

李政道研究所
Tsung-Dao Lee Institute



上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

Searches for dark matter with the ATLAS detector

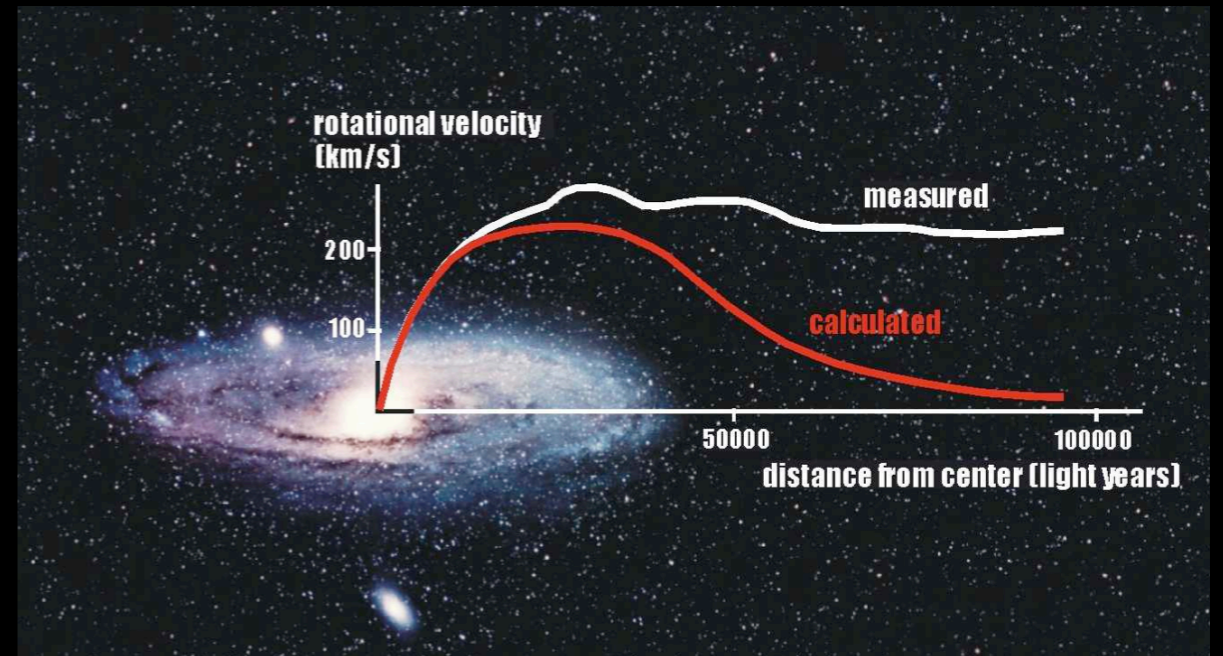


Changqiao LI
On behalf of the ATLAS collaboration

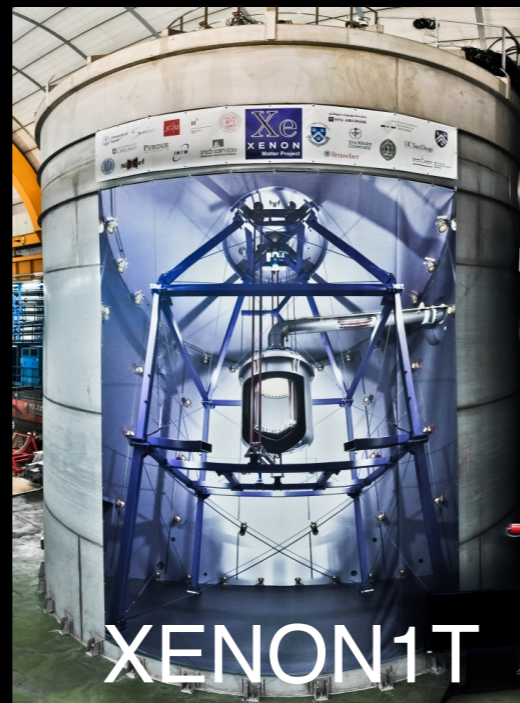
Oct. 25-29th, 2021
TeV Particle Astrophysics Conference

Search for the dark matter

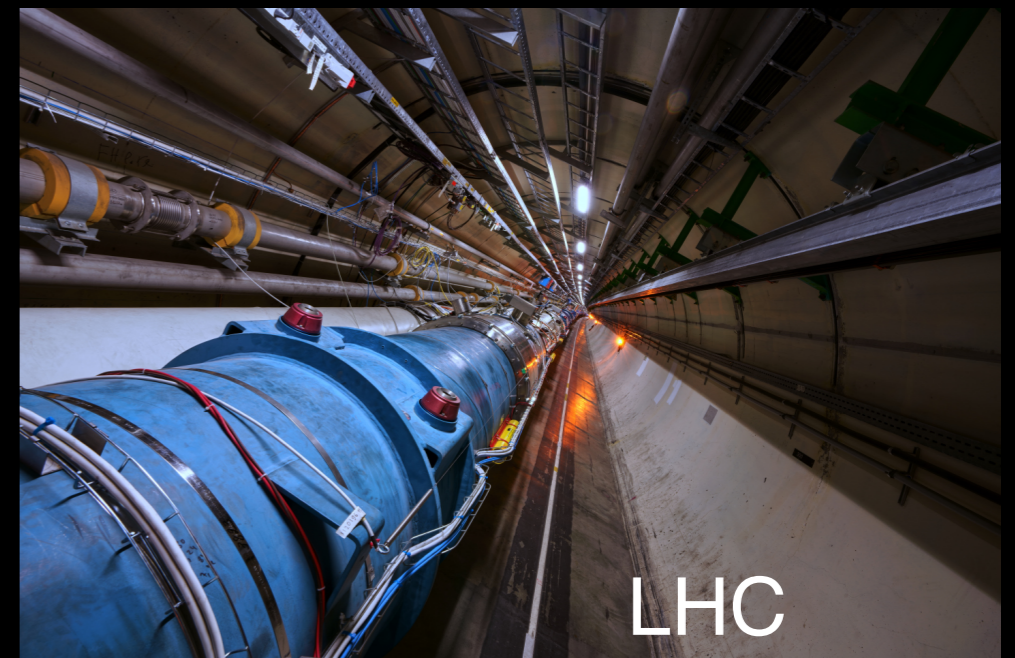
- ▶ Astrophysics evidence for DM
- ▶ DM searches via:
 - ▶ satellite
 - ▶ underground
 - ▶ LHC



Fermi-LAT



XENON1T



LHC

MAGIC, H.E.S.S., Planck...

LUX, Panda-X,
Picasso...

Search for the dark matter

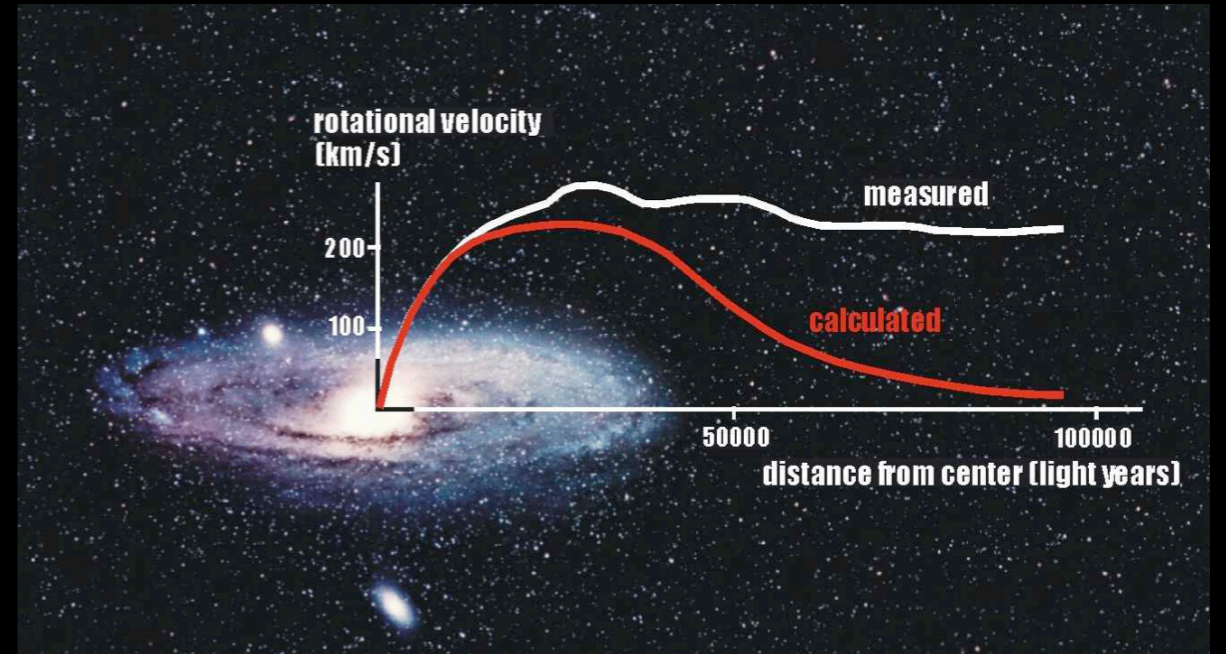
▶ Astrophysics evidence for DM

▶ DM searches via:

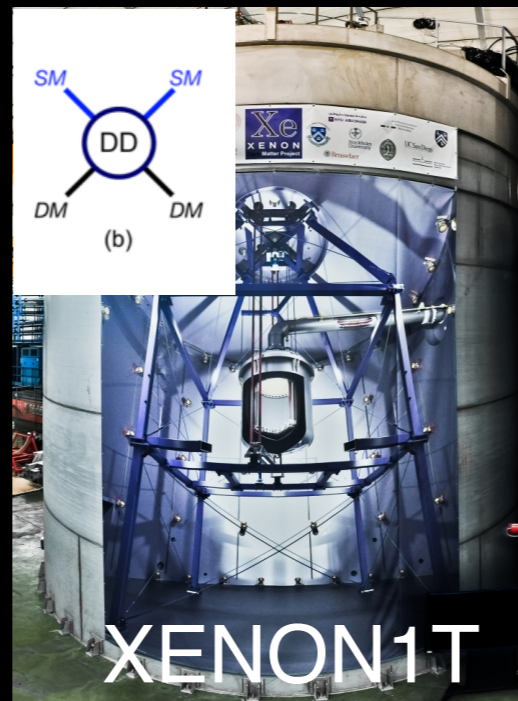
- ▶ satellite
- ▶ underground
- ▶ LHC

▶ Rich DM searches with ATLAS:

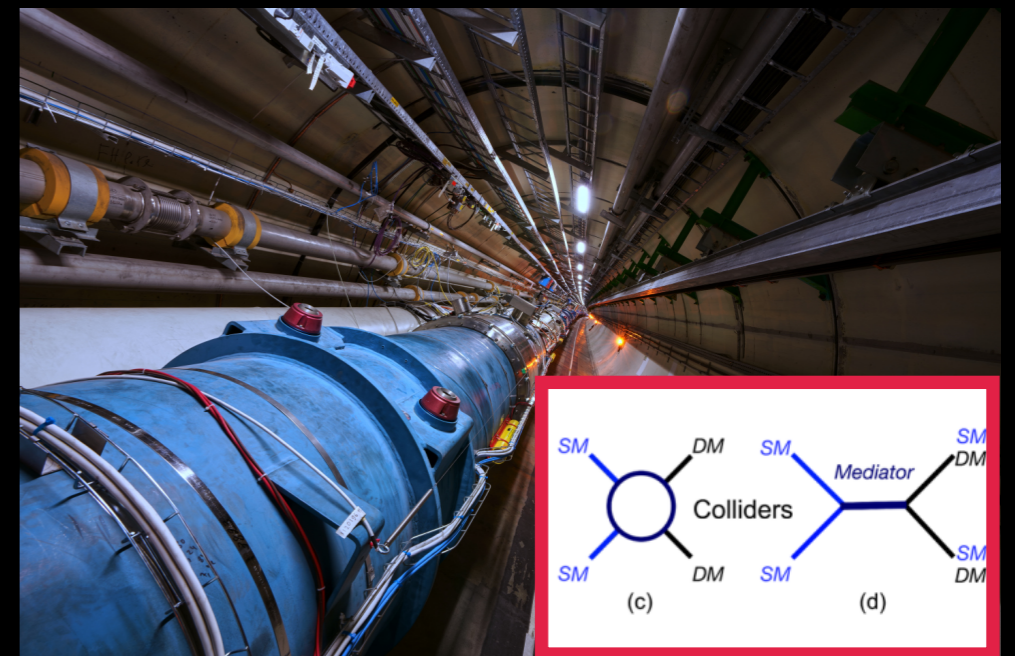
- ▶ Search for the mediator
- ▶ **Search for recoiling DM (X+MET)**
- ▶ **Search for the DM with Higgs acting as the mediator (decays to invisible) and Dark Higgs recoil against DM**



Fermi-LAT



XENON1T



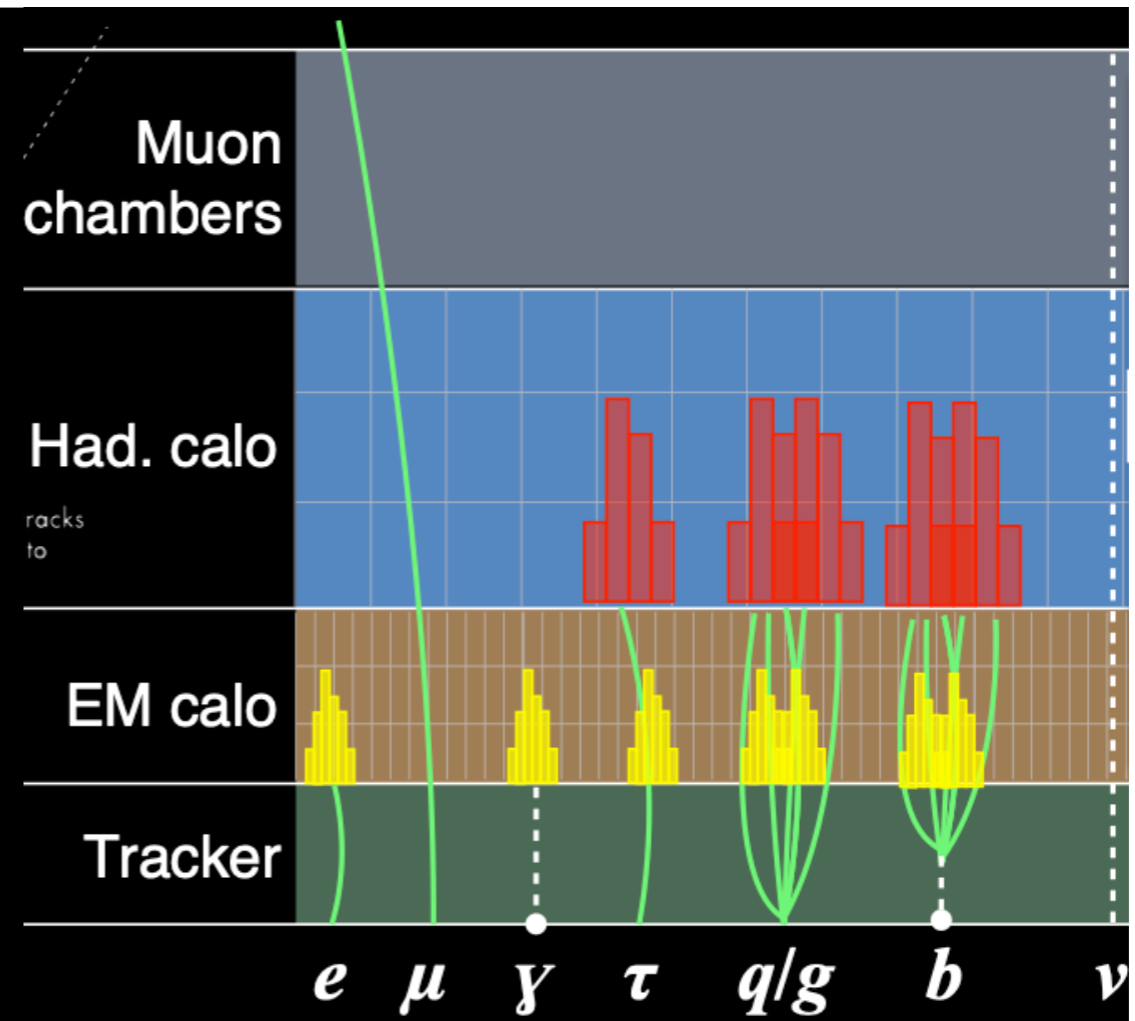
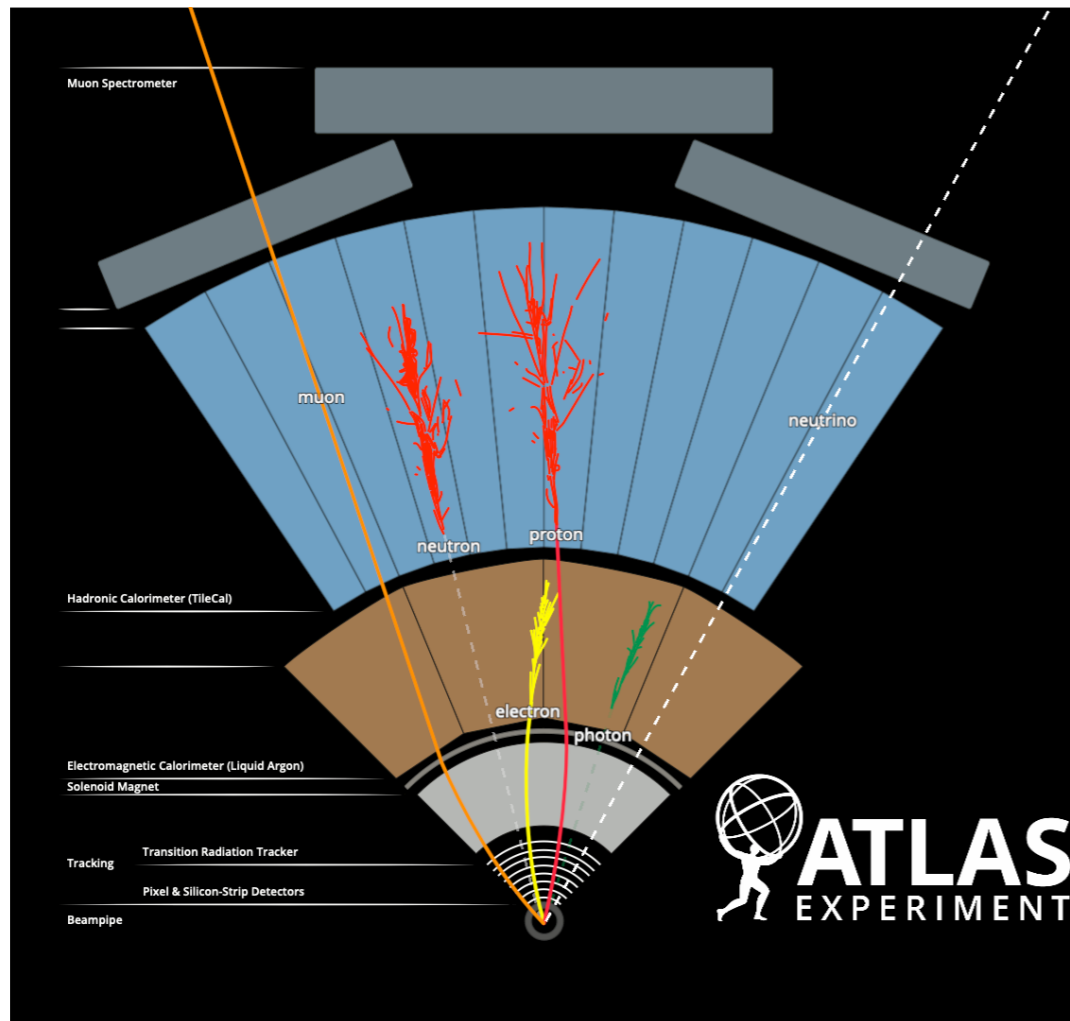
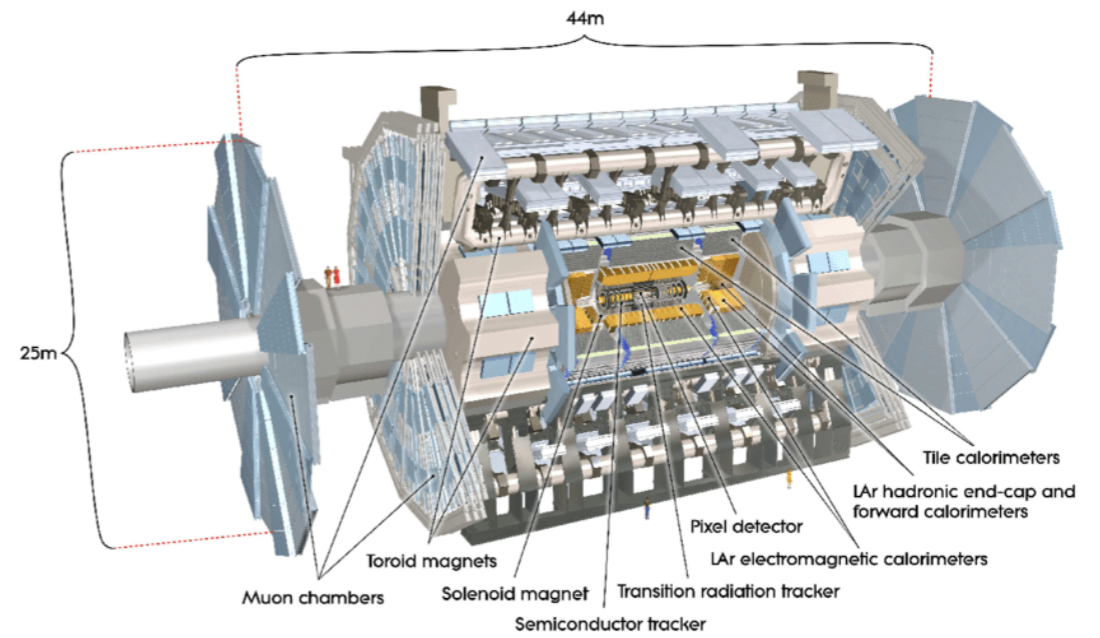
(c)

