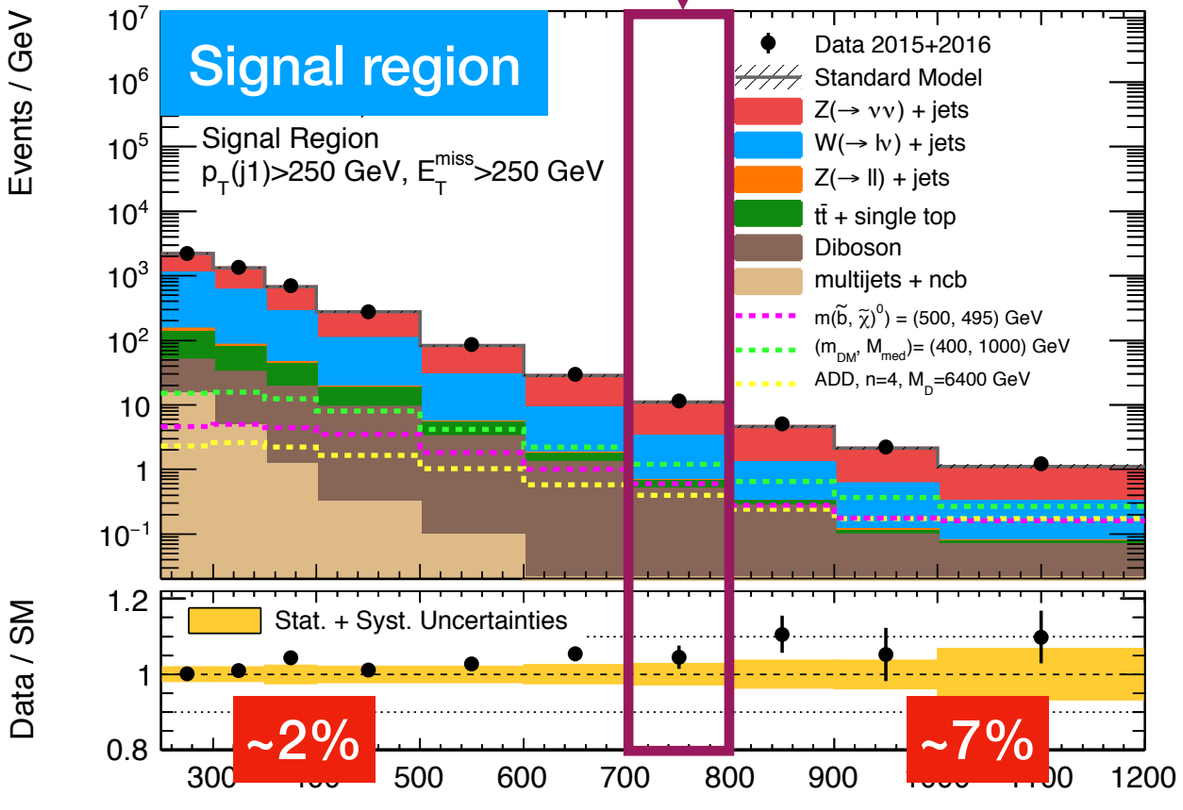



$$\frac{\mathrm{d}\sigma(V_2)}{\mathrm{d}p_T} = \left[\frac{\mathrm{d}\sigma(V_2)/\mathrm{d}p_T}{\mathrm{d}\sigma(V_1)/\mathrm{d}p_T}\right]_{\text{theory}} \times \left[\frac{\mathrm{d}\sigma(V_1)}{\mathrm{d}p_T}\right]_{\text{measured}}$$

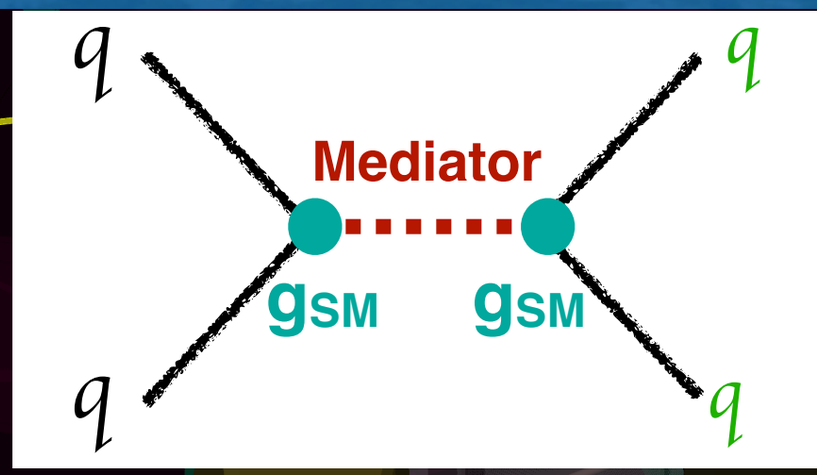



**theory**



# Di-Jet




Jet

ATLAS EXPERIMENT

Run: 305777
Event: 4144227629
2016-08-08 08:51:15 CEST

Mjj = 8.1 TeV

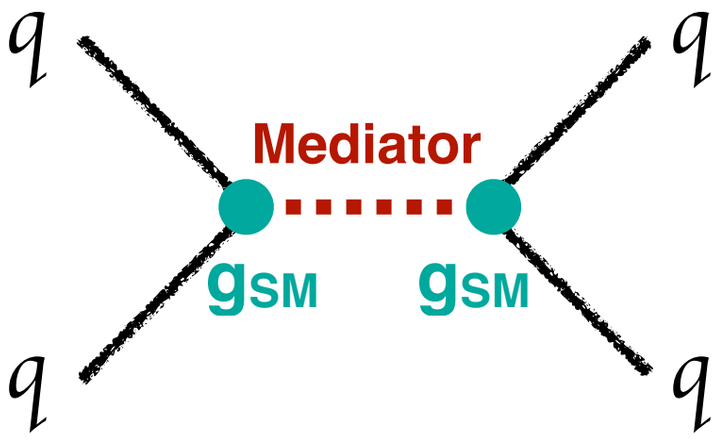
Jet

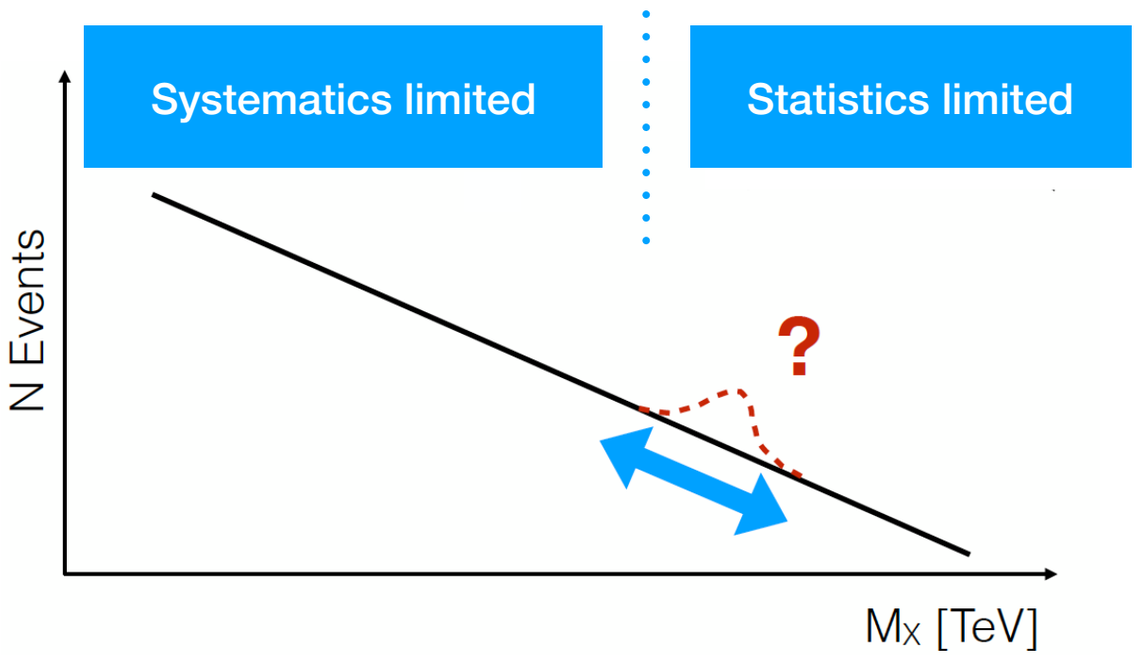
# Di-Jet

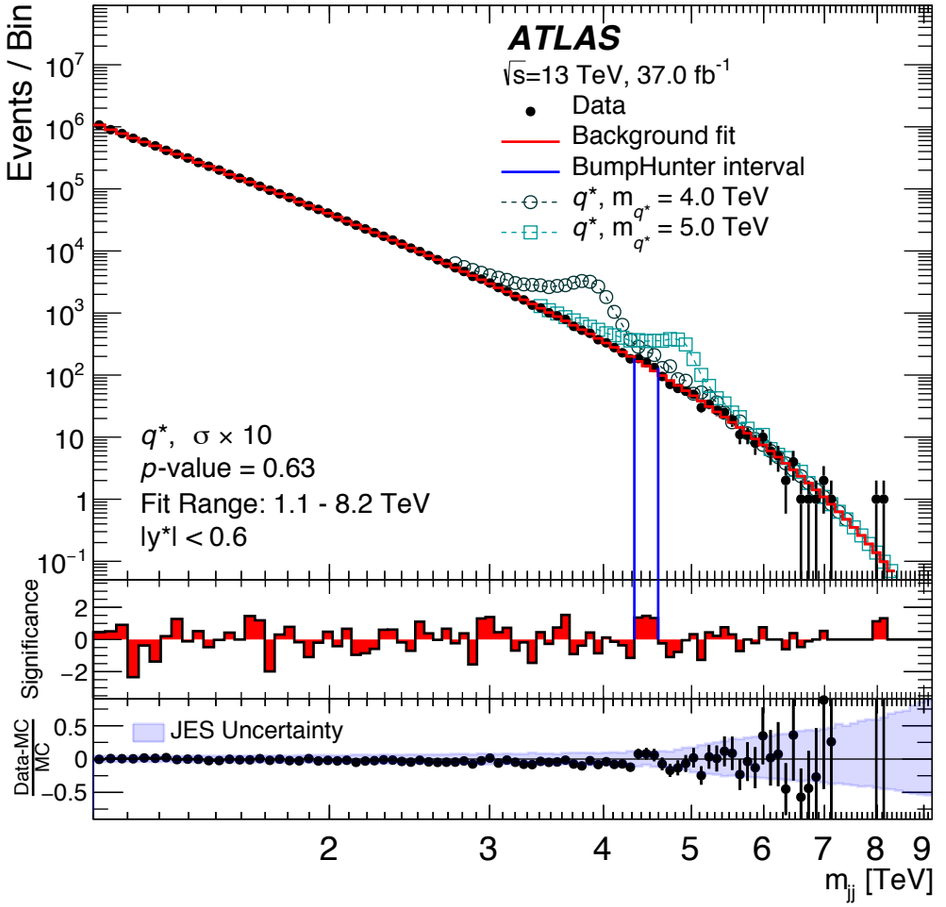
PRD 96, 052004 (2017)

## High mass di-jets

- Look for a **bump** along an entire mass range: **mediator** mass not predicted
- Leading jet pT > 440 GeV **limited** by the **online tight filters** of interesting events (trigger)
- Constraint for mediators with m > 1.5 TeV
- Need alternative approaches to access mediators below 1.5 TeV



