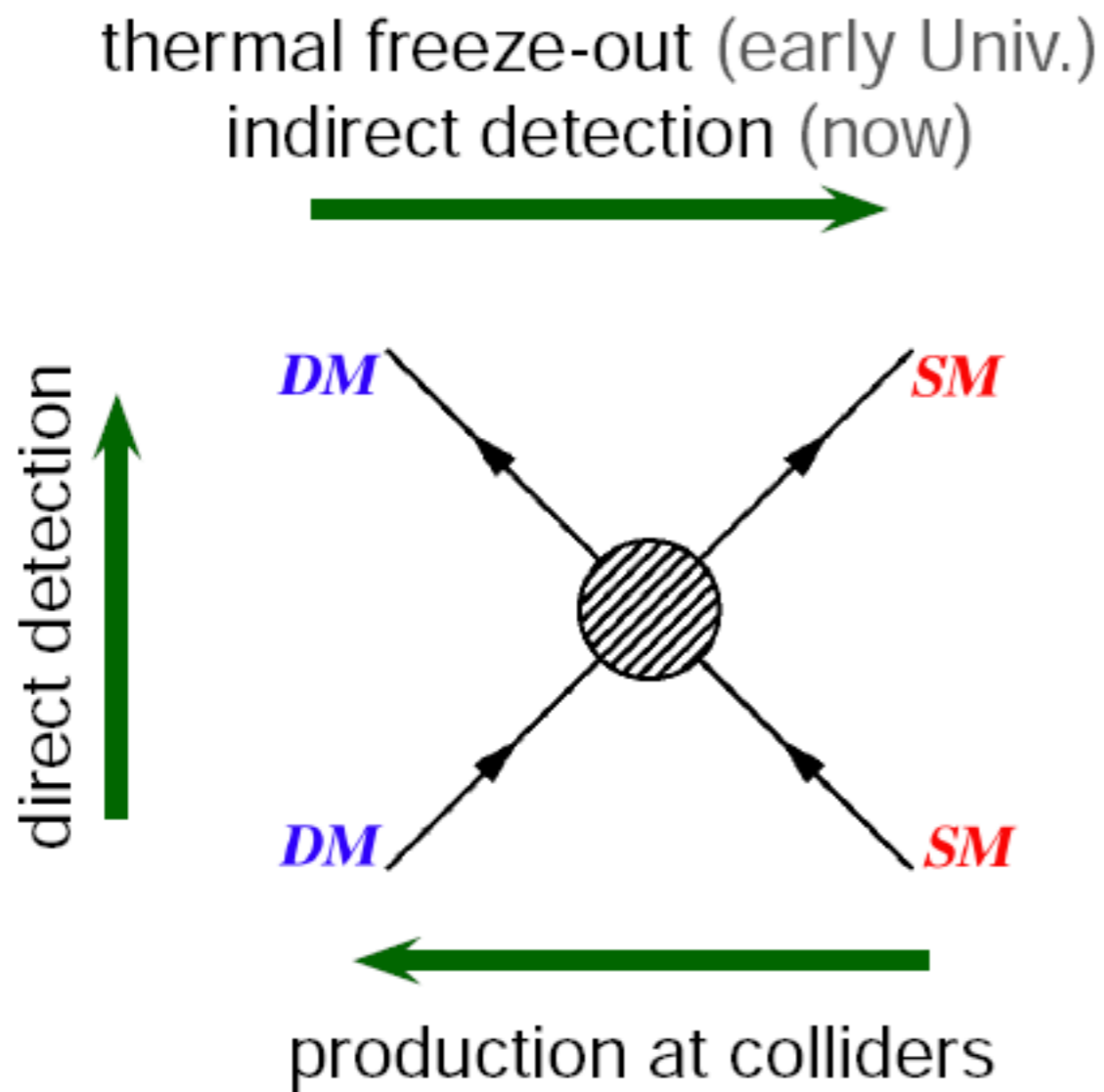


# Dark Matter @ LHC

D.Kovalskyi (MIT)  
for  
CMS and ATLAS Collaborations

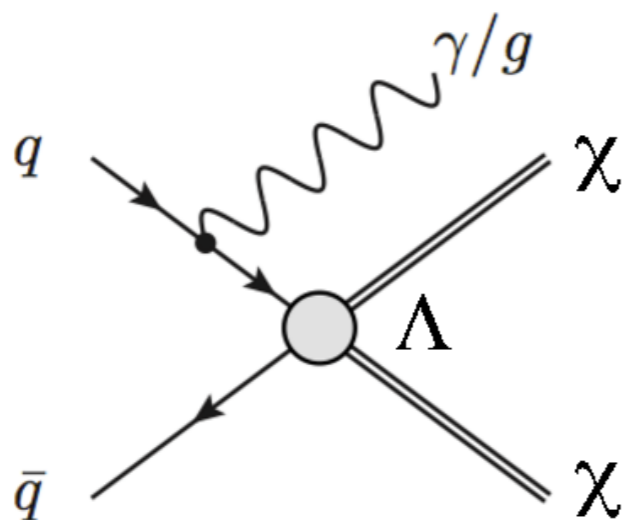


- ▶ Momentum Transfer
  - ▶ Direct Detection: 10keV - 1MeV
  - ▶ Indirect Detection: ~DM mass
  - ▶ LHC: up to ~TeV
- ▶ Effective Field Theory validity

$$Q^2 < M_{\text{med}}^2 = g_q g_\kappa \Lambda^2$$

Interpretation of Dark Matter searches  
at LHC is model dependent

## EFT



- ▶ Effective Field Theory
  - ▶ Small parameter space
  - ▶ Not adequate for LHC - momentum transfer is too large

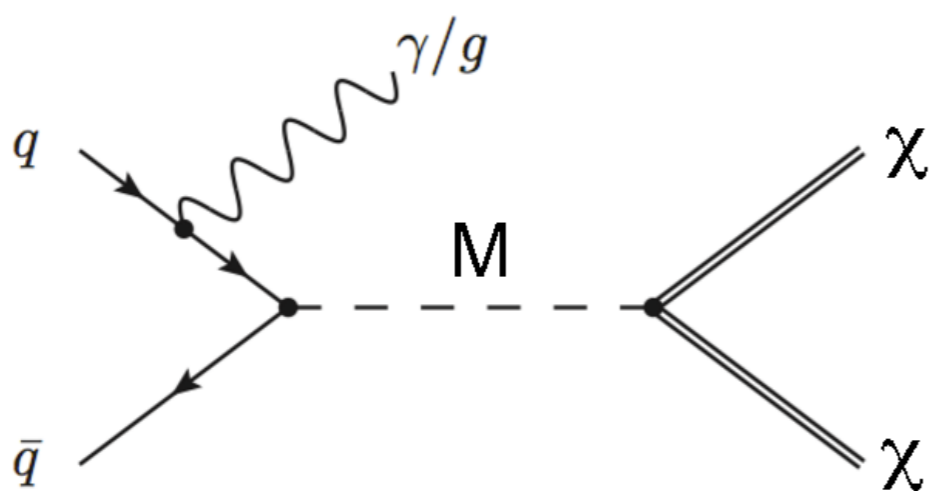
## Simplified Models

- ▶ Minimal number of extra degrees of freedom
- ▶ A mediator particle is needed to connect SM and DM sectors
- ▶ For heavy mediator EFT is a good approximation
- ▶ Direct searches for mediators (di-jet search at colliders)

## Complete Models

- ▶ Large parameter space
- ▶ SUSY, Composite Higgs

## Simplified Model

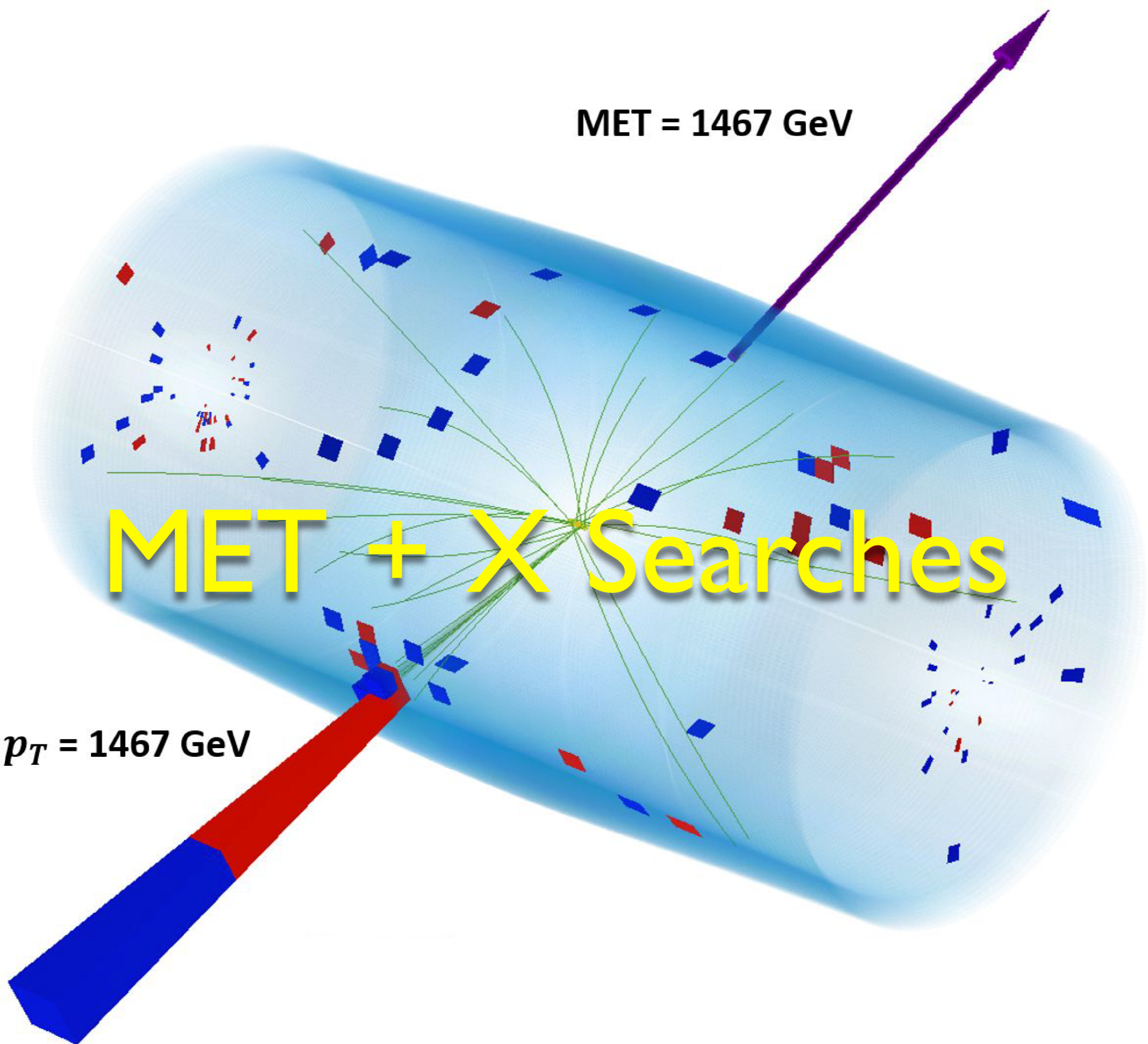


- ▶ Dark Matter particle nature is unknown
  - ▶ Need to cover all possibilities
    - ▶ LHC DM Strategy: searches in different final states
- ▶ ATLAS-CMS Dark Matter Forum (LHC-DMF)
  - ▶ <https://twiki.cern.ch/twiki/bin/view/LHCDFMF>
  - ▶ Publications
    - ▶ arXiv:1507.00966 [hep-ex] - Dark Matter Benchmark Models for Early LHC Run-2 Searches
    - ▶ arXiv:1506.03116 [hep-ph] - Simplified Models for Dark Matter Searches at the LHC
    - ▶ arXiv:1603.04156 [hep-ex] - Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

**MET = 1467 GeV**

# MET + X Searches












**Jet  $p_T = 1467$  GeV**

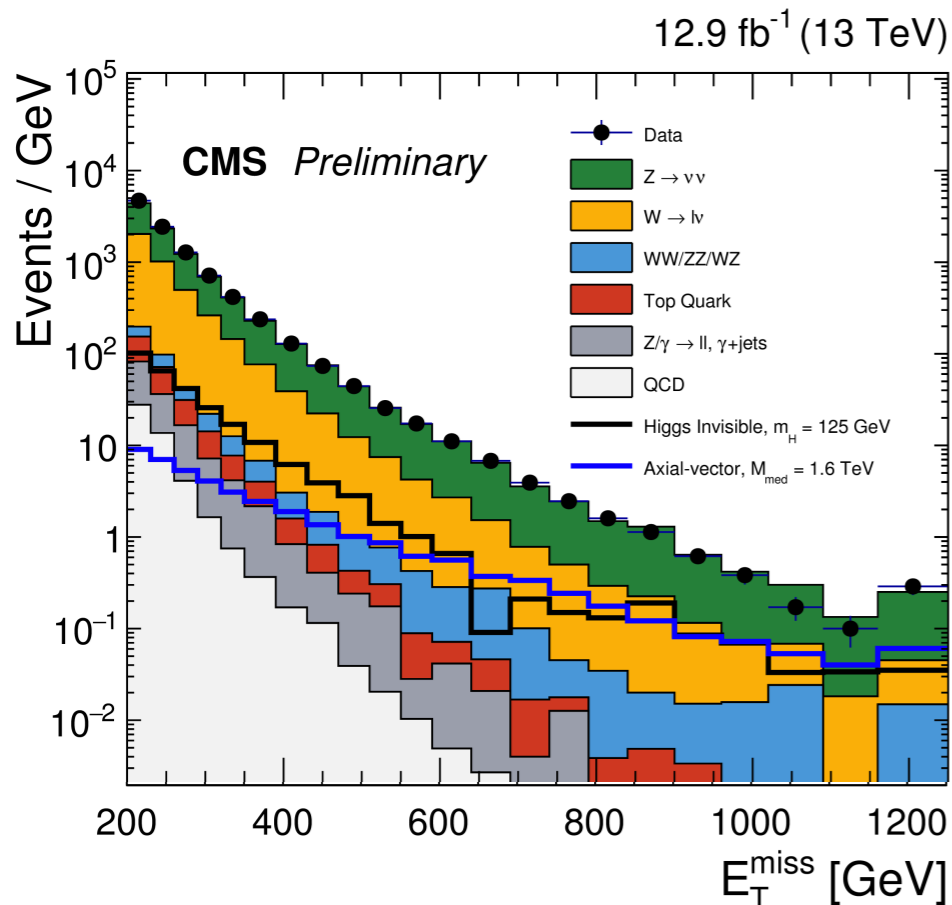
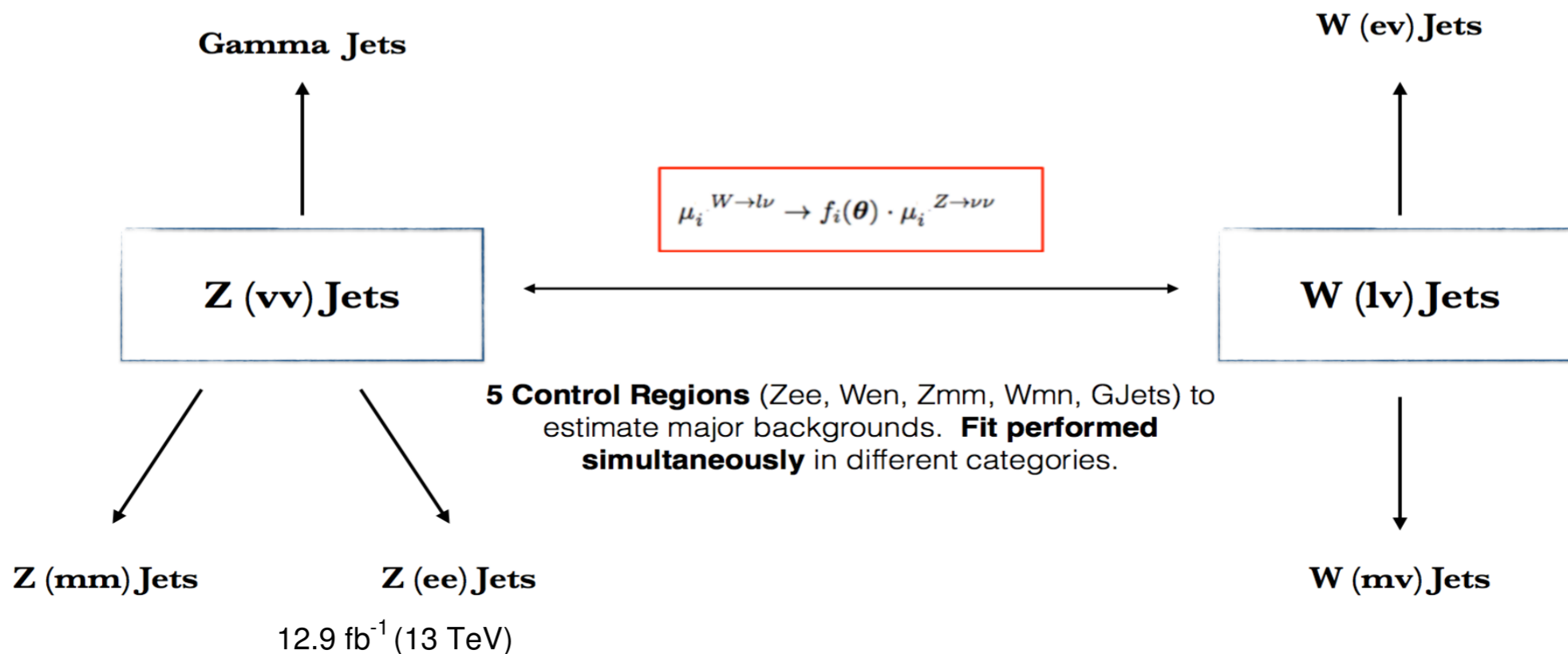




