# Dark Matter searches with the ATLAS experiment at the LHC

Marco Vanadia on behalf of the ATLAS collaboration
Tor Vergata University of Rome and INFN

"From the LHC to Dark Matter and Beyond"
*21st March 2017 Aspen (USA)*

Introduction

- Overwhelming astrophysical evidence for **Dark Matter** (DM) in our Universe
  - DM accounts for **~26% of the Universe content**
- Ok, so what is DM?
  - **gravitationally interacting** matter
  - huge number of candidates
- I'll focus on the **WIMP** paradigm (weakly interacting massive particles)
  - several nice features, weak cross section -> correct relic abundance, stable, cold
 - excellent interplay between **indirect**, **direct** and **collider** searches

DM   Indirect   **SM**

Direct

DM   Collider   **SM**
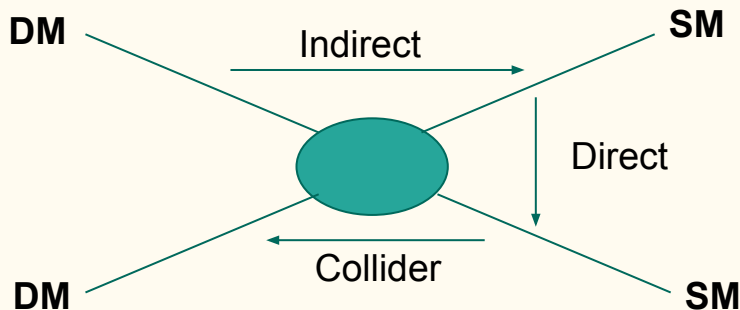
The Large Hadron Collider and the ATLAS exp.

- LHC started **run-2** in 2015, proton vs proton @ $\sqrt{s} = \mathbf{13}$ **TeV**
- **Parton luminosity** for producing **massive states** is greatly **enhanced** -> great opportunity for **searches!**
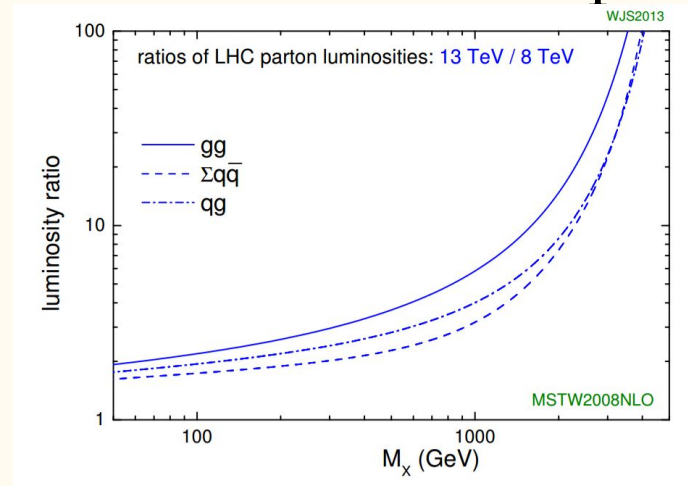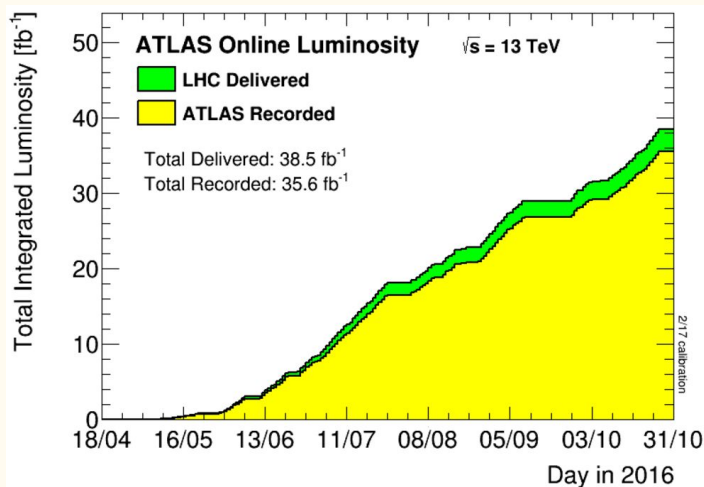
- Almost **40/fb of data collected** by the ATLAS experiment with excellent performance
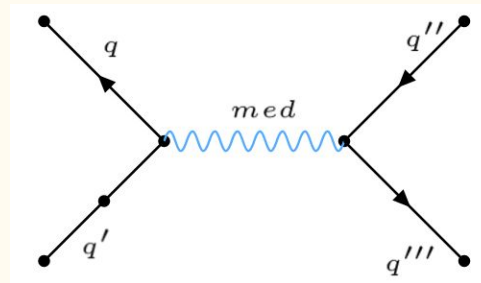 - already more than run-1!

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Overview on DM searches in ATLAS
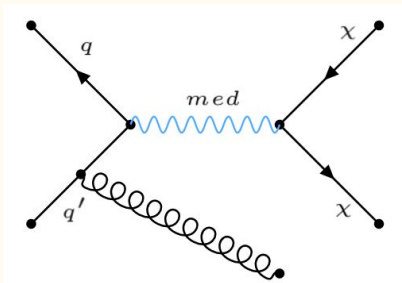
Benchmark models moving from **EFT** to **simplified model** approach (see arXiv: [1507.00966](), [1603.04156]())

Mono-x searches

- Jet+X
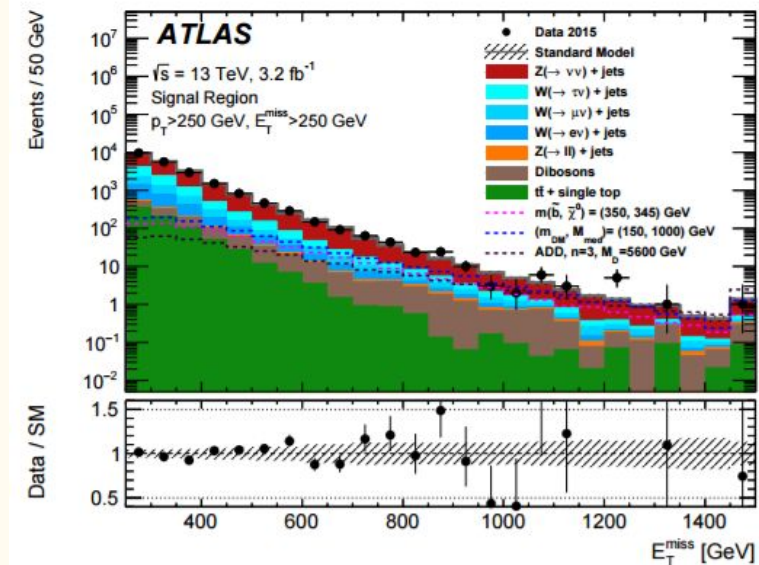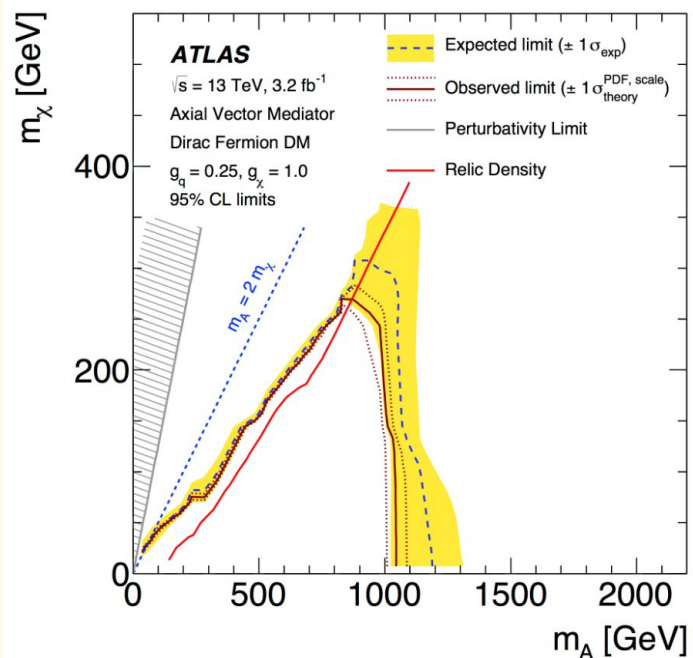- Photon+X
- H+X
- W+X
- Z+X
- $\ell\ell$+X
- tt+X
- bb+X
- ...