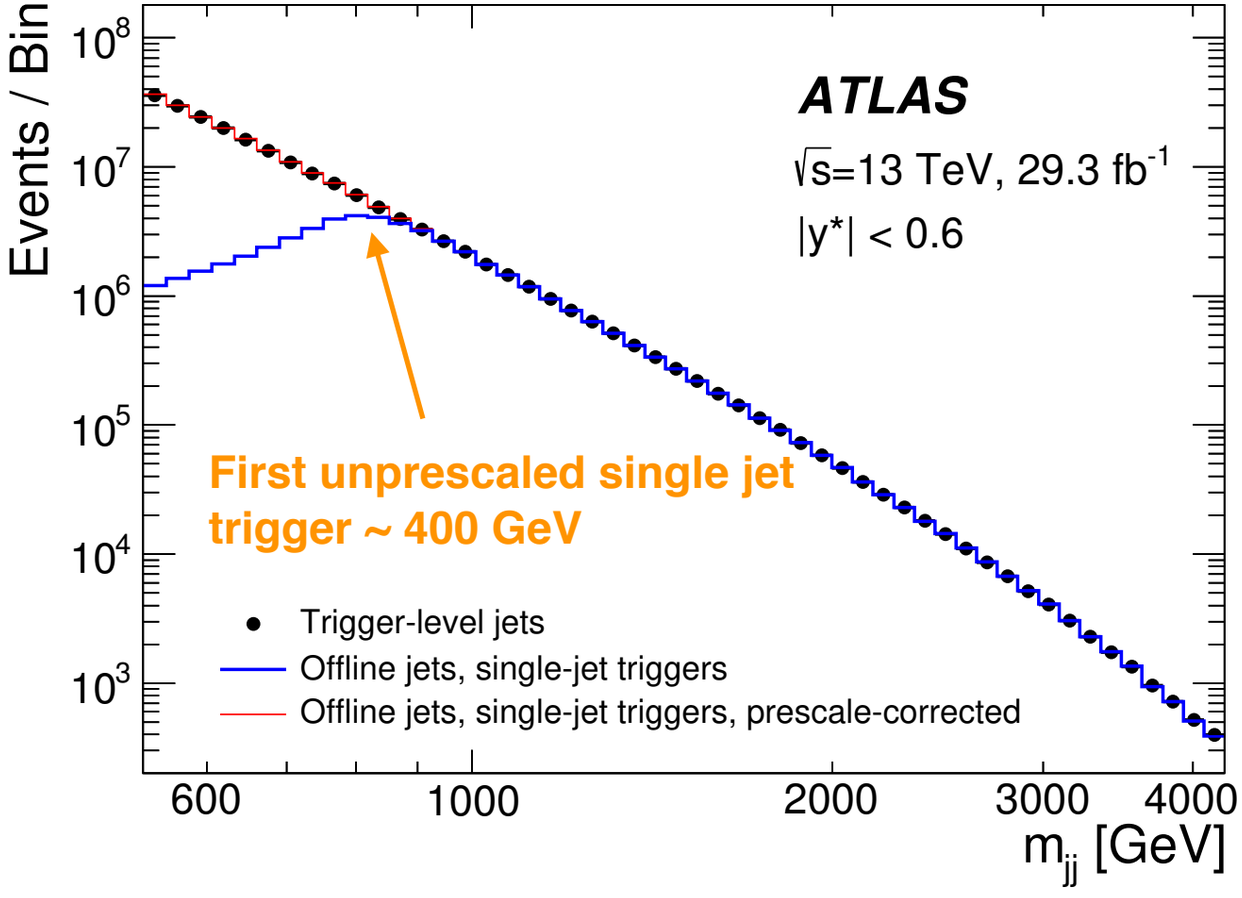



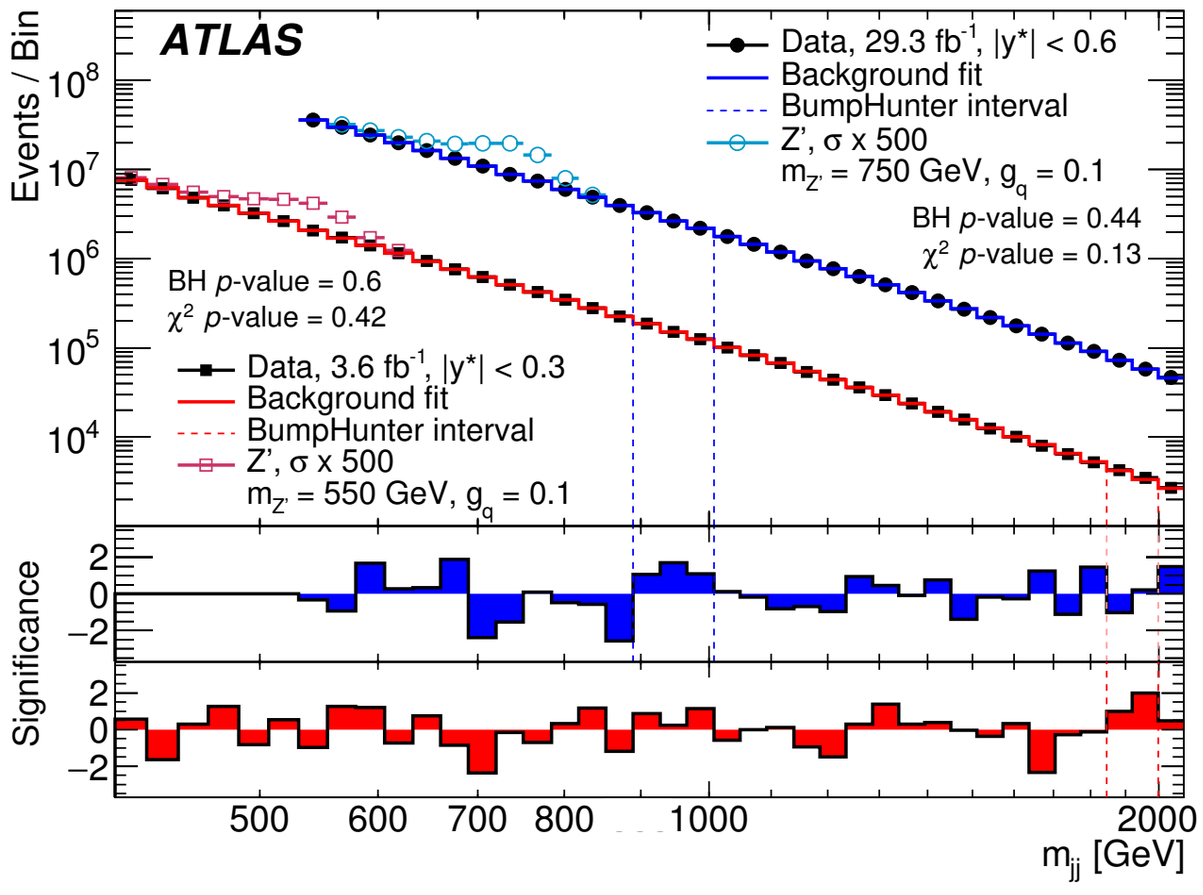
# Di-Jet

arXiv:1804.03496

**Low mass di-jets**

- Use trigger level objects in a reduced event format (0.5%) to take data at much higher rates (20x)
  - Comparable performance to offline jet reconstruction (~0.05%)
  - Sensitive to the region 450 GeV to 1 TeV
- Extend range to lower masses with initial state radiation (photon or jet)

