Searches for boosted resonances (non-VV) and semi-visible jets with the ATLAS detector

Davide Melini
IFIC Valencia

BOOST24, 31st July 2024

Introduction

The presence of non-visible dark matter (DM) is supported by astronomical observations. Directly probing DM would be a clear evidence for new physics.

At the LHC, DM interacting with the Standard Model (SM) particles can be looked for.

Will focus on two signatures:

- single massive resonances decaying fully hadronically (and in particular boosted)
- DM produced in a particle shower in association with SM particles

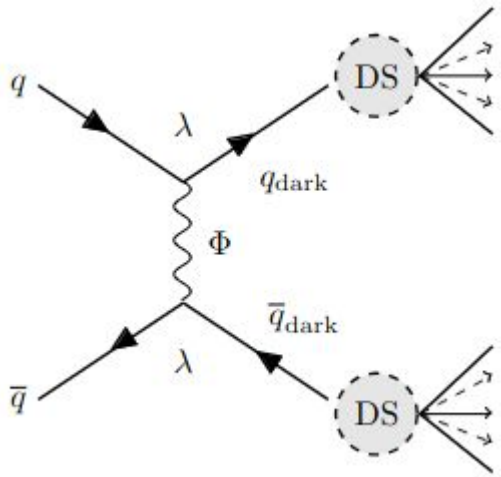
Report three ATLAS analyses exploiting the full Run2 dataset:

- Dark Higgs to bb pair: arXiv:2407.10549
- Semi-visible jets in t-channel: Phys. Lett. B 848 (2024) 138324
- Low mass Z' resonance: CERN-EP-2024-188 (public soon!)

Semi-visible jets (*t*-channel) - intro

Dark sector can be strongly coupled and give rise to showers (dark showers, DS), as parton showers:

- depending on the fraction of stable dark particles (R_{inv}), different experimental signatures possible
  - R_{inv}=1 corresponds to E^T_{miss}(+jets), R_{inv}=0 to multijets production
  - intermediate R_{inv} values give rise to semi-visible jets (SVJ)



News of this search:

- First SVJ search in the *t*-channel
  - there's a *s*-channel search by CMS (JHEP 06 (2021) 156)
- Consider jets "aligned" with E^T_{miss}, as that's a feature of SVJs
  - at least one jet close to E^T_{miss} required
    - angular distance between the E^T_{miss} and the closest jet decreases with higher R_{inv}
  - signature typically discarded in other analyses (mis-measured jets)

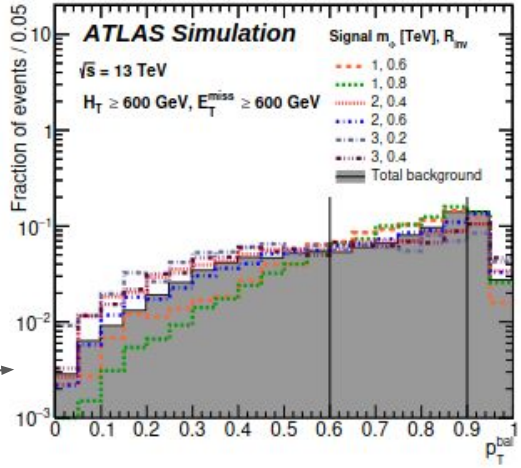
Semi-visible jets (*t*-channel) - event selection

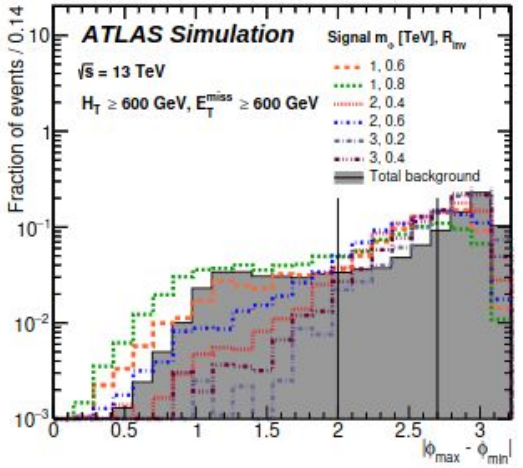
Basic event selection:

- E^{T}_{miss}>600GeV, H_T>600GeV, >=2 R=0.4 jets (one close to E^{T}_{miss})
- dedicated overlap removal, E^{T}_{miss} recomputed if μ present (allow for μ from DS particles)

Signal region defined with {0 leptons, <=1 b-tag}

- use pTbalance and Δϕ of the two jets closest to E^{T}_{miss}
- dominant bkgs are V+jets, VV, ttbar
- bkg MC based, norm constrained in CRs with leptons:
  - {1 μ, 0 b-tag} ; {1 μ, 1 b-tag};{$\mu^+\mu^-$,66GeV<m(μμ)<116GeV}
- additional CR with 250GeV<E^{T}_{miss}>300GeV, to reweight simulated multijet background
  - obtained in high Δϕ bin, for each pTbalance bin
  - reweight factor = (data- NonQcdBkgs)/QcdBkgMC





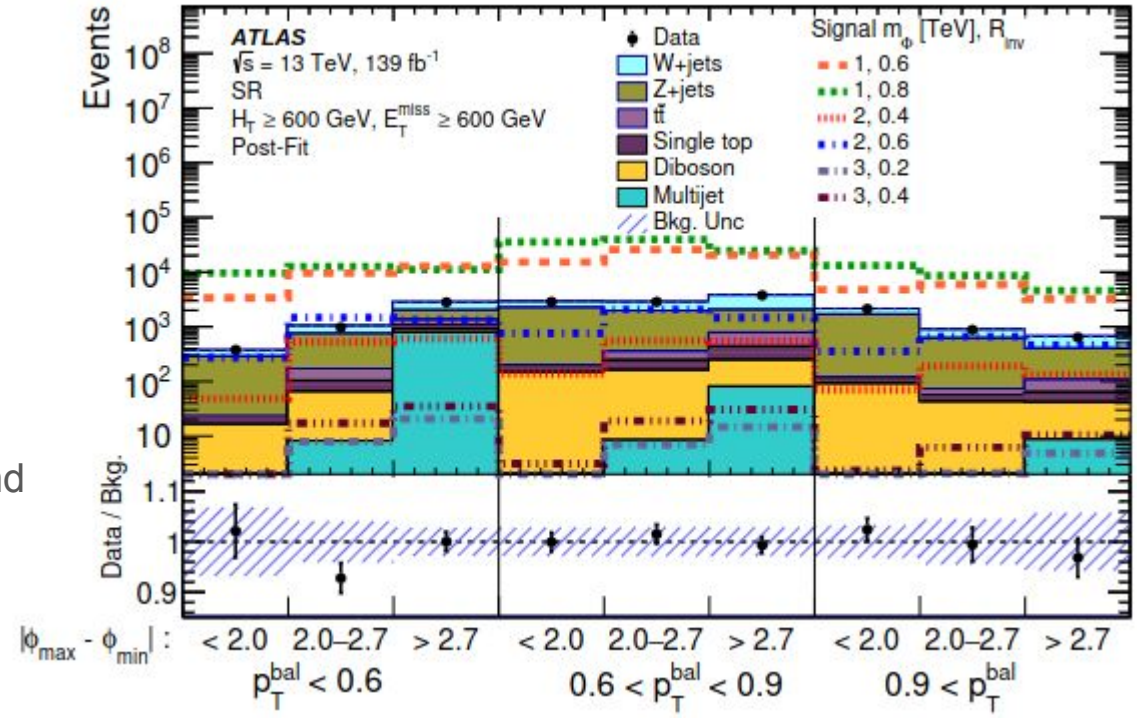
Semi-visible jets (*t*-channel) - postfit SR

A first fit is performed in low E^T_{miss} CR to get the multijet re-weighting factors.