Di-x searches

- Di-jet
- Di-jet @ trigger level
- Di-jet + ISR
- Di-b-jet
- ...

- Long-lived particles: talk by Andrew Haas
- BSM Higgs, Higgs->invisible: talk by Nikolina Ilic
- More exotics results: talk by Jacob Searcy

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Jet + X 3.2/fb @ 13 TeV, PRD 94 (2016) 032005

- Select events with **high p_T jet(s)** and **E_T^{miss}**
- Trigger fully efficient for $E_T^{miss} > 250$ GeV
- Dominant bkg **Z(->νν)+jets, W(->ℓν)+jets**
  - constrained in **control regions (CRs)** with leptons

- **Simultaneous fit** to **CRs** and **signal region (SR)**
- No excess -> **limits** on several models
- ADD for Large Extra-Dimensions, squark pairs production, **WIMPs** produced by axial-vector mediator
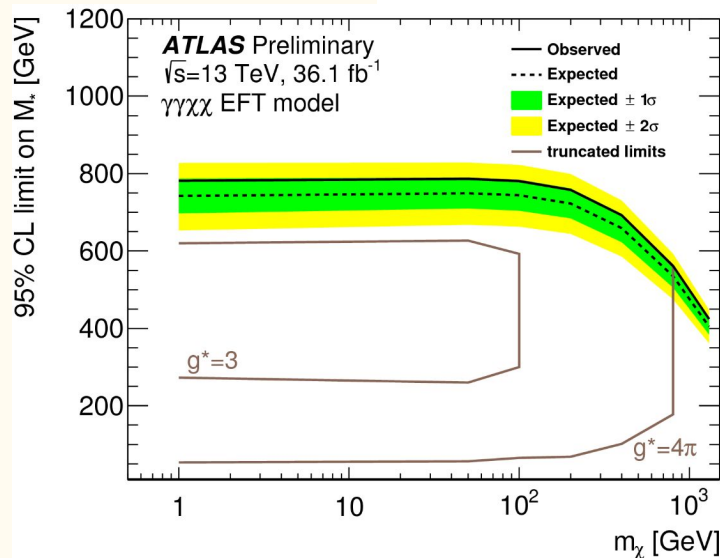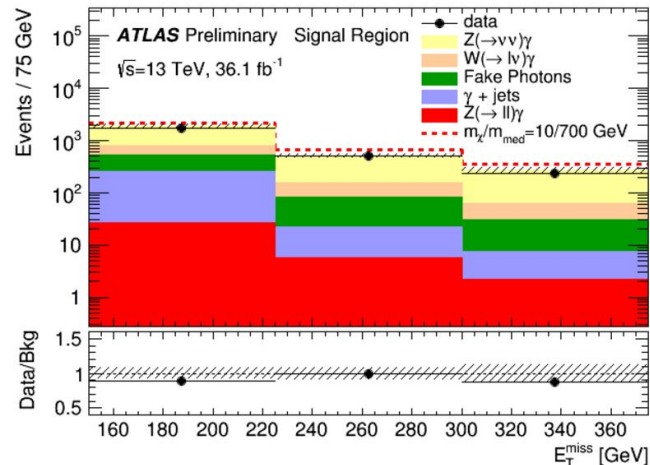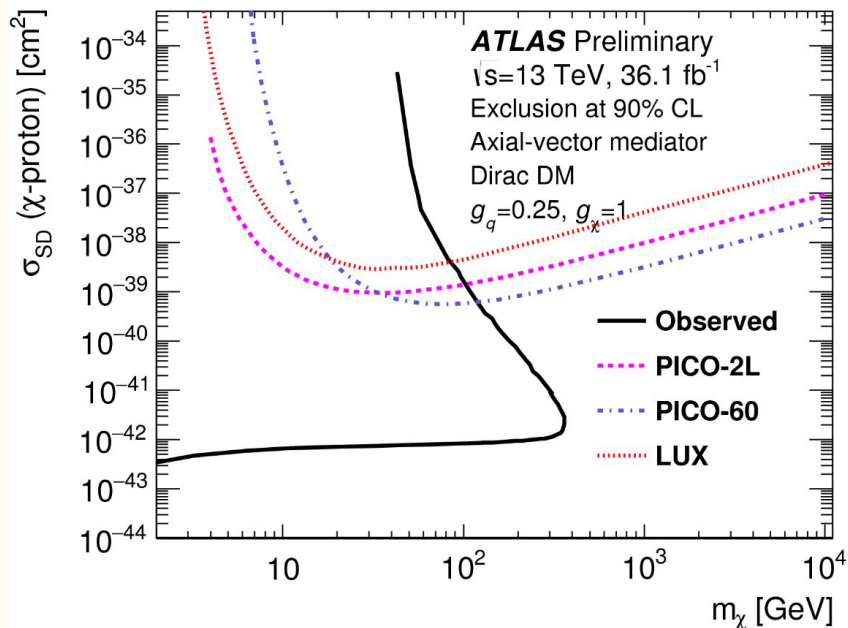
$\gamma + X$ NEW, 36/fb ATLAS-EXOT-2016-032