# MET + X Searches

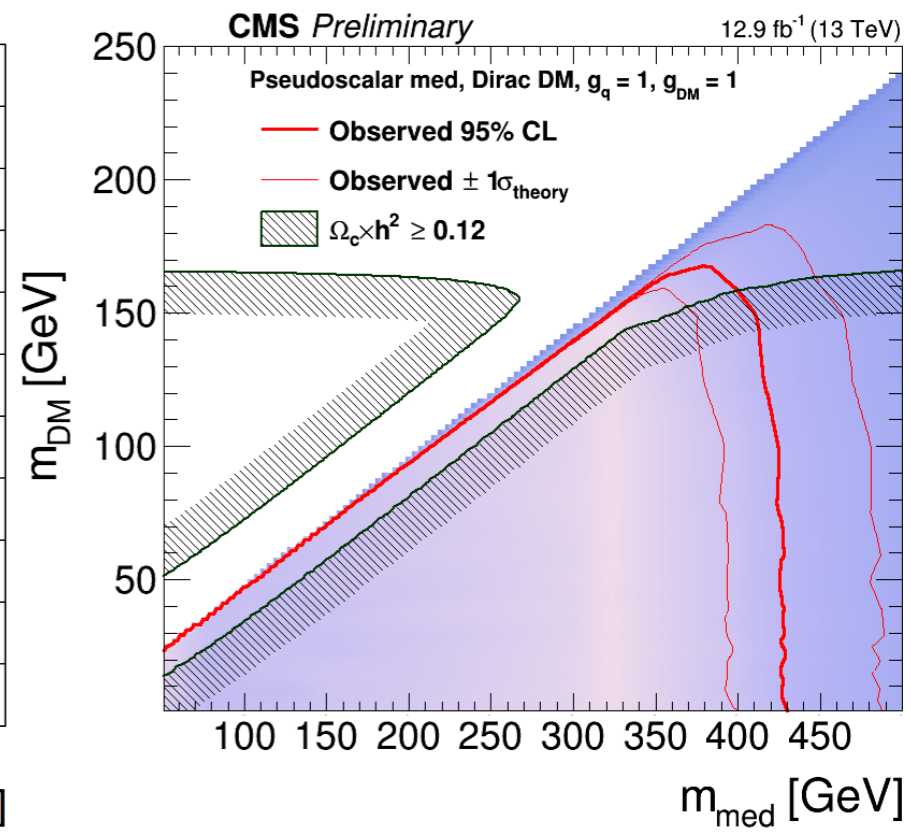
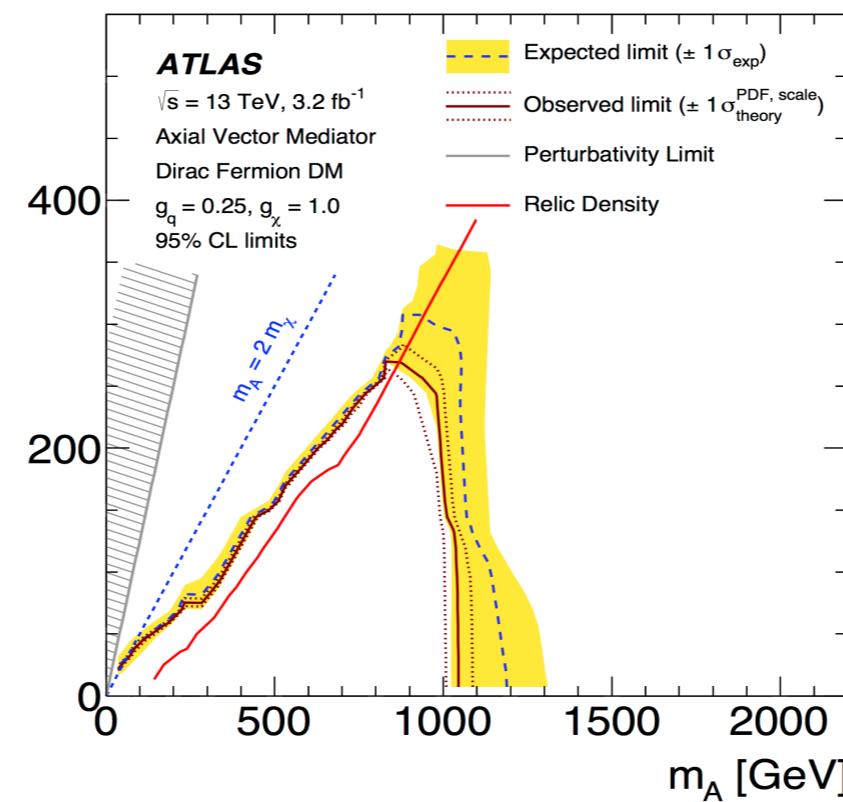
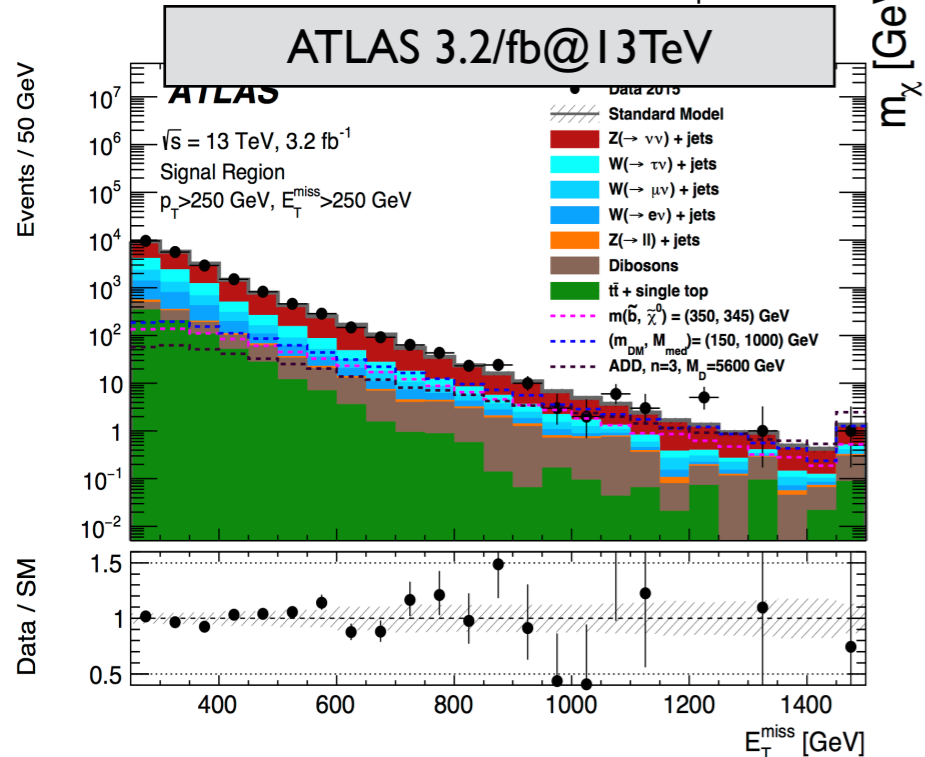
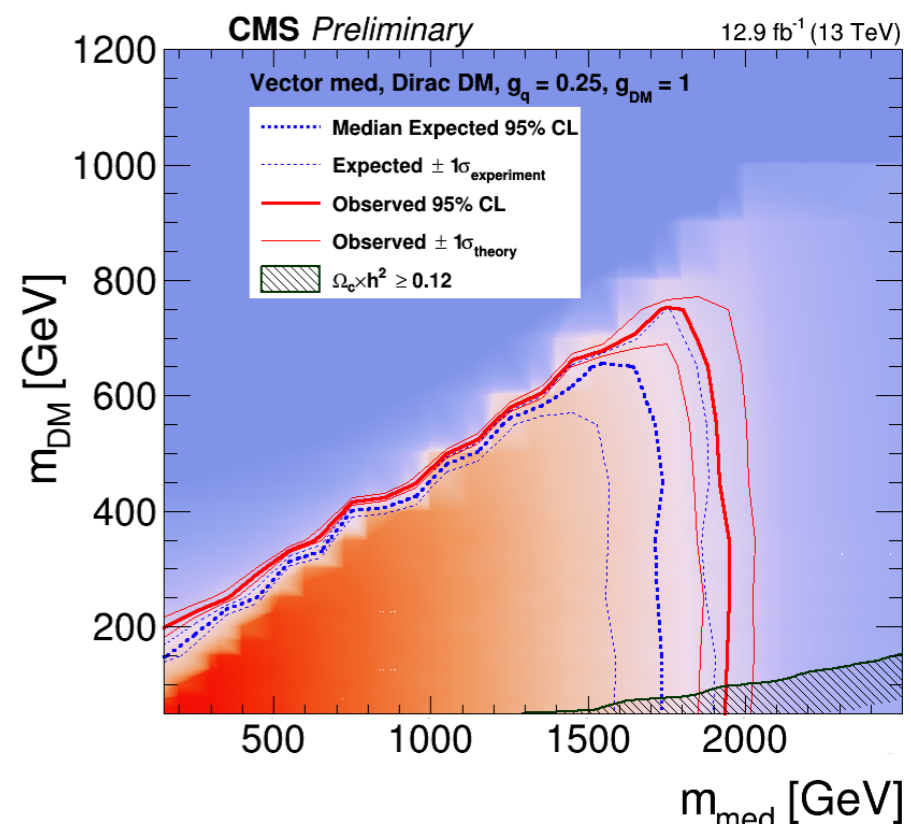
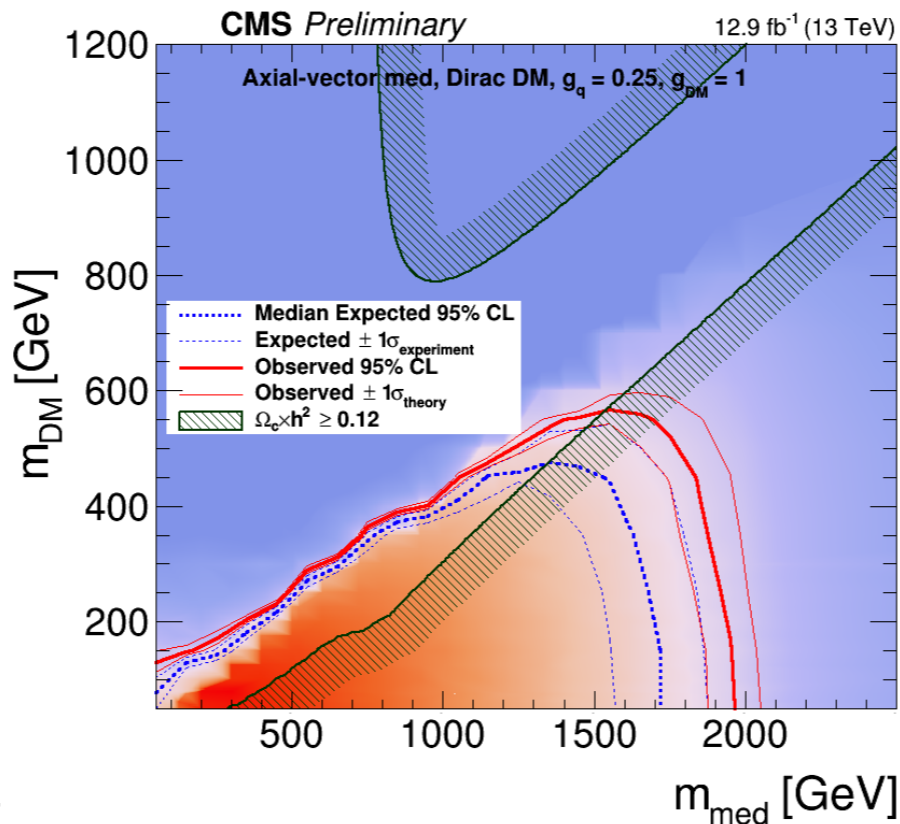
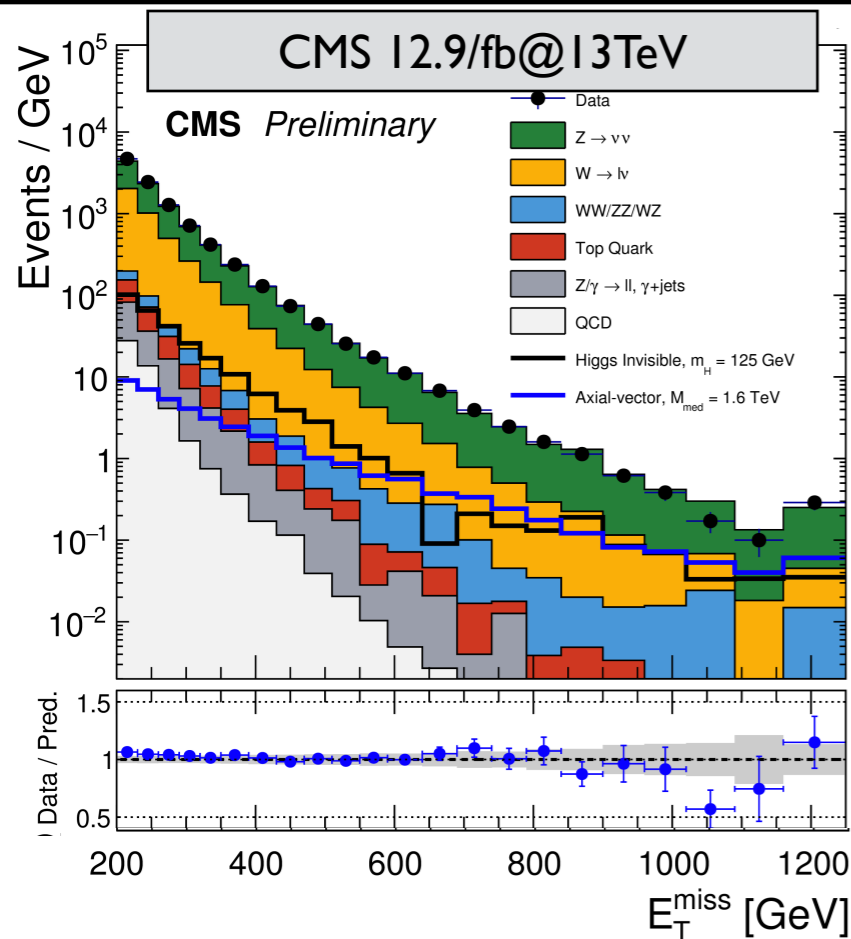


Signature	ATLAS	CMS
MET + Jets	<u>EXOT-2015-03</u>	<u>PAS EXO-16-037</u> 
MET + $\gamma$	<u>EXOT-2015-05</u>	<u>PAS EXO-16-039</u> 
MET + Z( $\ell\ell$ )	<u>ATLAS-CONF-2016-056</u> 	<u>PAS EXO-16-010, PAS EXO-16-038</u> 
MET + W/Z(qq)	<u>EXOT-2015-08</u> 	<u>PAS EXO-16-037</u> 
MET + Higgs	<u>EXOT-2015-23, ATLAS-CONF-2016-087, ATLAS-CONF-2015-059</u> 	<u>PAS EXO-16-011, PAS EXO-16-012</u> 
MET + ttbar	<u>ATLAS-CONF-2016-077, ATLAS-CONF-2016-050, ATLAS-CONF-2016-076</u> 	<u>PAS EXO-16-005</u> 
MET + top		<u>PAS EXO-16-040</u> 
MET + b-jets	<u>ATLAS-CONF-2016-086</u> 	<u>PAS B2G-15-007</u>

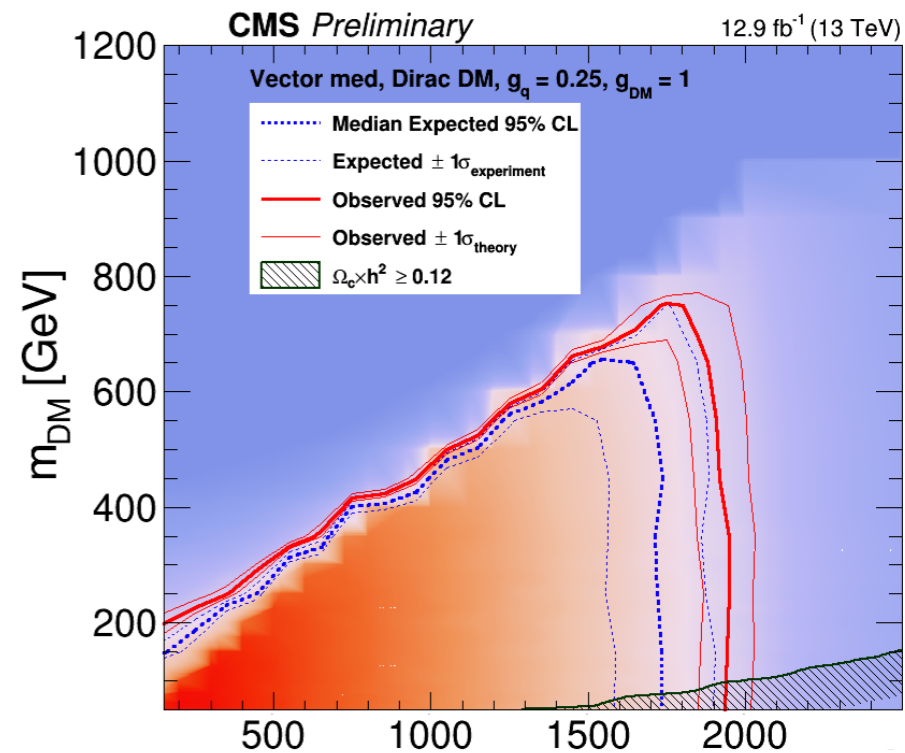
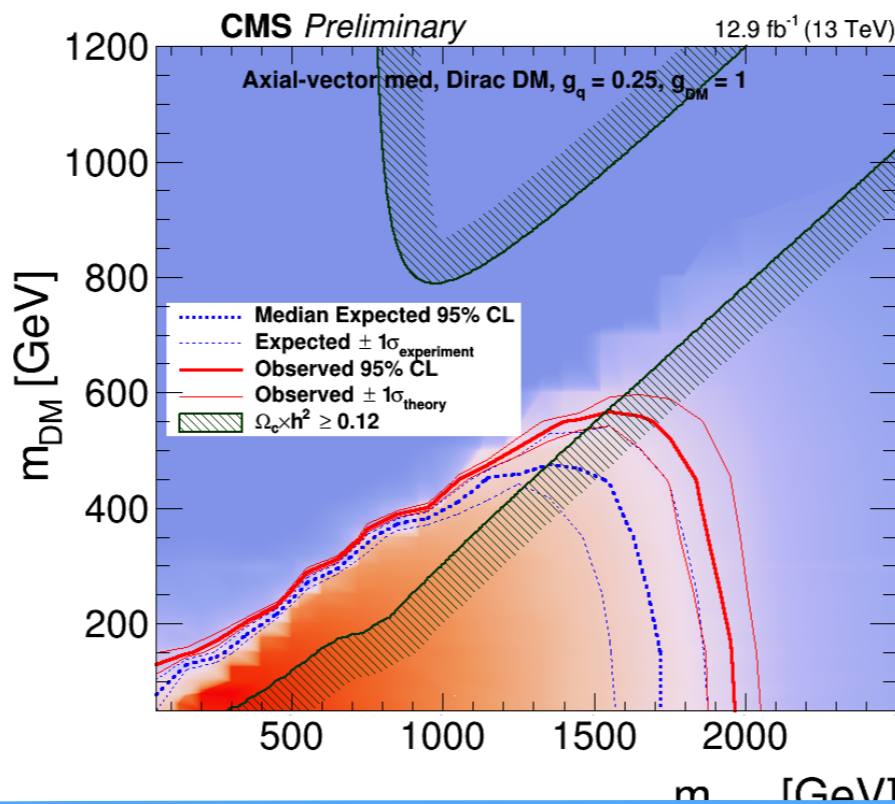
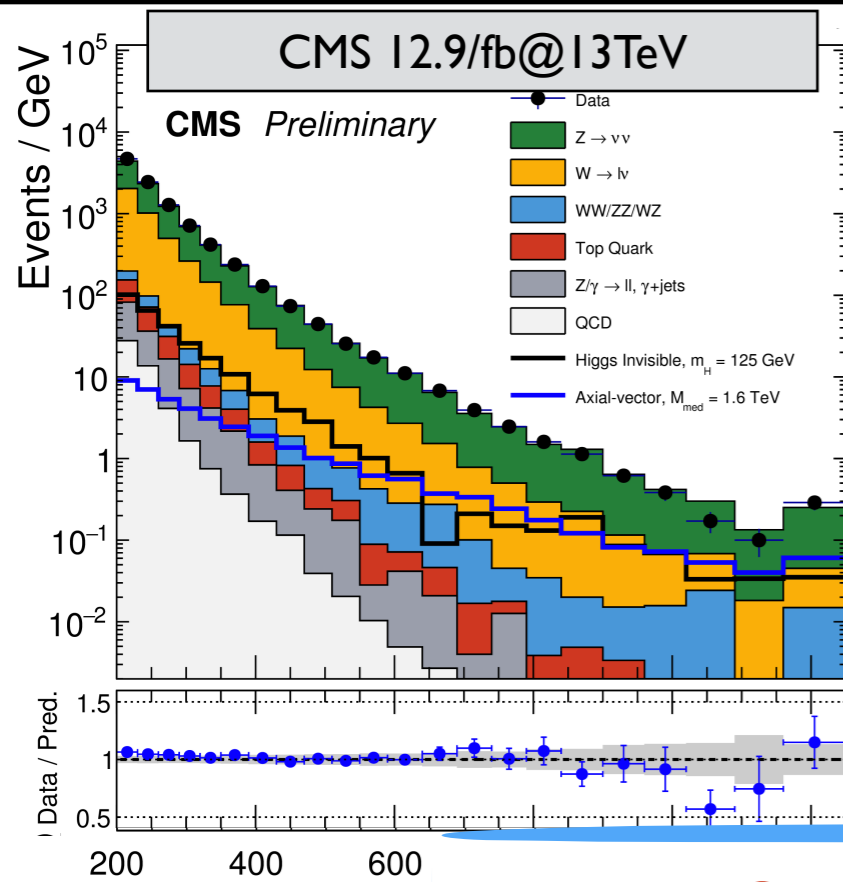


- ▶ Primary backgrounds in most Dark Matter searches
  - ▶ Z(νν) + X and W(lν) + X (charged lepton is lost in W case)
- ▶ Methods to estimate the backgrounds:
  - ▶ Low MET: use visible Z(lℓ)+X and W(lν)+X
    - ▶ Dominant systematics: lepton reconstruction efficiency
  - ▶ High MET: use γ+X and theoretically predicted ratio of processes
    - ▶ Dominant systematics: NLO EWK effects