A final fit of the [pTbalance and Δϕ] 2D distribution, with all high E^T_{miss} regions, is done:

- largest uncs on pTbalance and Δϕ shapes comes from signal, Z+jets and ttbar modelling (10%)

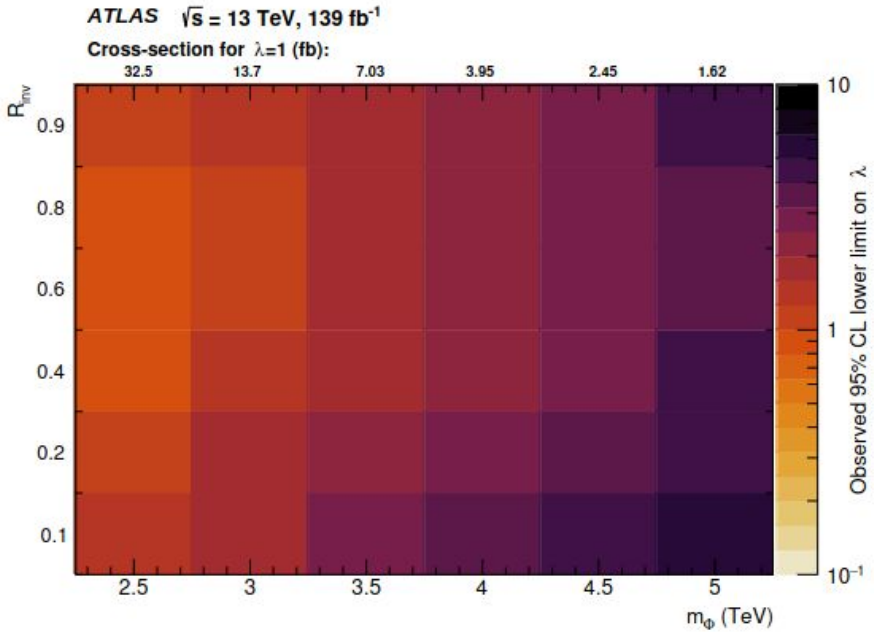
Results found to be compatible with SM-only hypothesis

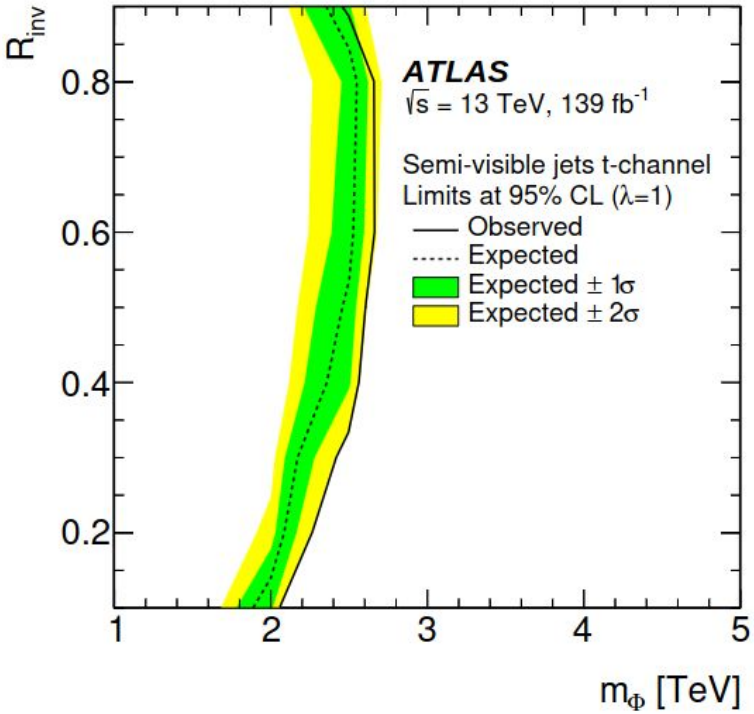


Semi-visible jets (*t*-channel) - 95% CL limits

Limits set in {$R_{inv,}$ DMmediator mass} plane, at fixed DMmediator-SM coupling (=1).

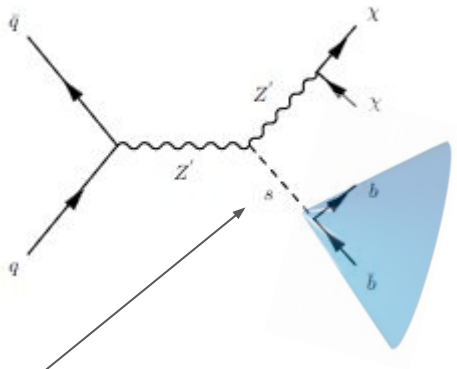
- limits get worse at higher Rinv as the observables chosen becomes more bkg-like





Including systematics weakens the limits set by 25%

Dark Higgs to bb - intro



Tackling a E^{T}_{miss} + (bb) final state with m(bb)<150 GeV

- final state studied for H(bb)+E^{T}_{miss} analysis

Dominant backgrounds:

- Z(nunu)+jets, W(lnu)+jets, ttbar (at lower E^{T}_{miss})
- control regions (CR) with μ or $\ell^{\mp}\ell^{\pm}$ +jets constraint backgrounds in the SRs

Optimization and interpretation of search:

- model with 2 DM mediators {Z', DarkHiggs} and χ dark particles
  - three masses, 2 couplings, 1 mixing angle {DarkH,H}
- The Dark Higgs can be produced boosted or resolved
  - will of course focus more on the boosted regions here

Dark Higgs to bb - event selection

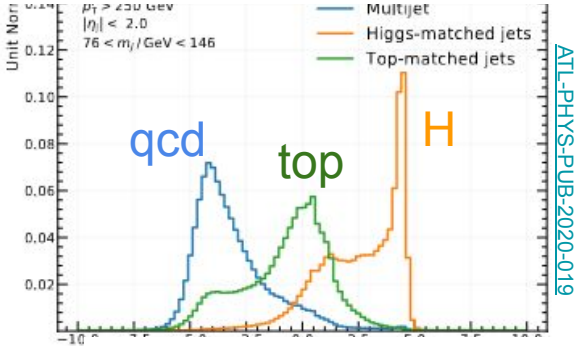
Basic event selection:

- no leptons (SRs) or single-μ or $\ell^{\mp}\ell^{\pm}$ (CRs). No τ-leps
- E^{T}_{miss} >150GeV (150-to-500GeV resolved SRs, E^{T}_{miss}>500GeV boosted SR)
- three pT-leading jets with $\Delta\phi(E^{T}_{miss})$>20° [reduce multijet bkg and mismeasured jets]
- $0.7 < E^{T}_{miss} / p^{bb}_{T} < 1.3$ [DarkHiggs and DM produced back-to-back, reduces ttbar, W+jets]
- two small-R b-tagged jets or one large-R jet with double-b-tag.