- **>=1 isolated photon** and E_T^{miss}
- **3 E_T^{miss} regions**: 150-225, 225-300, >300 GeV
- **Z** and **W** bkg from **CRs** with **leptons**
- **Fake photons from electrons** from Z->eγ/Z->ee
- **Fake photons from jets** with ABCD method, CRs with inverted isolation/inverted quality cuts
- $\gamma+$**jet** with a **wrong jet reconstruction:** low E_T^{miss} **CR**
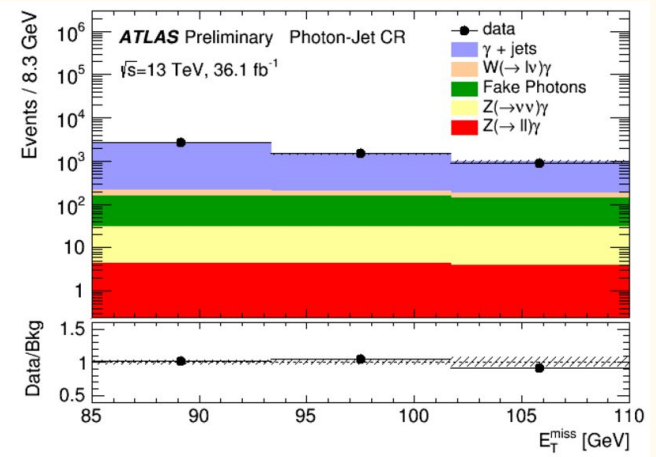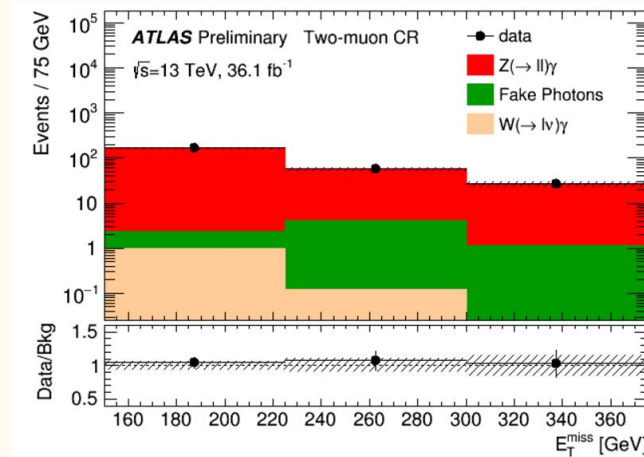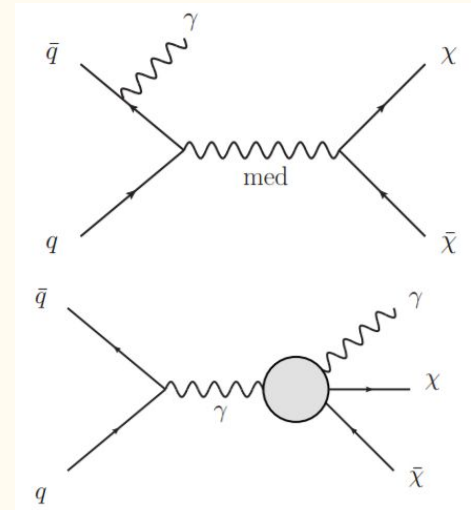
$\gamma + X$ **NEW**, 36/fb ATLAS-EXOT-2016-032

simultaneous fit to all **CRs** and **SR,** no shape fit

- **Statistically limited** measurement
- Limits on **DM production** via **vector/axial-vector**
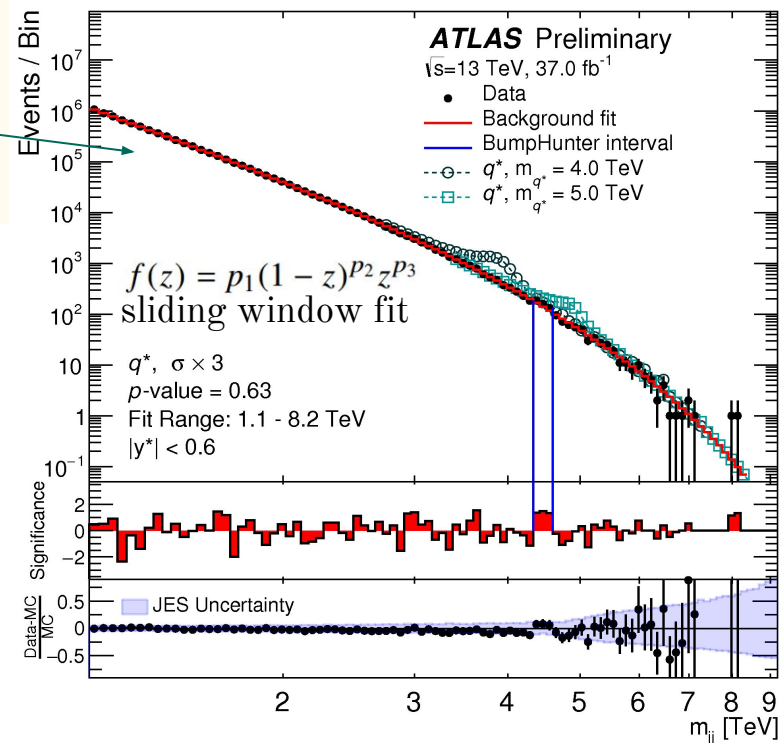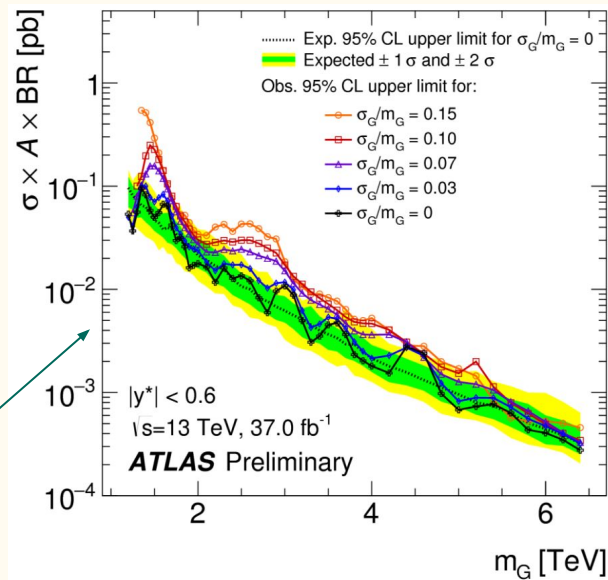 - **X+MET @ collider important for low DM mass, and particularly for spin-dep. int.**

Limits on $\gamma\gamma\chi\chi$ via dimension-7 **EFT** operator

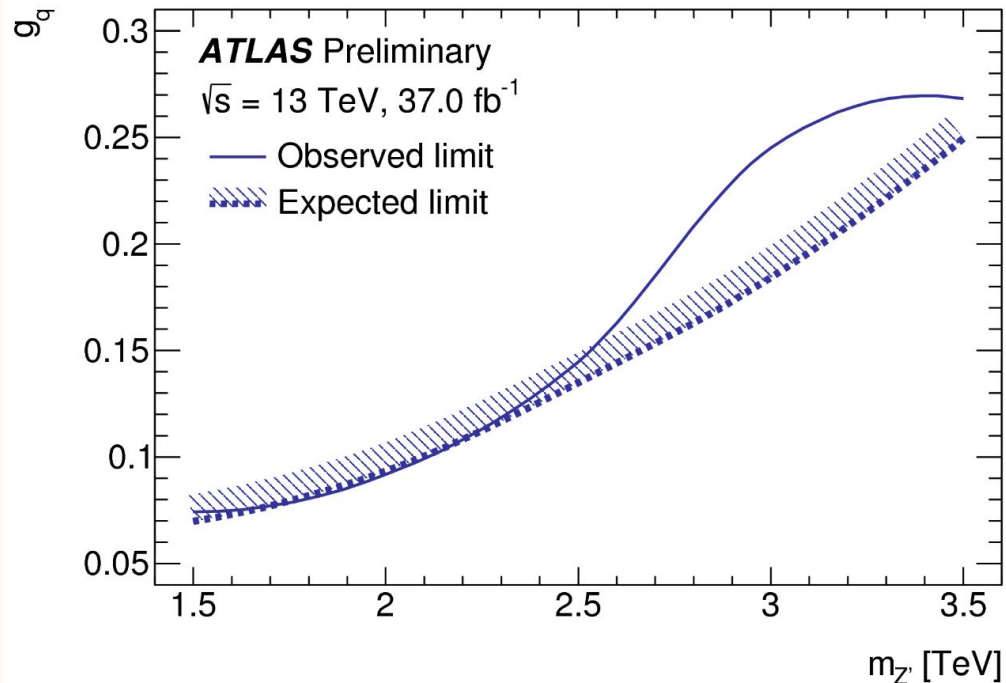# Di-jet analysis NEW, 37/fb, ATLAS-EXOT-2016-021

