Dark Matter searches with the ATLAS Detector

Ava Myers, on behalf of the ATLAS collaboration

ICNFP21

August 26, 2021

https://indico.cern.ch/event/1025480/

University of Pittsburgh

ATLAS EXPERIMENT

Outline

1. **Introduction**
   - **Dark matter detection**
   - **Simplified models**
2. Search for the mediator
   - Dilepton resonance
   - Dijet resonance
3. Search for recoiling DM (X+MET)
   - Jet + MET
   - Z(ll) + MET
4. Heavy flavor
   - tt and single-top + MET
5. The Higgs and DM
   - Higgs (dark Higgs) recoil against DM
   - Higgs is the mediator (decays to invisible)

Searching for dark matter

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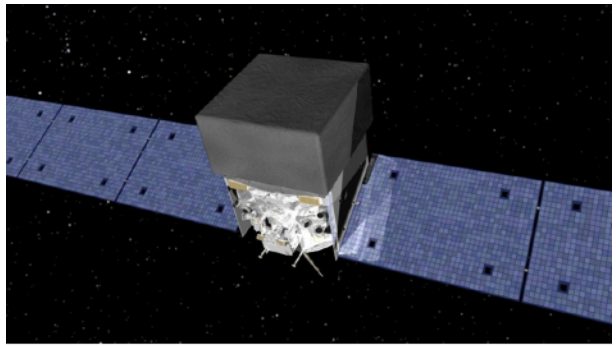
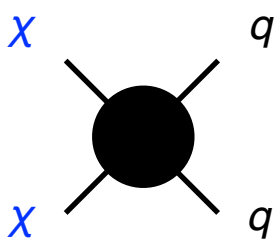


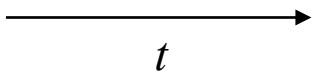
[Fermi-LAT](#)

MAGIC, H.E.S.S.

Annihilation



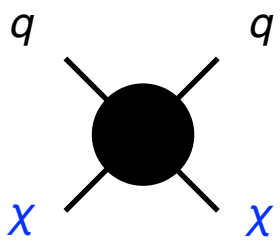
Indirect



[XENON1T](#)

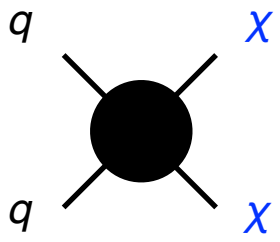
LUX, Panda-X, Picasso…

Scattering

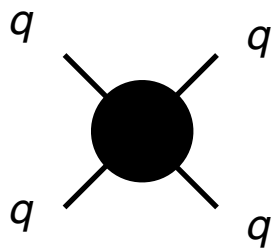


Direct

Production



Mediator



Collider

Dark Matter at colliders

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- Astrophysics evidence for DM
- WIMP miracle → DM at the EW scale
- Collider searches:
  1. **Direct DM mediator searches**: dijet (dilepton) resonances
  2. **X+MET**: Add object "x" for DM to recoil against
  3. **Higgs portal models**: Some mediator (Higgs) to invisible
  4. **Other models**: 2HDM, Z', SUSY

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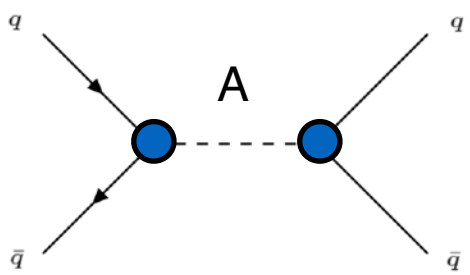
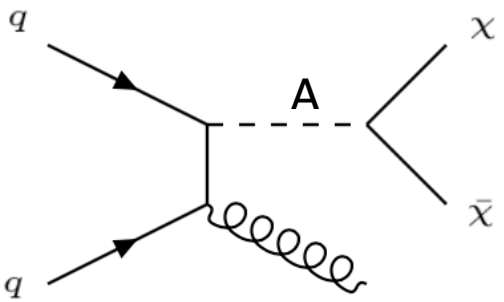
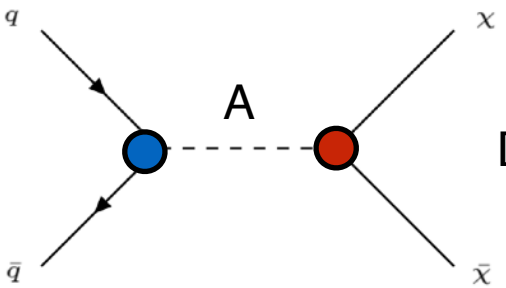
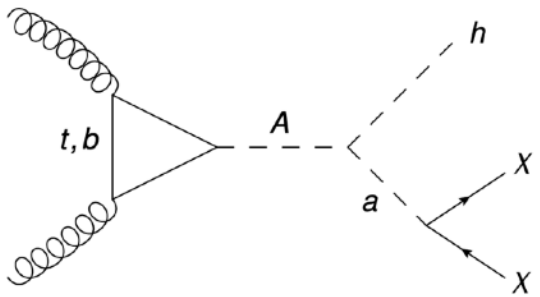
(1) SM  SM

(2) SM  DM + "x"

(3) SM  DM

(4) SM  2HDM+a

2HDM models

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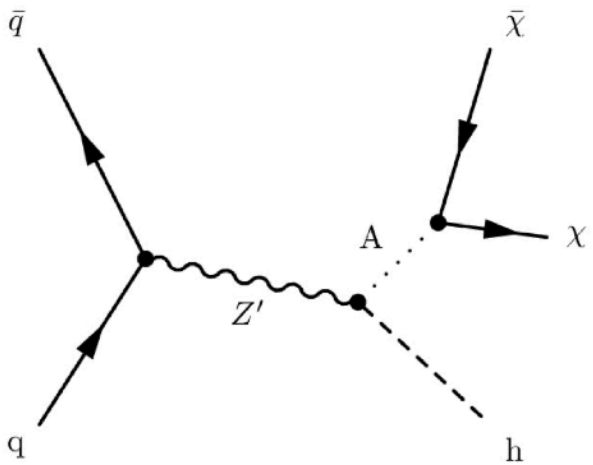
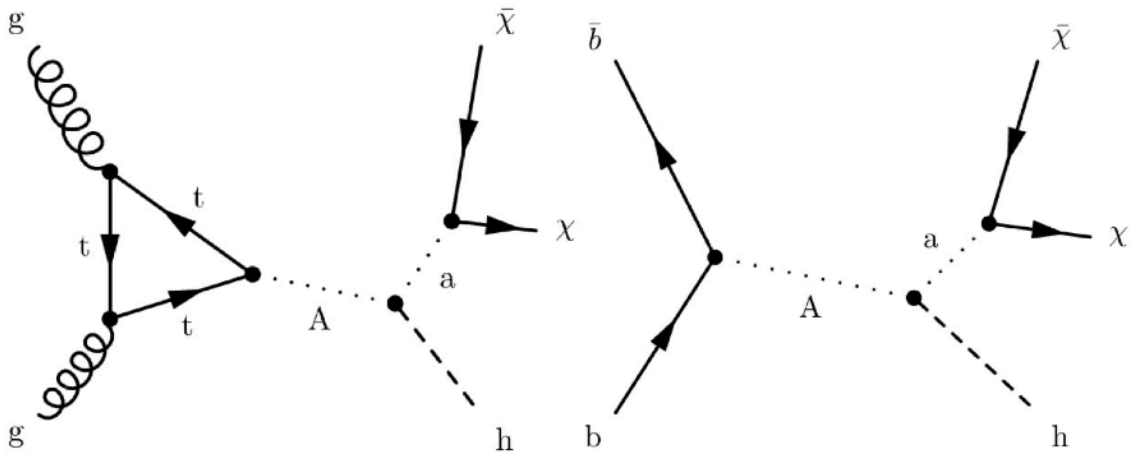
Quick aside on 2HDM models

- Another extended Higgs sector
- Two Higgs doublet model with charged heavy Higgs ($H^{\pm}$)
- Additional pseudo scalar mediator to DM (a) or vector Z'
- Couplings prioritize third generation and signatures with vector and Higgs boson

Z'-2HDM



2HDM+a



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Dilepton resonance searches

Phys. Lett. B 796 (2019) 68
Mar 14, 2019

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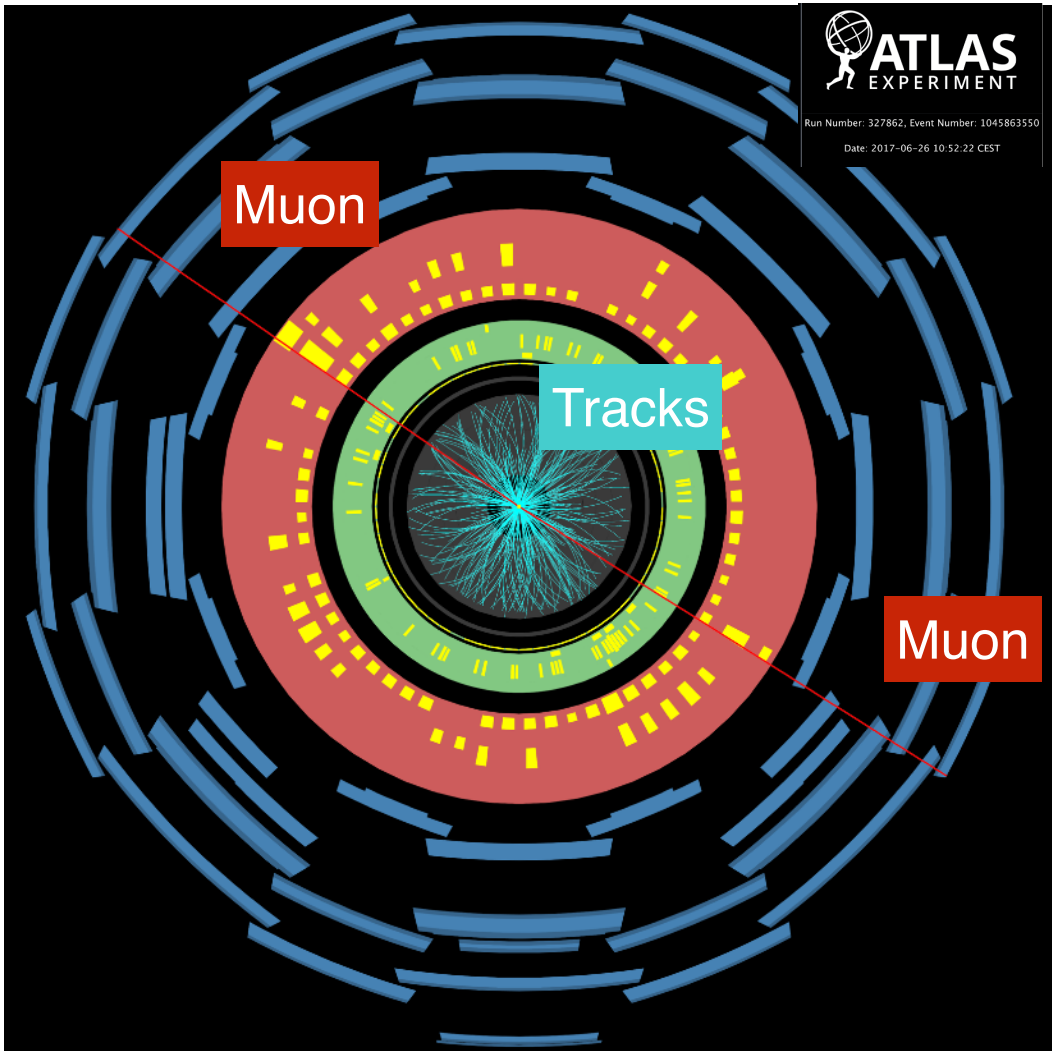
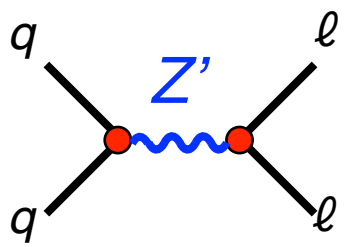
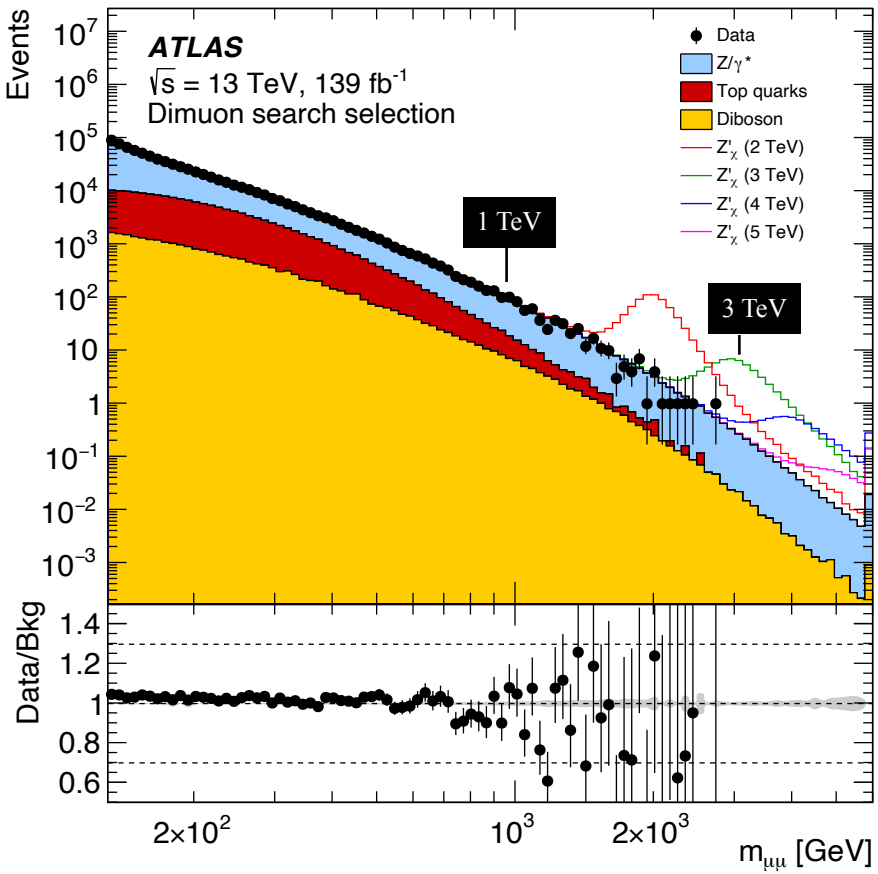
Look for $m_{\mu\mu}$ resonance to identify high mass mediator

- Probe m > 250 GeV
- Clear signature, easy to trigger
- Improved mass range due to increased √s
- Limit on coupling improved from luminosity