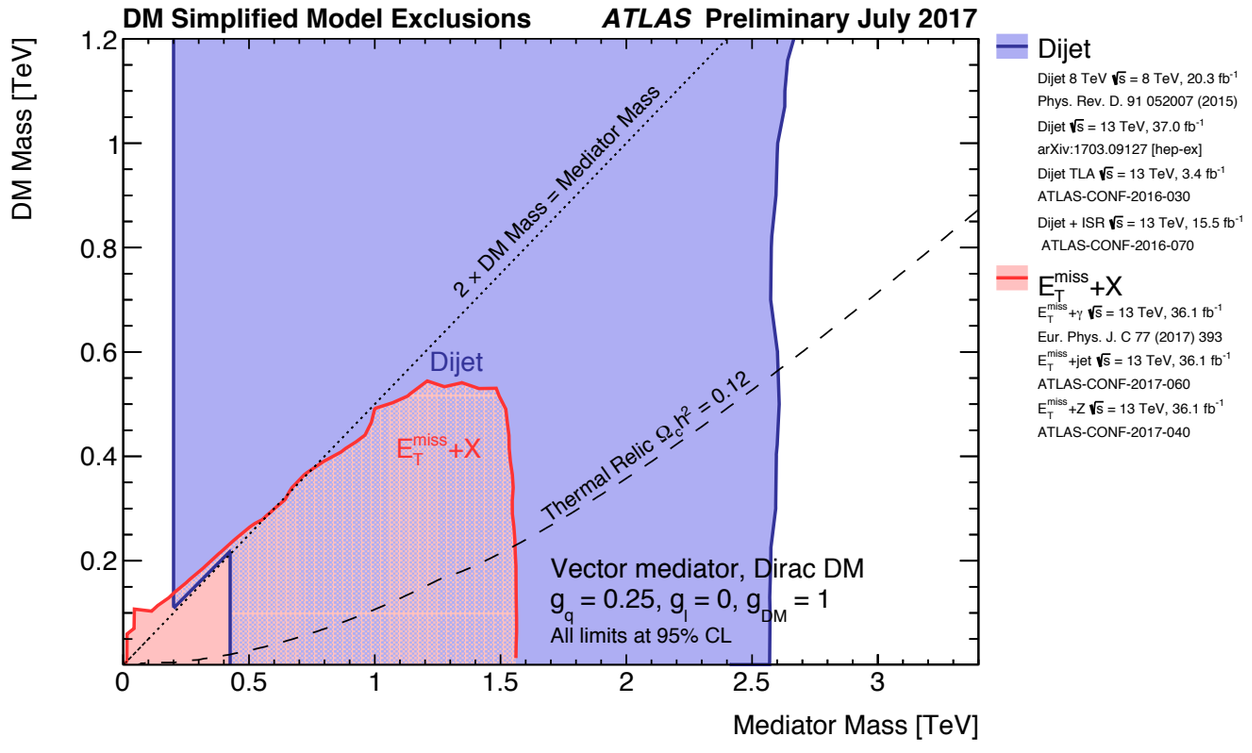


# Mono-X and di-X

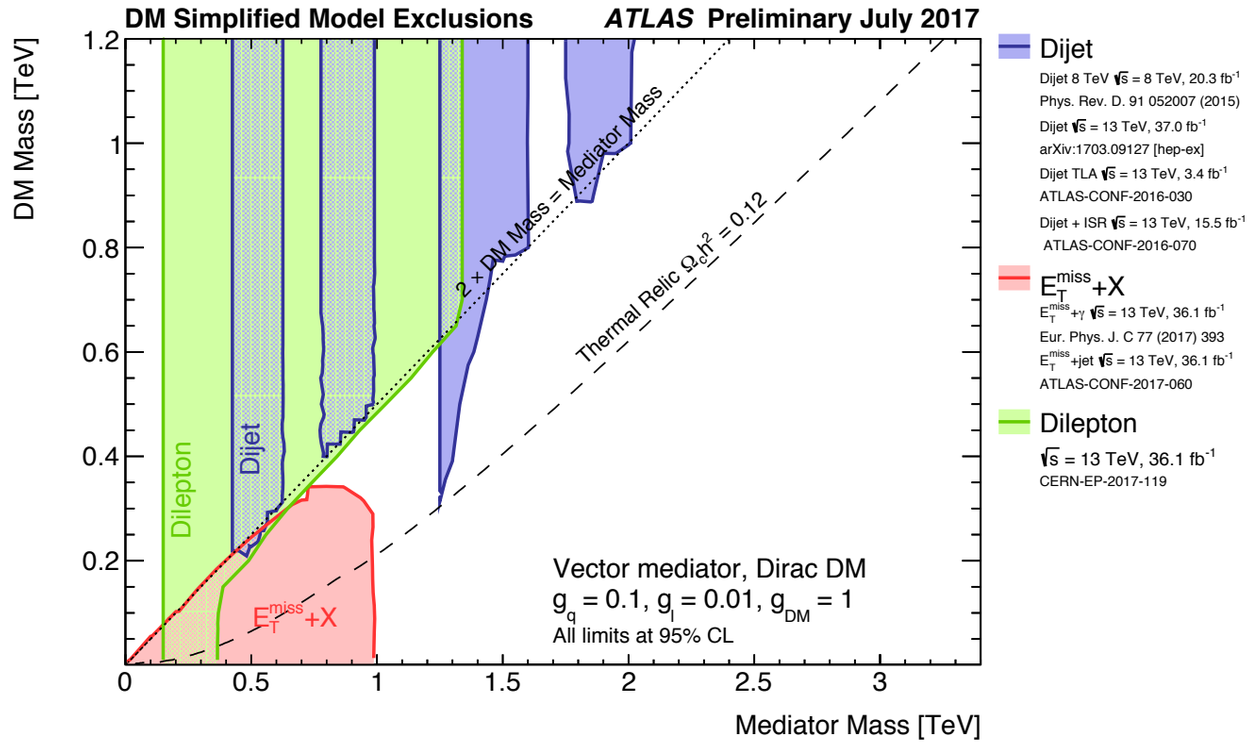
- Complementarity between **mono-X** and **resonance** searches
- Relative exclusion power depends on the model couplings

No couplings to leptons




$g_q = 0.25$, $g_l = 0$, $g_{DM} = 1$

Non-zero couplings to leptons

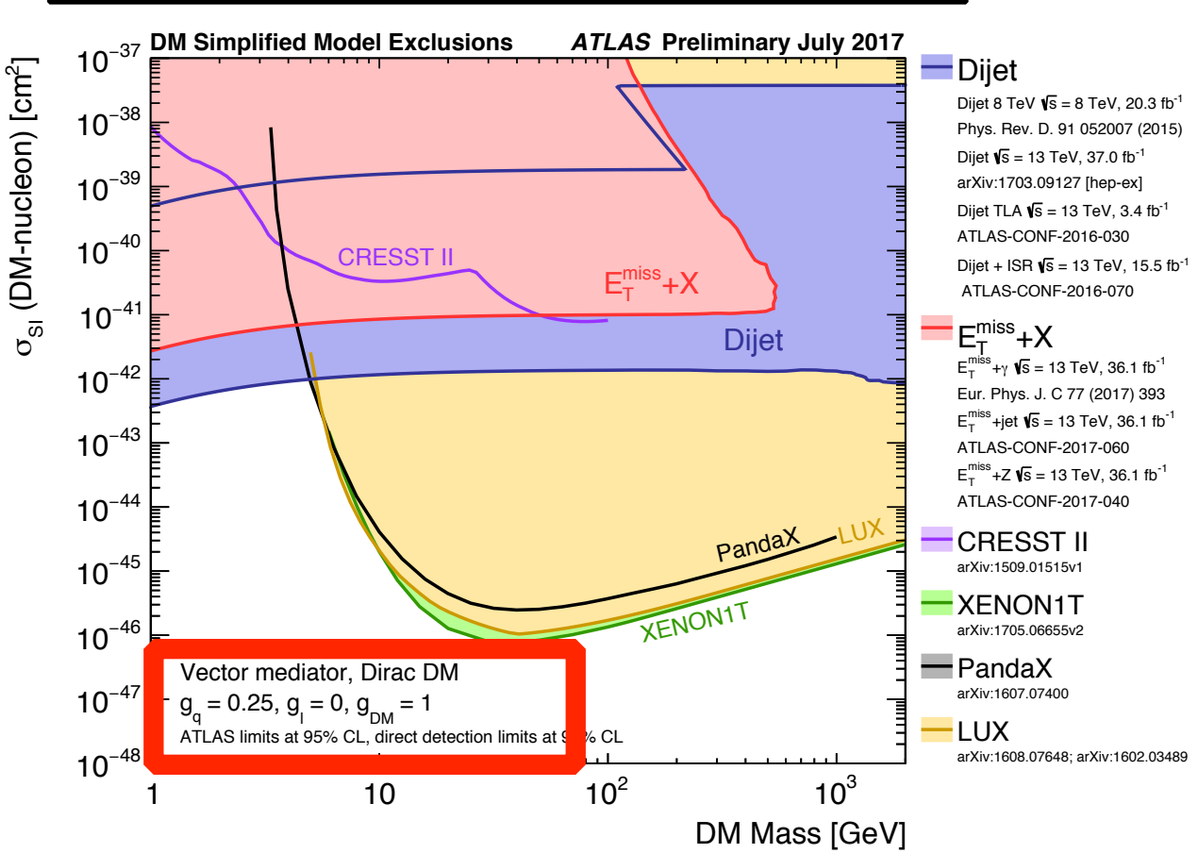



$g_q = 0.1$, $g_l = 0.01$, $g_{DM} = 1$

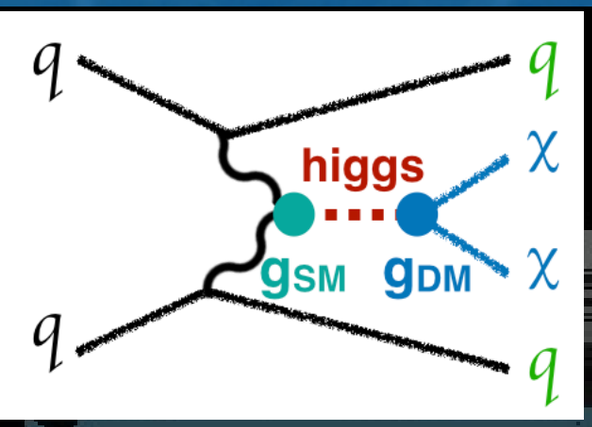
# Collider and Direct detection

- Rates of DM production are used to calculate cross sections of other processes involving DM particles
  - ✦ DM annihilation cross section: relic abundance and indirect detection
  - ✦ DM-nucleon scattering: event rate in direct detection (see below)
- **Important** to establish connection with non-collider experiments and cosmological observations if a **DM signal is observed**

Spin Independent - Nucleon



# VBF Higgs to Invisible



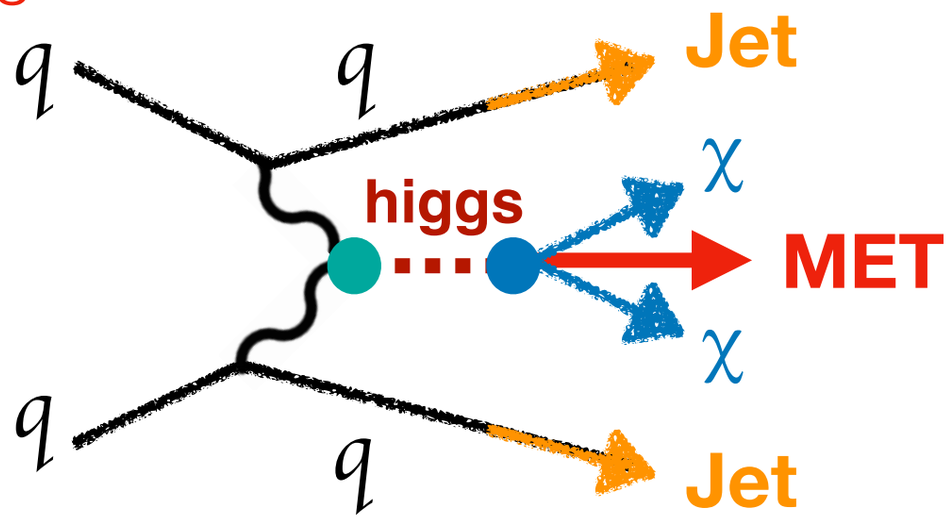

MET

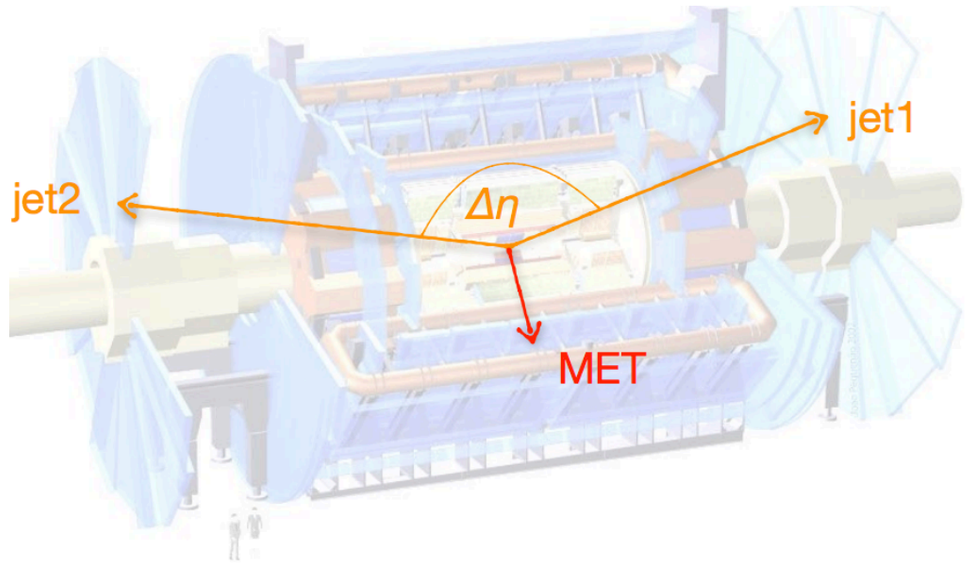
Jet

Jet

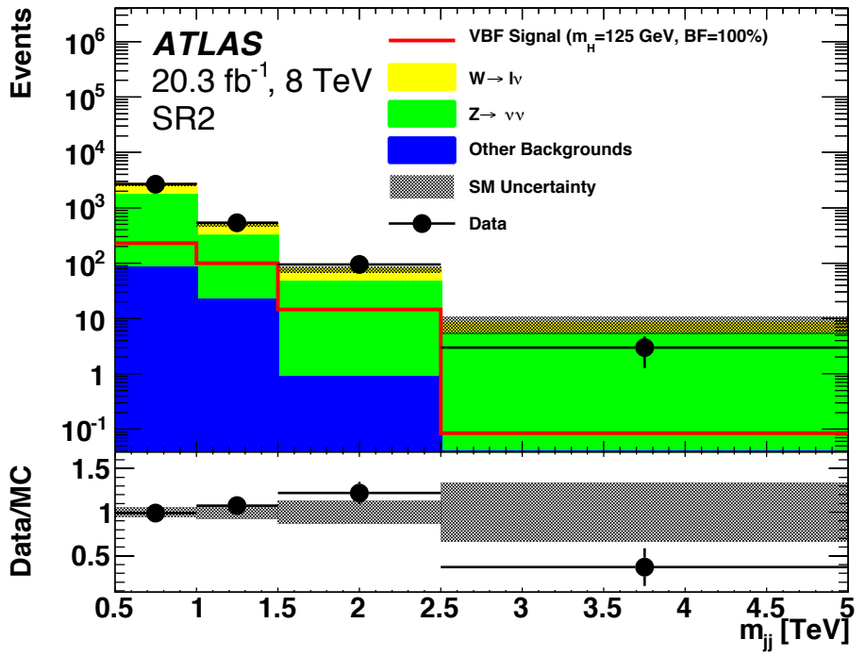
# VBF Higgs to Invisible

- Signature: select events with **2 well-separated jets** and triggered by **MET**




