SEARCHING FOR DM AT THE LHC

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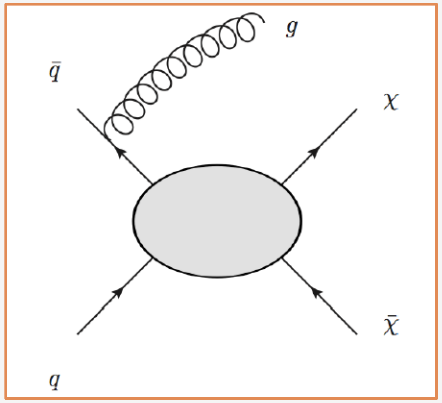
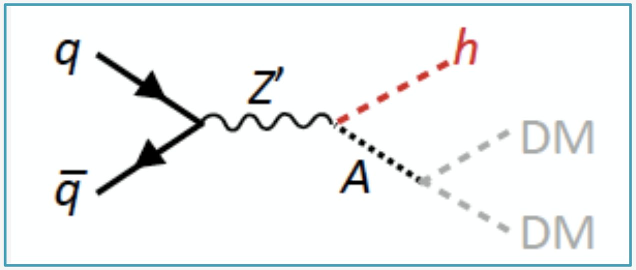
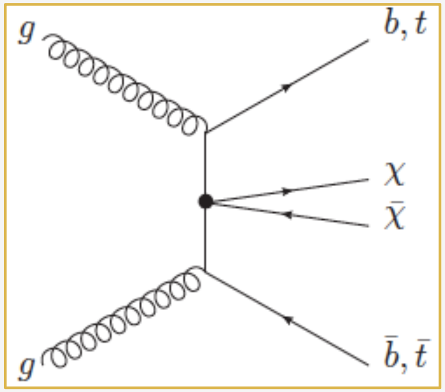
cnrs IN2P3
Les deux infinis

The E_T^{miss}+X searches

- All we see is the X, accompanied by large missing transverse energy from the DM production
- X can come from ISR, or from a more complicated interaction involving more than one new states
- X can be a single object (*mono-X searches*), or a more complex final state (e.g. at top-quark pair)







The E_T^{miss}+X searches in Run-2

X	ATLAS	CMS
Jet	Phys. Rev. D 94, 032005 (2016)	**CMS-PAS-EXO-16-037**
W or Z (qq)	arXiv:1608.02372 (subm. to PLB)	
Z(ll)	**ATLAS-CONF-2016-056**	**CMS-PAS-EXO-16-038**
Photon	JHEP 1606 (2016) 059	**CMS-PAS-EXO-16-039**
b quark(s)	**ATLAS-CONF-2016-086**	CMS-PAS-B2G-15-007
Top quark(s)	**ATLAS-CONF-2016-050 (1-lepton)** **ATLAS-CONF-2016-076 (2-lepton)** **ATLAS-CONF-2016-077 (0-lepton)**	CMS-PAS-EXO-16-005 (0/1-lepton tt) CMS-PAS-EXO-16-028 (2-lepton tt) **CMP PAS EXO-16-040** (1 boosted top)
H($\gamma\gamma$)	**ATLAS-CONF-2016-087**	CMS-PAS-EXO-16-011
H(bb)	arXiv:1609.04572 (subm. to PLB)	CMS-PAS-EXO-16-012
H(4l)	ATLAS-CONF-2015-059	

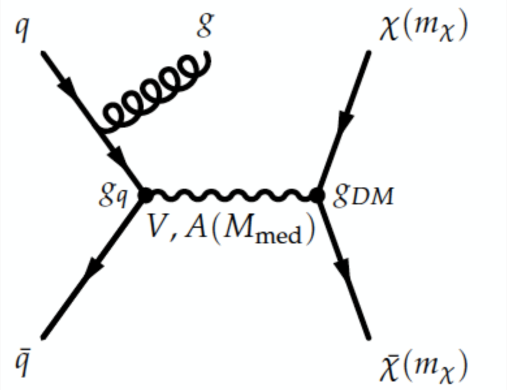
2015 dataset or **ICHEP 2016 dataset**

Mono-X general strategy

- Define a signal region (SR) by selecting events such as to get an enhanced signal-over-BG ratio:
    - Select events with a high-p_T X and a large E_T^{miss}
    - Veto extra objects (e.g.: no e or μ in mono-γ)
    - Avoid mismeasured objects which could lead to fake E_T^{miss} (e.g.: no jet pointing in the E_T^{miss} direction, clean against non-collision BG…)

- Estimate the BG contribution in the SR (data-driven or using MC)

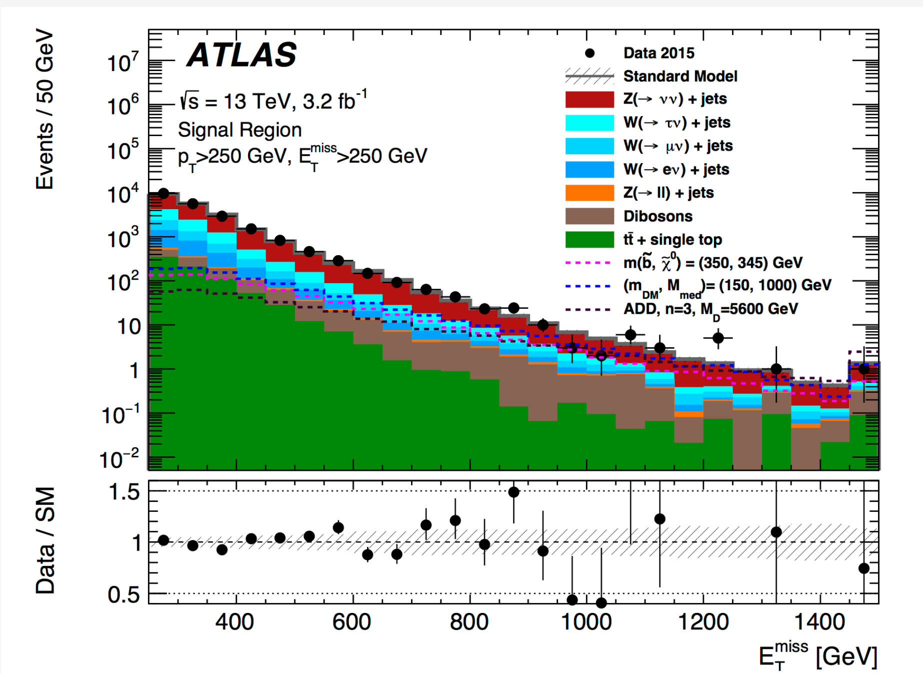
- If no excess in the SR: show the limits on models, following the recommendations of the ATLAS/CMS Dark Matter Forum ([arXiv:1507.00966]) and of the LHC DM WG ([arXiv:1603.04156])
    - Favours the use of simplified models
    - Benchmarks with specific couplings
    - Limits in the m_{DM}/m_{Med} plane



E_T^{miss} + jet in ATLAS

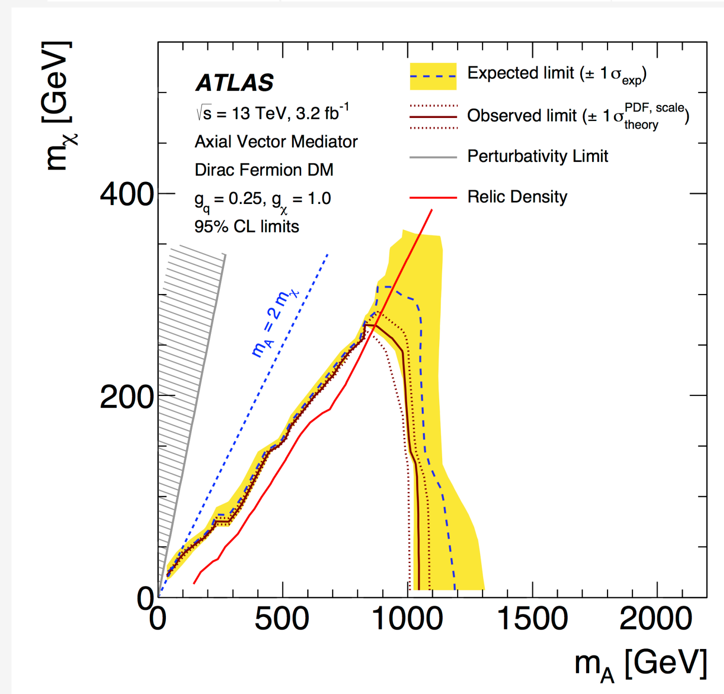
Selection:

- Leading central jet within p_T > 250 GeV
- 7 inclusive SRs with E_T^{miss} thresholds from >250 GeV to >700 GeV
- $\Delta\phi$(sel. jets, E_T^{miss})>0.4
- Lepton veto and more than 4 central jets



Main BG from W control regions:

Background process	Method	Control sample
$Z(\to \nu\bar{\nu})$+jets	MC and control samples in data	$W(\to \mu\nu)$
$W(\to e\nu)$+jets	MC and control samples in data	$W(\to e\nu)$
$W(\to \tau\nu)$+jets	MC and control samples in data	$W(\to e\nu)$
$W(\to \mu\nu)$+jets	MC and control samples in data	$W(\to \mu\nu)$
$Z/\gamma^*(\to \mu^+\mu^-)$+jets	MC and control samples in data	$Z/\gamma^*(\to \mu^+\mu^-)$
$Z/\gamma^*(\to \tau^+\tau^-)$+jets	MC and control samples in data	$W(\to e\nu)$
$Z/\gamma^*(\to e^+e^-)$+jets	MC only	
$t\bar{t}$, single top	MC only	
Diboson	MC only	
Multijets	data-driven	
Non-collision	data-driven	



E_T^{miss} + W/Z(hadronic) in ATLAS

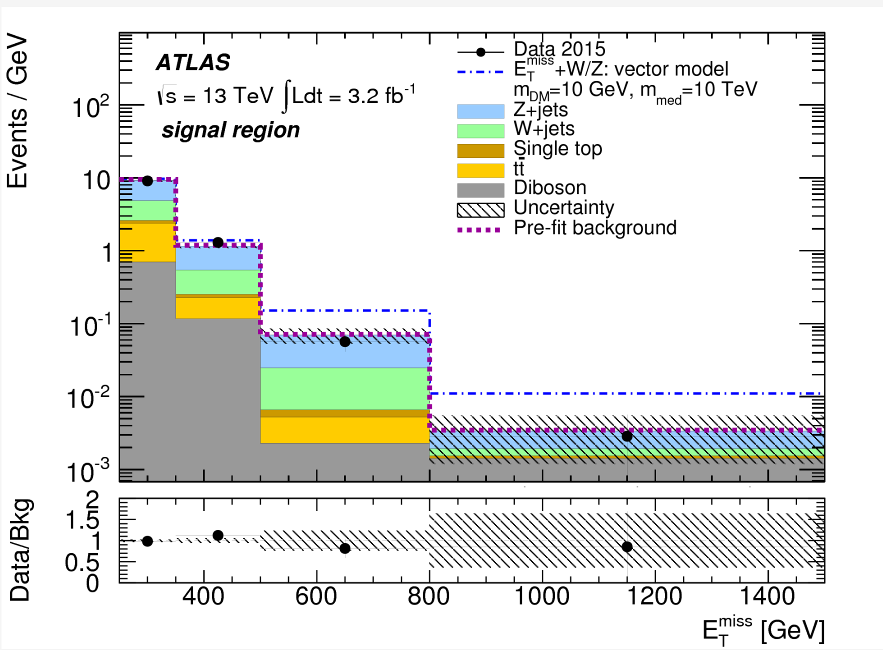
Highly boosted W/Z: decay products merged in a 'fat' jet