- Search for **resonances** on m_{jj} **spectrum**
- Completely data-driven: **functional fit**
- **New sliding window fit**, robust for high stat

- No significant excess: **limits** on q^*, quantum black holes, **W', Z'**, W^*
- **New folding** with transfer-matrix: limits on generic gaussian with a **truth-level** width
- Angular analysis: see talk by Jacob

ATLAS Preliminary
$\sqrt{s}$=13 TeV, 37.0 fb^{-1}
- Data
— Background fit
— BumpHunter interval
q^*, m_{q^*} = 4.0 TeV
q^*, m_{q^*} = 5.0 TeV

$f(z) = p_1(1-z)^{p_2}z^{p_3}$
sliding window fit

q^*, $\sigma \times 3$
p-value = 0.63
Fit Range: 1.1 - 8.2 TeV
$|y^*| < 0.6$

JES Uncertainty

$y^*=(y_1-y_2)/2 < 0.6$ explored (1.2 for W^*)
leading jet $p_T > 440$ GeV (due to trigger)
$m_{jj} > 1.1$ TeV (due to trigger)

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Di-jet analysis NEW, 37/fb, ATLAS-EXOT-2016-021

ATLAS Preliminary

$\sqrt{s}$ = 13 TeV, 37.0 fb^{-1}

Observed limit

Expected limit

g_q axis, $m_{Z'}$ [TeV]

NEW Limits on Z'

Limits from previous publication
PLB 754 (2016) 302

ATLAS

$\sqrt{s}$ = 13 TeV

3.6 fb^{-1}

$|y^*|$ < 0.6

$\sigma_{limit}/\sigma_{theory}$

g_q axis, $M_{Z'}$ [TeV]
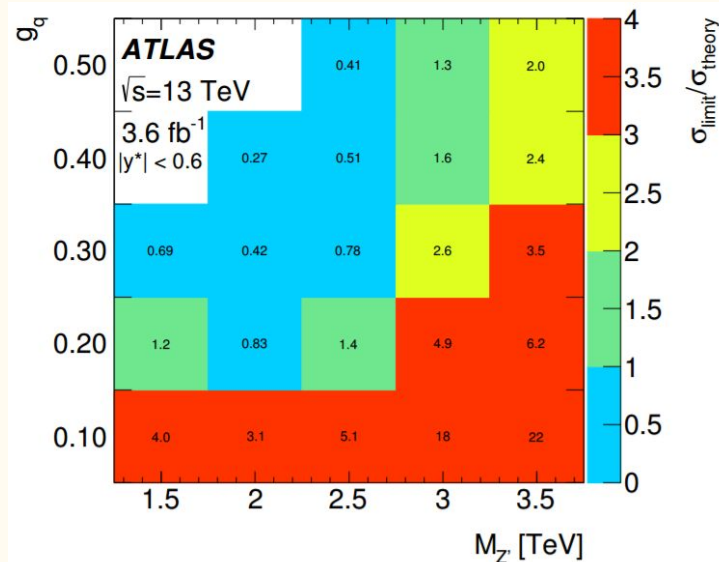
Di-jet @ low mass link

Di-jet + ISR
ISR γ/jet -> **trigger**
search in m_{jj} of dijet
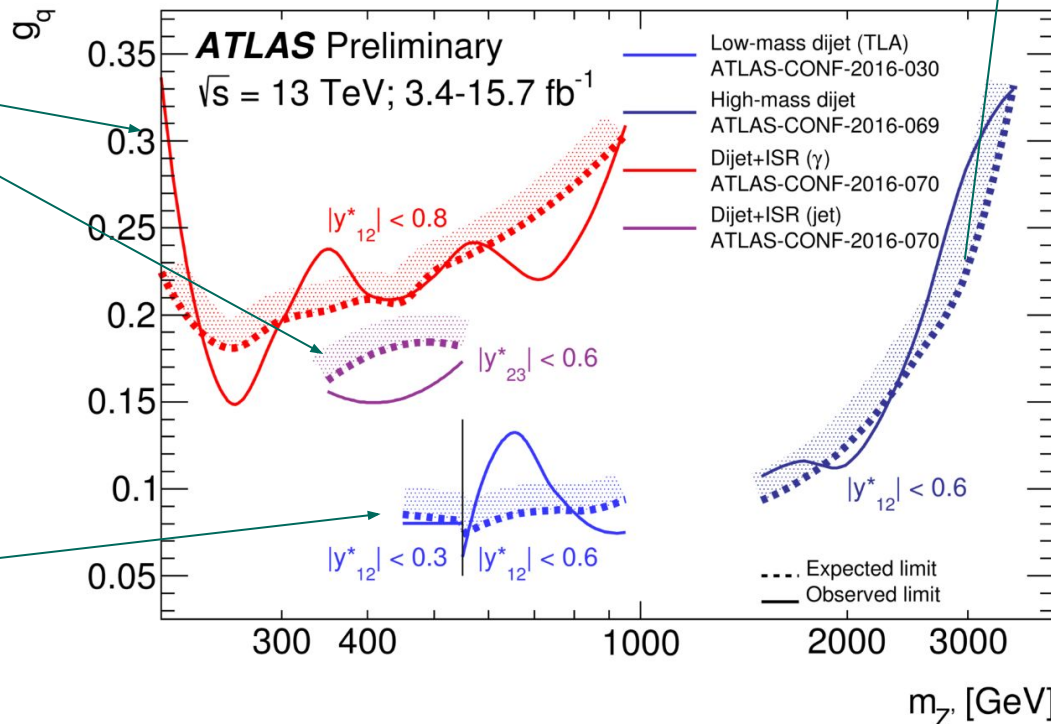
Trigger Level Analysis
- **partial info** stored
- ad-hoc calibration
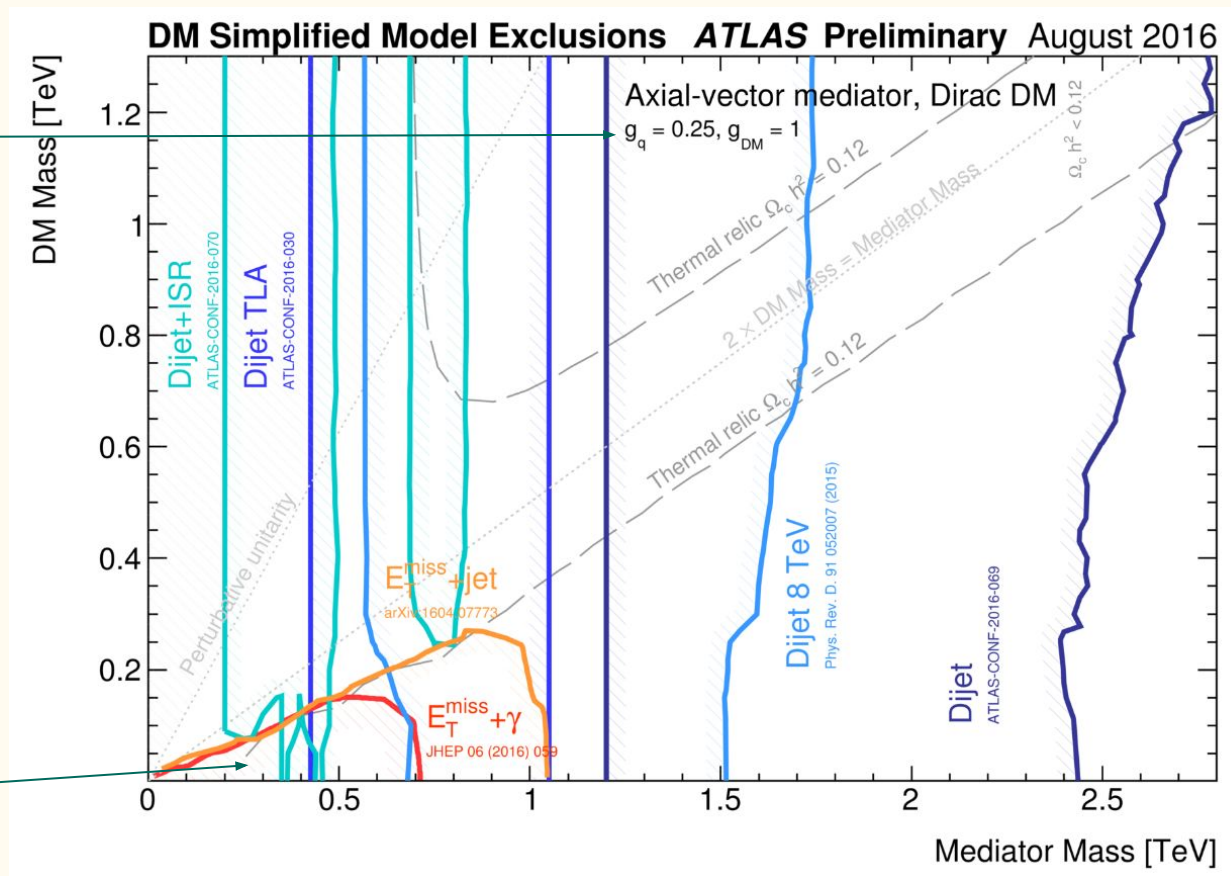- huge statistics