Details of the boosted selection:

- re-cluster radius R=0.4 jets into R=1.0 jets:
  - boost requirement: 2m/pT<0.6
  - double-btag from associated track jets for mJ<50GeV, Dxbb tagger on associated calorimeter large-R jet for mJ>50GeV

Dxbb has an expected 50% improved sensitivity, also mass de-correlated



DXbb discriminant

Dark Higgs to bb - analysis regions

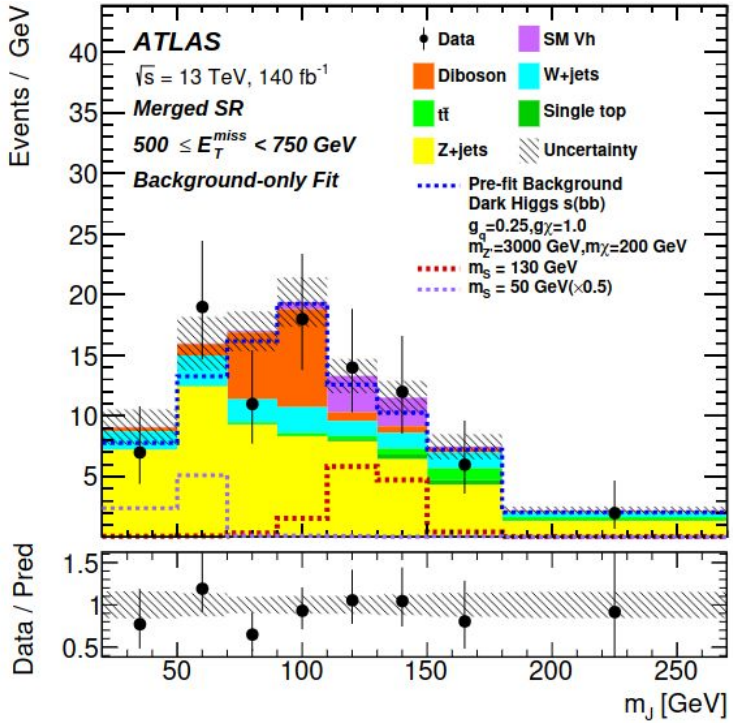
SR / CR	SR	1 muon CR	2L CR
MET / METproxy [GeV]	> 750	> 500	> 500
	500-750		
	350 - 500	350 - 500	350 - 500
	200 - 350	200 - 350	200 - 350
	150 - 200	150 - 200	150 - 200
Fitted variable	m(DarkH candidate)	muon charge	Yield

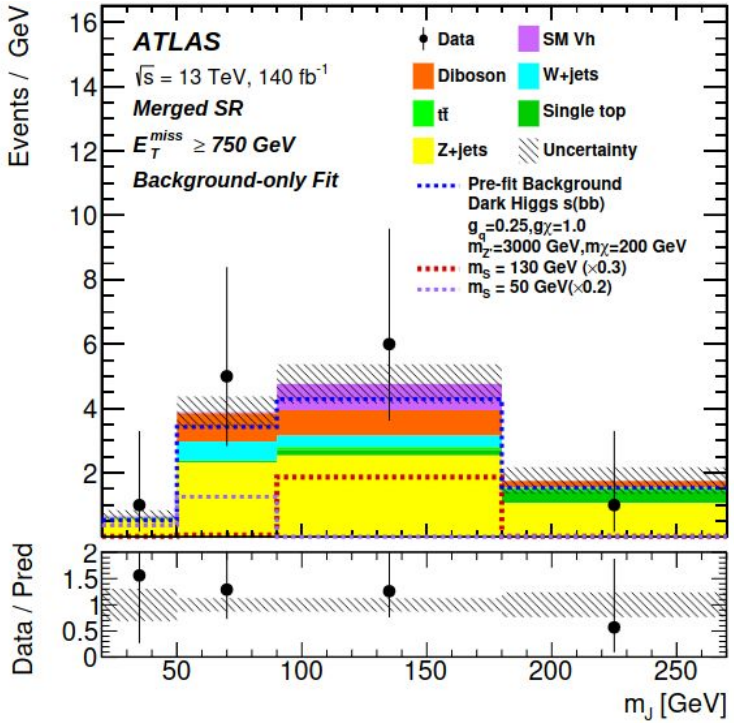
BOOSTed

resolved

Bkg norm constrained separately for each MET interval

Dark Higgs to bb - fitted Dark Higgs candidate mass (boosted)



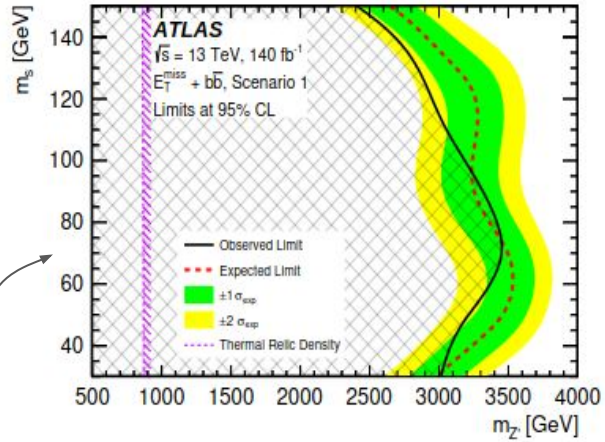


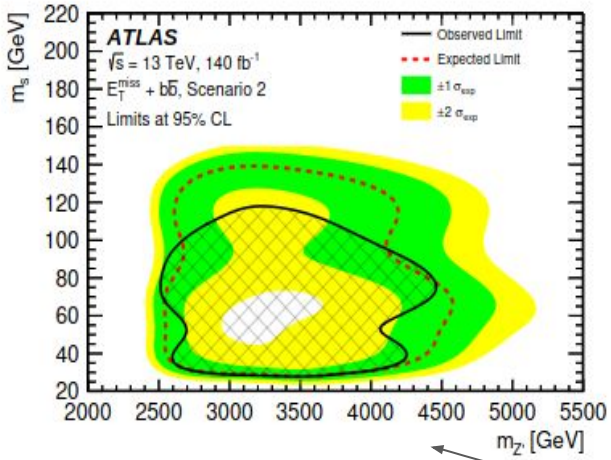
Fit goes down to 20GeV in large-R jet mass!

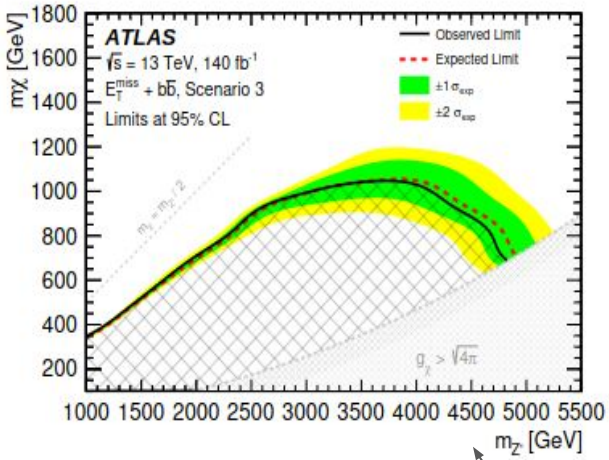
Simultaneous maximum-likelihood fit of signal and background simulations in all regions:

- Largest unc are stat (~75%), largeR jet b-tagging, V+jets bkg modelling and norm
- Fitted mass compatible with SM-only hypothesis, can set limits

Dark Higgs to bb - 95% CL limits



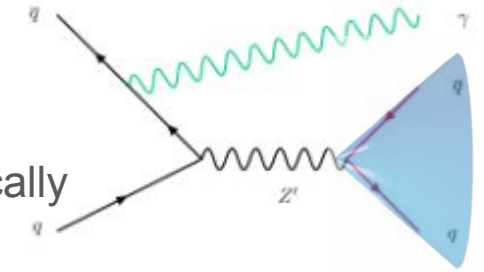




Limits set for three scenarios of the same model [g(q)=0.25, sin(Θ)=0.01]:

- g(χ)=1, m(χ)=200GeV [no DarkH->χχ allowed, relic density fixed by m(Z')]
  - highest reach on m(Z'), compared to other similar searches
- g(χ) varied, m(χ)=900 GeV and matching relic density [m(darkH),m(Z') free]
- g(χ) varied, m(darkH)=70 GeV and matching relic density [m(χ),m(Z') free]