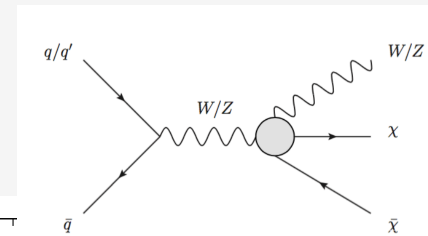
Selection:

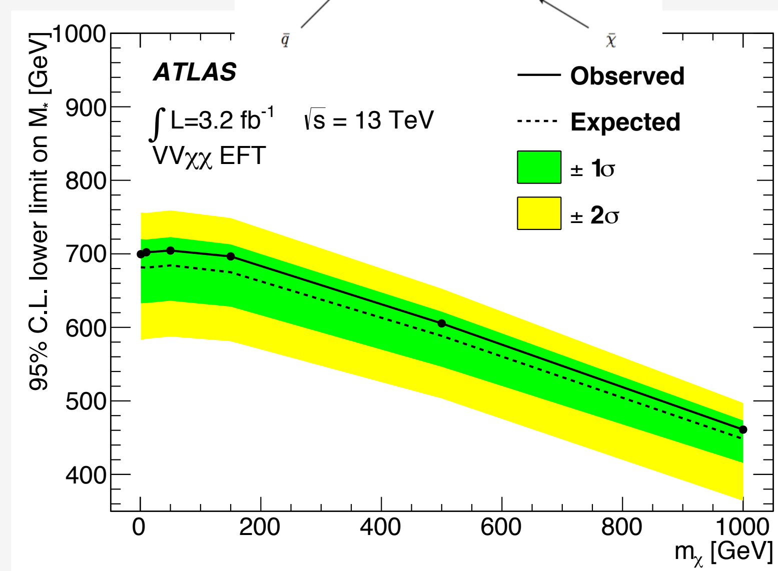
- E_T^{miss} >250 GeV, p_T^{miss} > 30 GeV and $\Delta\phi(p_T^{miss}, E_T^{miss})<\pi/2$, $\Delta\phi(\text{jet}, E_T^{miss})>0.6$
- Veto on leptons
- Central, p_T>200 GeV large-R trimmed jet tagged as a W/Z *(mass + D2 selection)*

BG estimation via leptonic CRs

(2μ for Z, 1μ + b-jet/no b-jet for top/W)





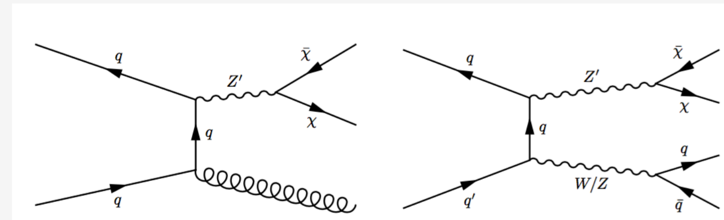


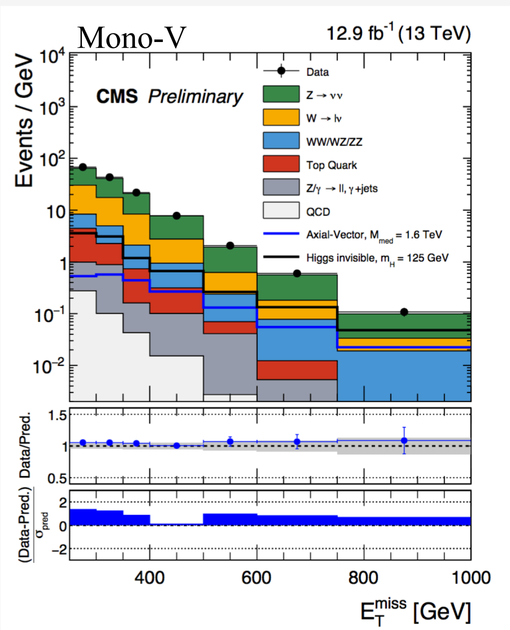
E_T^{miss} + *jet/Z/W(hadronic) in CMS*

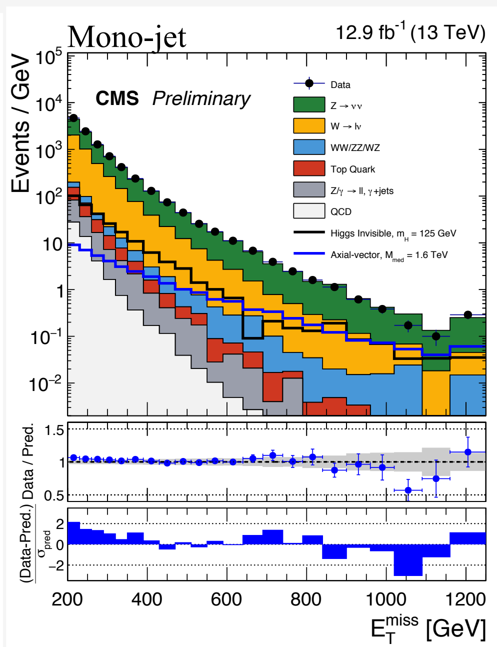
Mono-V:
- AK8 jet with $p_T > 250$ GeV, $E_T^{miss} > 250$ GeV, m_J in [65-105] GeV, $\tau_{21} < 0.6$

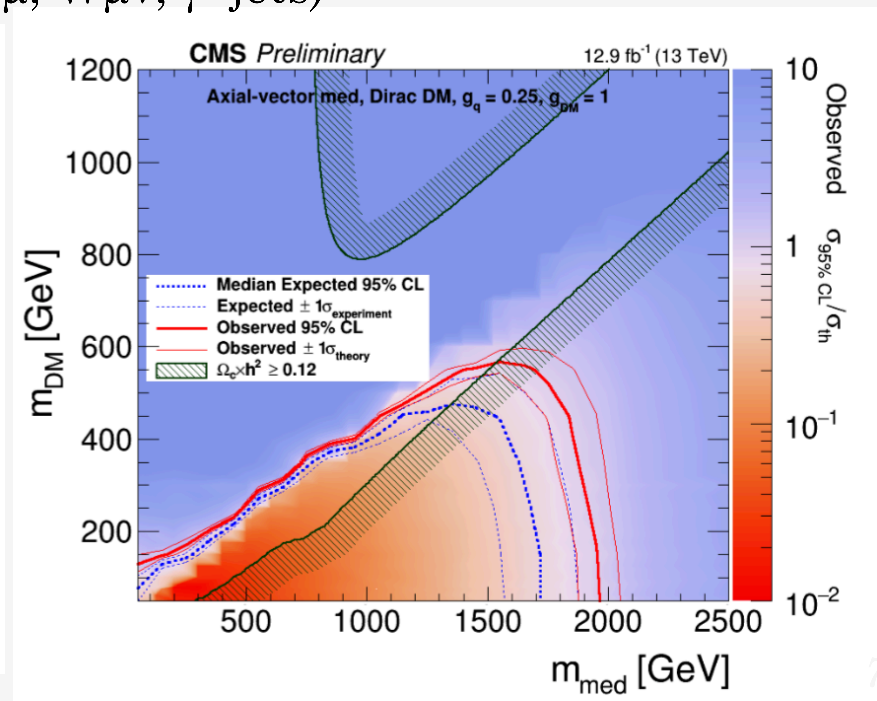
Mono-jet selects remaining events with:
- AK4 jet with $p_T > 100$ GeV, $E_T^{miss} > 200$ GeV

BG estimation via 5 CRs (Zee, Weν, Zμμ, Wμν, γ+jets)









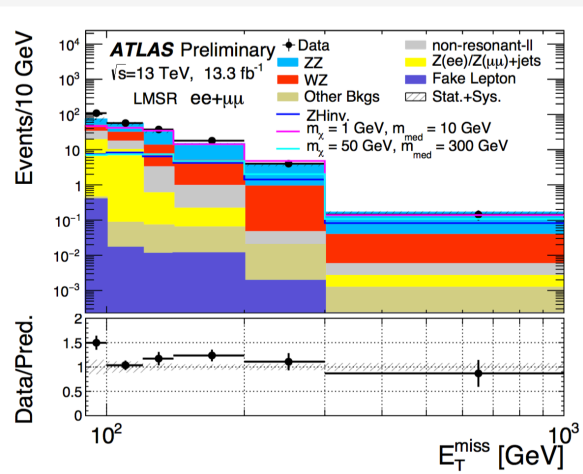
$E_T^{miss} + Z(ll)$

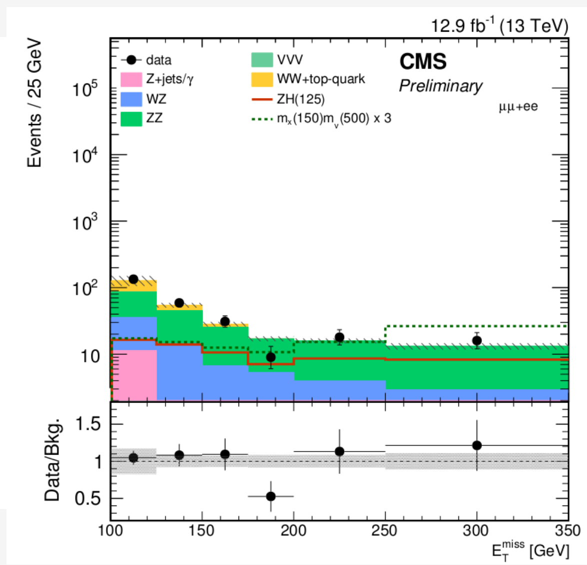
Selection:

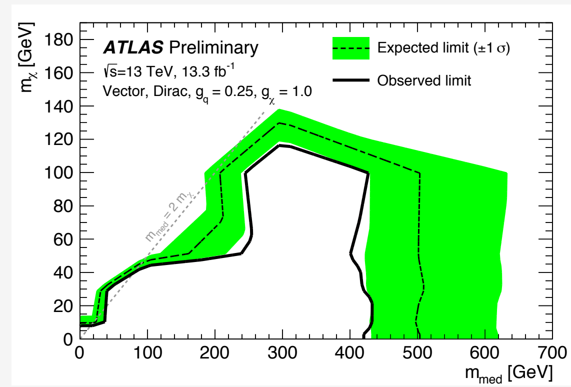
- ee or μμ (*ATLAS: close-by*) pairs compatible with the *Z* mass, away from E_T^{miss} and whose p_T is well balanced with the large E_t^{miss}
- jet/E_T^{miss} separation, no b-jet (*CMS: no extra jet, no hadronic tau*)

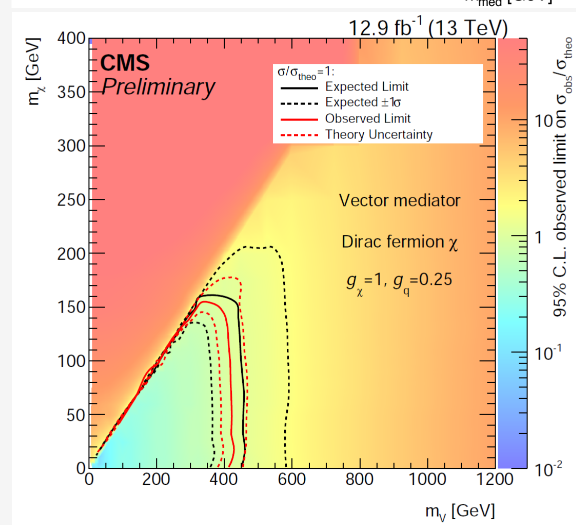
BG estimation:

ZZ (and WZ in CMS) from NNLO-corrected MC
WZ from 3-lepton CR in ATLAS









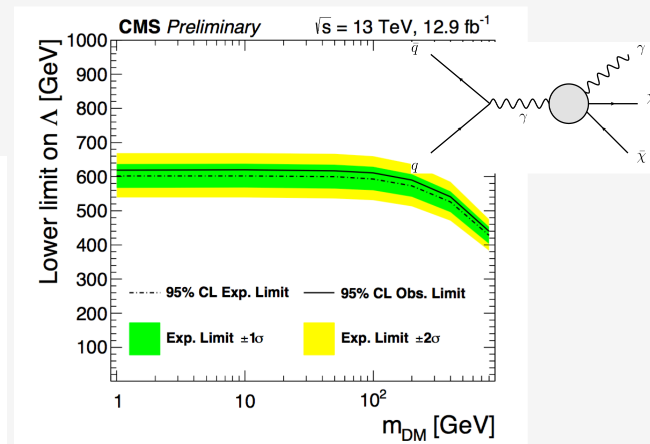
E_T^{miss} + photon

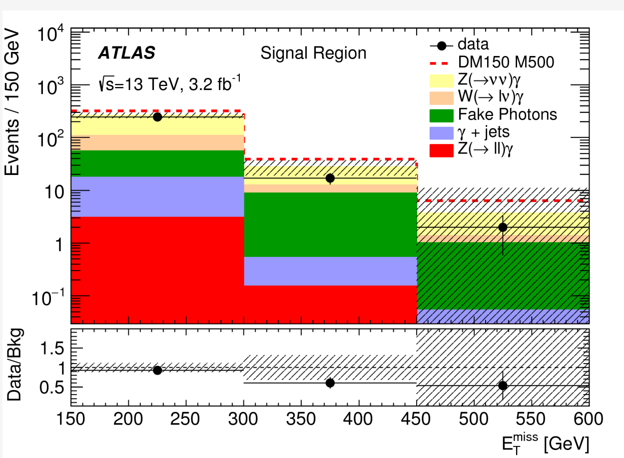
Selection:

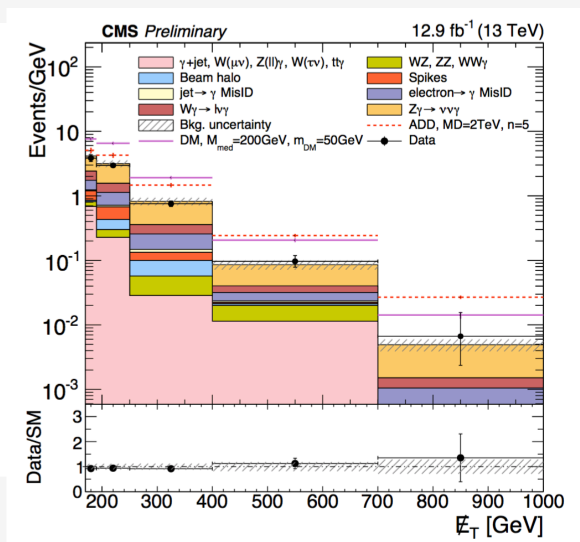
- High-p_T central photon (ATLAS: 150 GeV, loose cut on z_0, CMS: 175 GeV, no end-cap)
- Large E_T^{miss} (ATLAS: 150 GeV, CMS: 170 GeV) separated from the jets and the γ
- Lepton veto (+ veto on more than 1 jet in ATLAS)

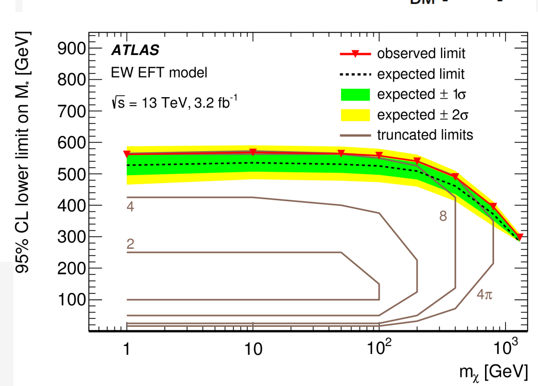
BG estimation:

- Z/W+γ from leptonic CRs (ATLAS) or from NLO-corrected MC (CMS)
- Fake photons from data-driven methods
- Non-collision BG negligible (ATLAS) or estimated with data (CMS)

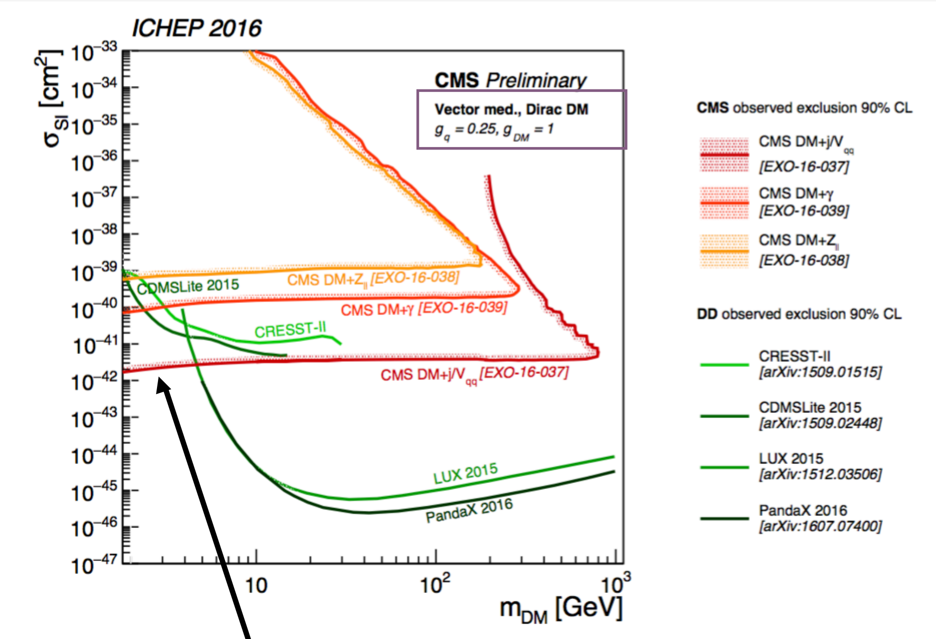




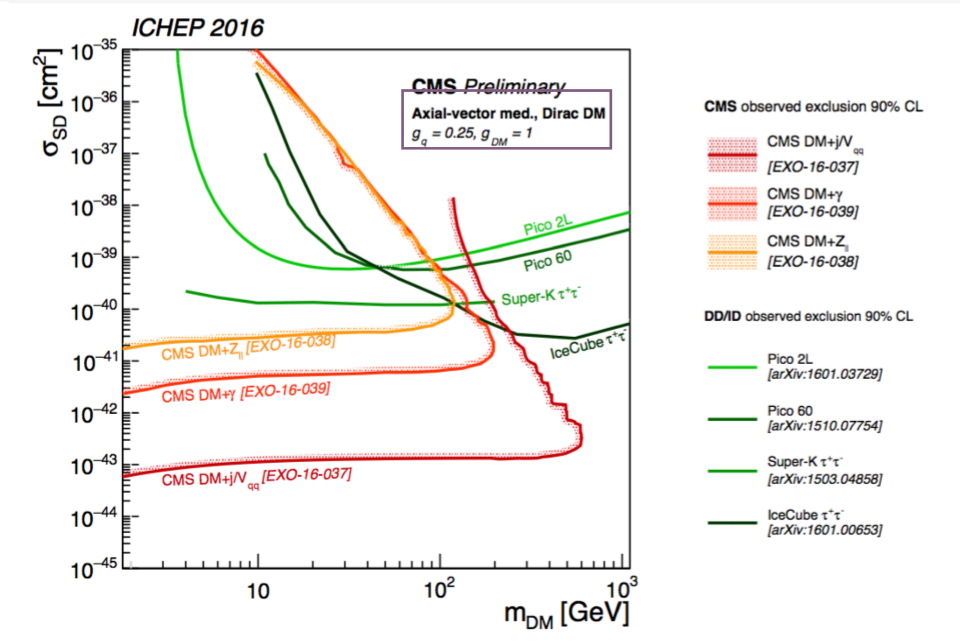




Comparison to direct detection



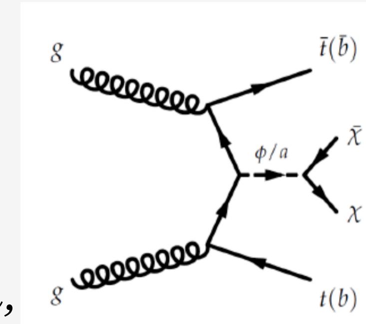
The LHC is able to probe
the low masses



The LHC is particularly
relevant in SD

But one must remember the **assumption of the model** considered.
It's not a competition with direct detection: we are complementary!

$E_T^{miss} + b$ quark(s)



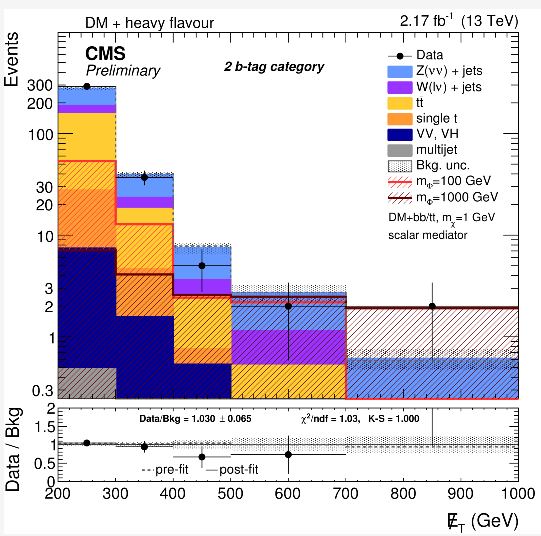
If the production of DM goes through a scalar interaction, one could enhance the coupling to heavy quarks

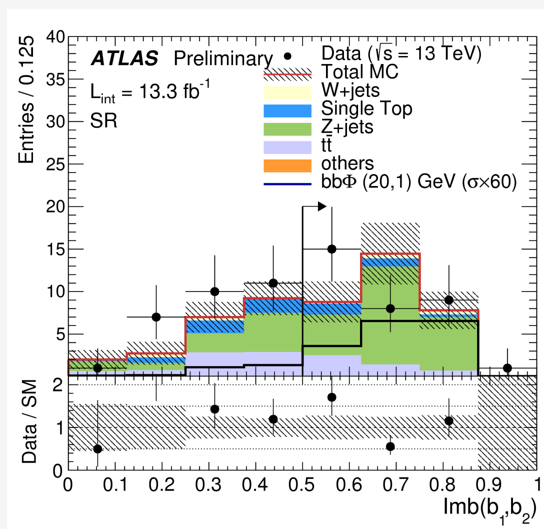
Selection:

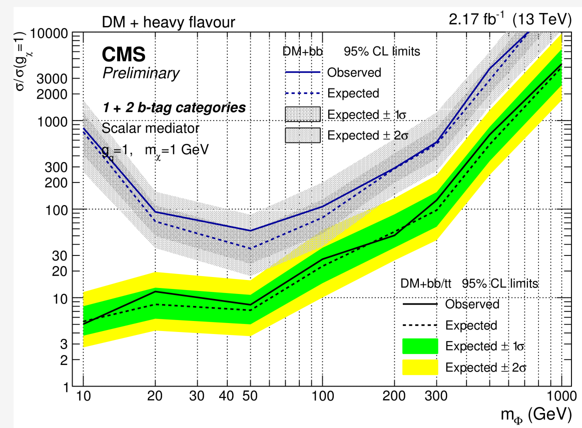
Large E_T^{miss} separated from the jets, b-jet(s) (ATLAS: 2, CMS: 1 or 2), lepton veto
ATLAS: angular separation of the jets, momentum imbalance of the two b-jets

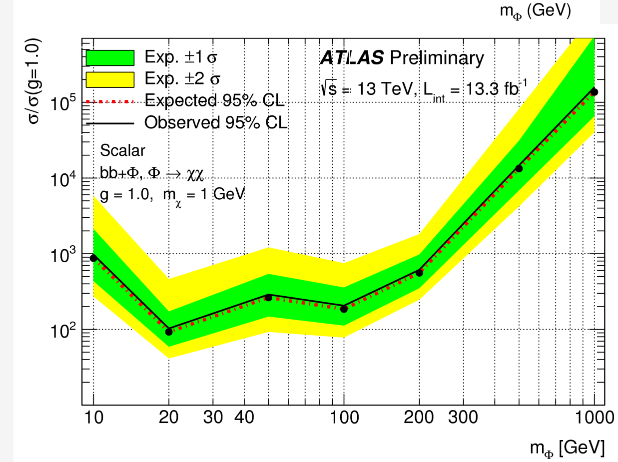
BG estimation:

Through leptonic CRs



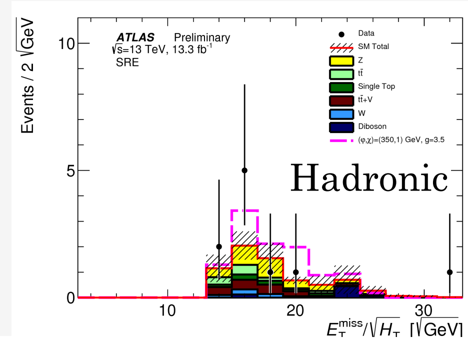






E_T^{miss} + top quarks in ATLAS

Dedicated signal regions in top squark searches

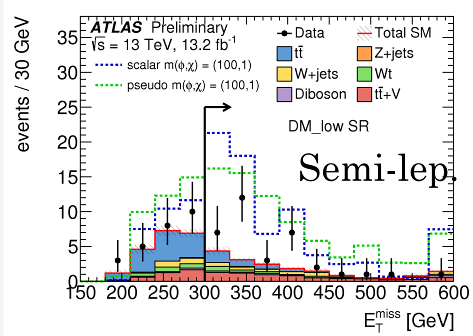


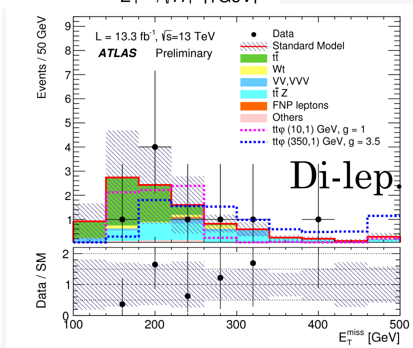
Hadronic:

E_T^{miss}, E_T^{miss} signif., ≥ 2 b-jets, 2 high-mass large-R jets, $m_T(b, E_T^{miss})$, lepton (incl. tau) veto

Semi-leptonic (e or μ):

E_T^{miss}, H_T^{miss} signif., ≥ 1 b-jet, m_T, am_{T2}, tau veto

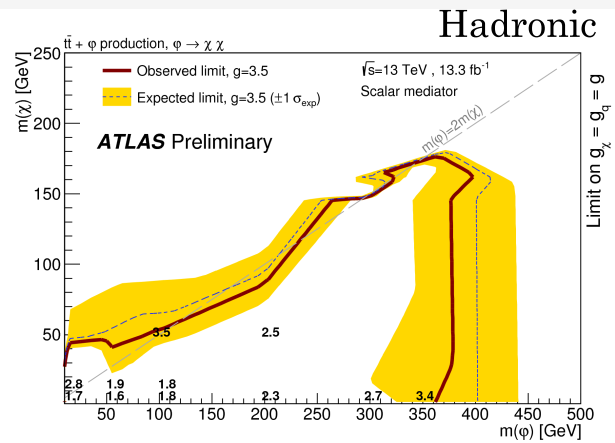


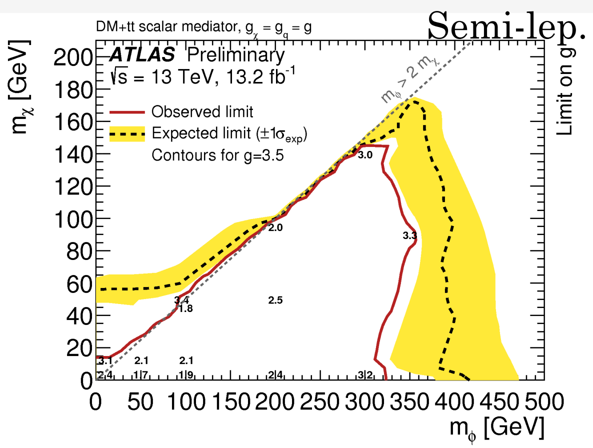


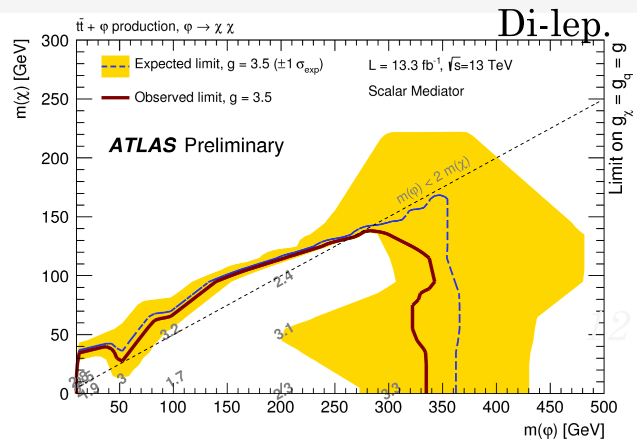
Di-leptonic (e or μ):

E_T^{miss}, Z(ll) veto, ≥ 1 b-jet, $\Delta\phi(E_T^{miss}, ll)$, $m_{T2}(ll)$

BG estimation using dedicated CRs







E_T^{miss} + top quarks in CMS

Hadronic:
E_T^{miss}, $\geq$ 1 or 2 b-jet, MVA resolved-hadronic-top tagger: categorize by number of top tags

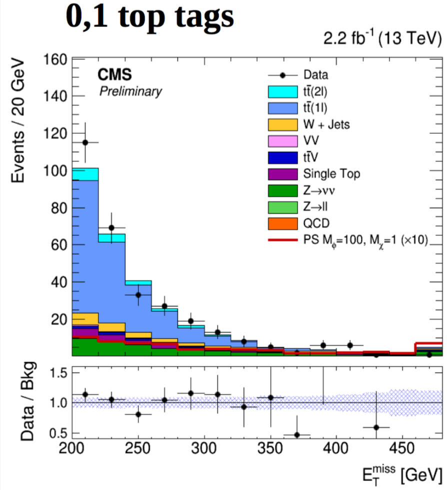
Semi-leptonic (e or μ):
E_T^{miss}, $\geq$ 1 b-jet, m_T, m_{T2}^W

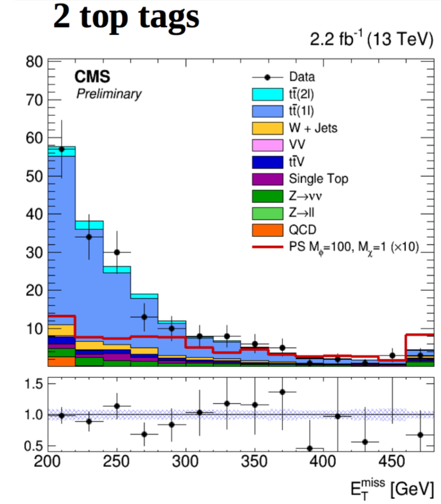
Di-leptonic (e or μ):
E_T^{miss}, Z(ll) veto, $\geq$ 1 b-jet, $\Delta\phi(E_T^{miss}, ll)$

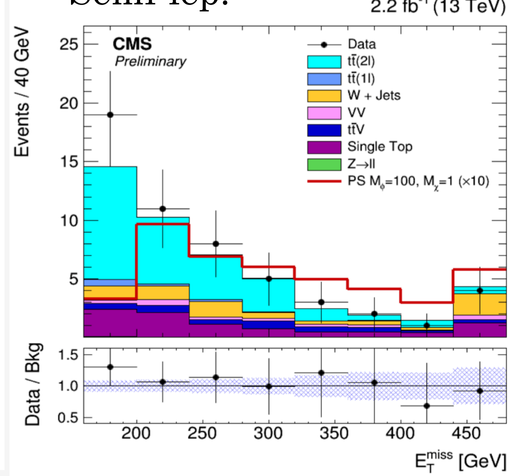
Combination of the three channels

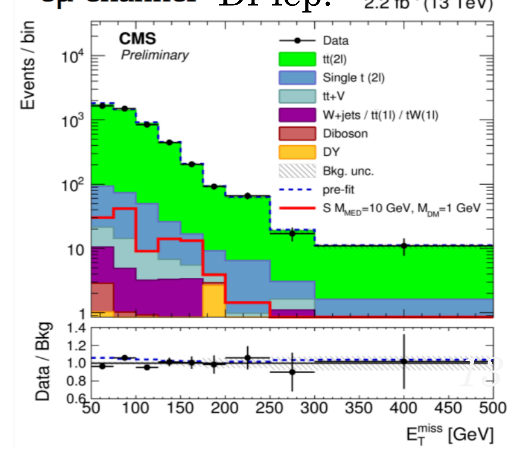
Fit to the E_T^{miss} distributions to extract the signal