fit technique more
complicated

di-bjet on 13.3/fb @ 13 TeV ATLAS-CONF-2016-060
γ+**jet** on 3.2/fb @ 13 TeV JHEP 03 (2016) 041

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Jet+X and di-jet: filling the empty space [link](#)

coupling to quarks **g_q** critical for the interplay between jet+x and di-jet

previous γ+X result, new one covers a much wider region

X+h->γγ 13/fb @ 13 TeV ATLAS-CONF-2016-087

- **Z'** and **Z'+2 Higgs doublets model**
- also **heavy scalar H** going to DM+h via EFT
- **two γ** with $p_T > 25$ GeV, $105 < m_{\gamma\gamma} < 160$ GeV
- **4 categories** formed based on S_{Etmiss} (E_T^{miss} **significance**) and $p_T^{\gamma\gamma}$, with different sensitivity for different signals
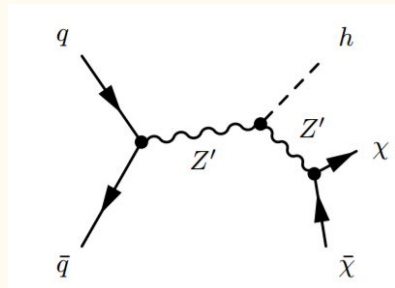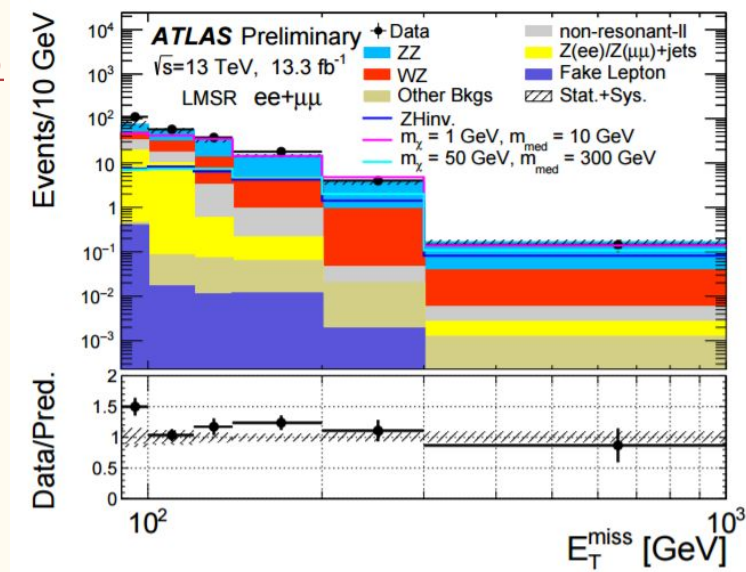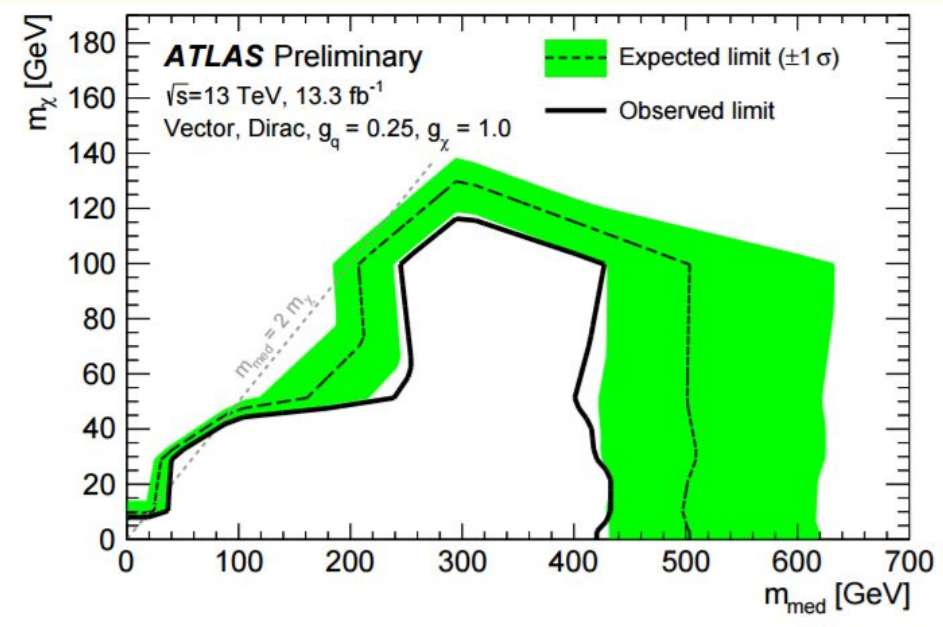
Category	$S_{E_T^{miss}}$ [$\sqrt{\text{GeV}}$]	$p_T^{\gamma\gamma}$ [GeV]
High $S_{E_T^{miss}}$, high $p_T^{\gamma\gamma}$	> 7	> 90
High $S_{E_T^{miss}}$, low $p_T^{\gamma\gamma}$	> 7	≤ 90
Intermediate $S_{E_T^{miss}}$	> 4 and ≤ 7	> 25
Rest	-	> 15

- **Fit to $m_{\gamma\gamma}$** with a functional form
- Exponential of a 2nd order polynomial for the bkg
- Double-crystal ball: signal, SM higgs