Dielectron result also considered in paper

Dijet resonance searches

Phys. Rev. D 96, 052004
Mar 27, 2017

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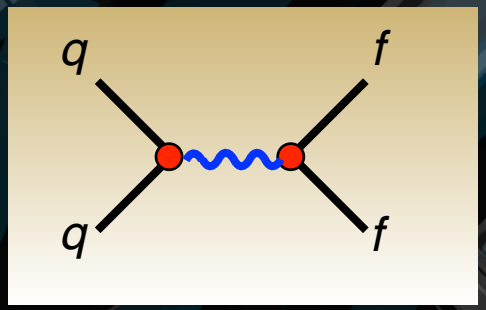
Among the highest dijet mass event recorded: m_{jj} = 8.12 TeV



dijet

mediator→SM

p_T = 3.79 TeV

Tracks

EM calorimeter energy

Hadronic calorimeter energy

p_T = 3.79 TeV

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

Dijet resonance searches

Phys. Rev. Lett. 121 (2018) 081801 Aug 22, 2018
JHEP 03 (2020) 145 Oct 18, 2019

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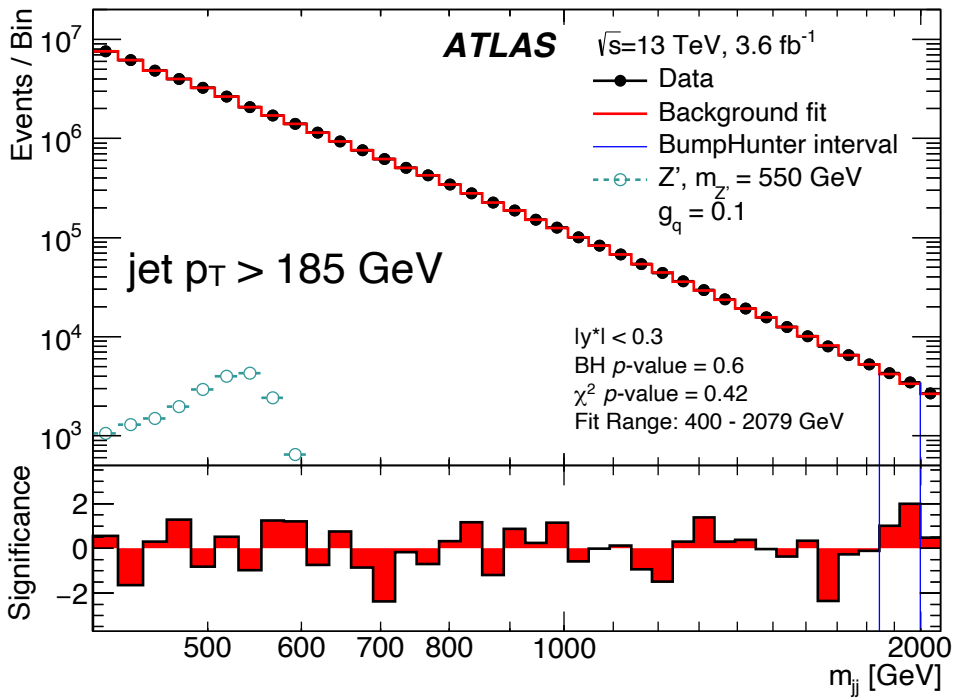
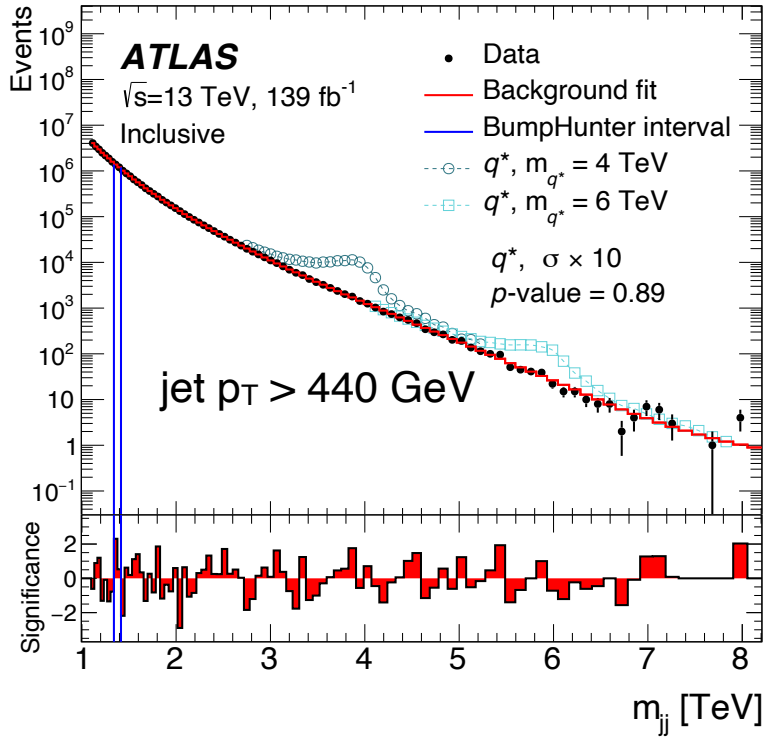
Large signal on a large background: signature is a "bump"

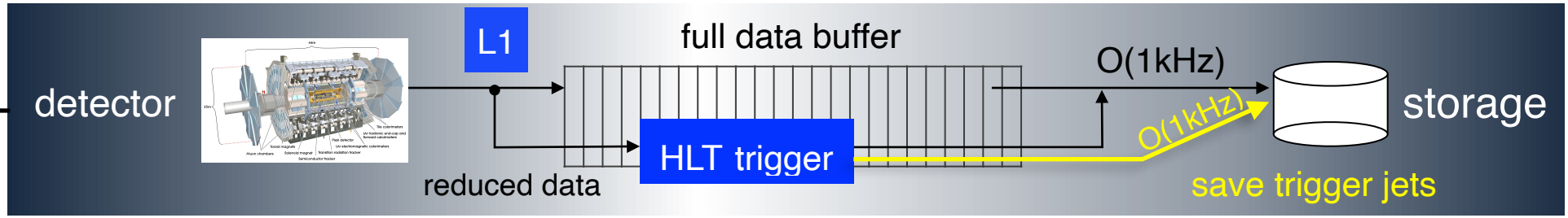
- Fit background using a smooth function
- BumpHunter is used to evaluate significance of deviations

TLA: save jets from HLT
"No bandwidth limit" → probe lower masses



Offline analysis
Full offline event → better jet resolution





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Jet + MET

Phys. Rev. D 103 (2021) 11200
arXiv:2102.10874 (Feb 22, 2021)

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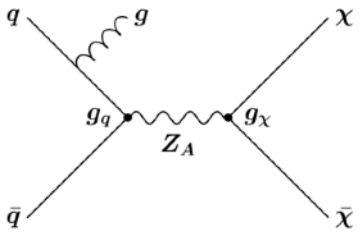
- Dedicated CRs for V+jets, $t\bar{t}$/single-top
- Multijet: jet smearing method in data

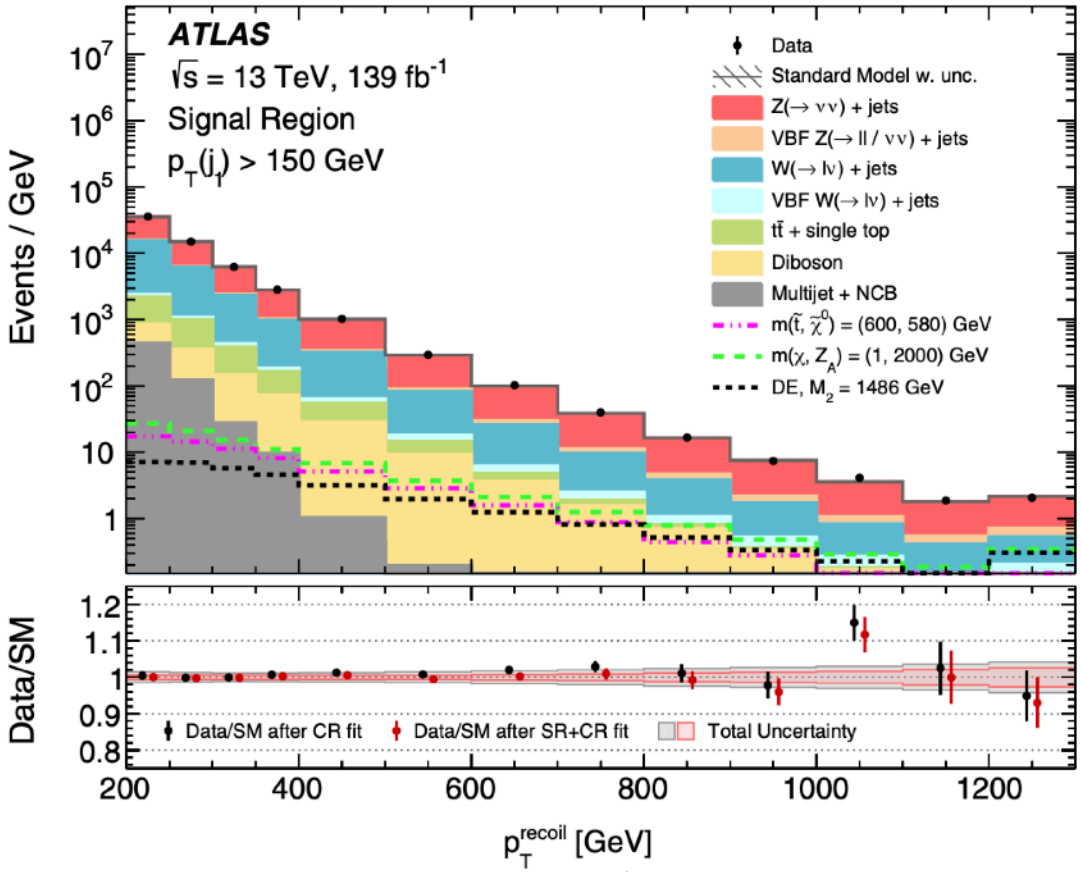
Simplified model (2) from intro



Event selection

MET > 200 GeV
p_T^{jet} > 30 GeV, |η| < 2.8
$p_T^{lead\ jet}$ > 150 GeV, $|\eta^{lead\ jet}|$ < 2.4

- Use simplified model with minimal number of free parameters



- **Results**: simultaneous, binned profile likelihood fit to p_T^{recoil} (SR + 5 CR)

MET hard-term

Z(ll) + MET

ATLAS-CONF-2021-029
(Jul 23, 2021)

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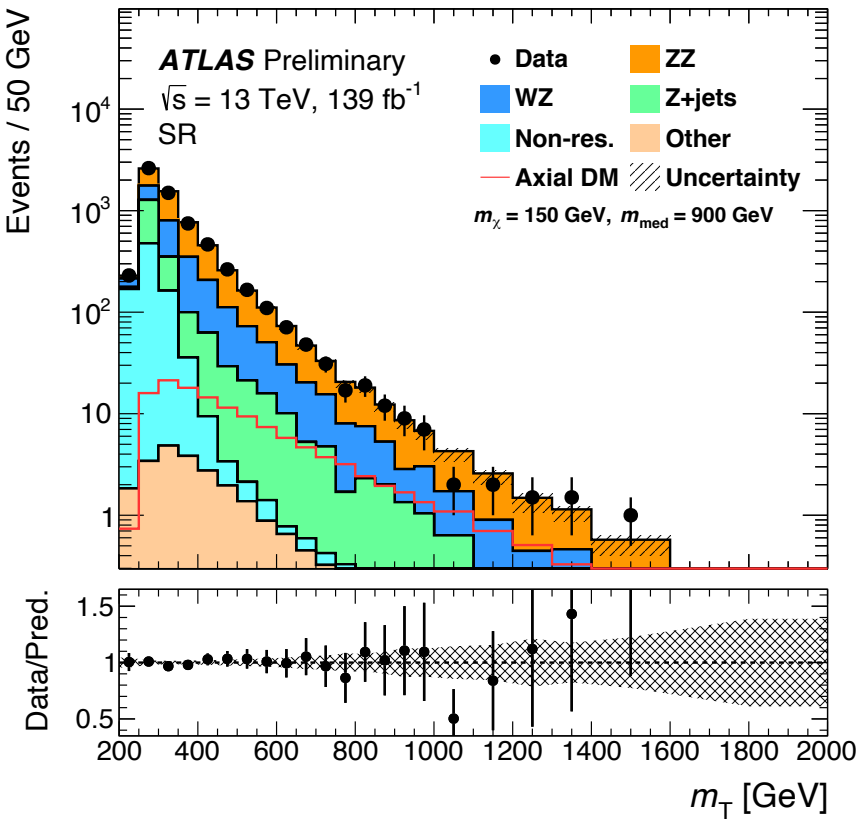
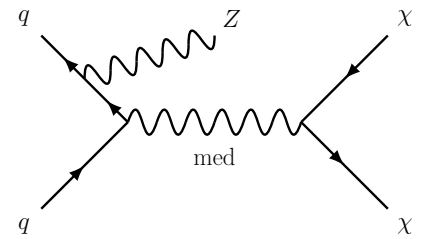
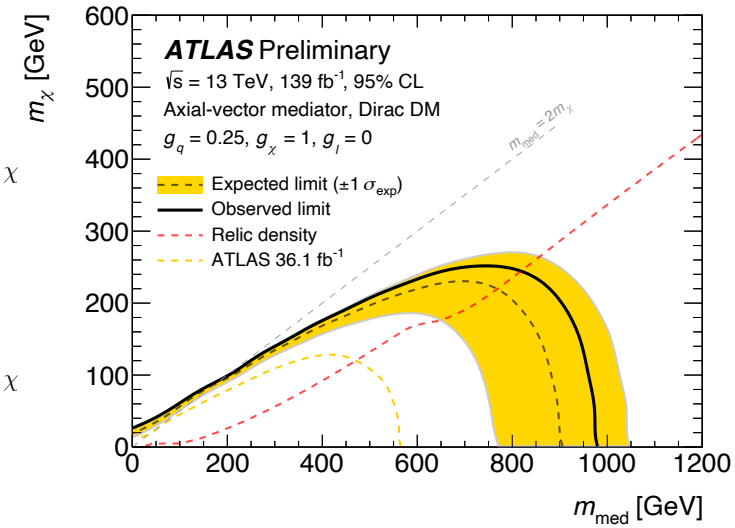
- Simplified model and 2HDM+a interpretations
- Also Higgs portal interpretation (later): BR(H→inv) < 0.18 at 95% CL

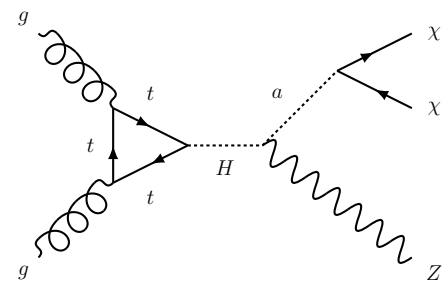
NEW!