- Main backgrounds: Z(νν)+jets and W+jets
- Constrain the W and Z backgrounds using control regions with visible leptons
- Treat leptons as invisible to mimic the signal region



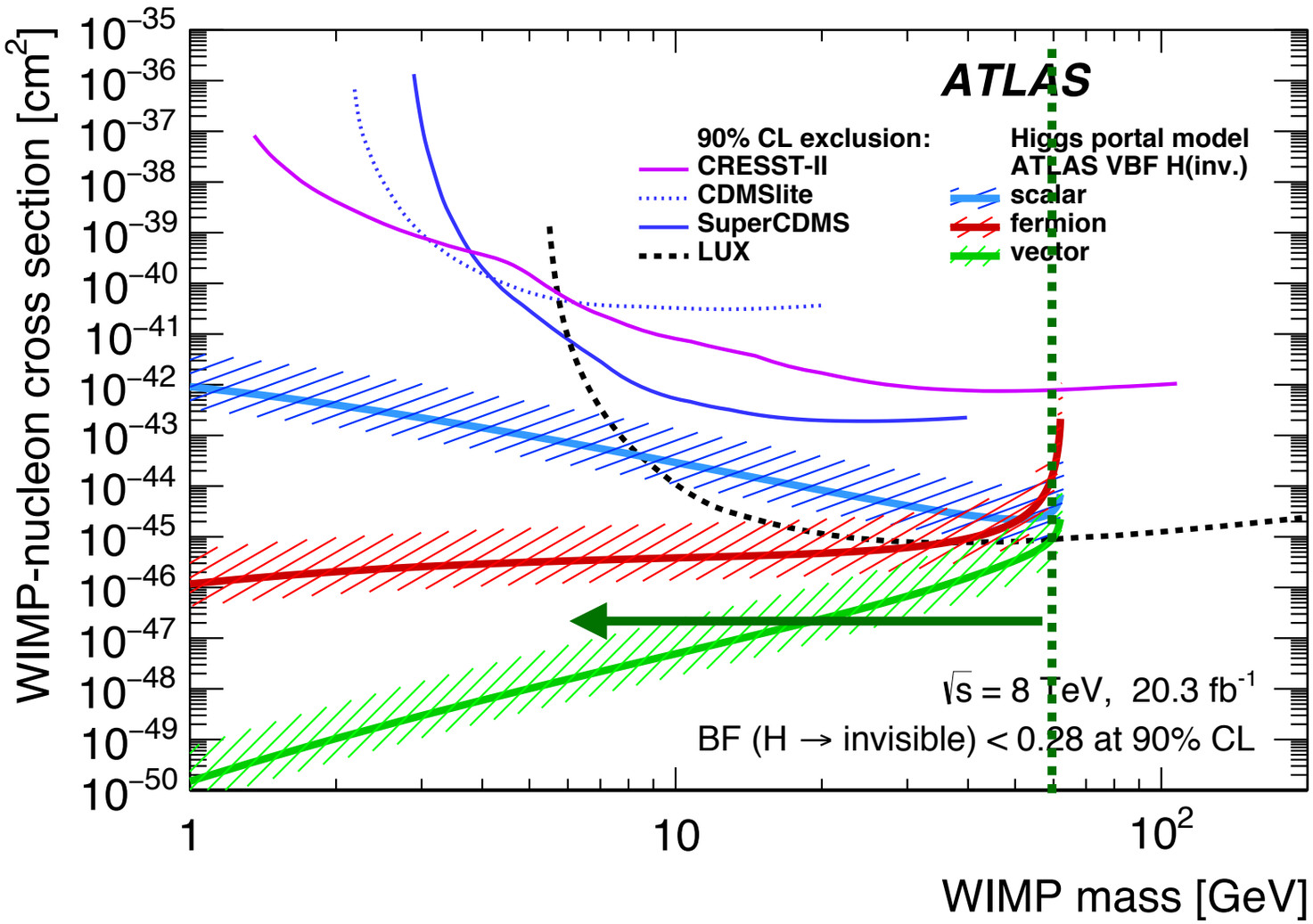

Upper bound on branching fraction of Higgs to Invisible at 95% CL:

**Observed = 0.28**

**Expected = 0.31**

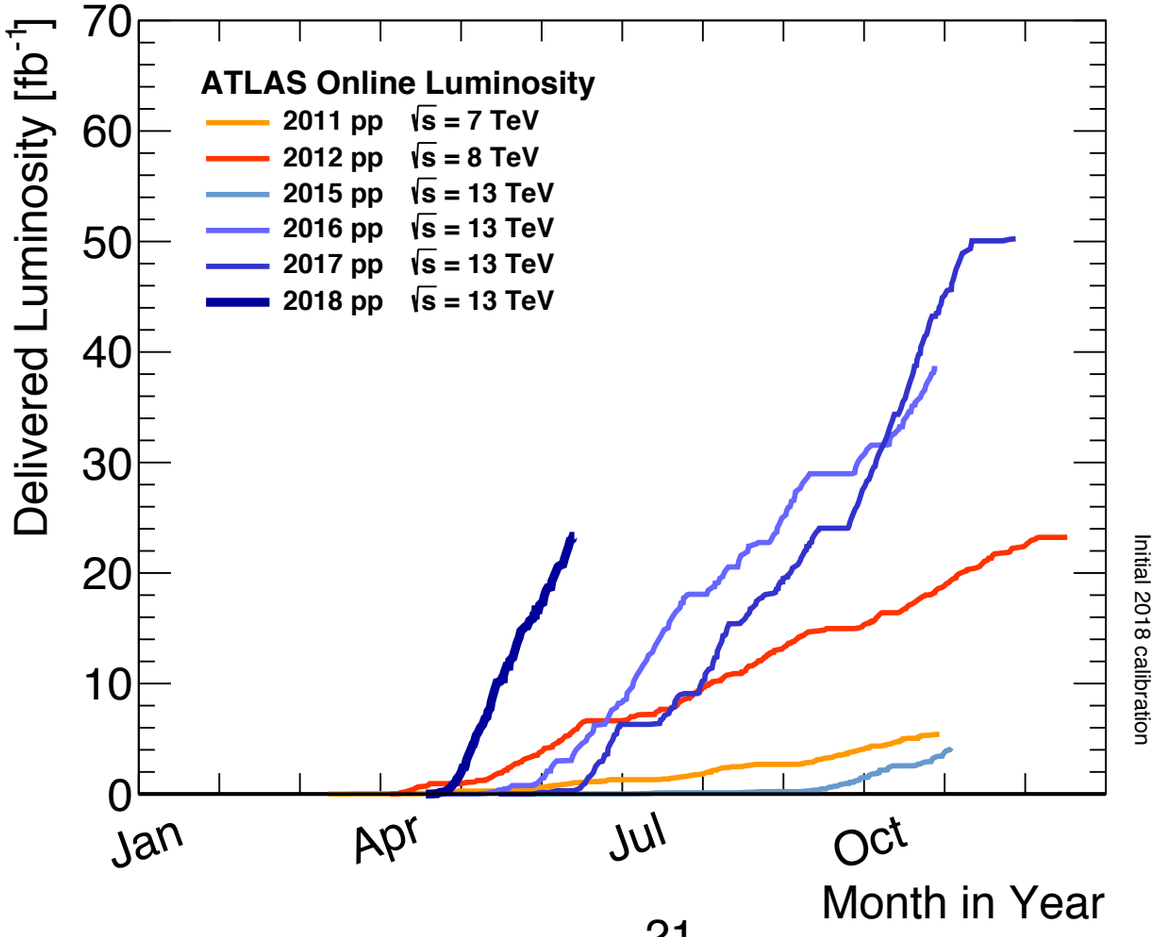
# VBF Higgs to Invisible

- Higgs to invisible will limit the potential Higgs coupling of candidate models with $m_{DM} \leq m_H/2$



# Summary

- Diverse program of dark matter searches in ATLAS
  - **Complementarity** between different final states
  - Proving a variety of benchmark models
- None of the DM searches have observed a significant excess over expected backgrounds
- Many more searches in progress and more data coming in!
  **Stay tuned…**



# Backup

# Phenomenology

Two important approaches to search for DM:

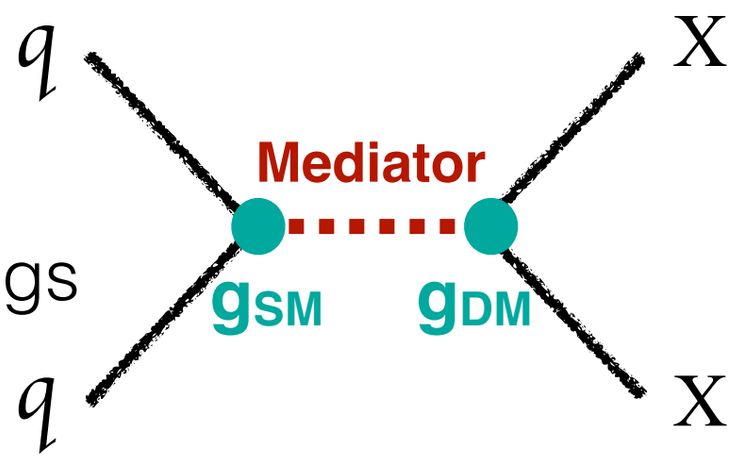
- **Effective field theory**: DM particle is the only accessible state beyond the SM at the LHC **Mediator energies >> Energy transfer at the LHC**
- **Simplified models**: Mediator is light enough to be produced at the LHC **Focus on this approach**

Interesting simplified models have been identified as benchmark scenarios for LHC searches focusing on s-channel light mediator:

- **Spin-1** models with **vector** or **axial-vector** mediators
- **Spin-0** models with **scalar** or **pseudo-scalar** mediators