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X+ℓℓ 13/fb @13 TeV [ATLAS-CONF-2016-056](#)
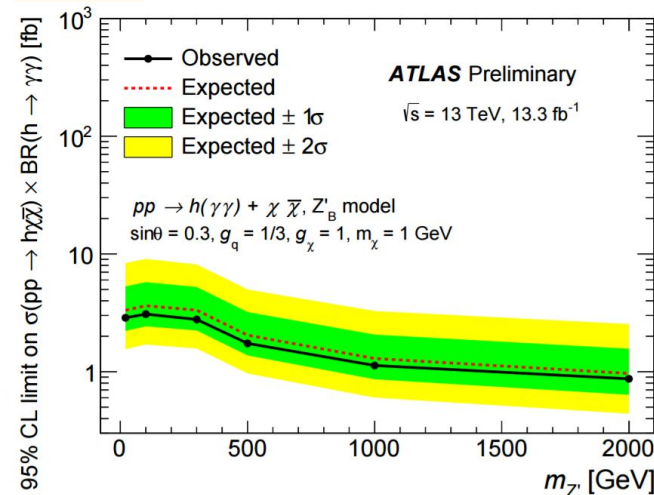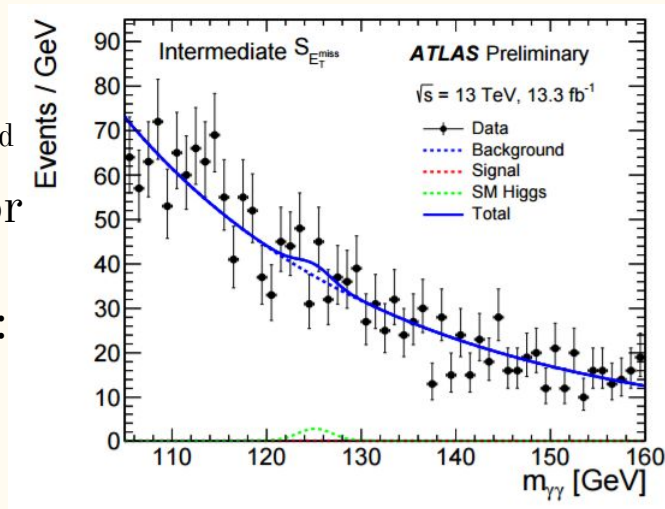
- ee/μμ + E_T^{miss}
- ZZ from MC, WZ 25% from 3ℓ CR
- Z+jets (small) with data-driven method

- **Non-resonant** (WW, tt, Wt, Z->$\tau\tau$) **from eμ** CR
- Bkg **uncertainty dominated by Z+jets**
- **Limits** produced for heavy Higgs, RS graviton, Zh with h->invisibile, **DM with vector mediator**

Searches in the boosted regime: large-R jets

- Results up to now use anti-k_T jets with R=0.4
- **boosted topologies**: two-jets overlap and form a **fat-jet**
- Fat-jets with R=1.0 e.g. in
  - **DM+h** with h->bb PLB 765 (2016) 11
  - **DM+W/Z** with W/Z->hadronic PLB 763 (2016) 251
- **Jet grooming** to **reduce** the impact of **pile-up**
  - jet trimming:
    - k_T algorithm to create sub-jets with R=0.2
    - sub-jets with $p_T^i/p_T^{jet} < 5\%$ are removed
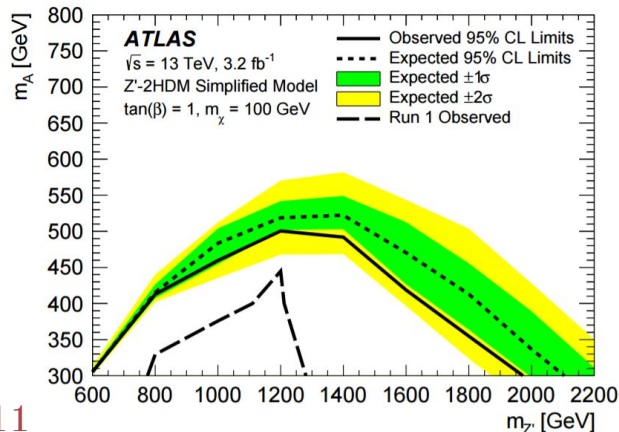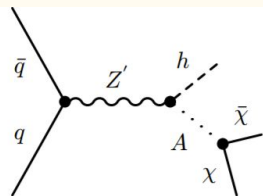- Bkg rejection possible with **substructure variables**, e.g. D_2 (paper) related to # sub-components
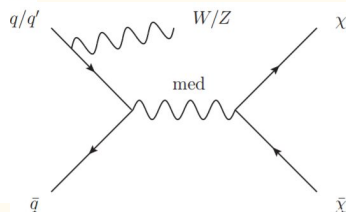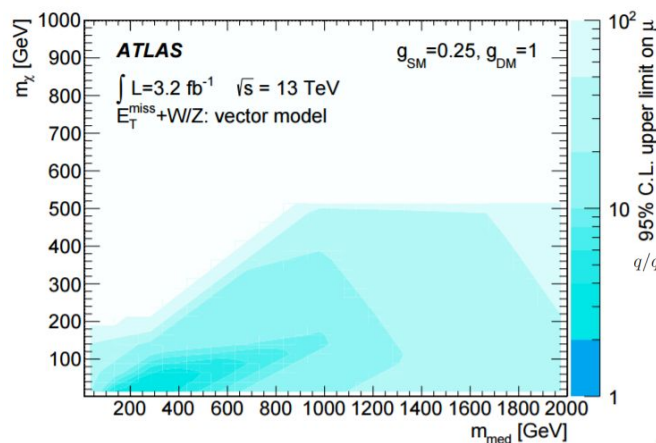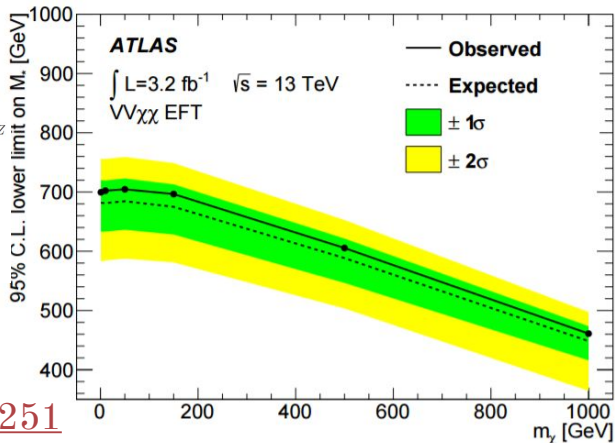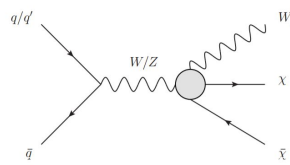
Much more details in Francesco Guescini's talk
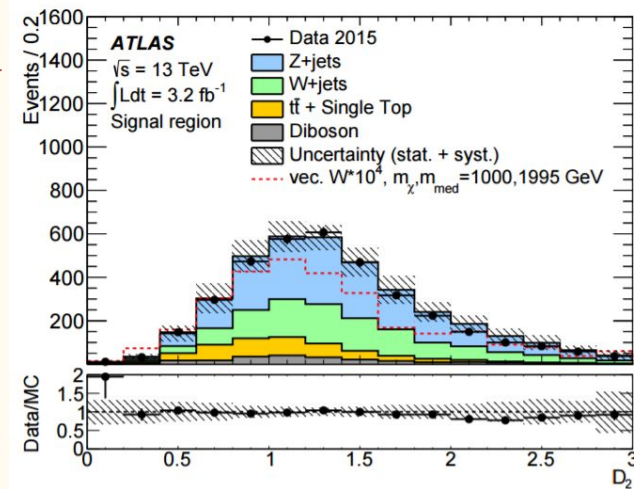
Large-R and sub-structure techniques are a very active field for experimental techniques