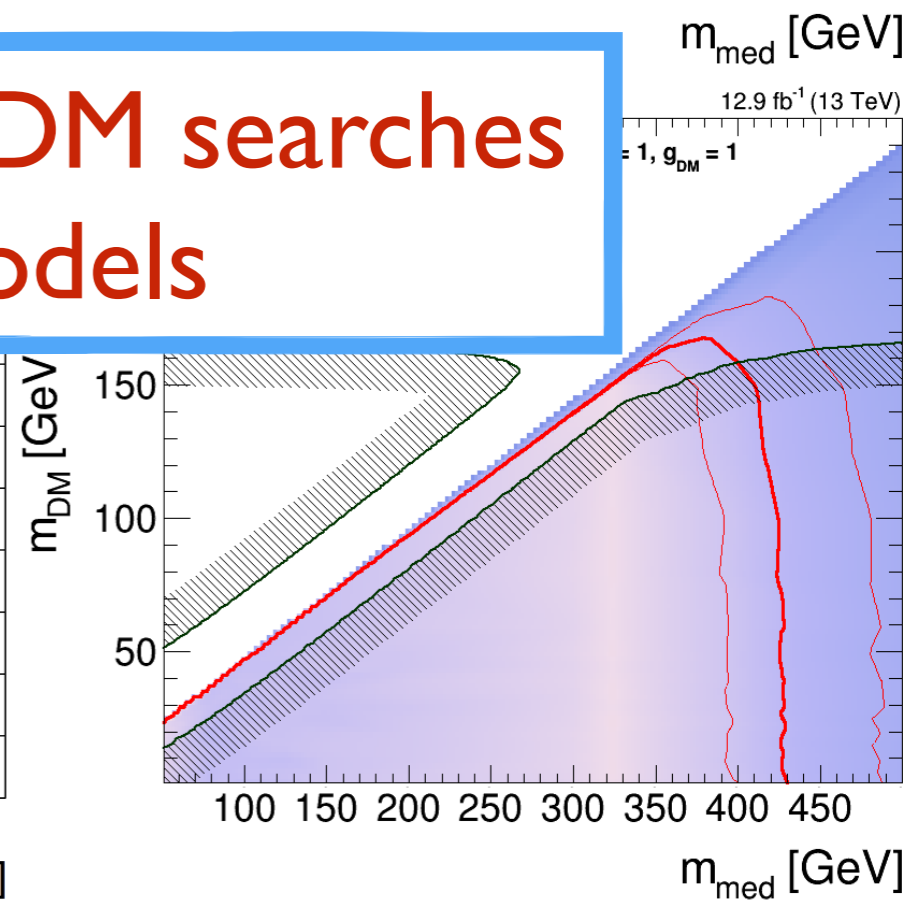
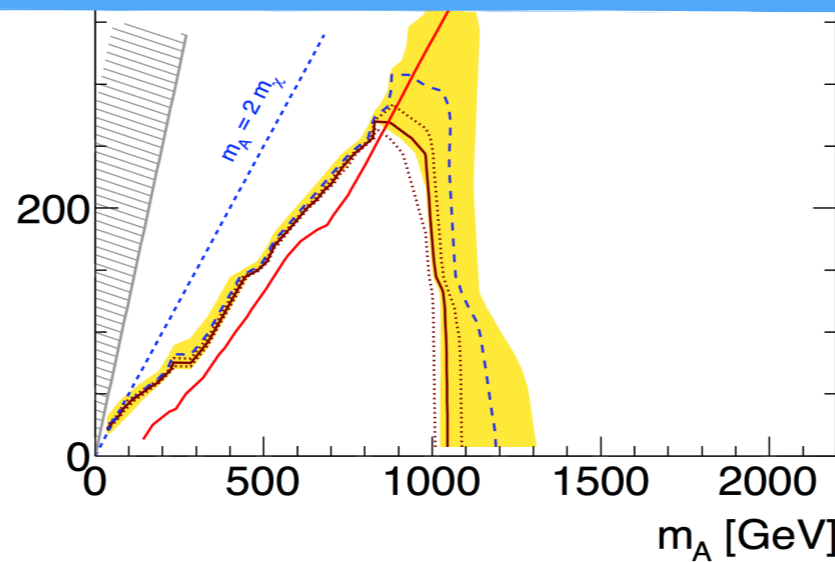
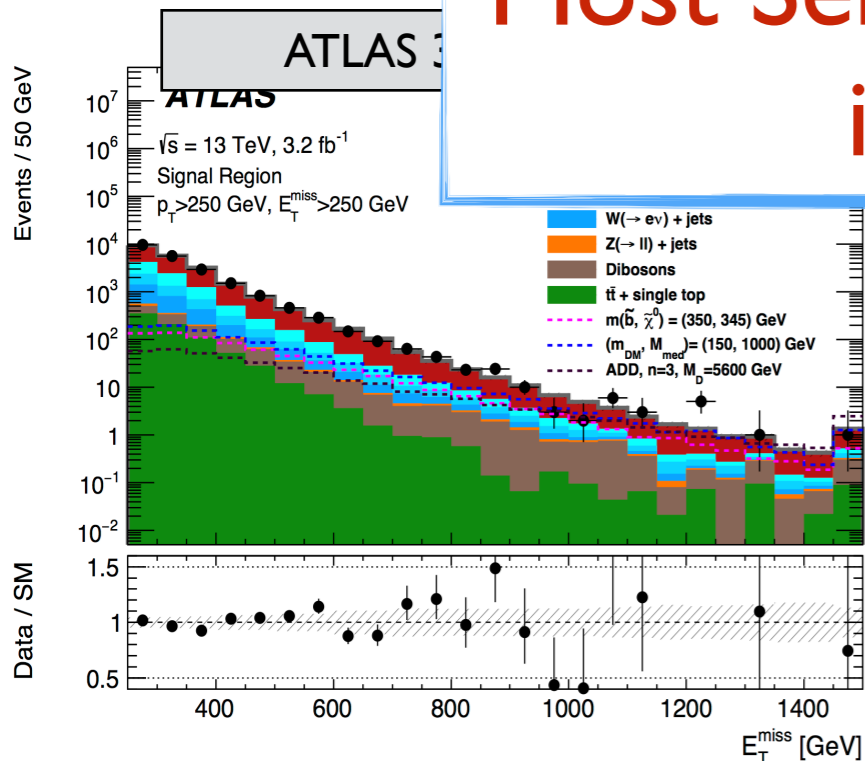
# MET + Jets

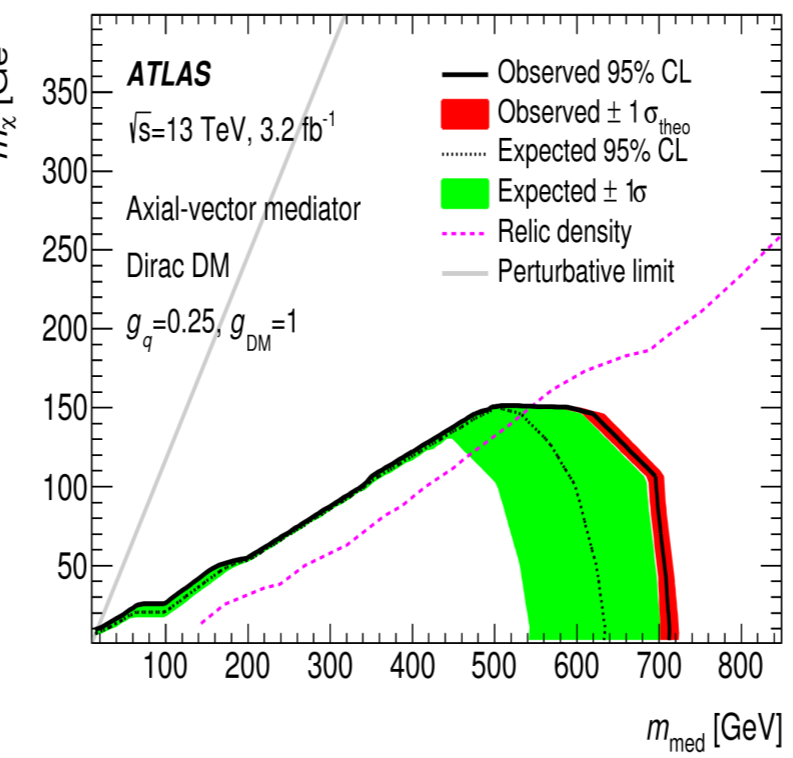
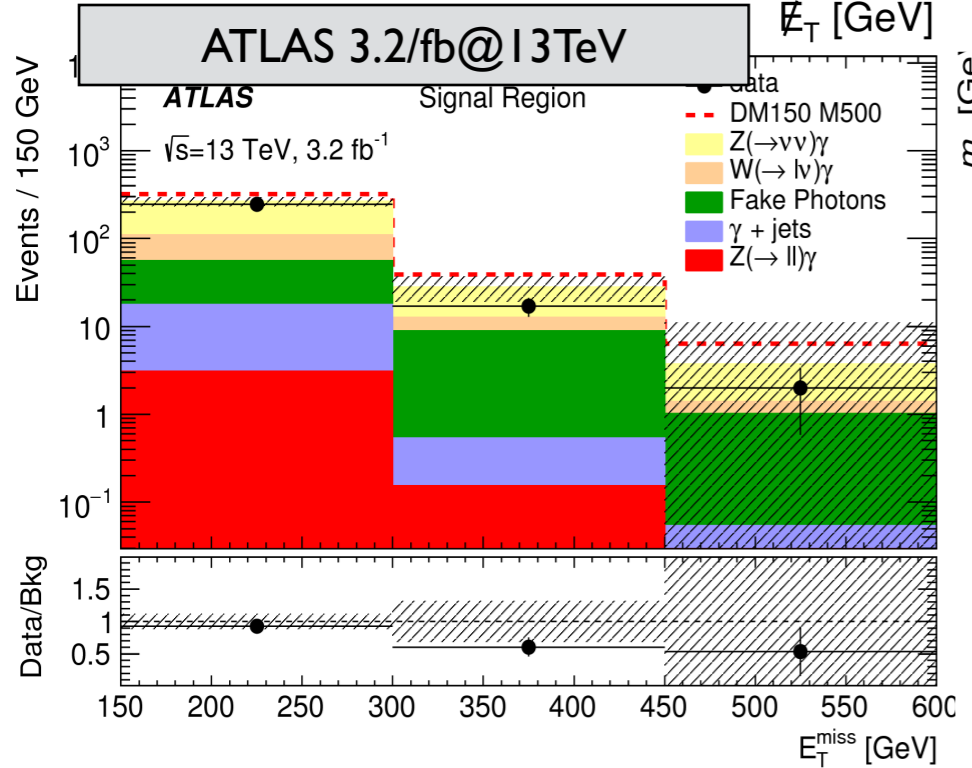
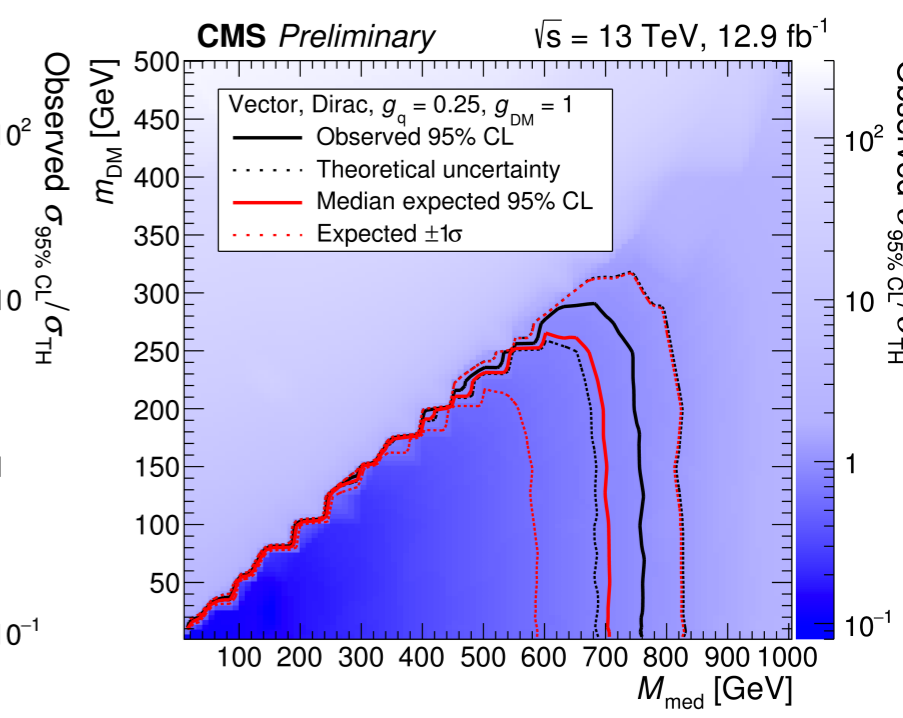
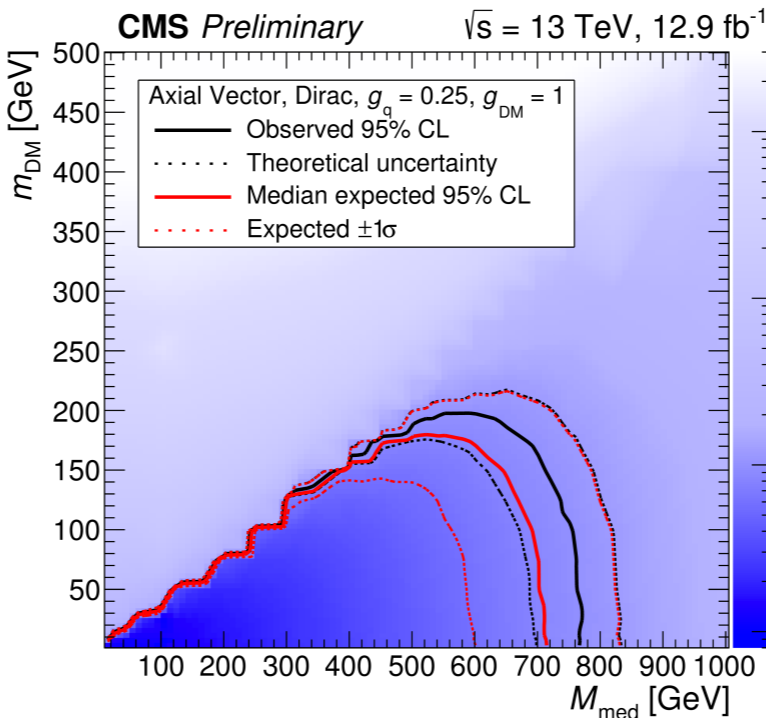
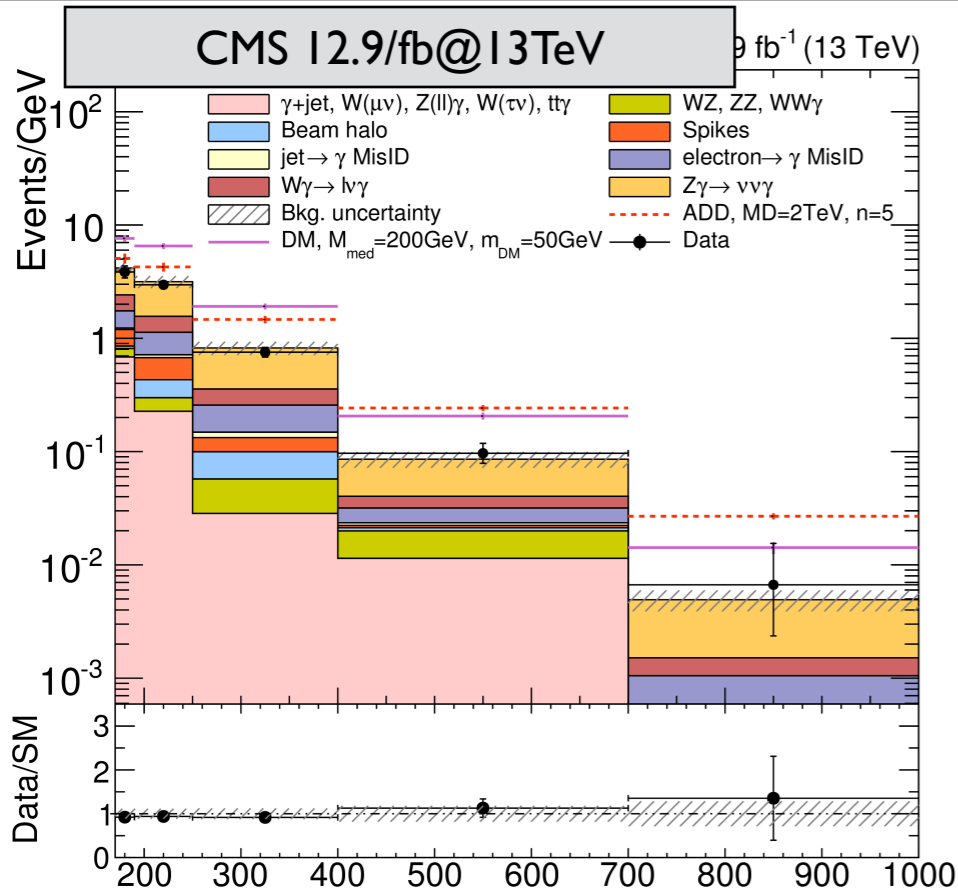






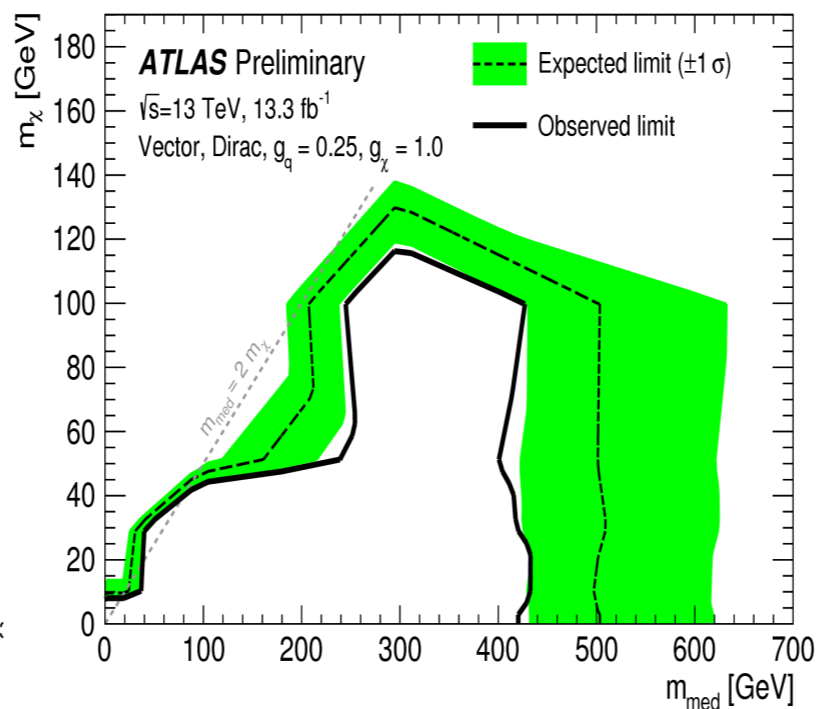
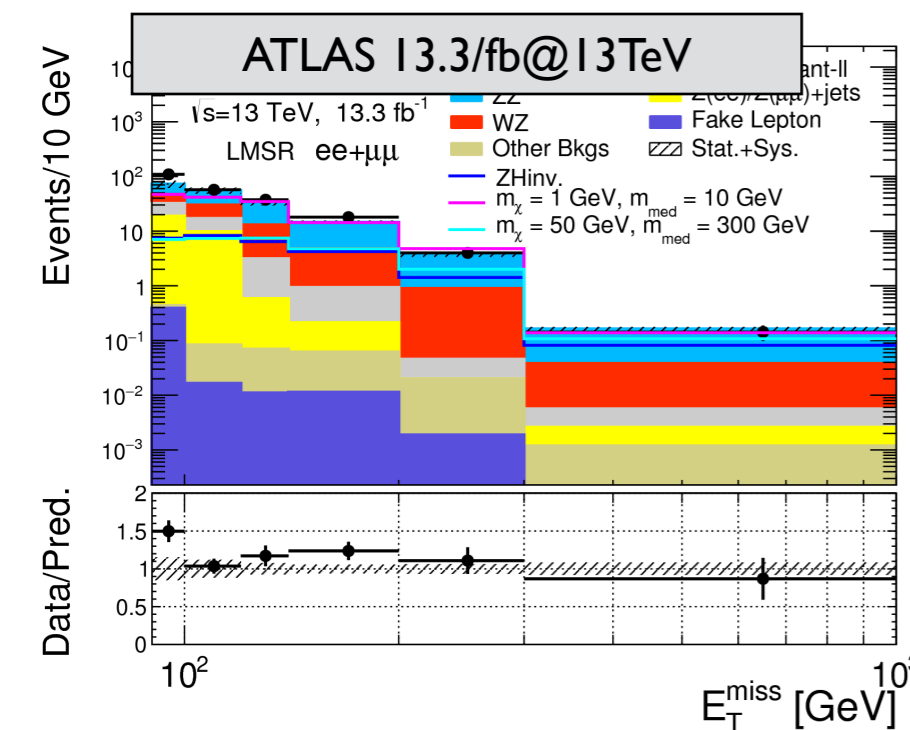
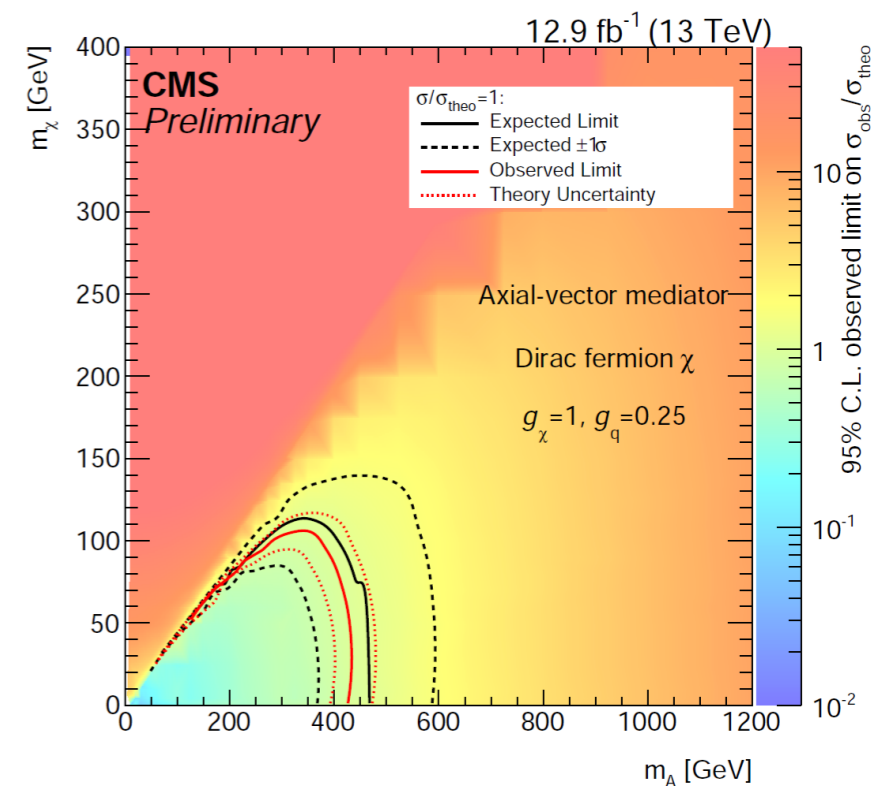
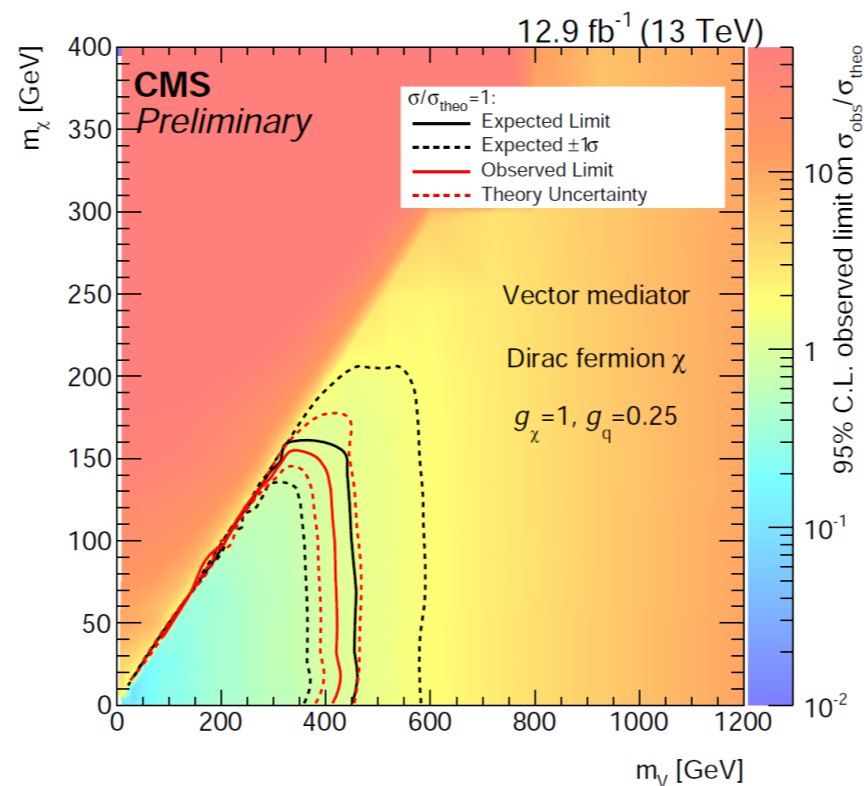
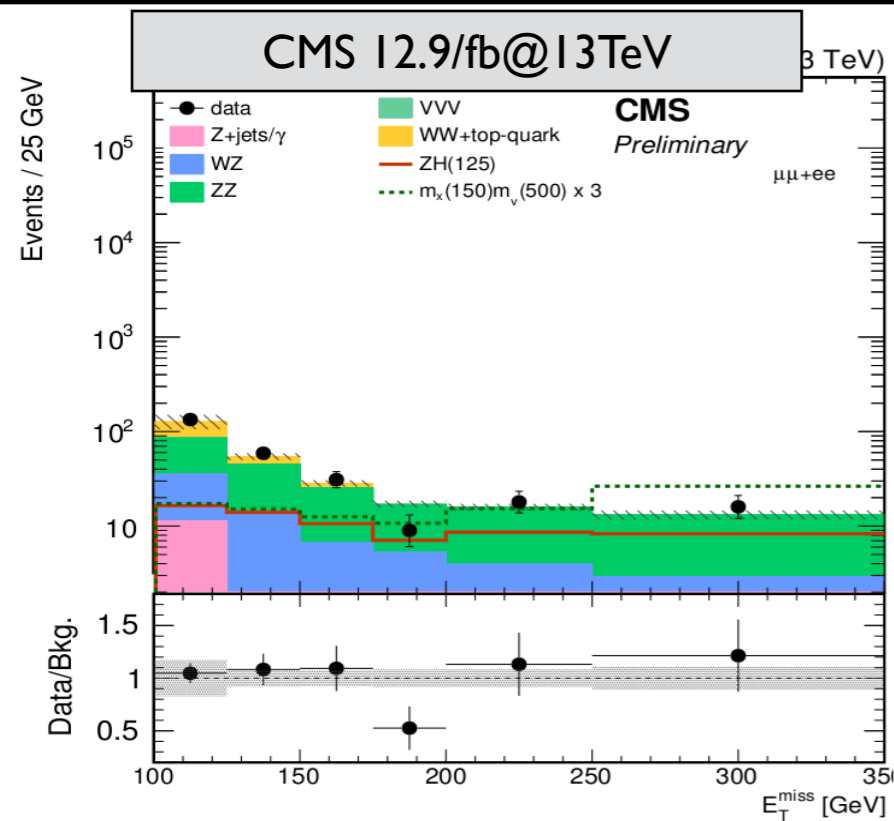
**Most Sensitive Channel for DM searches in a large class of models**





