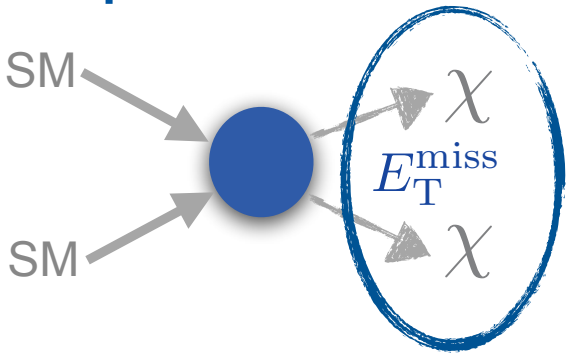
Searches for Missing Transverse Momentum and Standard Model Particles at the LHC

Dark Matter @ LHC 2019, Seattle

Nicolas Köhler

DM production in association with SM particles

- WIMPs escape the detector without interactions
  - Looking for signatures with large missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$
- However, need additional visible particle for triggering event readout and boost WIMP system



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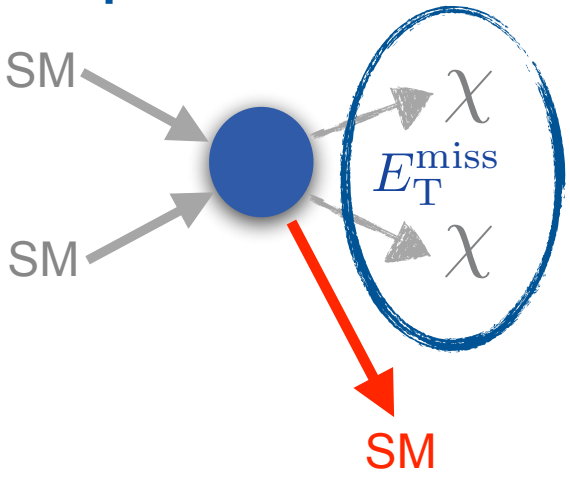

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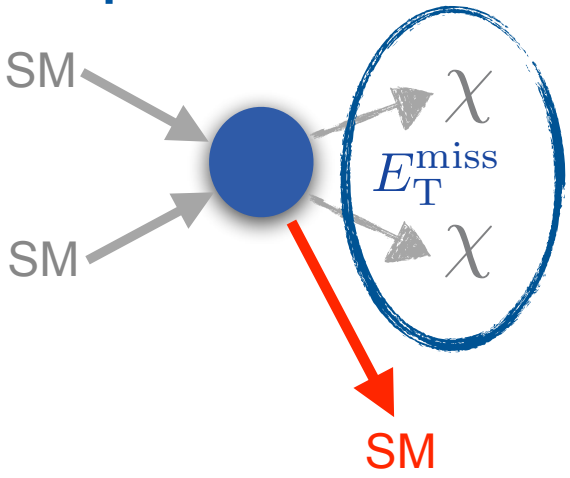
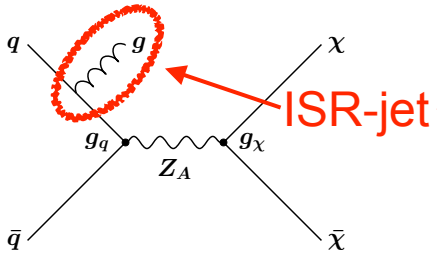
- This talk focusses on associated production with SM particles
- BSM particles (i.e. in heavy flavor final states) covered in next talk by B. Kilminster
- Di-jet mediator searches covered by K. Whalen



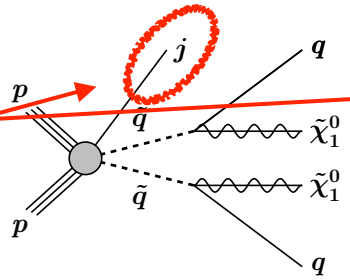
$E_{\mathrm{T}}^{\mathrm{miss}}$ and a high-energetic jet (Mono-Jet)

Axial mediator

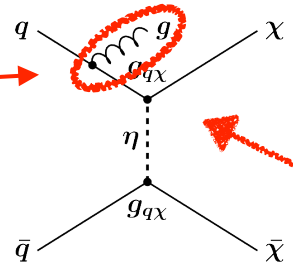


ISR-jet

SUSY



Scalar (color-charged) mediator



Sensitivity only in Mono-X

- Models with vector-like mediator, color-charged mediator or even full SUSY models can result in final states with one high-energetic jet and $E_{\mathrm{T}}^{\mathrm{miss}}$

$E_{\mathrm{T}}^{\mathrm{miss}}$ and a high-energetic jet (Mono-Jet)

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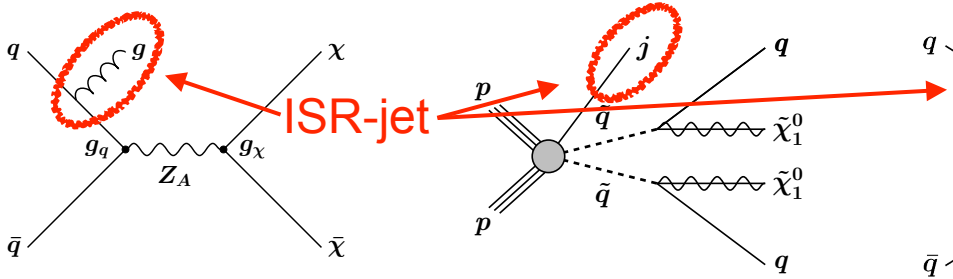

SUSY

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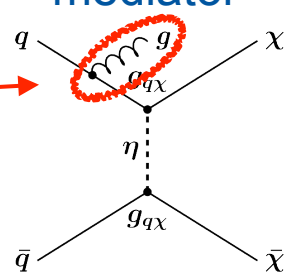
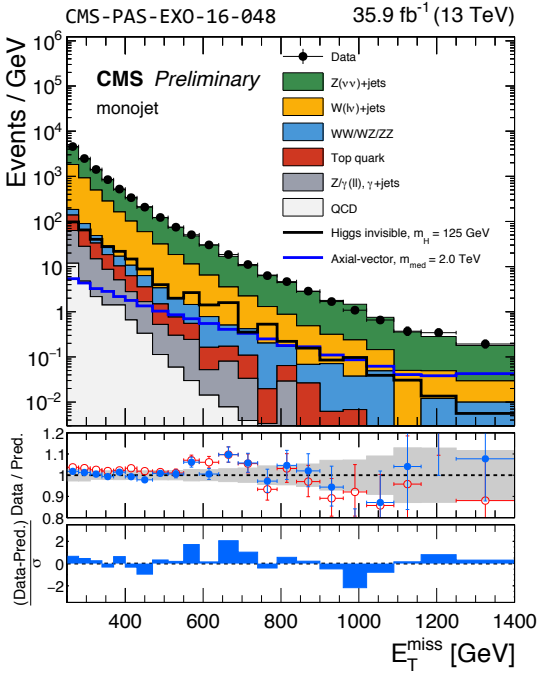