h+X with h->bb limits on a 2HDM+Z' model and on a Vector mediator model
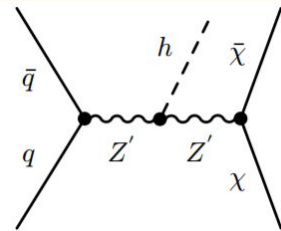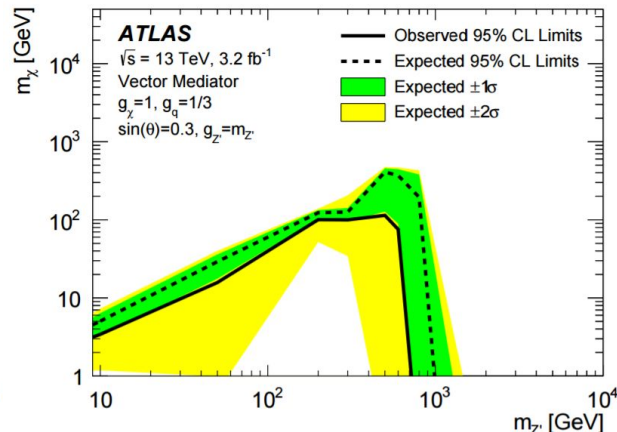
PLB 765 (2016) 11

PLB 763 (2016) 251

V+X with V->hadron limits on VVχχ EFT model and on a simplified model

DM+bb 13/fb @ 13 TeV ATLAS-CONF-2016-086

- Events with **exactly 2 b-jets** and E_T^{miss}, 3rd jet veto
- **b-tagging** based on **multivariate** algorithm with $\varepsilon=60\%$
- Dominant bkg from **Z+bb**, reduced with cut on ΔR_{jj} (separation)
- Cut on **momentum imbalance between jets** $\text{Imb}(b_1, b_2)$
- CRs defined for **2ℓ+1b** (->Z+bb), **1ℓ+2b** (->ttbar), **1ℓ+1b**(->W+hf, single-t)

- **Validation regions** used to validate bkg
- **Combined fit** to all CRs + SR
- **Dominant syst** from jet energy scale, b-tagging, V+jets modelling
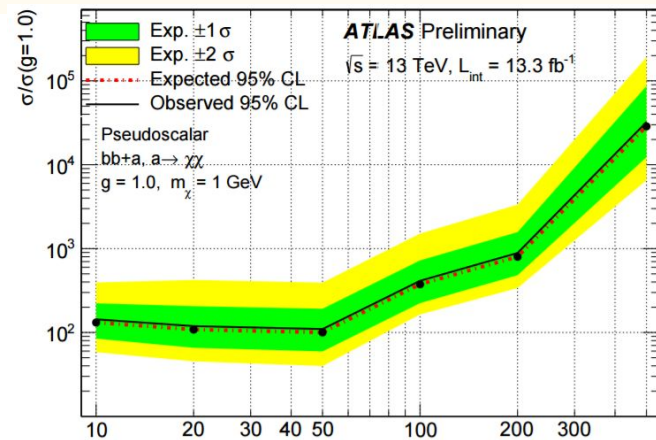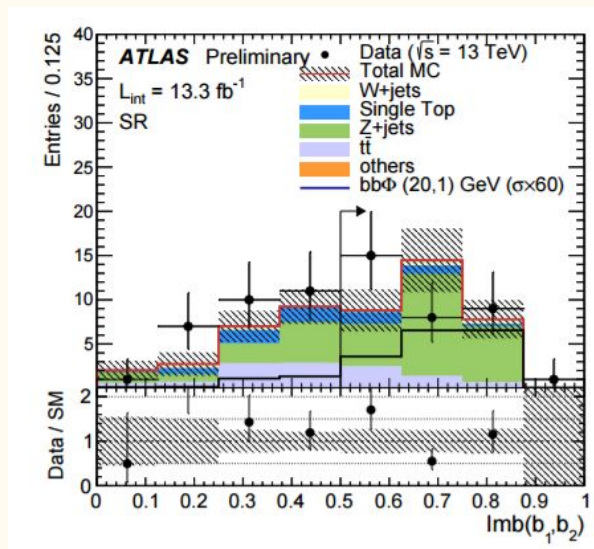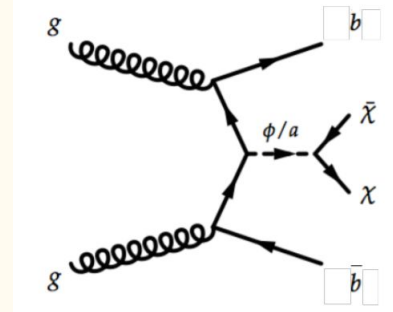
Limits on DM+ bb with pseudoscalar mediator