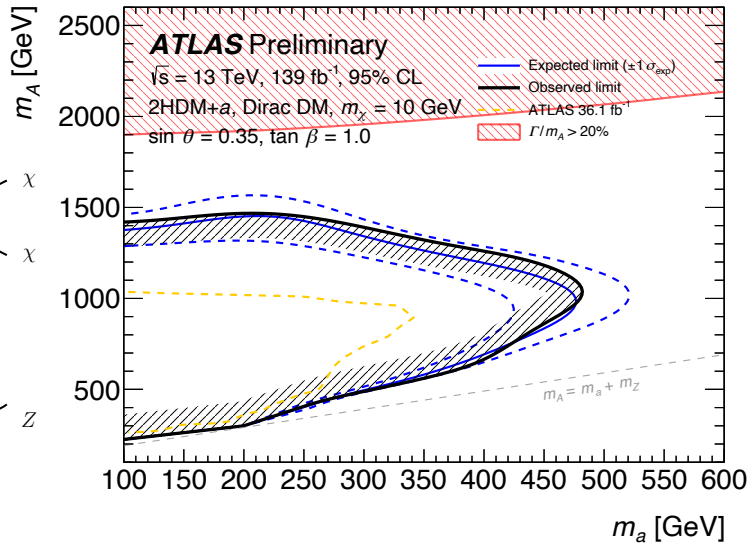




Axial-vector mediator







Exclusion limits set on 2HDM+a

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arXiv:2102.10874
(Nov 18, 2020)

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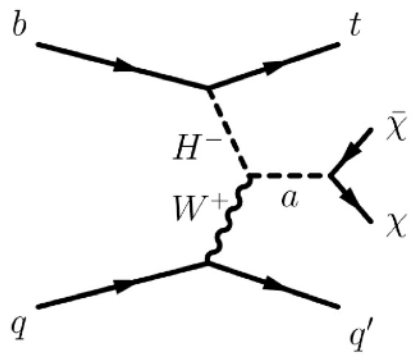
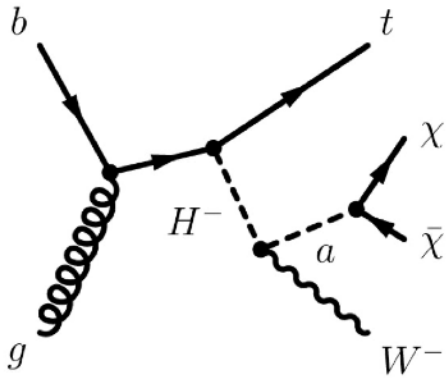
2HDM+a interpretation



t-channel

- 1 isolated lepton
- N_{jets} 1-4
- $N_{b\text{-}jets}$ 1-2
- MET > 200 GeV
- BDT trained to improve sensitivity



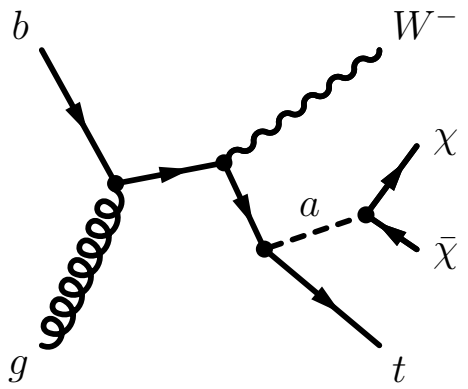
tW-channel

tW_{1L}

- 1 isolated lepton
- Njets >= 3
- Nb-jets >= 1
- MET > 250 GeV

tW_{2L}

- 2 OS isolated leptons
- Njets >= 1
- Nb-jets >= 1
- MET > 200 GeV



Single-top + MET

arXiv:2011.09308
(Nov 18, 2020)

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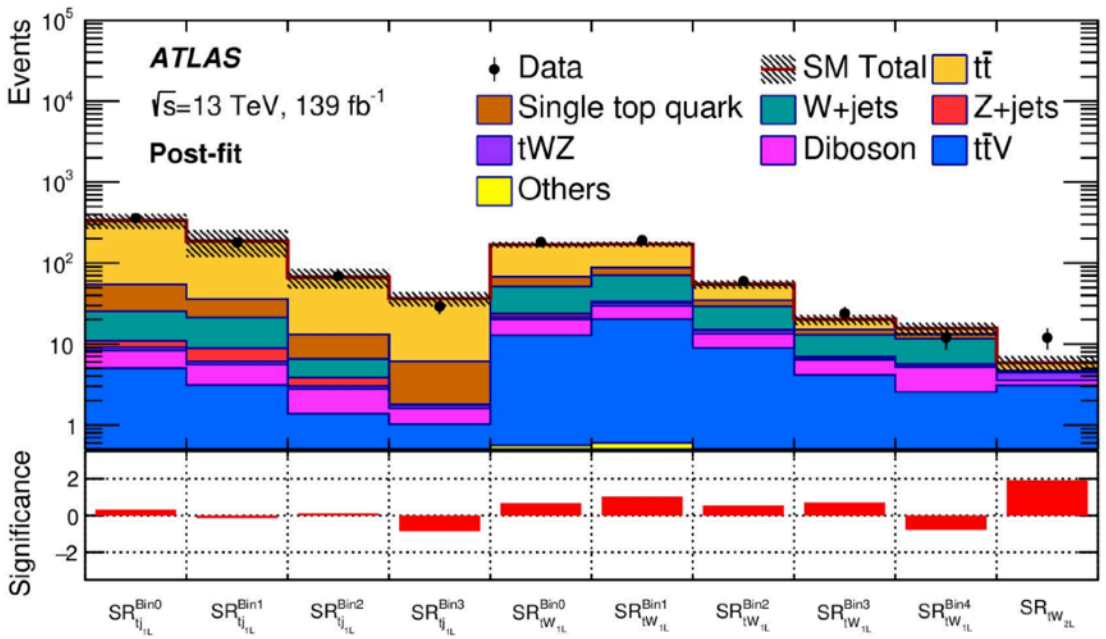
Targeting t+MET, but also sensitive to $t\bar{t}$+MET

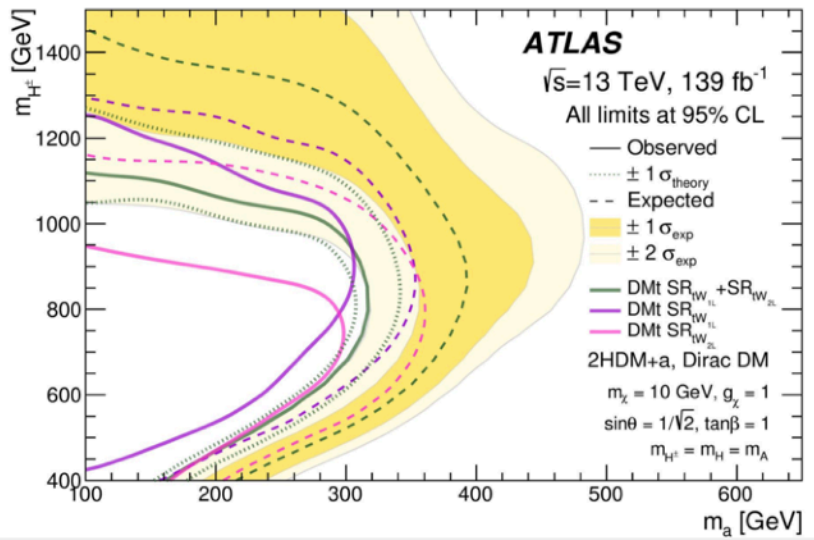
- Low $m_{H_\pm}$: dominated by t
- High $m_{H_\pm}$: dominated by $t\bar{t}$

Prominent backgrounds:

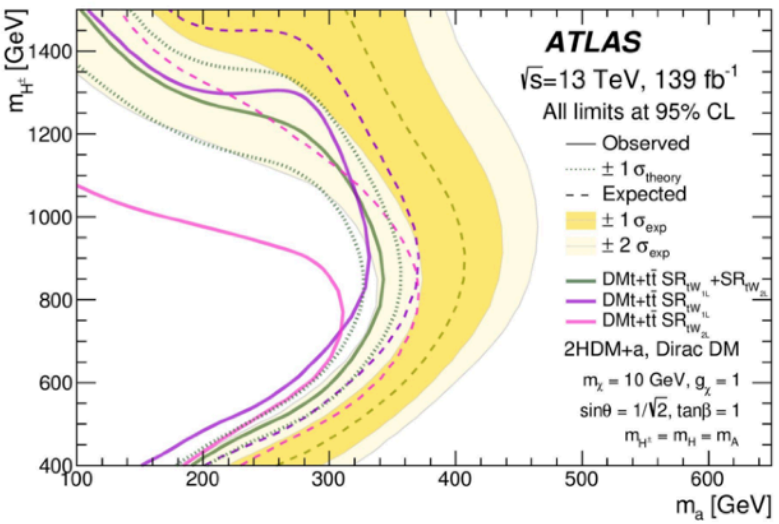
tj1L: $t\bar{t}$, W+jets
tW1L: $t\bar{t}$, W+jets
tW2L: $t\bar{t}$, $t\bar{t}$Z, $t\bar{t}$WZ



Assuming only t contributions
(tW only)



Assuming t and $t\bar{t}$ contributions



arXiv:2102.01444 (Feb 2, 2021)
arXiv:2012.03799 (Dec 7, 2020)

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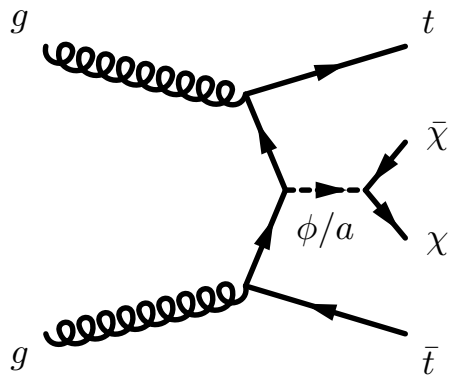
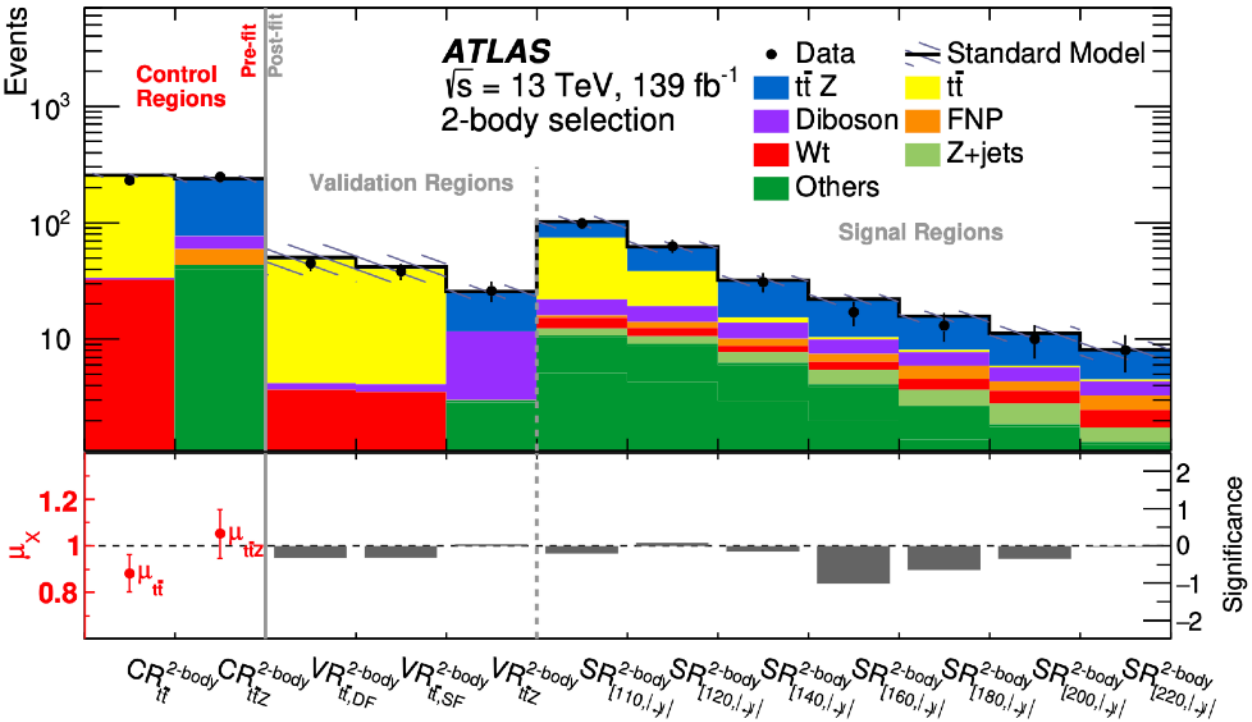
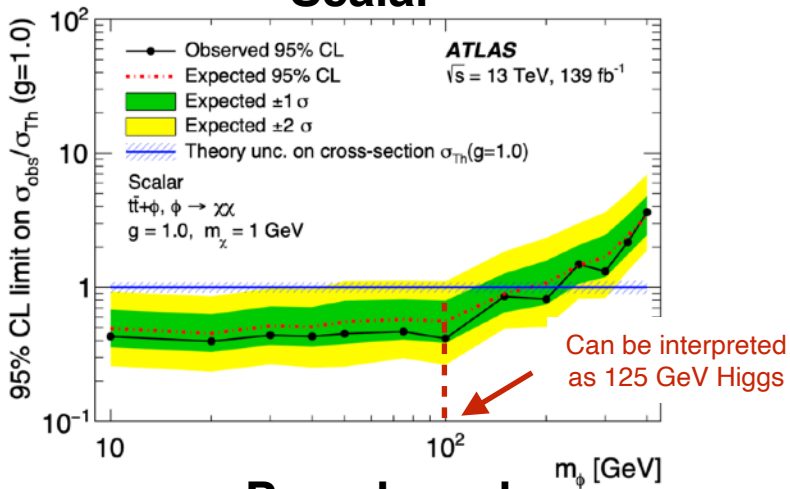
Spin-0 mediator model:

- Mediator (scalar ϕ, pseudoscalar a) is produced in association with $t\bar{t}$, decays to DM
- Largest coupling to heavy flavor
- 2-lepton channel most sensitive
- Dominant background from $t\bar{t}$, $t\bar{t}Z$

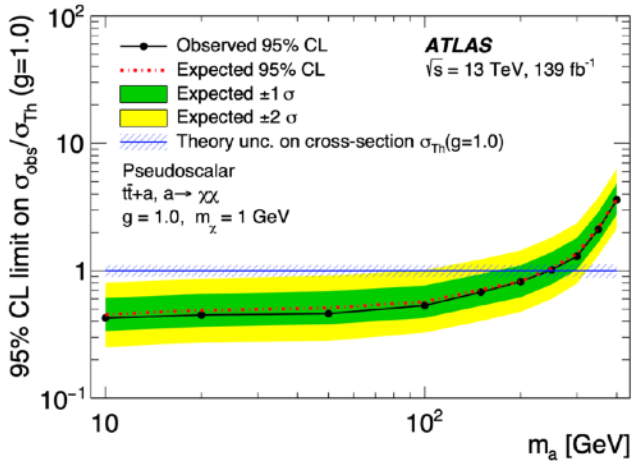




Scalar



Pseudoscalar



0-lepton search (less sensitive): SUSY-2018-12

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The Higgs and dark matter

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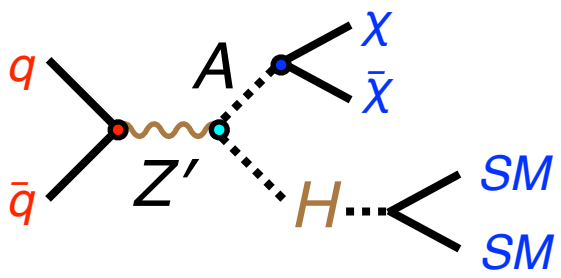
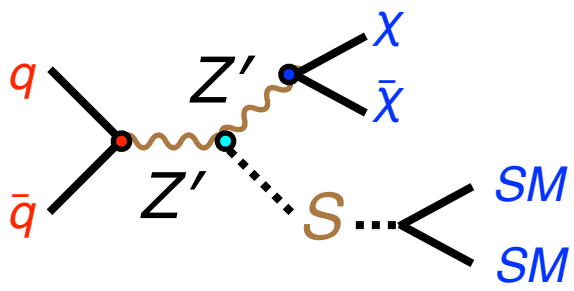
Higgs + MET



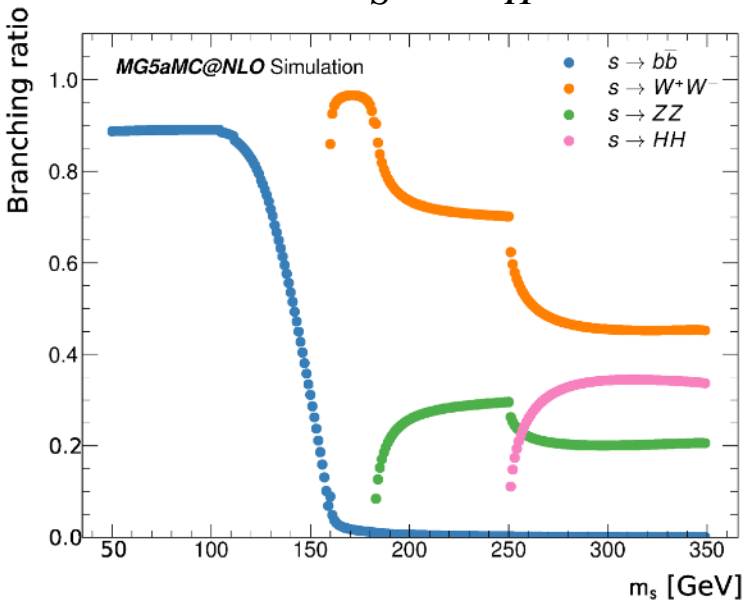
Higgs recoils against DM

Dark Higgs + MET



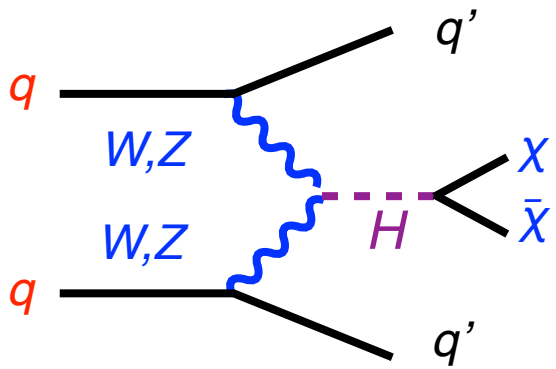
Scalar recoils against DM

$m_S \neq m_H$



Dominant decay to VV for $m_S > 200$ GeV

Higgs to invisible



Higgs decays to DM

<u>Decays</u>:

- bb → highest rate
- $\gamma\gamma$ → clean signature

<u>Production modes</u>

- VBF
- ZH, WH
- ttH
- Jet+MET (ISR ggF H→inv)

→ give something visible for invisible H to recoil against

ATL-PHYS-PUB-2019-032

H(bb) + MET

ATLAS-CONF-2021-006
(Mar 24, 2021)

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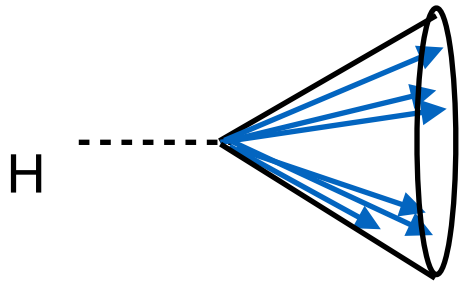
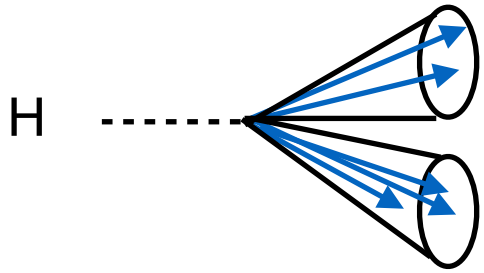
- Largest BR for Higgs decays (also possible for $\gamma\gamma$)
- Event selection based on Higgs boost

Merged



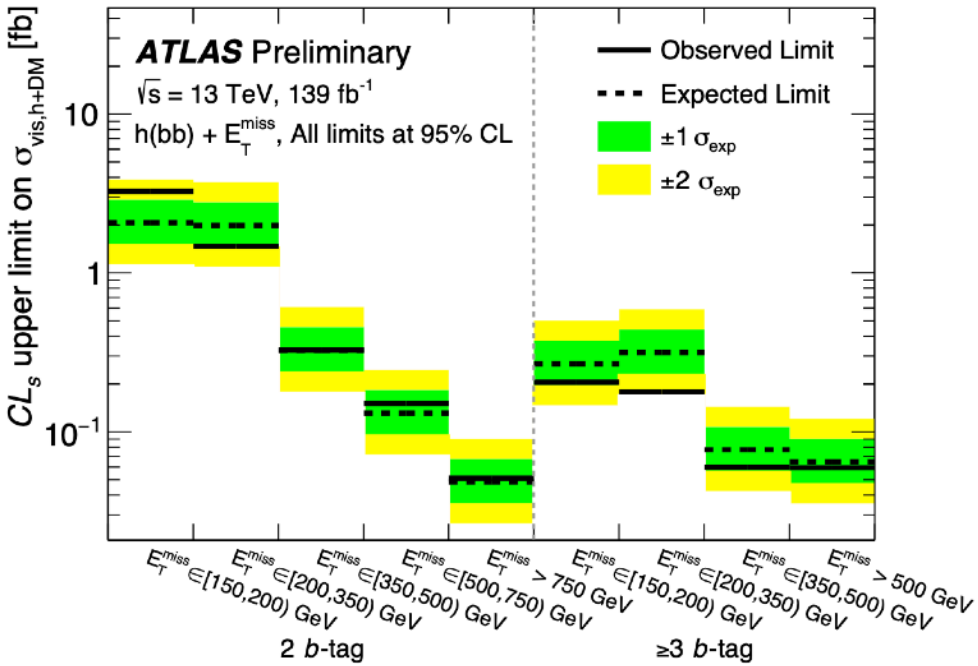
- ≥ 1 large-R jets, MET > 500 GeV
- Boosted Higgs identified with variable radius track jets

Resolved



- ≥ 2 small-R jets (≥ 2 b-tagged)
- 3 MET regions in range [150,500] GeV

- Backgrounds: V+ heavy flavor jets, $t\bar{t}$
- Binned profile likelihood fit to m_{bb}
- Gives upper limits on the cross-section in bins of MET (also 2-3+ b-jets)



H(bb) + MET model interpretations

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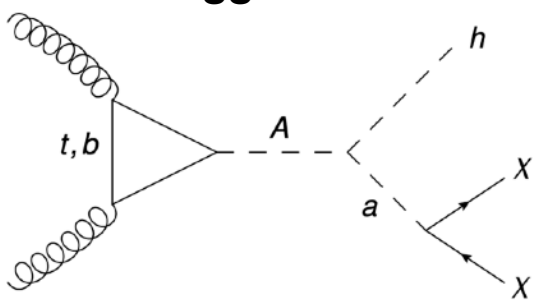
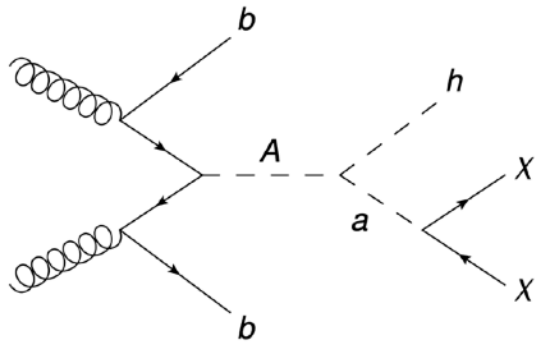
2HDM+a

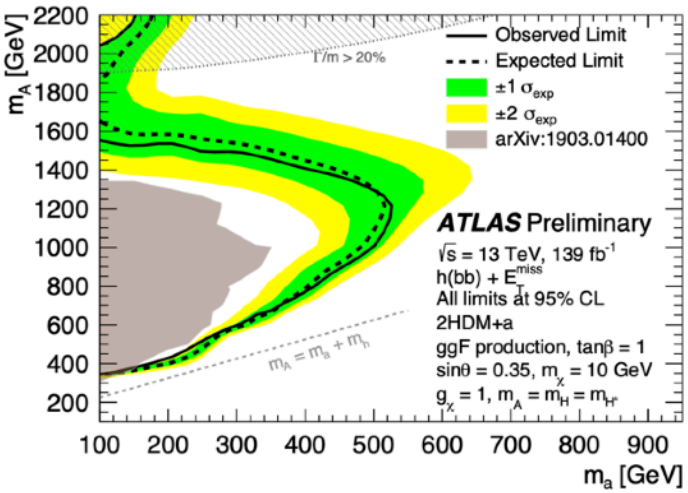
ggF



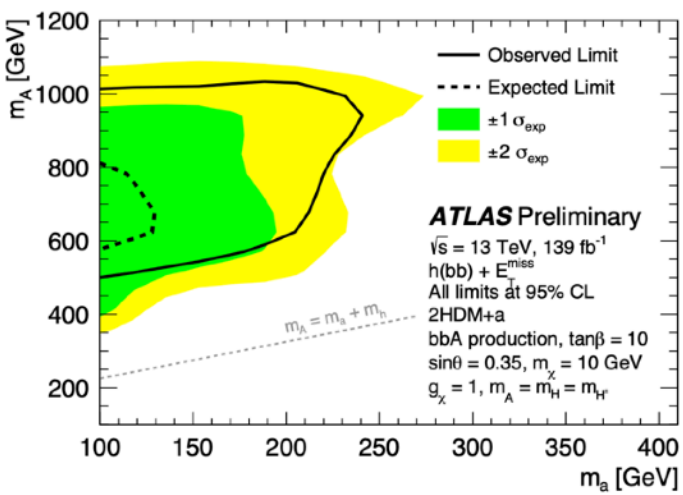
bbA



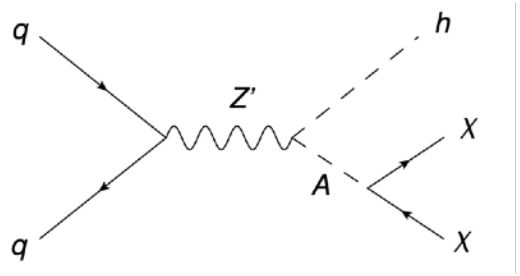
tanβ=1 (ggF)

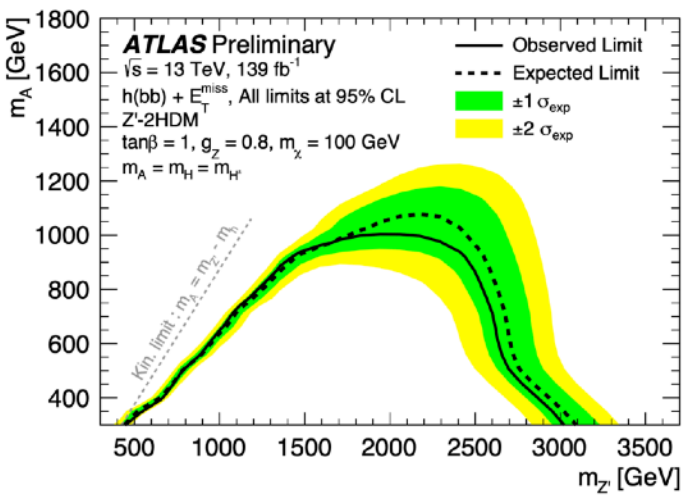


tanβ=10 (bbA)



Z'-2HDM





ATLAS-CONF-2021-006

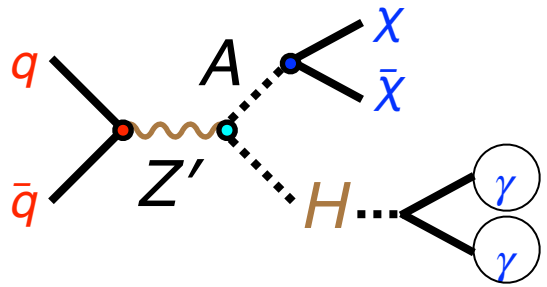
H→$\gamma\gamma$ + MET

arXiv:2104.13240
Apr 27, 2021

Ava Myers

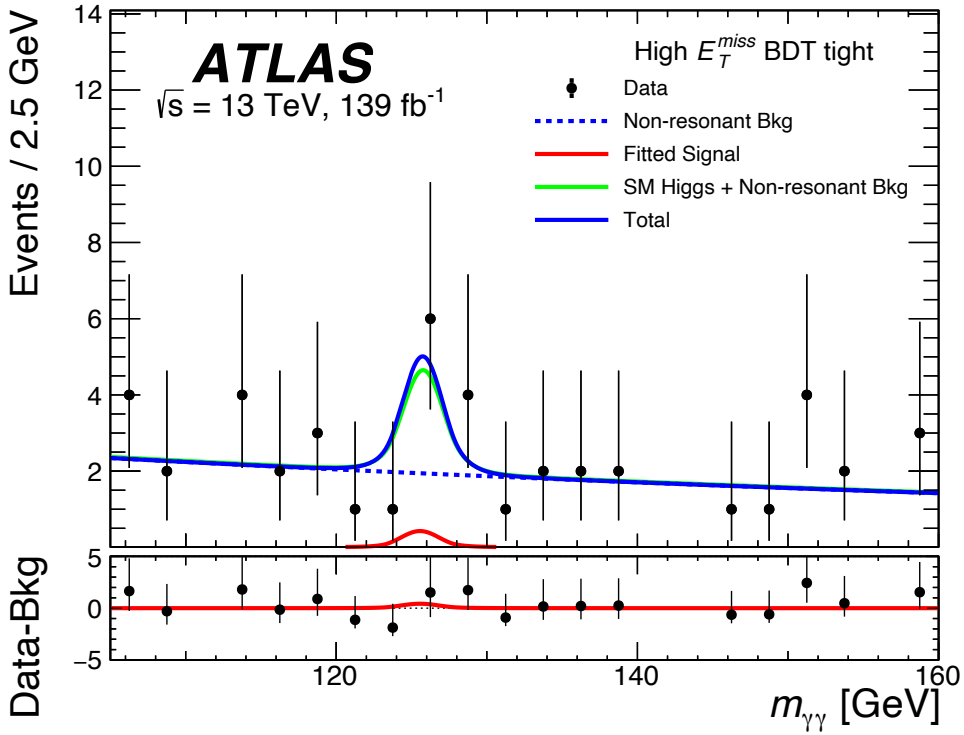
DM recoils against the Higgs

- Boosted (resolved) H → bb
- Resolved H → $\gamma\gamma$
- BDT trained with $p_T^{\gamma\gamma}$, $S_{E_T^{miss}}$

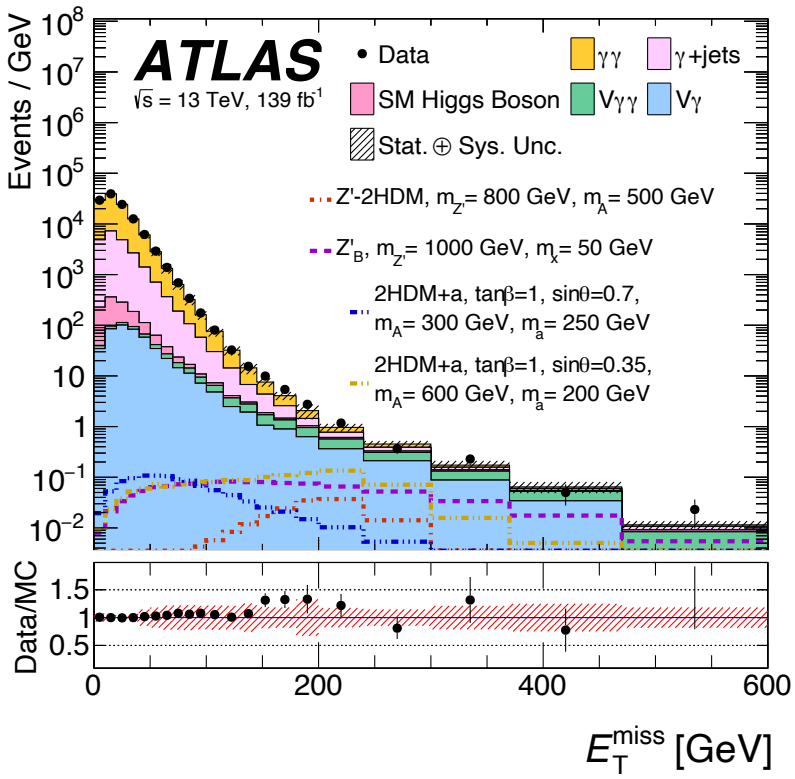


High rate
Clean signature

+ other models



Clean peak in tight BDT selection



Signals tend to have high MET

2HDM+a combination

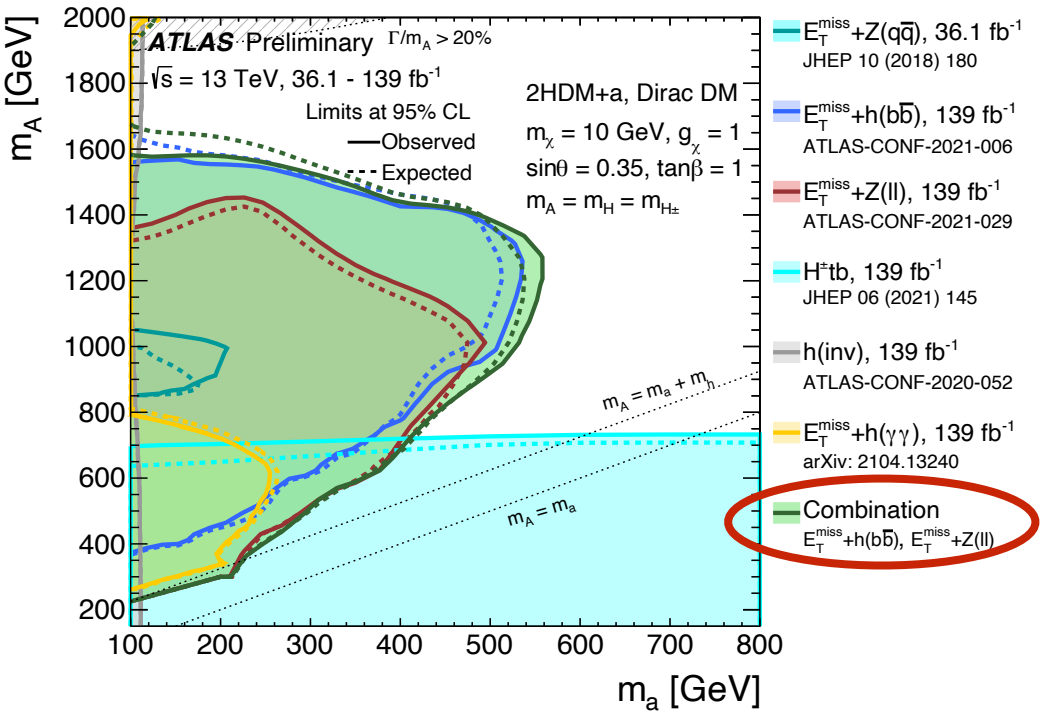
ATLAS-CONF-2021-041
(Jul 24, 2021)

