Searches for Dark Matter with the ATLAS detector

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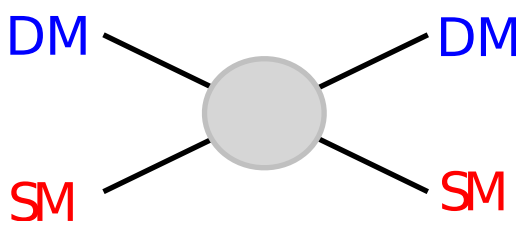
On behalf of the ATLAS Collaboration

ICHEP 2016 - Chicago, USA

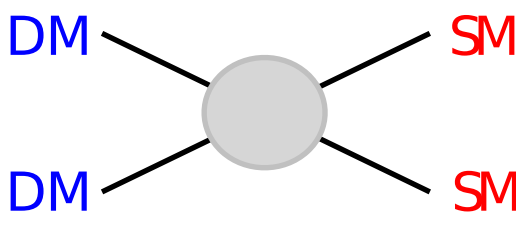
August 5, 2016

Dark Matter candidates and the LHC

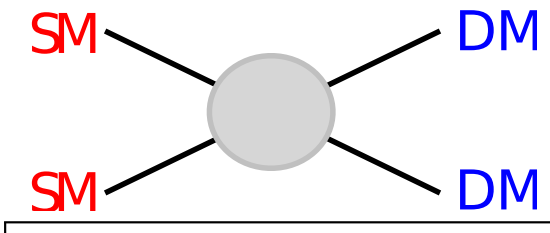
- Astrophysical observations point to the existence of Dark Matter
  - Galactic rotation curves, Bullet Cluster, CMB measurements, etc
- Dark Matter (DM) has no known interactions beyond gravity
- What if it couples to Standard Model (SM) particles very weakly?
  - Weakly Interacting Massive Particle (WIMP) interpretation
- ATLAS searches assume that DM is a WIMP



Direct detection
(WIMP-nucleon scattering)



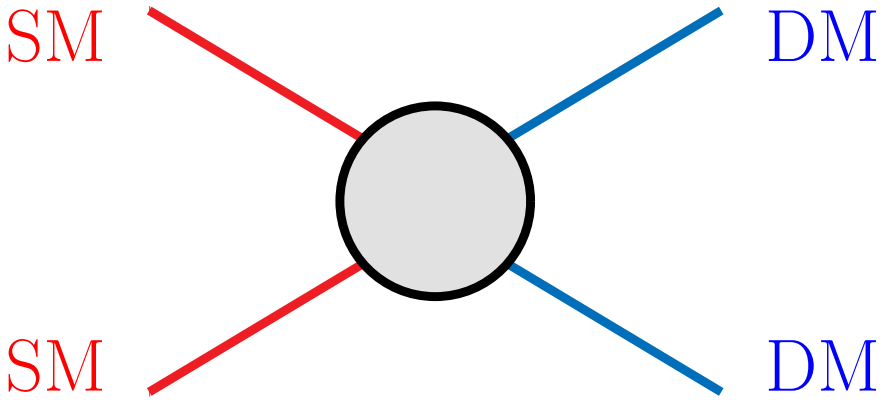
Indirect detection
(WIMP annihilation)



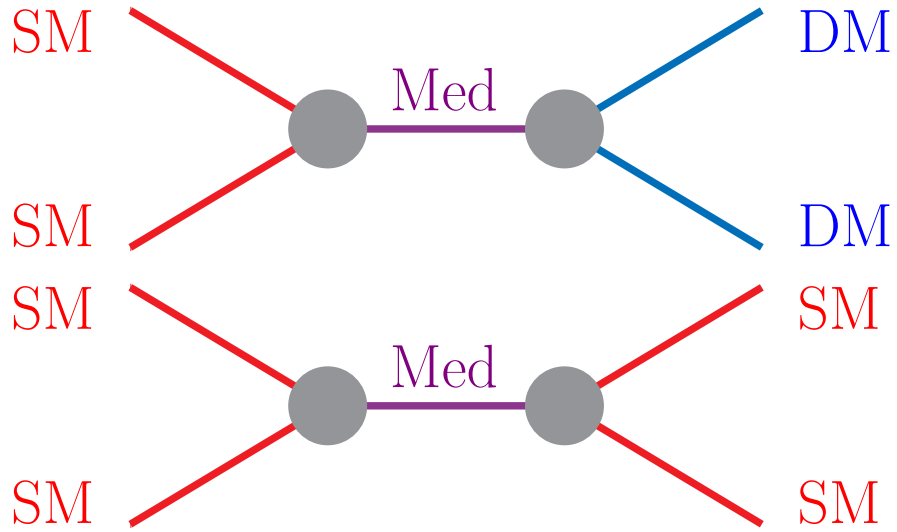
Collider searches
(WIMP pair production)

Searching for WIMPs at ATLAS

Run-I approach to DM:

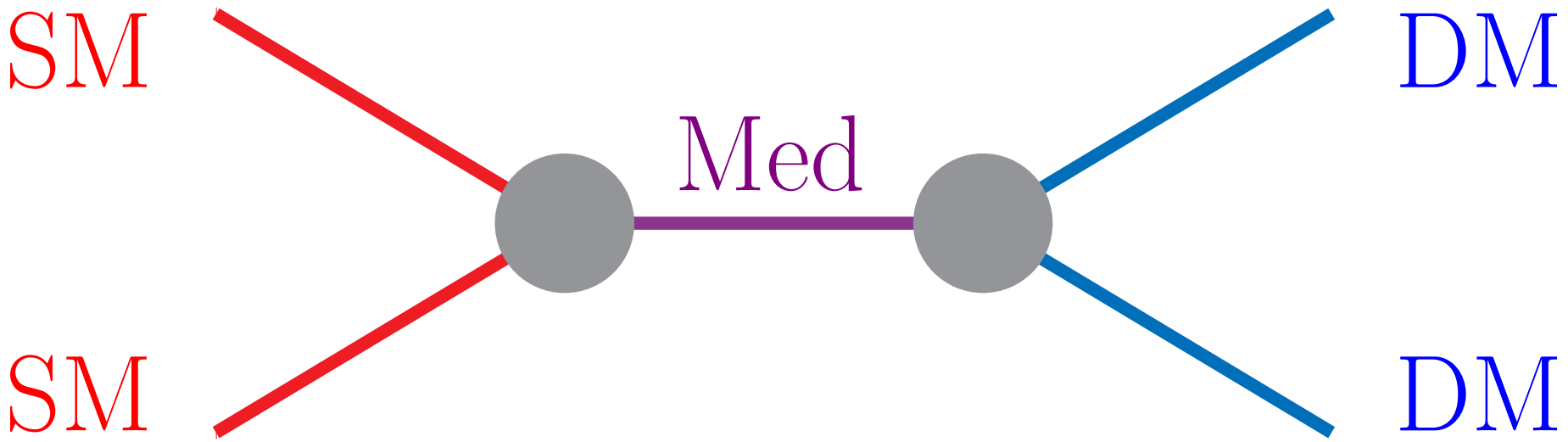


Run-II approach to DM:



- LHC probes much higher energy scales than direct detection searches
  - Avoid EFT validity concerns: focus on simplified models
    - Consider (V), axial-vector (A), and scalar (S) mediators
  - Guidelines and benchmark models detailed in arxiv:1507.00966
    - Product of intense discussions between ATLAS, CMS, and theorists
- Traditional searches: $\mathrm{E_T^{miss}}$+X ("mono-X"), X usually from ISR
  - Mediators produced by quarks/gluons can decay back to them
  - Direct mediator searches are now part of the ATLAS DM program

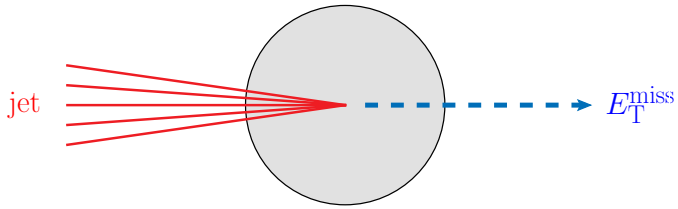
Production searches (E_T^{miss}+X)

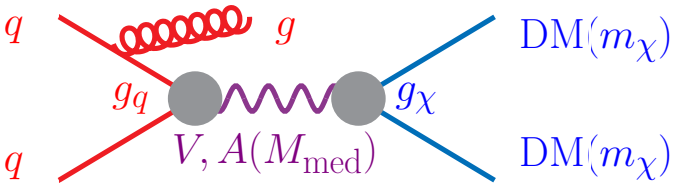


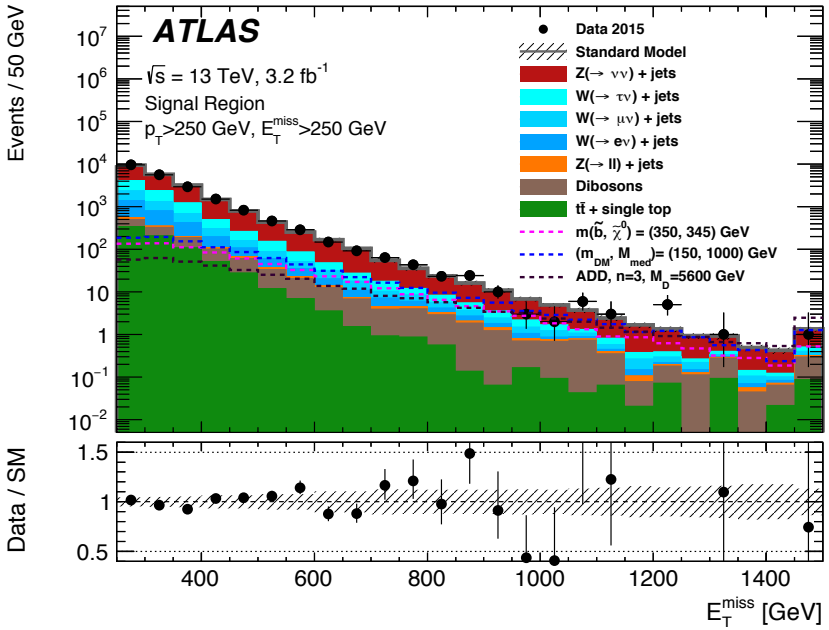
E_T^{miss}+jet

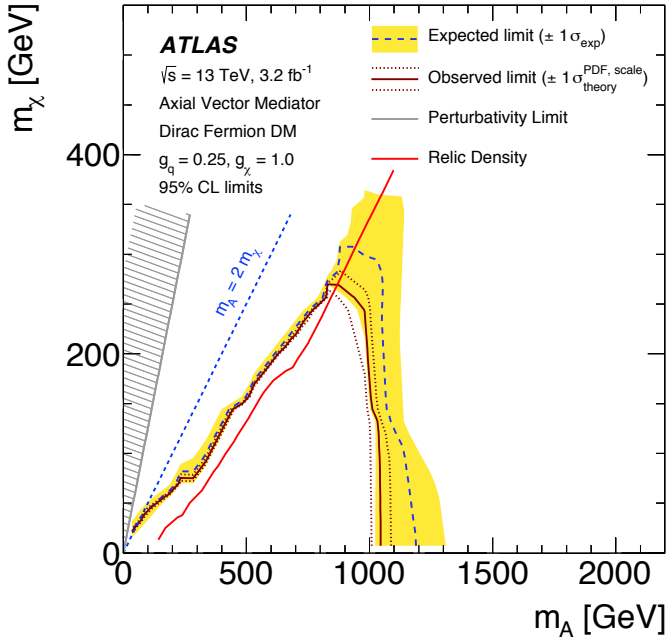
2015 data
EXOT-2015-03

- Largest E_T^{miss}+X cross-section at LHC
- Primary background: V+jets
  - $Z \to \nu\nu$+jets is irreducible
- Several inclusive+exclusive SRs
  - Increasing E_T^{miss} cuts
- Limits axial mediators $M_{med} \lesssim 1\,TeV$