- ▶ Clean signature
- ▶ Fake photons can be an issue at higher luminosity
- ▶ Fake from noise or beam-halo create fake MET as well

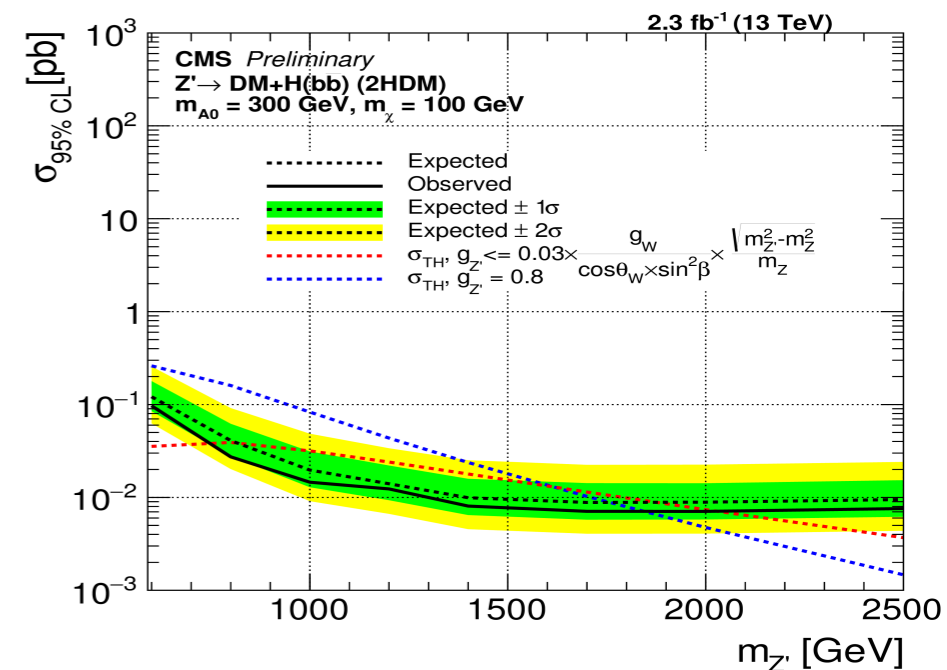
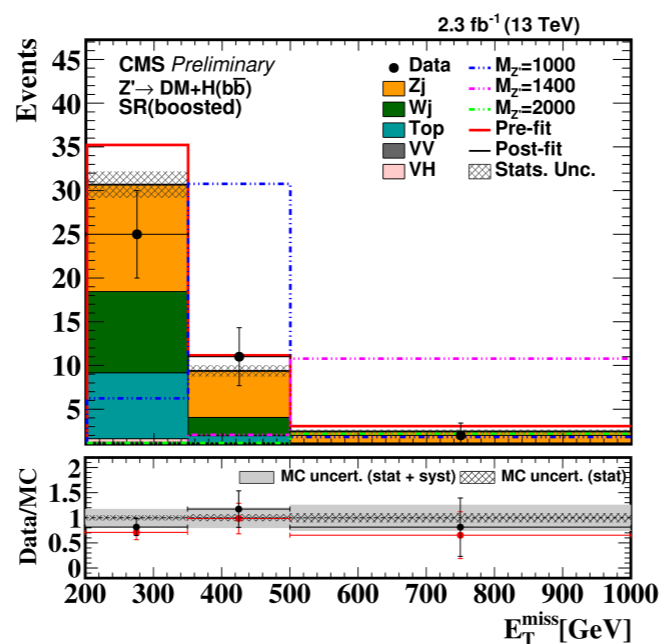
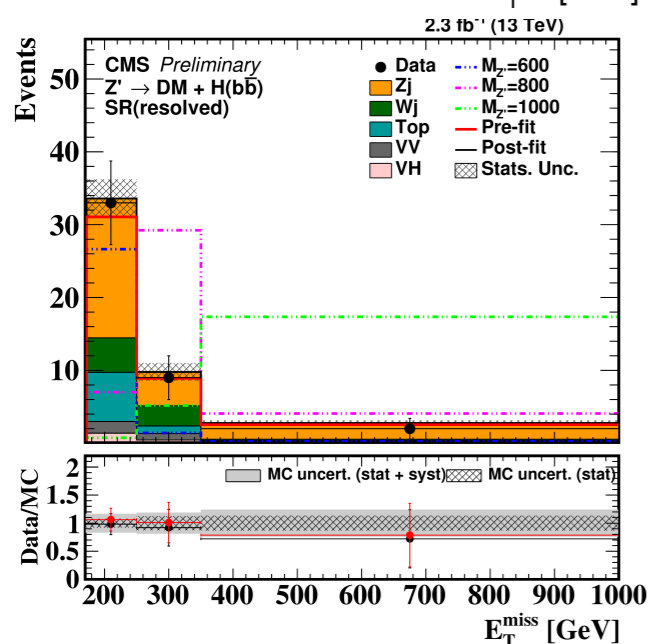
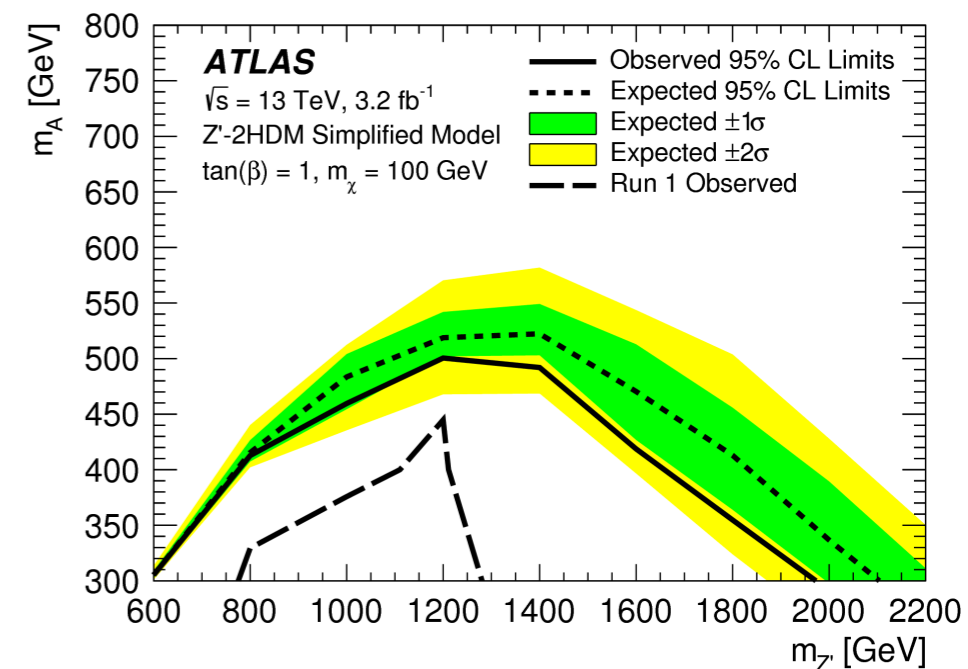
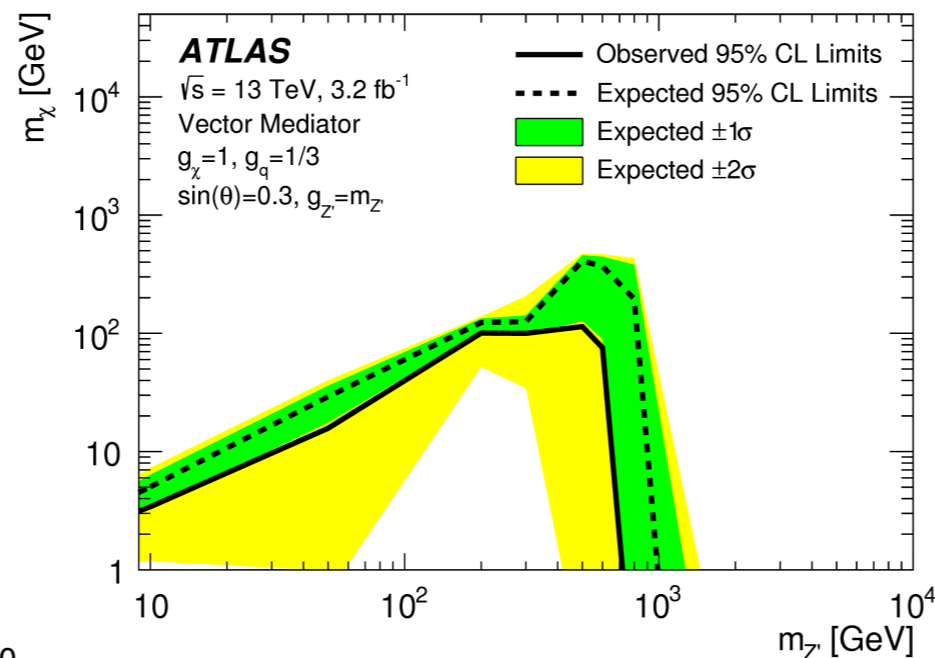
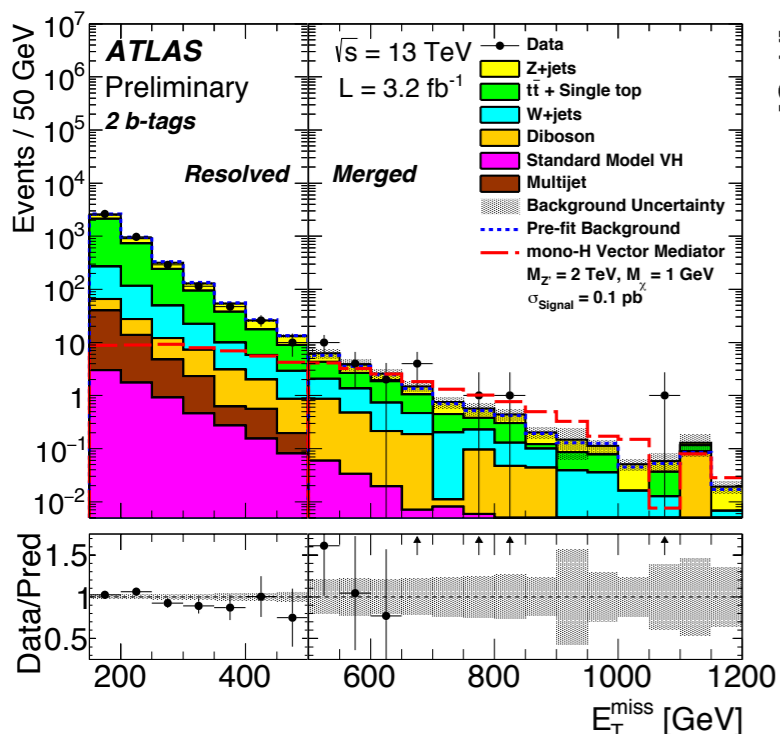
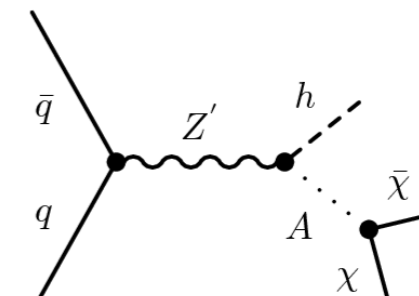
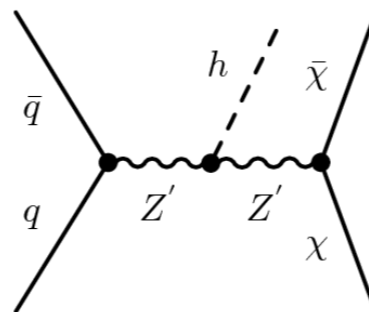
# MET + Z( $\ell\ell$ )



- ▶ Clean channel especially at high MET
- ▶ Low MET region gets a contribution from fake MET in Z+jets events
- ▶ Comparable sensitivity between ATLAS and CMS

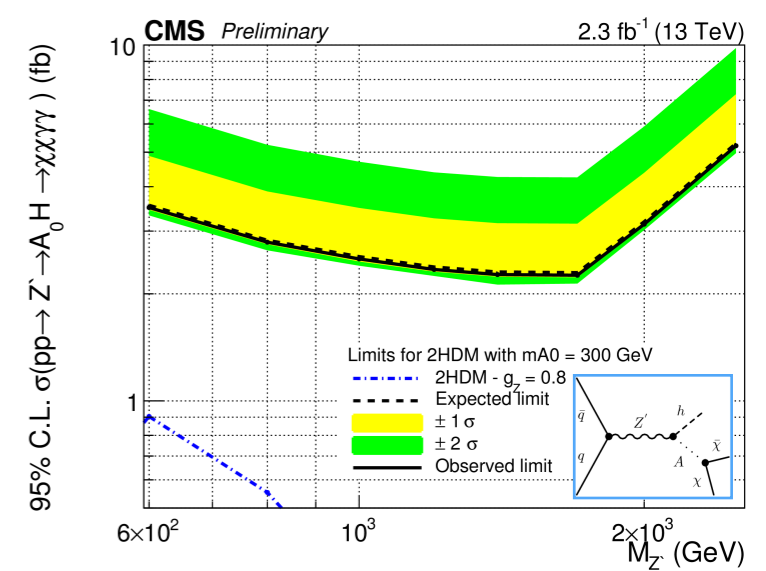
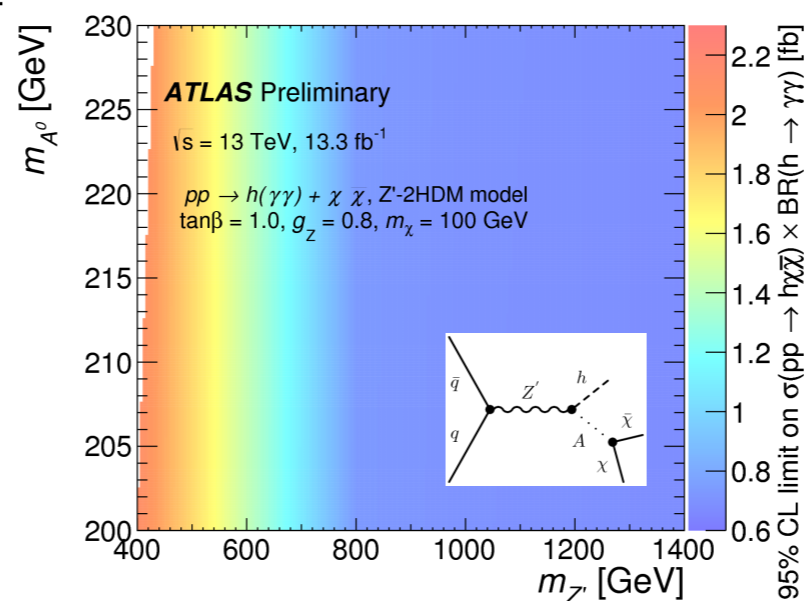
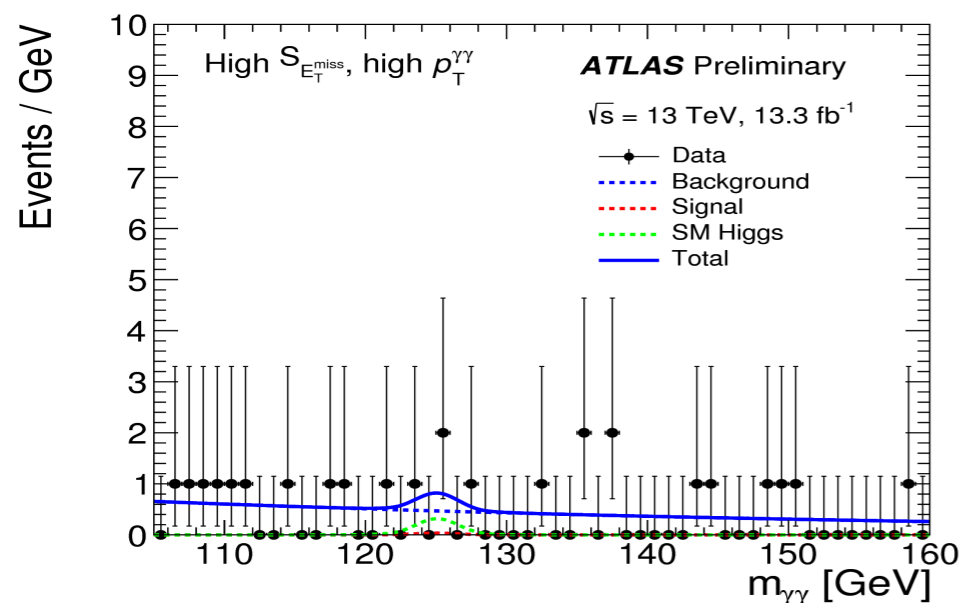
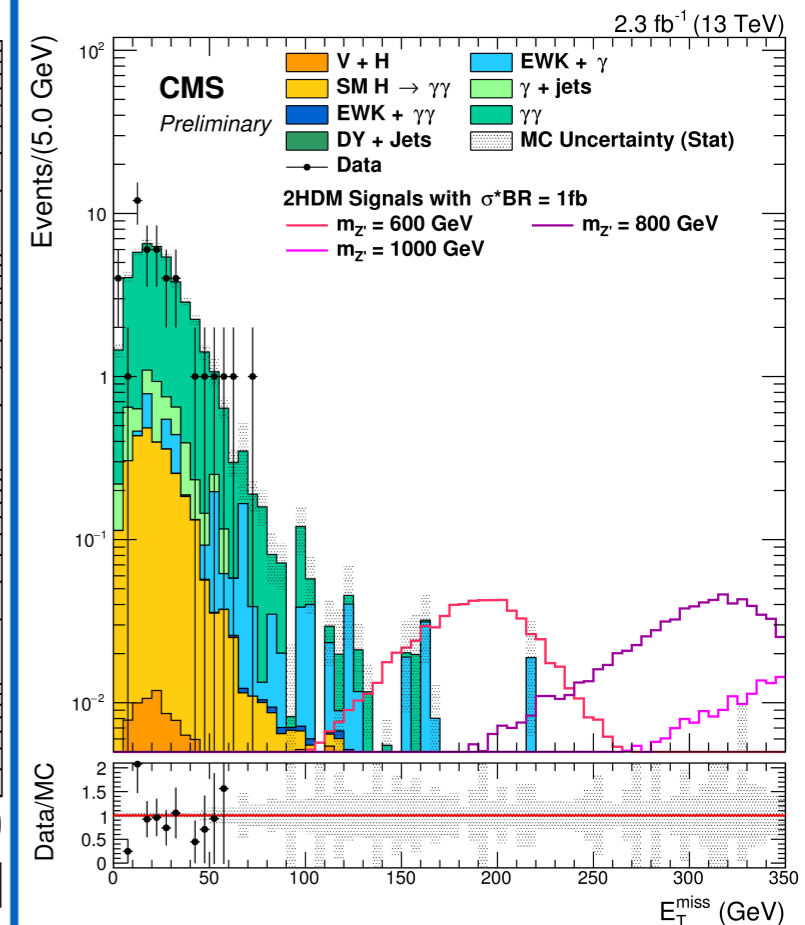
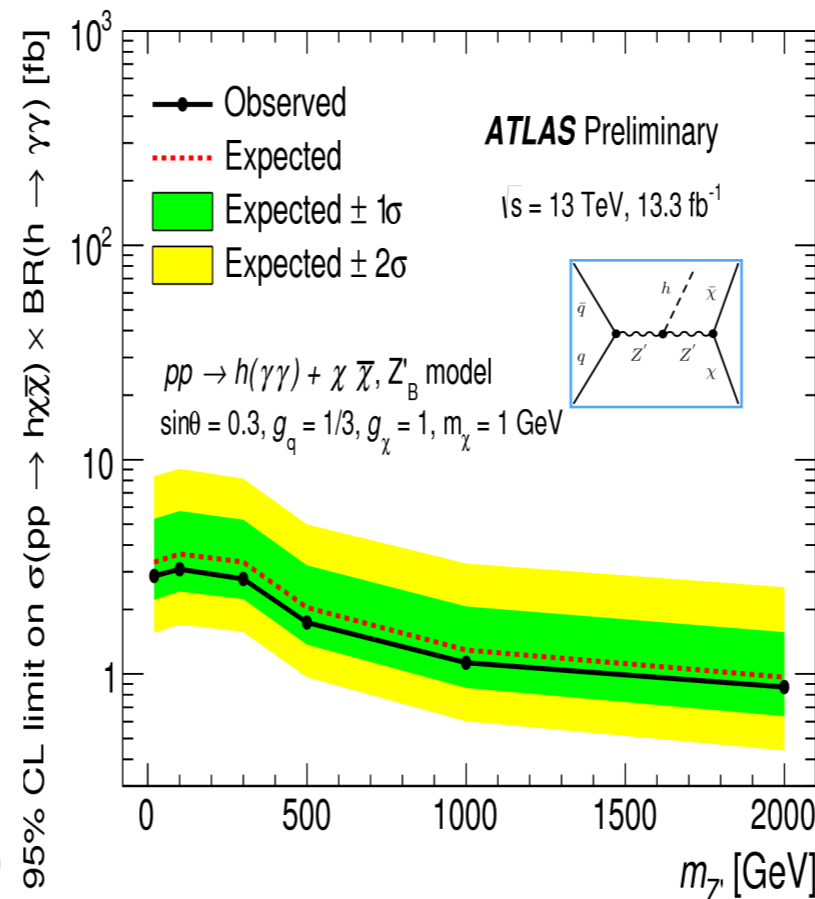
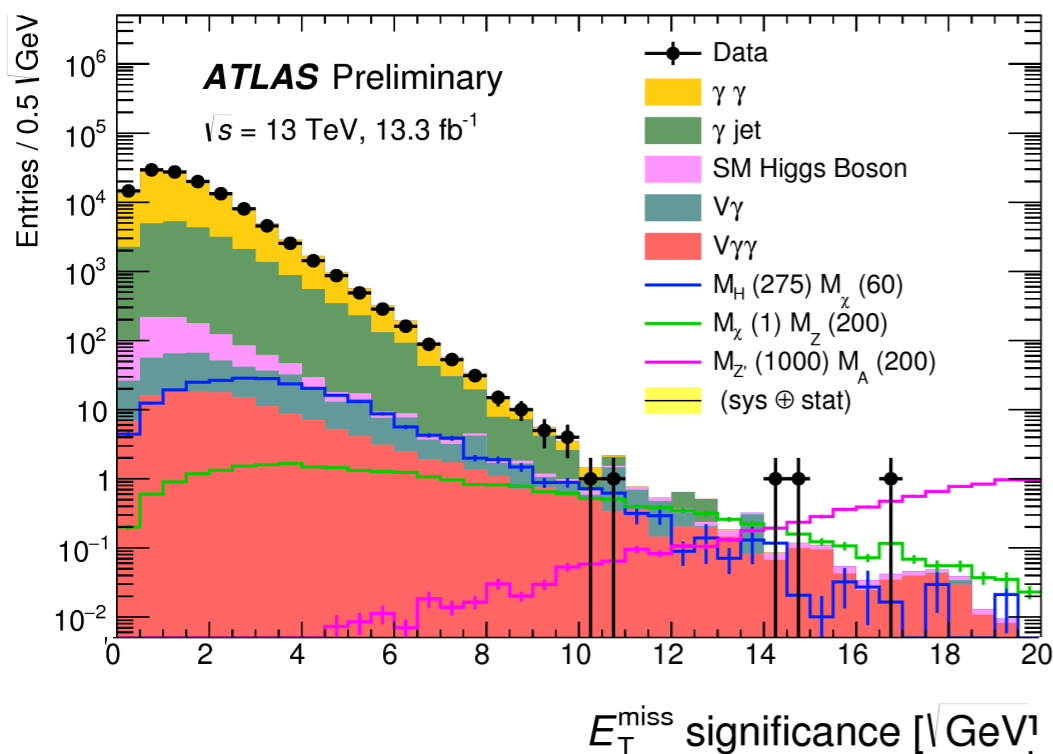
# MET + Higgs(bb)