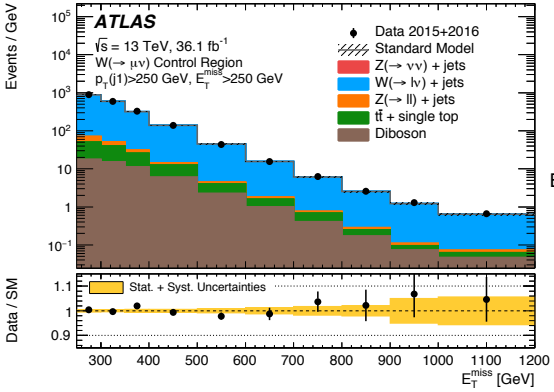
- Models with vector-like mediator, color-charged mediator or even full SUSY models can result in final states with one high-energetic jet and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Looking for excess on top of *Z*/*W*+jets production
- Search performed by both ATLAS and CMS using 2015 and 2016 LHC Data



Mono-Jet analyses

- *Z*/*W*+jets and $t\bar{t}$ production estimated from Data using 1/2-lepton control regions

$W(\rightarrow \mu + \nu)$ + jets



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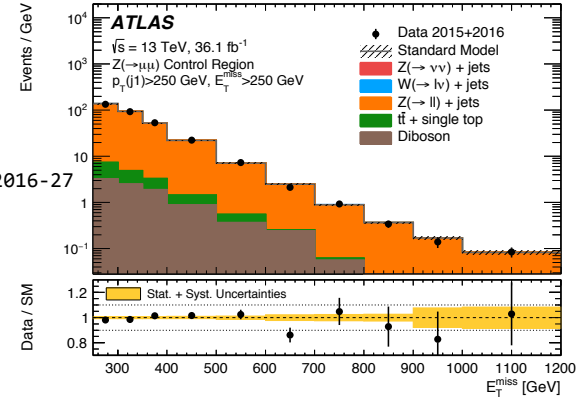
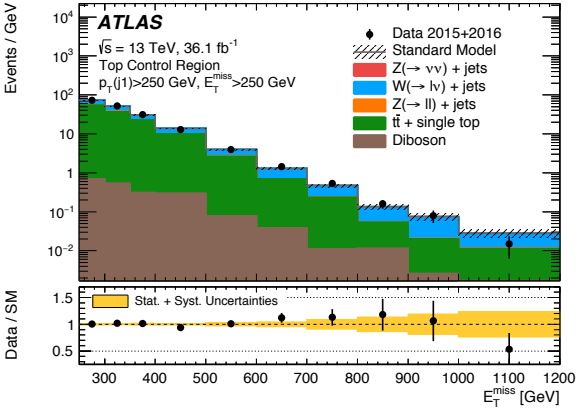


EXOT-2016-27

Semileptonic $t\bar{t}$



1 lepton CR

30 GeV < $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$ < 100 GeV

$Z \rightarrow \mu\mu$ CR

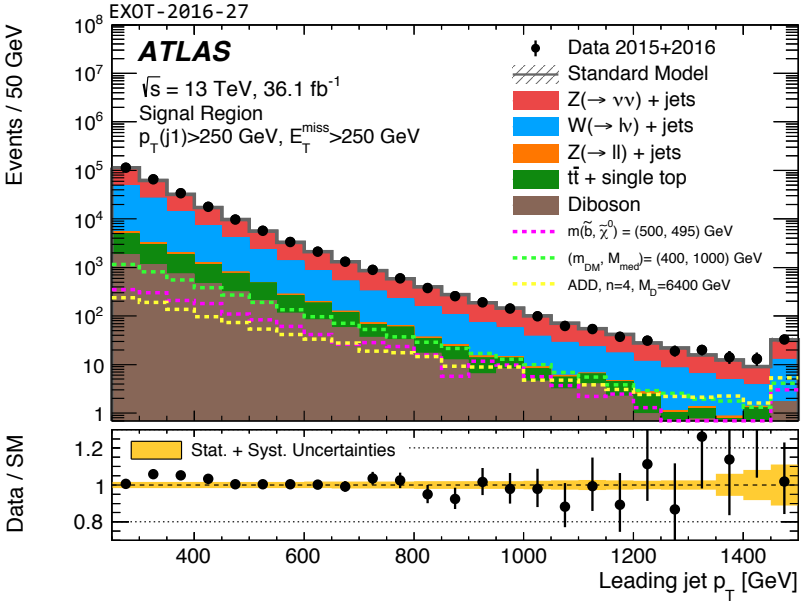
W+jets + 1 b-jet CR

- Estimate normalization of background processes to scale MC in signal regions

Mono-Jet analyses

- Further requirements to suppress SM backgrounds:

- **ATLAS** vetoes events containing more than four jets
  - Dominating systematic uncertainties: Lepton identification and reconstruction efficiencies in control region estimates, jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ energy scale and resolution
- **CMS** vetoes events with b-jets to suppress backgrounds involving top quarks
  - Dominating systematic uncertainties: Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ energy scale and resolution, $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency
- No excess above SM expectation observed
- Set exclusion limits on DM and mediator masses



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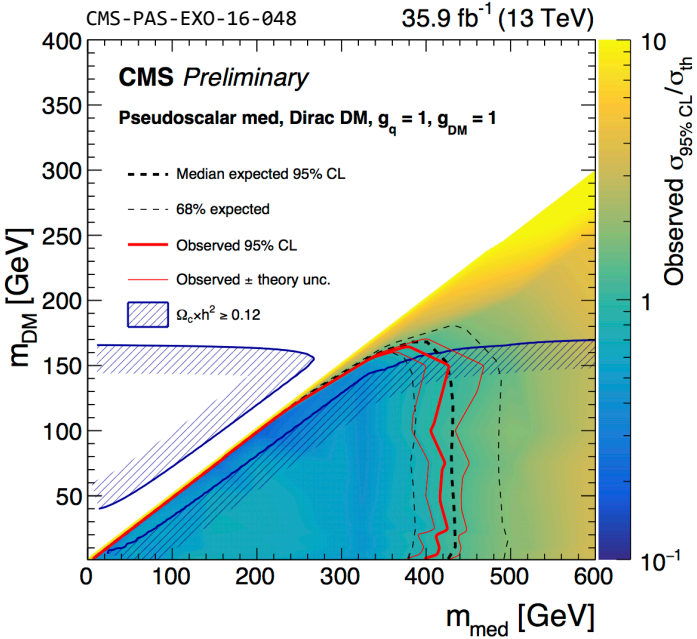
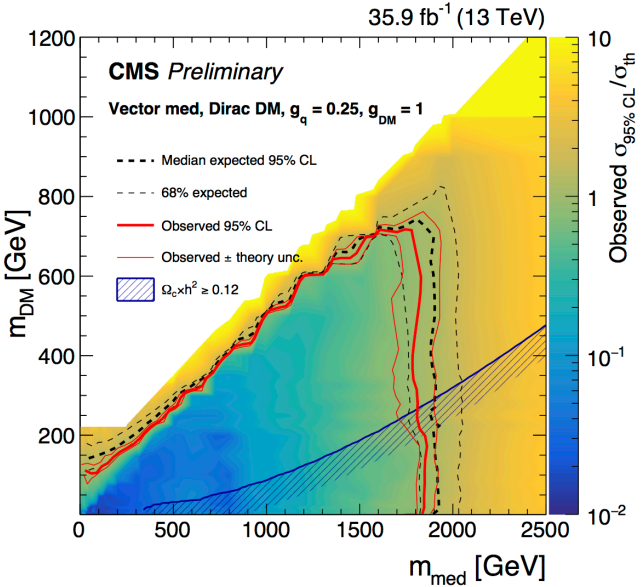