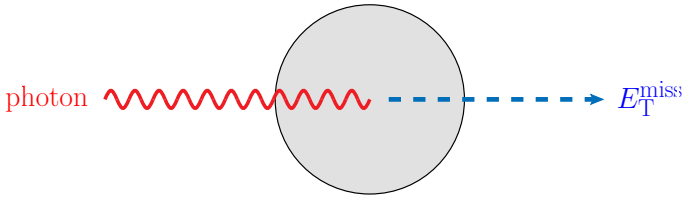


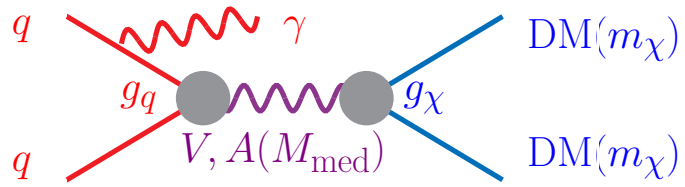


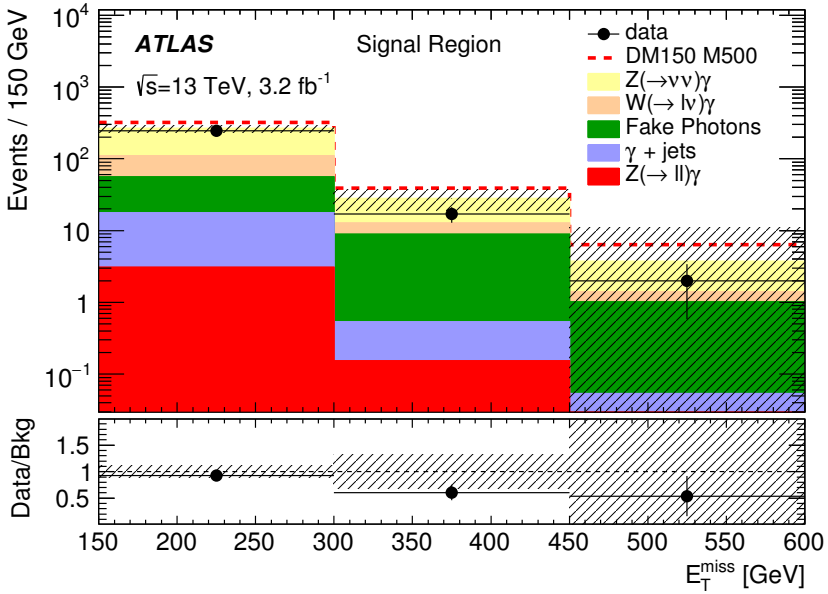
E_T^{miss}+photon

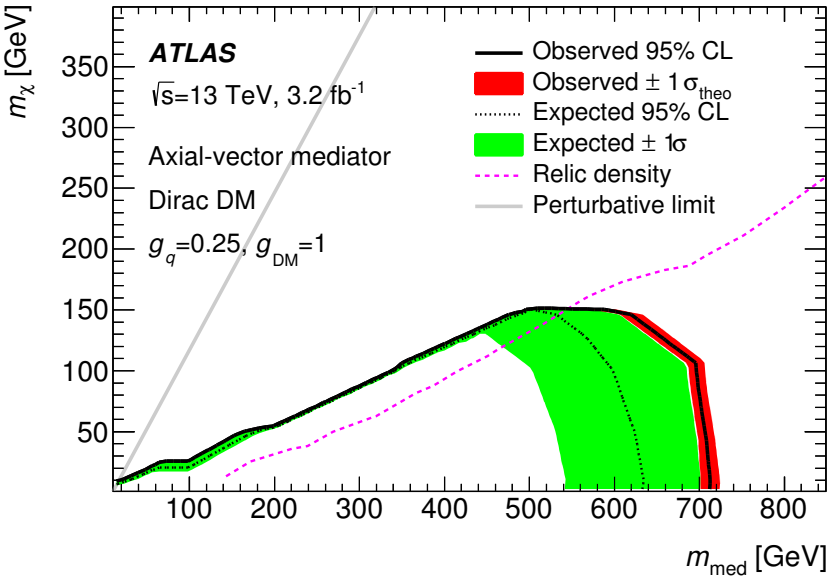
2015 data
EXOT-2015-05

- Very clean compared to E_T^{miss}+jet
  - However, much smaller cross-section
- Primary background: V+γ
  - $Z \to \nu\nu + \gamma$ is irreducible
- Limits axial mediators $M_{med} \lesssim 0.7\,\mathrm{TeV}$





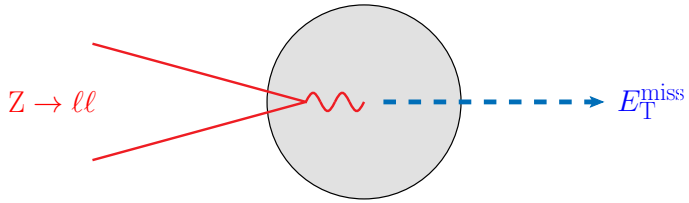


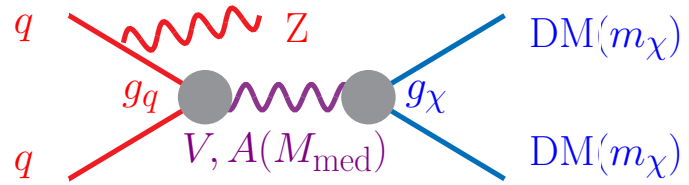


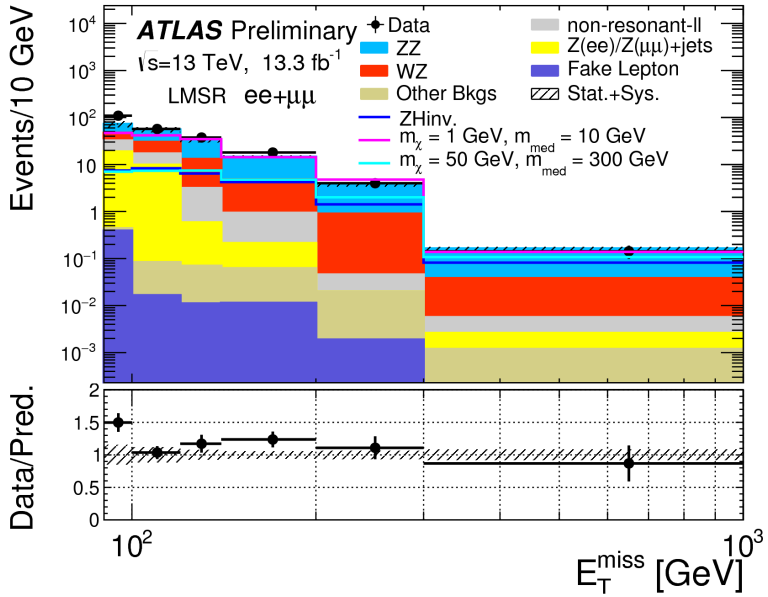
$E_T^{miss} + Z(\rightarrow \ell\ell)$

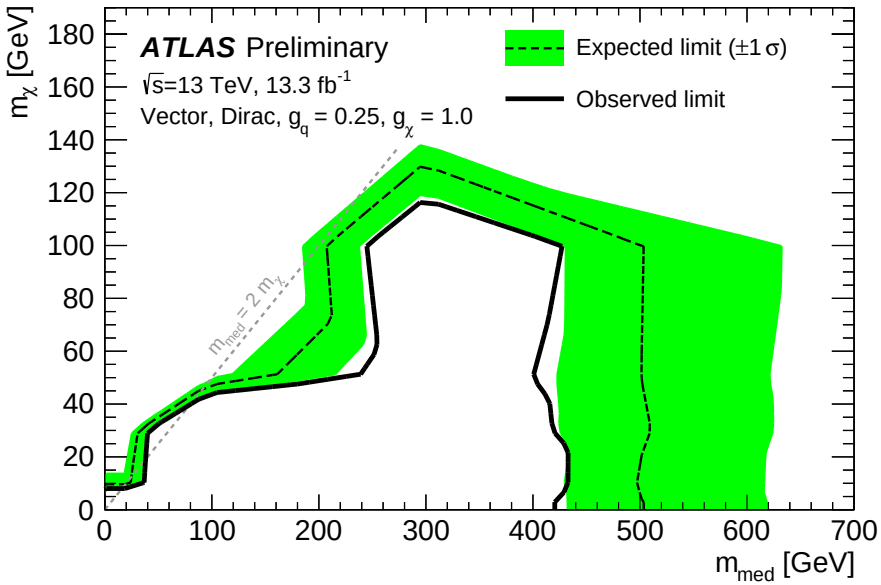
New! 2015+2016 data
ATLAS-CONF-2016-056

- An even cleaner final state
  - However, further reduced statistics
- Primary background: VV
  - $ZZ \rightarrow \nu\nu + \ell\ell$ is irreducible
- Limits vector mediators $M_{\text{med}} \lesssim 0.4\,\text{TeV}$





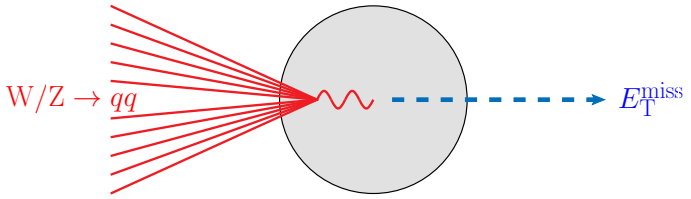


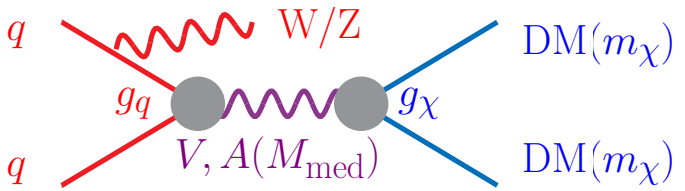


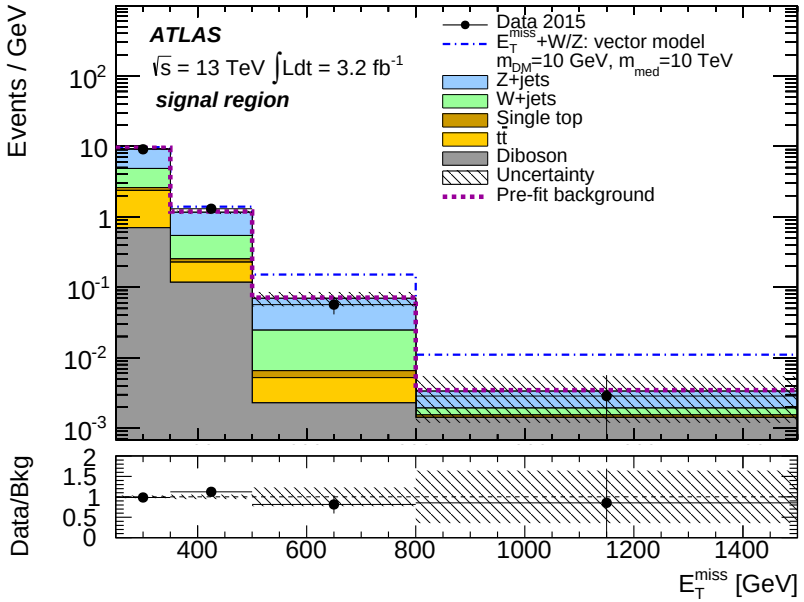
E_T^{miss}+W/Z($\to$qq)