(d)

MAGIC, H.E.S.S., Planck...

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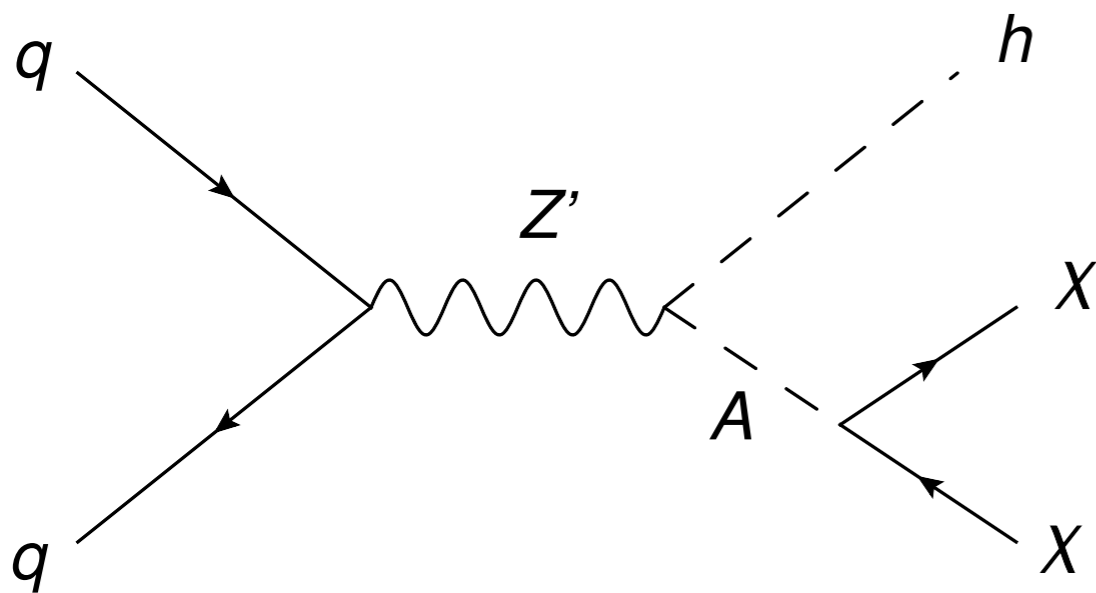
ATLAS detector



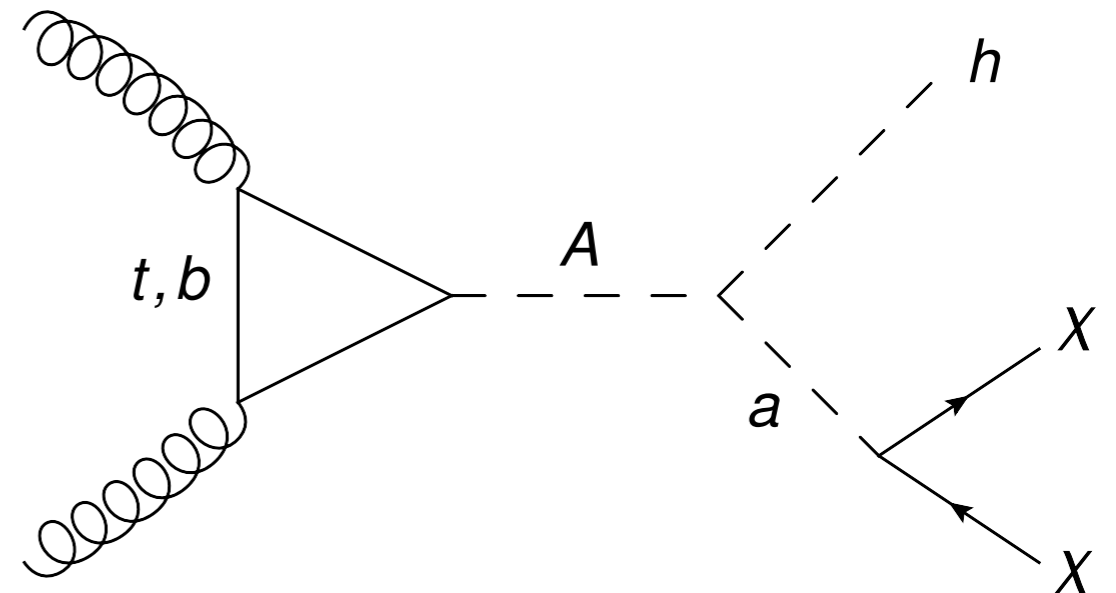
DM models

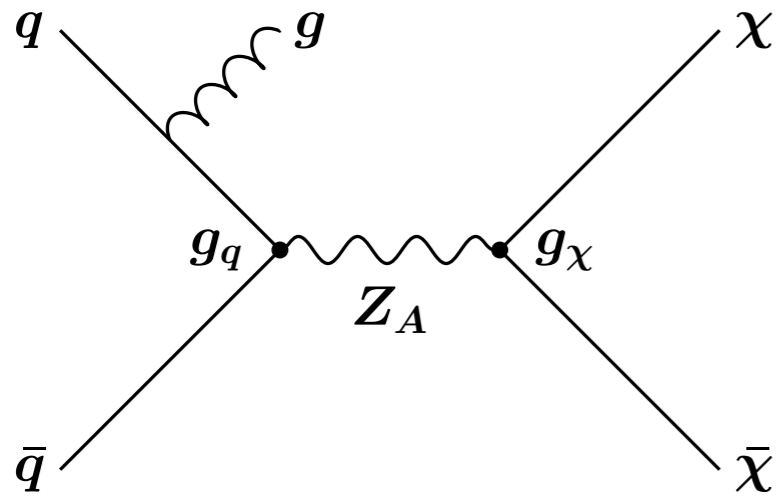
- ▶ Based on 2HDM models:
 - ▶ Another extended Higgs sector
 - ▶ Two Higgs doublet model with charged heavy Higgs (H^\pm)
- ▶ Quick aside on 2HDM models
 - ▶ Additional pseudo scalar mediator to DM (a) or vector Z'
 - ▶ Couplings prioritize third generation and signatures with vector and Higgs boson
- ▶ Dark Higgs sector introduced (discussed later)

Z'-2HDM



2HDM+a

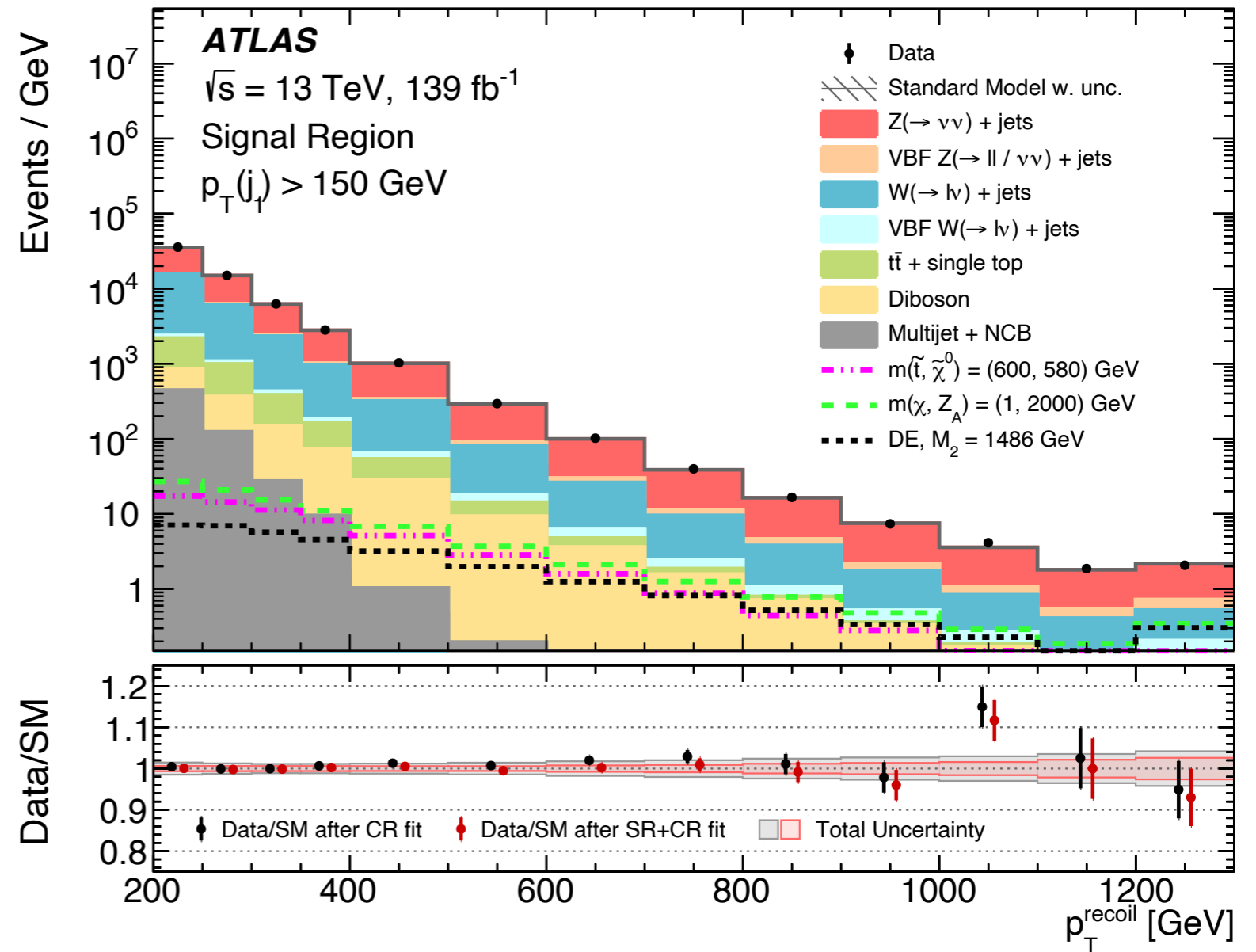


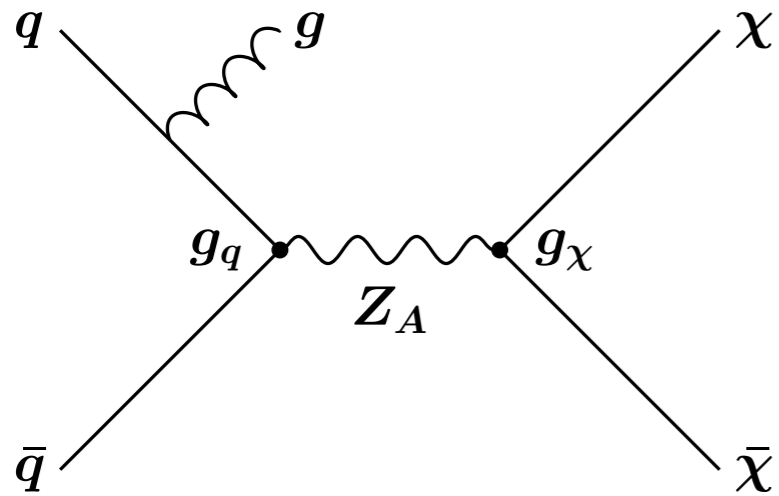


Simplified model with minimal number of free parameters

- ▶ An energetic jet and missing transverse momentum (MET)
 - ▶ MET > 200 GeV
 - ▶ $p_T(j_1) > 150$ GeV
 - ▶ $|\eta^{j_1}| < 2.4$

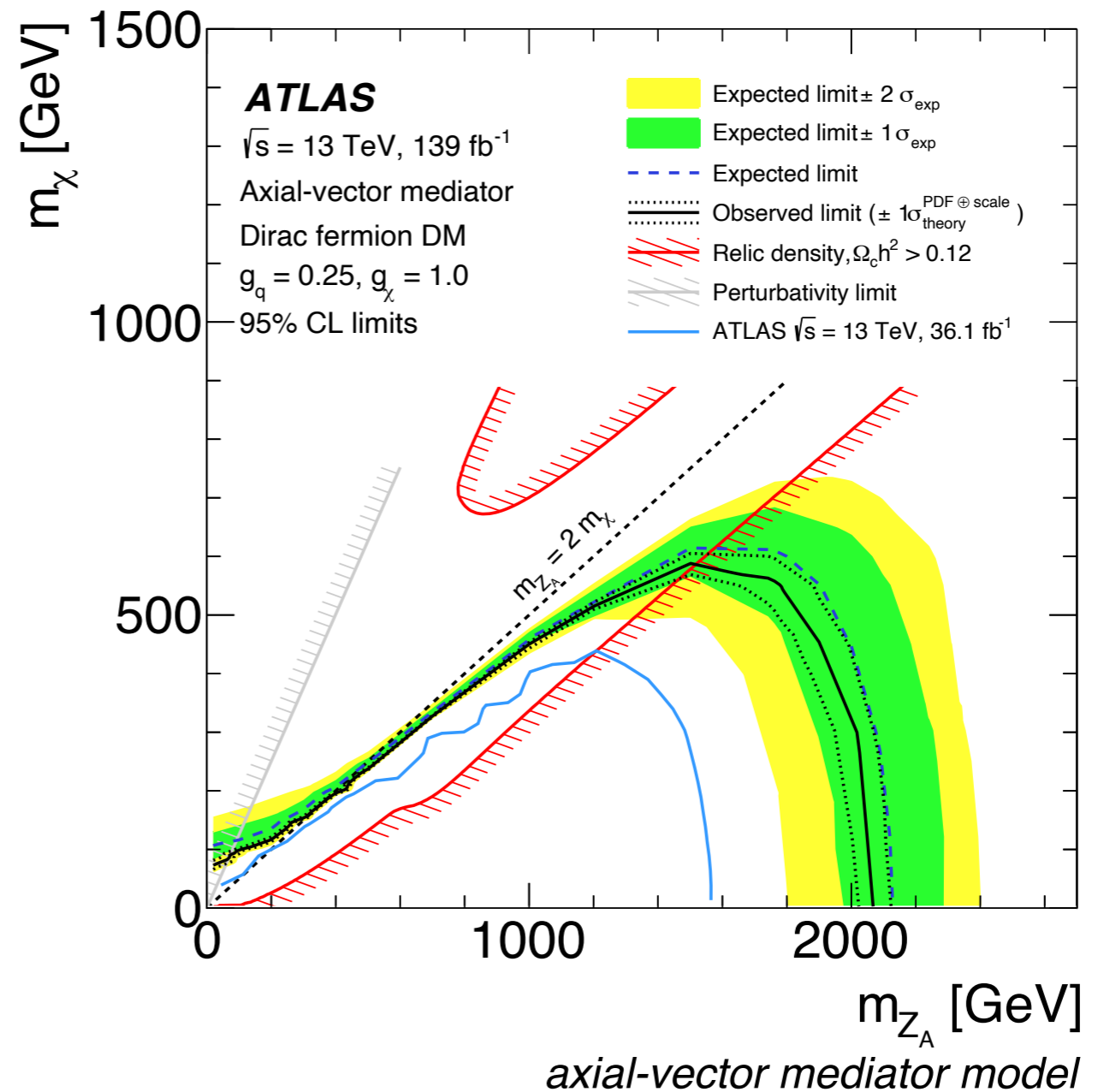
- ▶ Dedicated control regions (CRs) for V+jets, $t\bar{t}$ /single-top