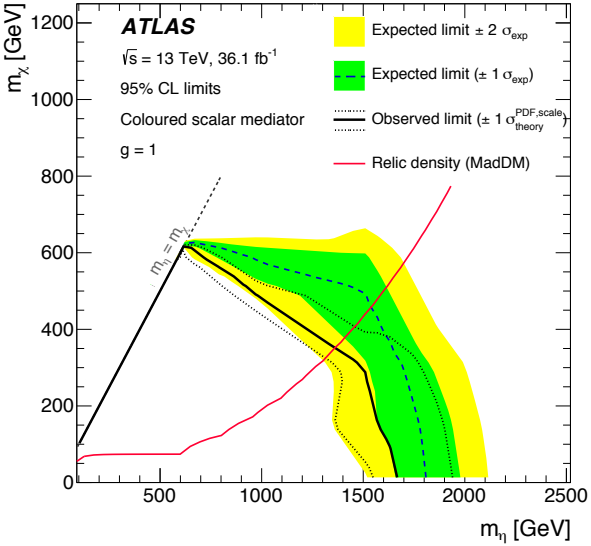
Mono-Jet results

Vector mediator

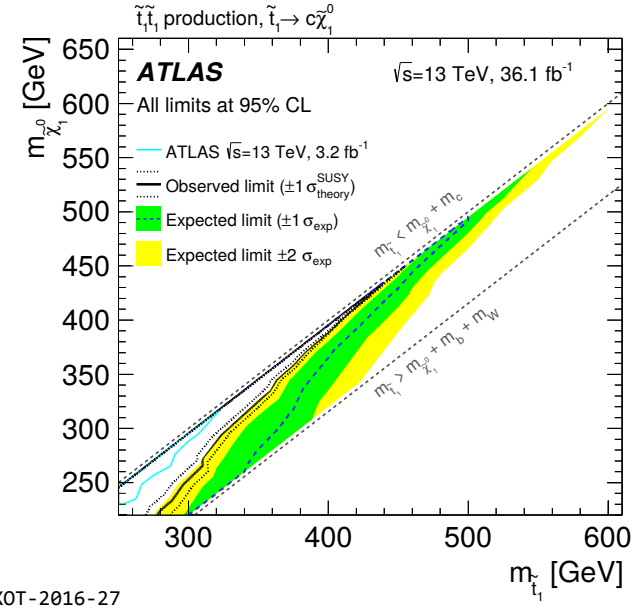


CMS-PAS-EXO-16-048

Scalar (color-charged) mediator



SUSY compressed stop



EXOT-2016-27

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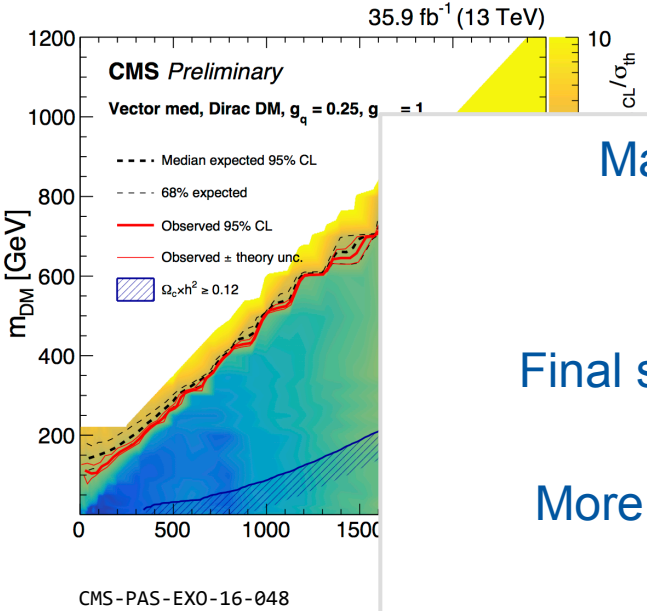

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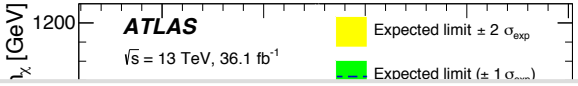

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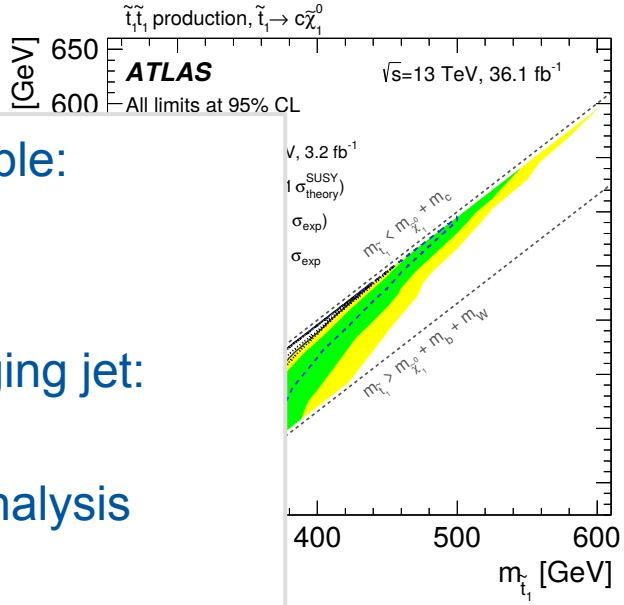


Many more interpretations possible:

ATLAS: EXOT-2016-27

CMS: CMS-PAS-EXO-16-048

Final state with Mono-Jet and emerging jet:

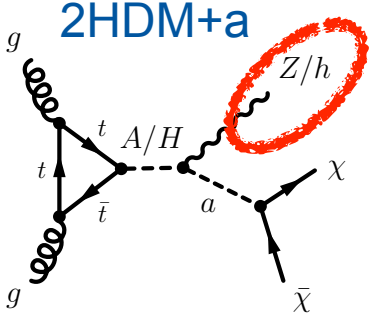
CMS-EXO-18-001

More details on ATLAS Mono-Jet analysis in J. Lindon's talk

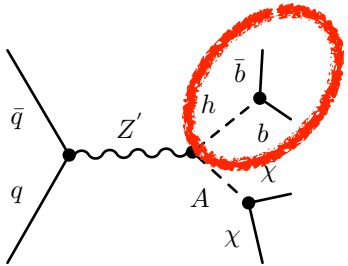
$E_{\mathrm{T}}^{\mathrm{miss}}$ and a Higgs boson

- The Higgs boson couples to every massive particle, why not to Dark Matter?
- Possible to look for invisible Higgs decays as well as for DM production in association of a Higgs boson
- Invisible Higgs decays covered by A. Elliot
- Production in association with Higgs boson realized in extended 2HDM or baryonic Z' models
- Searches performed by ATLAS (79.8fb^{-1}) and CMS (35.9fb^{-1})