Hadronic

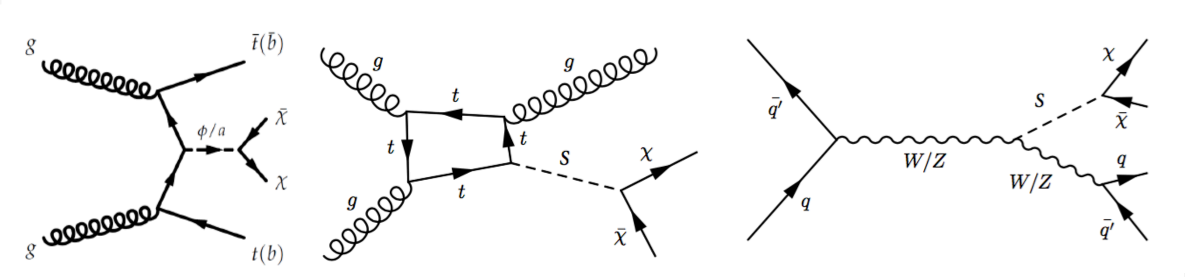


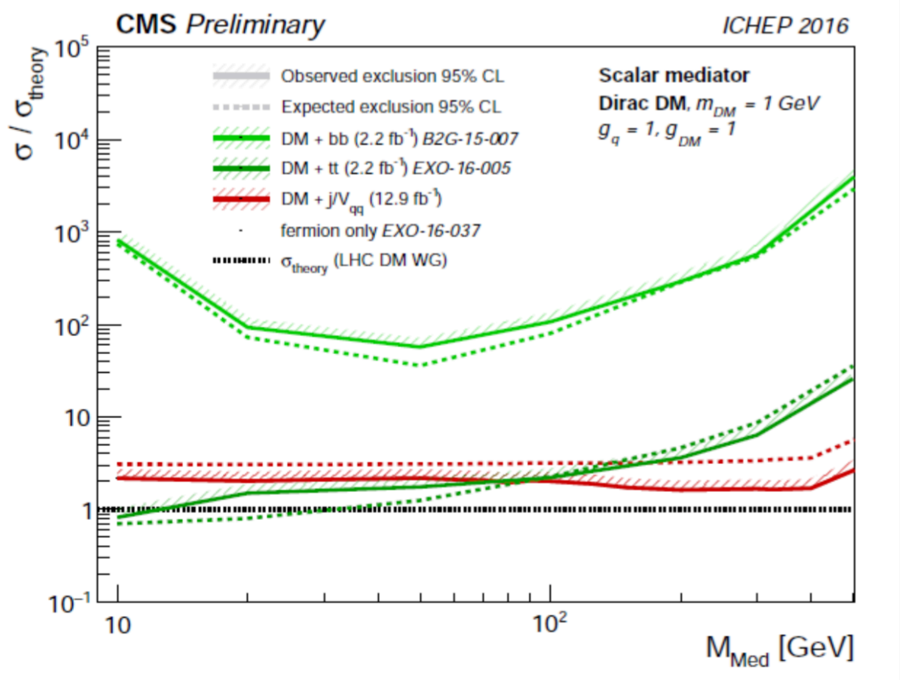






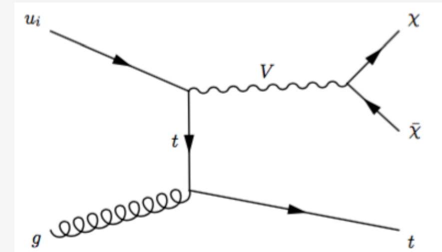
Summary: scalar mediator





$E_T{}^{miss}$ + top quark searches competitive with mono-jet/V at low M_{Med}
Future combination possible

E_T^{miss} + boosted top quark

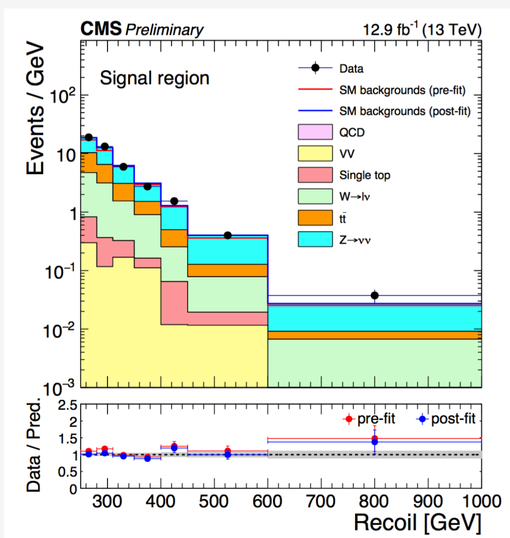


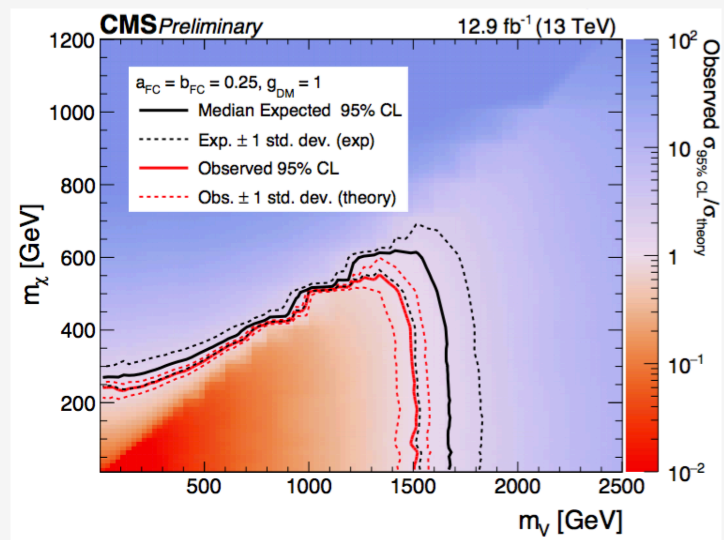
Can also probe more exotic models producing one top in the final state, e.g. this FCNC process:

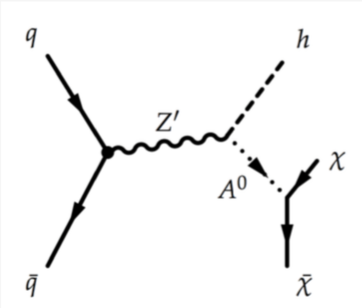
Selection:

E_T^{miss} > 250 GeV
High-p_T (>250 GeV) large jet (CA15) tagged as a top (m_J, τ_{32}, subjet b-tag)
Veto b-jets which are far away from the large jet and leptons (incl. τ)

BG estimation from leptonic CRs

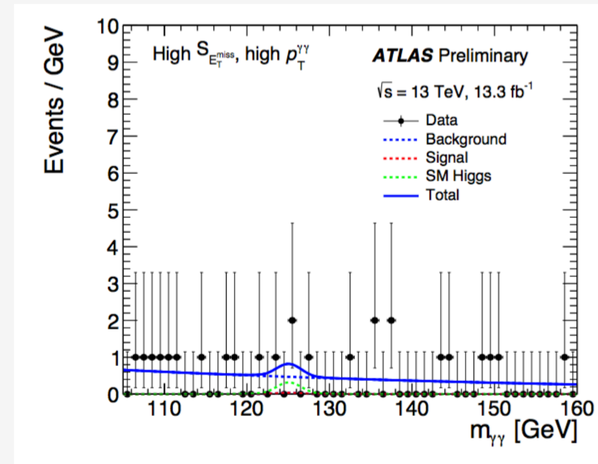






E_T^{miss} + Higgs

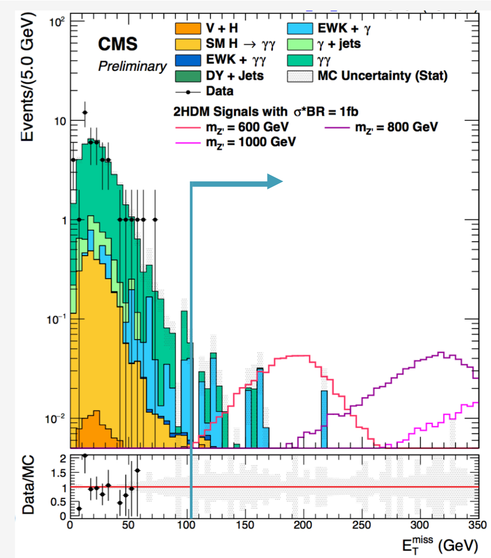
$h \to \gamma\gamma$: low BR but clean signal

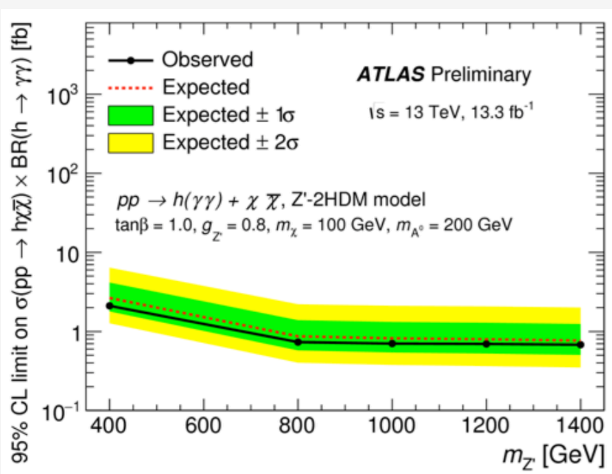


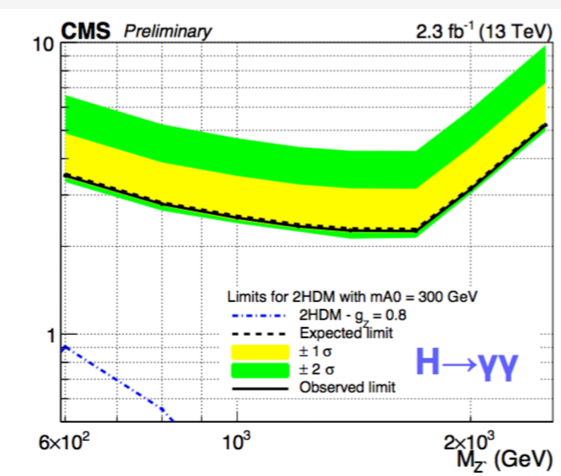
Selection (2HDM interpretation):

- $p_{T,\gamma 1}/m_{\gamma\gamma} > 0.35$ (CMS: > 0.5), $p_{T,\gamma 12}/m_{\gamma\gamma} > 0.25$
- $105 < m_{\gamma\gamma} < 160$ GeV (CMS: $120 < m_{\gamma\gamma} < 130$ GeV)
- E_T^{miss} significance > 7 GeV$^{1/2}$ (CMS: E_T^{miss} >105 GeV)
- $p_{T,\gamma\gamma}$ > 90 GeV

BG estimation in mass sidebands





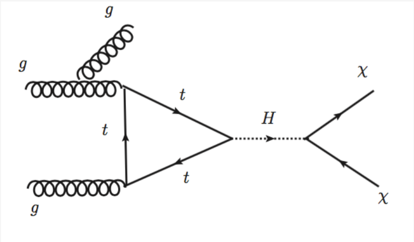


16

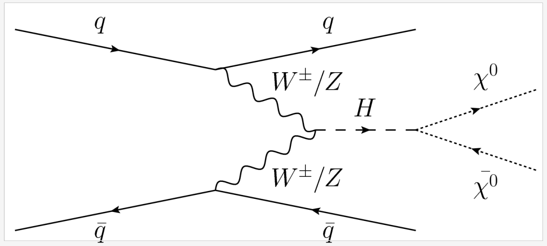
Higgs as a portal

What if the Higgs can decay to DM?