Low-mass Z' - intro



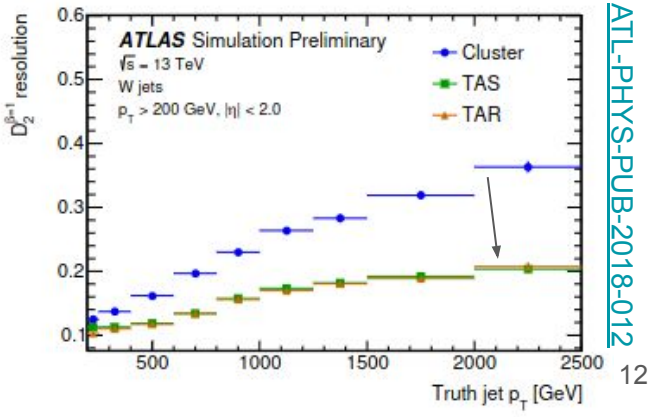
Explore the lowest mass range of Z'-like DM mediator decaying hadronically

- look for bumps in spectrum of Z' candidate mass
- remove limitations usually set by trigger, requiring associated production with an object (photon) on which trigger on
- resolved analyses (photon+2jets) down to 170/200 GeV m(Z') (arXiv:2403.08547)
- boosted analyses can go even lower (Phys. Rev. Lett. 123, 231803 (2019))

Considered model with very high DM particle mass (no effect on Z' width, no Z'->DM decay)

Use TrackAssisteReclustered (TAR) jets, with R=1 :

- fully calibrated R=0.2 jets as input, used tracker information to improve jet substructure resolution
- D2 jet substructure variable used to enhance 2-prong jet signal over Ɣ+jets background



ATL-PHYS-PUB-2018-012

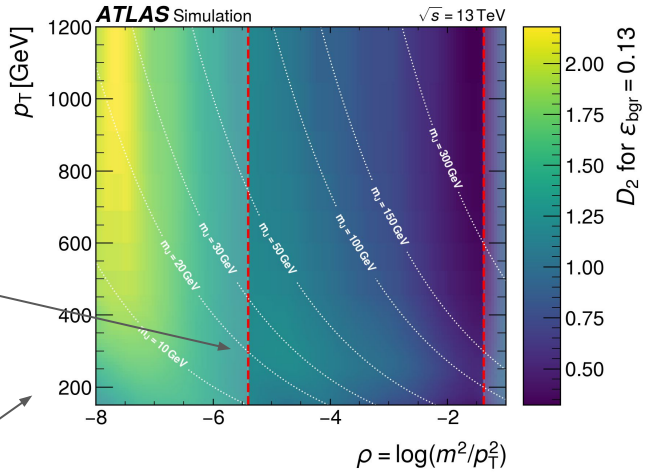
Low-mass Z' - event selection

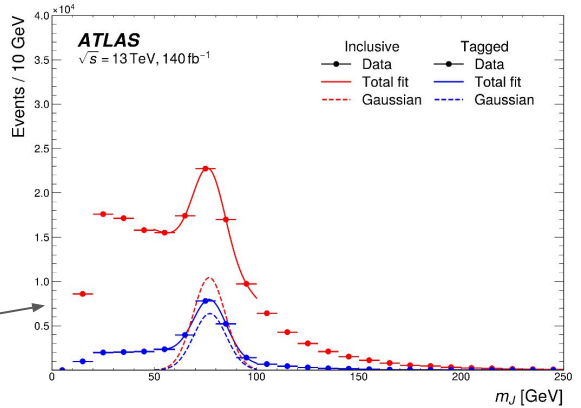
Final state is ɣ+TAR jet:

- photon & TAR pT >150GeV, TAR and ɣ required to be well separated (Δϕ>π/2), TAR in restricted m/pT range
- TAR jet boosted (2m/pT<1) and with at least 3 tracks (D2 defined)
- challenging ɣ+jets non-resonant bkg constrained with data
  - resonant bkg estimated from MC instead

D2-based tagger designed to have a fixed background efficiency (13%), stable against jet pT and log(m^2/pT^2):

- Designed-Decorrelated-Tagger (DDT) technique: ensures ratio of qcd background in tagged/untagged region designed to have no bumps… and still good in recovering the signal
- D2ddt calibrated in ttbar events through a signal scale factor SF=0.971+-0.025





Low-mass Z' - postfit

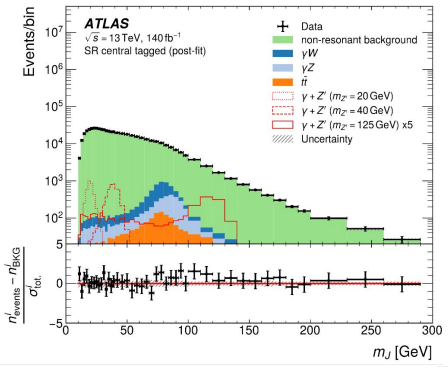
Simultaneous fit in 4 regions defined by D2ddt tagger (tagged/untagged) and photon |η|:

- "central" (|η|<1.3) regions more sensitive to Z' signal (quark annihilation production)
- non-resonant γ+jet background estimated in un-tagged regions and ported to tagged region with a Transfer Factor:
  - nonresbkg(tag)=TF*nonresbkg(untagg)
  - TF parametrised with 5th order poly:
    TF coeffs and nonres(untagg) free params

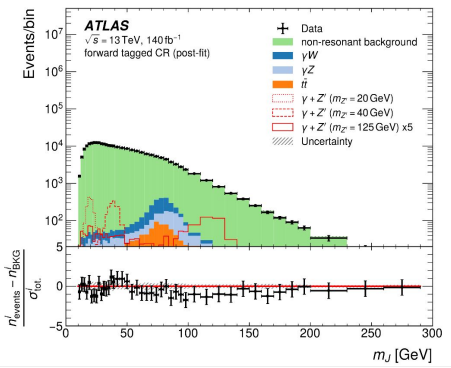
Leading uncertainties are statistical uncertainties and the TF modelling

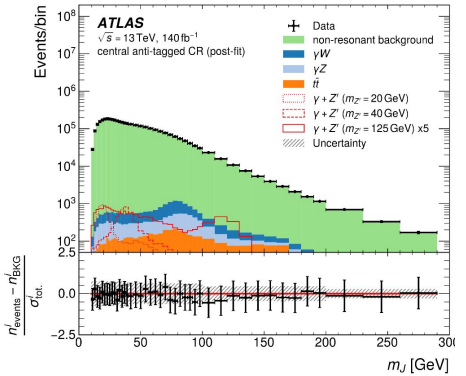
Bkg-only fit compatible with SM-only hypothesis