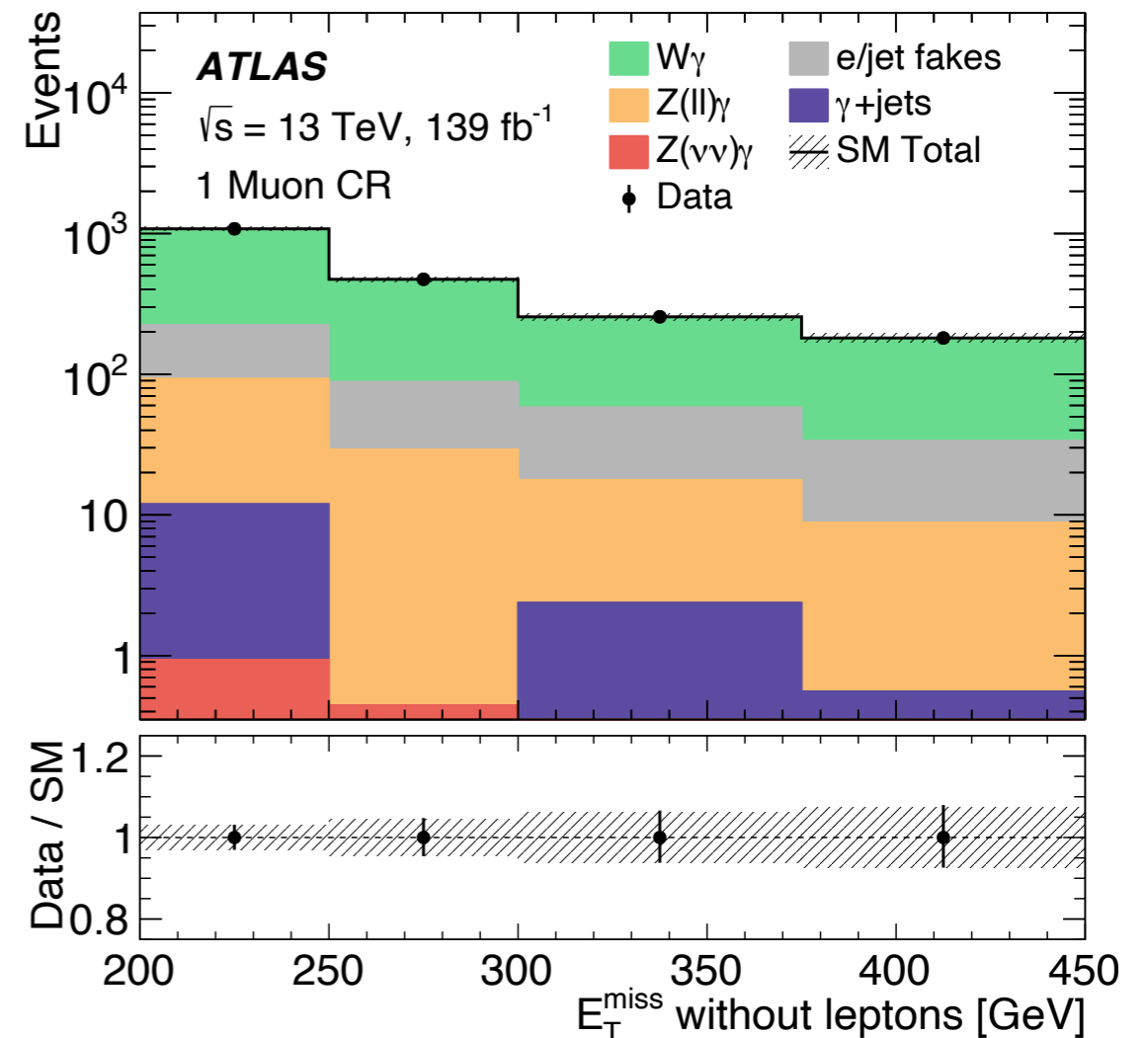
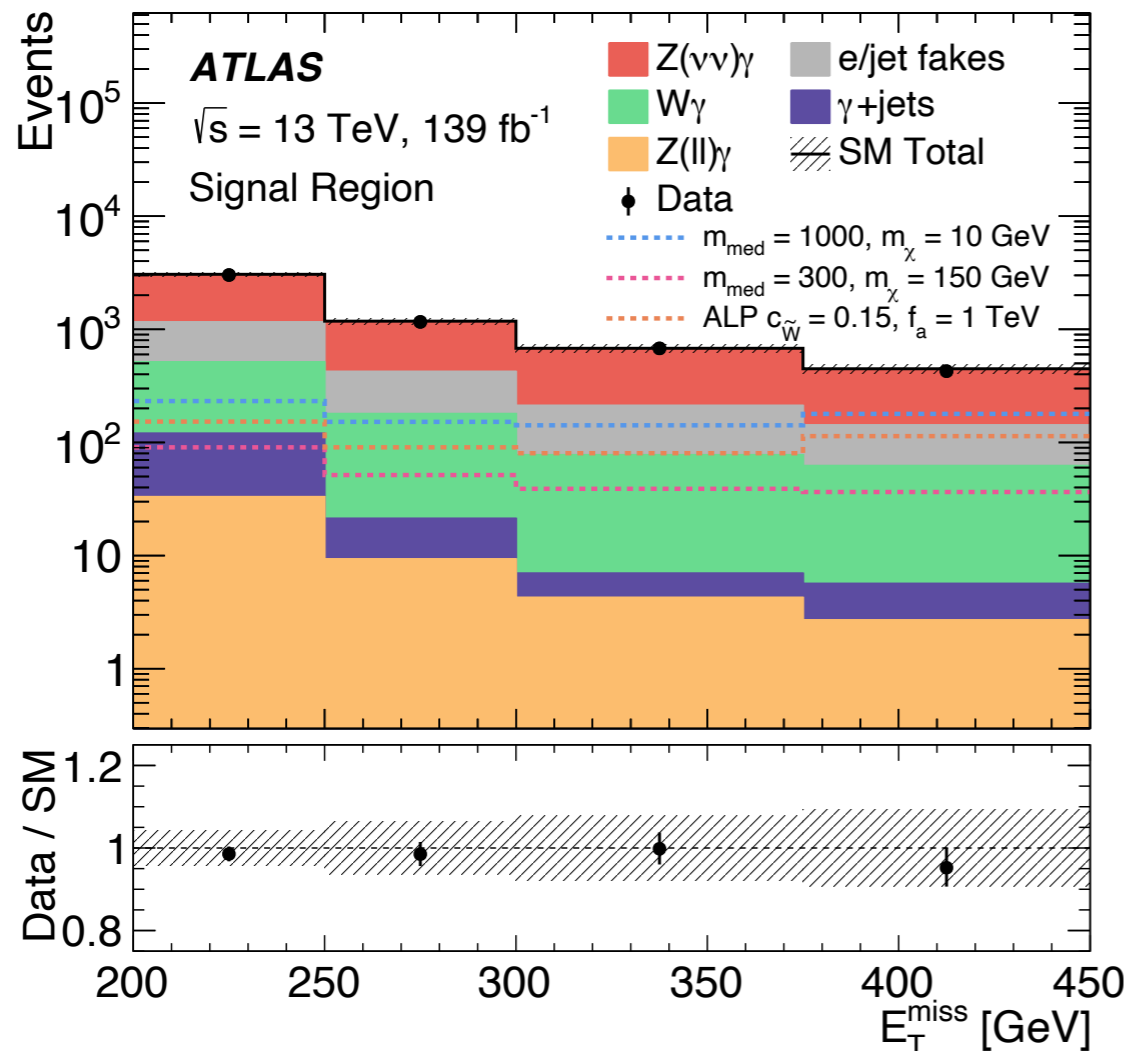
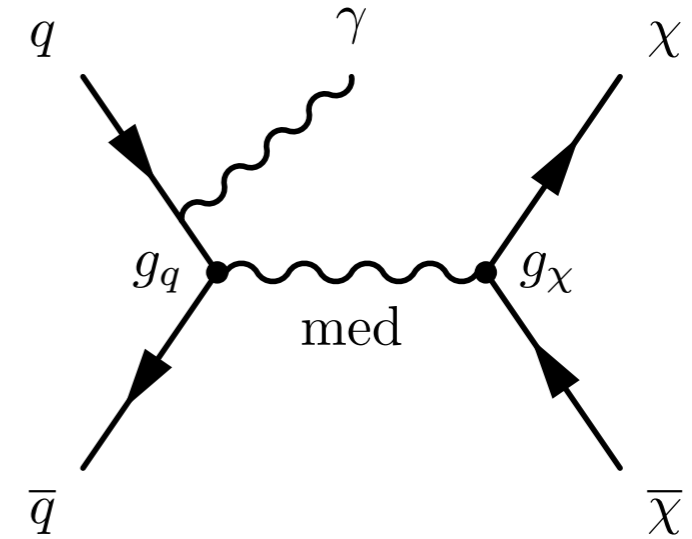
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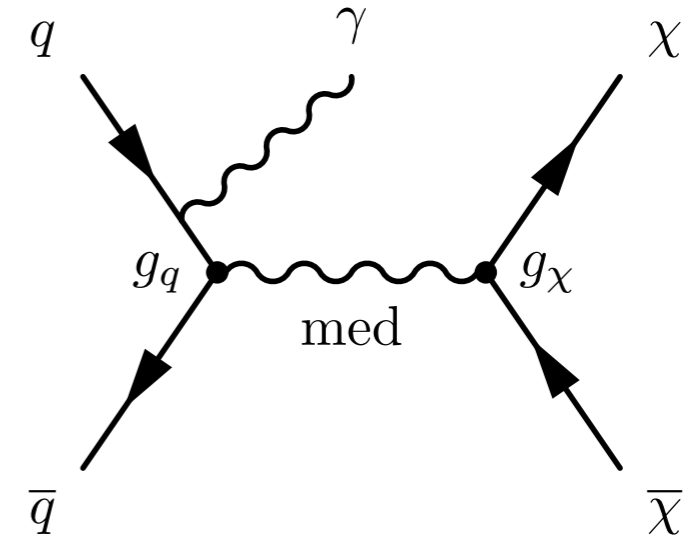


- ▶ Dedicated control regions (CRs) for V+jets, $t\bar{t}$ /single-top
- ▶ Results obtained by a binned profile likelihood fit to p_T^{recoil} from SR + 5CR simultaneously

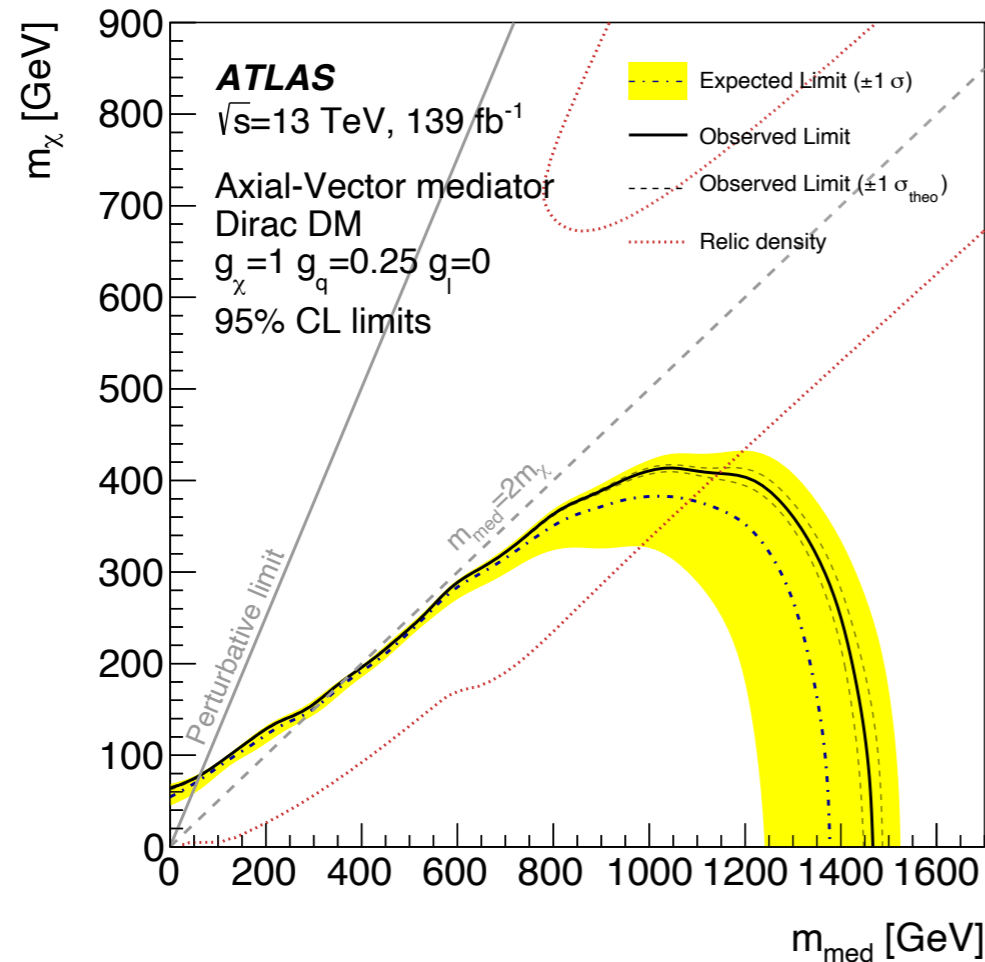
- ▶ Photon recoils against dark matter
 - ▶ $p_T(\gamma) > 150$ GeV
 - ▶ $MET > 200$ GeV
 - ▶ Dominated by $Z+\gamma$ and $W+\gamma$ background
 - ▶ Backgrounds constrained with control samples



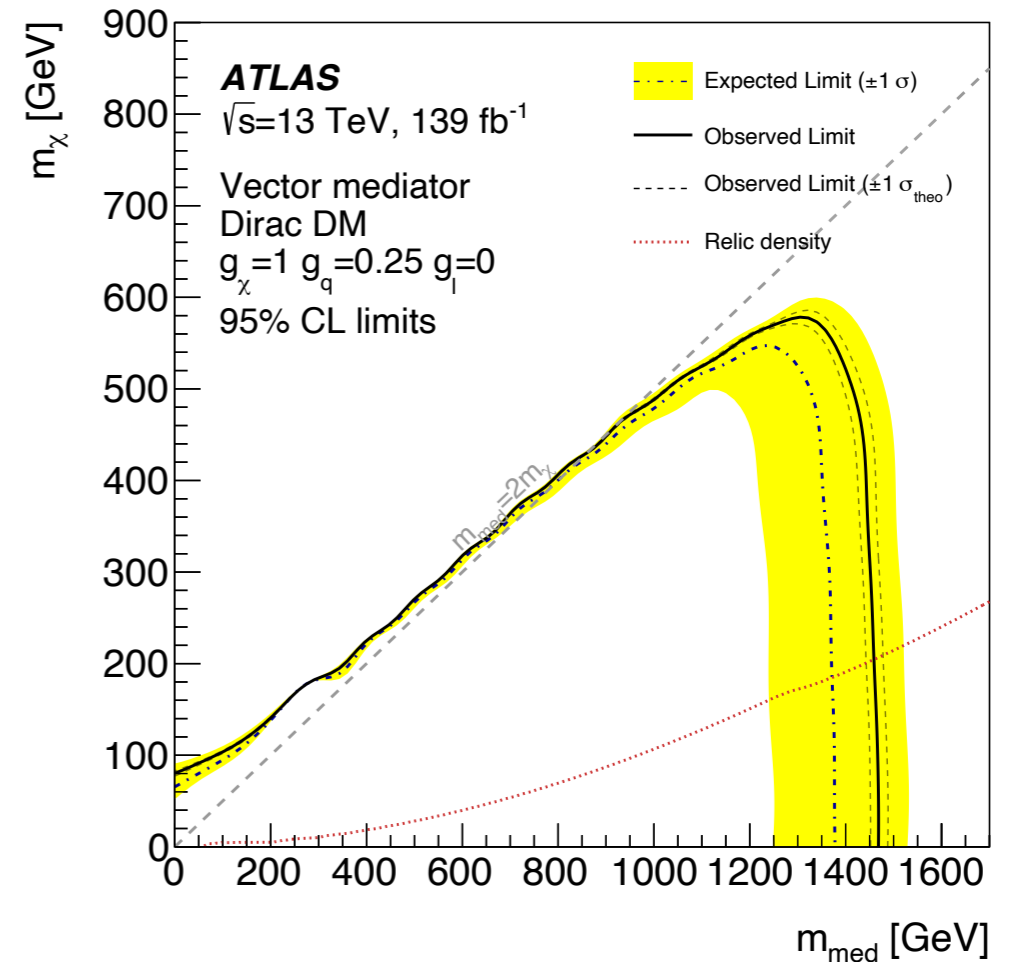
- ▶ Photon recoils against dark matter
 - ▶ $p_T(\gamma) > 150$ GeV
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 - ▶ Dominated by $Z+\gamma$ and $W+\gamma$ background
 - ▶ Backgrounds constrained with control samples
- ▶ Results interpreted
 - ▶ limit on the m_{med} and m_χ