Multiple topologies can be used:

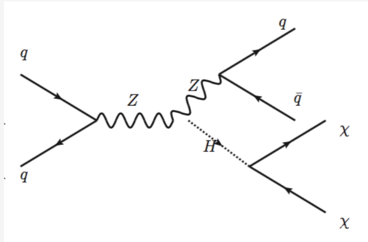


E_T^{miss} + jet



VBF + E_T^{miss}

- *Large* E_T^{miss} away from jets
- *2 high-p_T forward jets, in opposite hemisphere, large m_{jj}.*
- *Central jet veto.*

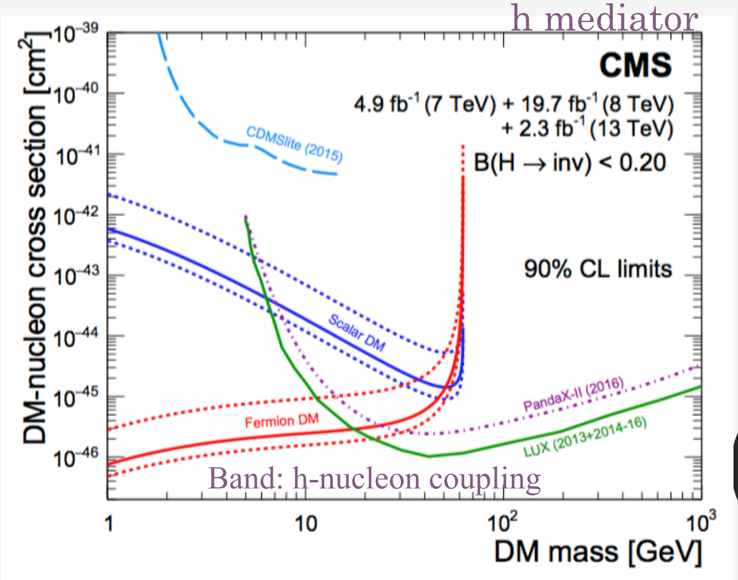


E_T^{miss} + Z

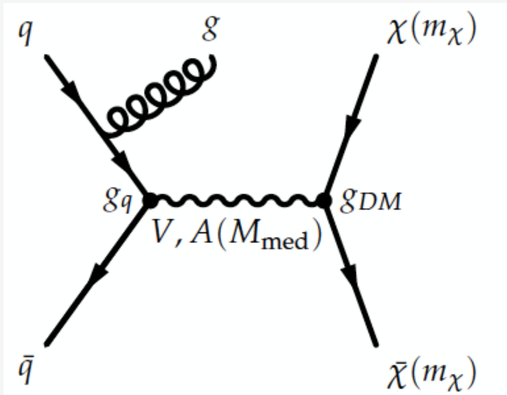
CMS Run-1 + 2015 (arXiv:1610.09218):
If SM prod, BR(h→inv) < 0.24 (expected: 0.23)

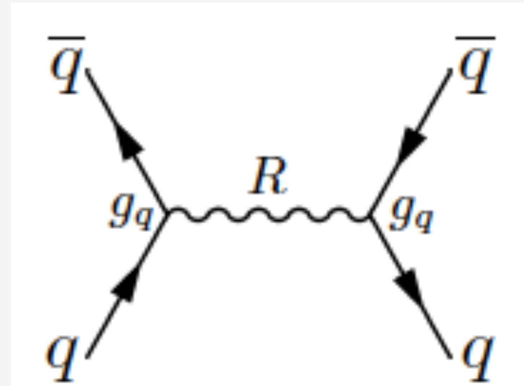
ATLAS Run-1 (JHEP 01 (2016) 172):
BR(h→inv) < 0.23 (expected: 0.24)
(including visible decay rate measurements)

h mediator



Searching for the mediators





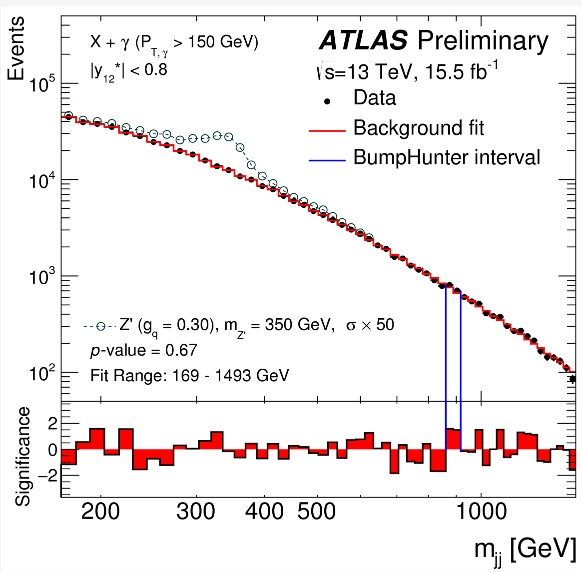
Resonance!

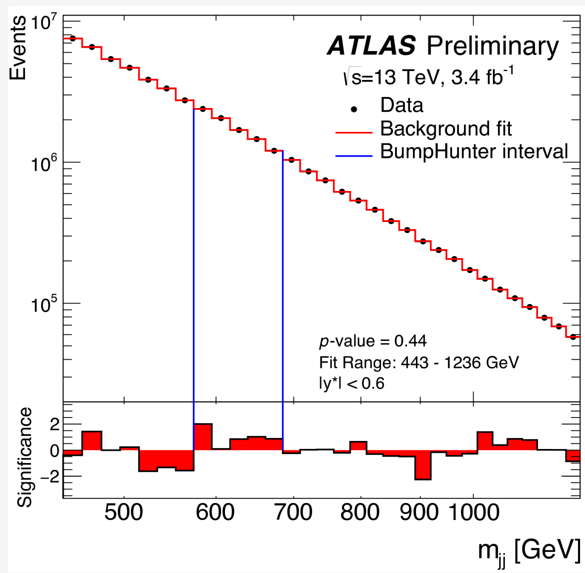
- Look for a bump in the dijet mass over a smoothly falling background
- To probe low masses, need some trick to by-pass the huge trigger rate wall:
    - *Use an ISR object on which to trigger (e.g. a photon)*
    - *Do the analysis at trigger level (TLA) :*
        - *Bandwith = rate x size ➔ reduce size*

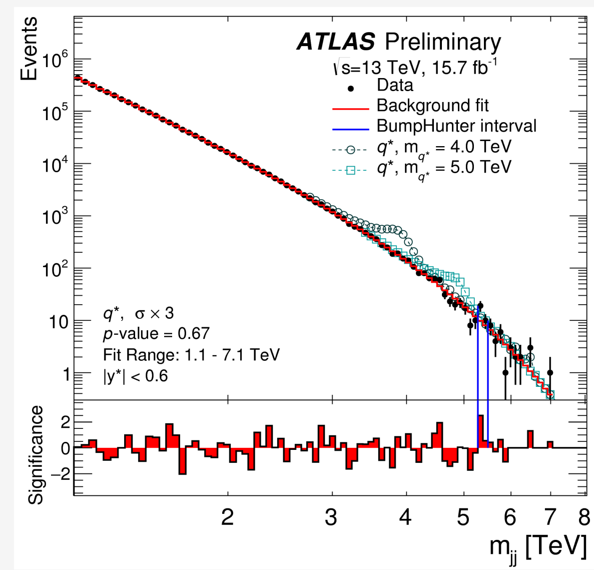
Searching for the mediators

2015 dataset or **ICHEP 2016 dataset**

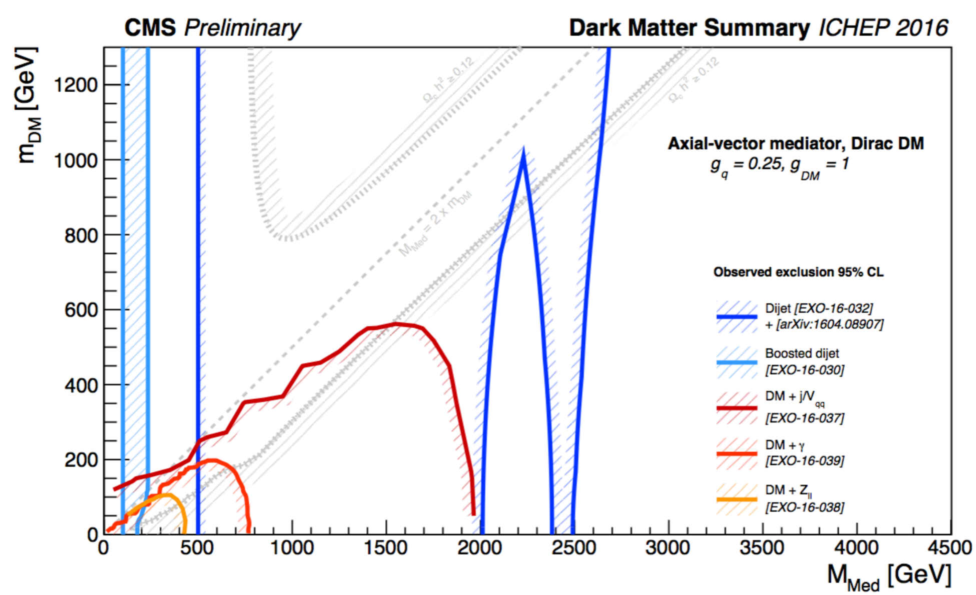
	ATLAS	CMS
Low-mass (ISR)	**ATLAS-CONF 2016-070**	CMS-PAS-EXO-16-030
Low-mass (TLA)	ATLAS-CONF 2016-030	**CMS-PAS-EXO-16-032**
High-mass	**ATLAS-CONF 2016-069**	