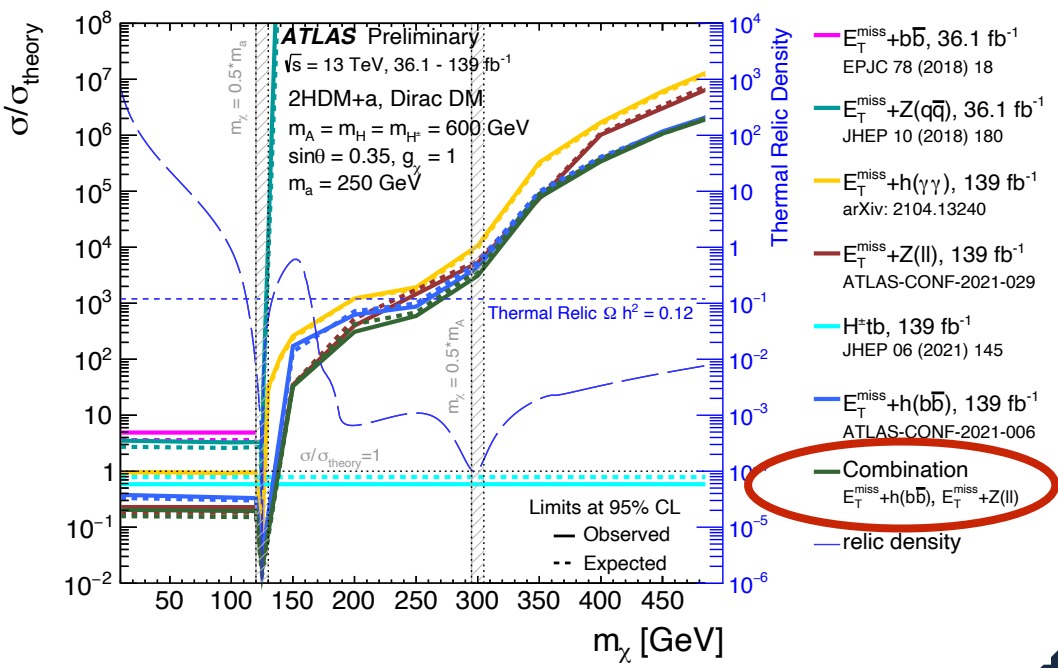
Ava Myers

Updates:

NEW!

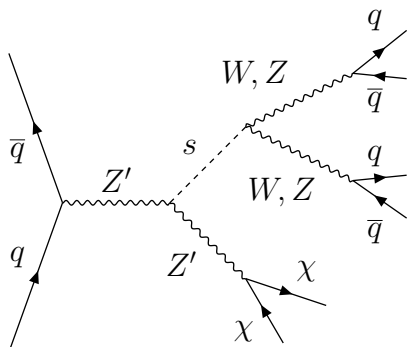
- Reinterpretation of $H^{\pm}tb$ (link) in context of DM models
- Statistical combination of H(bb)+MET and Z(ll)+MET
- Most sensitive searches updated to full Run-2 luminosity
- Significant complementarity from different channels

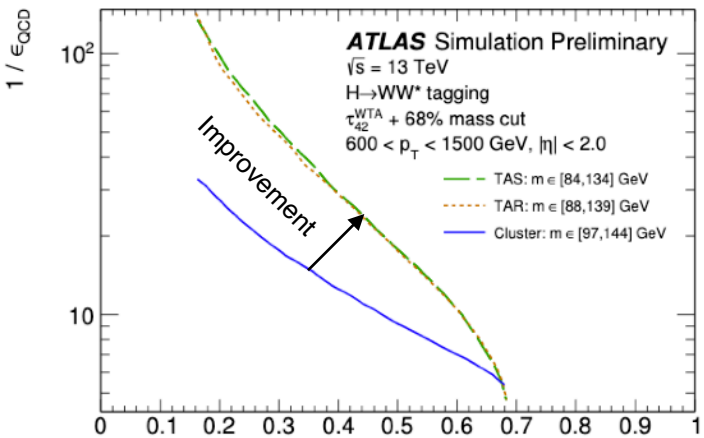


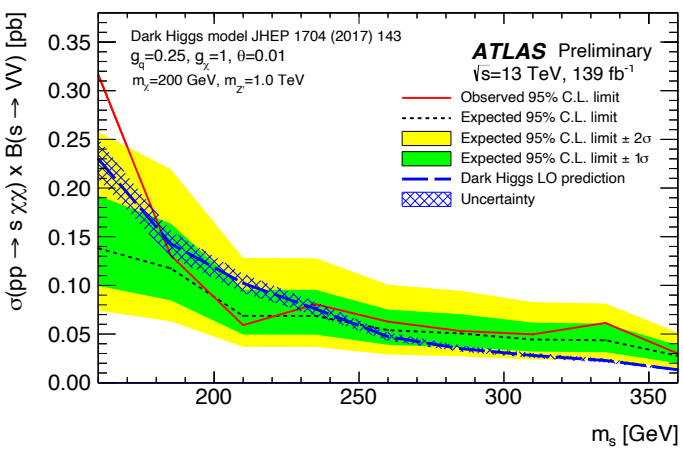


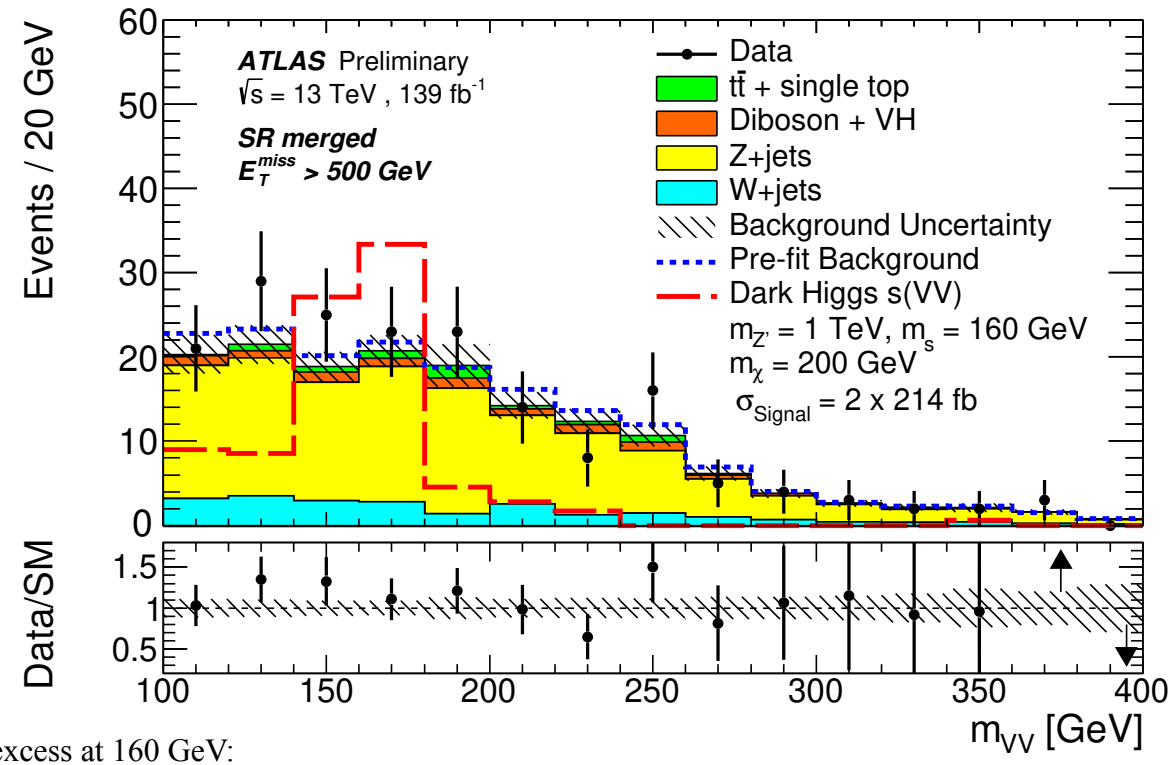
Dark sector Higgs (s) recoils against DM

- Mass of new scalar $s > 160$ GeV
- Primary decay mode to VV for large mass, utilize **hadronic** decays
- Use **T**rack **A**ssisted **R**eclustered (TAR) jets to improve jet mass and substructure resolution
- Require four prong jets using N-subjetiness









Mild excess at 160 GeV:
2.3σ local, 1.6 σ global

Higgs to invisible

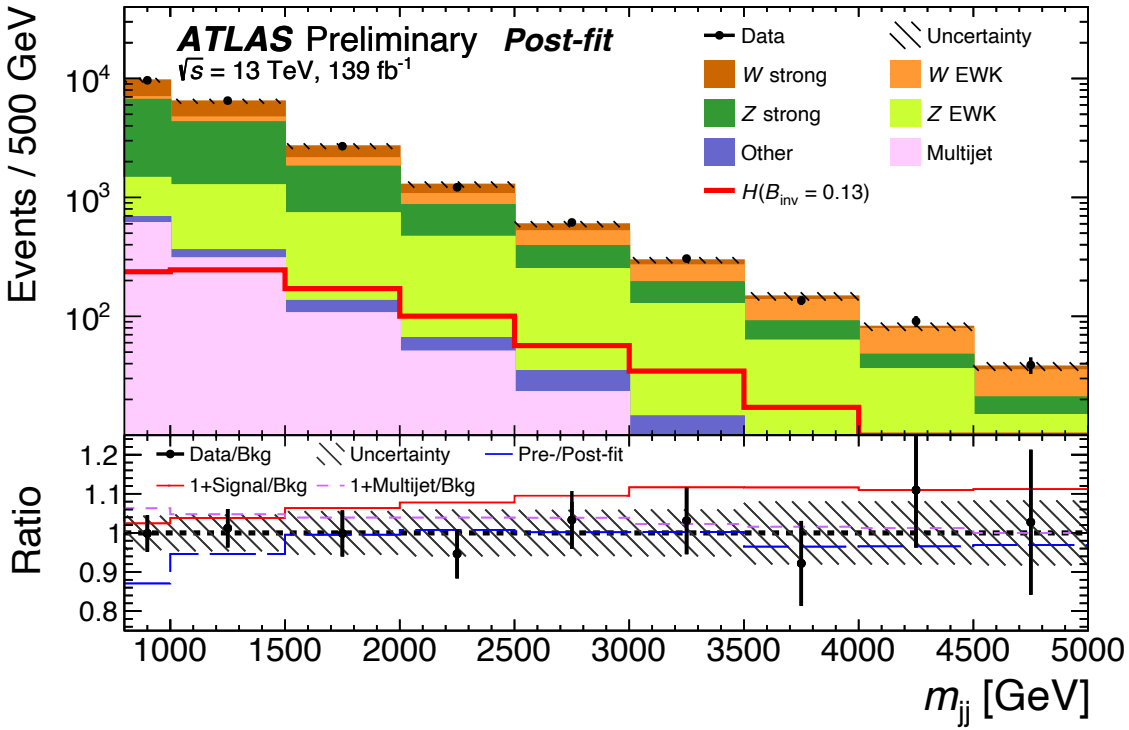
ATLAS-CONF-2020-008
(Apr 9, 2020)

Ava Myers

VBF channel updated with full Run-2 luminosity

- Most sensitive channel
- Improvements to optimization, additional bins of m_{jj} & $\Delta\phi_{jj}$, increased MC statistics
- Limit improved by ~factor of 2 compared to VBF with 36fb^{-1}
- Result is *preliminary*: updated results to come

Increasing S/B with increasing m_{jj}



Upper limit on VBF Hinv BR (95% CL)

Result	Expected	Observed
13 TeV (139fb^{-1})	13%	13%
13 TeV (36fb^{-1})	28%	37%

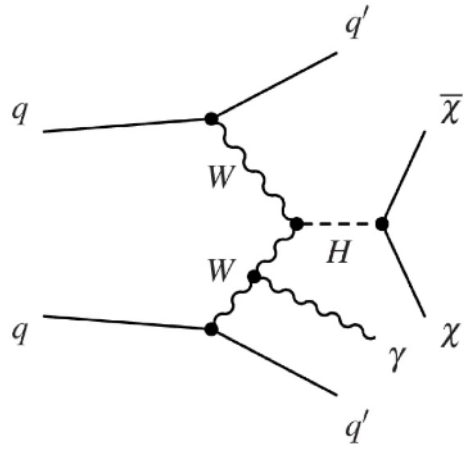
Higgs to invisible + γ

ATLAS-CONF-2021-004
(Mar 19, 2021)

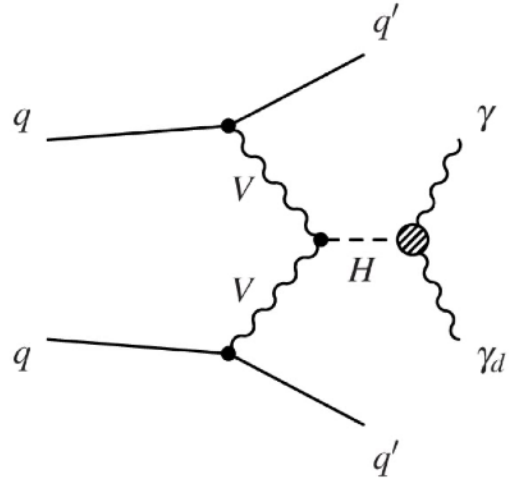
Ava Myers

Two interpretations:

$H \rightarrow \text{inv} + \gamma$

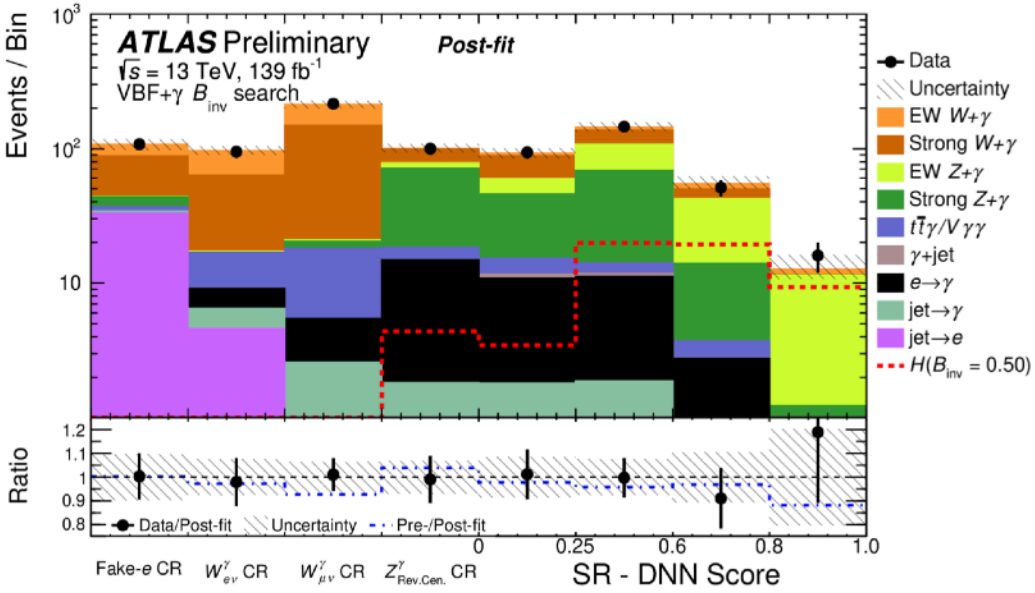


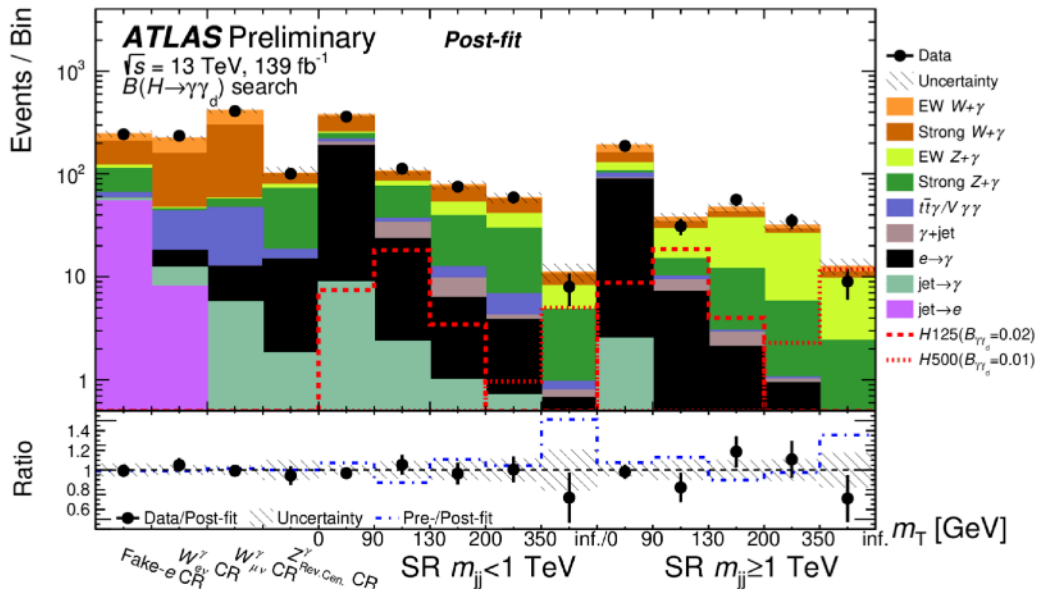
$H \rightarrow \gamma + \gamma_D$



Upper limit on BR (95% CL)

Result	Expected	Observed
$H \rightarrow \text{inv} + \gamma$	34%	37%
$H \rightarrow \gamma + \gamma_D$	1.7%	1.4%





SM-like Higgs with bins in DNN score

$H \rightarrow \gamma + \gamma_D$ with bins in m_T

Higgs to invisible combination

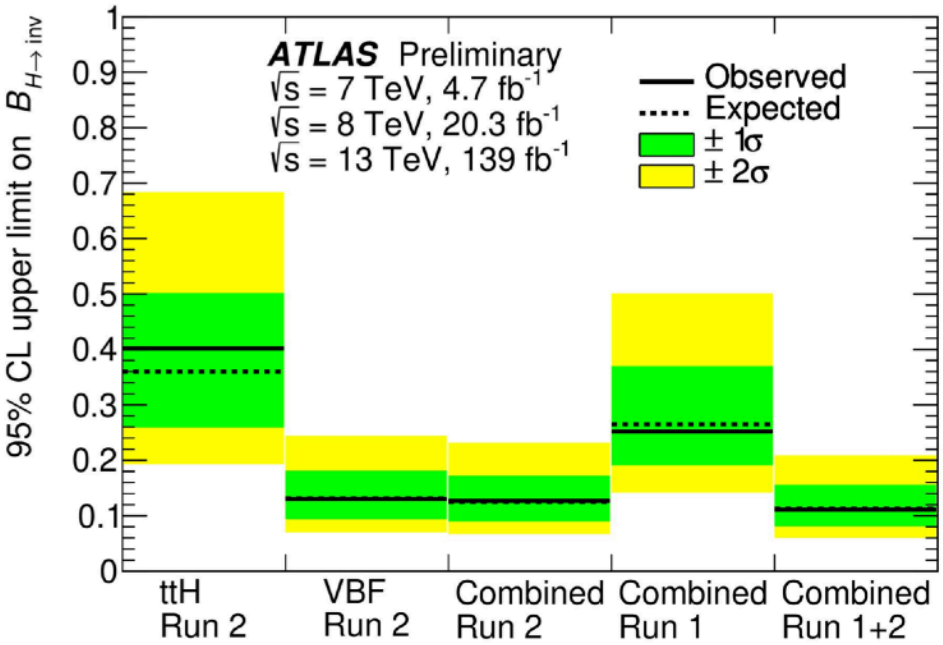
Ava Myers

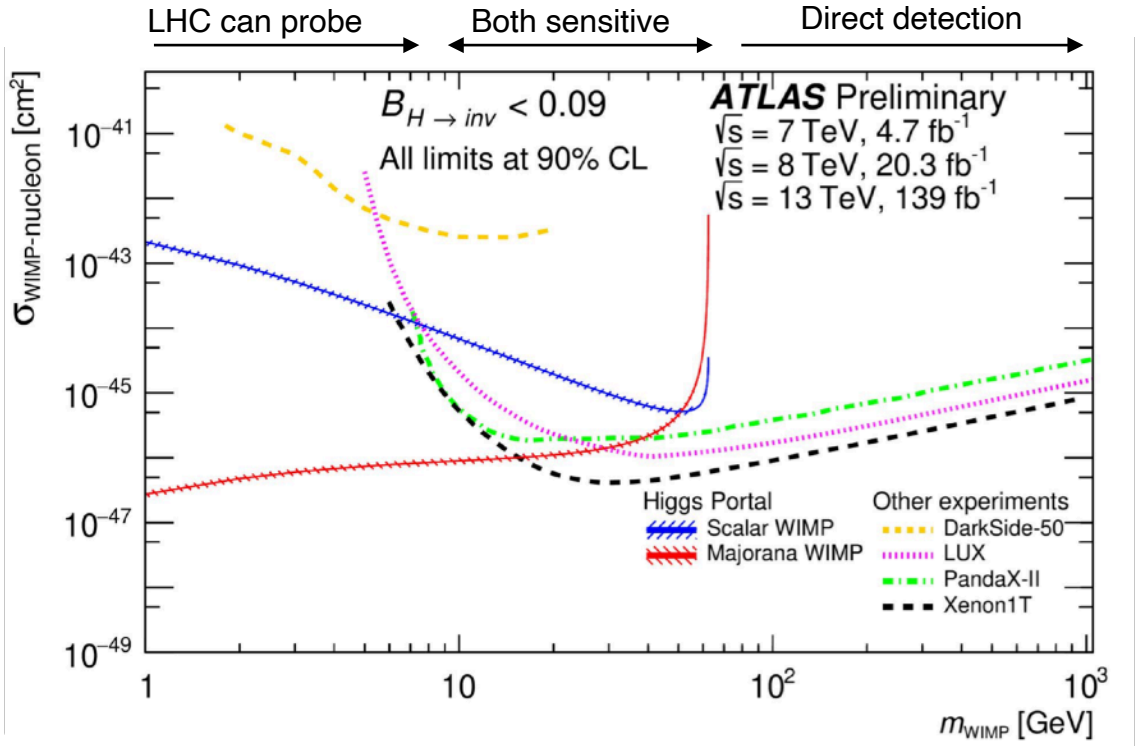
Updated (preliminary) combined result includes:

- $t\bar{t}$H
- VBF (most sensitive)
- More results such as Z(ll)+MET, VBF+gam to be added

ATLAS Run 1 + Run 2 result: BR(Hinv) < 0.11(0.11)

(Translates to spin-independent DM-nucleon elastic scattering cross-section limit)





[ATLAS-CONF-2020-052](#)

(Oct 29, 2020)

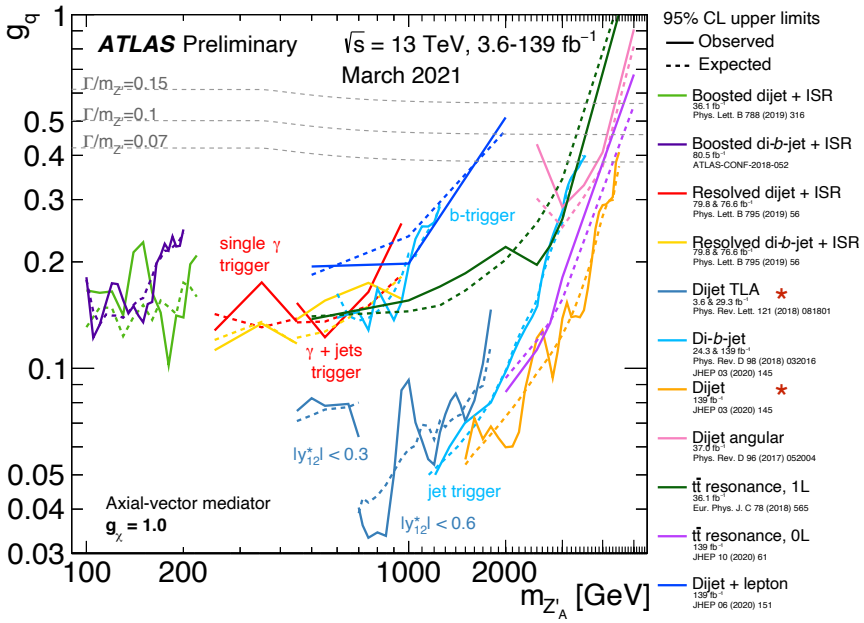
Compare to direct searches: assuming Higgs portal with 125 GeV Higgs decay to scalars or Majorana fermions

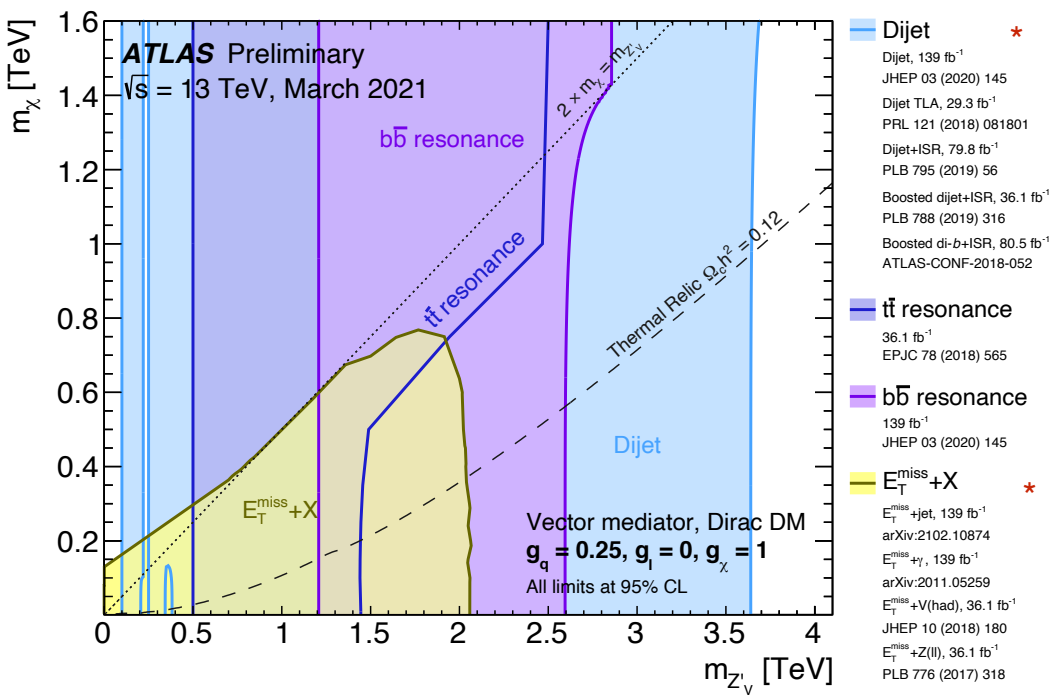
Summary plots

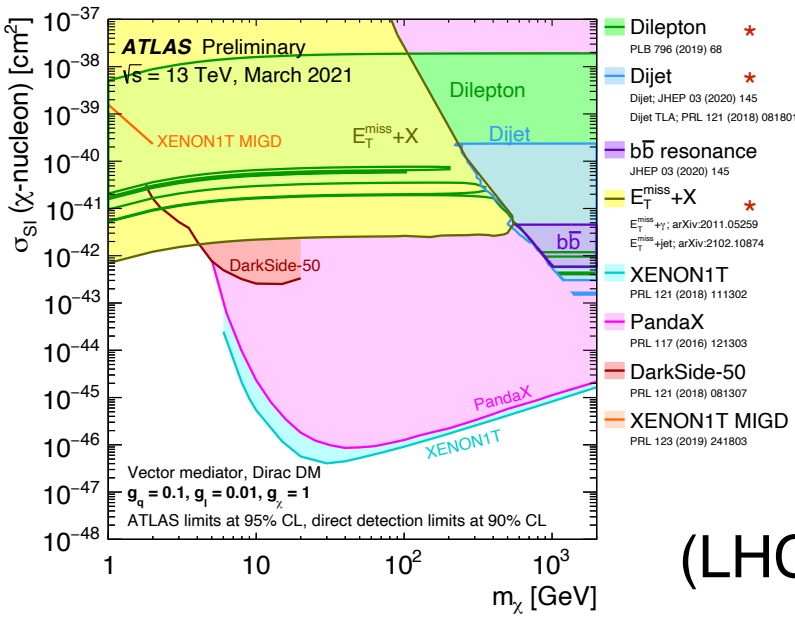
ATL-PHYS-PUB-2021-006

Ava Myers

A way to contextualize all of these searches







Some ways to summarize DM searches:

- m_χ vs. $m_{Z'_A}$
- g_q vs. $m_{Z'_A}$
- $\sigma_{\chi-nucleon}$ vs. m_χ

Translation is ***model dependent***

(LHC limits hold exclusively for considered models)

Summary & Outlook

Ava Myers

- Phenomenology of collider DM searches is rich, motivating a wide variety of searches
- Searches for DM on ATLAS are expanding
  - More interpretations and more final states
  - Complementary to direct detection experiments
- Even more searches in the pipeline for Run-2