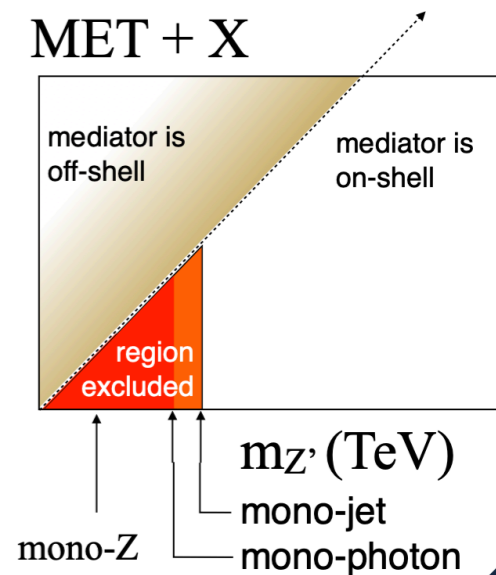
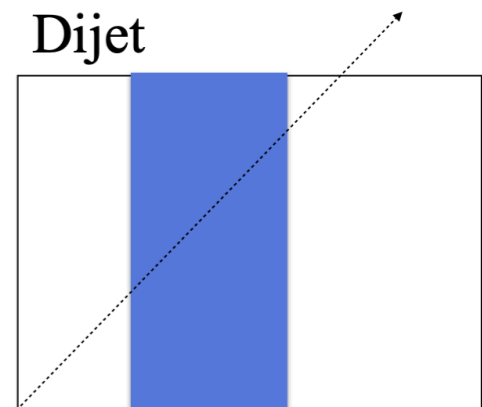
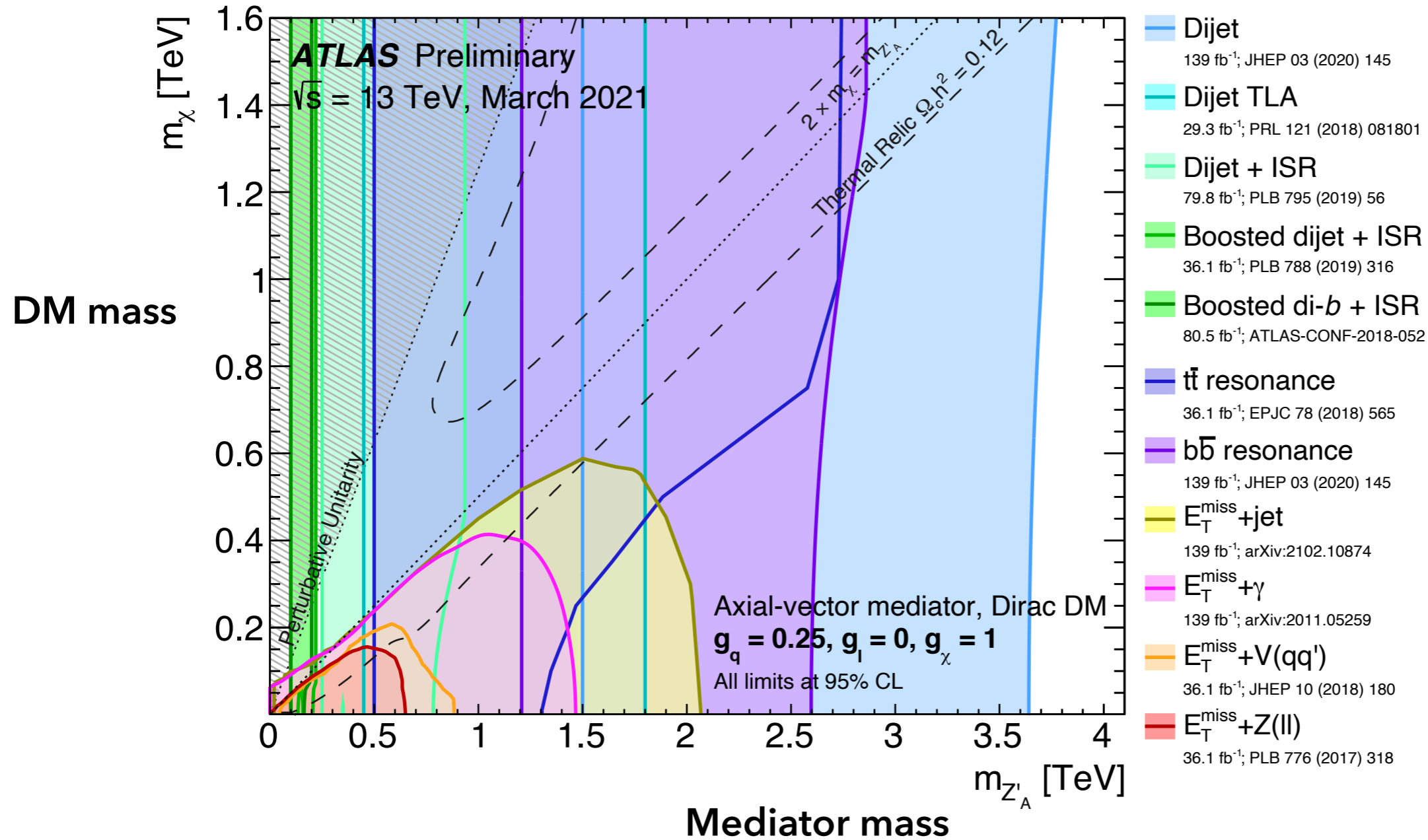


axial-vector mediator model



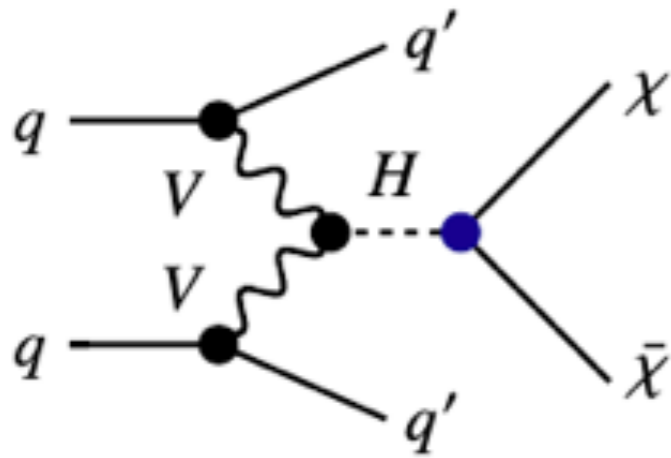
vector mediator model



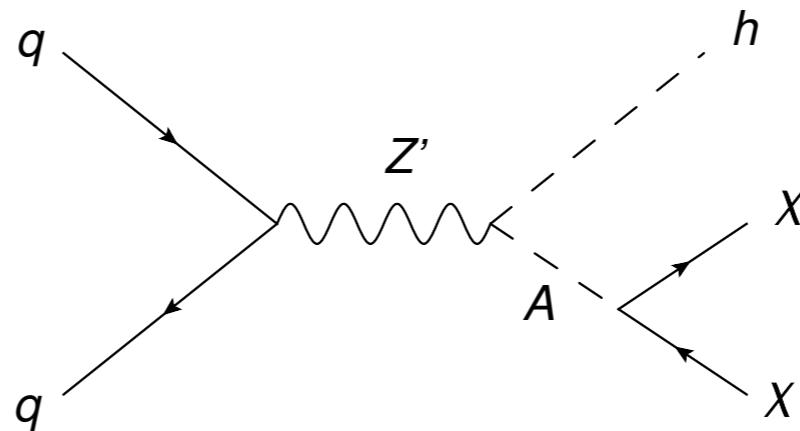


- ▶ Vertical band: search for the mediator directly
 - ▶ Dijet searches
- ▶ Triangular region: search for the DM and mediator
 - ▶ MET + X searches
- ▶ (Assuming no couplings to leptons, slightly different if allow)

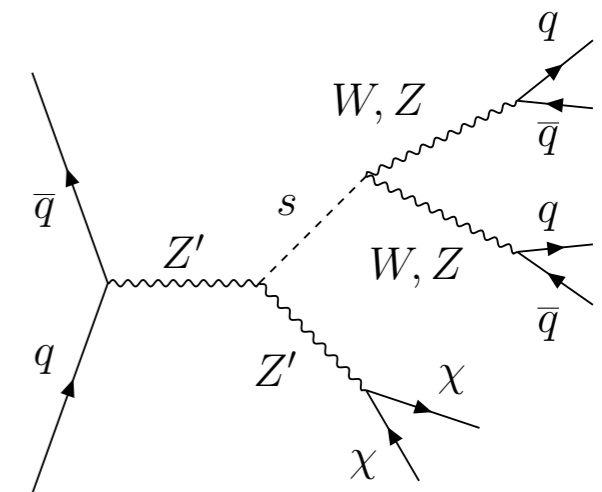
The Higgs and the dark matter



H decays to DM



H recoils against DM



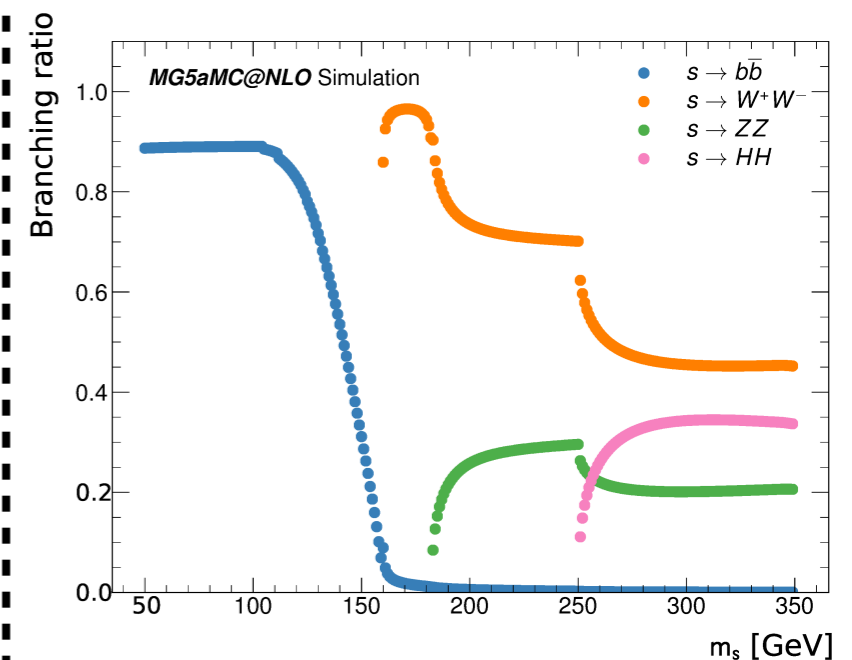
a new scalar S
(Dark Higgs)

Production mode:
visible to recoil against $H \rightarrow \text{inv.}$

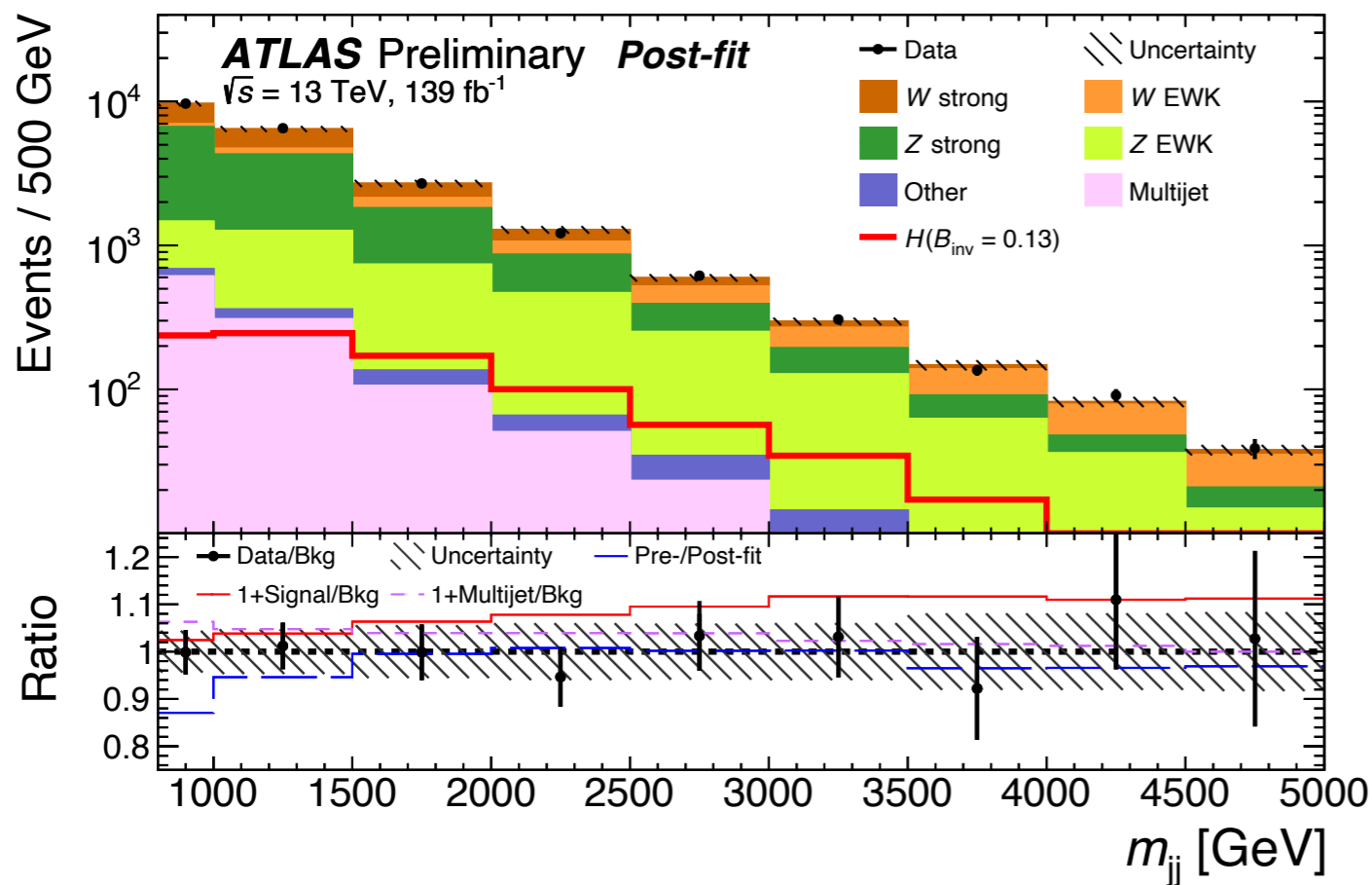
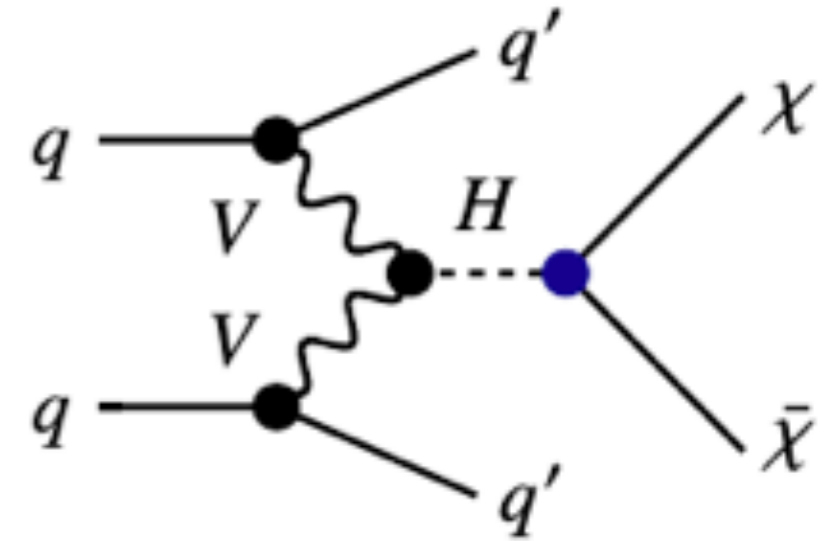
- ▶ VBF: 2 forward jets
- ▶ ttH: associated tt
- ▶ VH: V decays
- ▶ ggF: with ISR jet

Decay mode:

- ▶ bb: highest BR
- ▶ $\gamma\gamma$: clean signature



- ▶ Higgs-boson decays can potentially be invisible
 - ▶ acts as a “portal” between SM and DM
- ▶ VBF Higgs-boson production:
 - two jets that point in forward direction
 - combined with a large missing transverse momentum
 - a unique signature and most sensitive



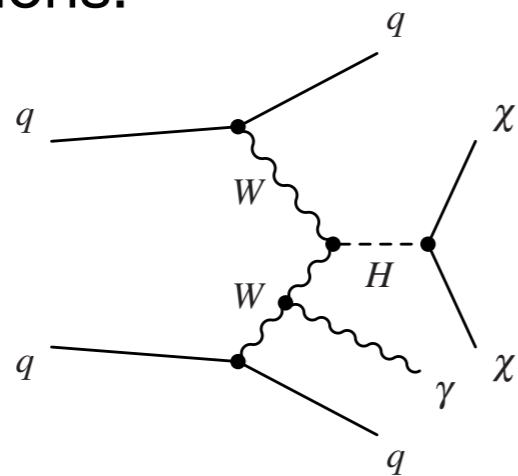
Upper limit on VBF $H \rightarrow \text{inv.}$ BR (95% CL)

Results	Expected	Observed
130 fb⁻¹ @ 13TeV	13%	13%
Previous (36 fb⁻¹ @ 13TeV)	28%	37%