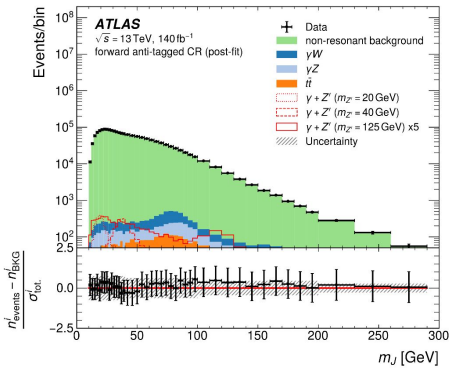
central γ, tagged TAR



forward γ, tagged TAR







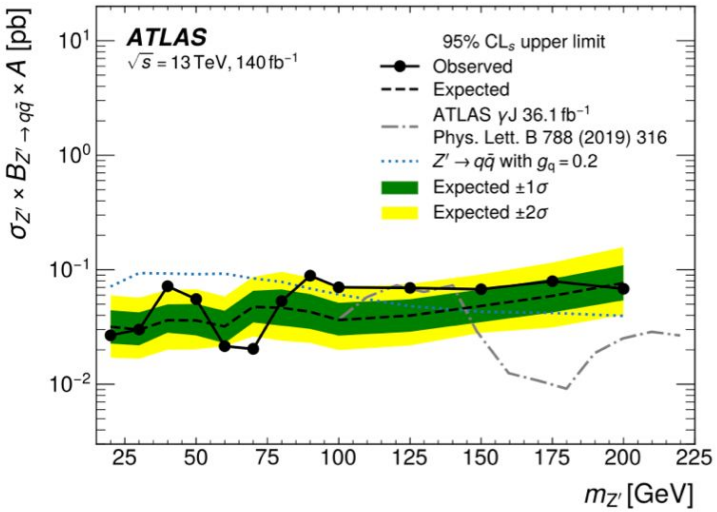
central γ, un-tagged TAR

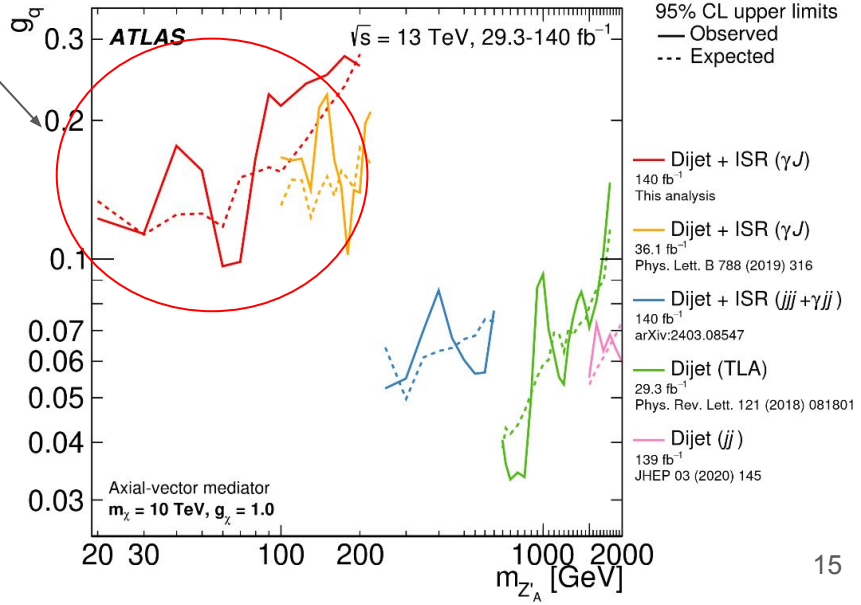
forward γ, un-tagged TAR

Low-mass Z' - 95% CL limits

Limits on Z'-to-quarks coupling (g_q) vs m(Z') :

- compatible with previous ATLAS result, in the >100 GeV range
- excluded Z' presence down to 20GeV
- the lowest ATLAS limits on m(Z') for hadronically decaying Z'





Conclusions

The ATLAS search program is vast and cover a multitude of final states.
In particular final states with jets are challenging as a potential new physics signal can be hidden under the (usually) large background

Presented three ATLAS searches, looking for DM particles and mediators decaying to single-jet final state (boosted) and to a shower mix of DM and SM (semivisible jets):

- Dark Higgs search extended limits in m(Z') to 3.4TeV and set new constraints on model (DM relic density match), thanks to new developments in analysis performance
- Semi-visible jet search studied for the first-time a model where DM is produced in the *t*-channel production mode, and tackled an innovative final state
  - interesting to study the semi-visible jet sub-structure?
- Boosted TAR +photon search extended ATLAS limits on Z' down to 20 GeV, thanks to a new analysis technique and improvements on previous analysis iterations

More ATLAS analyses using jets and boosted topologies are underway
ATLAS search program with Run2-only data is ~done. Stay tuned for Run3 results!

Back-up

Dark Higgs (bb) - event display

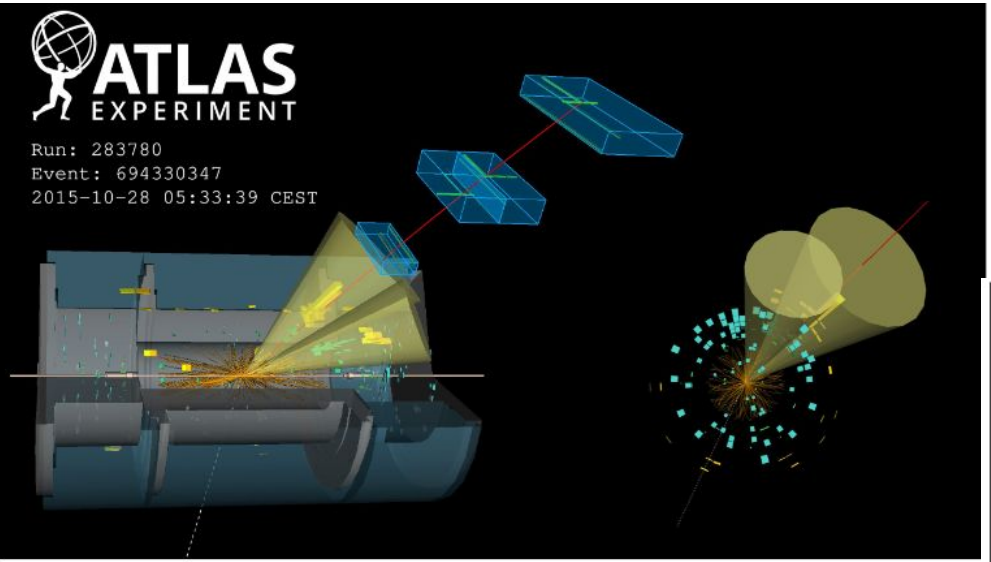


Figure 7: Event display for an event in the $200 < E_{\mathrm{T}}^{\mathrm{miss}} < 350$ GeV region of the resolved signal region. The even contains two b-tagged jets, indicated by yellow cones, with an invariant mass of 63 GeV and $E_{\mathrm{T}}^{\mathrm{miss}} = 232$ GeV denoted by the white dashed line. Within one of the b-tagged jets, a muon candidate is indicated with a red line, with the hits in the muon spectrometer chambers illustrated in green.