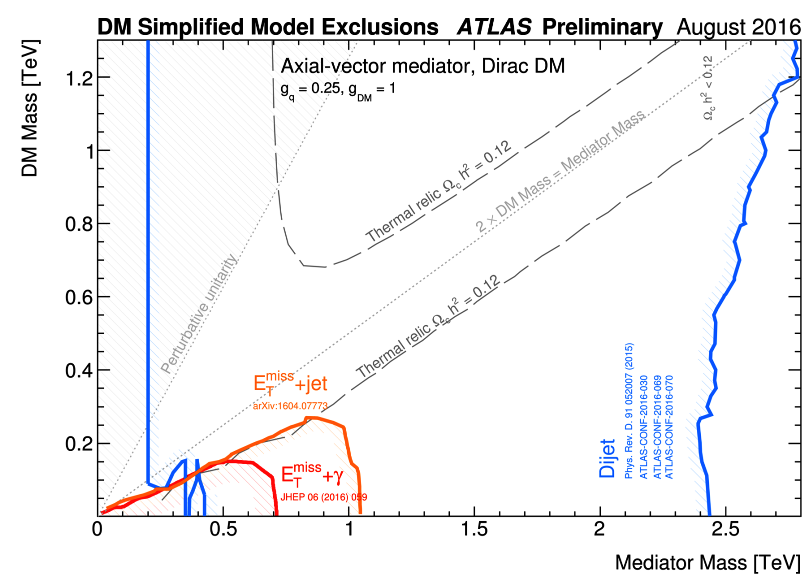






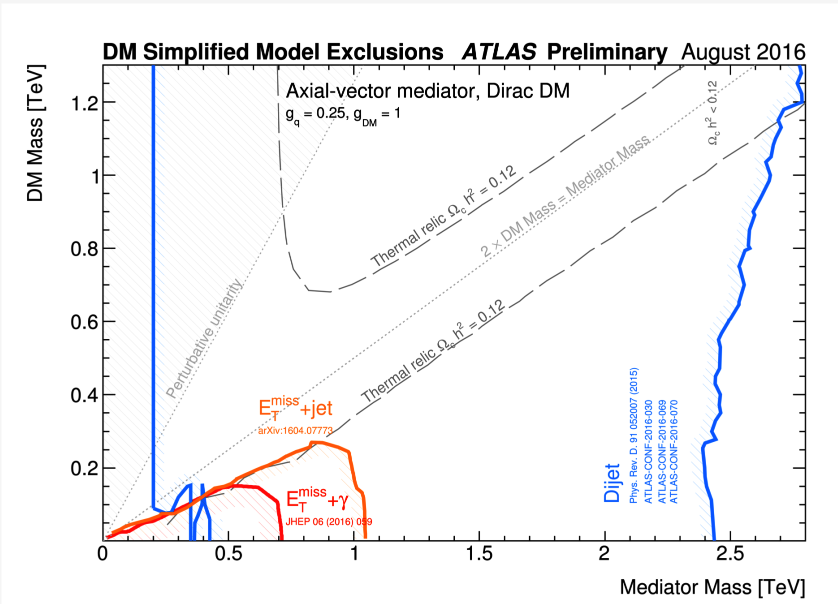
Summary: axial-vector mediator



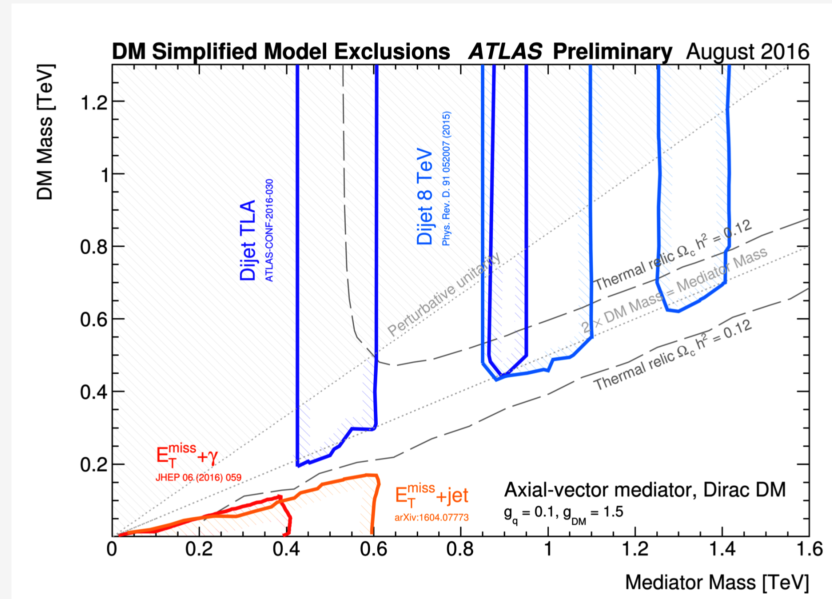


Mono-jet / dijet interplay

g_q=0.25, g_{DM}=1



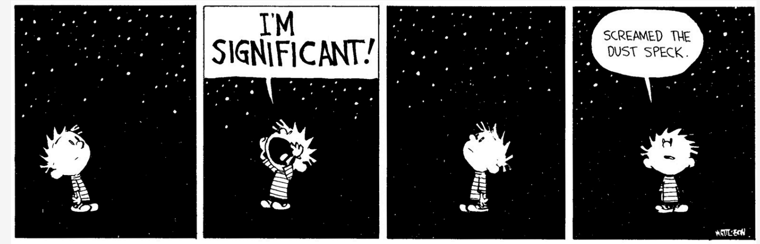
g_q=0.1, g_{DM}=1.5



The interplay depends on the couplings…
Complementary approaches to probe the DM parameter space thoroughly

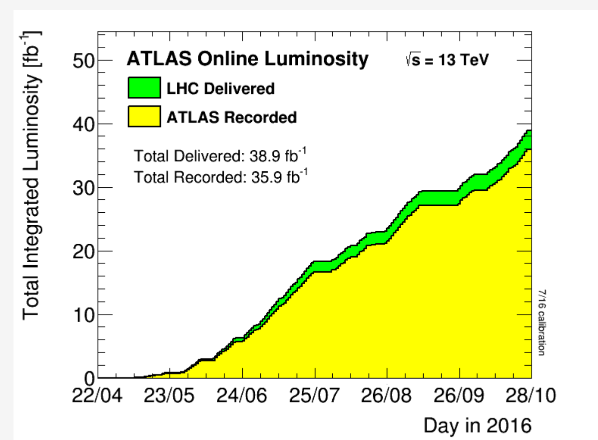
Summary

- Many new results by CMS and ATLAS this summer
  - No significant excess seen
  - Complementary to other DM searches

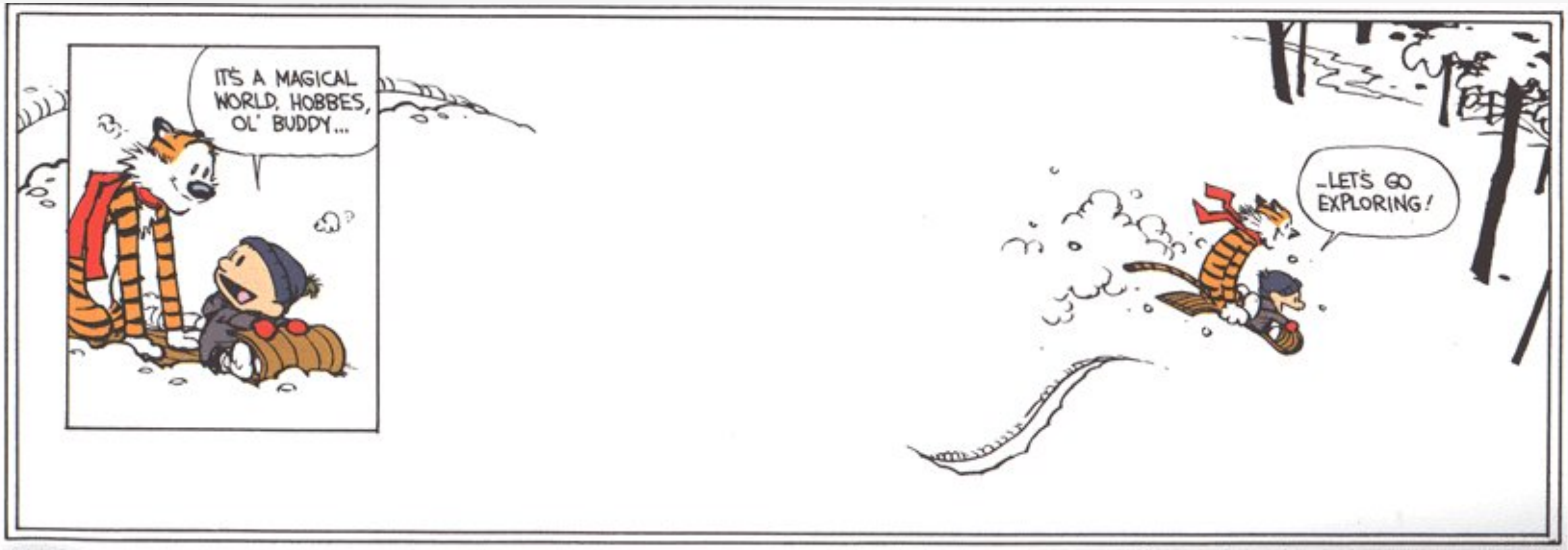


- Quickly evolving field; lively discussions in the LHC DM WG
  - New focus in run-2 on simplified models
  - Using various complementary searches / combinations to probe the parameter space

- Results being prepared with the full dataset (36-38 fb^{-1}) recorded in 2016



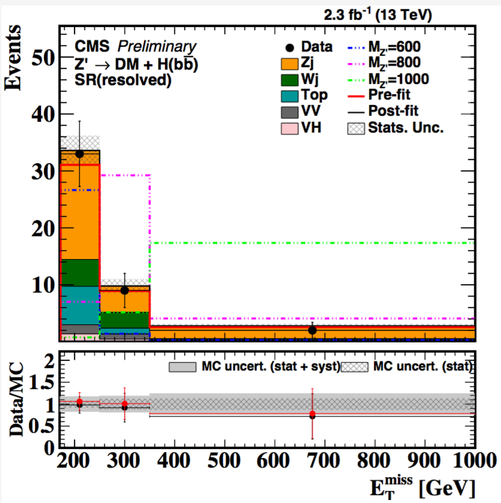
Stay tuned!

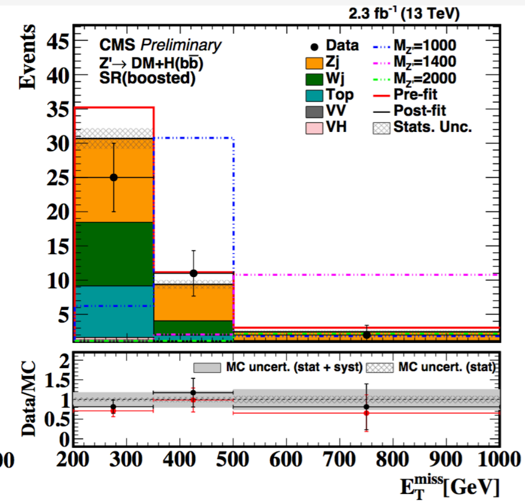

IT'S A MAGICAL WORLD, HOBBES, OL' BUDDY...
...LET'S GO EXPLORING!

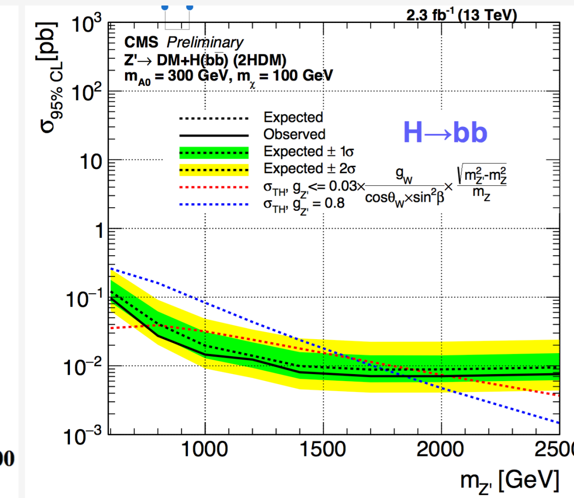
$E_T^{miss} + h(bb)$ in CMS

CMS:

- Resolved: 2 AK4 b-tagged jets, $p_T(bb)$ / E_T^{miss} > 150 / 170 GeV
- Boosted: 1 AK8 jet with subjets b-tagged, p_{Tj} / E_T^{miss} > 200 GeV







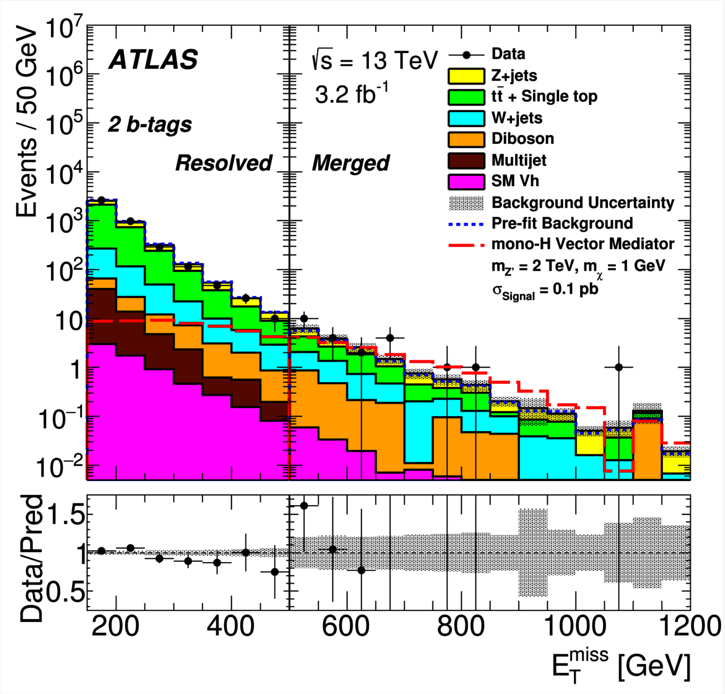
E_T^{miss} + h(bb) in ATLAS

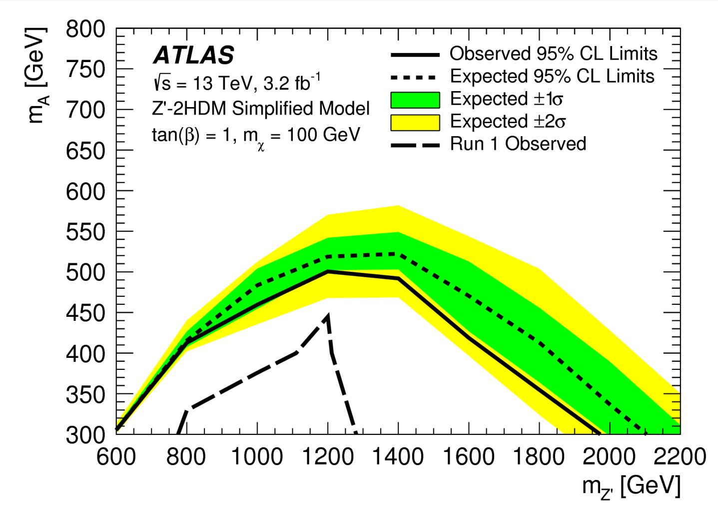
- The two b-jets from Higgs decay can be resolved or merged into a fat jet, depending on the boost : cover both possibilities