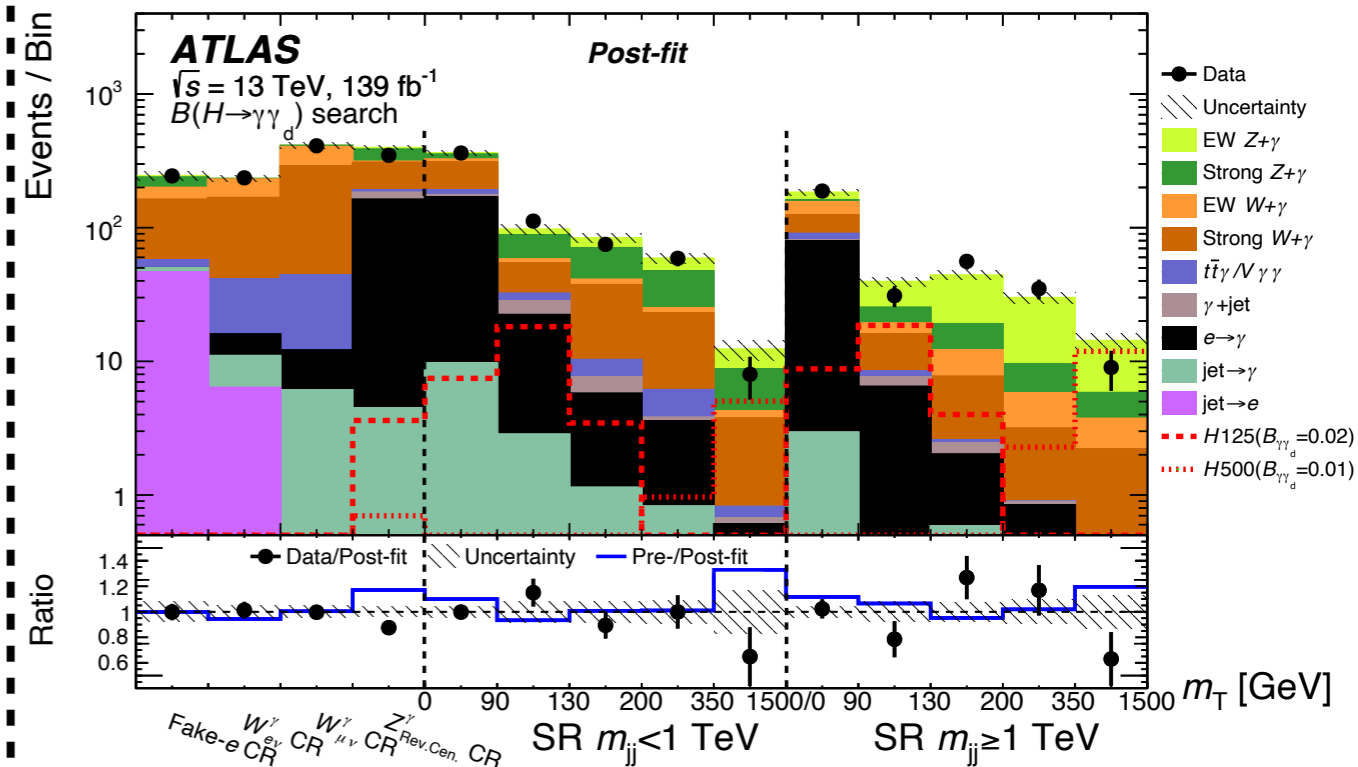
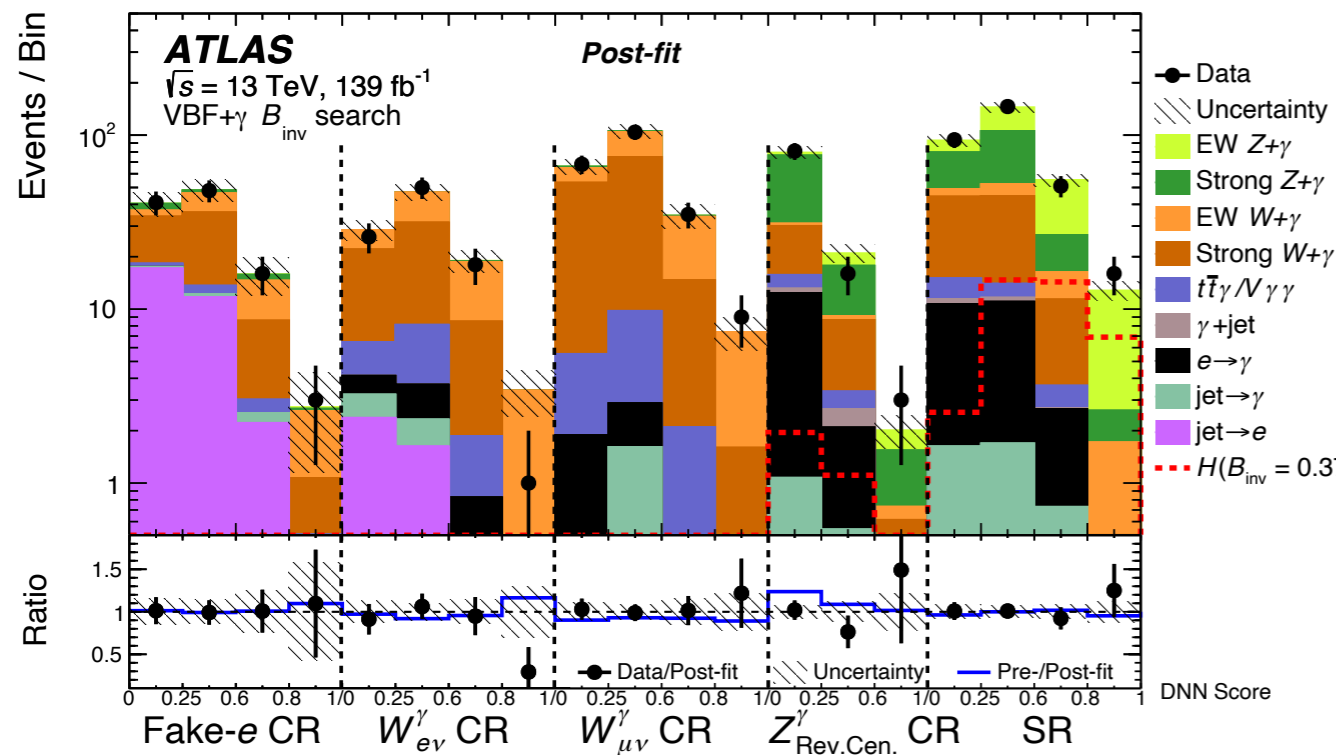
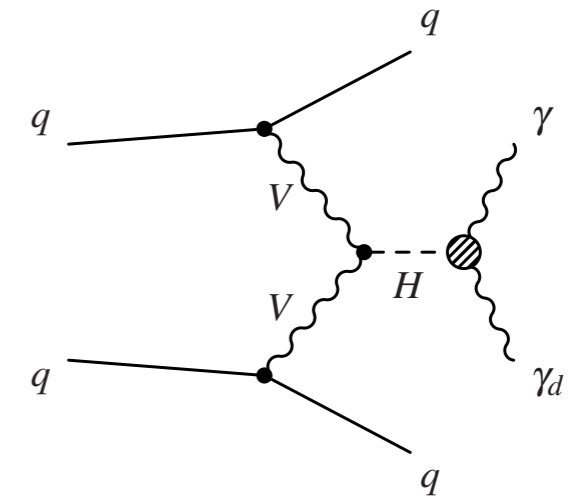
- ▶ Limit on $H \rightarrow \text{inv.}$ obtained

► Two interpretations:

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



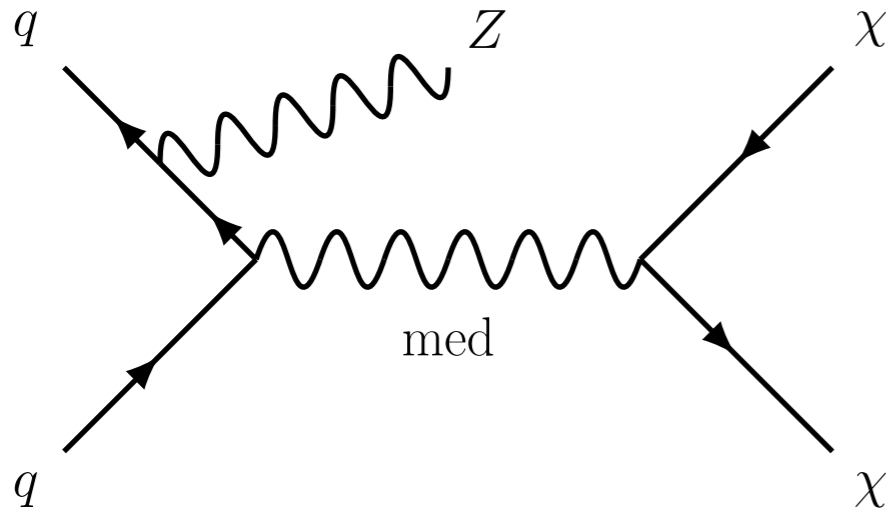
$H \rightarrow \gamma + \gamma_d$



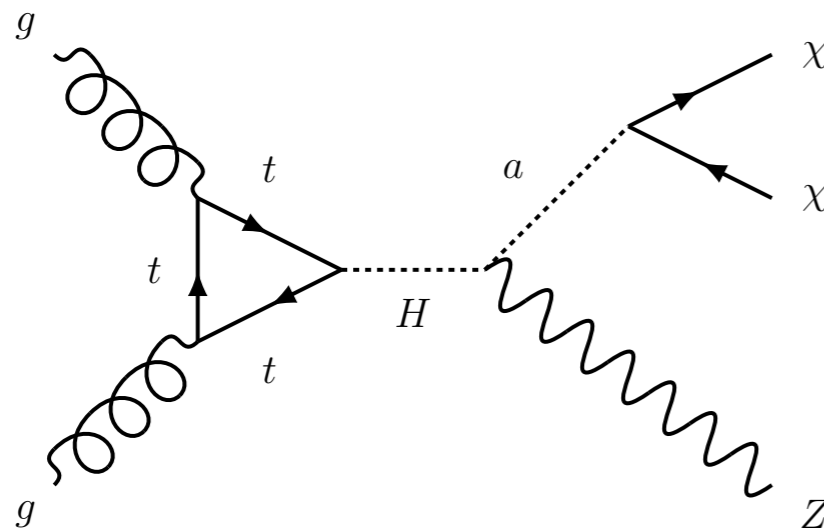
Upper limit on BR (95% CL)

Results	Expected	Observed
$H \rightarrow \text{inv.} + \gamma$	34%	37%
$H \rightarrow \gamma + \gamma_d$	1.7%	1.8%

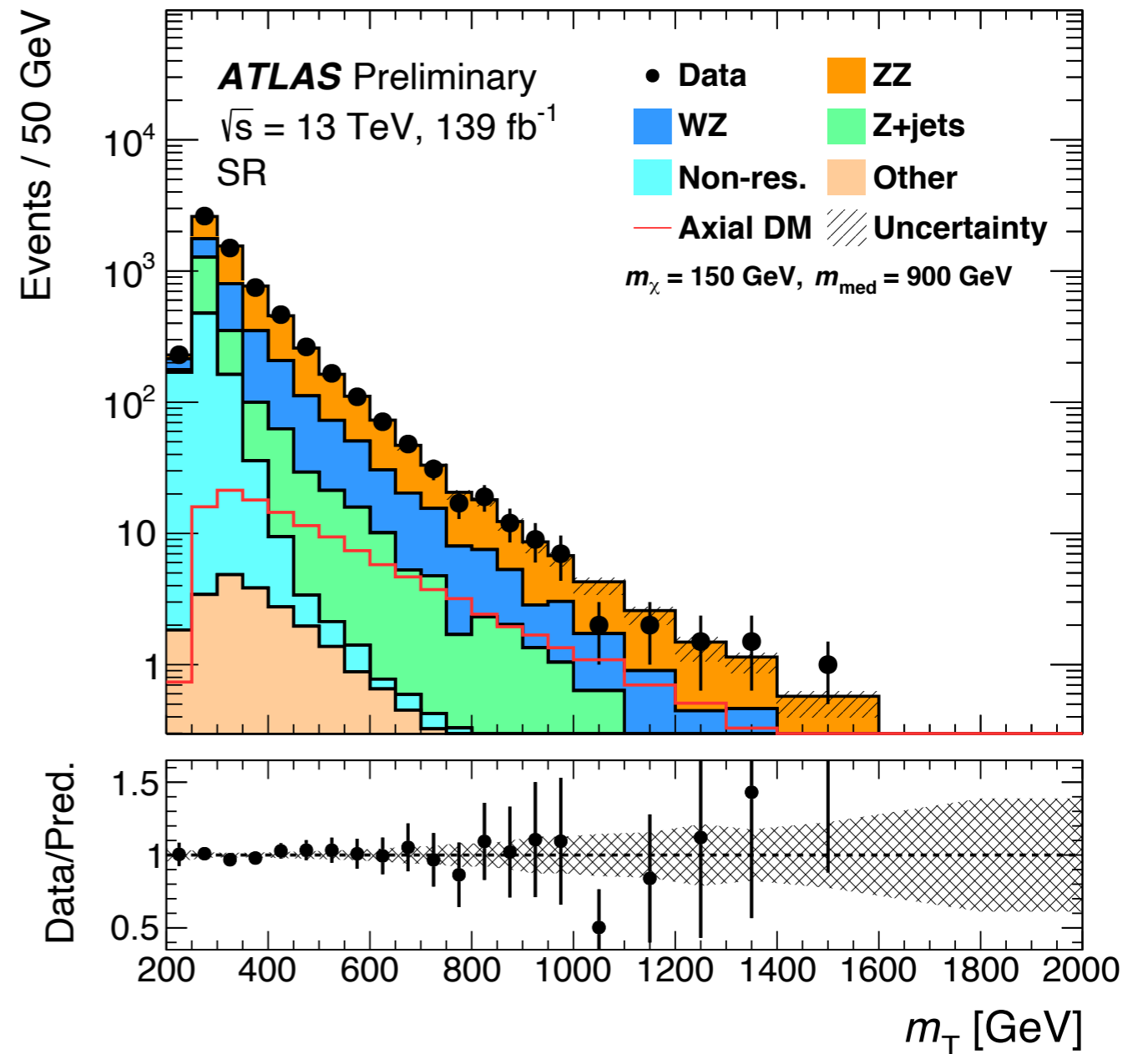
- ▶ Simplified model and 2HDM+a interpretations



- ▶ Also Higgs portal interpretation

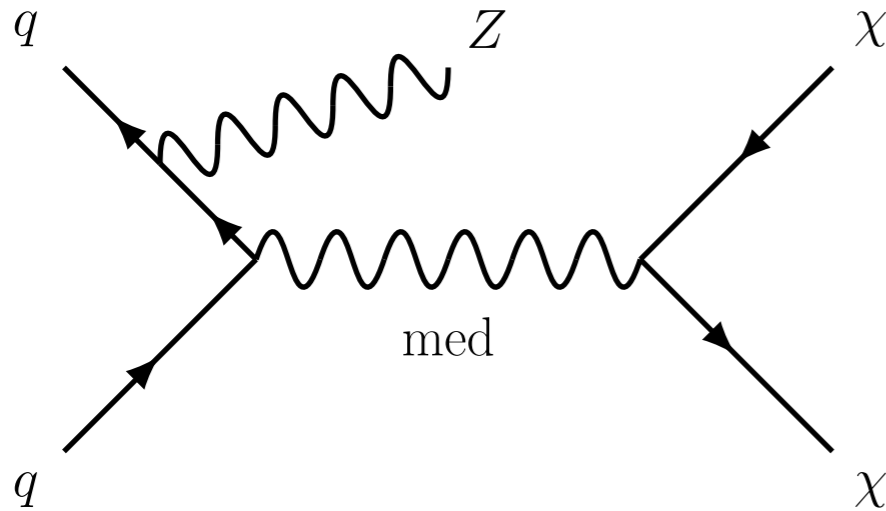


- ▶ Transverse mass distribution (m_T) is used in the maximum-likelihood fits
- ▶ $\text{Br}(H \rightarrow \text{inv.}) < 18\%$ at 95% C.L.

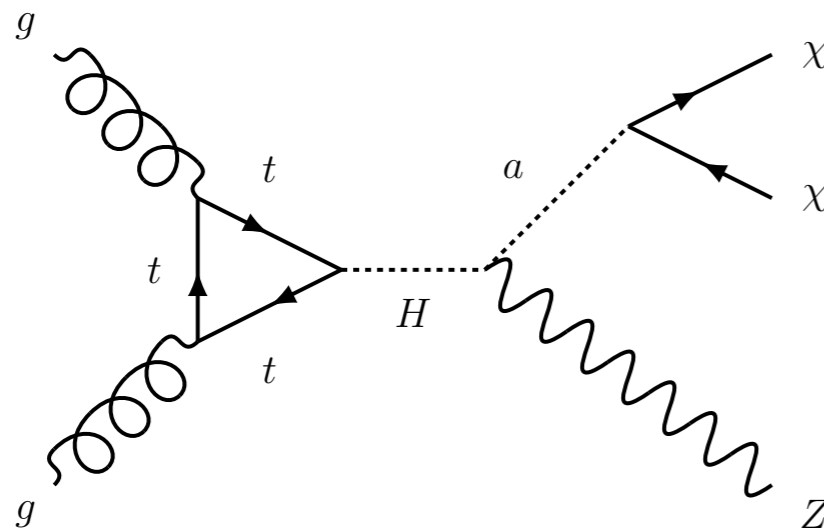


$$m_T = \sqrt{\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2} - (\vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}})^2}$$

- ▶ Simplified model and 2HDM+a interpretations

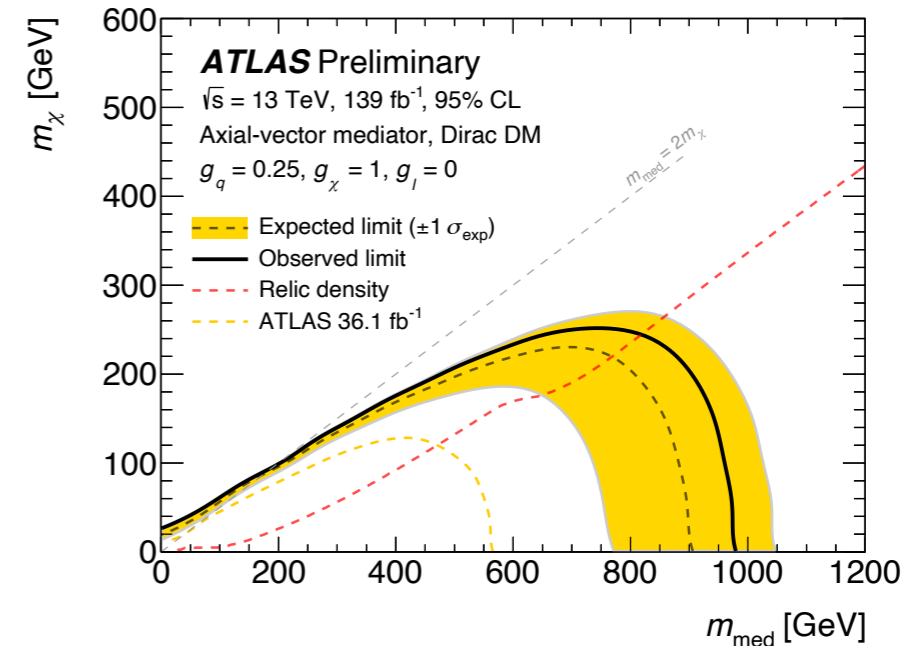


- ▶ Also Higgs portal interpretation

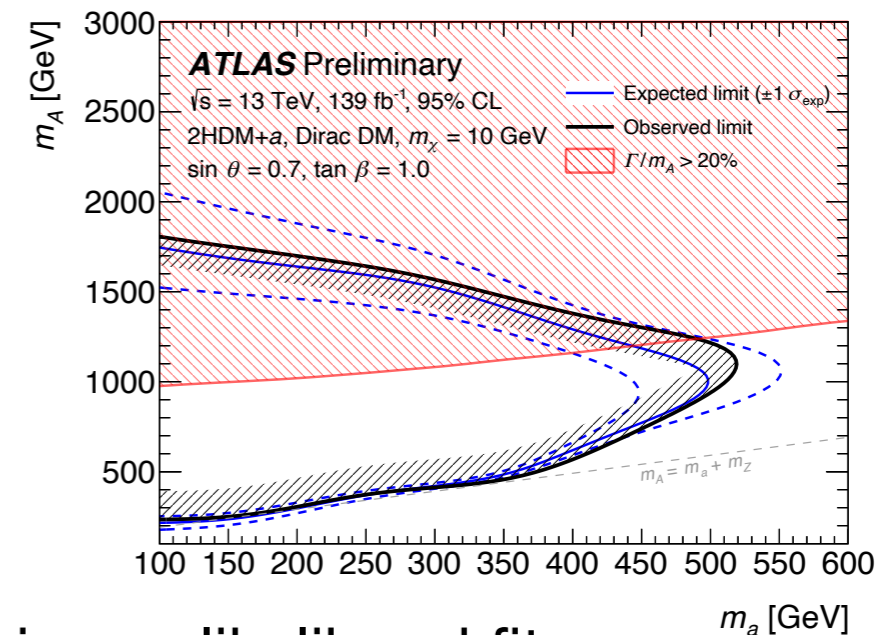


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- ▶ $\text{Br}(H \rightarrow \text{inv.}) < 18\%$ at 95% C.L.