- ▶ Different production mechanism
  - ▶ ISR-like production is Yukawa-suppressed
- ▶  $H \rightarrow bb$  - highest cross-section



# MET + Higgs( $\gamma\gamma$ )

- ▶  $H \rightarrow \gamma\gamma$  - clean Higgs signal
- ▶ Dominant backgrounds are non-resonant
- ▶ Fit in  $M_{\gamma\gamma}$  spectrum to find signal

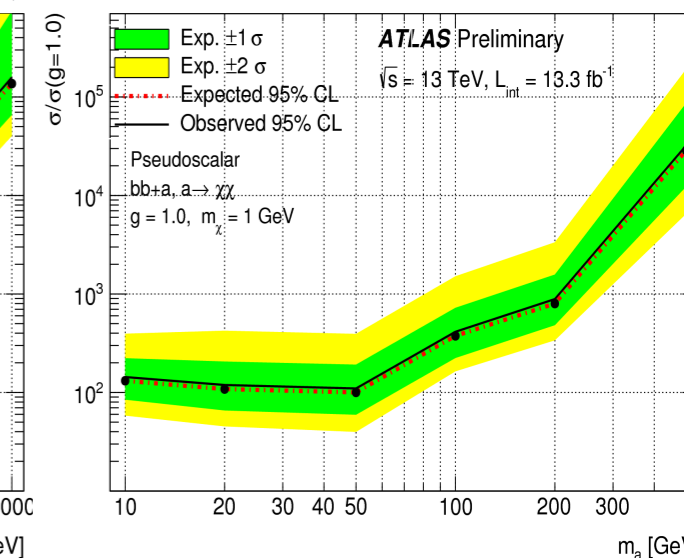
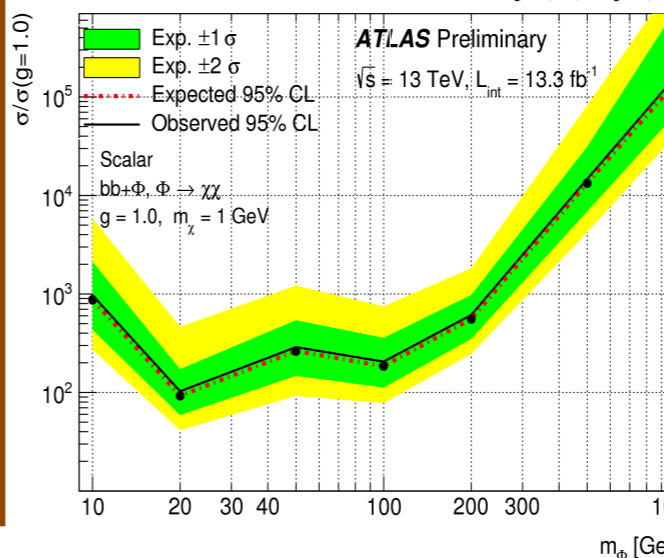
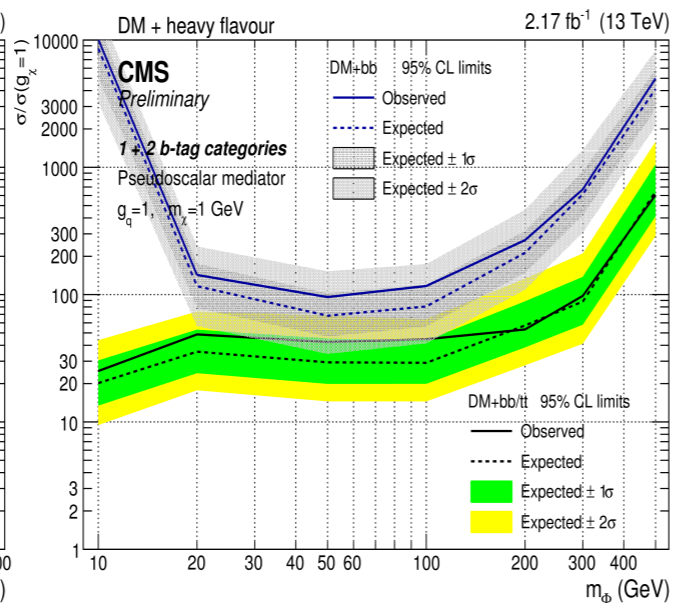
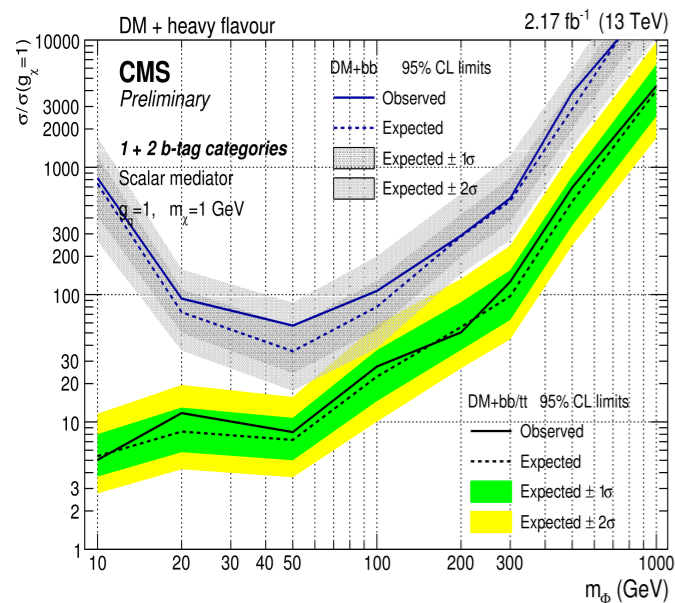
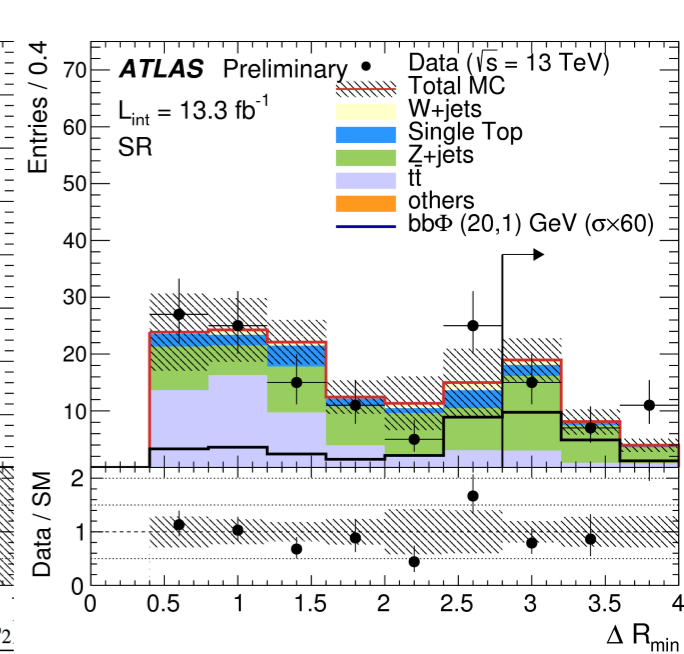
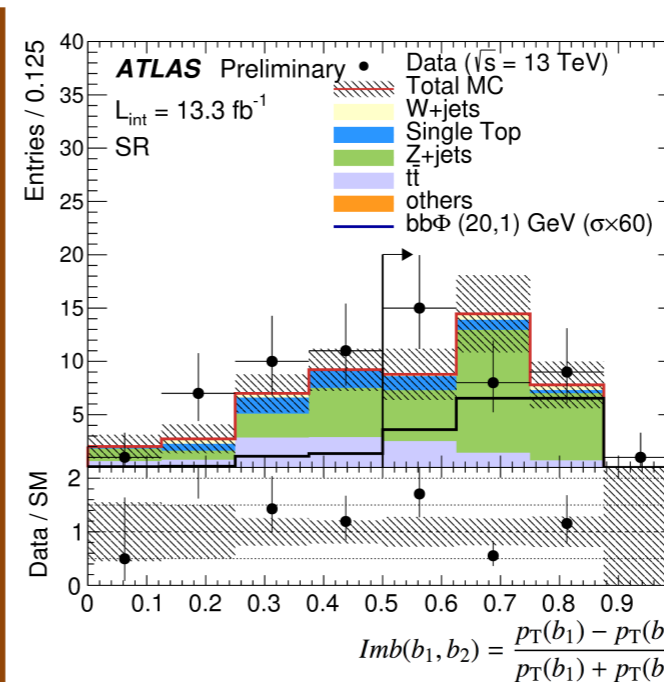
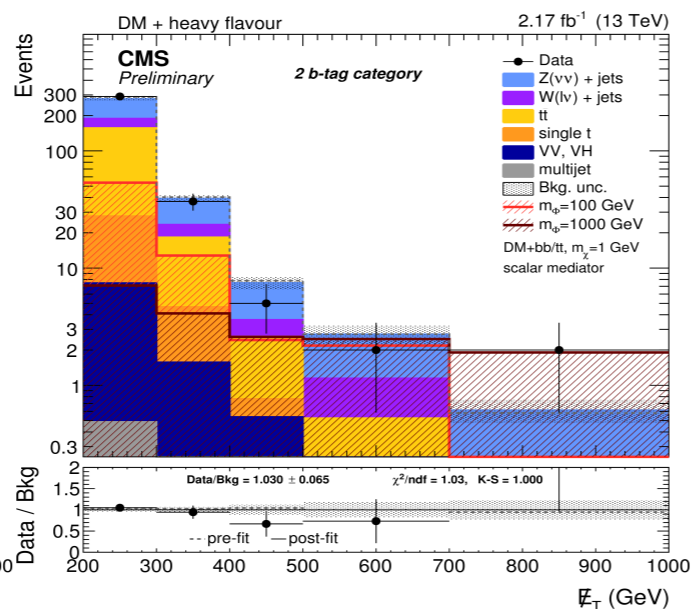
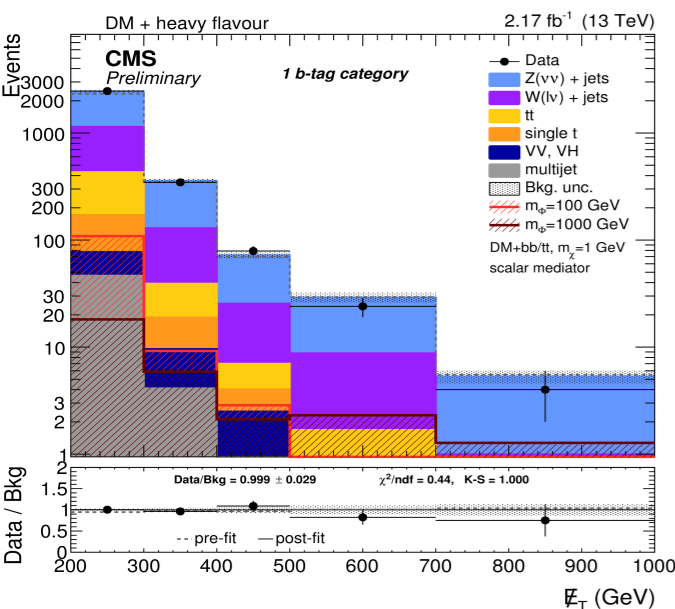
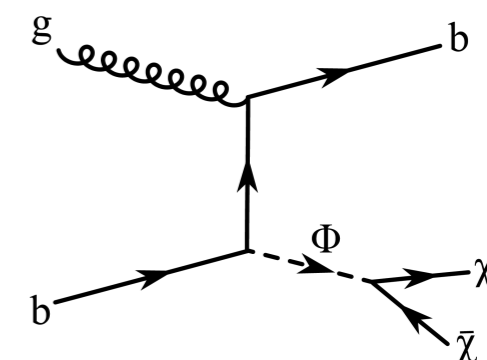
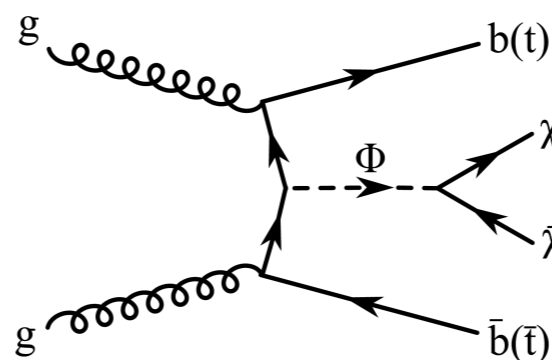