resolved category

boosted category

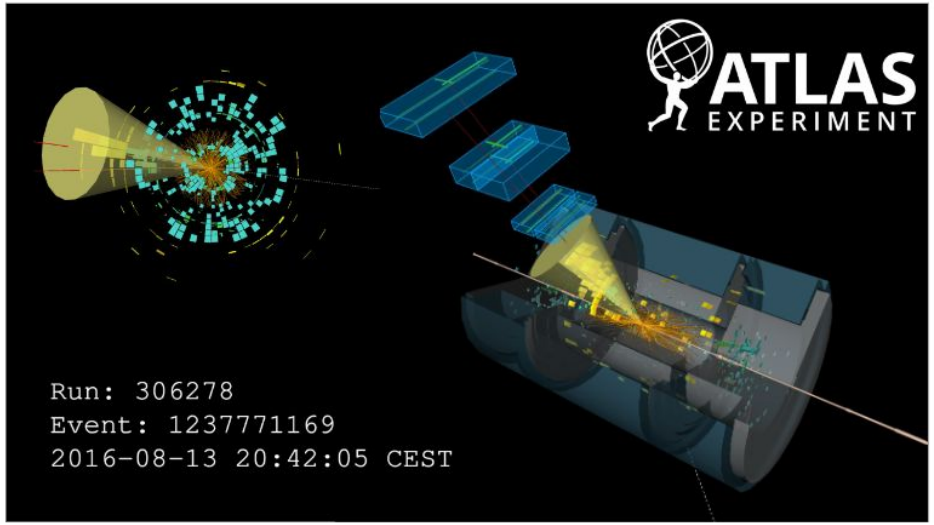
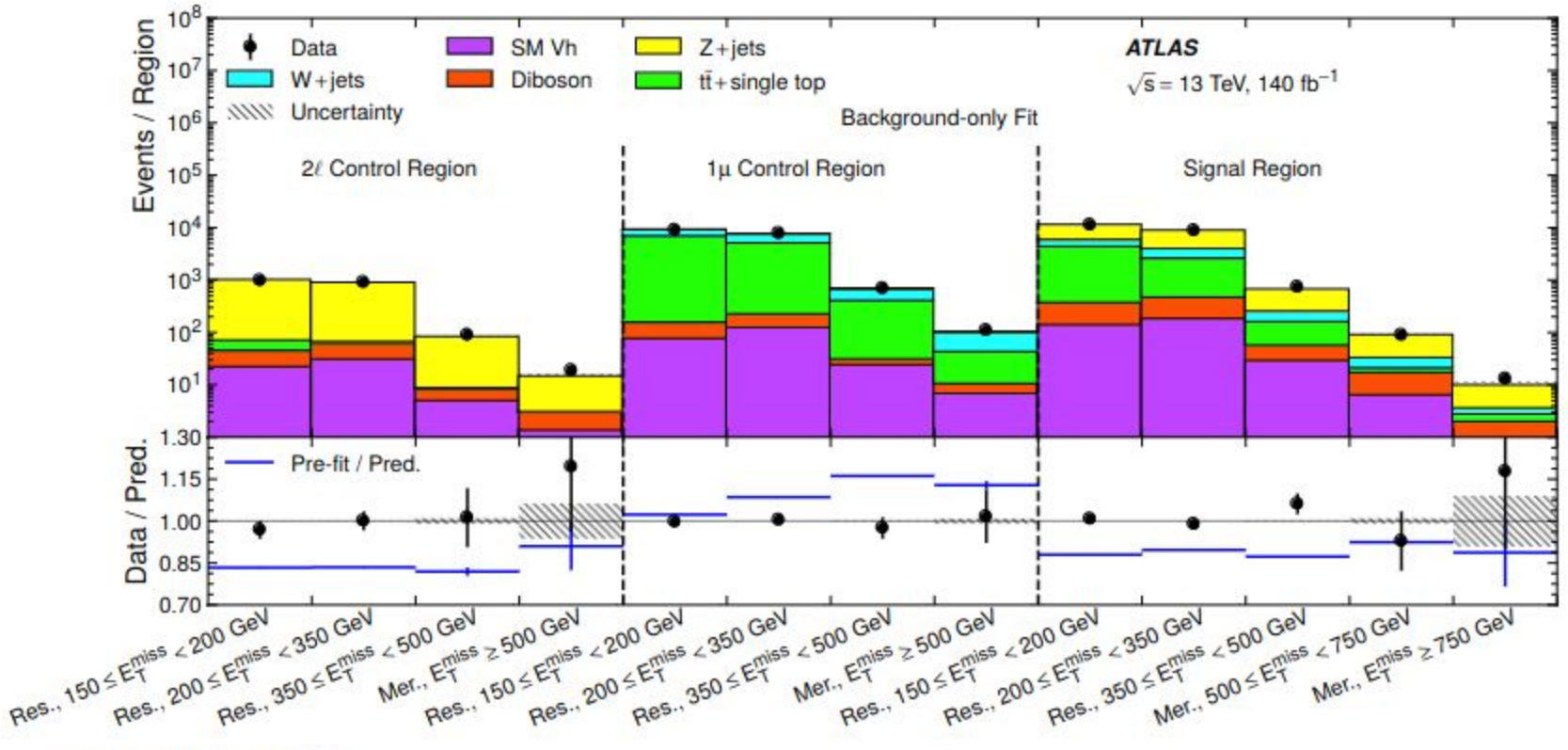
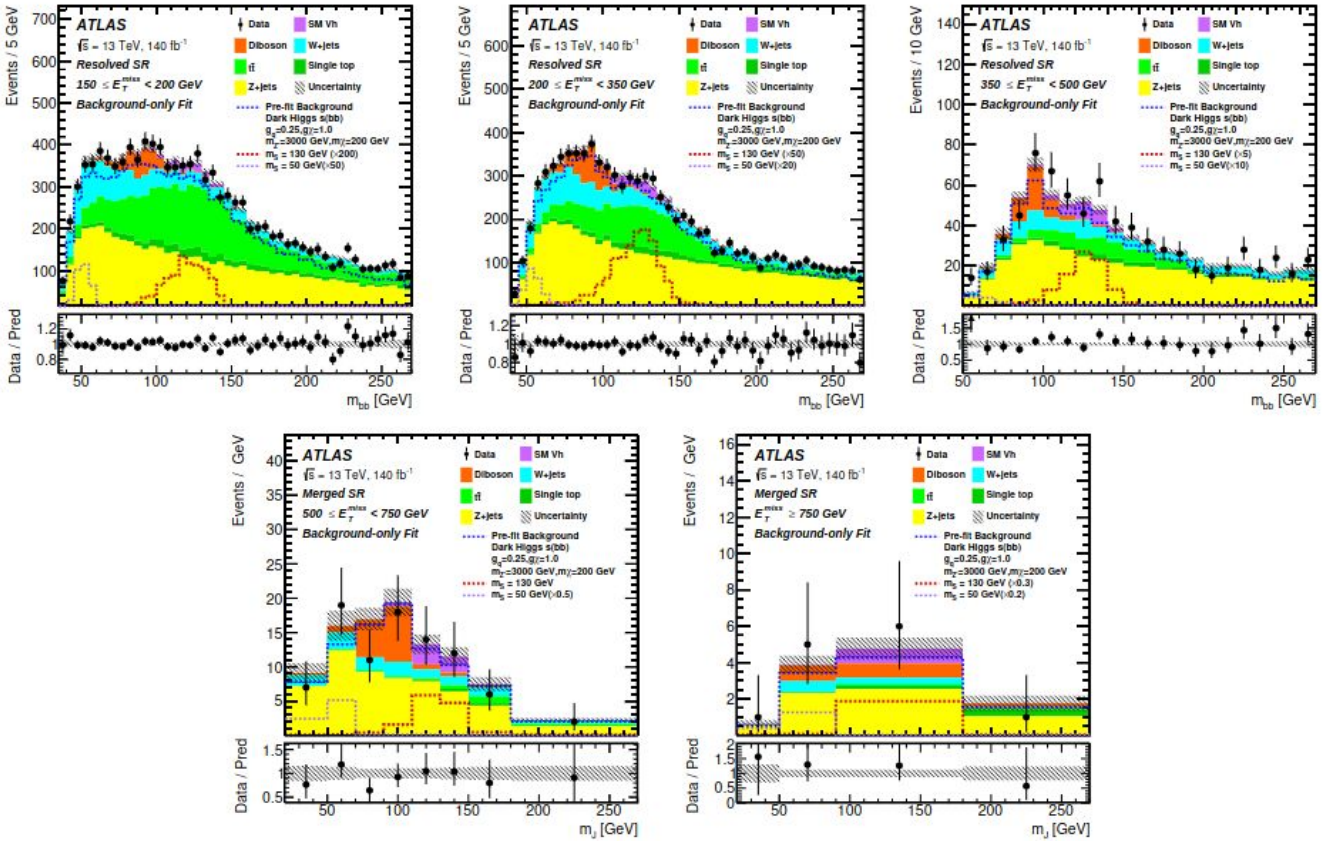


Figure 8: Event display for an event in the $500 < E_{\mathrm{T}}^{\mathrm{miss}} < 750$ GeV region of the merged signal region. The event contains a large-R jet indicated by the broad yellow cone, which passes $\mathrm{D_{Xbb}}$ tagging requirements, has $p_{\mathrm{T}} = 487$ GeV and an invariant mass of 54 GeV, and significant $E_{\mathrm{T}}^{\mathrm{miss}} = 560$ GeV, denoted by the white dashed line. Two muon candidates from decays within the jet are indicated with red lines, with the hits in the muon spectrometer chambers illustrated in green.