Resolved	Boosted
$150 < E_T^{miss} < 500$ GeV (split in 3 regions)	$E_T^{miss} > 500$ GeV
≥ 2 jets, ranked by b-tagging, centrality and p_T	≥ 1 large-R jet associated with ≥ 2 track jets
The 2 highest ranked reconstruct the Higgs mass	Split in different b-tagging categories
Large p_T sum of the jets, $j_{h,1}$ or $j_{h,2}$ has p_T>45 GeV	Shape fit of the large-R mass distribution
Df(jets, E_T^{miss})>20°	$p_T^{miss} > 30$ GeV
$p_T^{miss} > 30$ GeV and Df(p_T^{miss}, E_T^{miss})<p/2	
Df(E_T^{miss},h_{bb})>120°	
Df($j_{h,1}$, $j_{h,2}$)<140°	
Veto on leptons	

- The main BG is top pairs, Z(νν)+jets, W+jets
  - Use mass sidebands + leptonic CRs

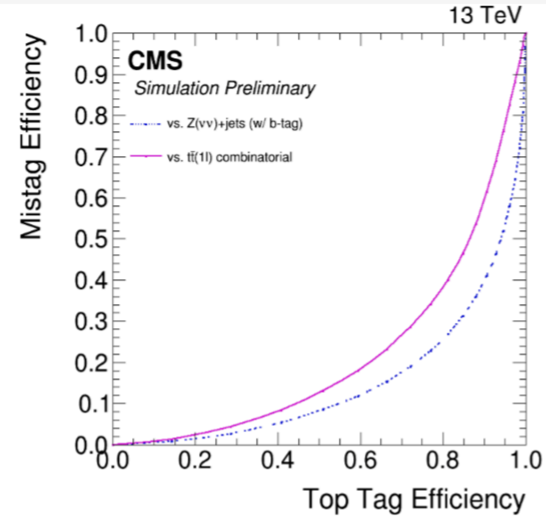
$E_T^{miss} + h(bb)$ in ATLAS

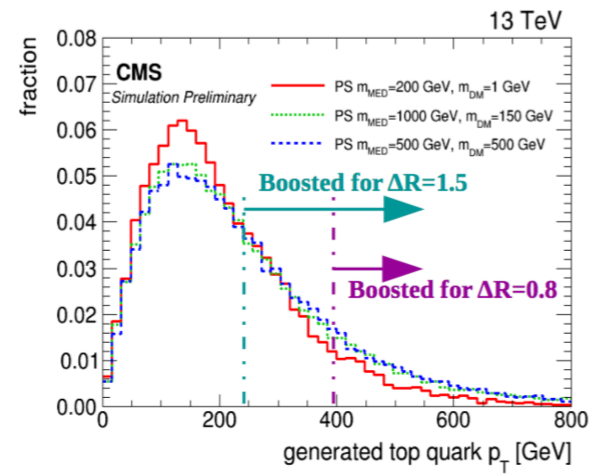




Resolved top tagger in CMS

- MVA discriminant to identify tri-jet combinations from top quark decays
- Training a BDT with simulated $t\bar{t}$ events
- Input variables:
  - Kinematic fit probability
  - b-tag discriminant
  - Quark/gluon likelihood
  - $\Delta R(j_1,b)$, $\Delta R(j_2,b)$
  - $\Delta\varphi(j_1,b)$, $\Delta\varphi(j_2,b)$
- Efficiencies in MC calibrated with $t\bar{t}$ events in data
- Tops in $t\bar{t}$+DM production generally have moderate p_T

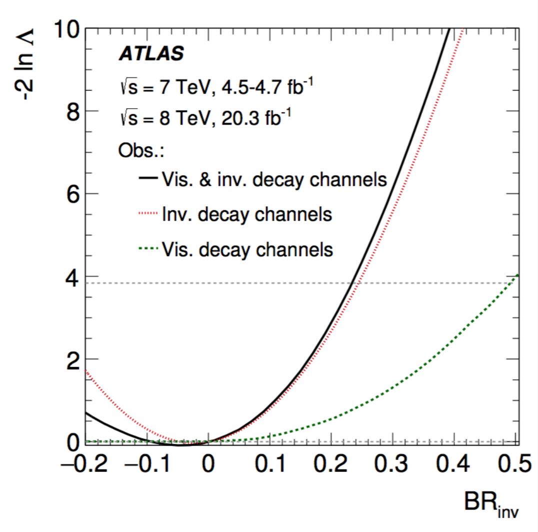


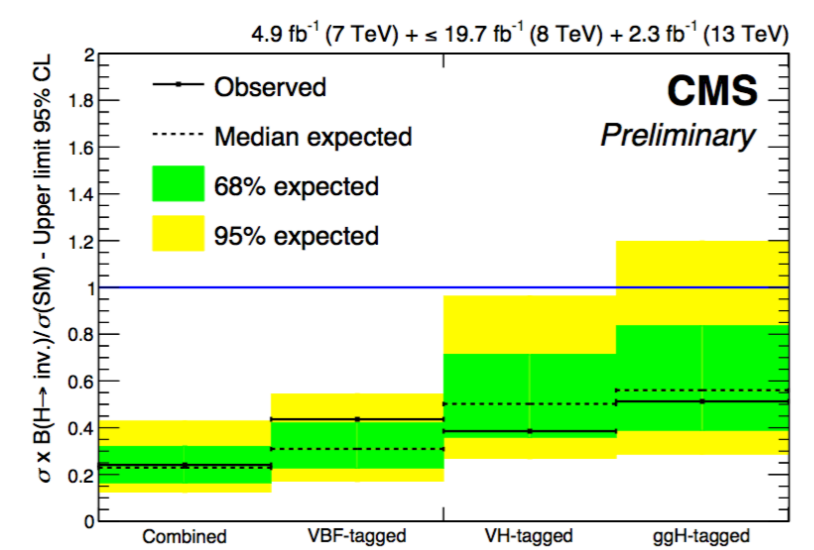


CMS-PAS-EXO-16-005

Higgs portal

Channel	Expected	Observed
VBF	0.31	0.28
V(jj)H	0.86	0.78
$Z(\ell\ell)$H	0.62	0.75
Combine	0.27	0.25





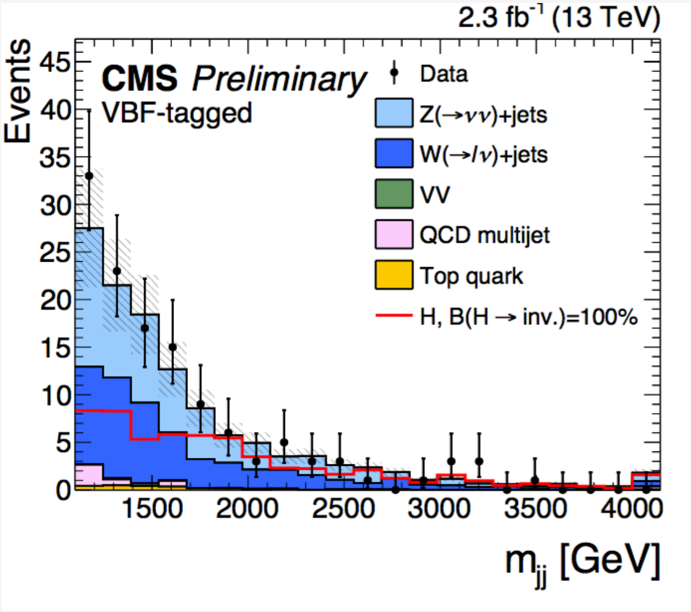
E_T^{miss} + VBF in CMS

CMS-PAS-HIG-16-016

Selection:

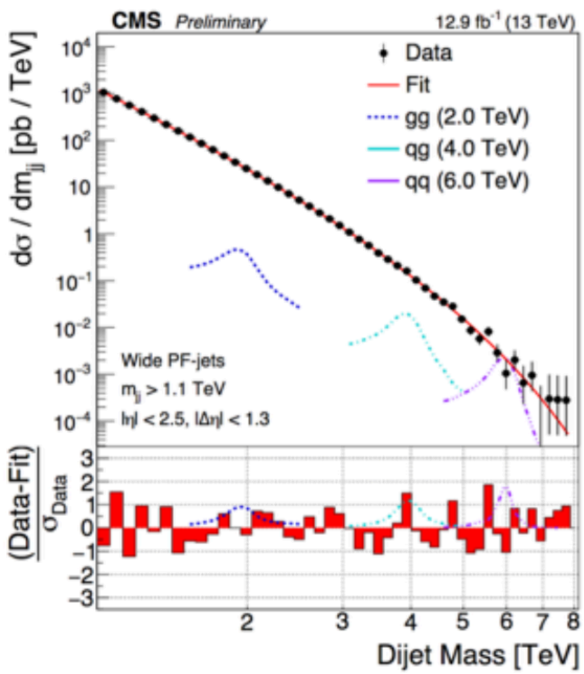
- $p_{T,j1(j2)} > 80\ (70)$ GeV, $\Delta\eta(j_1,j_2) > 3.6$, $m_{jj} > 1.1$ TeV
- $E_T^{miss} > 200$ GeV and $\Delta\phi(jet, E_T^{miss}) > 2.3$

BG estimation through W/Z CRs

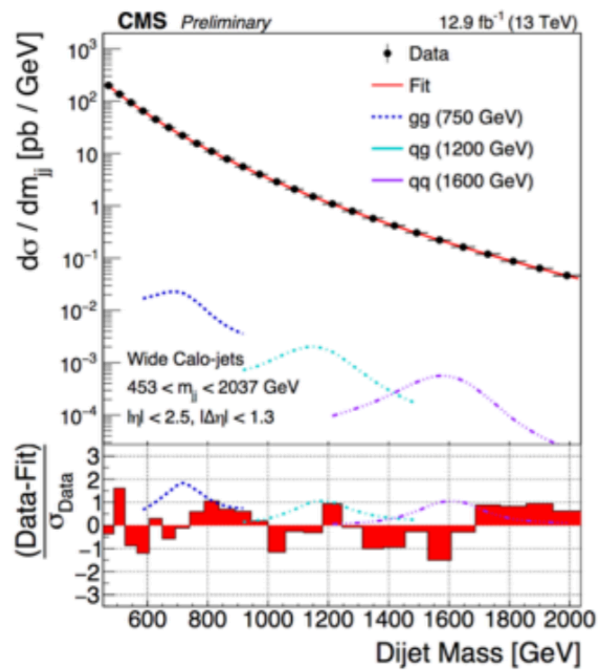


CMS dijet searches

High mass



With trigger



With ISR