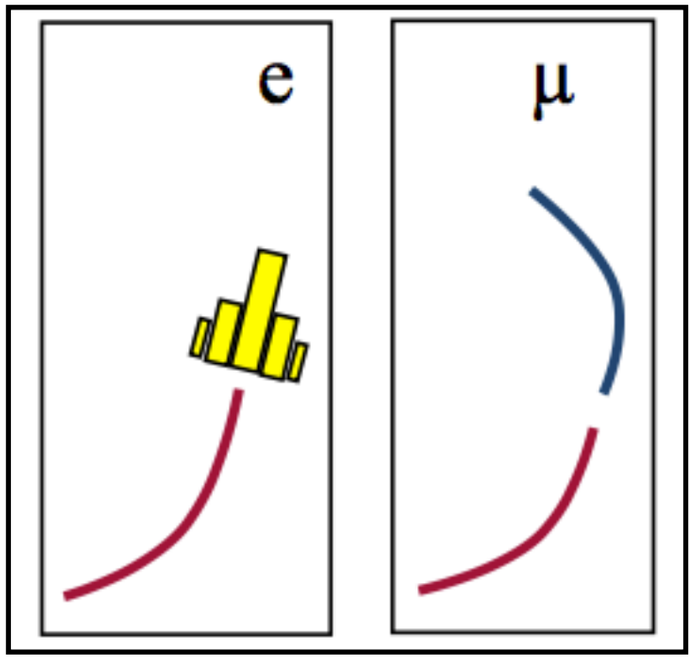
Fully characterised by five parameters:

- Masses $m_{mediator}$ and $m_{DM}$
- Mediator couplings: $g_{SM}$, $g_{DM}$
- Mediator width $\Gamma_{mediator}$ fixed minimal allowed value for chosen masses and couplings

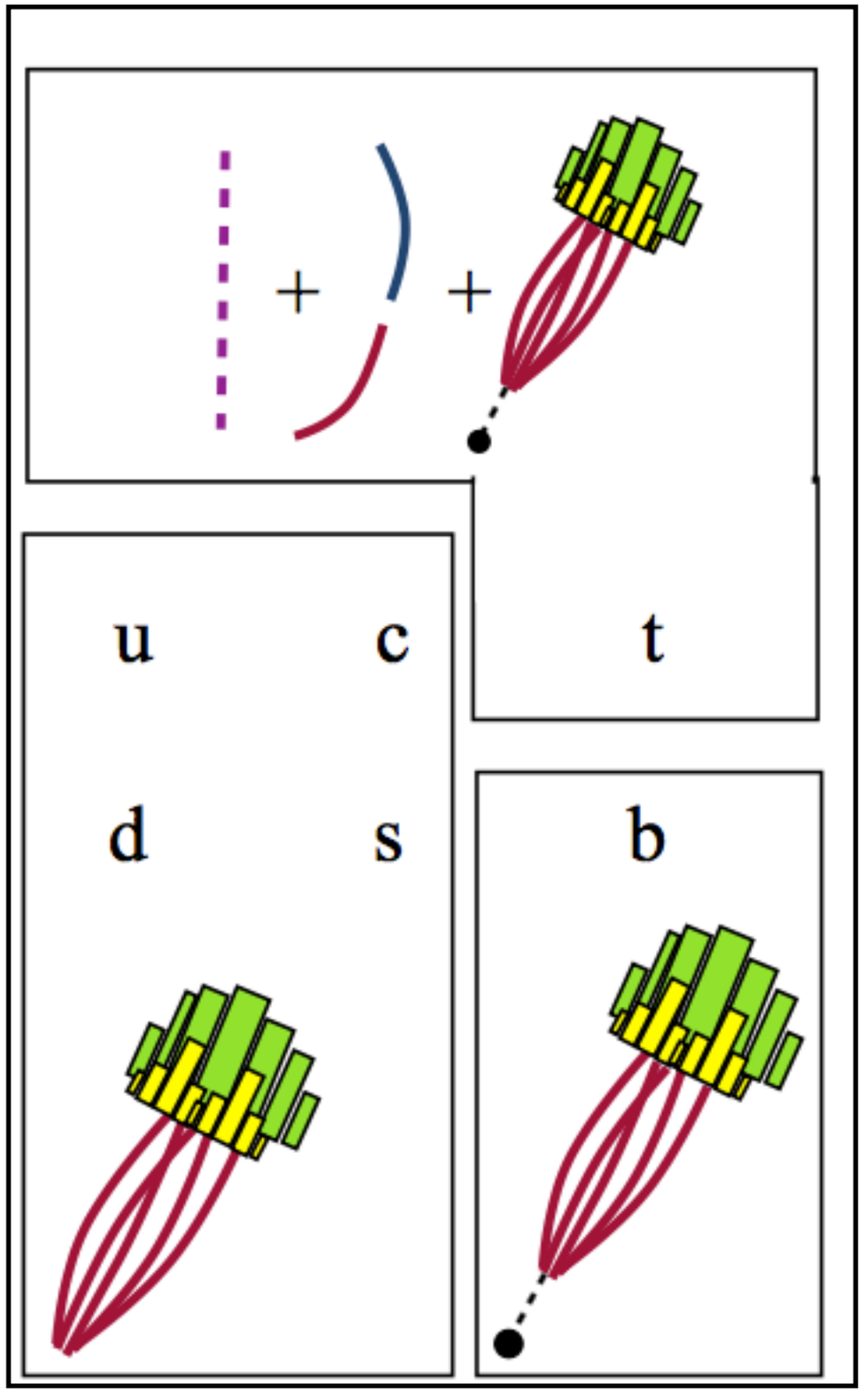



**Disclaimer:** only covering examples of the ATLAS DM search program!

# Identifying Particles

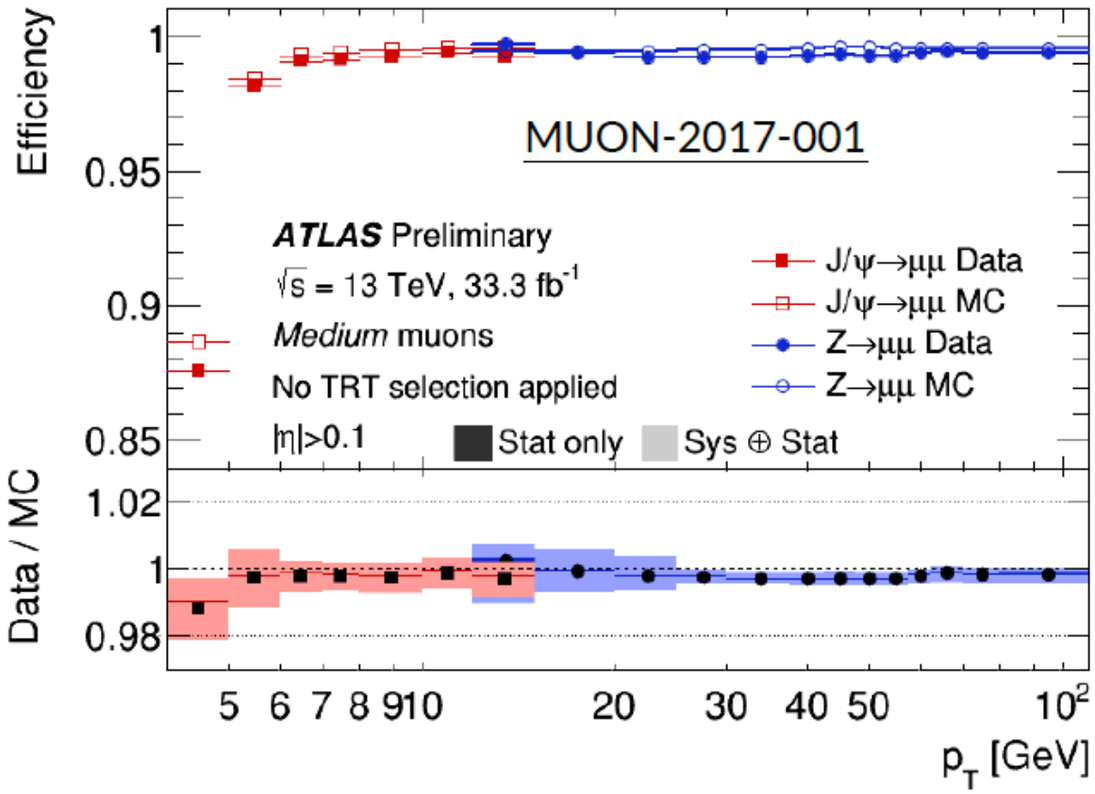


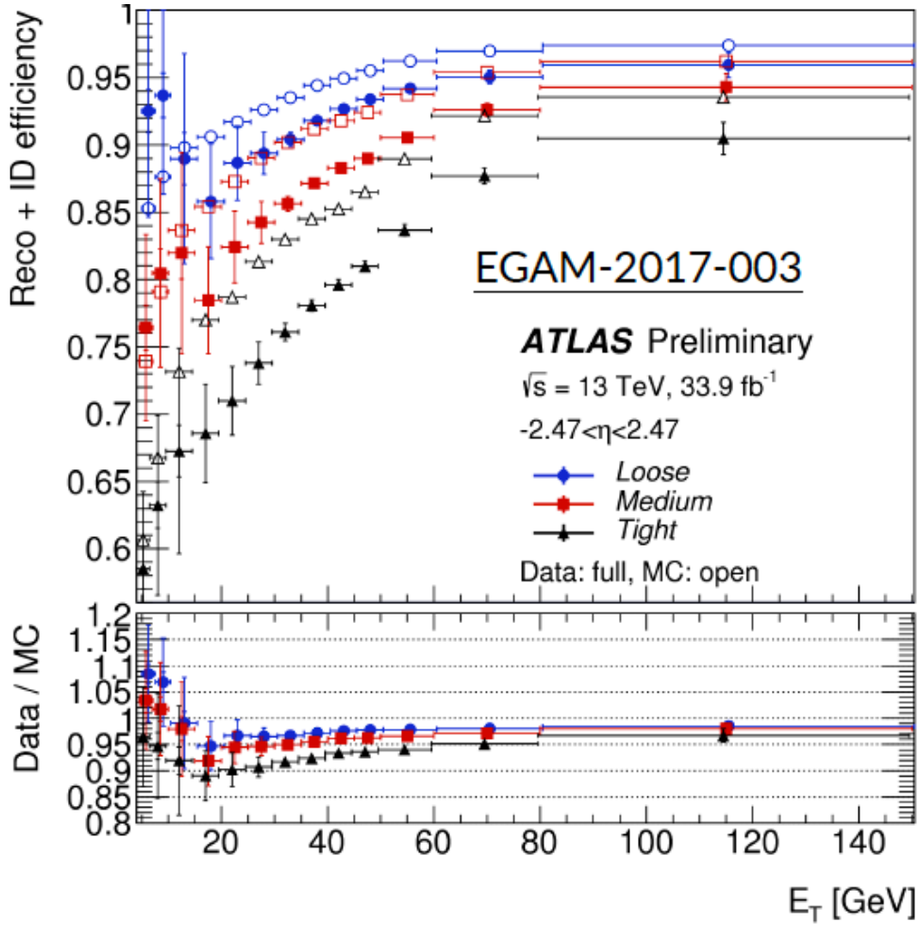

A lot of effort goes in the algorithms that identify these particles



# Performance

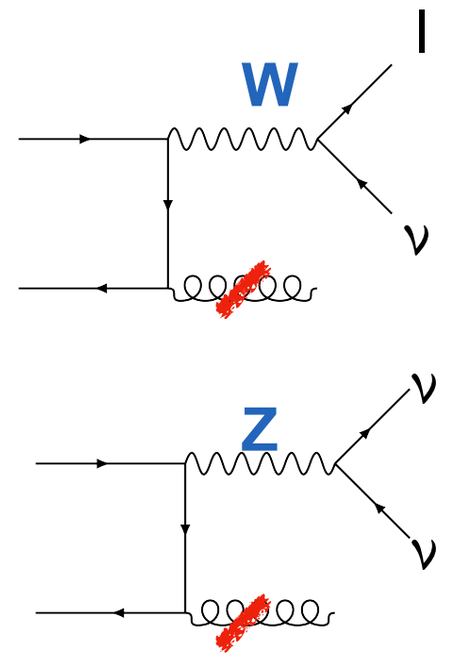
- **Lepton reconstruction performance** is crucial to exploit W/Z physics at the TeV scale
- Rely on **lepton Identification and reconstruction uncertainties** to constrain standard model backgrounds from the data (especially for Zvv)