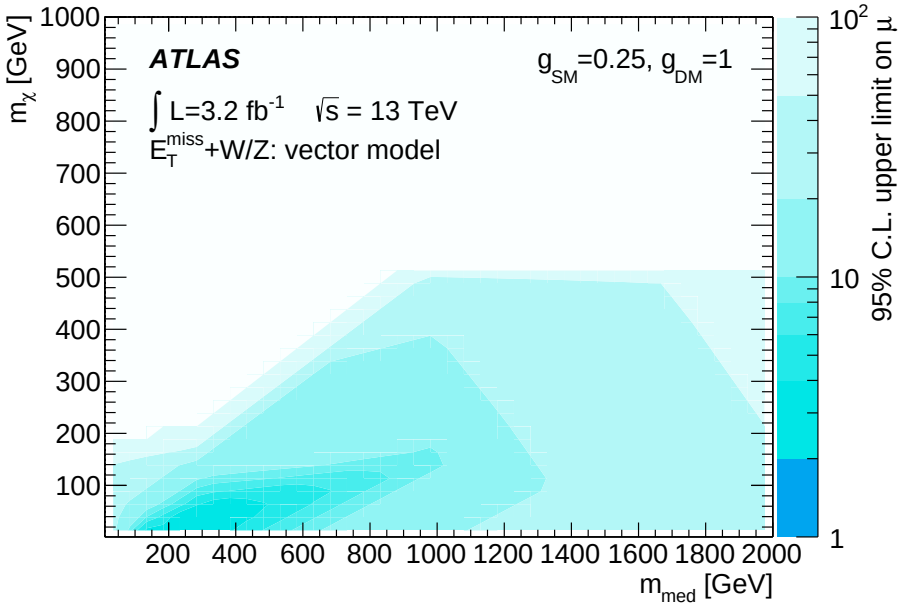
New! 2015 data
EXOT-2015-08

- Hadronic W/Z decays more common
  - $\mathrm{BR}(\mathrm{W} \to qq) \approx 3 \times \mathrm{BR}(\mathrm{W} \to \ell\nu)$
  - $\mathrm{BR}(\mathrm{Z} \to qq) \approx 10 \times \mathrm{BR}(\mathrm{Z} \to \ell\ell)$
- Makes use of jet substructure
- Primary background: V+jets
  - $Z \to \nu\nu$+jet, jet fakes W/Z decay





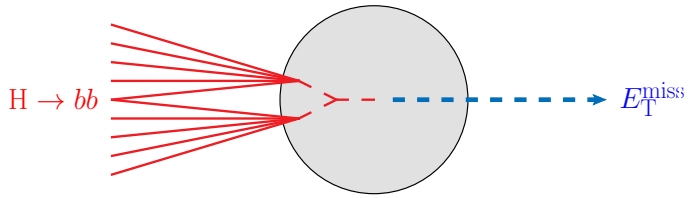


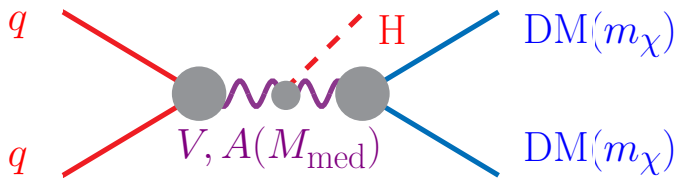


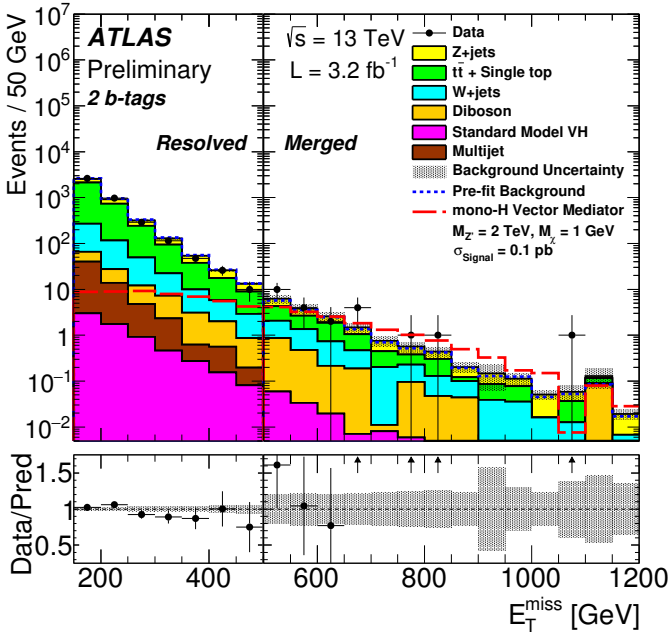
E_T^{miss}+H(→bb)

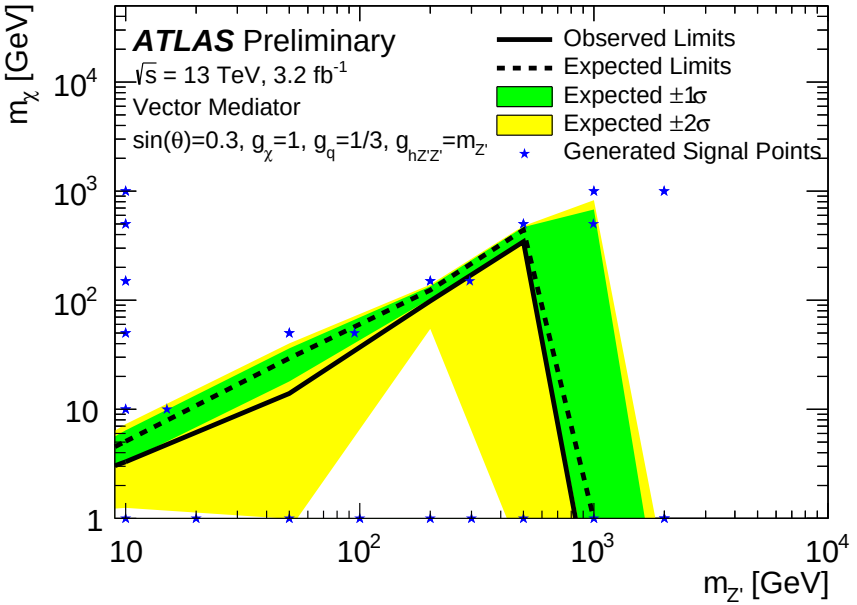
2015 data
ATLAS-CONF-2016-019

- Higgs may mix with new dark mediators
  - $H \to bb$ is $\sim 60\%$ of BR(H→all)
  - Largest cross-section for Higgs+DM
- Two analyses: resolved and boosted
- Primary backgrounds: V+jets, top
- Limits vector mediators $M_{\text{med}} \lesssim 0.7\,\text{TeV}$





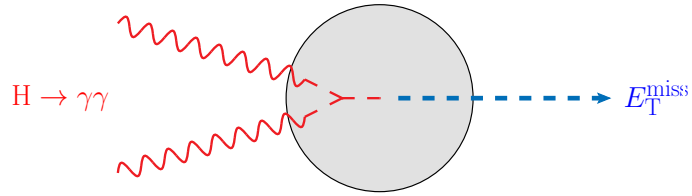


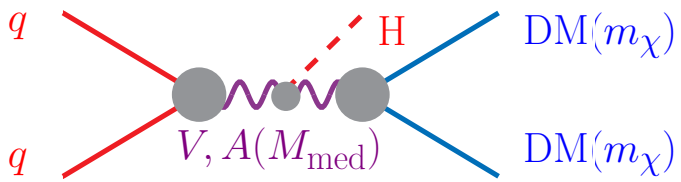


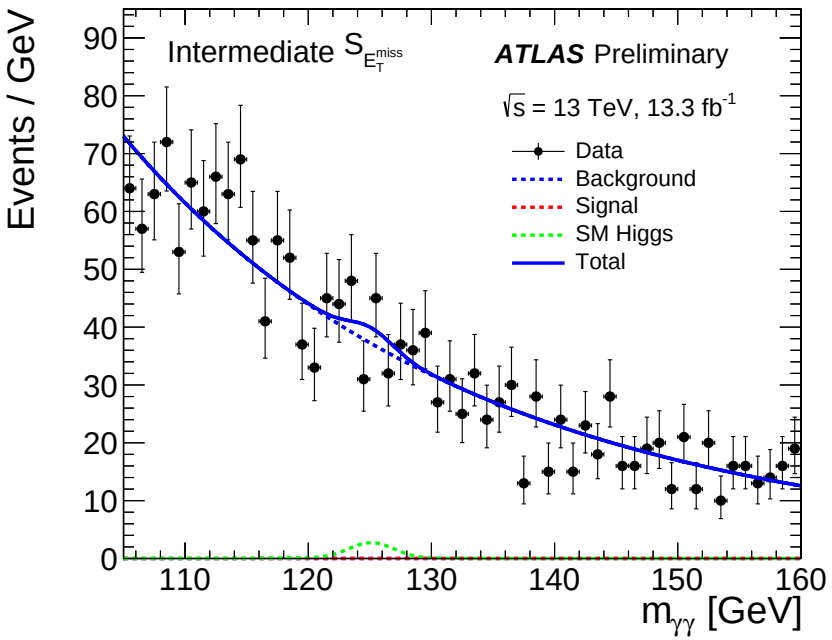
E_T^{miss}+H($\rightarrow \gamma\gamma$)

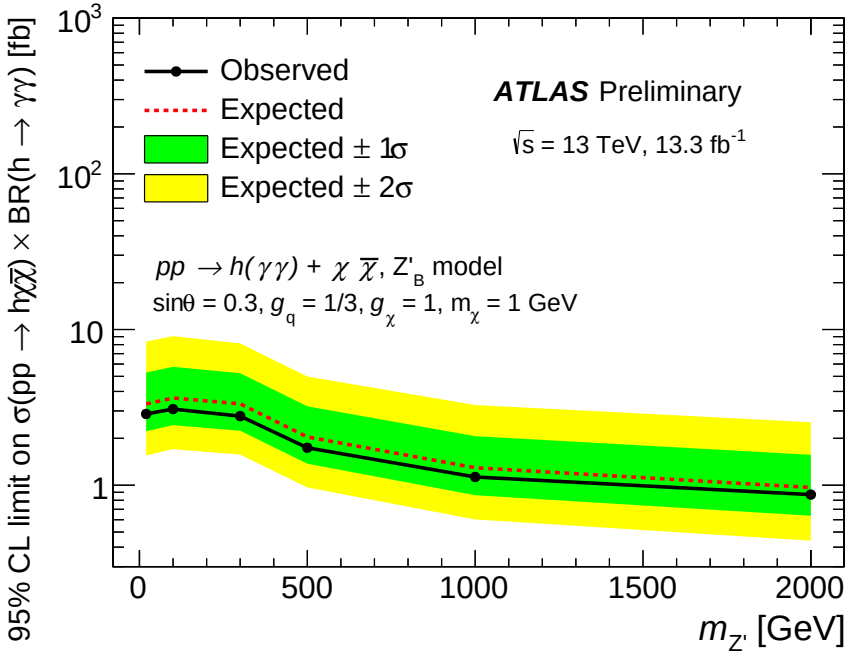
New! 2015+2016 data
ATLAS-CONF-2016-087

- Higgs may mix with new dark mediators
  - $H \rightarrow \gamma\gamma$ is very clean final state
- Background taken from data-driven fit
  - Multiple signal regions, each with a fit
- Primary backgrounds: SM $\gamma\gamma$, γ+jet