DM+tt 13/fb @ 13 TeV, ATLAS-CONF-2016-077, 2016-050, 2016-076

- In **searches for stops** with 0, 1 or 2 charged leptons, **produced limits also on DM** via **scalar/pseudoscalar med.**
- **Many SRs**, based on kinematics/topological **discriminating variables**, and have **regions dedicated to DM searches**
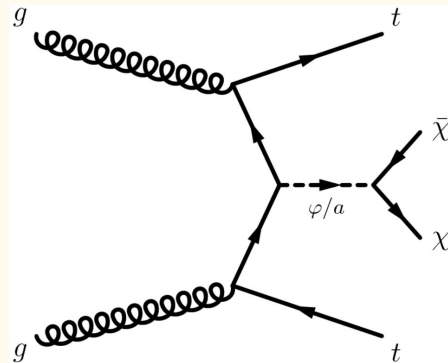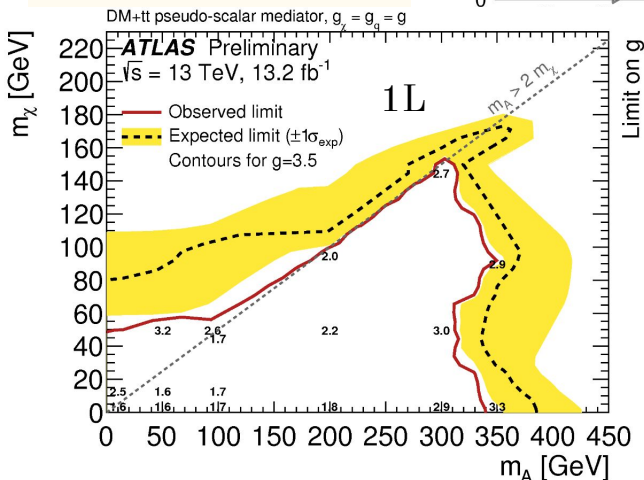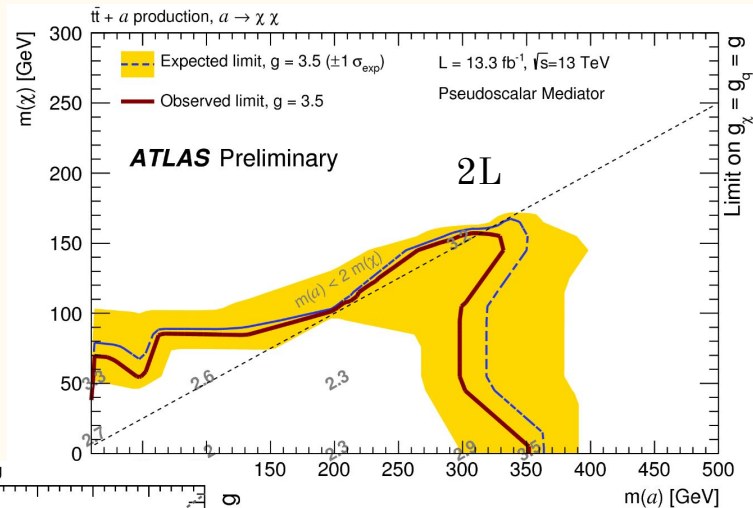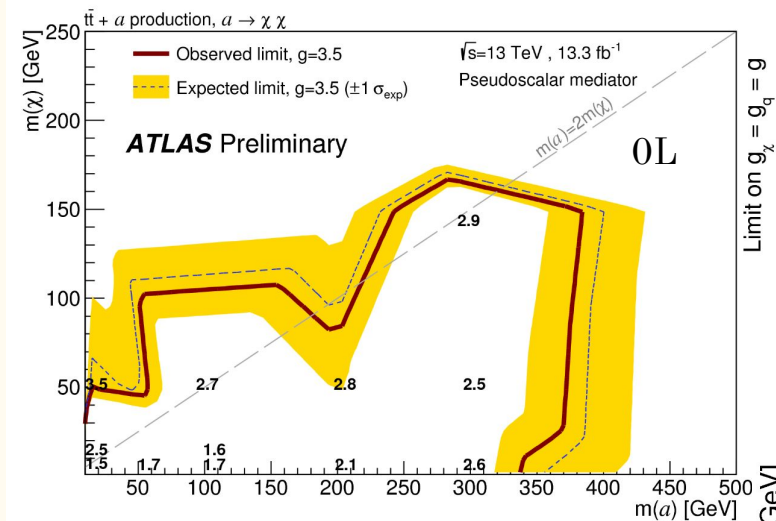
- **Slight excess** in one SR in 1-lepton analysis $(3.3\ \sigma)$
- **Not unexpected**, when considering the **huge number of regions explored**
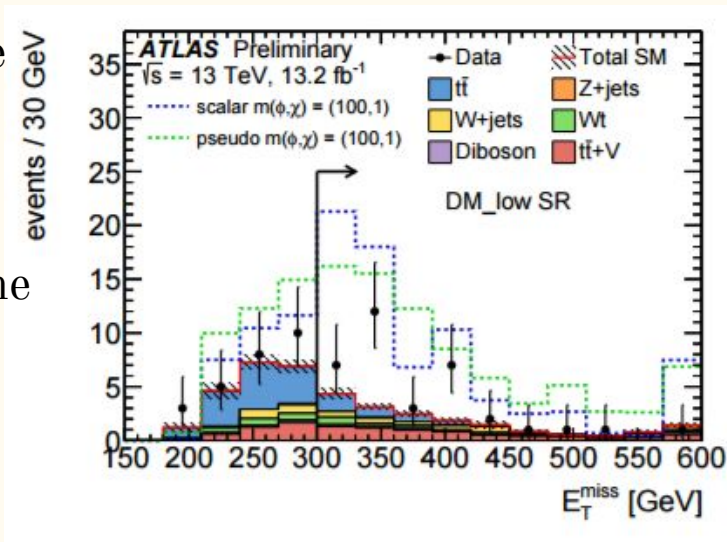
Variable	DM_low
≥ 4 jets with $p_T >$ [GeV]	(60 60 40 25)
E_T^{miss} [GeV]	> 300
$H_{T,sig}^{miss}$	> 14
m_T [GeV]	> 120
am_{T2} [GeV]	> 140
$\min(\Delta\phi(\vec{p}_T^{\,miss}, jet_i))(i \in \{1-4\})$	> 1.4
$\Delta\phi(\vec{p}_T^{\,miss}, \ell)$	> 0.8
$\Delta R(b_1, b_2)$	$-$
Number of b-tags	≥ 1

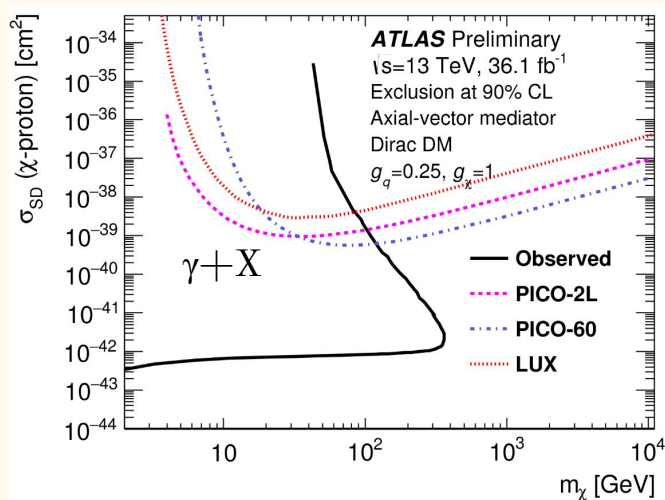# DM+tt 13.2/fb @ 13 TeV, ATLAS-CONF-2016-077, 2016-050, 2016-076

Comparable sensitivity
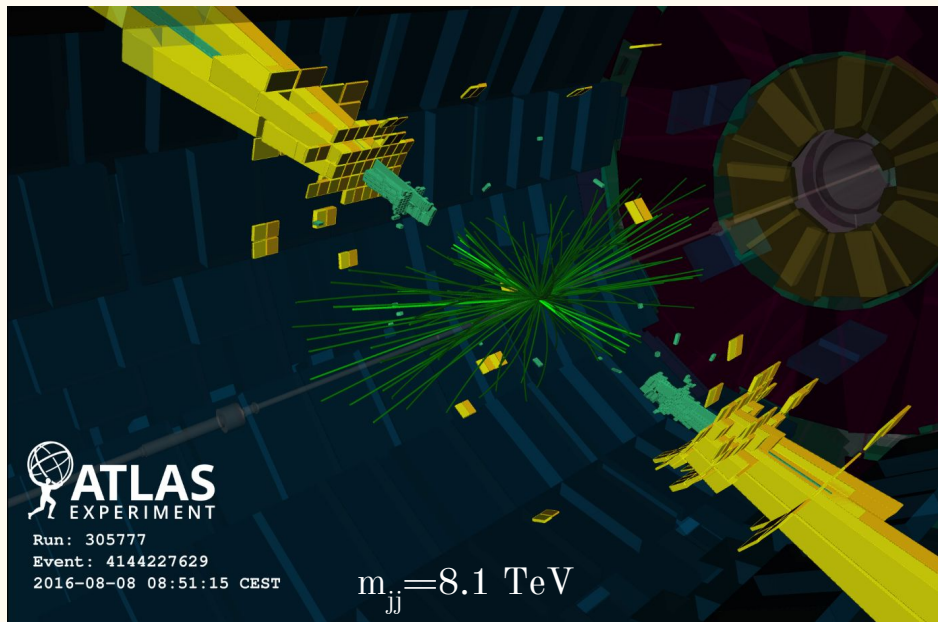 for the different searches

Conclusion

Searches for **Dark Matter at colliders:**

Complementary with other DM searches

Challenging! Invisible particles, control of detector performance in extreme regimes, control of backgrounds...

- **2015+2016 dataset > Run 1**
- Many ways to improve:
  - **experimental techniques**: fitting strategies, jet substructure, flavour tagging, ...
  - **interaction with theorists**: higher-order prediction for bkg, better control of theoretical uncertainties (relevant for many measurement), ...
- **ATLAS+CMS+theorists** working together <u>Dark Matter Working Group</u>