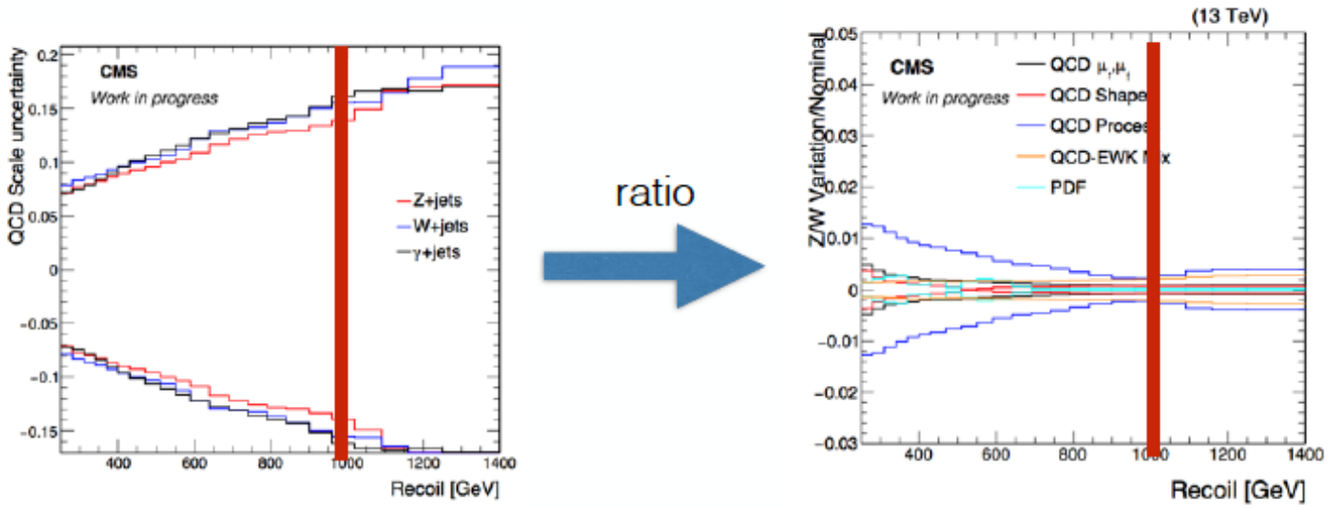


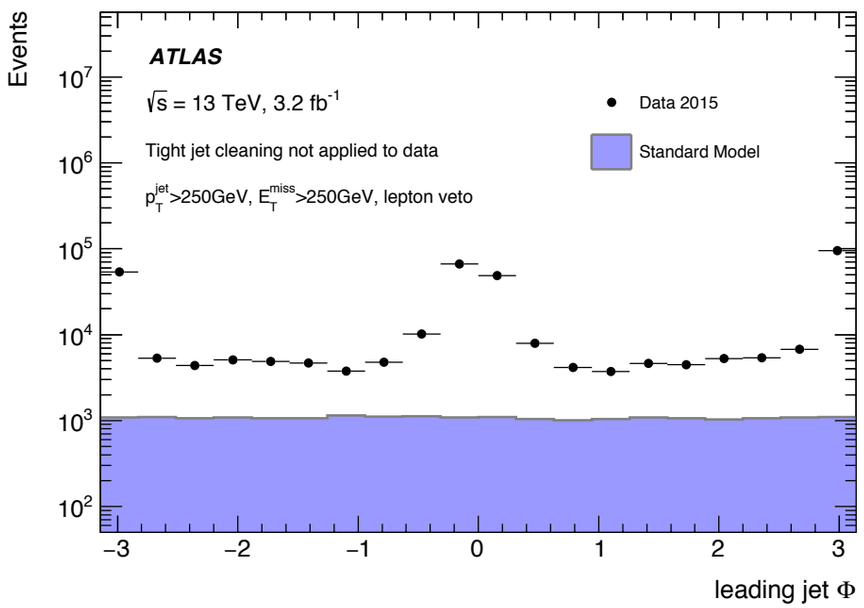



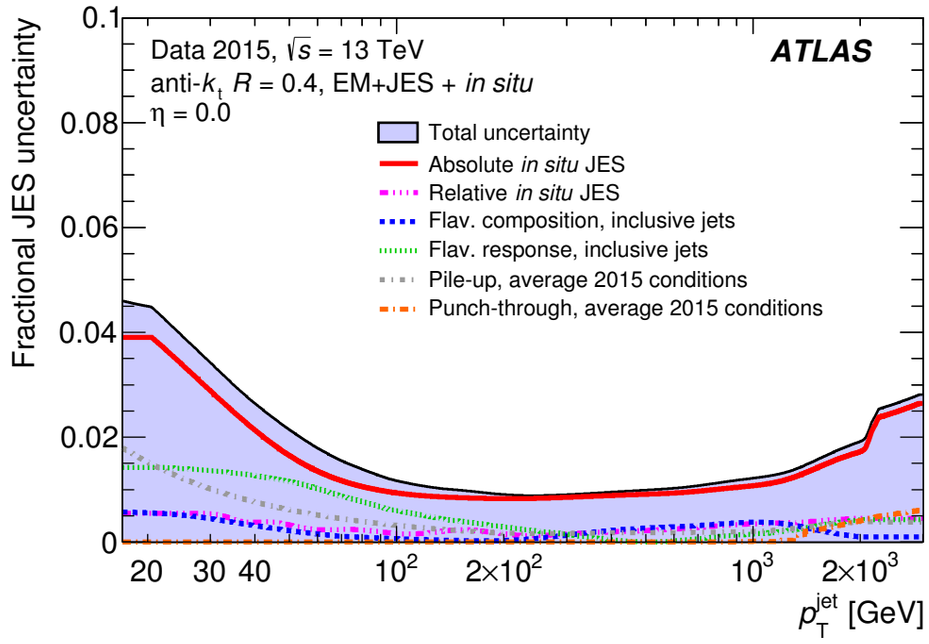
# Mono-jet

- MET Trigger with **250 GeV** threshold
- Backgrounds from **Z(vv)+jets** (56%) and **W(lv)+jets** (37%)



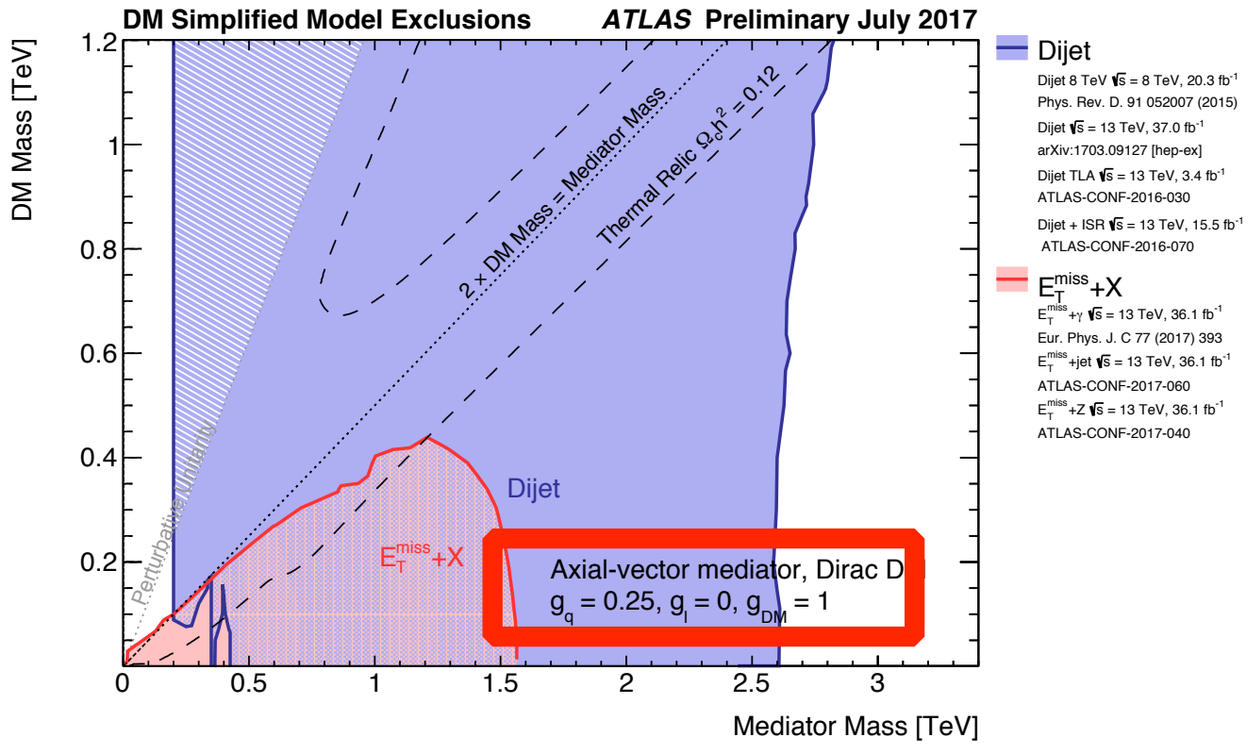



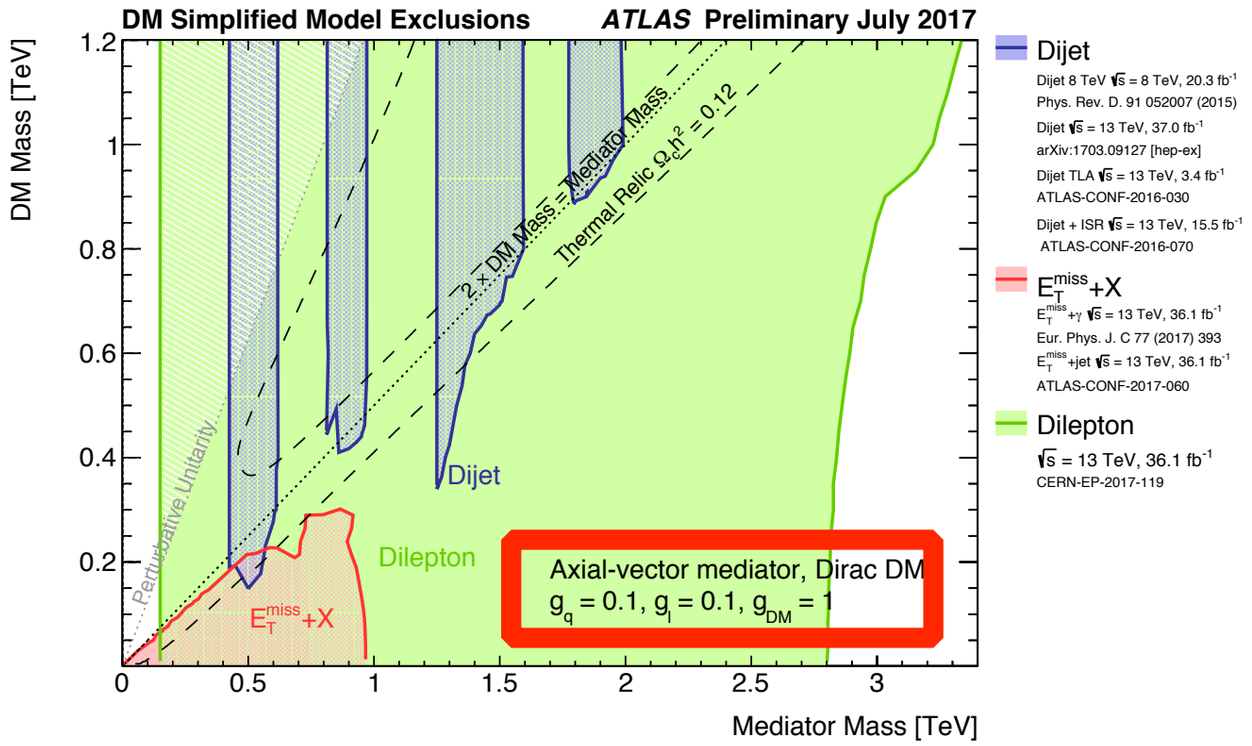
# mono-X and di-X

- Example result for axial-vector mediator
- Complementarity between **mono-X** and **resonance** searches