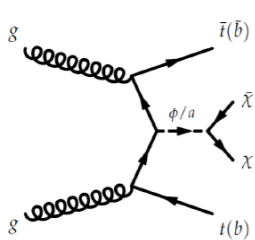
# MET + b-jets

► For Spin-0 mediator coupling to SM is most likely of Yukawa type

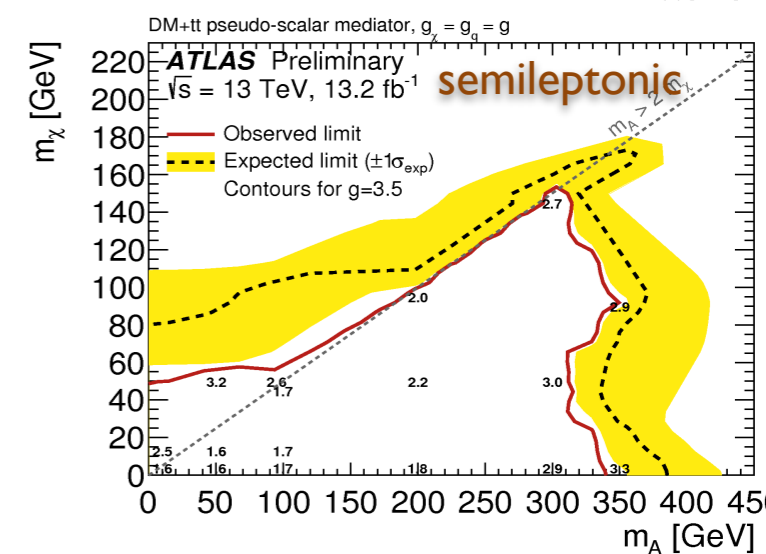
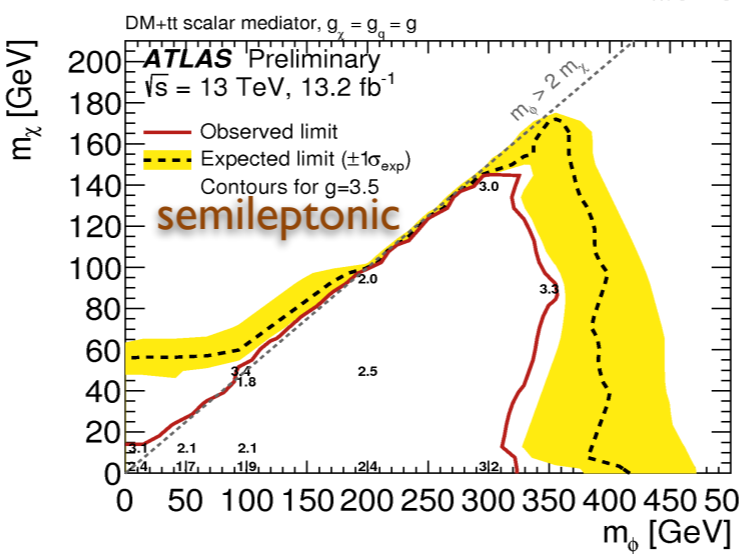
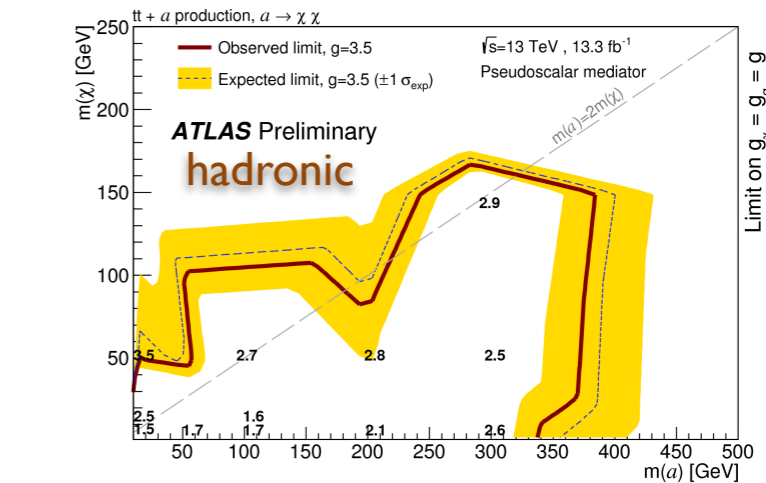
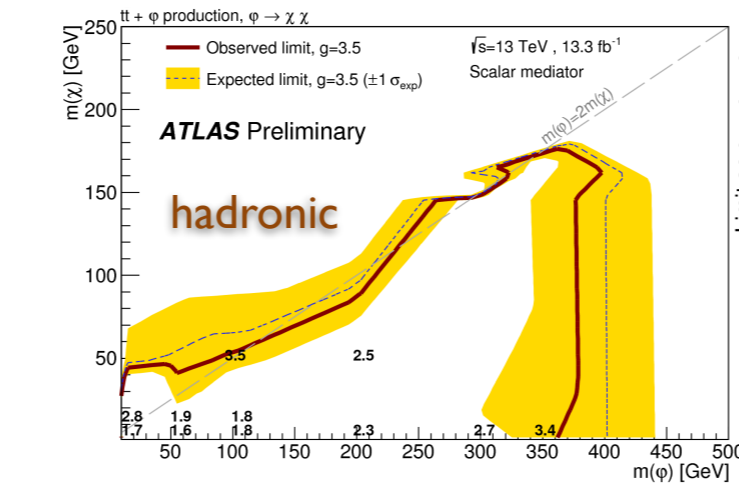
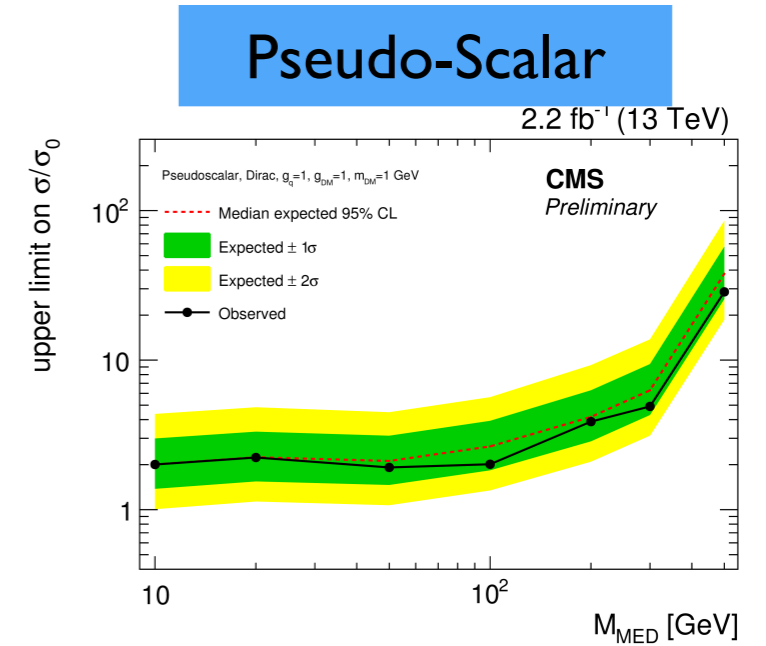
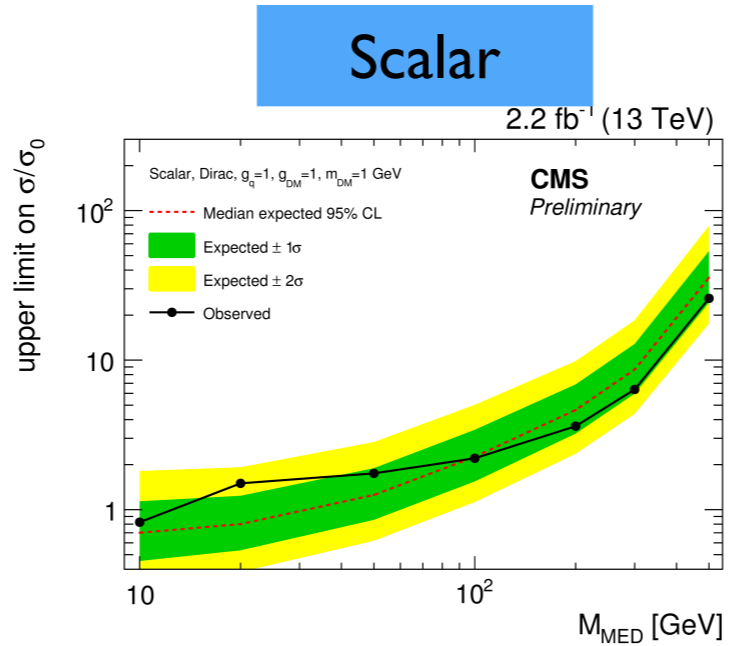
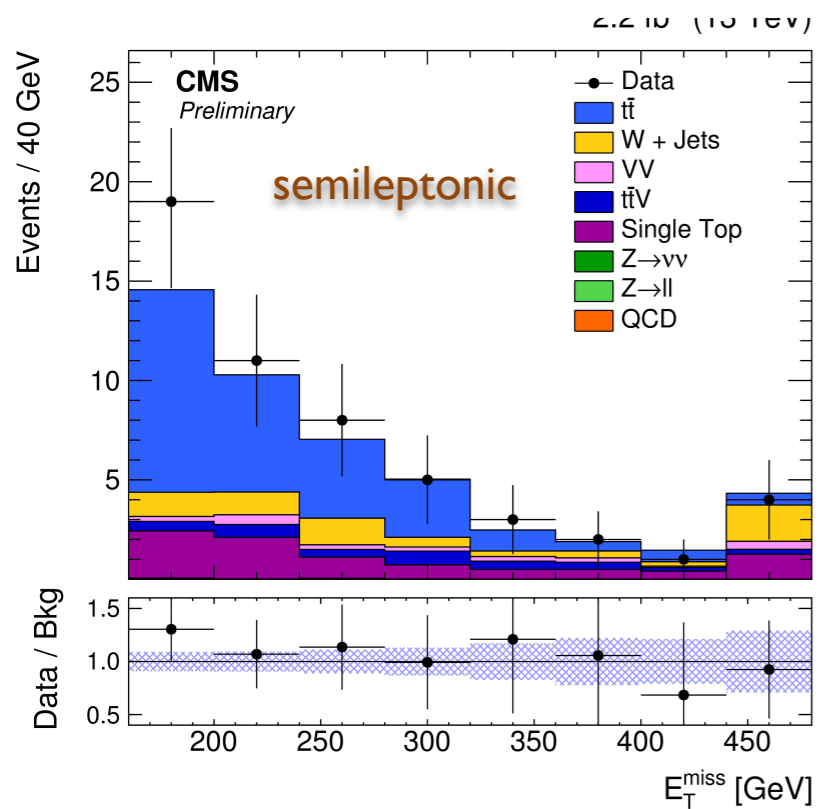
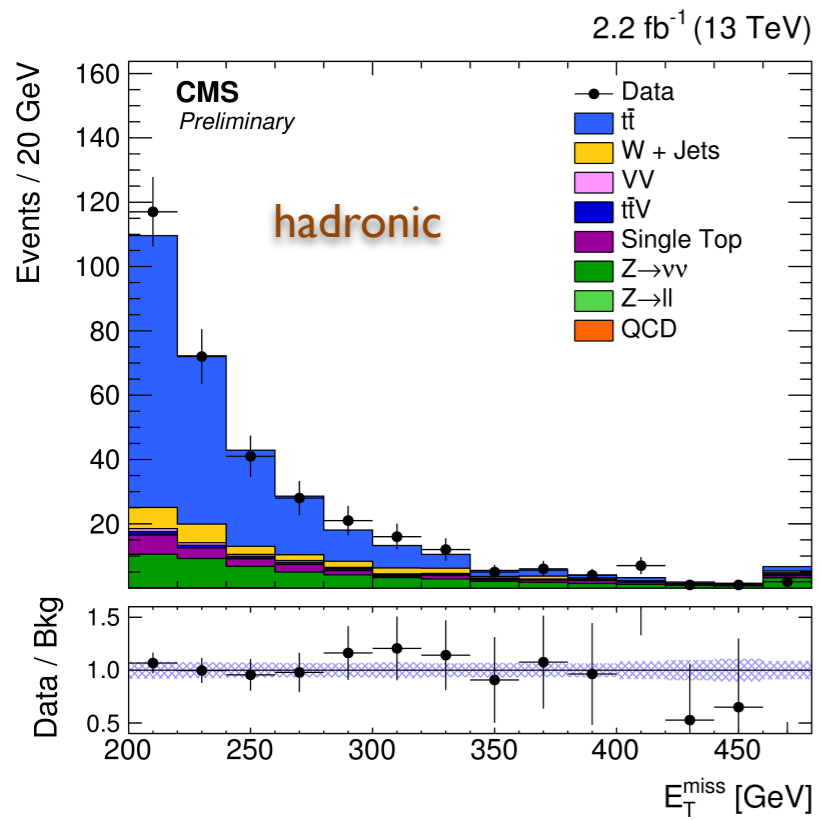
► Proportional to SM mass

► MET + heavy flavor quark → better sensitivity

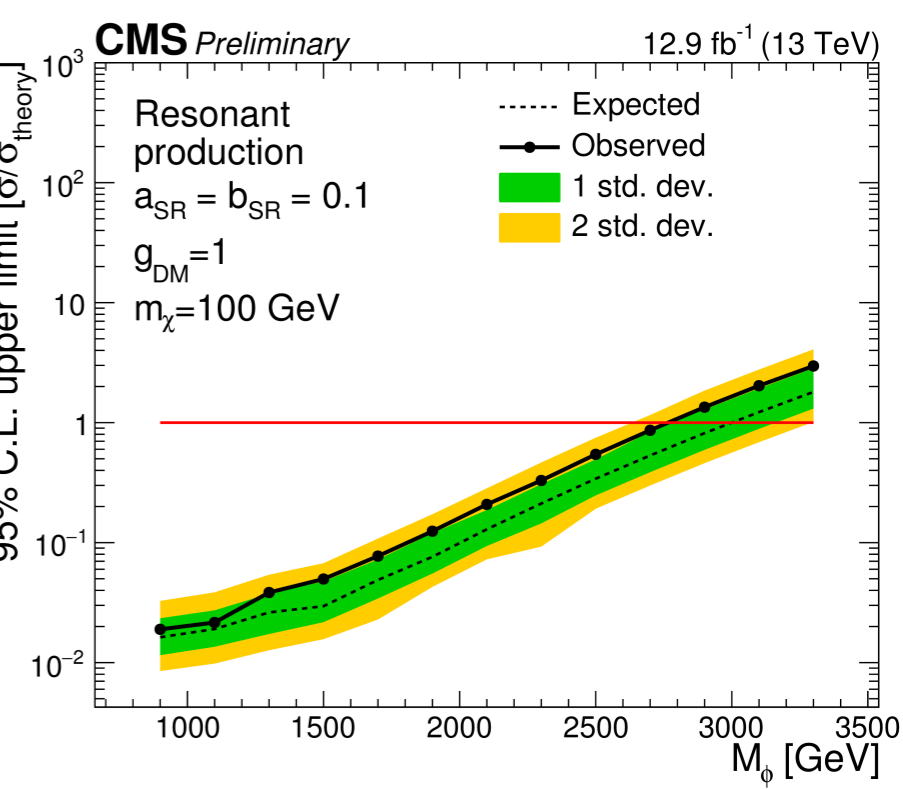
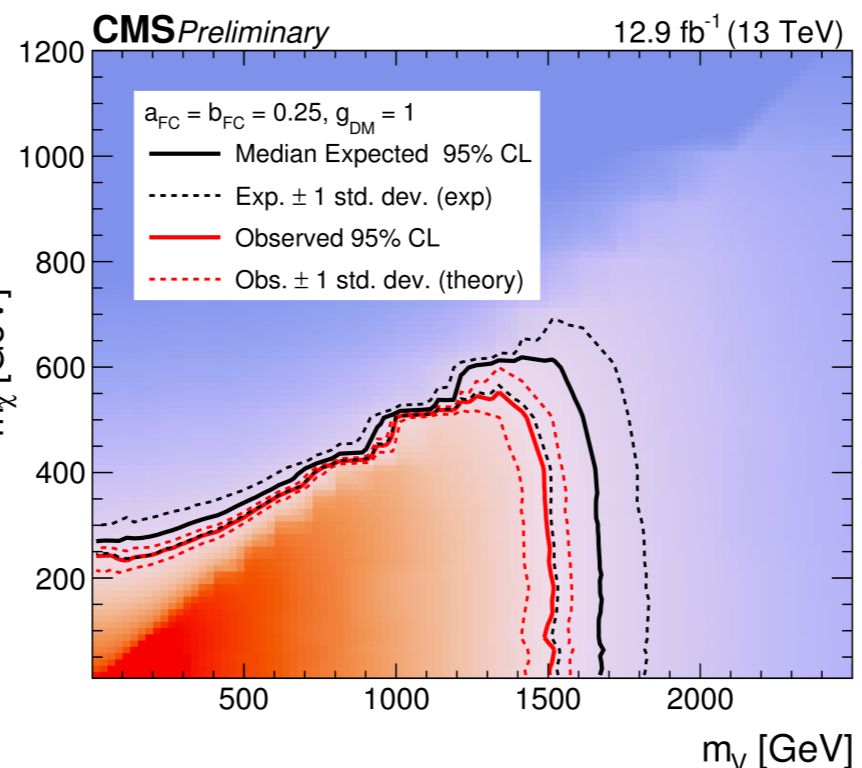
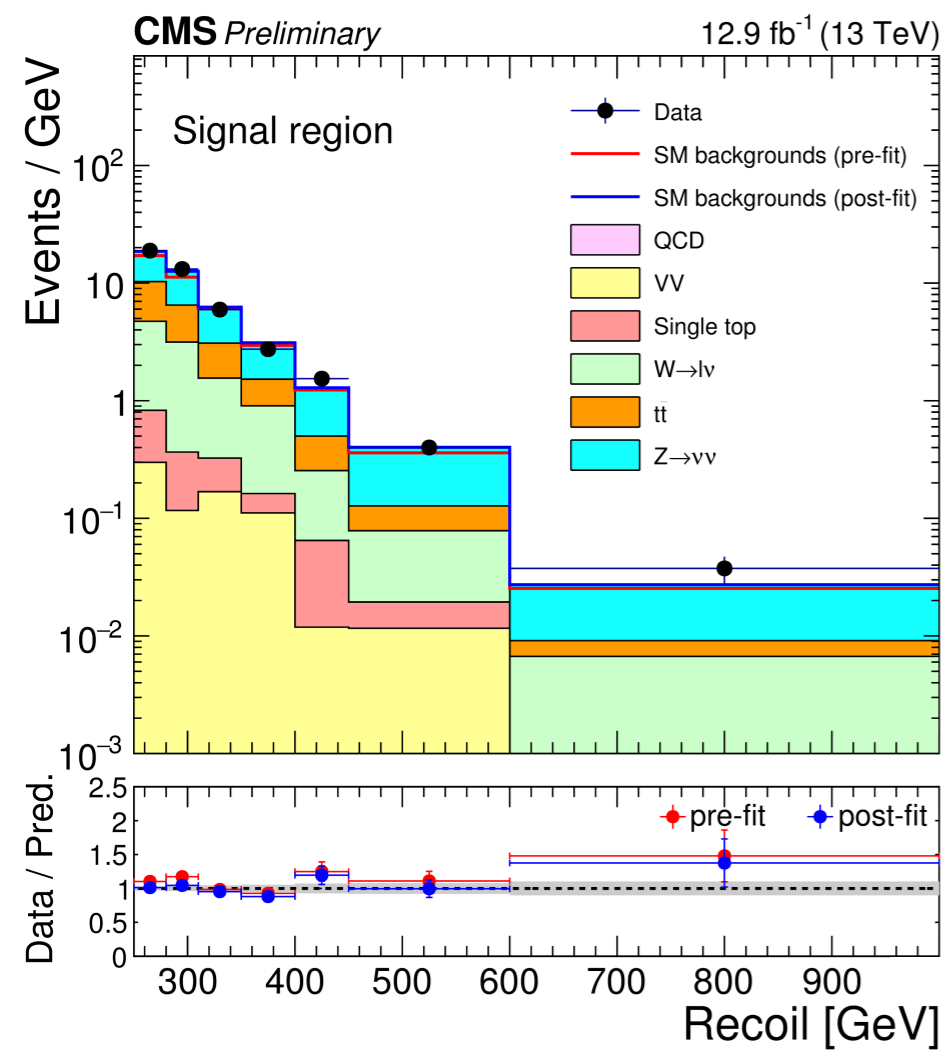
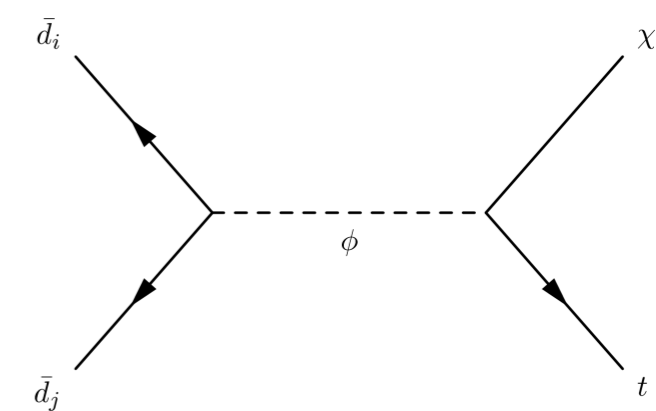
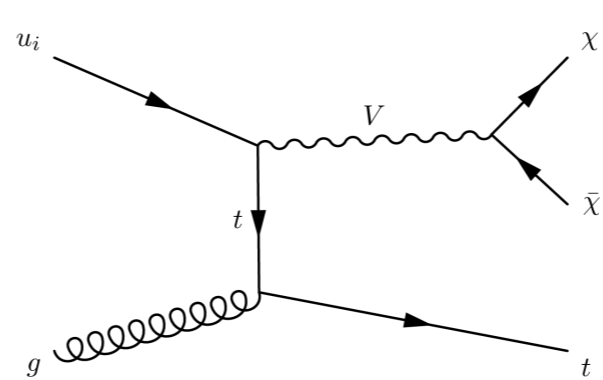
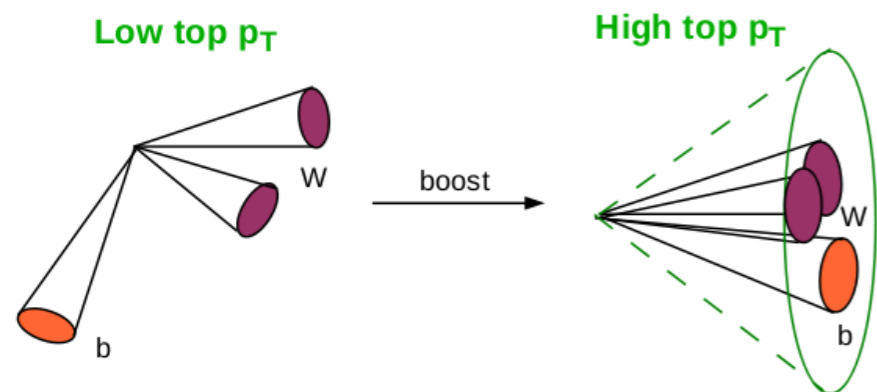