Dark Higgs (bb) - yields



Dark Higgs (bb) - postfit Dark Higgs candidate mass (all)



Dark Higgs (bb) - DL1r vs DXbb double-*b*-tagging

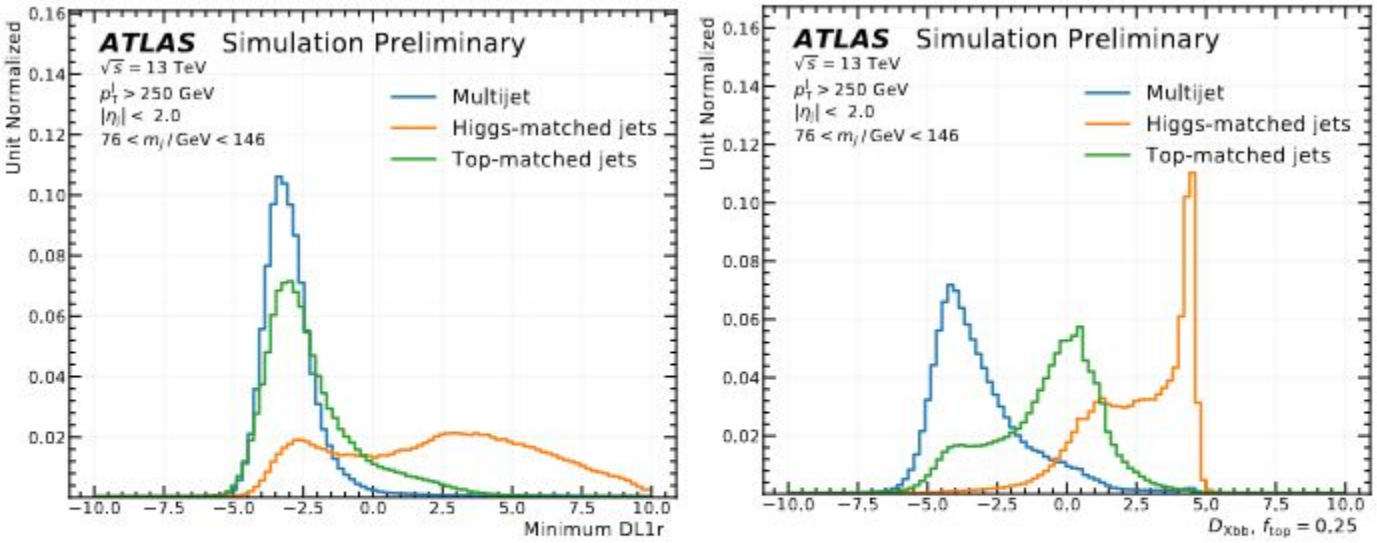


Figure 2: The discriminant distribution, for the DL1r-based benchmark defined as the minimum of the two leading subjet discriminants (left), and the double b-tagging algorithm D_{Xbb} with a top fraction of f=0.25 (right). Distributions are normalized to unity.

SVJ

postfit distributions

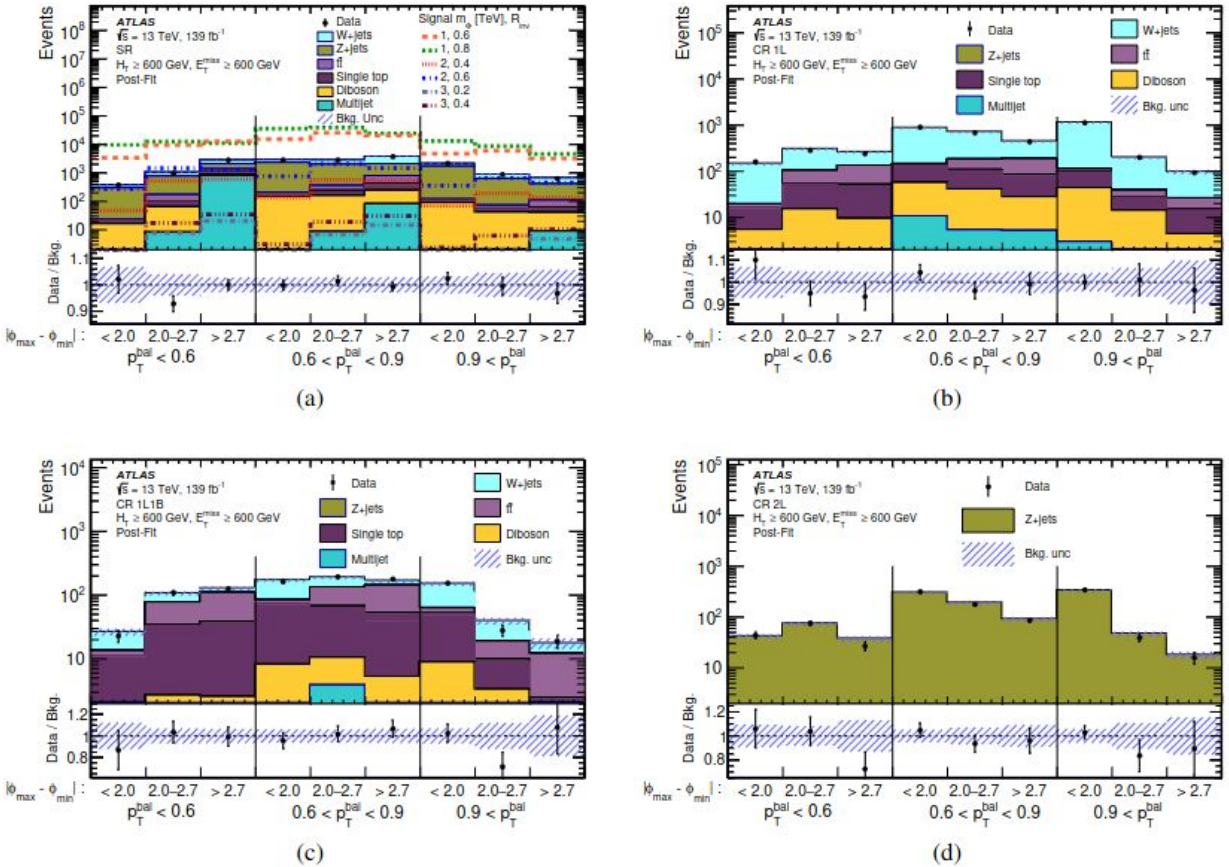
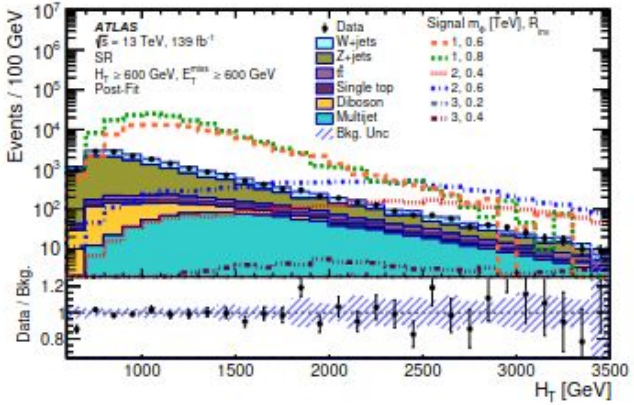


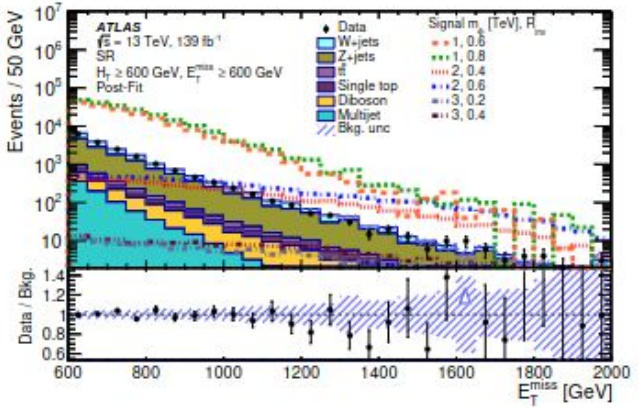
Figure 3: The post-fit yields in the nine bins of the $(p_{\mathrm{T}}^{\mathrm{bal}}, |\phi_{\mathrm{max}} - \phi_{\mathrm{min}}|)$ grid are shown for the (a) SR, (b) 1L CR, (c) 1L1B CR, and (d) 2L CR. Data are compared with background predictions, and six signal predictions covering a representative mediator mass and invisible fraction range are overlaid in the SR. Figure (a) shows a background-only fit in the SR. The uncertainties include all systematic and statistical components.