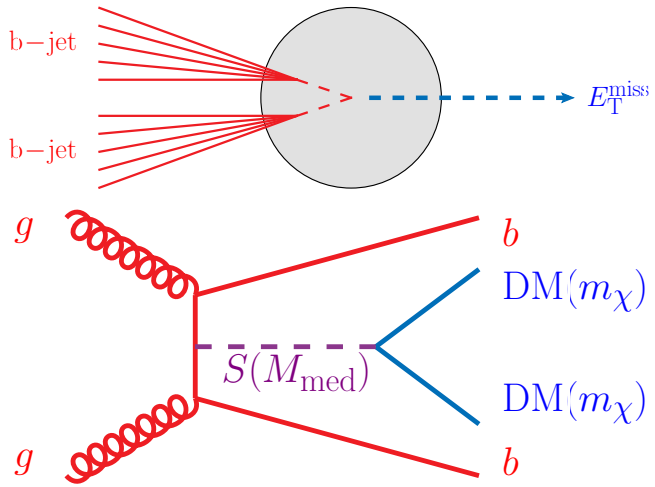


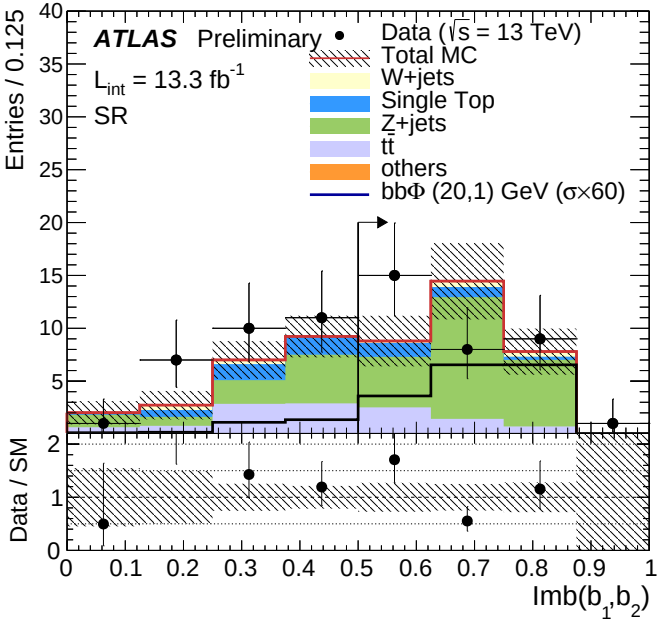


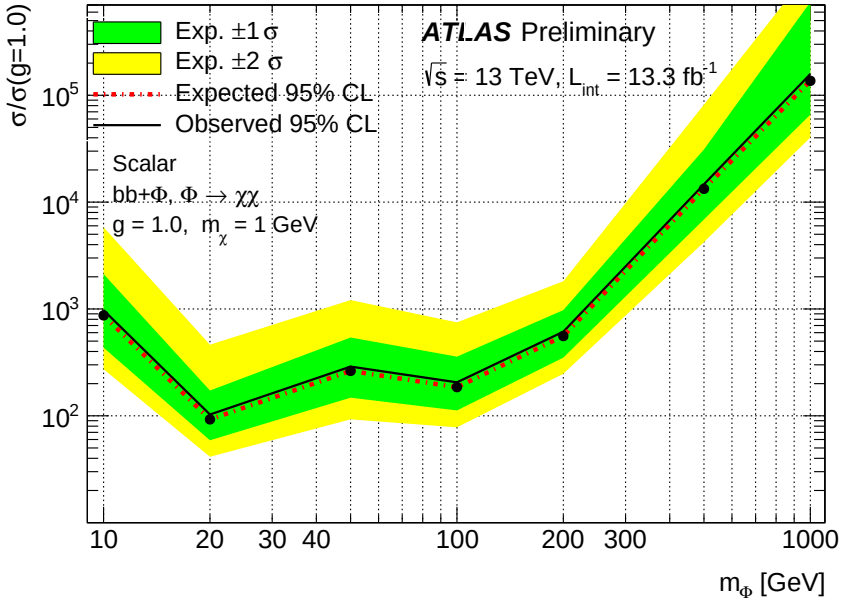
E_T^{miss}+b-jets

New! 2015+2016 data
ATLAS-CONF-2016-086

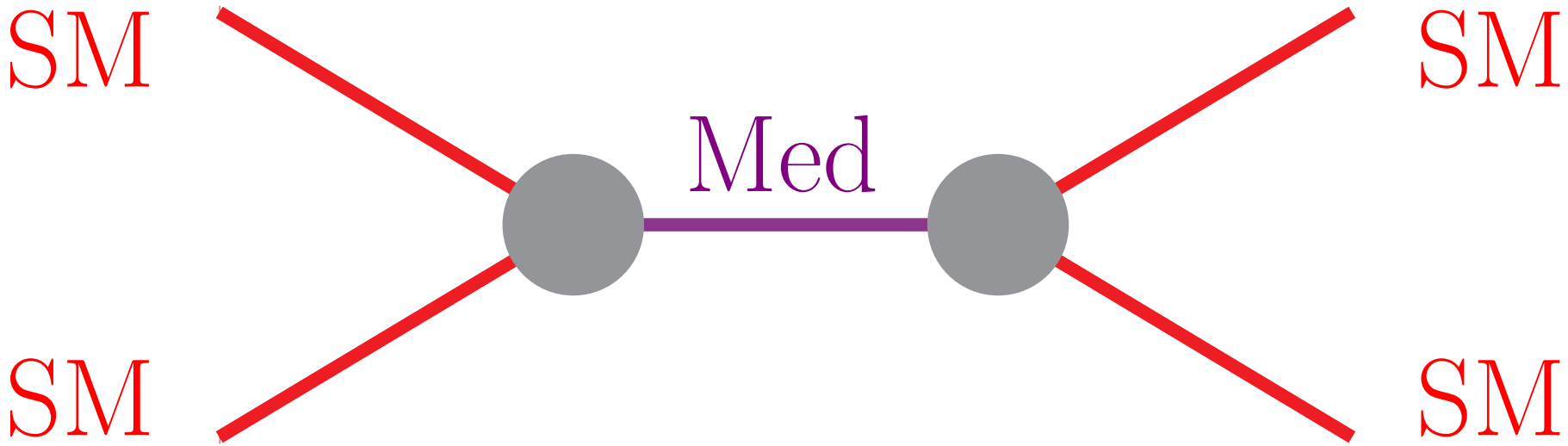
- All so far: searches for V/A mediators
- What if DM mediator is a scalar?
- Single and di-b-jet diagrams possible
  - Di-b-jet diagram dominates at LHC
- Primary backgrounds: top, V+jets
  - Suppress top by multiplicity: $N_{\text{jet}} = 2$
- Note: $E_T^{miss}+t\bar{t}$ covered by K. Rosbach







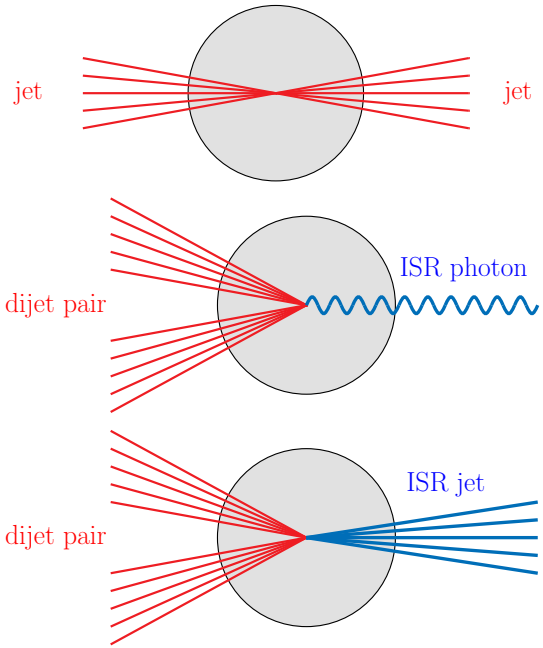
Mediator searches



Dijet searches

- Dijet searches probe dark mediators
  - If produced by q/g, it can also decay

- Standard dijet search:
  - Sensitive to $m_{Z'} \gtrsim 1.5\,\text{TeV}$
- Can we circumvent the trigger barrier?
  - Trigger-level search:
    - Bandwidth = size $\times$ rate, reduce size
    - Reaches mediator mass of $\gtrsim 450\,\text{GeV}$
  - Dijet+ISR search:
    - Trigger on ISR jet or ISR photon
    - ISR jet: mediator mass of $\gtrsim 350\,\text{GeV}$
    - ISR γ: mediator mass of $\gtrsim 200\,\text{GeV}$

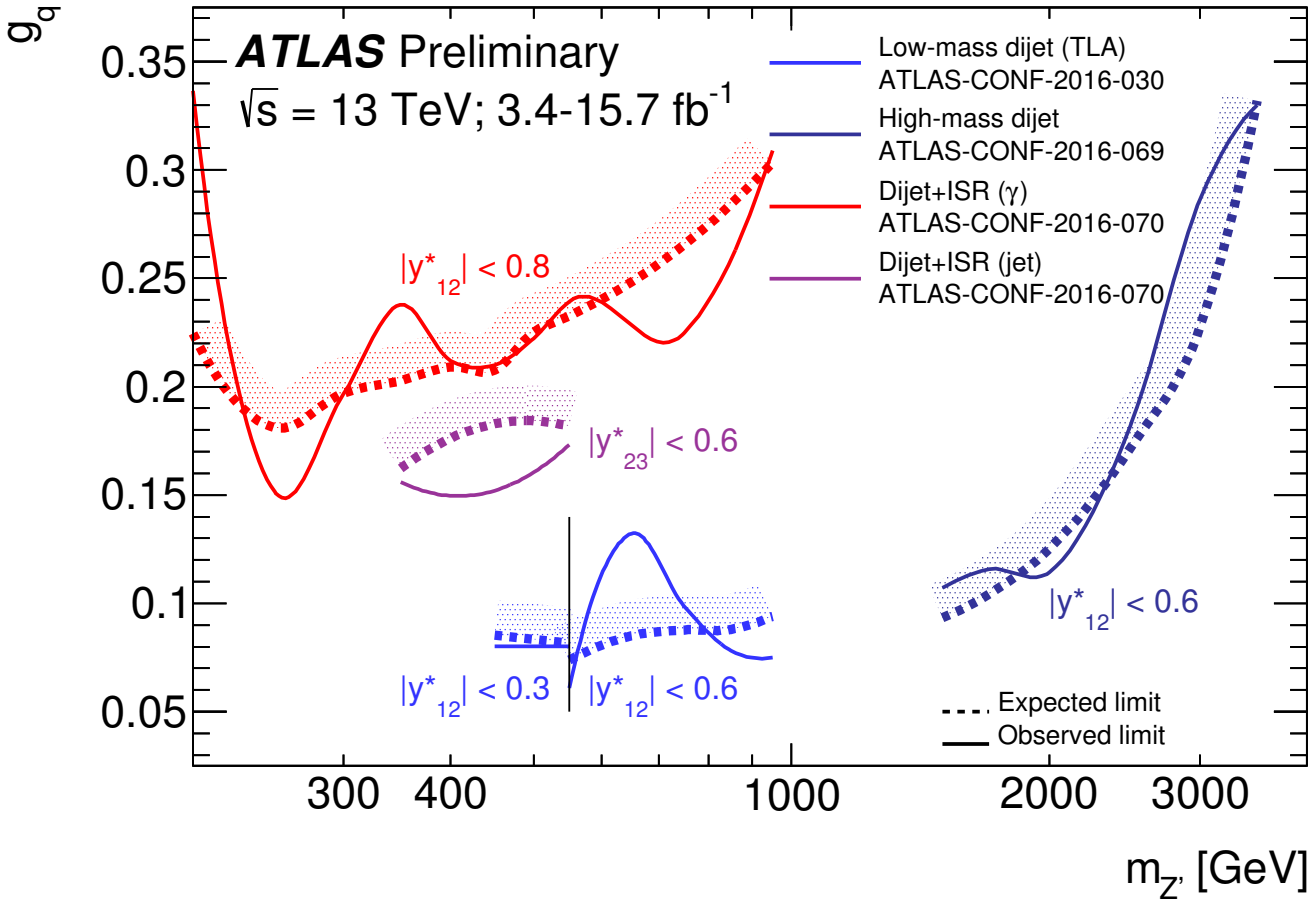


- See Sapta's talk at 17:00 today for details on all three analyses (and more)

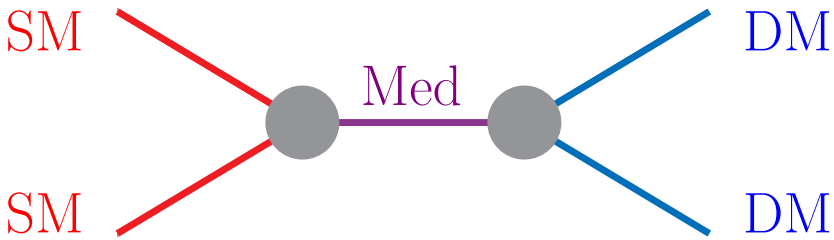
Dijet summary

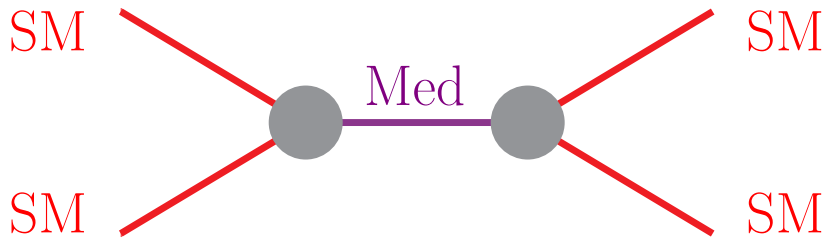
New! 2015+2016 data
Exotics summary plot