# MET + ttbar



# MET + Single Top

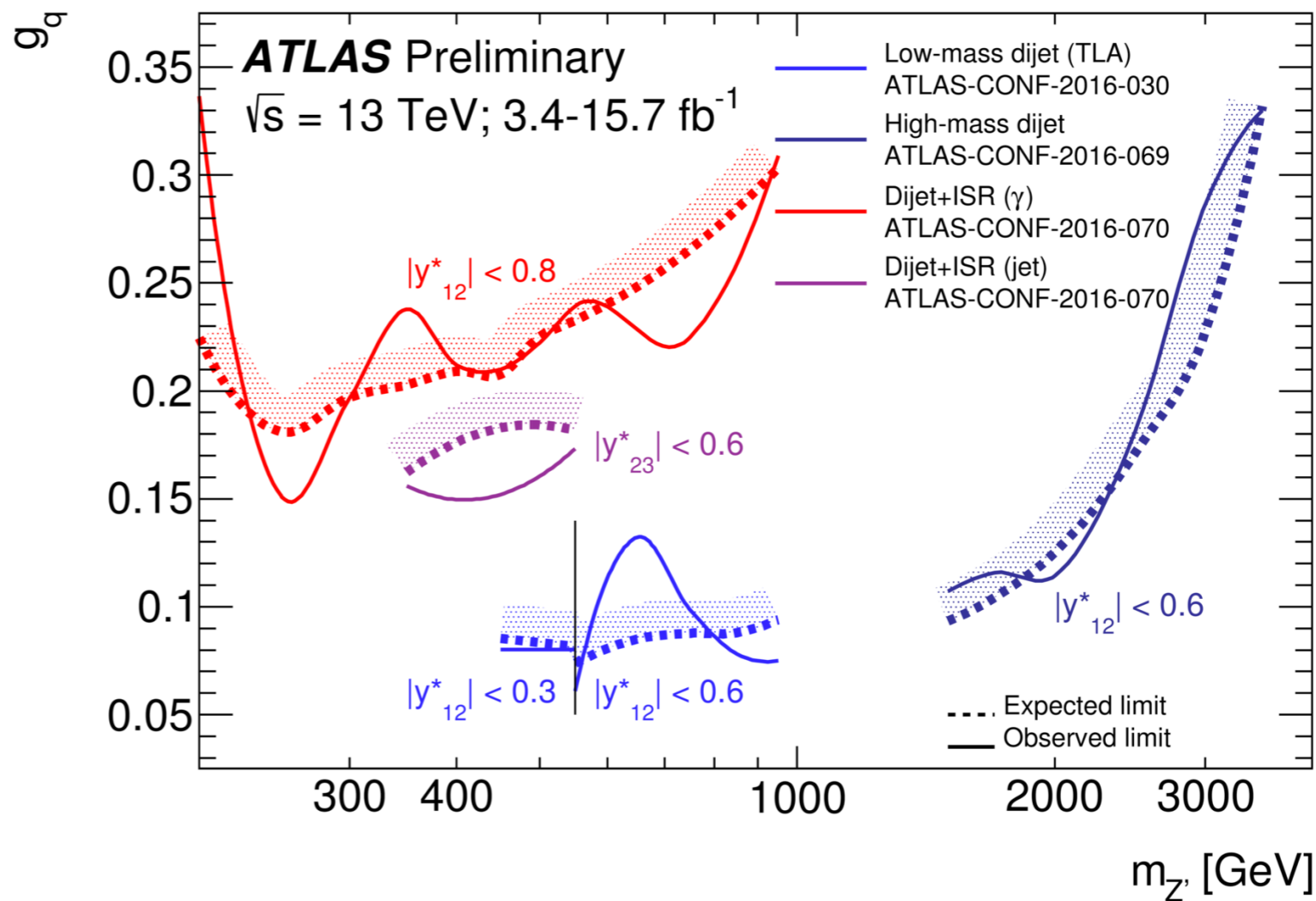
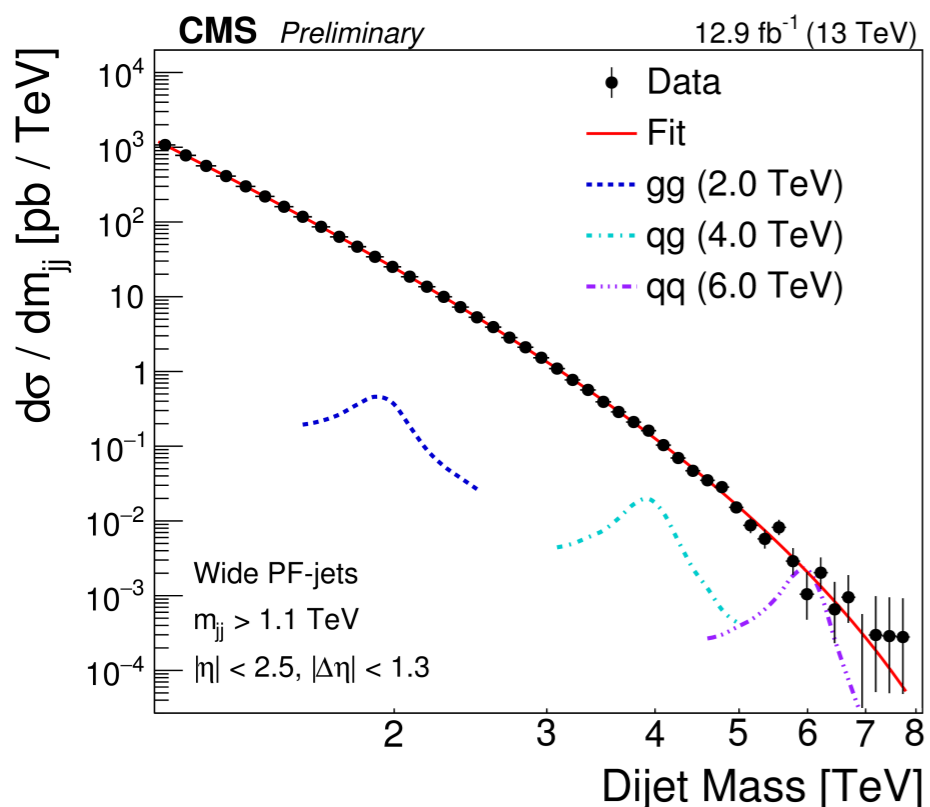
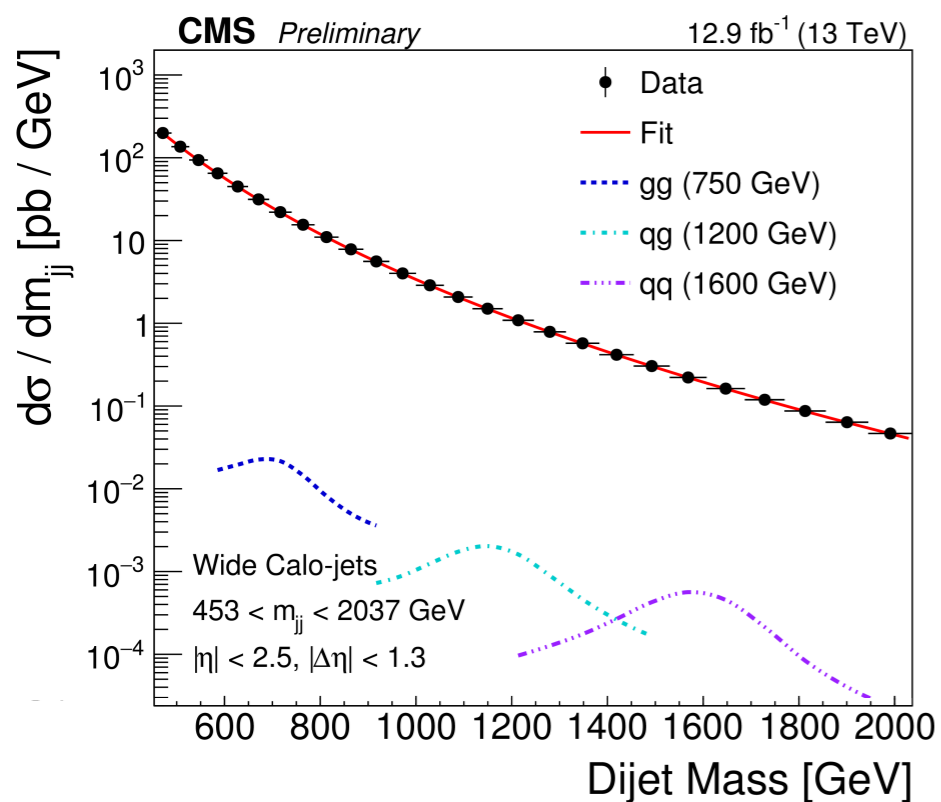


- ▶ Signature:
- ▶ hadronically decaying boosted single top quark + MET
- ▶ “Exotic” final state - suppressed in SM



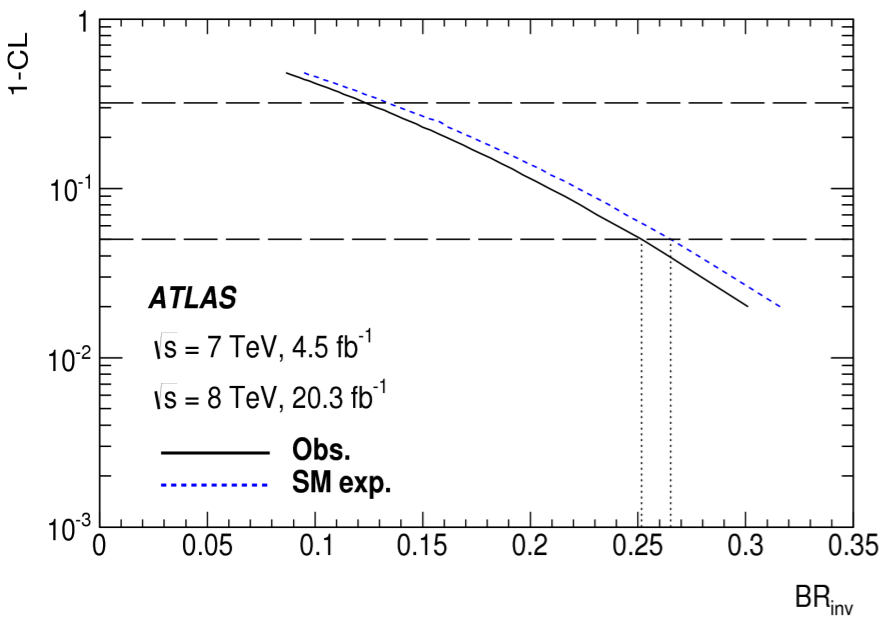
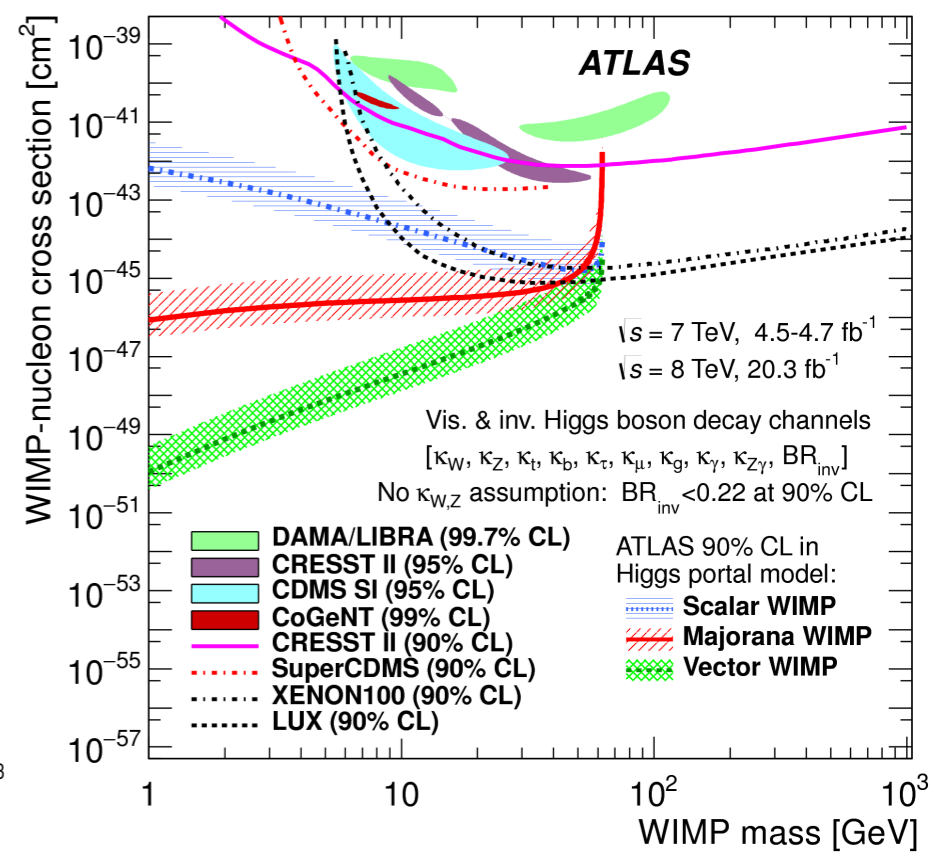
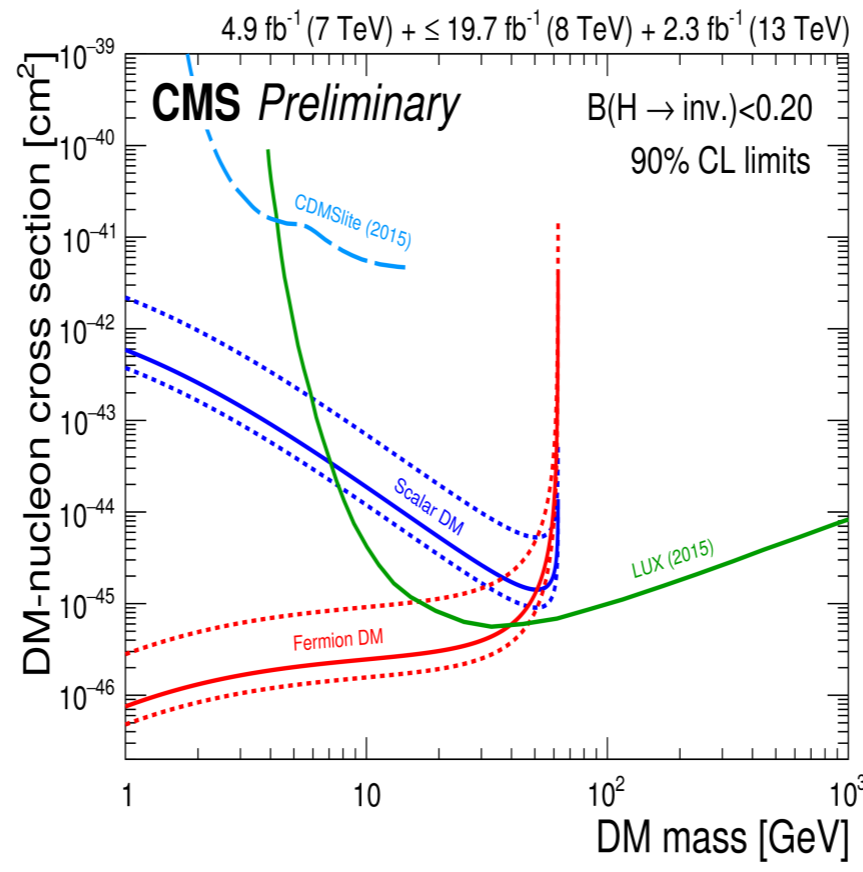
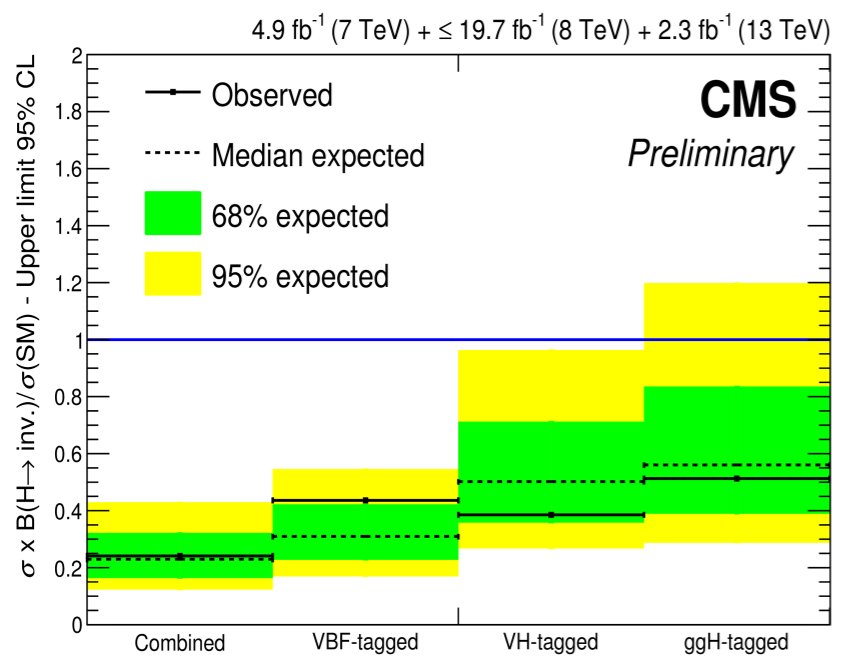
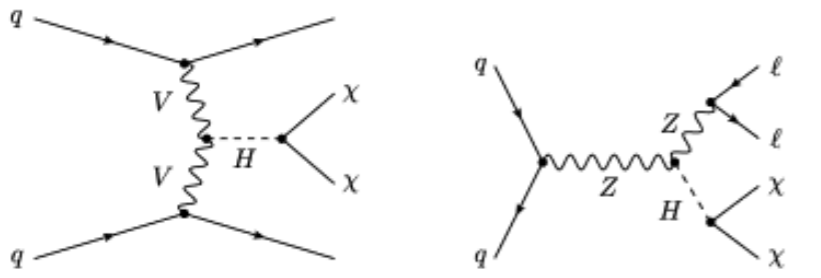
# Other Searches

# Dijet Searches



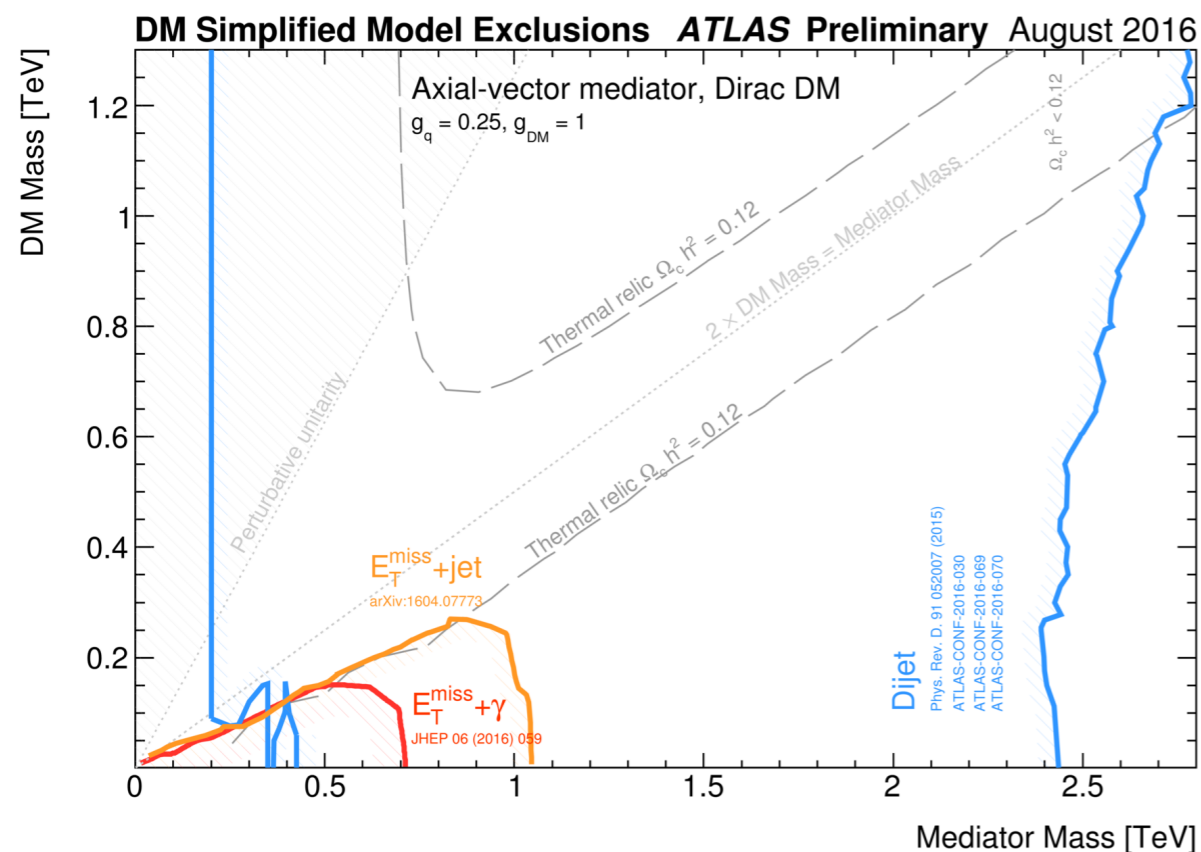
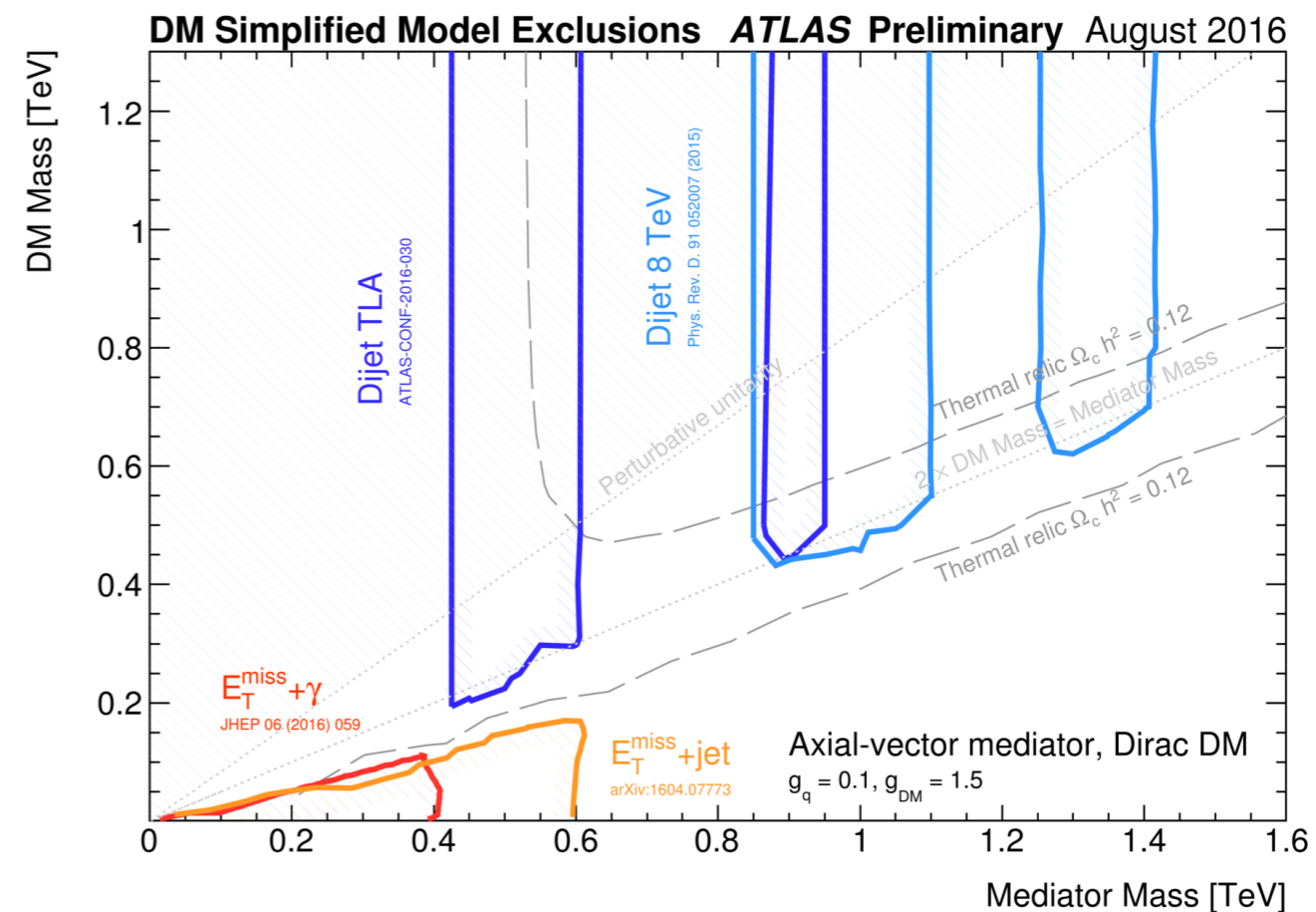
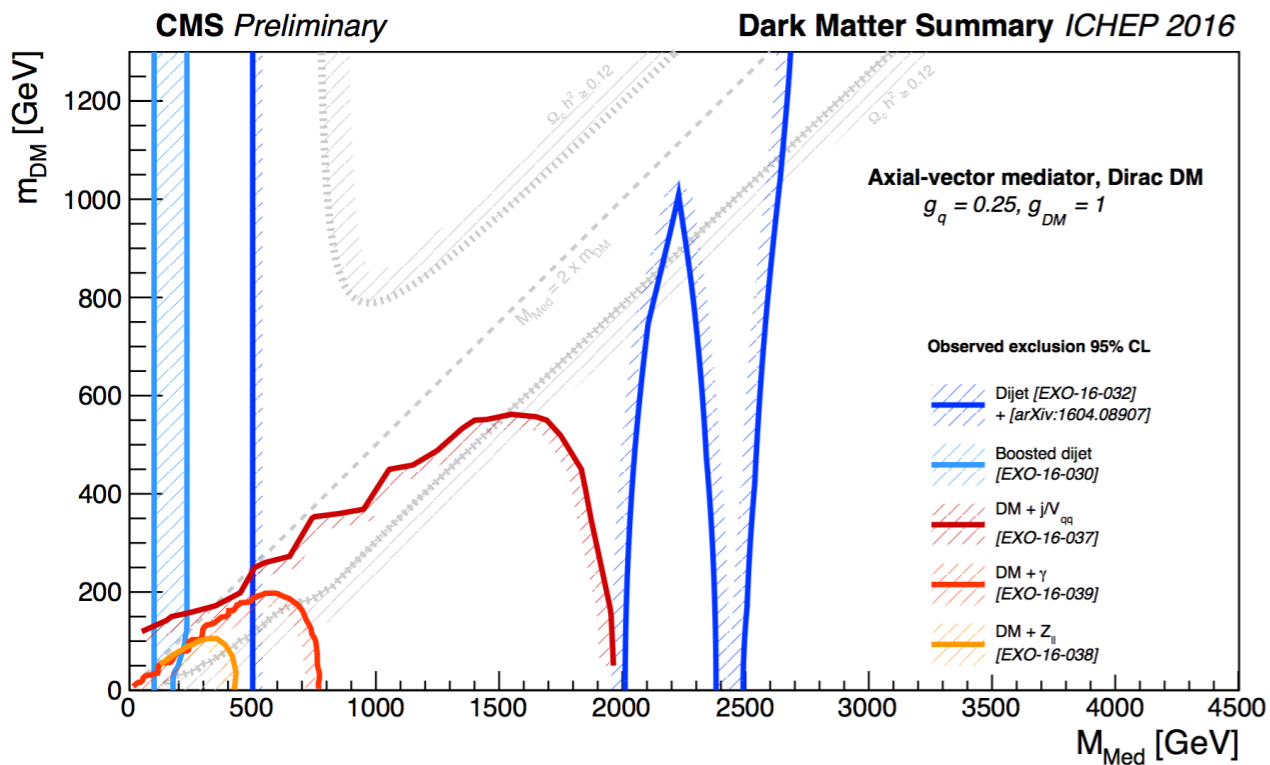
- ▶ Mediators coupling to quarks and gluons can be searched for in di-jet final state
  - ▶ one of the most sensitive channels for new dijet resonances
- ▶ Strong limits are set for mediators with couplings to SM as low as  $g_q \sim 0.1$