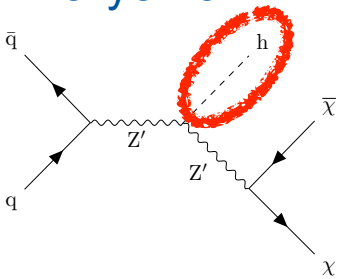
2HDM+a



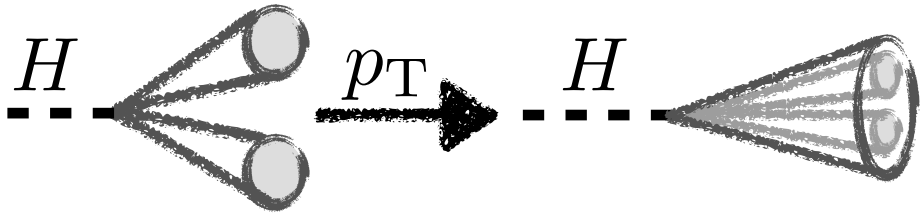
Z' 2HDM



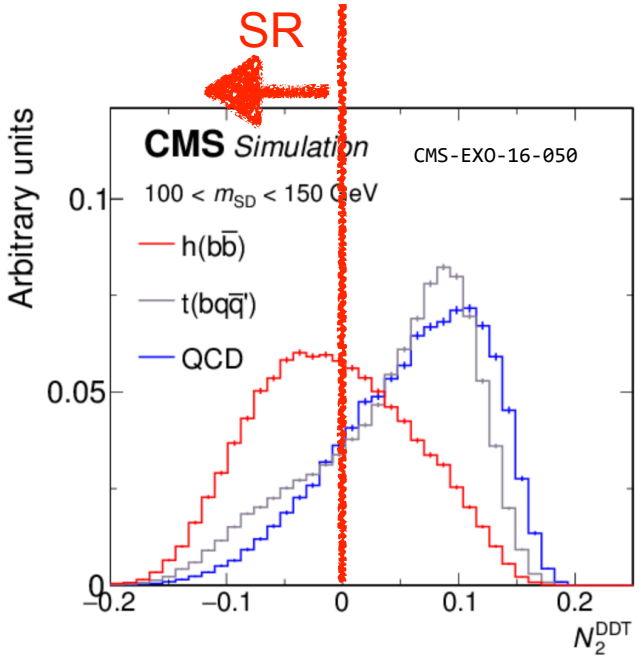
Baryonic Z'



$H(\rightarrow b\bar{b}) + E_{\mathrm{T}}^{\mathrm{miss}}$



- Dominating Higgs decay is $H \rightarrow b\bar{b}$
- Large sensitivity for boosted Higgs scenarios
- Veto leptons, require large $E_{\mathrm{T}}^{\mathrm{miss}}$
- **CMS** exploits $R = 1.5$ jets using the Cambridge-Aachen algorithm for boosted Higgs bosons ($p_{\mathrm{T}} > 200$ GeV)
- Use multivariate discriminant N_2^{DDT} to select jets containing *b*-quarks



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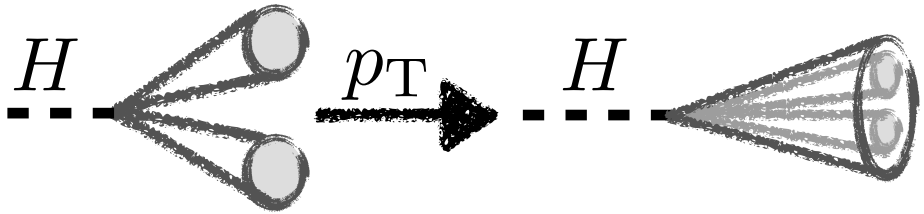

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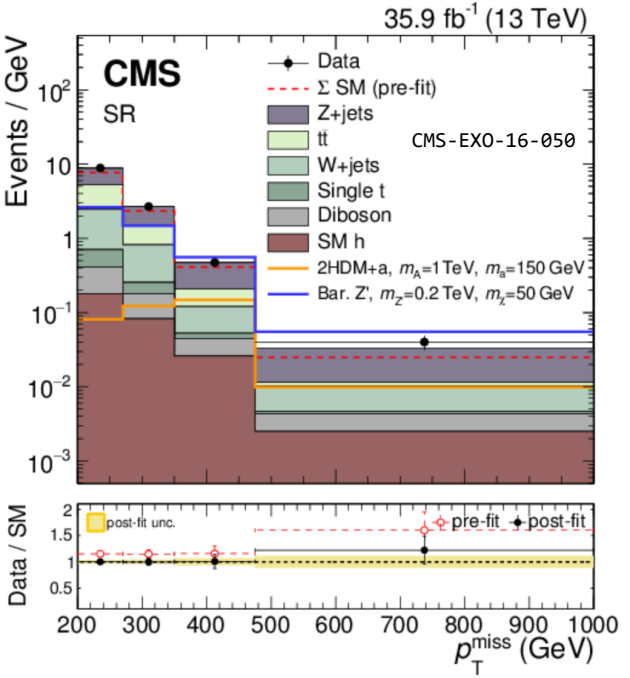
- Remaining backgrounds: Z+jets, $t\bar{t}$
- Estimated in 1L regions w/o b-tagged anti-k_{T} $R = 0.4$ jet outside the $R = 1.5$ jet



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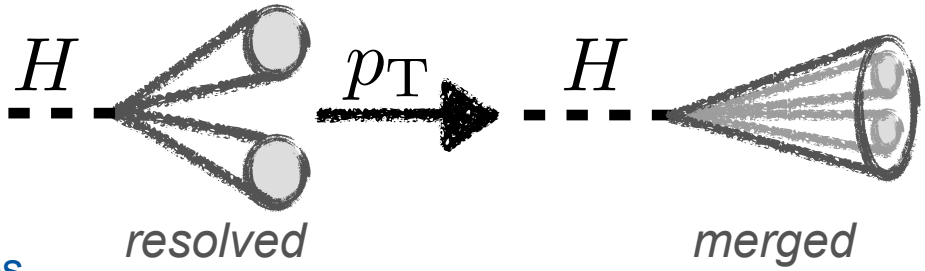

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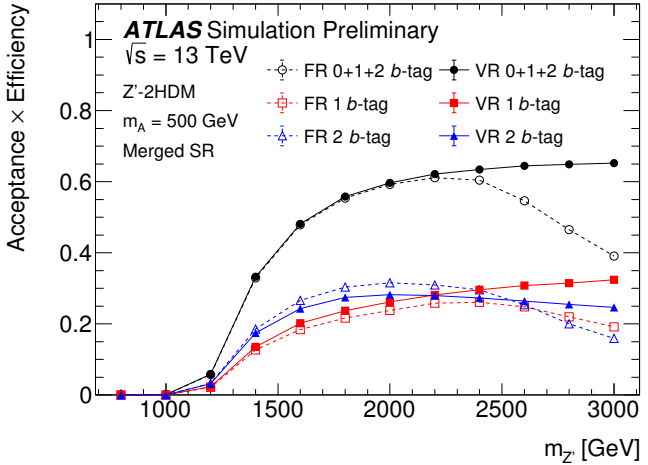
- Use $R = 0.4$ anti-k_{T} jets for *resolved* and R=1.0 anti-k_{T} jets for *merged*, *b*-tag variable-*R* ($\sim 1/p_{\mathrm{T}}$) track-jets that are matched to $R = 1.0$ jets