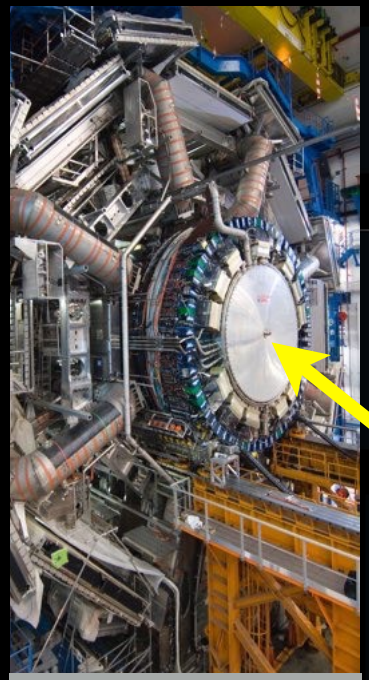
- Analysis groups are providing projections of their results for HL-LHC - more to come!
  - Mono-γ and VBF Hinv (ATL-PHYS-PUB-2018-038)
  - Jet + MET (ATL-PHYS-PUB-2018-043)
  - Heavy flavor (ATL-PHYS-PUB-2018-036)
  - Charginos and Neutralinos (ATL-PHYS-PUB-2018-048)

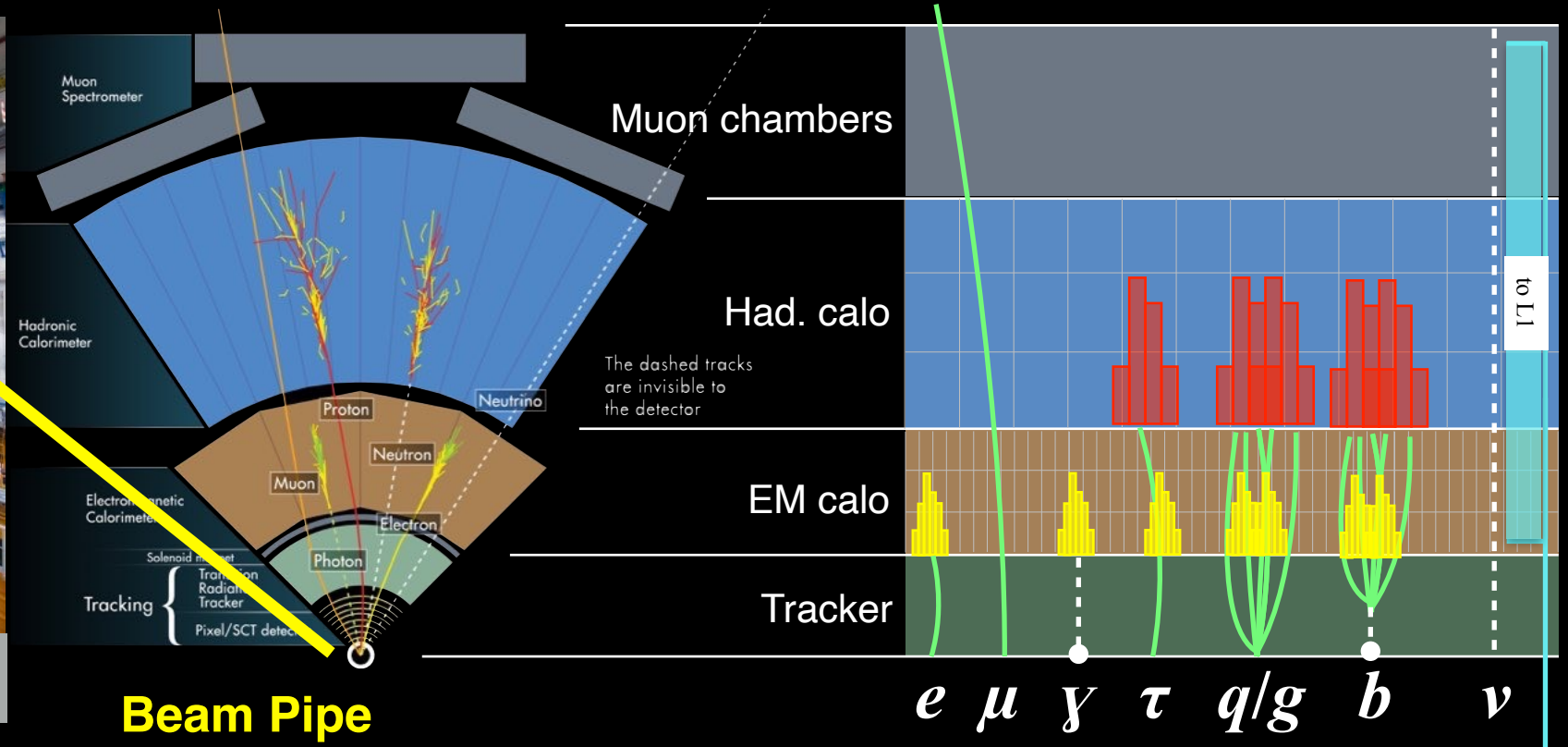
Thank you!

Back-up

The ATLAS Detector

Ava Myers





Hardware trigger (L1): select in 2.2 μs

40 MHz

coarse calorimeter and muon to L1

full calorimeter and muon data to HLT

100 kHz

Software trigger (HLT) select in ~0.1 s

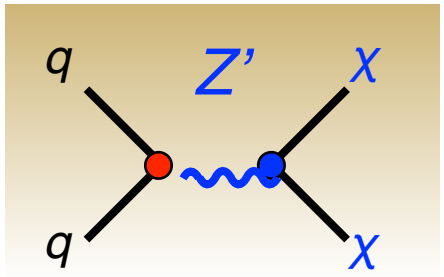
~1 kHz

Save to permanent storage

Dark matter at colliders

1703.05703, 1810.09420
(LHC DM working group)

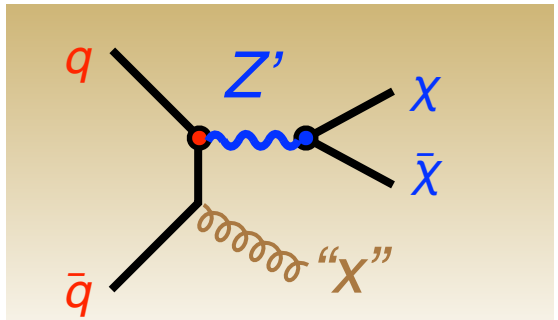
Ava Myers



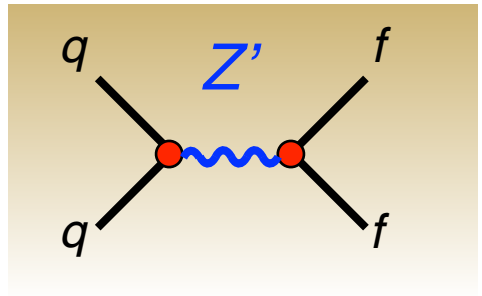
e.g., Z'

mediator→DM

Add "X"



mediator→DM + X



e.g., dijet

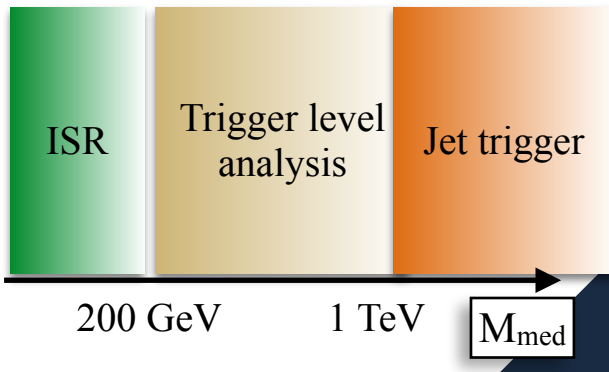
mediator→SM

Look for stable dark matter candidate by requiring that the system recoil against a visible "x"

x	objects
Jet	$P_T \geq 150$ GeV
Photon	$P_T \geq 150$ GeV
Weak bosons (W/Z)	$l\nu/l^+l^-$
	$q\bar{q}$
Higgs boson	$b\bar{b}$
	$\gamma\gamma$
Heavy flavors	b, $b\bar{b}$
	t, $t\bar{t}$

Direct mediator searches:
dijet (dilepton) resonances

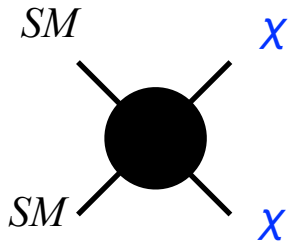
Trigger technique



Comparing to direct detection

Ava Myers

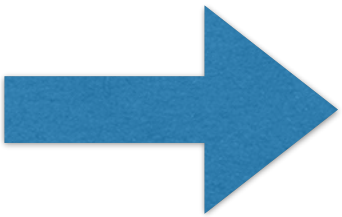
Production



Collider

Constraint:
Br(H→inv.)

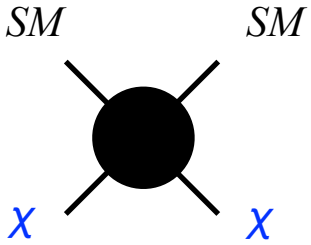
Compare to



Simplified model.
Convert to a limit on

$\sigma_{WIMP\text{-}nucleon}$

Scattering



Direct detection

LUX, Panda-X, Picasso…

Constraint:

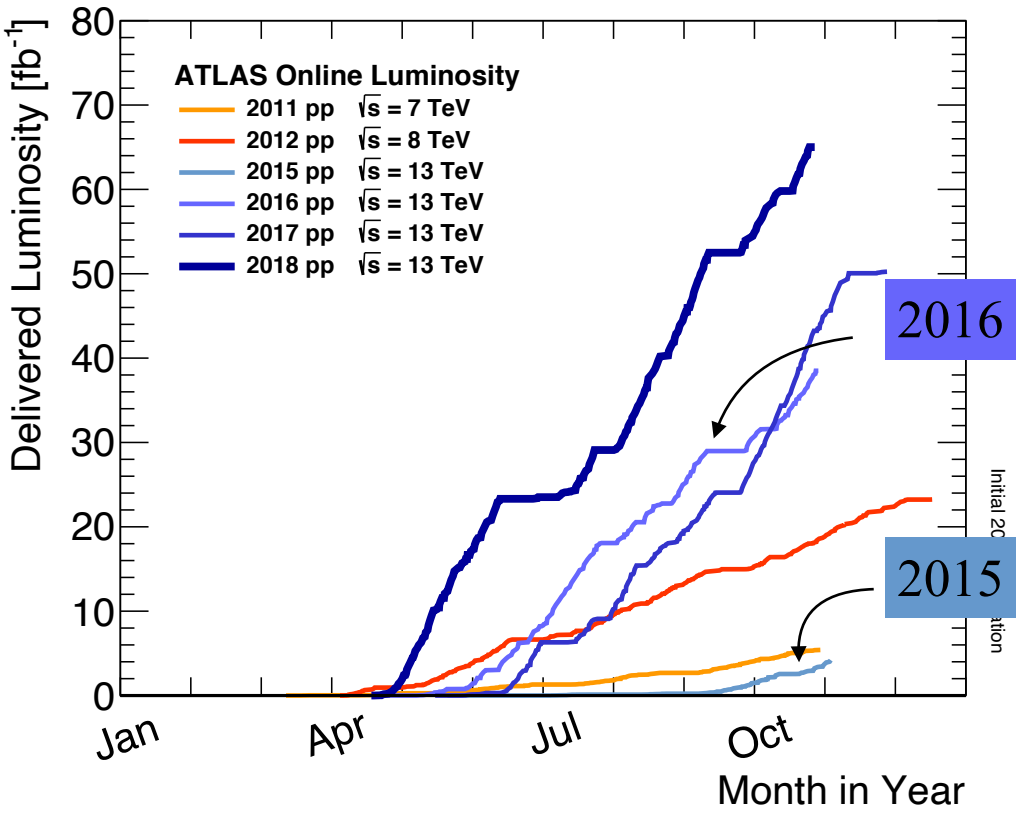
$\sigma_{WIMP\text{-}nucleon}$

ATLAS data

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

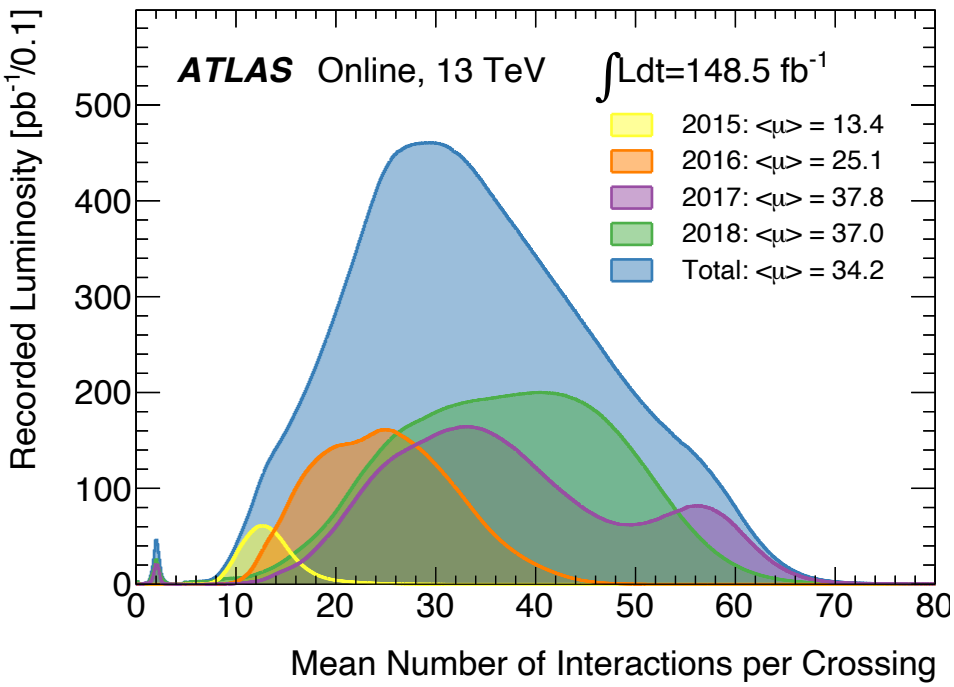
Ava Myers

The slope dramatically increased over the seven years plotted



At the cost of increasing pileup

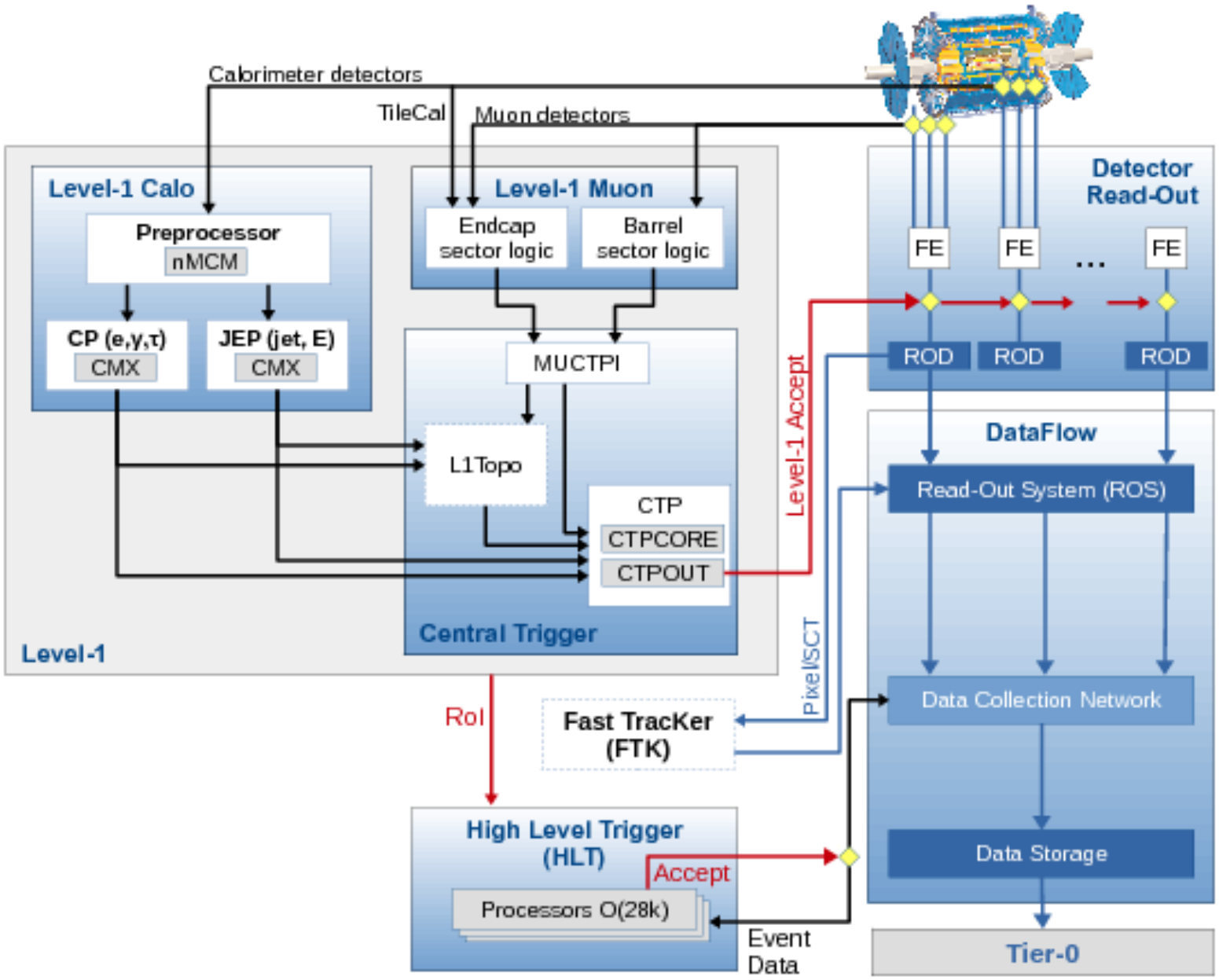
multiple interactions per bunch crossing