Axial-vector mediator

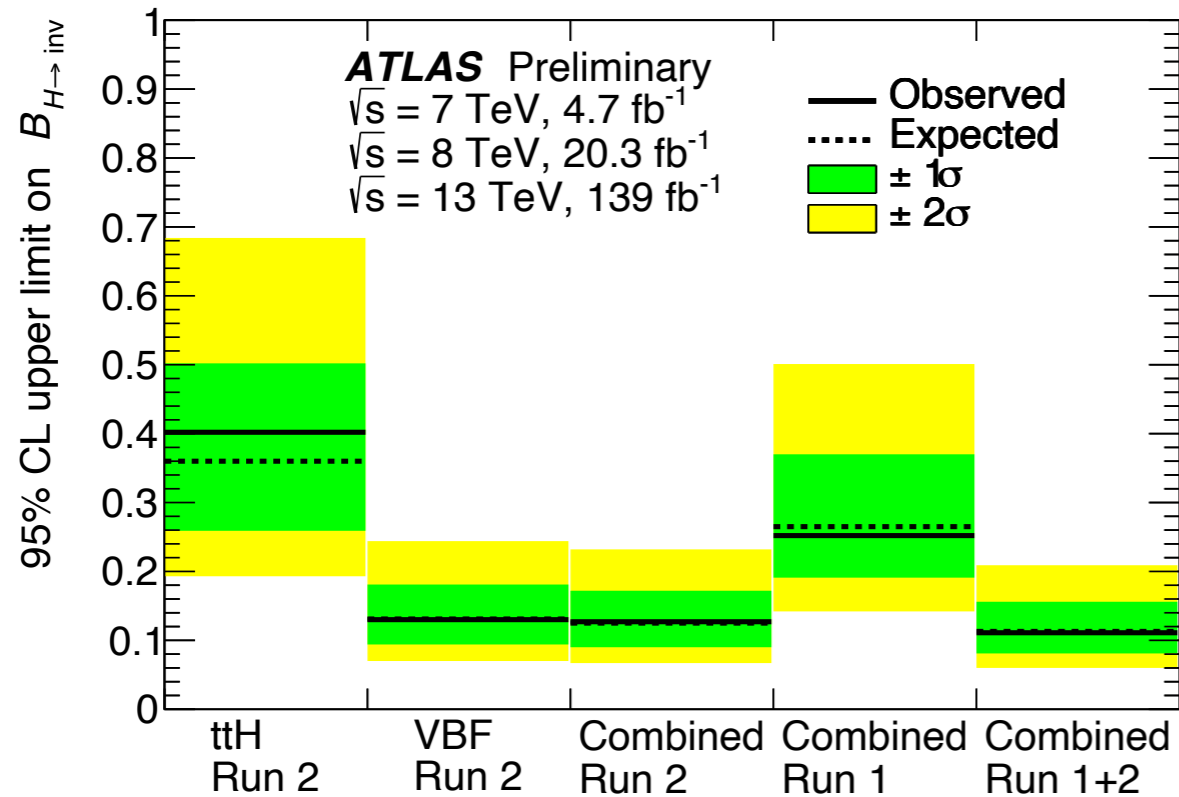


Exclusion limits set on 2HDM+a



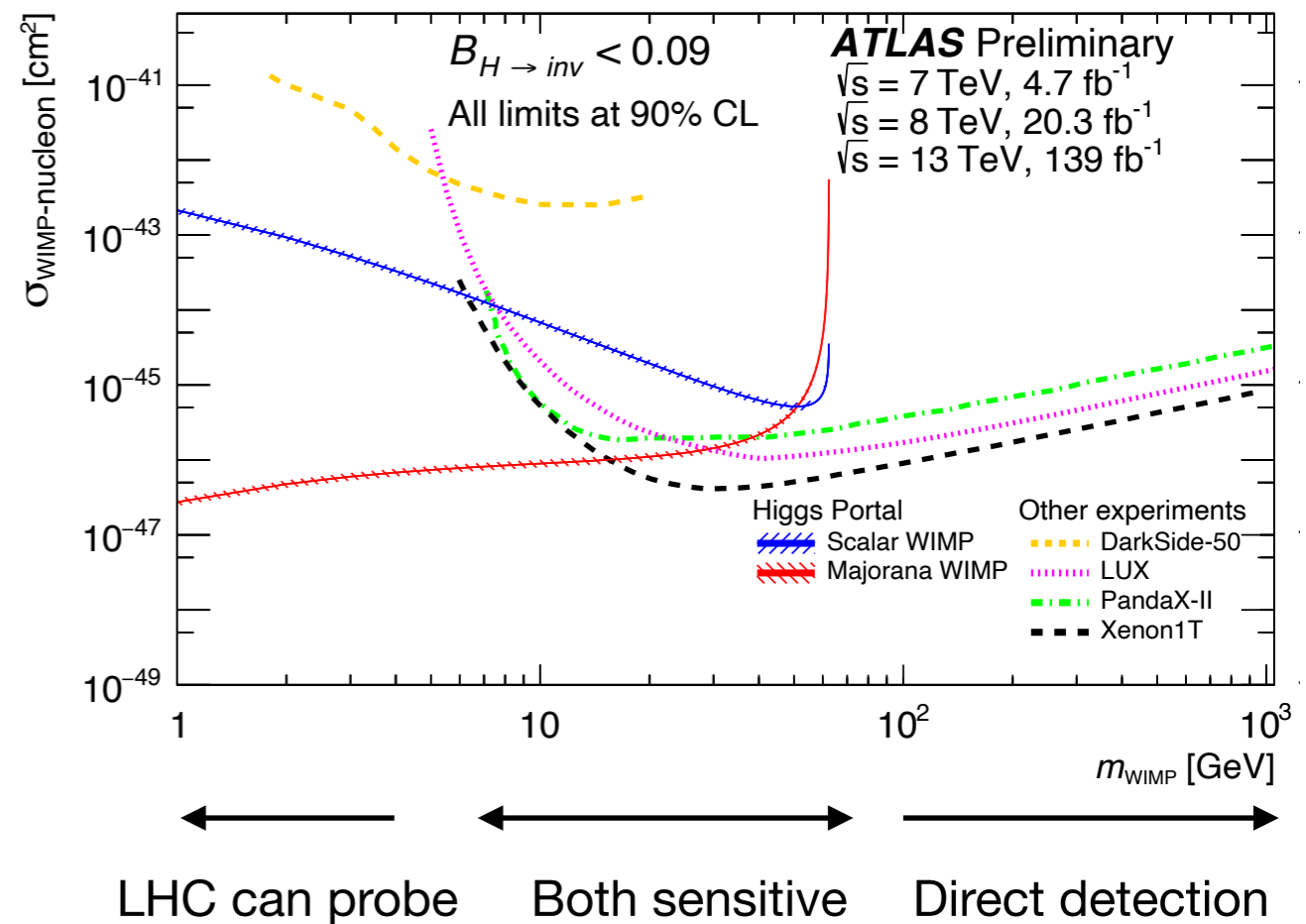
$$m_T = \sqrt{\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{\text{miss}})^2} - (\vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}})^2}$$

- ▶ Combining with ttH and VBF
- ▶ More results such as Z(l)l+MET, VBF+photon to be added

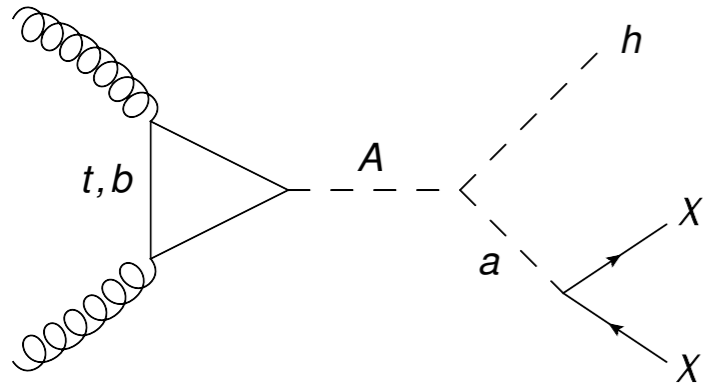


most sensitive

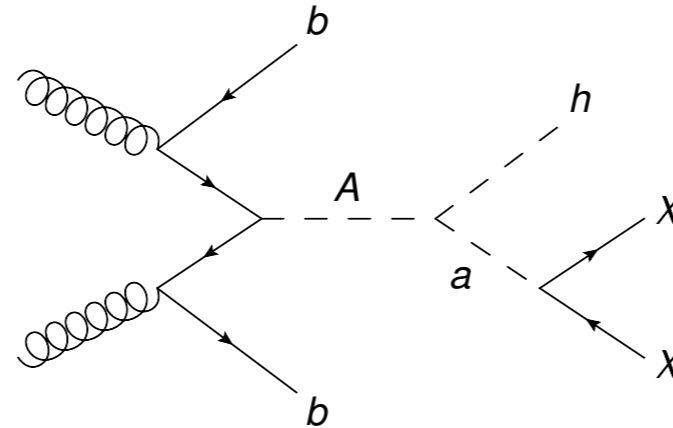
- ▶ ATLAS Run 1 + Run 2 result: $\text{Br}(H \rightarrow \text{inv.}) < 0.11$ (0.11)
- ▶ Translated to spin-independent DM-nucleon elastic scattering cross-section limit



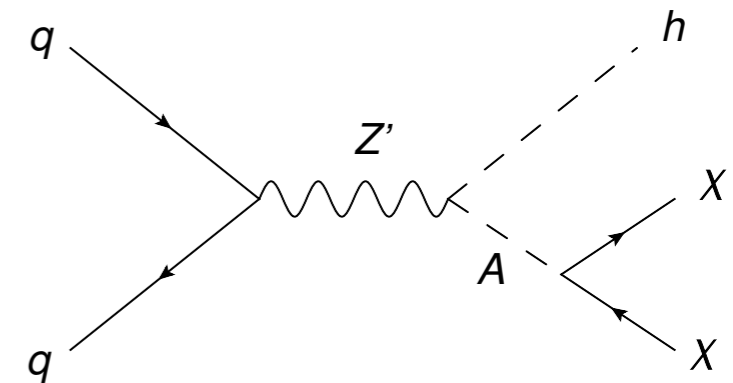
2HDM+a
(ggF)



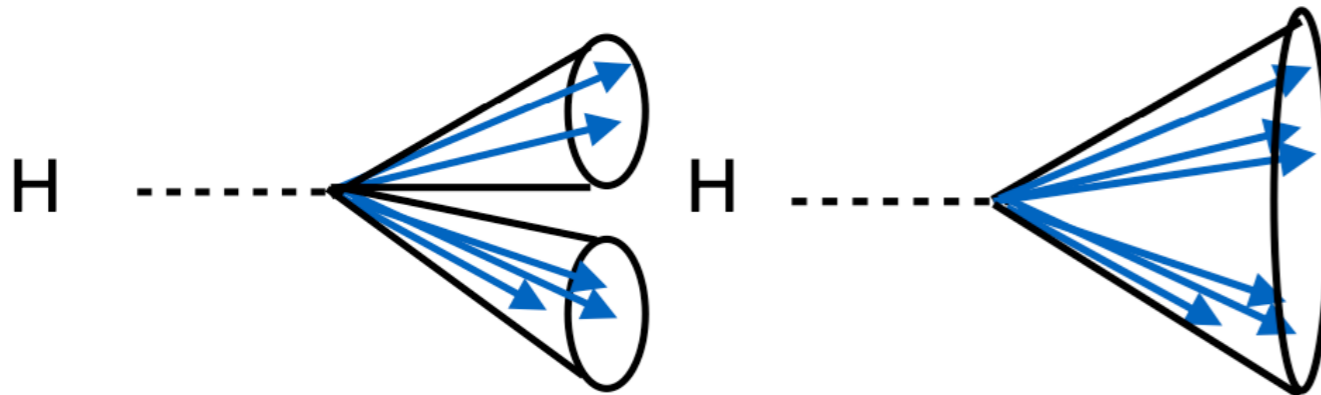
2HDM+a
(bbA)



Z'-2HDM



- ▶ Largest BR for Higgs decays
- ▶ Event selection based on Higgs boost:

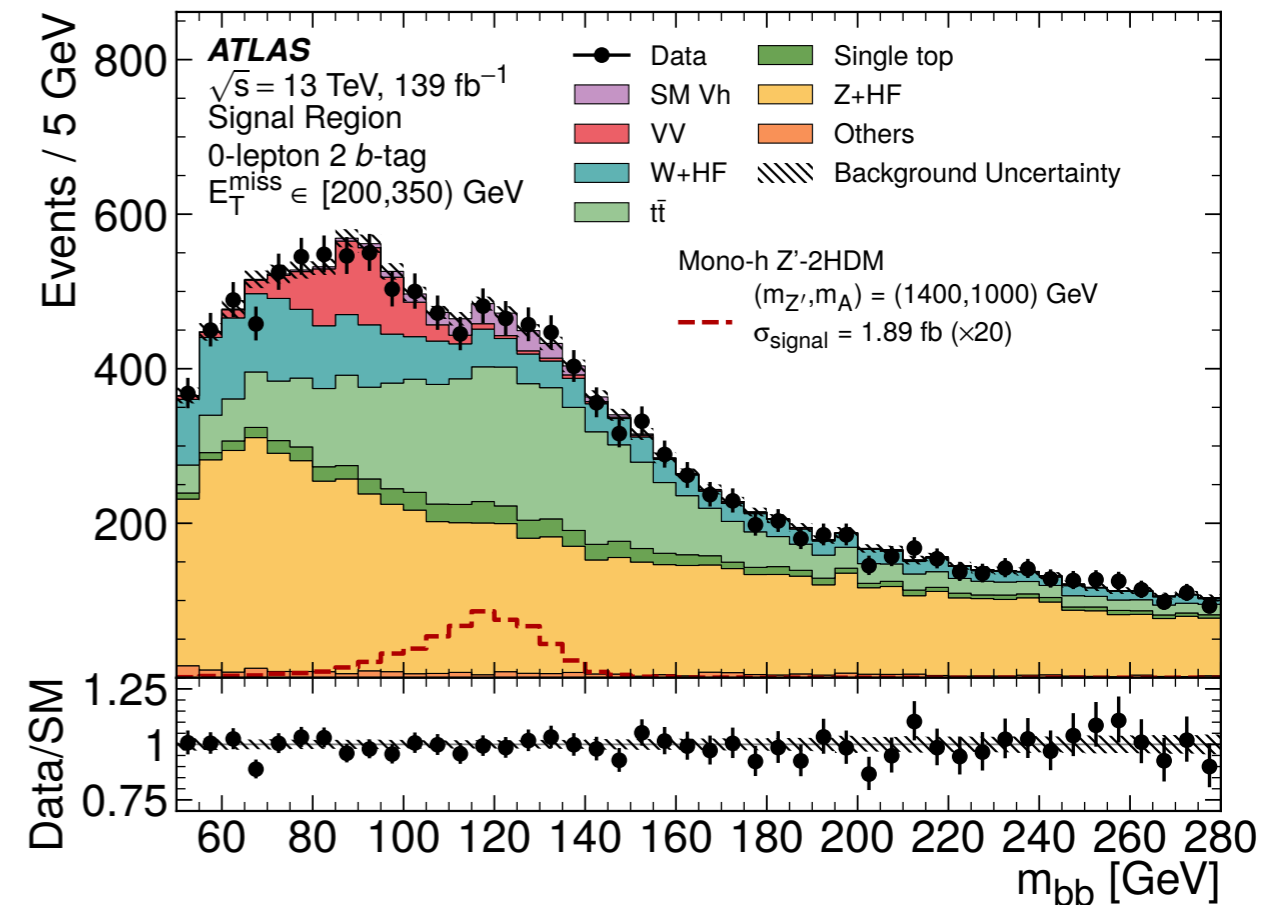


Resolved

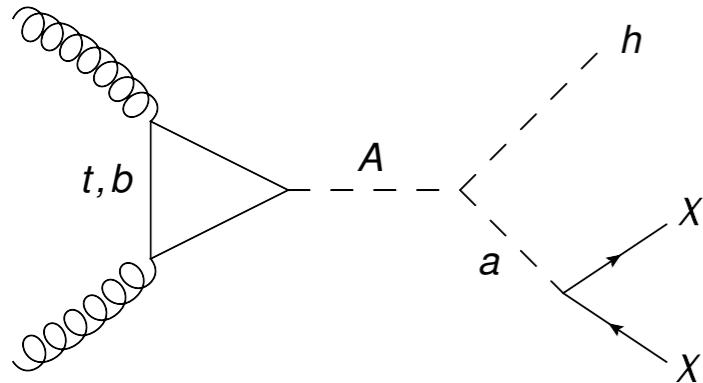
≥ 2 small-R jets
MET < 500 GeV

Merged

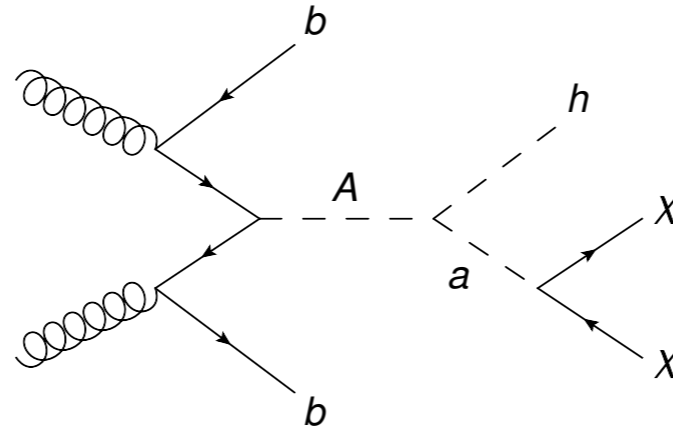
≥ 1 large-R jets
MET < 500 GeV



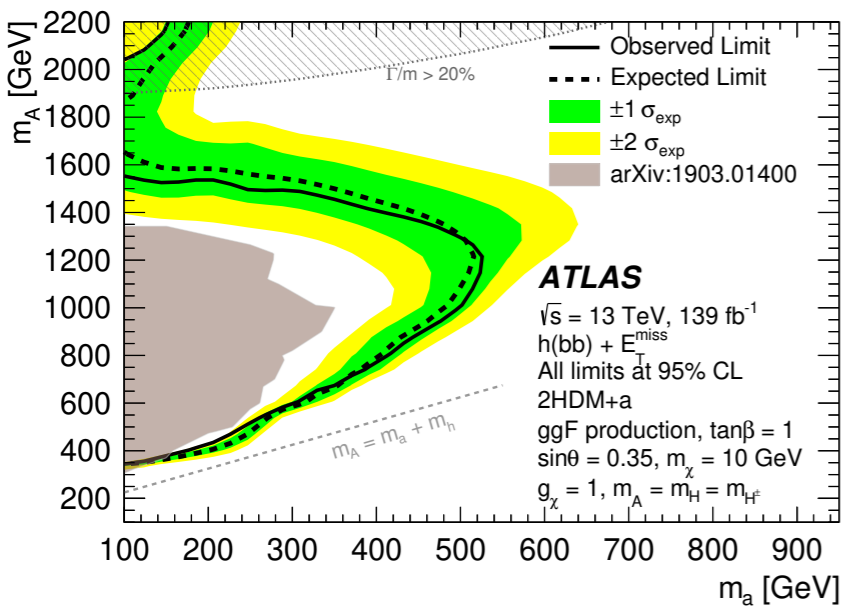
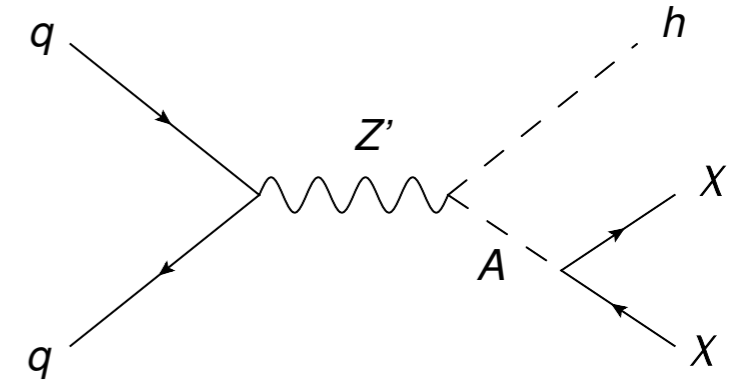
2HDM+a
(ggF)



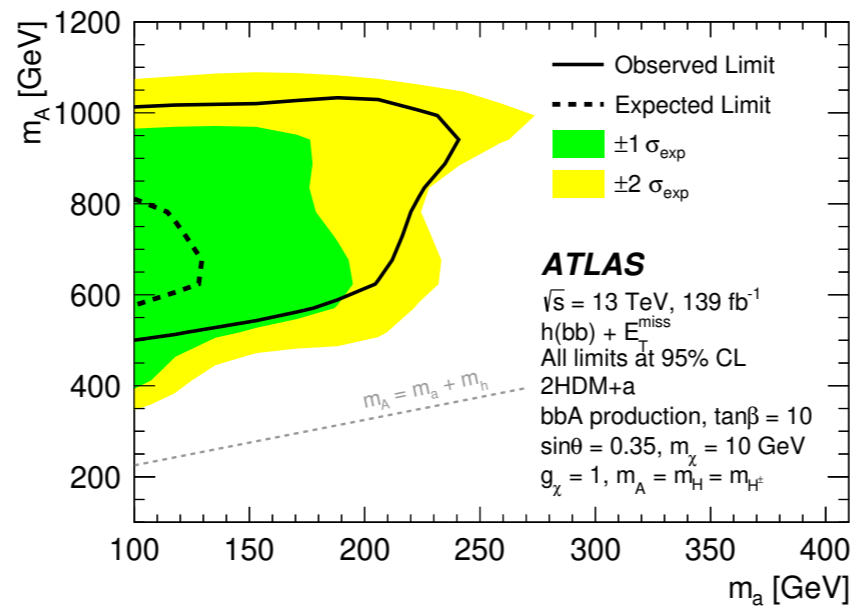
2HDM+a
(bbA)



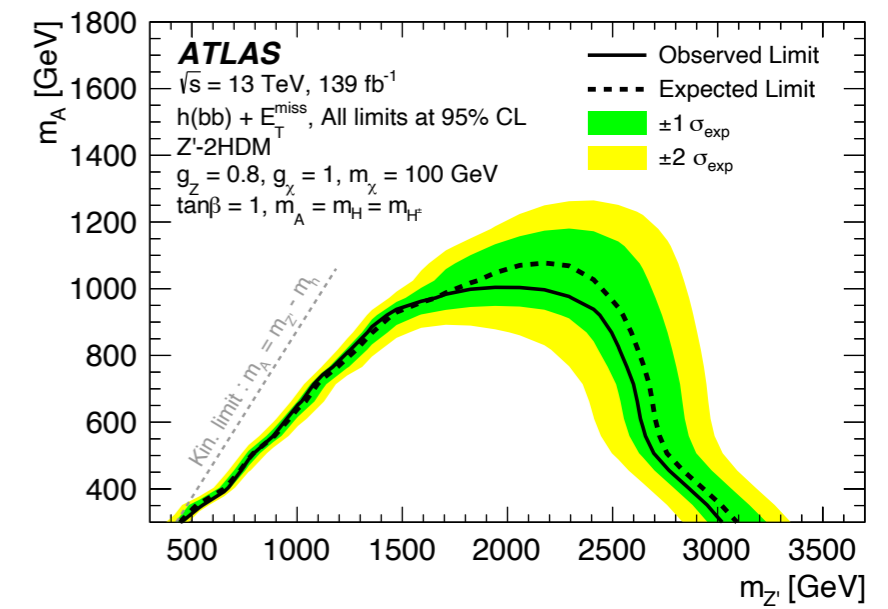
Z'-2HDM



$\tan\beta=1$



$\tan\beta=10$

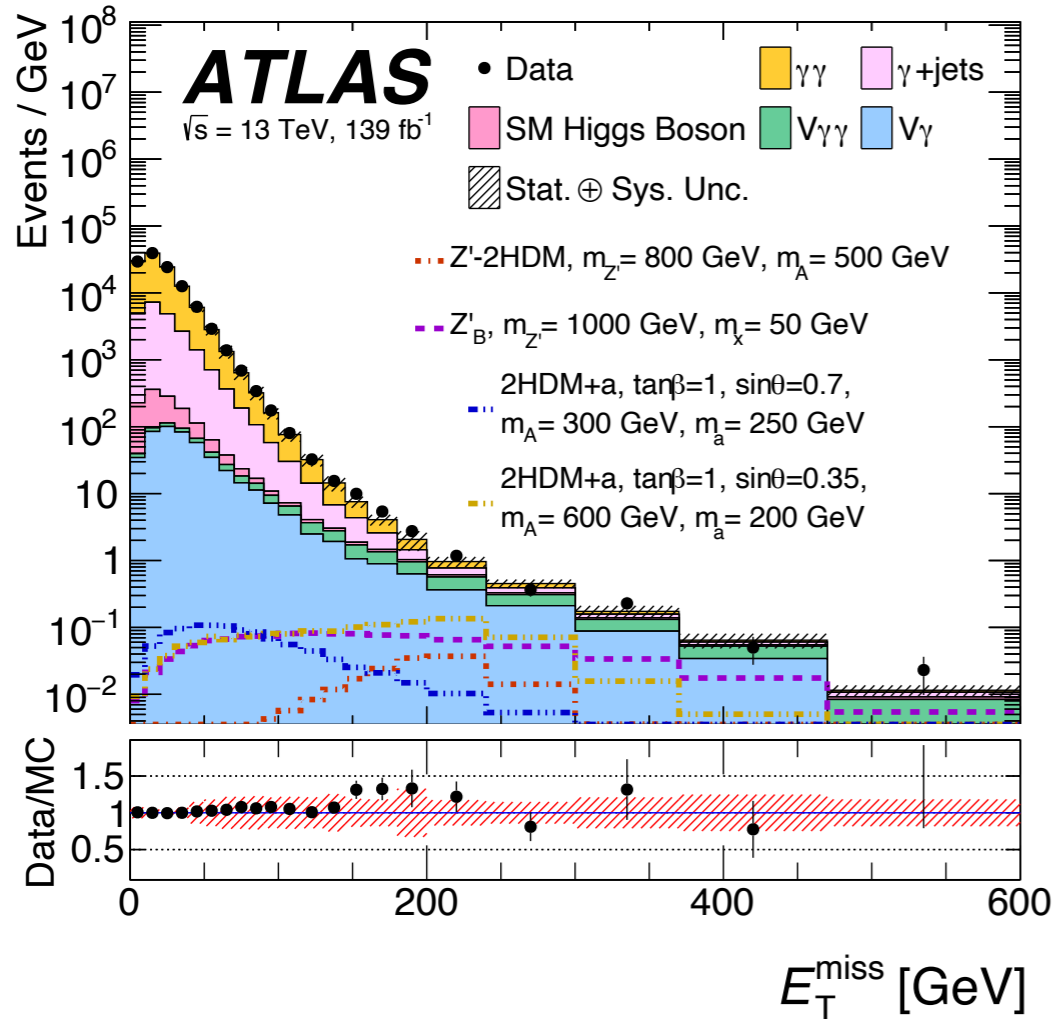
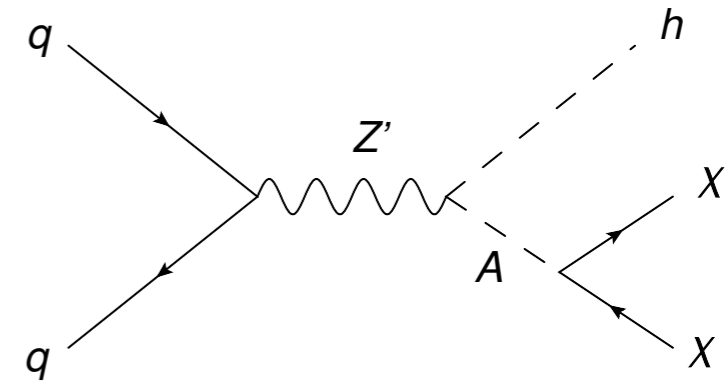


$\tan\beta=1$

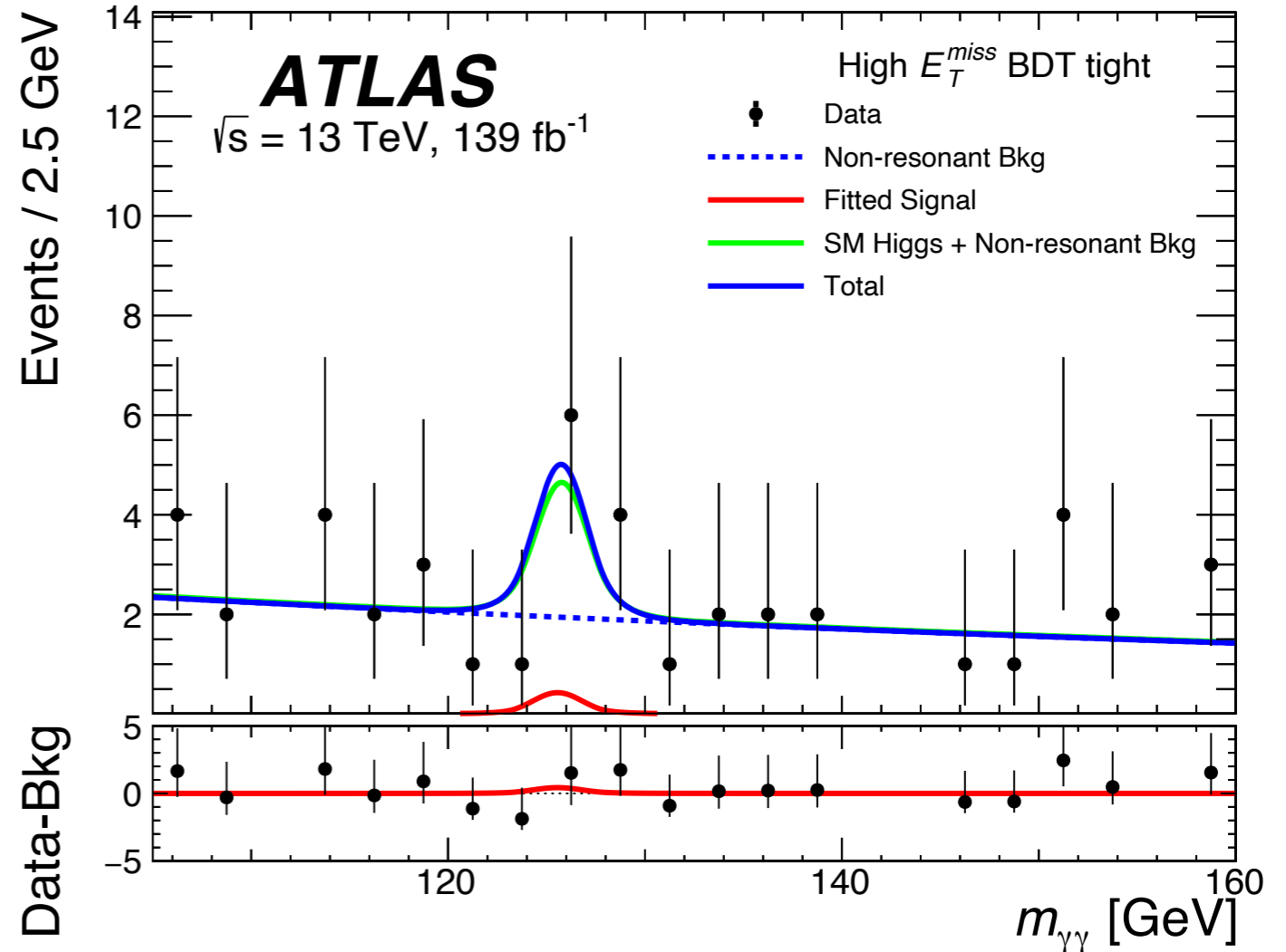
MonoH $\rightarrow \gamma\gamma$

- ▶ Z'-2HDM model as same as the previous (+ other models)
- ▶ Clean signature: 2 photons
- ▶ A BDT trained with $p_T^{\gamma\gamma}$ and S_{MET}
 - ▶ High MET (> 150 GeV) and Low MET separately