ATLAS-CONF-2018-039



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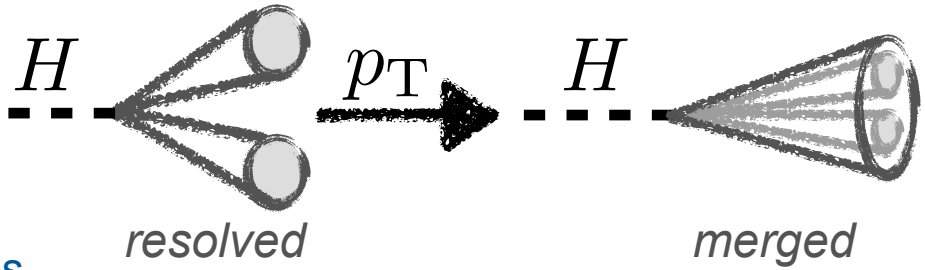

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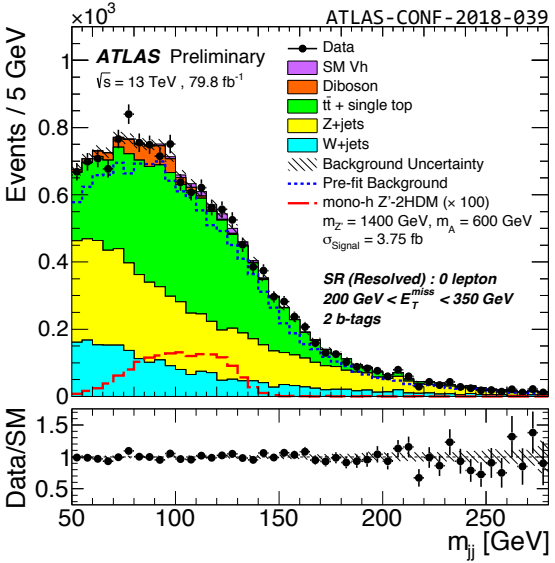
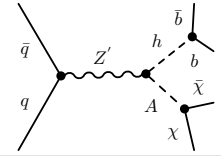
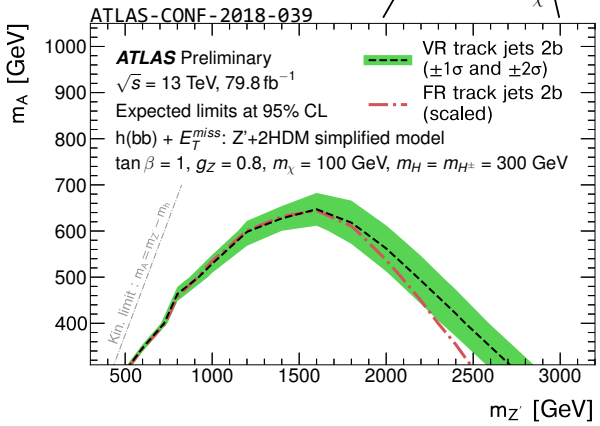
- Looking at m_{jj} in different bins of $E_{\mathrm{T}}^{\mathrm{miss}}$
- Remaining backgrounds: *Z*+jets, $t\bar{t}$ (resolved), mainly *Z*+jets (merged)
- Estimated in 1L and 2L control regions



$H(\to b\bar{b}) + E_{\mathrm{T}}^{\mathrm{miss}}$ results

Z' 2HDM





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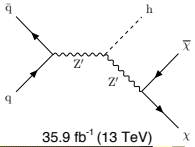
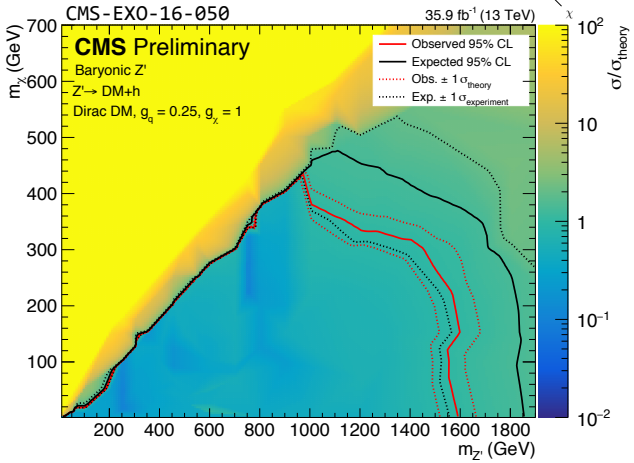
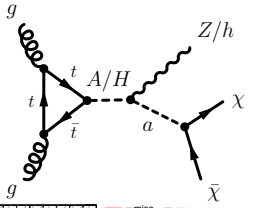
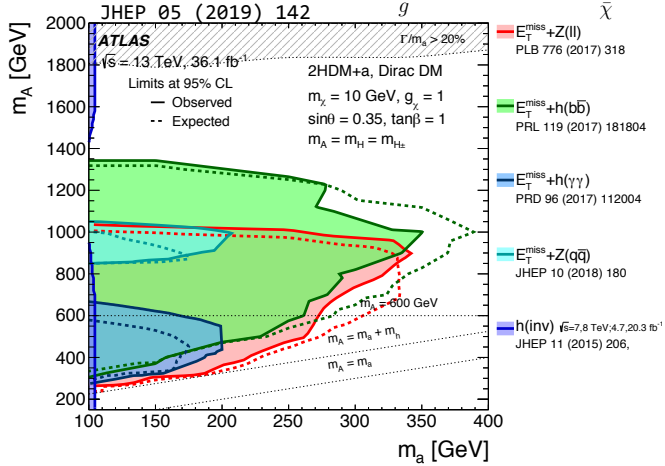