- Different dijet searches sensitive to different mass regimes
  - Analyses are working together to probe dark mediator parameter space
  - Below combination assumes a lepto-phobic axial-vector mediator



Summary of searches

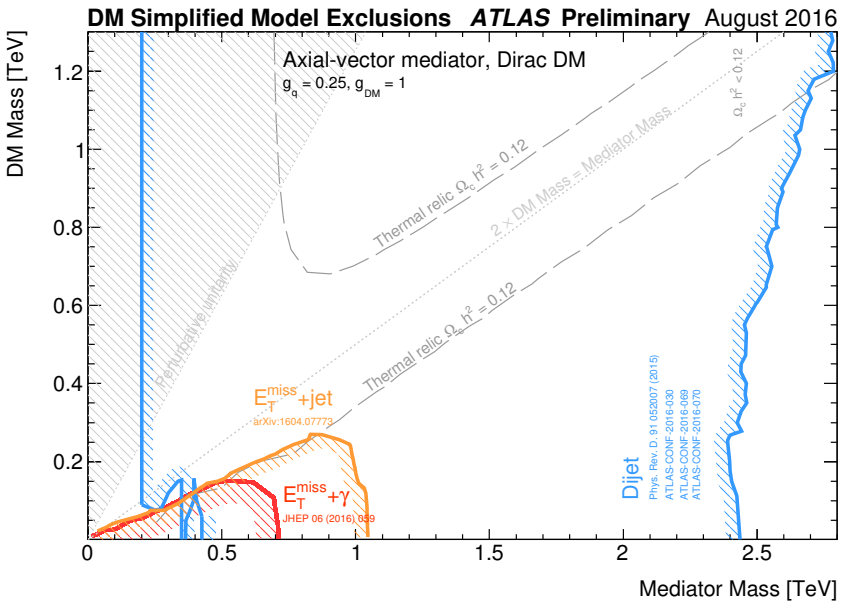


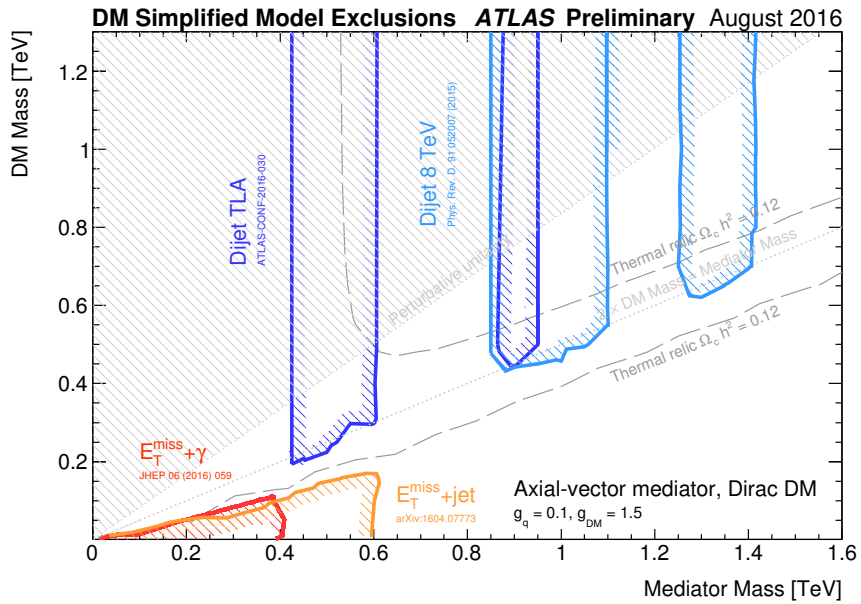


Combining search strategies

New! 2015+2016 data
Exotics summary plots

- E_T^{miss}+X searches cover V/A/S mediators to pair-produced DM
- Dijet searches probe the production of dark-sector mediators
- These approaches are complimentary
  - Below combination assumes a lepto-phobic axial-vector mediator
  - The DM parameter space is being probed ever more thoroughly





Analysis summary table

Analysis	Dataset	Public link	
Production search:			
E_T^{miss}+jet	2015	Paper: EXOT-2015-03	
$E_T^{miss}+\gamma$	2015	Paper: EXOT-2015-05	
$E_T^{miss}+Z(\rightarrow \ell\ell)$	2015+2016	Note: ATLAS-CONF-2016-056	new!
$E_T^{miss}+W/Z(\rightarrow qq)$	2015	Paper: EXOT-2015-08	new!
$E_T^{miss}+H(\rightarrow bb)$	2015	Note: ATLAS-CONF-2016-019	
$E_T^{miss}+H(\rightarrow \gamma\gamma)$	2015+2016	Note: ATLAS-CONF-2016-087	new!
$E_T^{miss}+H(\rightarrow \ell\ell\ell\ell)$	2015	Note: ATLAS-CONF-2015-059	
E_T^{miss}+b-jets	2015+2016	Note: ATLAS-CONF-2016-086	new!
$E_T^{miss}+t\bar{t}$ (0ℓ)	2015+2016	Note: ATLAS-CONF-2016-077	new!
$E_T^{miss}+t\bar{t}$ (1ℓ)	2015+2016	Note: ATLAS-CONF-2016-050	new!
$E_T^{miss}+t\bar{t}$ (2ℓ)	2015+2016	Note: ATLAS-CONF-2016-076	new!
Mediator search:			
Dijet	2015+2016	Note: ATLAS-CONF-2016-069	new!
Trigger-level dijet	2015	Note: ATLAS-CONF-2016-030	
Dijet+ISR	2015+2016	Note: ATLAS-CONF-2016-070	new!
Summary plots:			
Mediator searches	2015+2016	Plot: Summary plot page	new!
Search combination	2015+2016	Plot: Summary plot page	new!

Summary

- DM searches remain a key piece of the ATLAS physics program
  - Strategy has moved from EFT interpretations to simplified models
  - Simplified models also enable direct searches for DM mediators

- Several final states have been probed with $\sqrt{s} = 13\,\mathrm{TeV}$ data:
  - $\mathrm{E_T^{miss}}$+X: jet, photon, Z$\to \ell\ell$, W/Z$\to$qq, H$\to$(bb,$\gamma\gamma$), b-jets, $t\bar{t}$
  - Mediators: dijet, trigger-level dijet, dijet+ISR (photon and jet)
- Multiple results using 2016 data are already available
- No significant excesses have been observed in any final state
  - Limits have been set, and the search continues

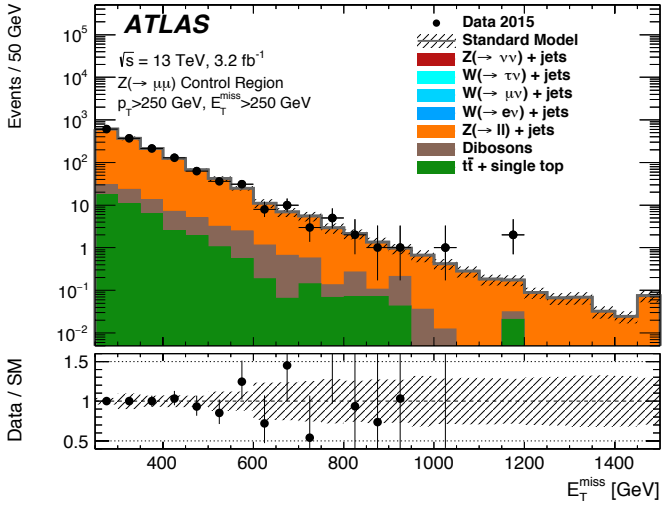
- The 2016 program has only just begun, stay tuned for more!

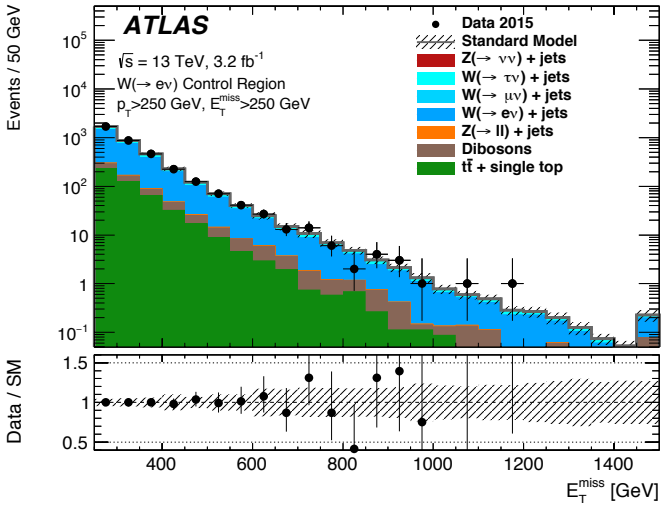
Backup Material

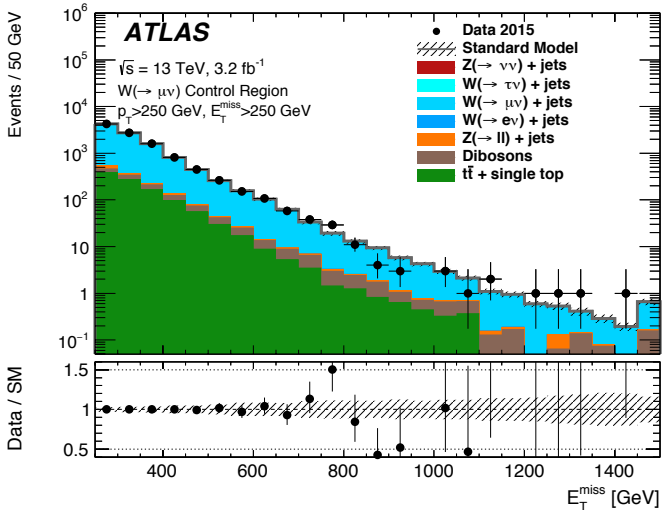
E_T^{miss}+jet

2015 data
arxiv:1604.07773

- $W(e\nu) \rightarrow W(e\nu), W(\tau\nu)$
- $W(\mu\nu) \rightarrow W(\mu\nu), Z(\nu\nu)$
- $Z(\mu\mu) \rightarrow Z(\mu\mu)$