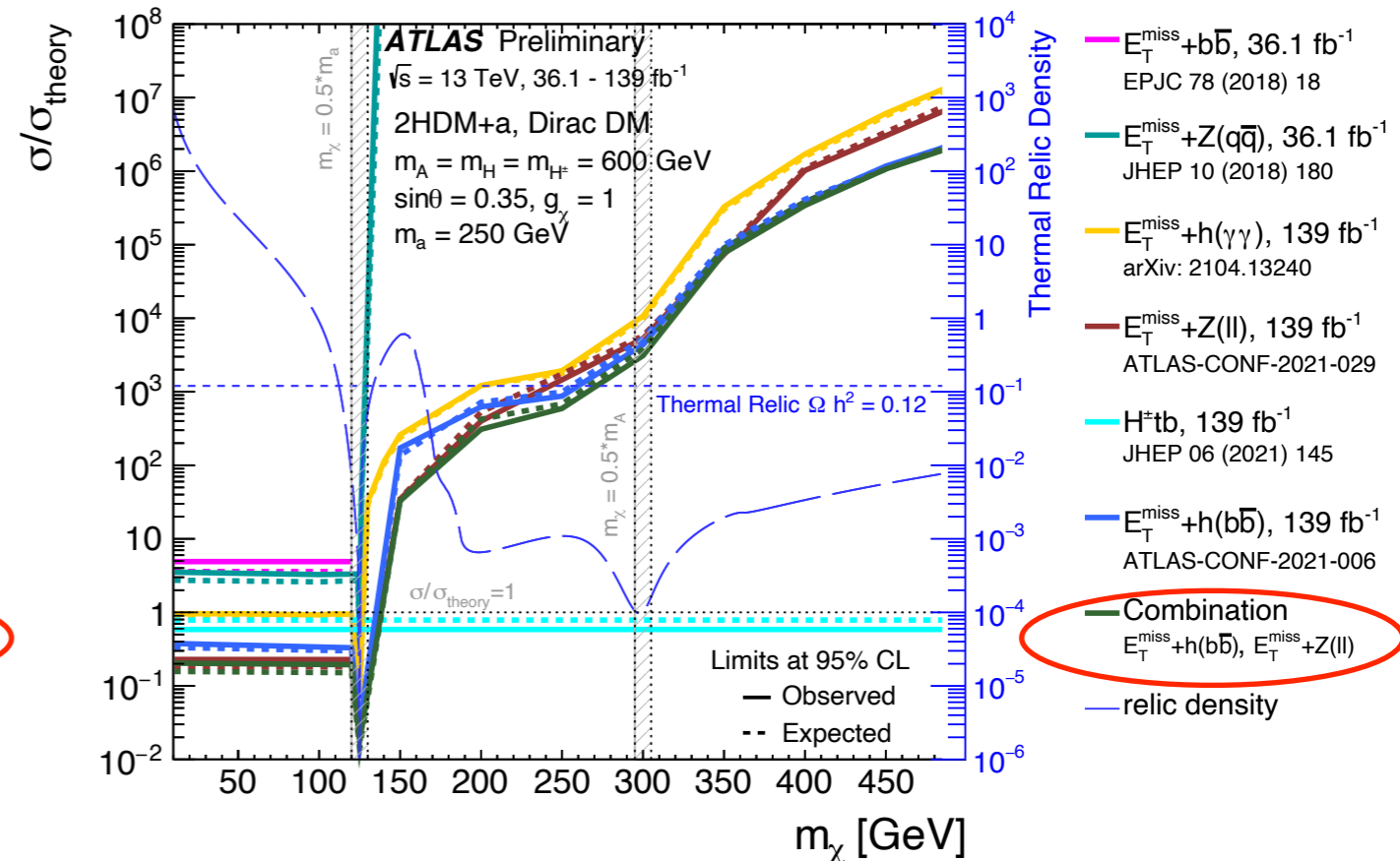
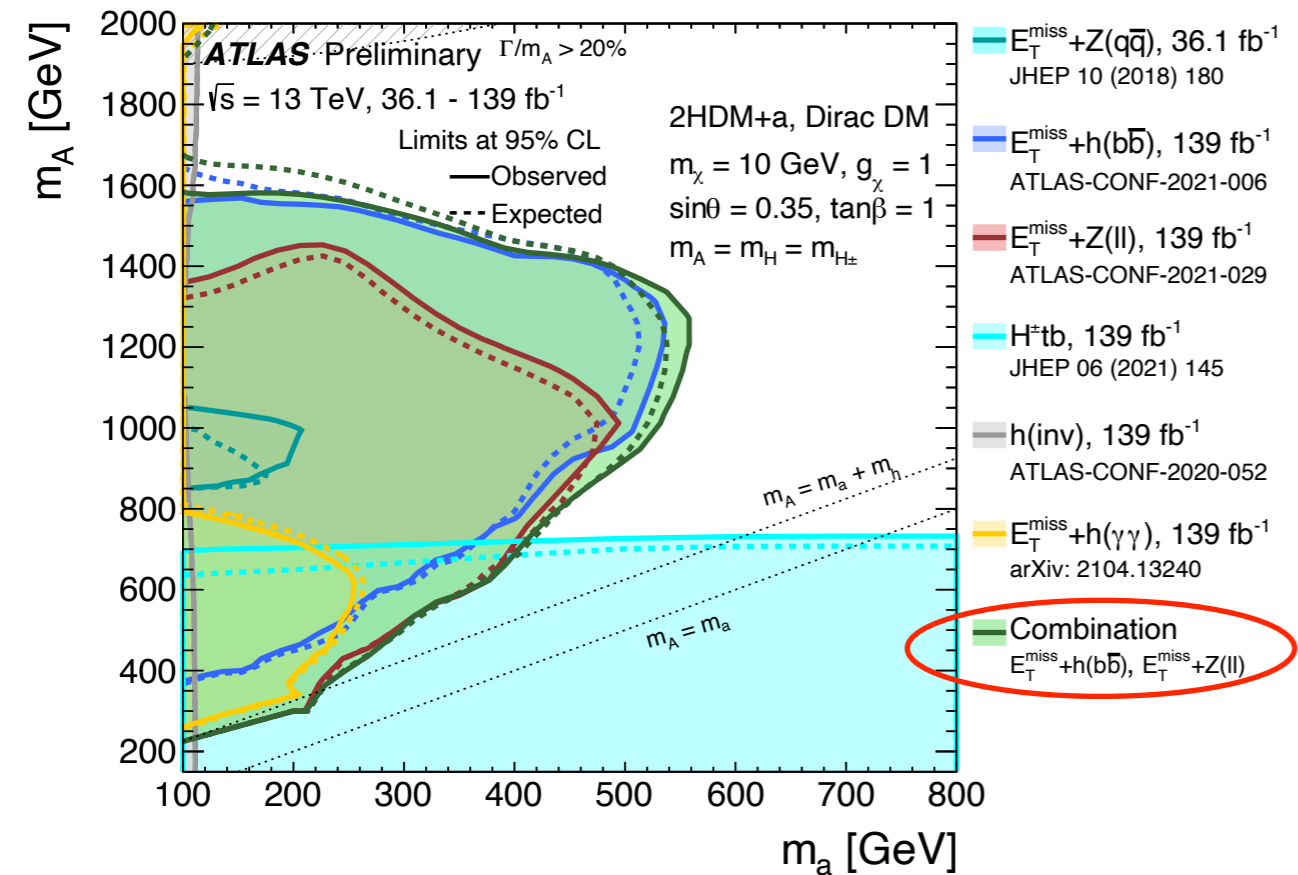
Z'-2HDM



Signals tend to have high MET



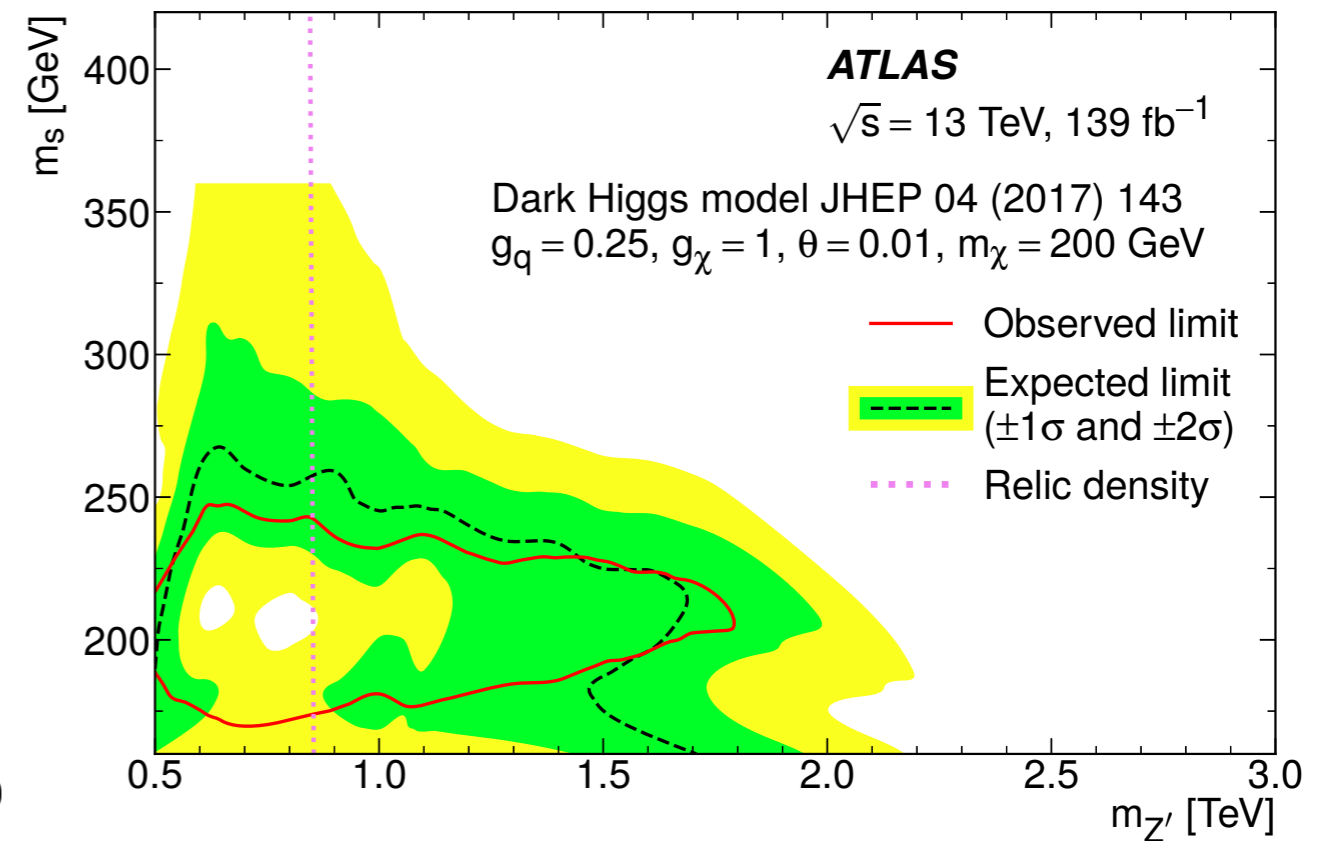
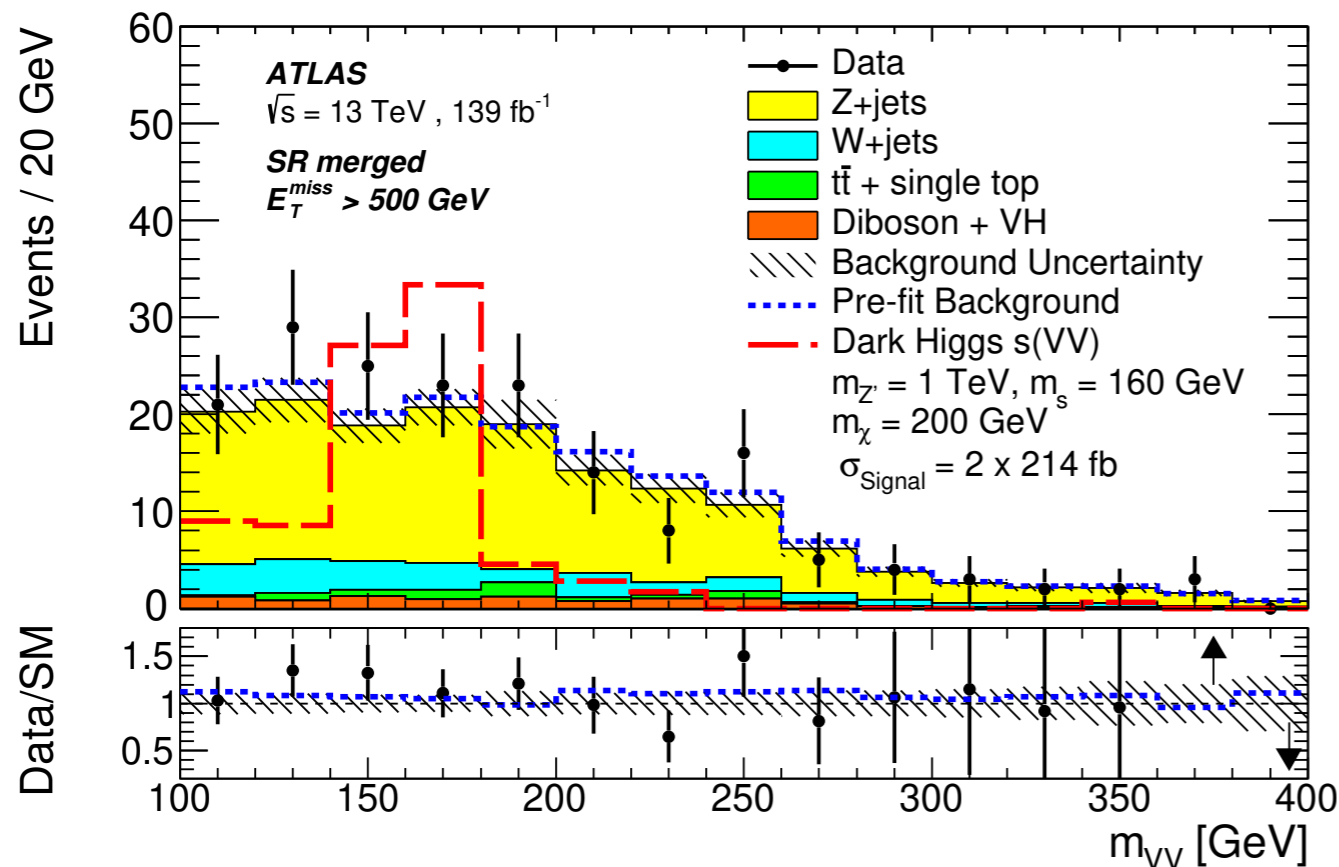
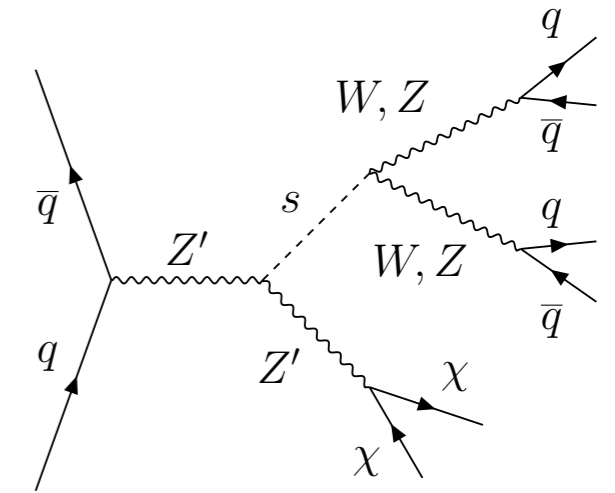
- ▶ Statistical combination of H(bb)+MET and Z(ll)+MET
- ▶ Most sensitive searches updated to full Run-2 luminosity
- ▶ Significant complementarity from different channels



Dark Higgs MonoS \rightarrow VV

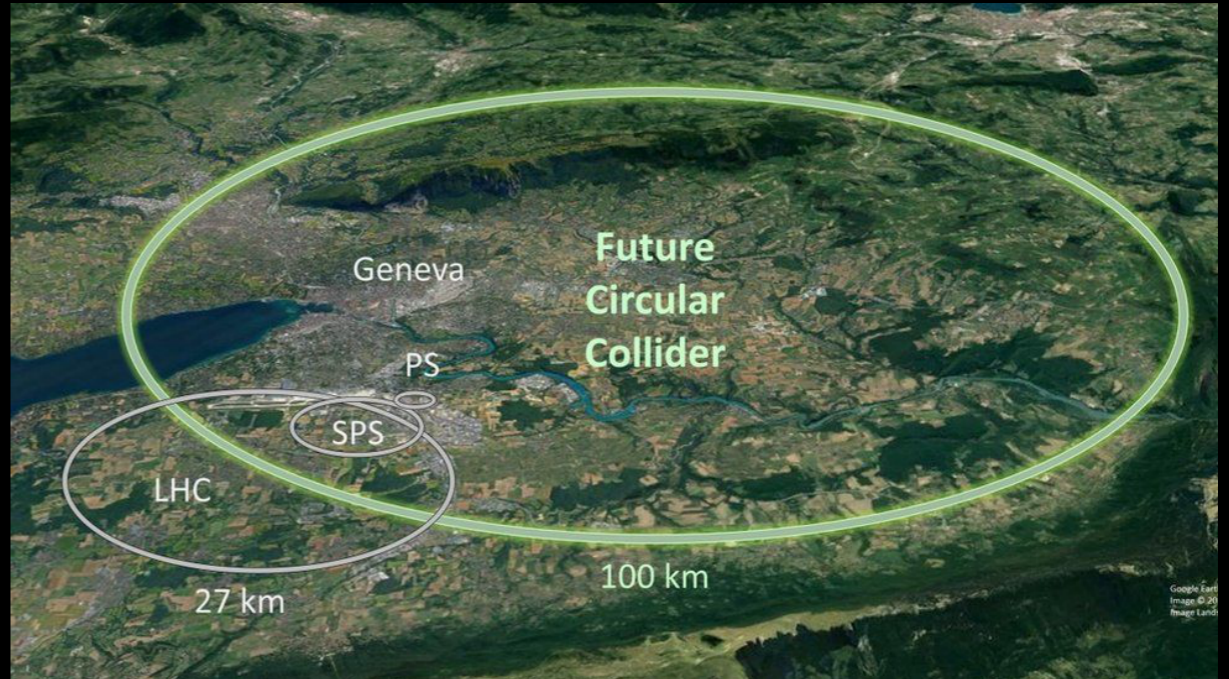
Phys. Rev. Lett. 126 (2021) 121802

- ▶ A dark Higgs (S) decays into VV
- ▶ Mass of new scalar S > 160 GeV to guarantee the high BR
- ▶ Utilize hadronic decay of W or Z
- ▶ S \rightarrow VV reconstructed with:
 - ▶ Track Assisted Reclustered (TAR) jets to improve jet mass and substructure resolution
 - ▶ Four prong required



Summary & Outlook

- ▶ Various DM searches performed with ATLAS
 - ▶ The mediator search
 - ▶ Dijet and Dilepton
 - ▶ Search for the recoiling DM
 - ▶ Jet/photon + MET
 - ▶ $Z(\ell\ell)$ + MET
 - ▶ Search with the Higgs boson
 - ▶ $\text{mono}H(bb)$
 - ▶ $\text{mono}H(\gamma\gamma)$
 - ▶ $\text{mono}S(VV)$
 - ▶ More interpretations and more final states expected
 - ▶ eg. $\text{mono}S(bb) + \text{mono}S(WW\text{-lep})$
- ▶ Though we are still in the darkness, however more interesting results expected from the up-coming LHC Run-3, HL-LHC and the FCC



Backup