2HDM+a

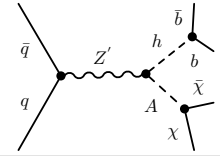


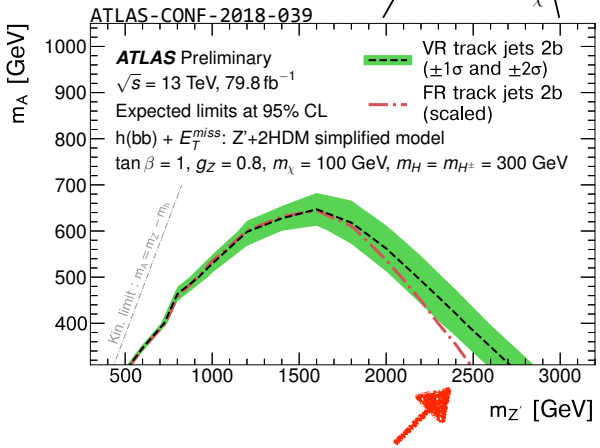


- WIMP masses up to 500GeV excluded in Z' model
- First results on 2HDM+a model

$H(\to b\bar{b}) + E_{\mathrm{T}}^{\mathrm{miss}}$ results

Z' 2HDM





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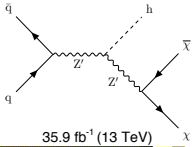
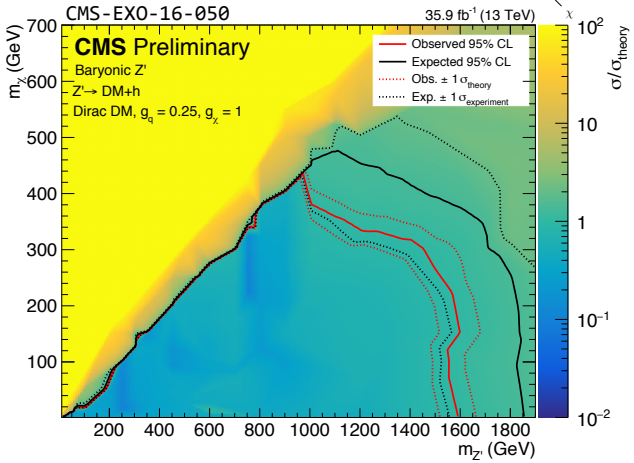
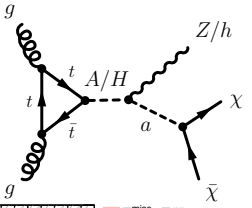
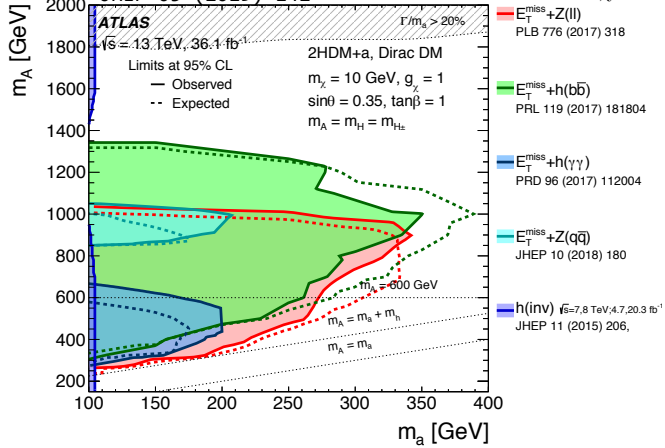




2HDM+a





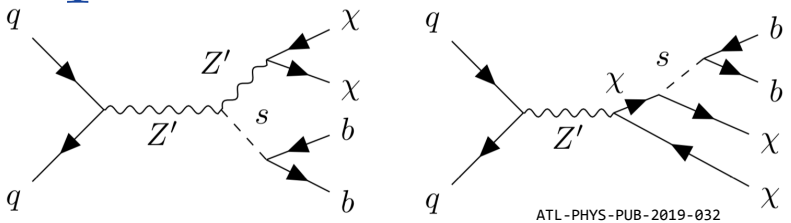
Improvement due to usage of VR track-jets

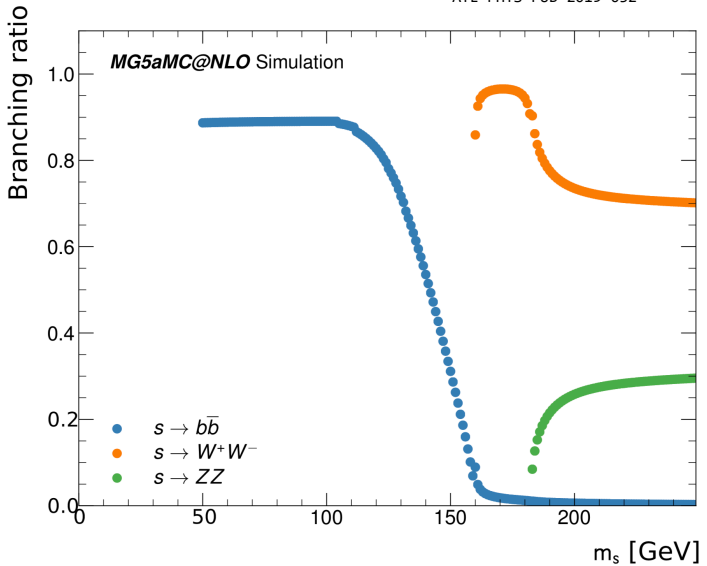
- WIMP masses up to 500GeV excluded in Z' model
- First results on 2HDM+a model

Reinterpreting the $H(\to b\bar{b}) + E_{\mathrm{T}}^{\mathrm{miss}}$ results

NEW!

- Looking at Dark Matter production in association with a hypothetical dark Higgs boson *s* decaying into a pair of b-quarks
- DM mass is generated by Higgs mechanism in the dark sector
- Can relax the DM relic abundance constraints by $\chi\chi \to ss$ annihilation
- Dark Higgs can have any mass
- Reinterpreted `ATLAS 2015-2017` Mono-*H* analysis
- For more information cf. poster of A. Schuy: *RECAST for Mono-S(bb) with ATLAS*

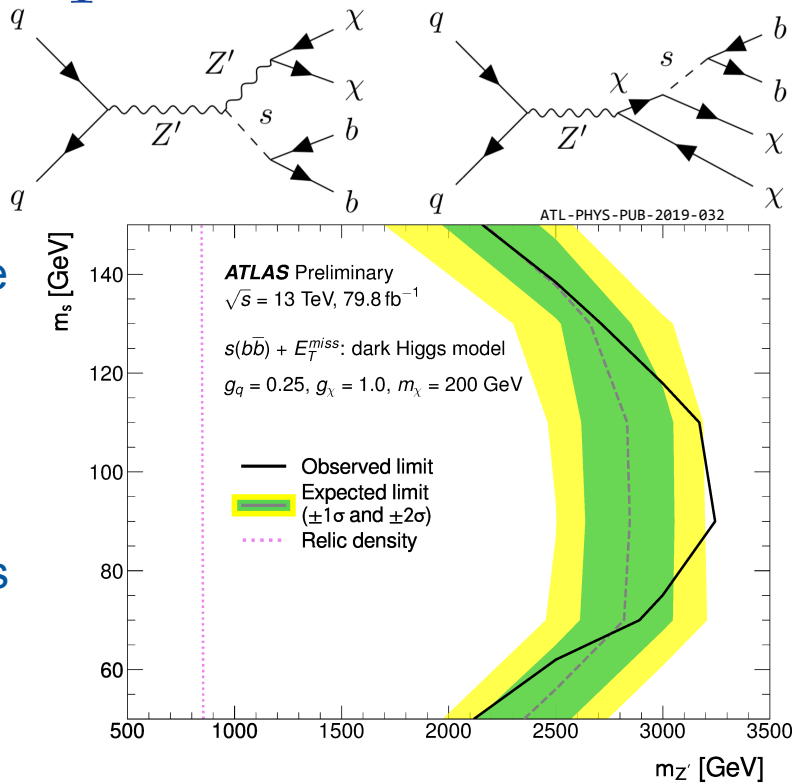




Reinterpreting the $H(\to b\bar{b}) + E_{\mathrm{T}}^{\mathrm{miss}}$ results

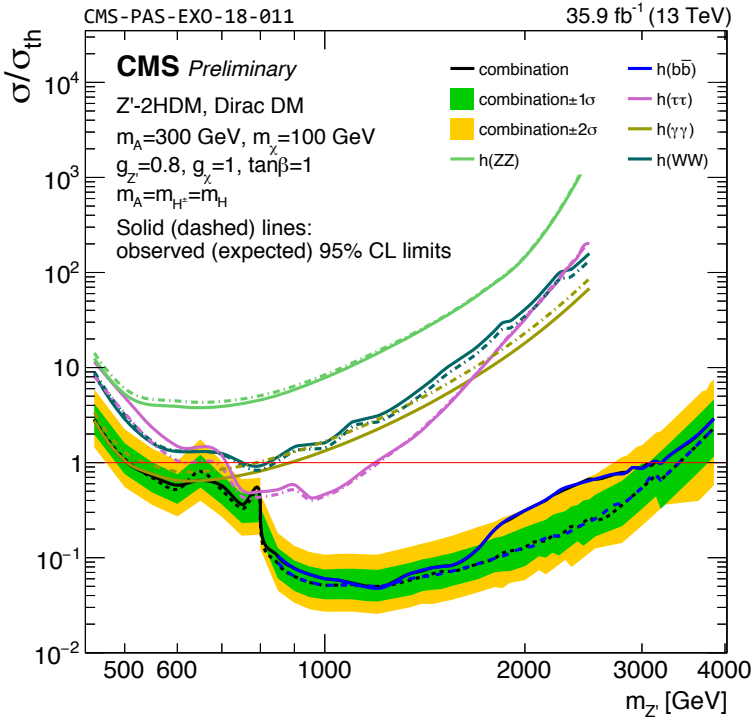
NEW!