No couplings to leptons



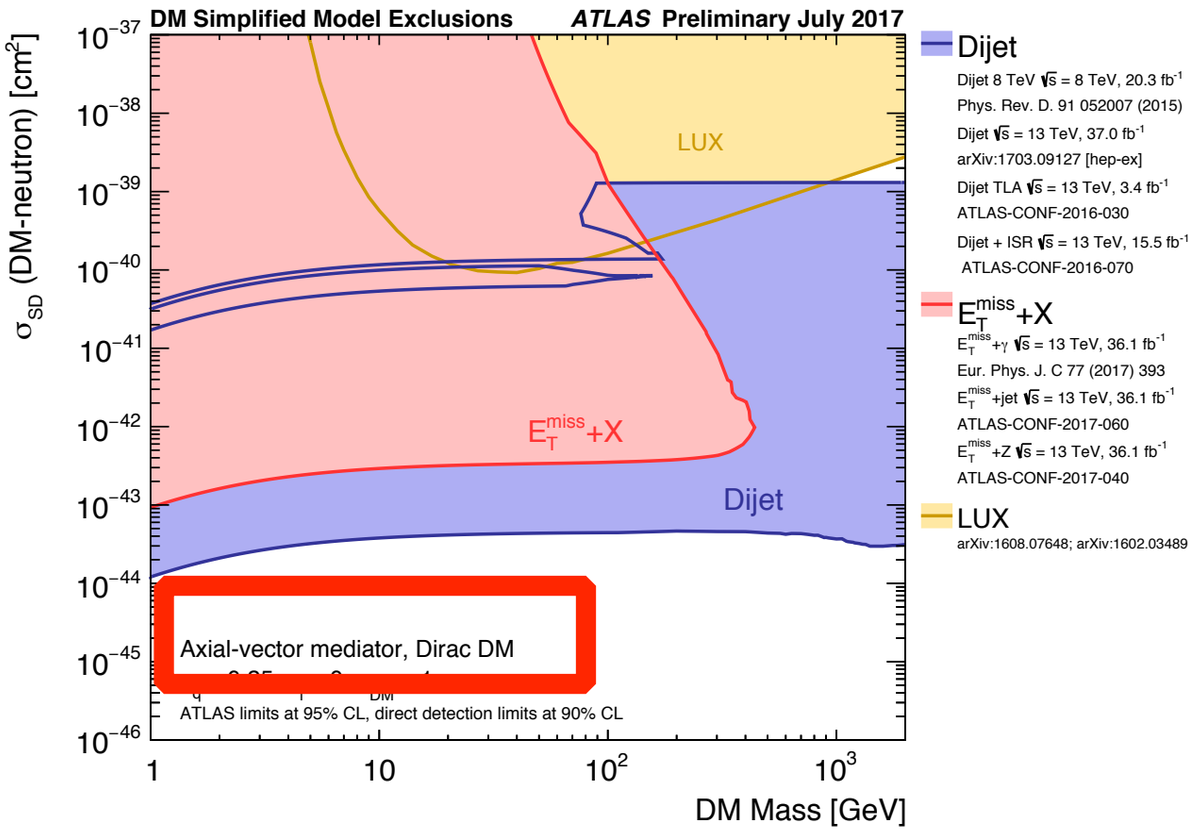

Non-zero couplings to leptons



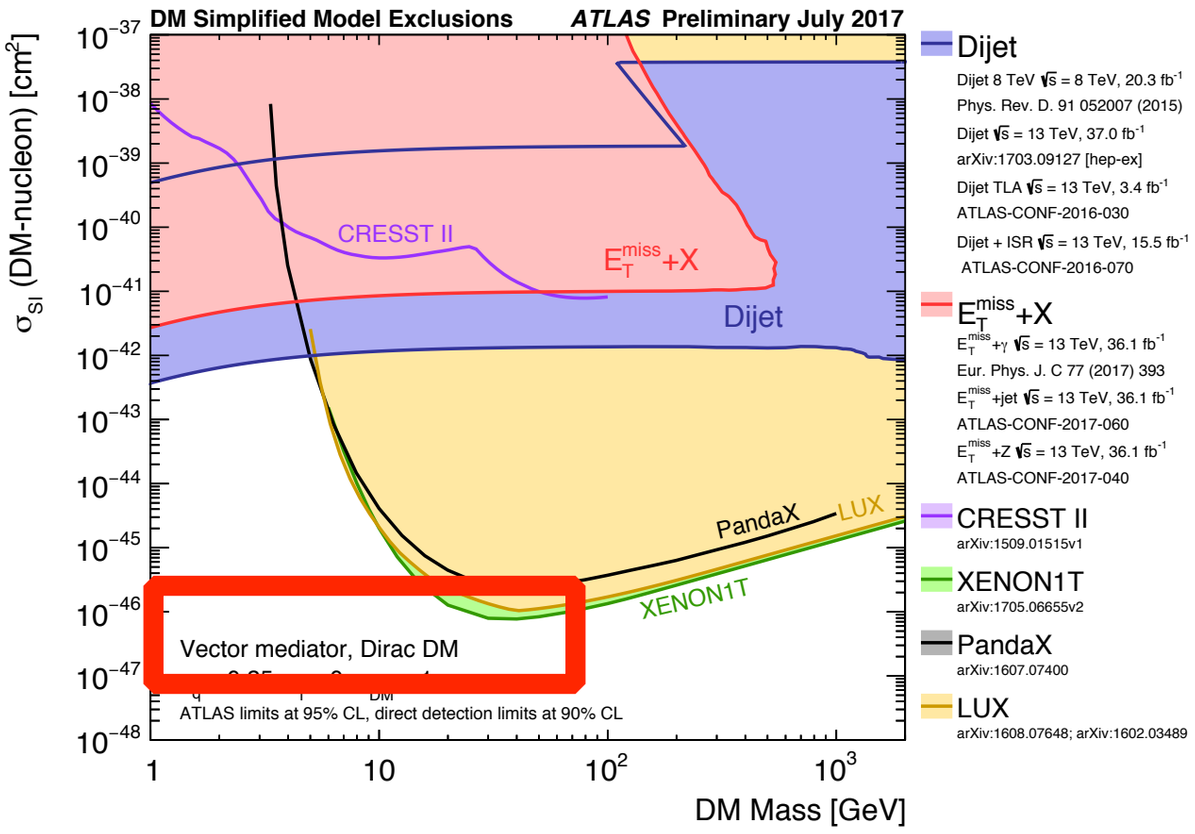
# Comparison with Direct Detection

- Complementarity between **colliders** and **direct detection**

## Spin Dependent - Neutron



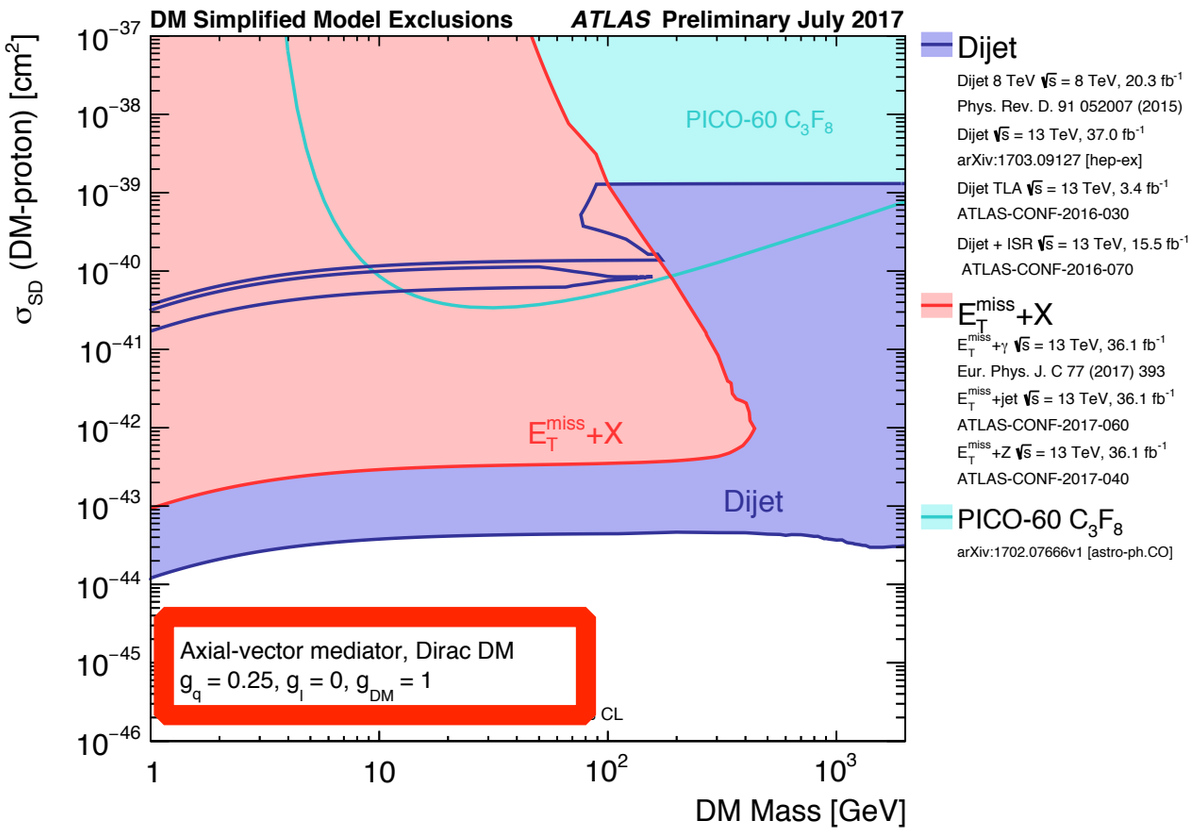

## Spin Independent - Nucleon



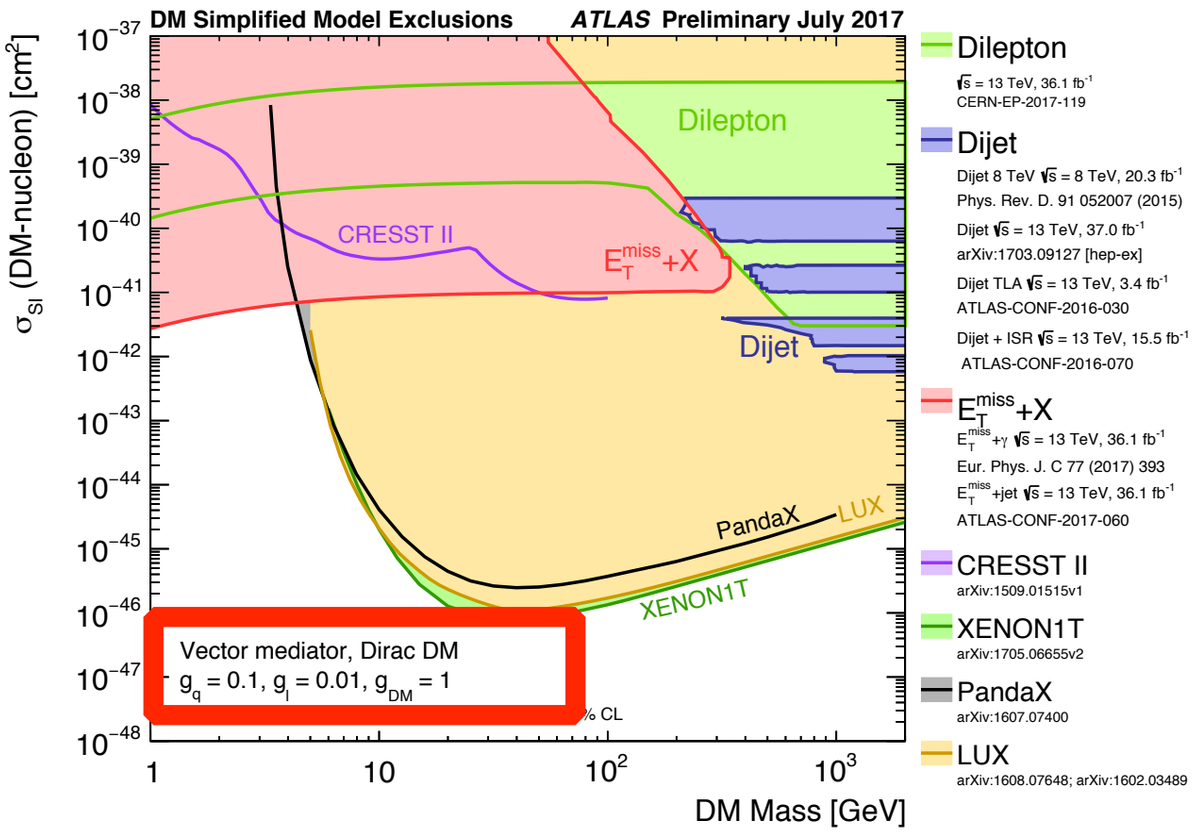
# Comparison with Direct Detection

- Complementarity between **colliders** and **direct detection**

## Spin Dependent - Proton



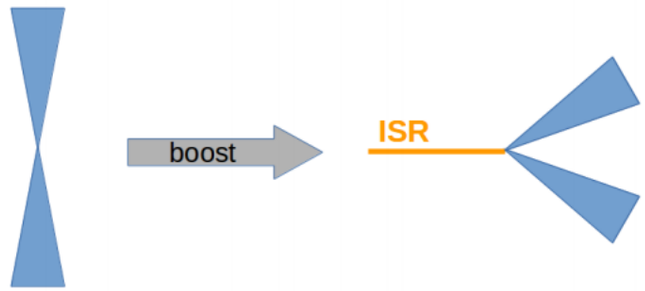

## Spin Independent - Nucleon

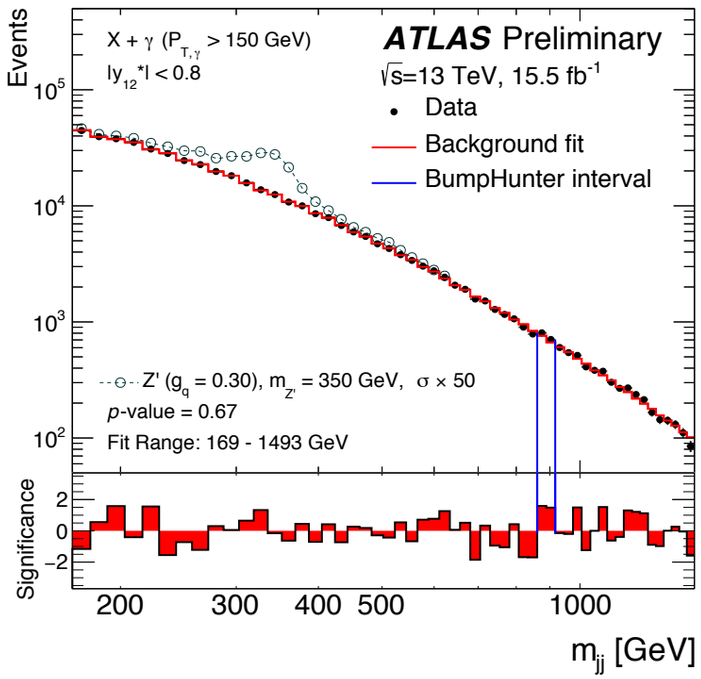


# Di-jets + ISR

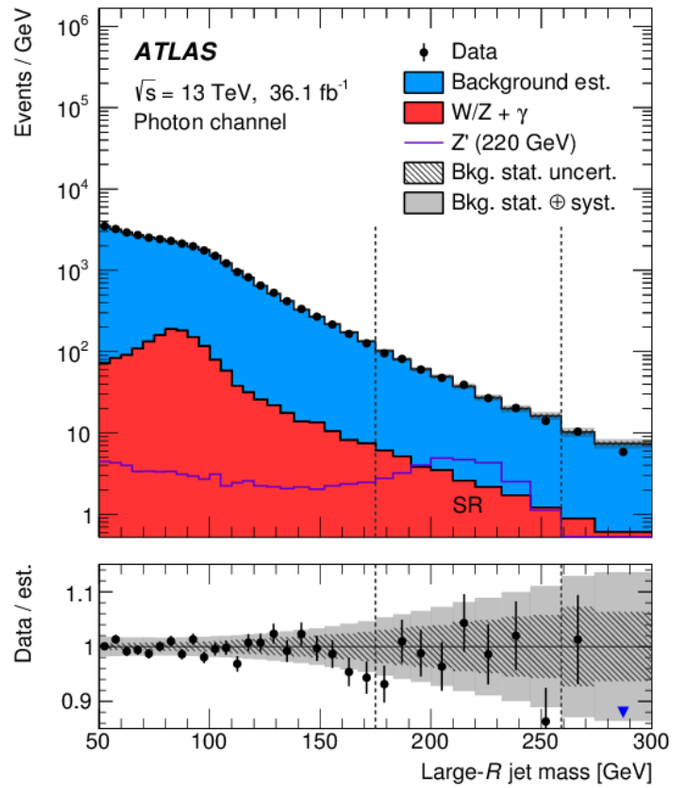
- Complementarity between **colliders** and **direct detection**