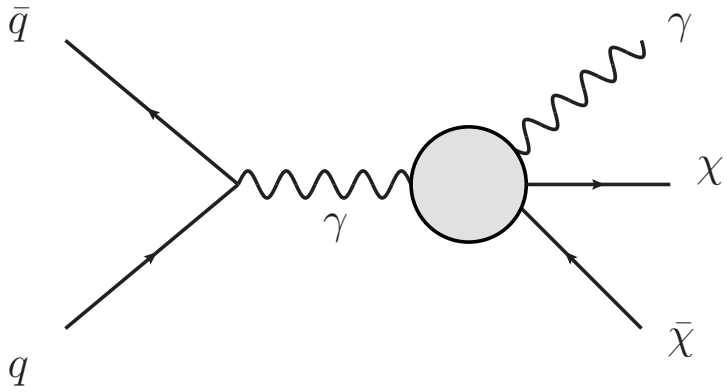


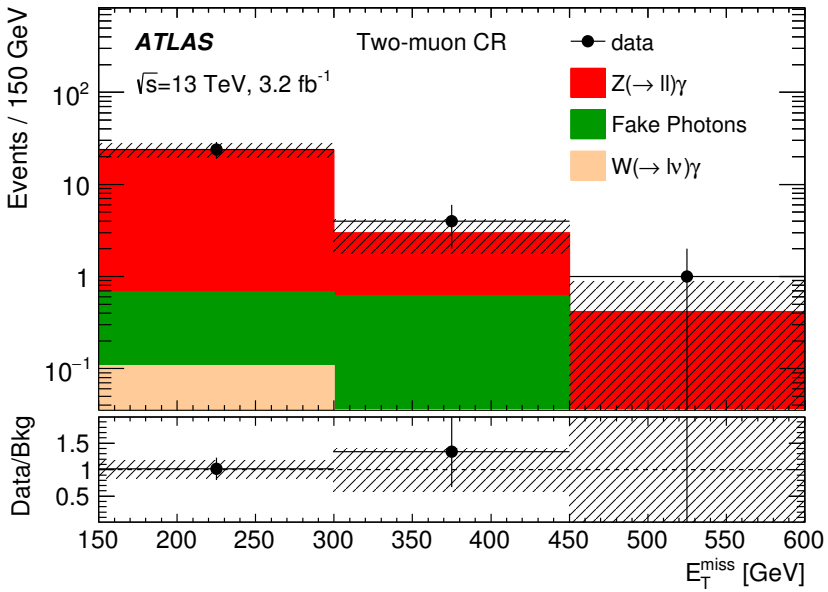


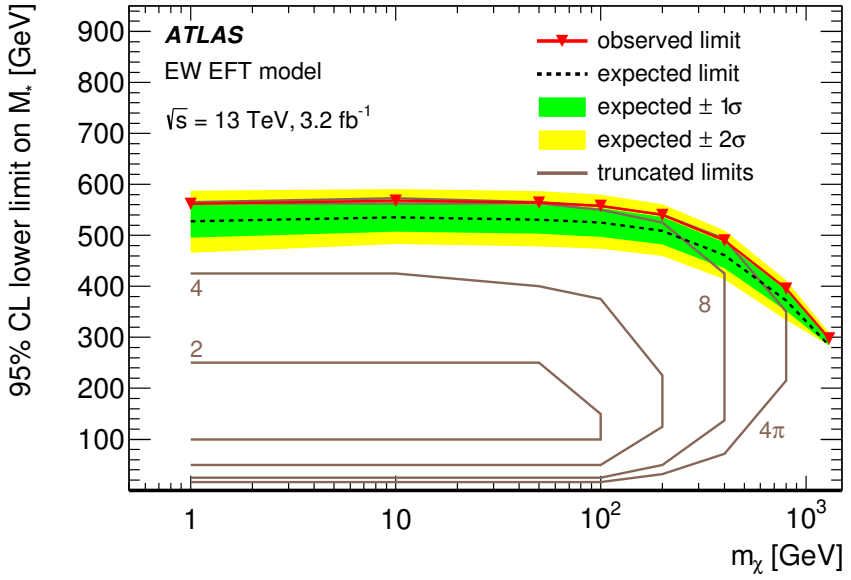
E_T^{miss}+photon

2015 data
JHEP 06 (2016) 059

- CRs: 1μ, 2μ, $2e$, $\gamma + \text{jet}$
- What if DM couples to photons?
  - Considered with an EFT diagram
  - Dimension-7 $\gamma\gamma\chi\chi$ coupling



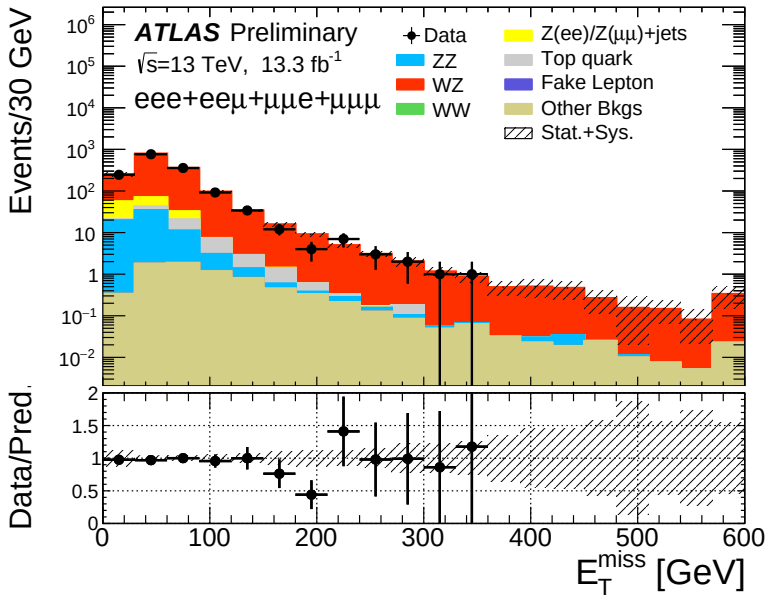


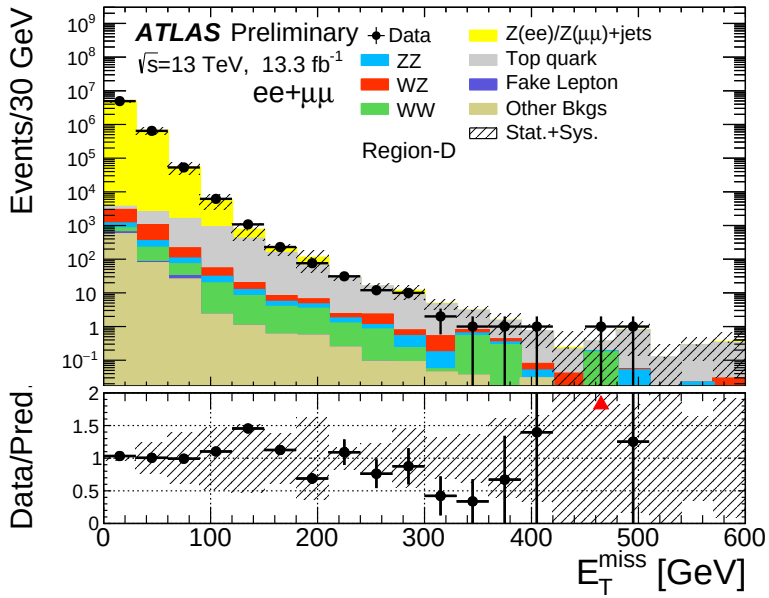


$E_T^{miss}+Z(\rightarrow \ell\ell)$

New! 2015+2016 data
ATLAS-CONF-2016-056

- ZZ: MC, qqZZ (NNLO QCD + NLO EW) and ggZZ (LO + k-factor)
- WZ: *eee*, *ee*μ, $\mu\mu e$, $\mu\mu\mu$ CRs for normalization
- Z+jets: ABCD method

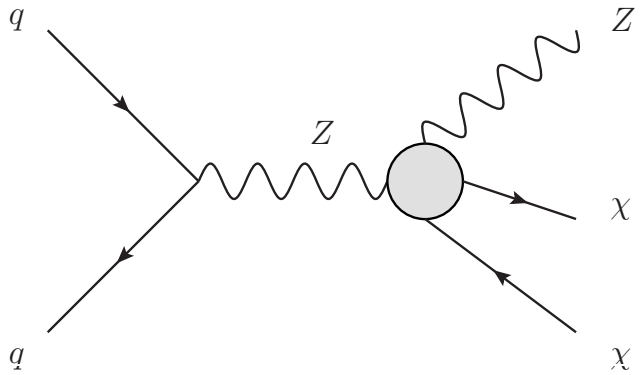


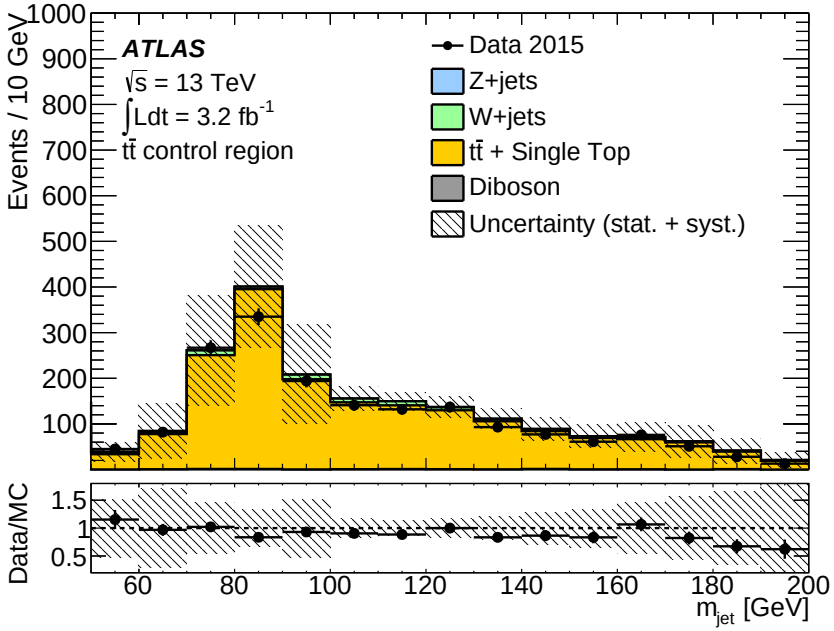


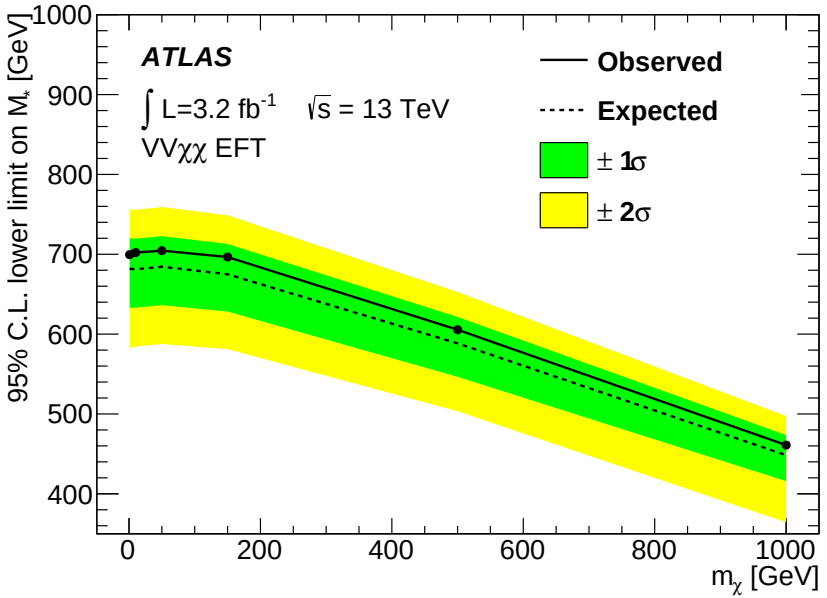
E_T^{miss}+W/Z($\to$qq)

New! 2015 data
EXOT-2015-08

- CRs: W (μ), Z ($\mu\mu$), and $t\bar{t}$ (μ+b-tag)
- What if DM couples to Z?
  - Considered with an EFT diagram
  - Dimension-7 $ZZ\chi\chi$ coupling