- Looking at Dark Matter production in association with a hypothetical dark Higgs boson *s* decaying into a pair of b-quarks
- DM mass is generated by Higgs mechanism in the dark sector
- Can relax the DM relic abundance constraints by $\chi\chi \to ss$ annihilation
- Dark Higgs can have any mass
- Reinterpreted ATLAS 2015-2017 Mono-*H* analysis
- For more information cf. poster of A. Schuy: *RECAST for Mono-S(bb) with ATLAS*

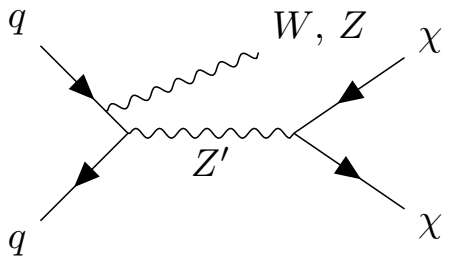


$E_{\mathrm{T}}^{\mathrm{miss}}$ and a Higgs boson: Other decay channels

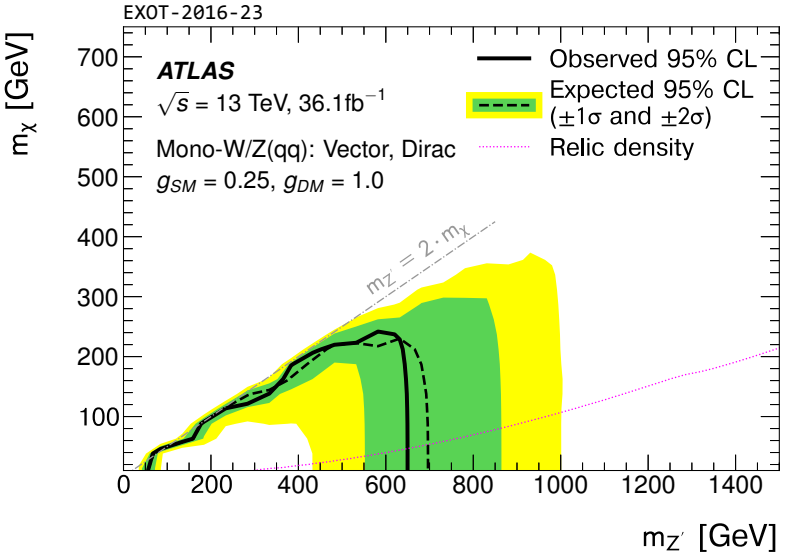
- $H \to \gamma\gamma$ channel: increased sensitivity towards low $E_{\mathrm{T}}^{\mathrm{miss}}$, better mass resolution:
  `ATLAS: Phys. Rev. D 96 (2017) 112004`
  `CMS: JHEP 09 (2018) 046`
- $H \to \tau\tau$ channel (hadronic and semi-leptonic taus): less SM background contributions, increased sensitivity towards low $E_{\mathrm{T}}^{\mathrm{miss}}$
  `CMS: JHEP 09 (2018) 046`
- $H \to ZZ$ channel (leptonic final states): low SM backgrounds, good mass resolution, but low branching ratio
  `CMS: PAS EXO-18-011`
- $H \to W^+W^-$ channel ($e\mu + E_{\mathrm{T}}^{\mathrm{miss}}$ final state): use BDT trained on transverse masses, lepton momenta and angular variables to suppress *WW* and $t\bar{t}$ backgrounds
  `CMS: PAS EXO-18-011`



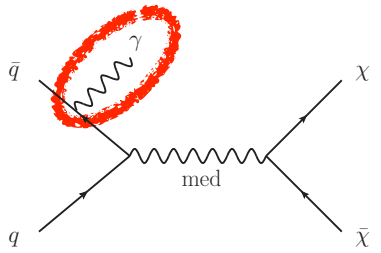
$E_{\mathrm{T}}^{\mathrm{miss}}$ and a *W*/*Z* boson



- Looking for hadronic *W*/*Z* decays
- **CMS** requires anti-k_{T} $R = 0.8$ jets with additional requirements on substructure variables
  - Invariant mass of jet constituents required to be compatible with *W*/*Z* mass (`CMS PAS EXO-16-048`)
- **ATLAS** categorizes into *resolved* and *merged* (as done in Mono-*H*) using anti-k_{T} $R = 1.0$ jets and *b*-jet veto in the *merged* region
  - Fit in $E_{\mathrm{T}}^{\mathrm{miss}}$ is performed
- Interpreted in Z' model (`JHEP 10 (2018) 180`)
- $Z(\rightarrow \ell\ell) + E_{\mathrm{T}}^{\mathrm{miss}}$ in CMS covered by *C. Freer*



$E_{\mathrm{T}}^{\mathrm{miss}}$ and a high energetic photon

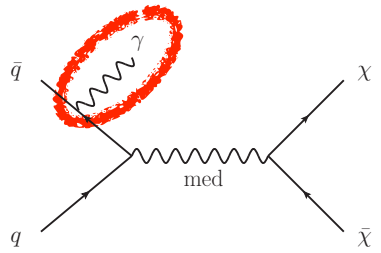


- Photon trigger
- High energetic photon and large $E_{\mathrm{T}}^{\mathrm{miss}}$

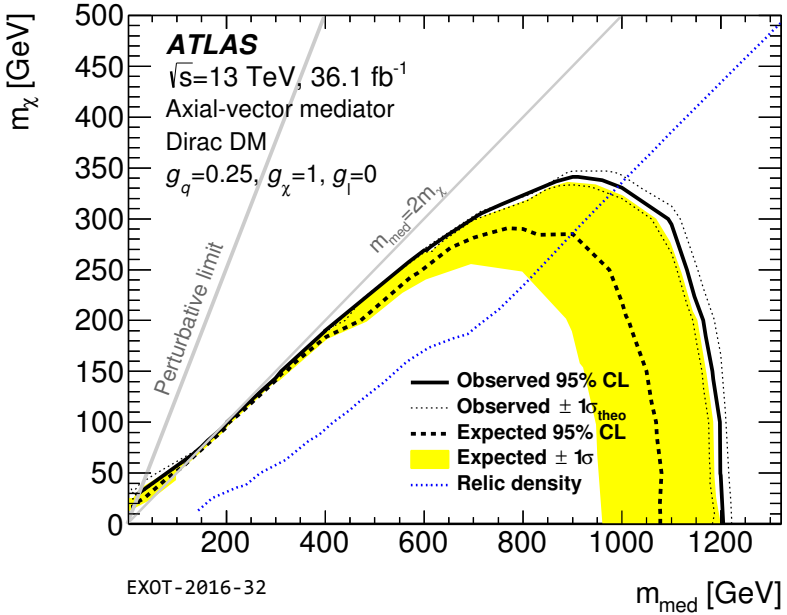
	ATLAS	CMS
γ + jets suppression	$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{\sum E_{\mathrm{T}}} > 8.5\ \sqrt{\mathrm{GeV}}$	$E_{\mathrm{T}}^{\gamma}/E_{\mathrm{T}}^{\mathrm{miss}} < 1.4$
$W\gamma$ suppression	Lepton veto	Lepton veto for $\Delta R(\ell,\gamma) > 0.5$
Signal extraction	Single bin fit	Fit of E_{T}^{γ}