In total, recorded a total integrated luminosity of **149fb^{-1}**

ATLAS Trigger

Ava Myers



~40 MHz
Bunch x-ing rate

100 kHz
L1 accept rate

1 kHz
HLT output rate

Heavy scalar→inv interpretation

Ava Myers

Improvement at higher scalar mediator mass due to better S/B

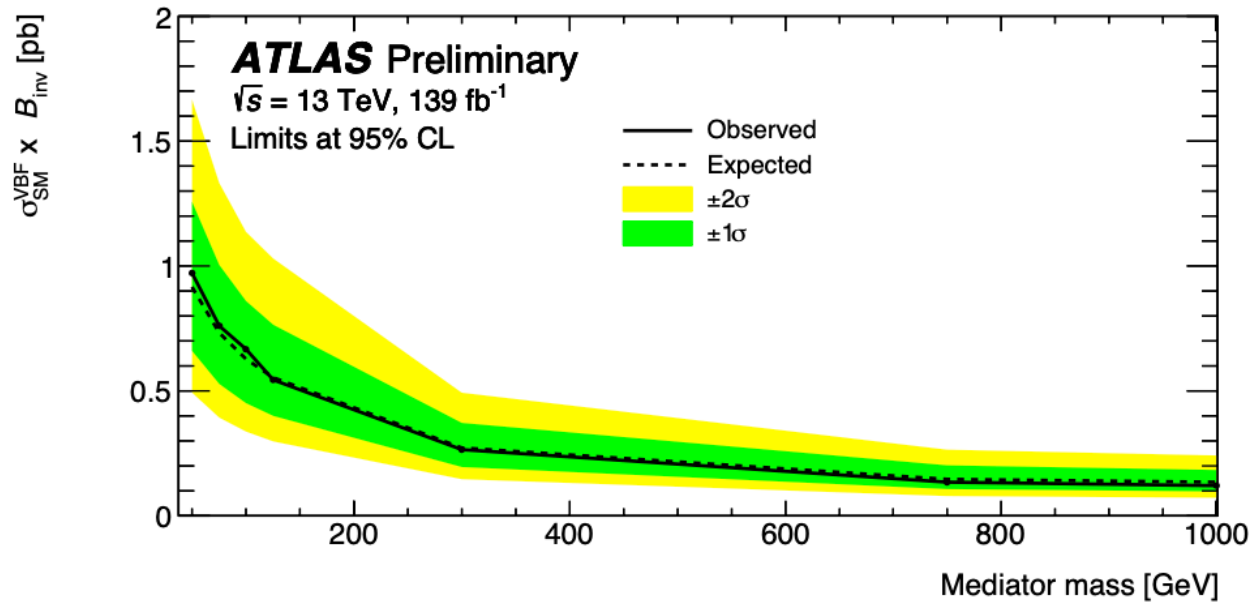


Figure 11: Upper limit on cross section times branching ratio to invisible particles for heavy scalar mediator particle as a function of its mass.

95% CL upper limit on $\sigma^{VBF} \times \mathcal{B}r(H \rightarrow inv)$ ranges from 0.97 pb (50 GeV mediator mass) to 0.12 pb (1 TeV mediator mass

CMS Run-1 paper on VBF and *ZH*,

9 Dark matter interactions

We now interpret the experimental upper limit on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$, under the assumption of SM production cross section, in the context of a Higgs-portal model of DM interactions [7–9]. In these models, a hidden sector can provide viable stable DM particles with direct renormalizable couplings to the Higgs sector of the SM. In direct detection experiments, the elastic interaction between DM and nuclei exchanged through the Higgs boson results in nuclear recoil which can be reinterpreted in terms of DM mass, M_χ, and DM-nucleon cross section. If the DM candidate has a mass below $m_\mathrm{H}/2$, the invisible Higgs boson decay width, Γ_inv, can be directly translated to the spin-independent DM-nucleon elastic cross section, as follows for scalar (S), vector (V), and fermionic (f) DM, respectively [8]:

$$\sigma^{\mathrm{SI}}_{\mathrm{S-N}} = \frac{4\Gamma_\mathrm{inv}}{m_\mathrm{H}^3 v^2 \beta} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_\mathrm{N})^2}, \tag{8}$$

$$\sigma^{\mathrm{SI}}_{\mathrm{V-N}} = \frac{16\Gamma_\mathrm{inv} M_\chi^4}{m_\mathrm{H}^3 v^2 \beta (m_\mathrm{H}^4 - 4M_\chi^2 m_\mathrm{H}^2 + 12M_\chi^4)} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_N)^2}, \tag{9}$$

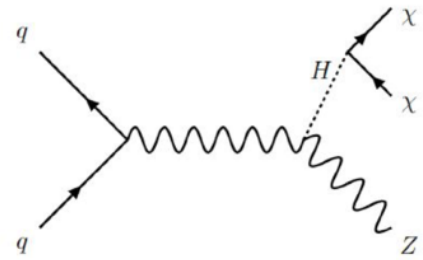
$$\sigma^{\mathrm{SI}}_{\mathrm{f-N}} = \frac{8\Gamma_\mathrm{inv} M_\chi^2}{m_\mathrm{H}^5 v^2 \beta^3} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_\mathrm{N})^2}. \tag{10}$$

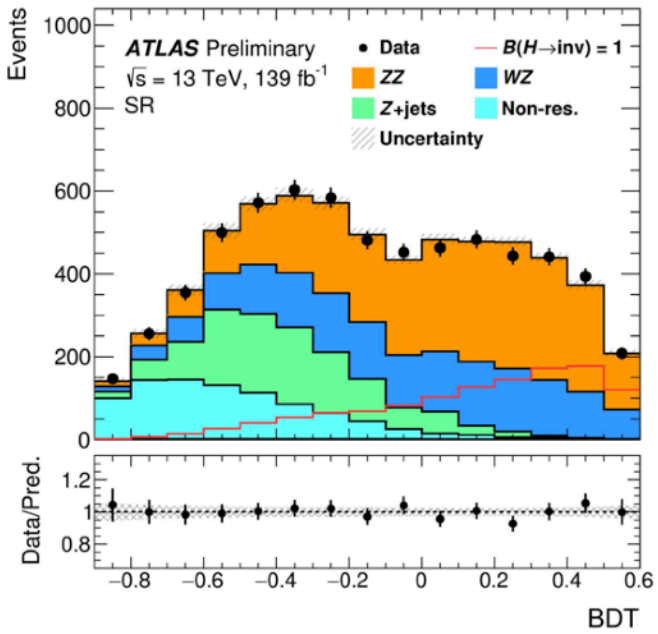
Here, m_N represents the nucleon mass, taken as the average of proton and neutron masses, 0.939 GeV, while $\sqrt{2}v$ is the Higgs vacuum expectation value of 246 GeV, and $\beta = \sqrt{1 - 4M_\chi^2/{m_\mathrm{H}}^2}$. The dimensionless quantity f_N [8] parameterizes the Higgs-nucleon coupling; we take the central values of $f_\mathrm{N} = 0.326$ from a lattice calculation [69], while we use results from the MILC Collaboration [70] for the minimum (0.260) and maximum (0.629) values. We convert the invisible branching fraction to the invisible width using $\mathcal{B}(\mathrm{H} \to \mathrm{inv}) = \Gamma_\mathrm{inv}/(\Gamma_\mathrm{SM} + \Gamma_\mathrm{inv})$, where $\Gamma_\mathrm{SM} = 4.07$ MeV.

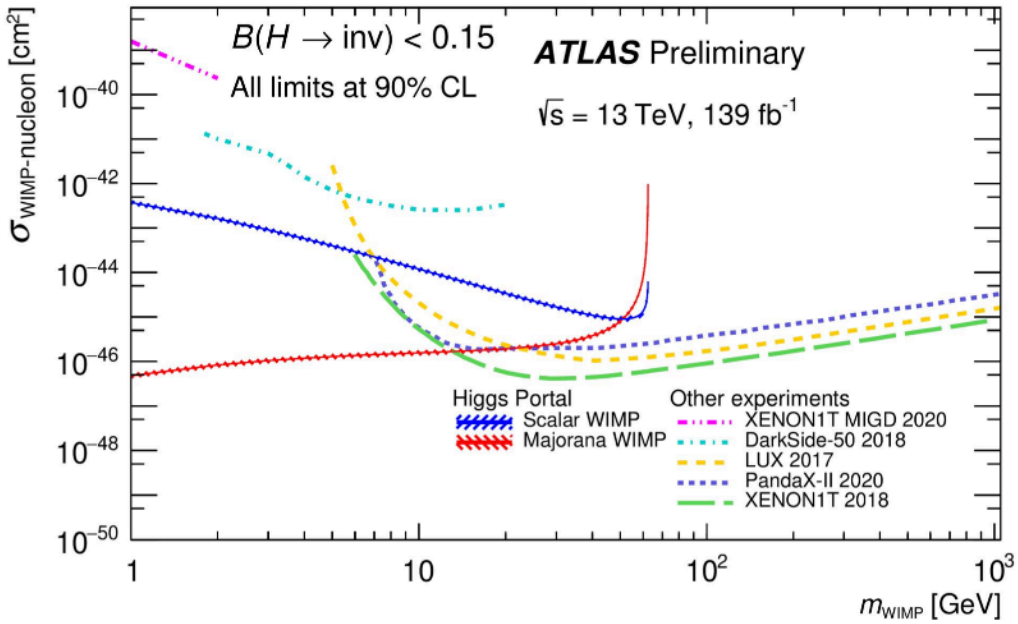
Z(ll) + MET - Higgs portal

Ava Myers

- Translate to WIMP-nucleon cross section limit
- Assuming Higgs portal scenarios with 125 GeV Higgs decays to DM
- Discriminate with BDT score (8 variables):
  - MET/H_T
  - MET significance
  - H_T
  - f_{soft}
  - $m_{\ell\ell}$
  - $\Delta R_{\ell\ell}$
  - $y_{\ell\ell}$
  - $\Delta\phi(\ell\ell, MET)$

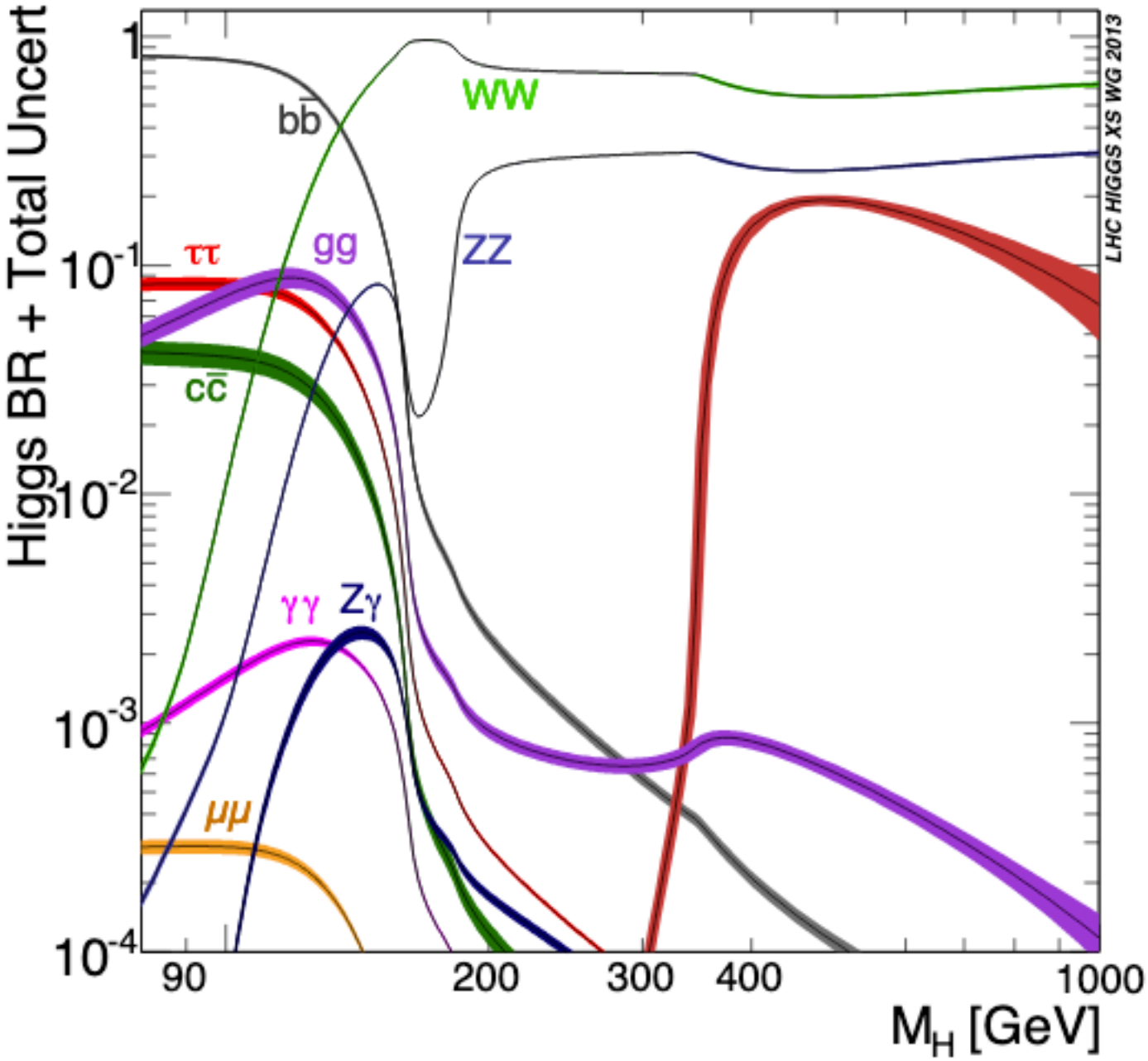






Dark Higgs branching ratio

Ava Myers



LHC XS WG (2013)
arXiv: 1307.1347

Dark Higgs: bb + MET

Ava Myers