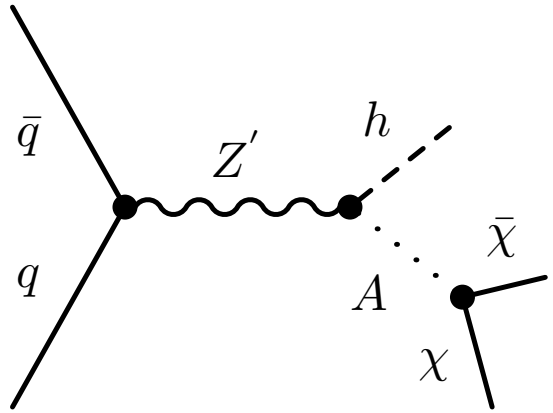


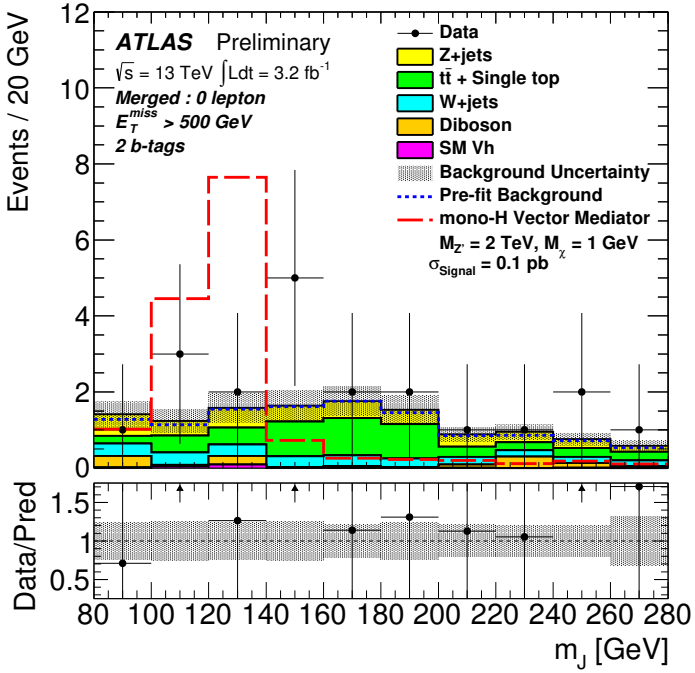


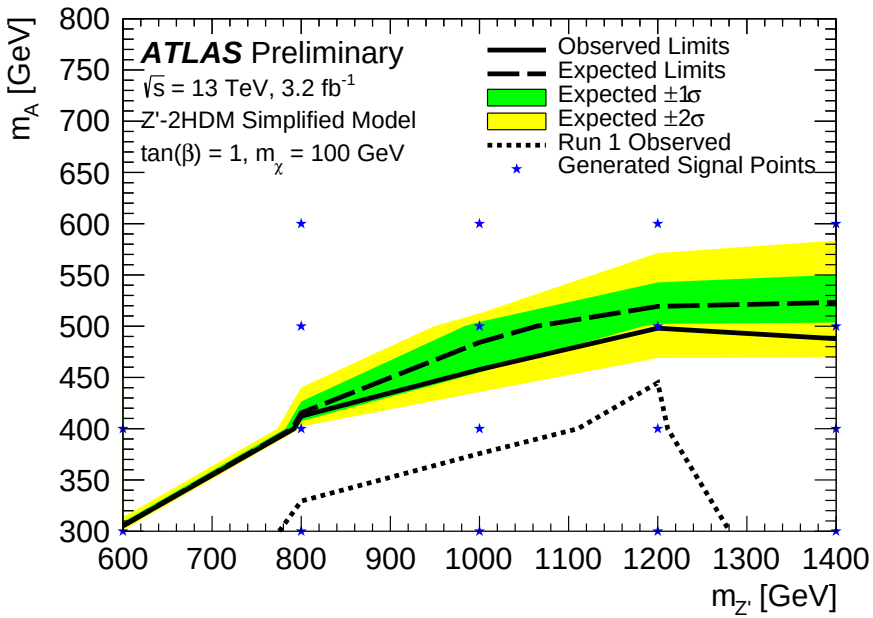
E_T^{miss}+H(→bb)

2015 data
ATLAS-CONF-2016-019

- 1μ CR: W+jets and $t\bar{t}$
- 2ℓ CR: Z+jets
- What if DM couples via a 2HDM?
  - Considered as a second model



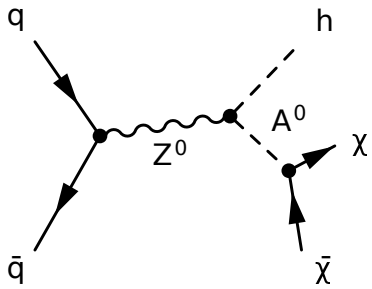


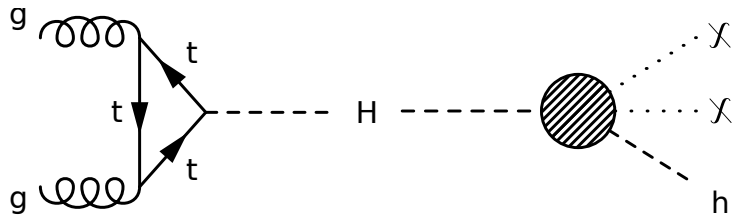


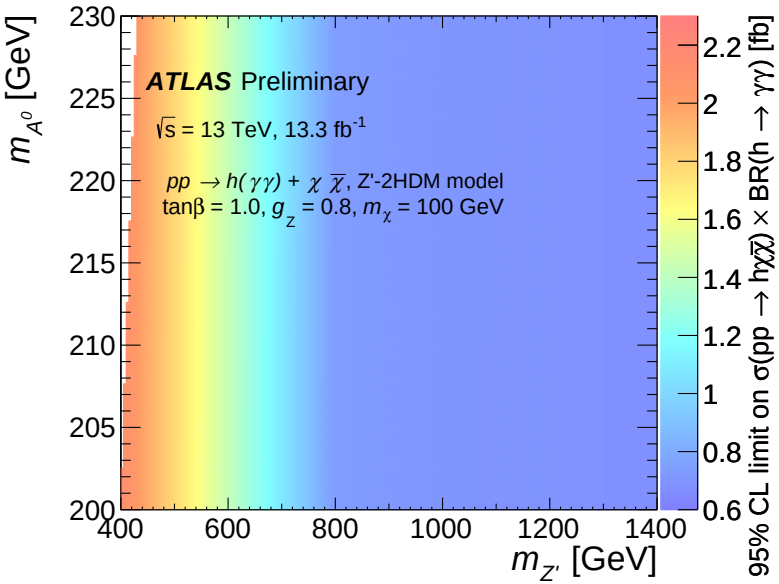
E_T^{miss}+H($\rightarrow \gamma\gamma$)

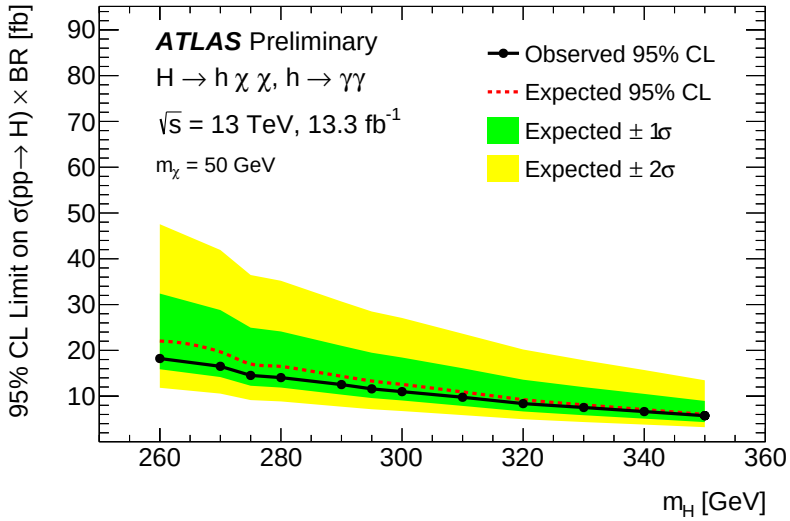
New! 2015+2016 data
ATLAS-CONF-2016-087

- Considered a pair of other DM models (2HDM + heavy scalar)





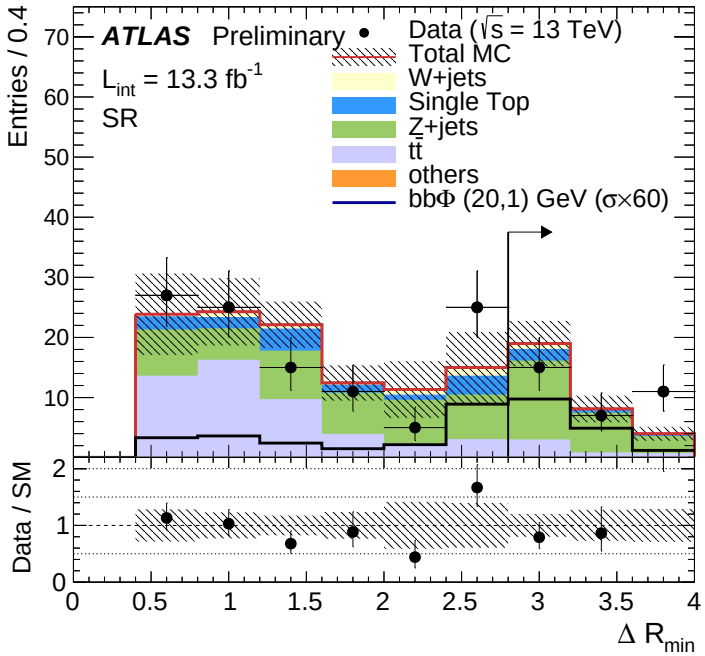


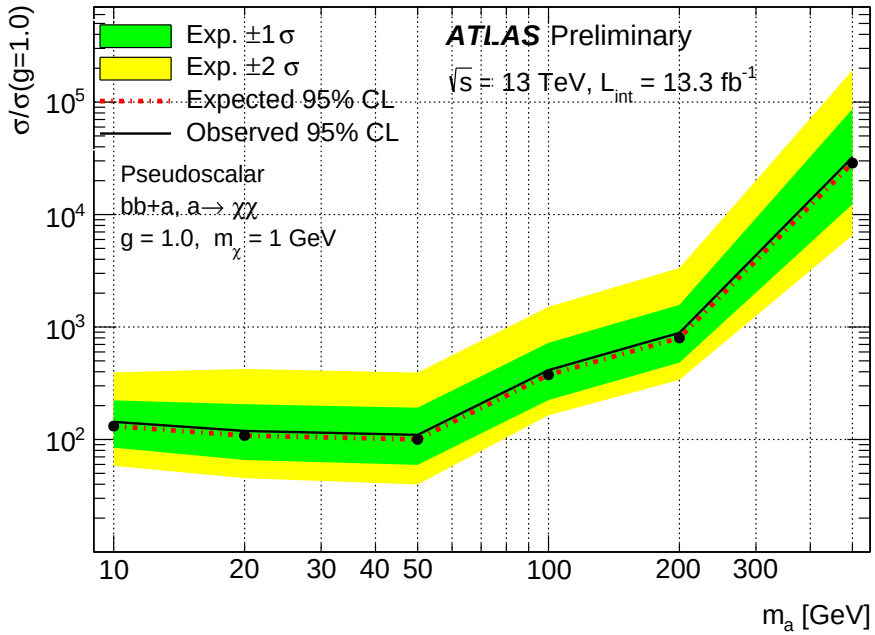


E_T^{miss}+b-jets

New! 2015+2016 data
ATLAS-CONF-2016-086

- Simultaneous fit to three CRs:
  - Z+jets: ee or $\mu\mu$ + 1 b-tag (CRZ1b)
  - $t\bar{t}$: e or μ + 2 b-tag (CRW2b)
  - W+jets: e or μ + 1 b-tag (CRW1b)
- Main cuts: $\mathrm{Imb}(b_1,b_2) = (p_T^{b_1} - p_T^{b_2})/(p_T^{b_1} + p_T^{b_2})$, $\min \Delta R(j_1, j_2)$
- Also considered pseudoscalar mediator model