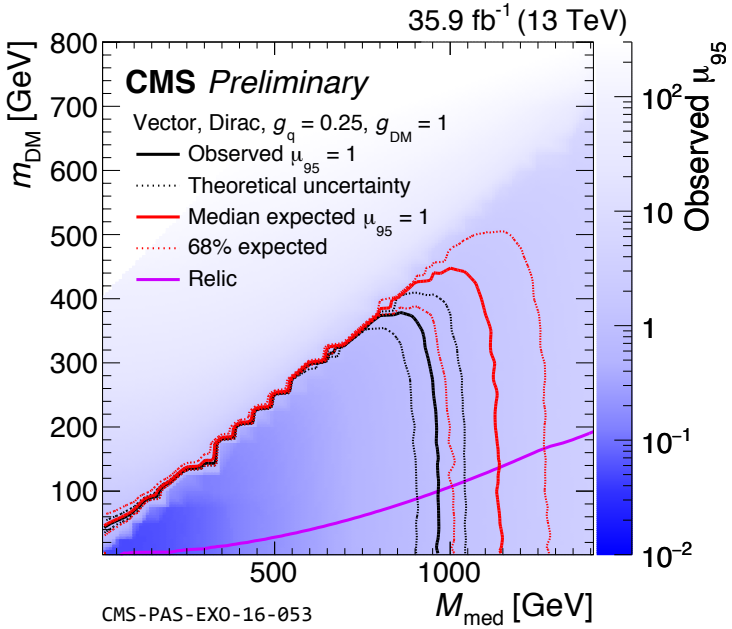
- Remaining backgrounds: $Z\gamma$ and $W\gamma$
- Dominating uncertainties: Photon fake estimation, jet energy scale, statistical uncertainty in control regions

$E_{\mathrm{T}}^{\mathrm{miss}}$ and a high energetic photon



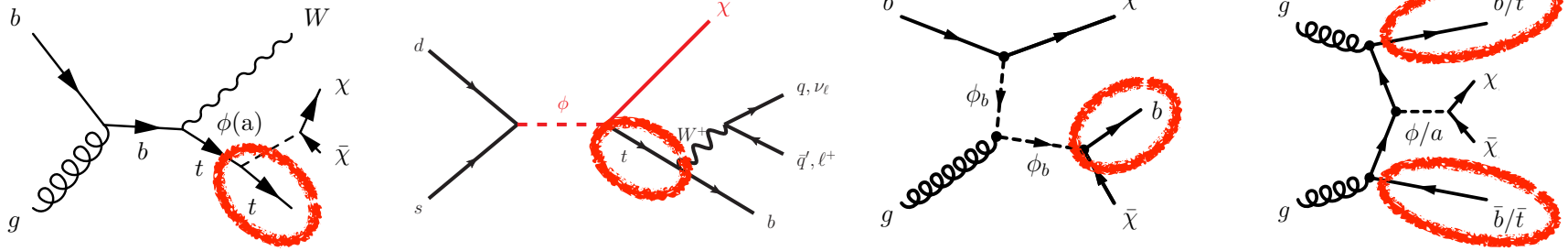
Setting exclusion limits based on 2015-16 dataset:





$E_{\mathrm{T}}^{\mathrm{miss}}$ and a top/bottom quark

- DM scenarios with minimal flavor violation assume the same Yukawa coupling structure for a DM mediator as for SM particles
  - Coupling to third-generation quarks preferred
- Sensitivity to a variety of different theoretical models including single- and pair-production of heavy flavor quarks



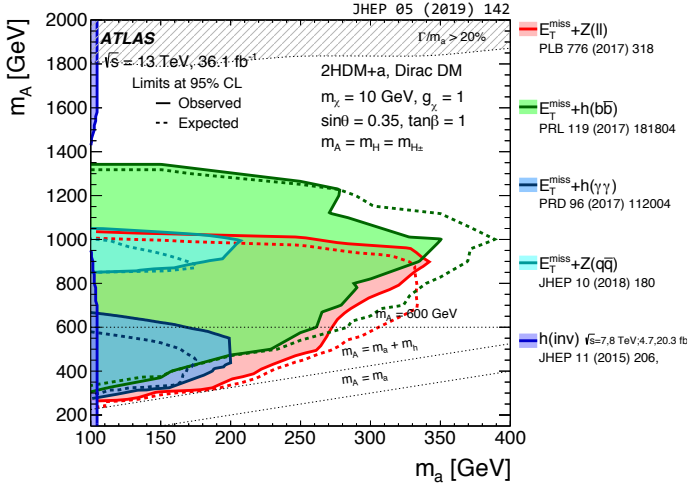
- Final states with heavy flavor quarks and
- Can be reinterpreted in different BSM models, e.g. leptoquarks
  - ***DM and flavor at the LHC*** by B. Kilminster

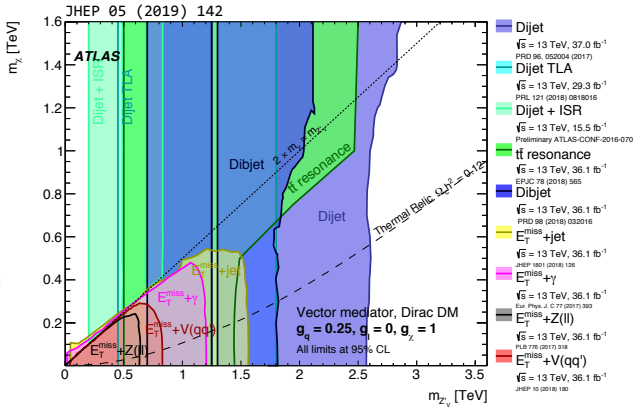
Also have a look at:

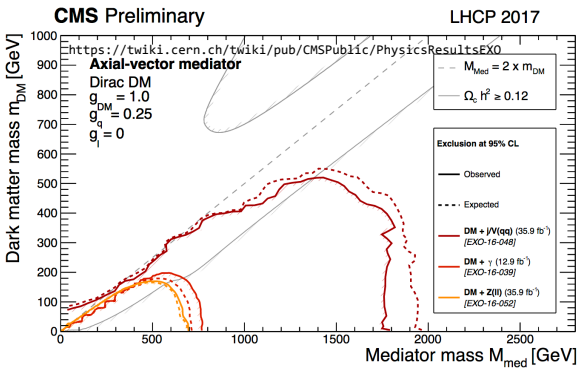
Search for dark matter in third generation quarks in ATLAS by M. Anthony

Summary

- Searches for Dark Matter at the LHC can be performed in a variety of final states
- Focussed on $E_{\mathrm{T}}^{\mathrm{miss}}$+ SM particle production
- Both ATLAS and CMS have a vast Dark Matter search program, but no excess found yet!







- Many analyses still in the pipeline based on the full LHC Run 2 dataset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