# Invisible Higgs



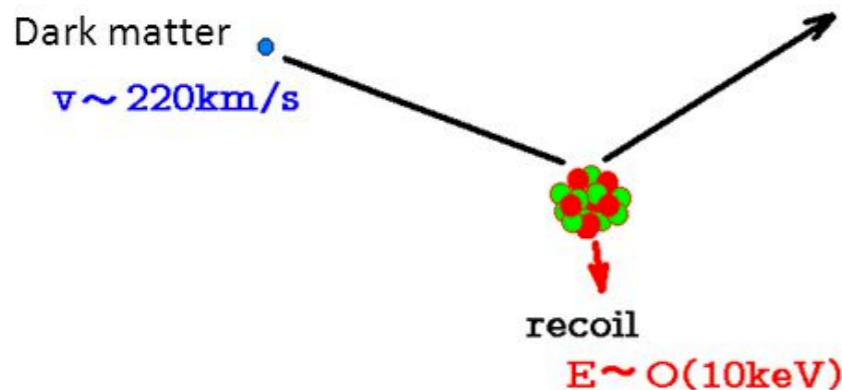
- ▶ Higgs boson can be the mediator between Dark Matter and SM sector
- ▶ Direct and Indirect searches for invisible Higgs decay provide stringent limits on this model
- ▶ Expand limits set by DD searches at low DM mass

# Summary Plots



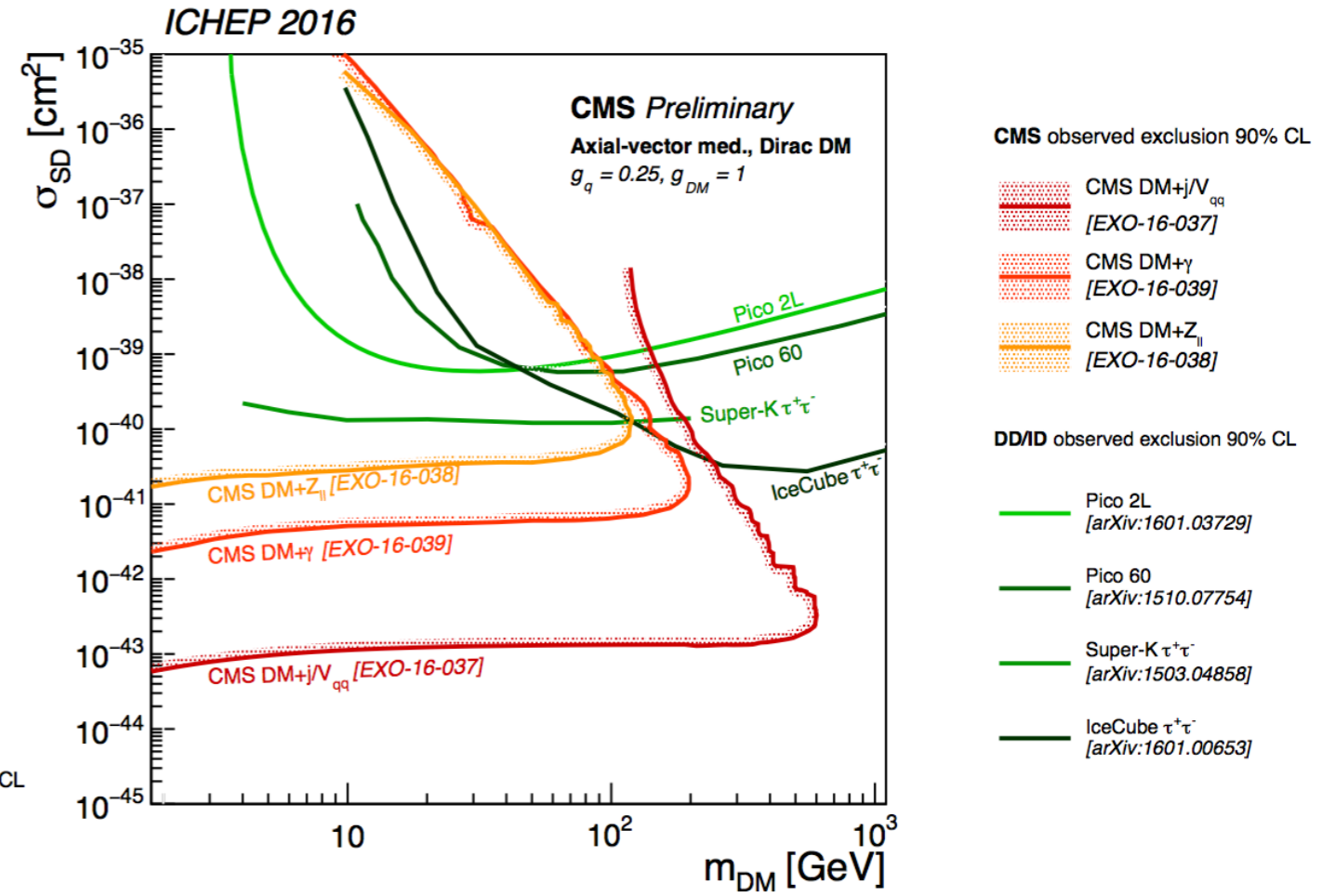
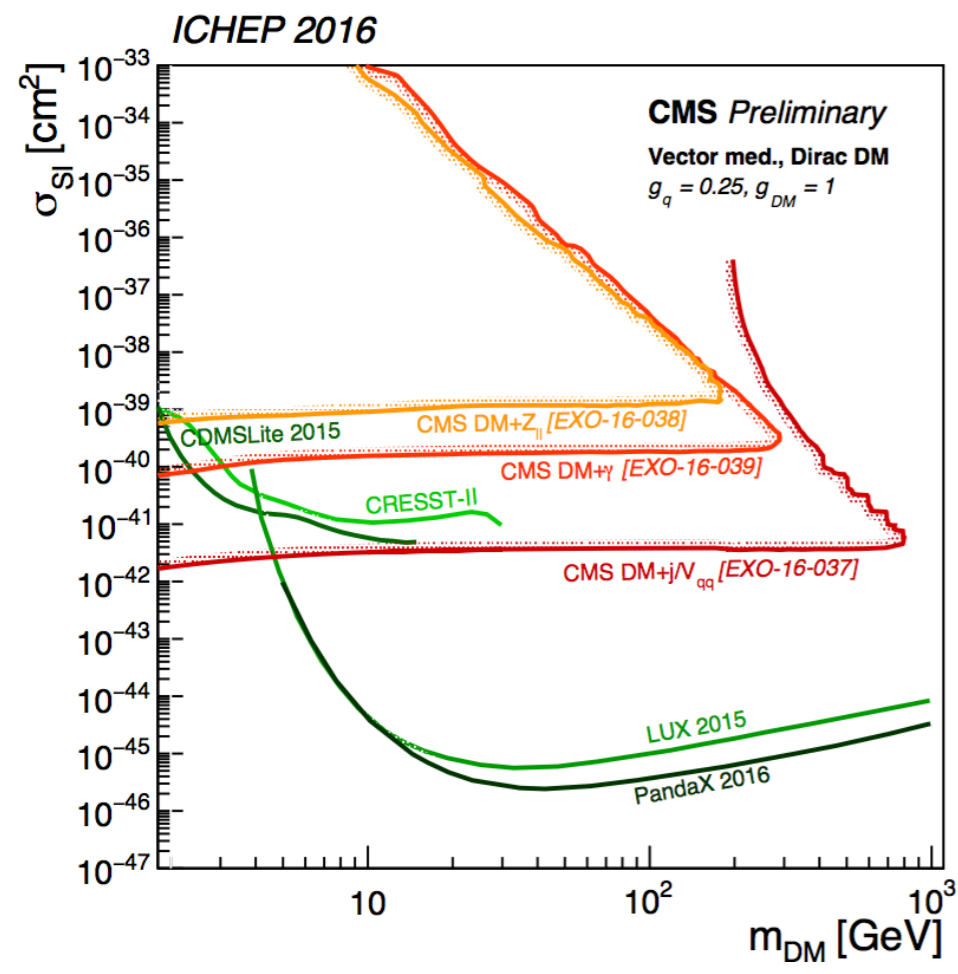
- ▶ MET+X Dark Matter searches can be combined with the dijet Mediator searches
- ▶ Plots show Simplified Model with axial-vector mediator
- ▶ For  $g_q=0.25, g_{DM}=1$  dijet results dominate, but the picture is changing when couplings to SM are reduced

# Comparison with DD and ID searches



$$\mathcal{L} = \sum_{N=p,n} f_N \bar{\chi}^0 \chi^0 \bar{N} N + a_N \bar{\chi}^0 \sigma_a \chi^0 \bar{N} \sigma_a N$$

Spin-independent (SI) interaction      Spin-dependent (SD) interaction

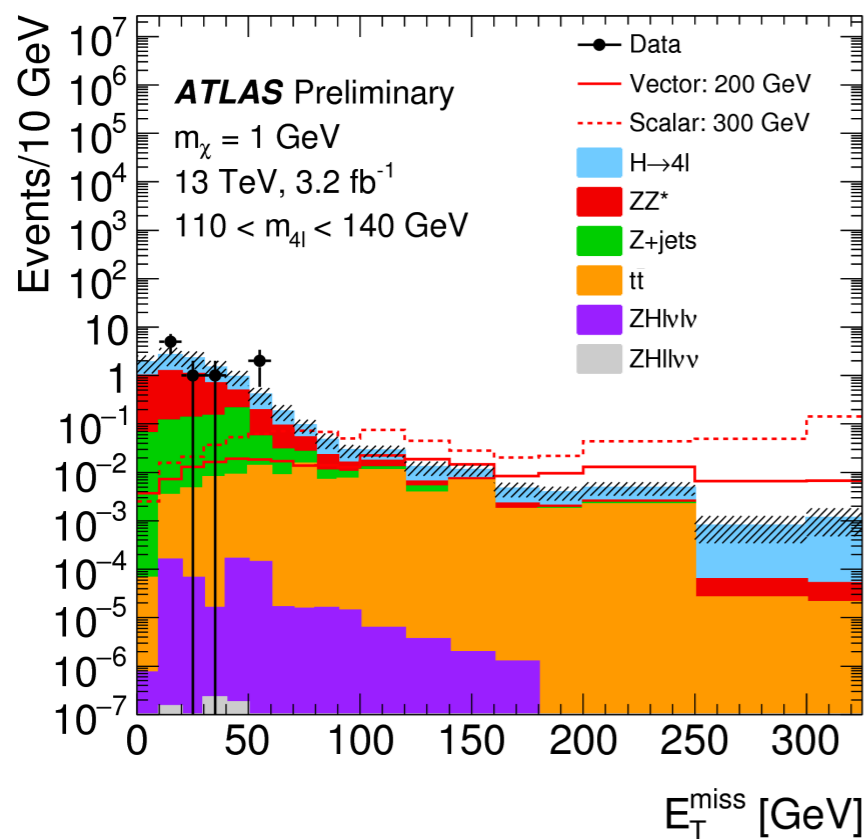


- ▶ Simplified Models allow for comparisons with Direct and Indirect Detection searches
- ▶ Relict density is not used in the constraints
- ▶ Results strongly depend on the choice of SM and DM couplings

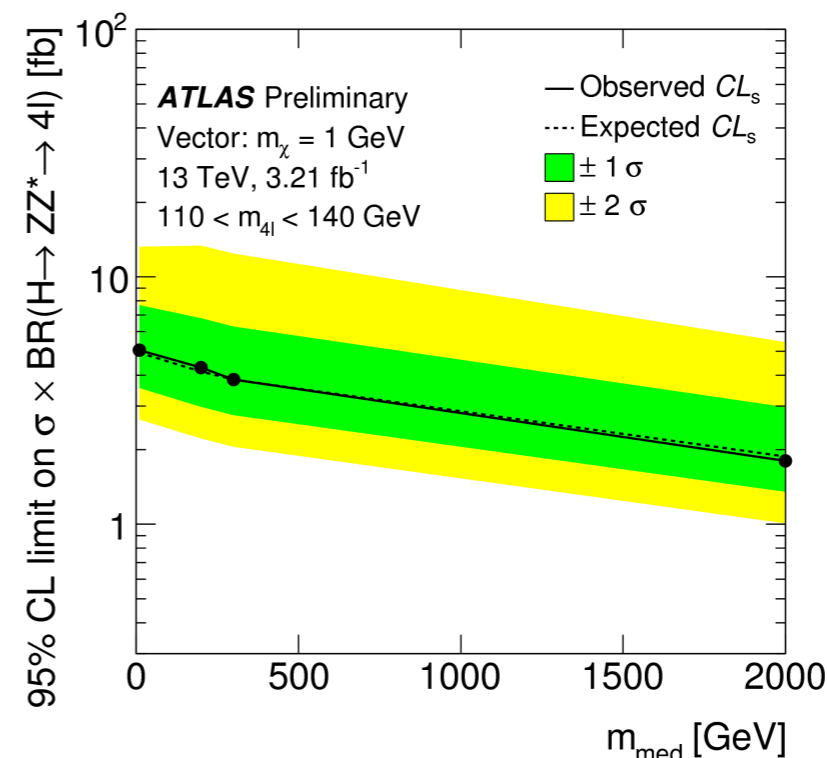
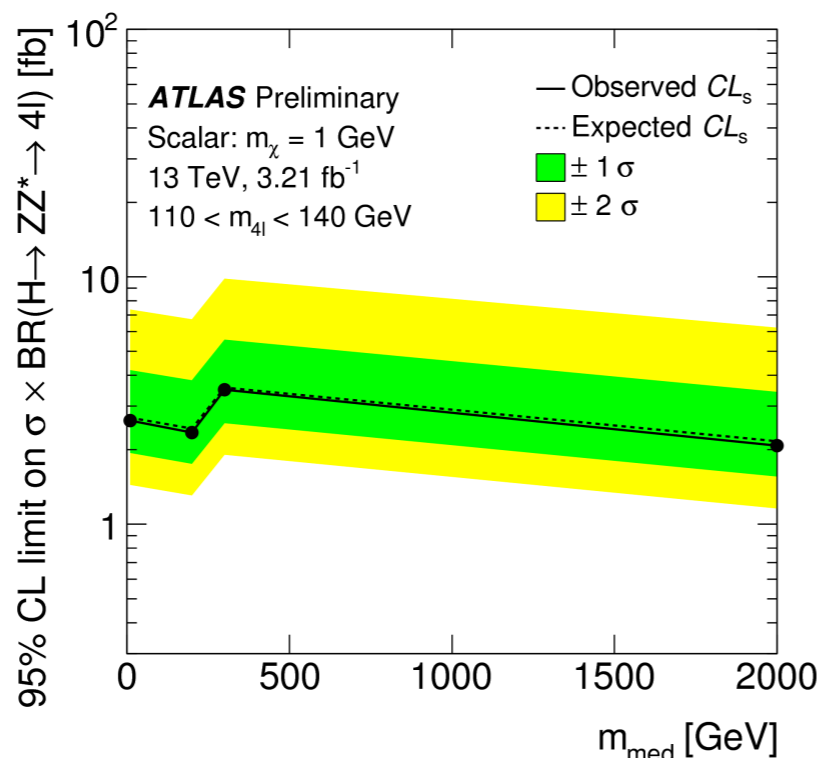
- ▶ Dark Matter searches at LHC is a complementary approach to Direct and Indirect Searches
- ▶ Dark Matter particle nature is unknown
  - ▶ Need to explore all possible final states
- ▶ ATLAS and CMS are moving toward a common theoretical framework based on Simplified Models
- ▶ No evidence of Dark Matter is observed so far, but the efforts are growing with more channels added each year

# Backup Slides

# MET + Higgs(4l)



Process	High- $E_T^{\text{miss}}$ category ( $E_T^{\text{miss}} > 100 \text{ GeV}$ )	Low- $E_T^{\text{miss}}$ category ( $E_T^{\text{miss}} < 100 \text{ GeV}$ )
$H \rightarrow ZZ^* \rightarrow 4l$	$(2.1 \pm 0.6) \cdot 10^{-2}$	$4.9 \pm 0.5$
$ZZ^*$	$(0.7 \pm 0.4) \cdot 10^{-2}$	$4.4 \pm 0.4$
Z+jets and $t\bar{t}$	$(3.1 \pm 1.2) \cdot 10^{-2}$	$0.8 \pm 0.5$
$ZH(l\nu l\nu)$	$(1.2 \pm 0.6) \cdot 10^{-5}$	$(5.8 \pm 0.8) \cdot 10^{-4}$
$ZH(\ell\nu\nu)$	$(1.3 \pm 0.8) \cdot 10^{-7}$	$(8.2 \pm 1.5) \cdot 10^{-7}$
Total background	$(5.9 \pm 1.6) \cdot 10^{-2}$	$10.1 \pm 1.0$
Vector mediator signal $m_\chi = 1 \text{ GeV}, m_{\text{med}} = 200 \text{ GeV}$	$(9.7 \pm 3.3) \cdot 10^{-2}$	$(1.3 \pm 0.6) \cdot 10^{-1}$
Scalar mediator signal $m_\chi = 1 \text{ GeV}, m_{\text{med}} = 300 \text{ GeV}$	$0.41 \pm 0.14$	$0.44 \pm 0.09$
Data	0	9





# EFT vs Simplified Model

- ▶ Compare EFT and Z' mediator model

- ▶ Cases

- ▶ EFT is valid

$$Q^2 < M_{\text{med}}^2 = g_q g_\kappa \Lambda^2$$

- ▶ Resonance enhancement - limits are conservative

$$Q^2 \approx M_{\text{med}}^2$$

- ▶ EFT is invalid - EFT limits are stronger

$$Q^2 > M_{\text{med}}^2$$

- ▶ [arXiv:1603.08002](https://arxiv.org/abs/1603.08002)