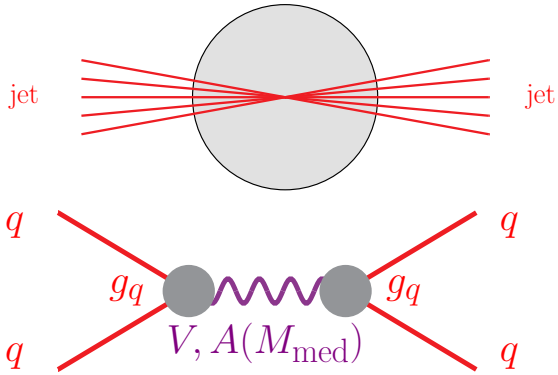


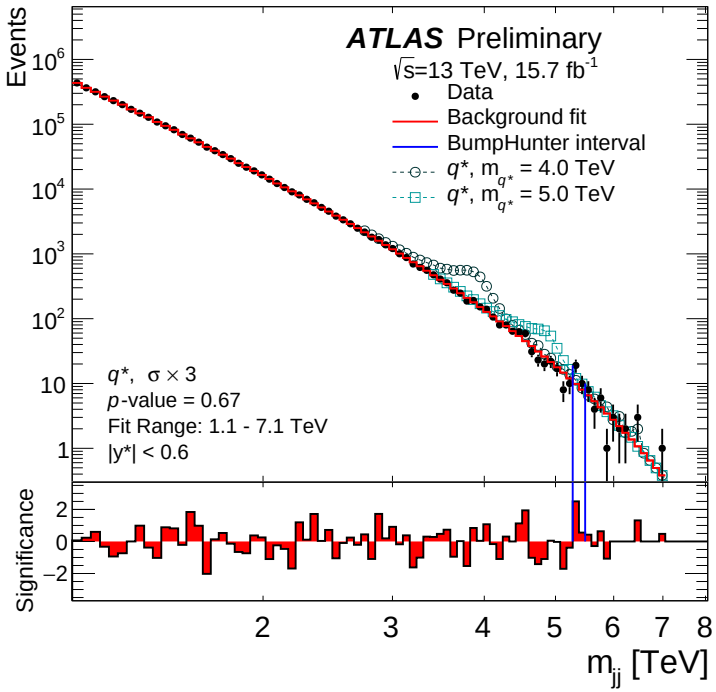


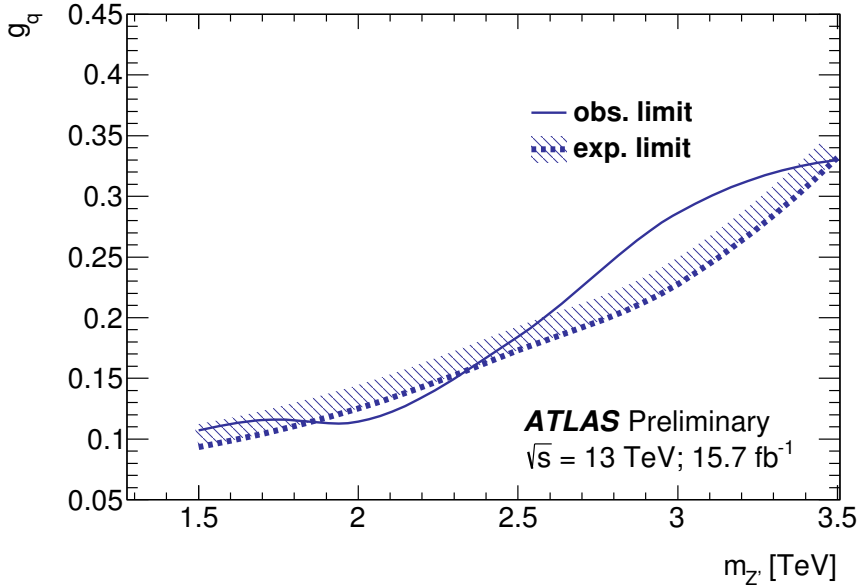
Dijet search

New! 2015+2016 data
ATLAS-CONF-2016-069

- Dijet searches probe dark mediators
  - If produced by q/g, it can also decay
- Data-driven background function fit
  - Look for bump on smooth background
- Leading limits for $m_{Z'} \gtrsim 1.5\,\mathrm{TeV}$



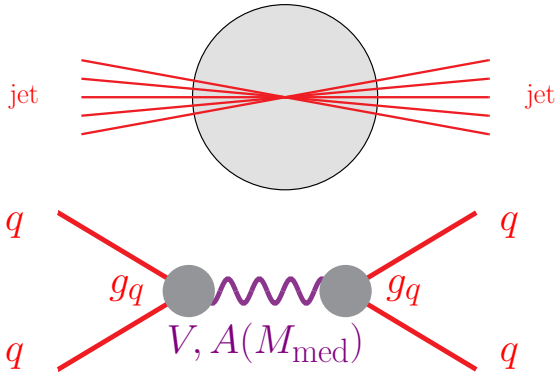


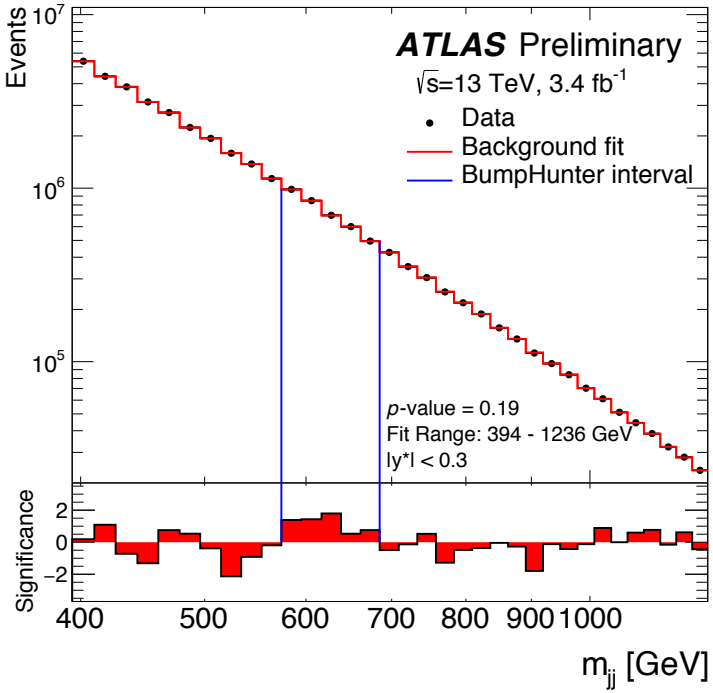


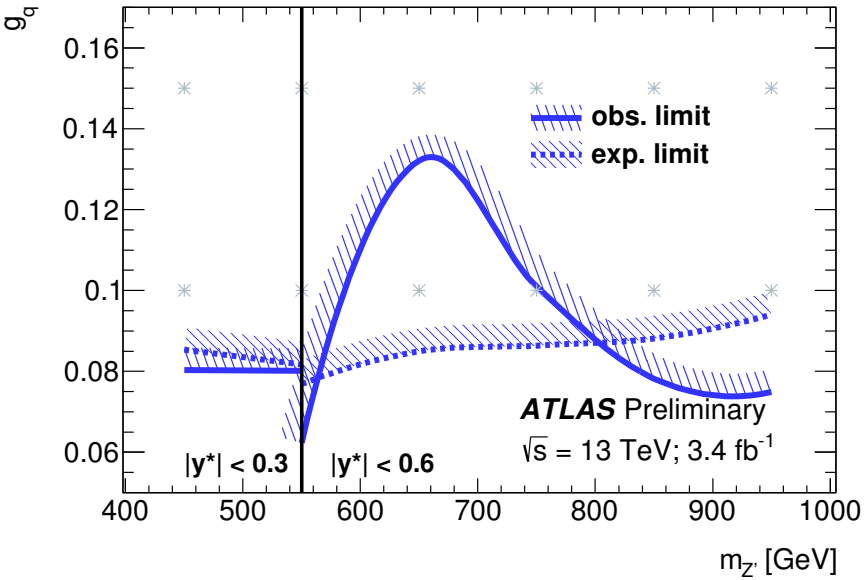
Trigger-level dijet search

2015 data
ATLAS-CONF-2016-030

- How can we lower the trigger barrier?
  - Bandwidth = size × rate
  - Reduce size: only save jet trigger info
- Record all events passing L1 (hardware)
- Reaches mediator mass of $\gtrsim 450\,\mathrm{GeV}$



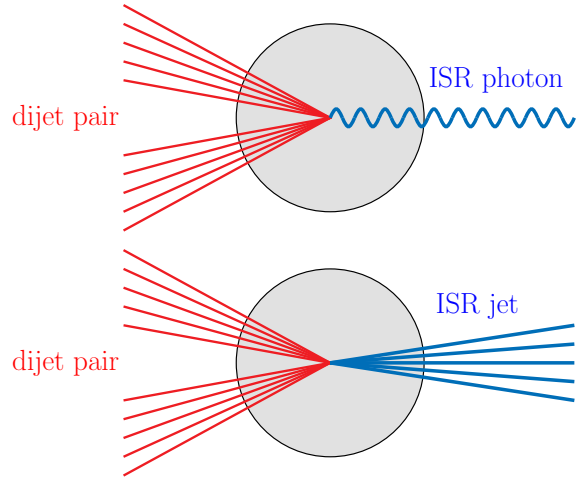


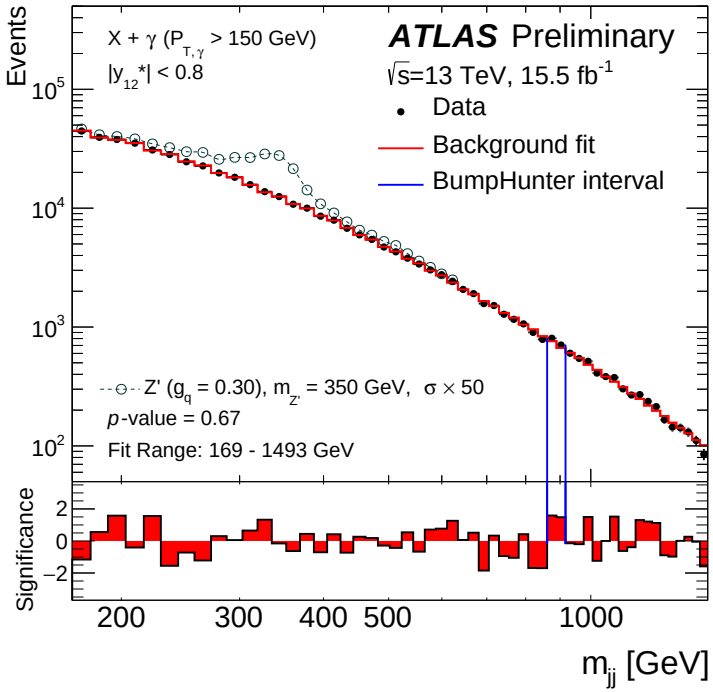


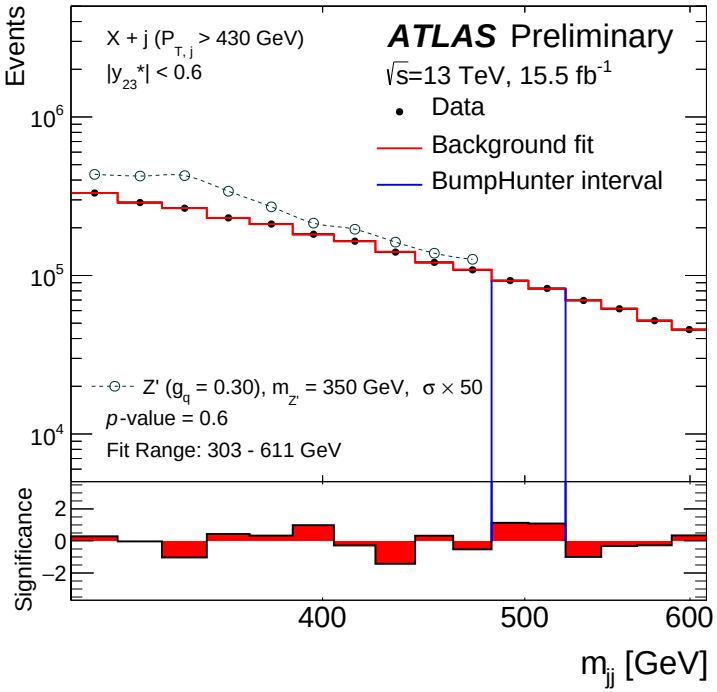
Dijet+ISR search

New! 2015+2016 data
ATLAS-CONF-2016-070

- L1 trigger threshold remains a limitation
- Circumvent by triggering on ISR object
  - ISR photon: $p_{\mathrm{T}}^{\gamma_{\mathrm{ISR}}} > 150\,\mathrm{GeV}$
  - ISR leading jet: $p_{\mathrm{T}}^{\mathrm{jet1}_{\mathrm{ISR}}} > 430\,\mathrm{GeV}$
- Fit background and look for bumps







Dijet+ISR search

New! 2015+2016 data
ATLAS-CONF-2016-070

- L1 trigger threshold remains a limitation
- Circumvent by triggering on ISR object
- Fit background and look for bumps
  - ISR photon: sensitive to smaller $m_{Z'}$
  - ISR jet: more sensitive (when possible)