  - Resolved: ATLAS-CONF-2016-070
  - Merged: arXiv:1801.08769

## Resolved Di-jets + ISR




## Merged Di-jets + ISR

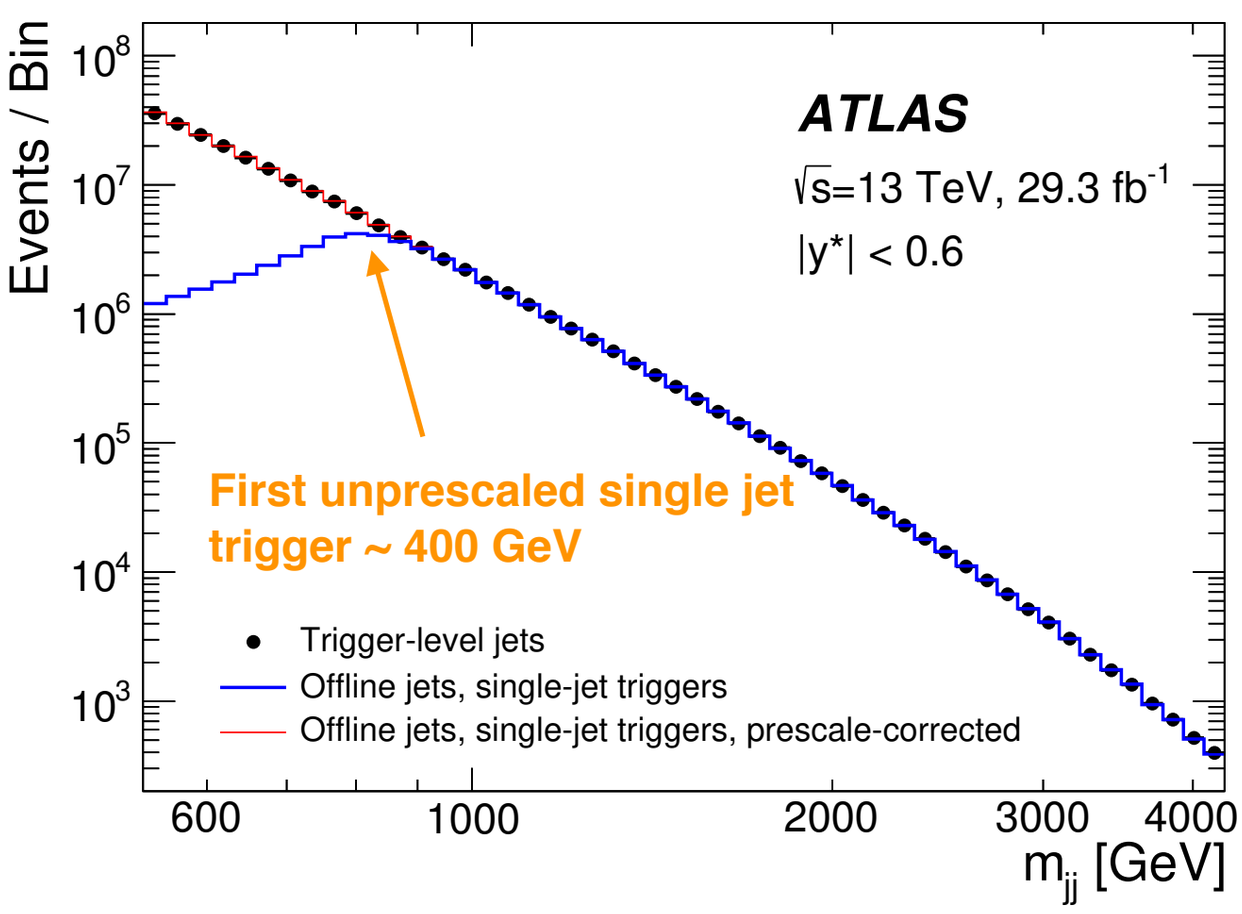



# TLA

arXiv:1804.03496

**Low mass di-jets**

- Limited sensitivity of classic dijet search for low masses due to trigger thresholds
  - Less sensitive to resonance masses < 900 GeV than SPS/Tevatron searches
- Analyse spectrum of trigger-level objects




- Use Select events at high-level trigger
- Require two jets with pT > 85 GeV
- Store only minimal event information
  - 4-vector calorimeter variables
- Event size: 0.5% the size of a full event
- Probe dijet masses
  450 GeV < mjj < 1800 GeV

# Complementarity of di-jet searches