SVJ

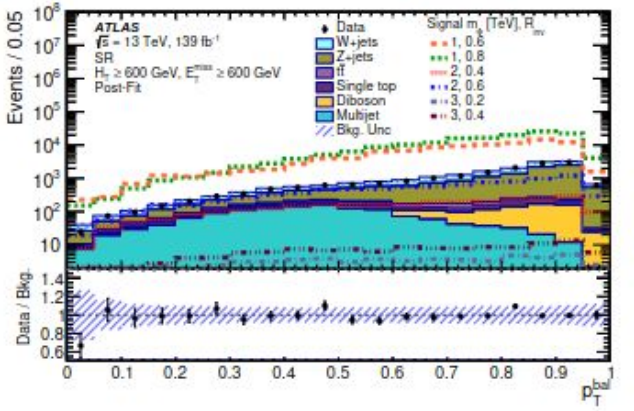
postfit distributions



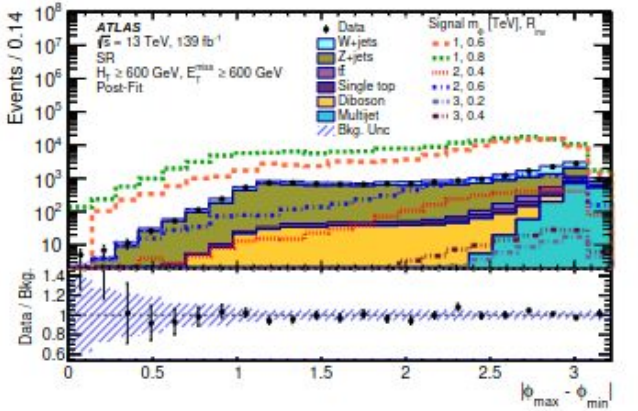
(a)



(b)

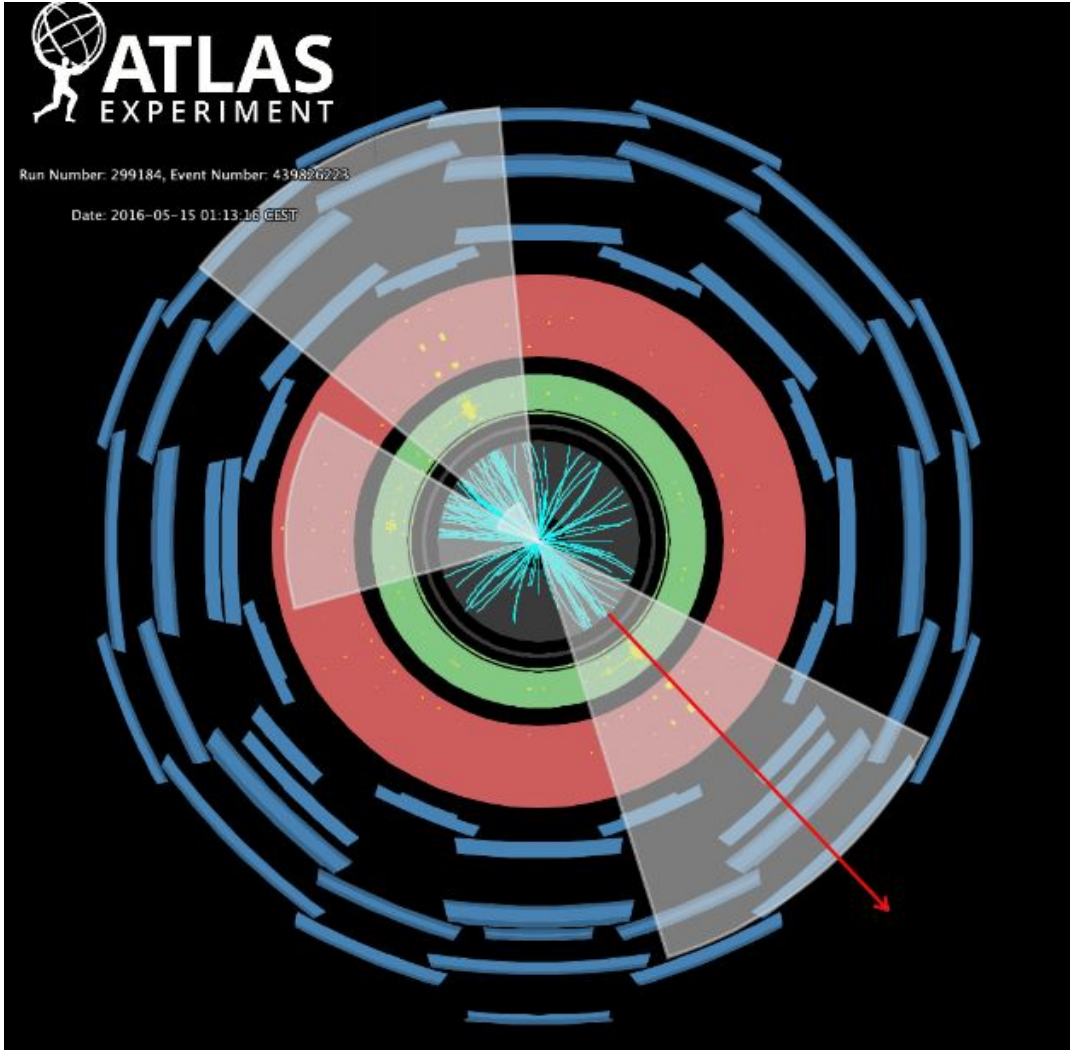


(c)

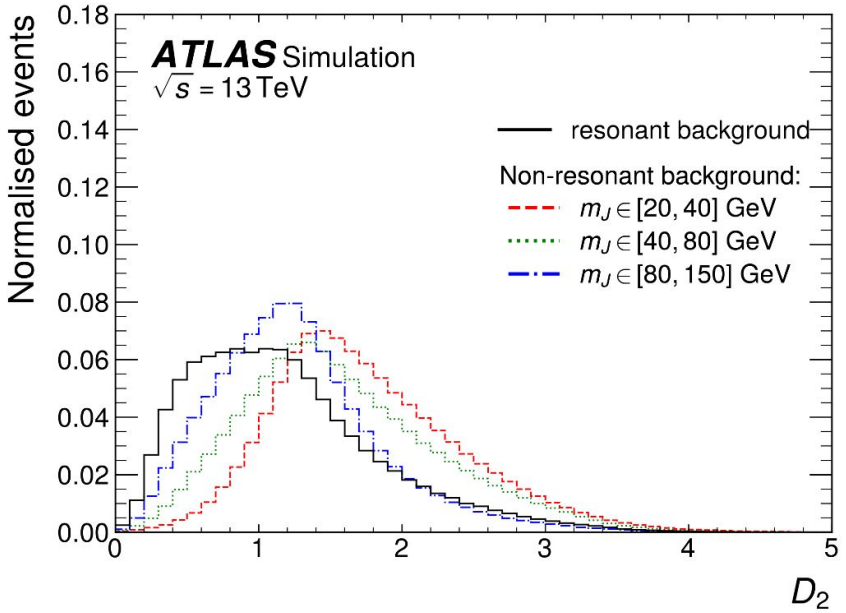


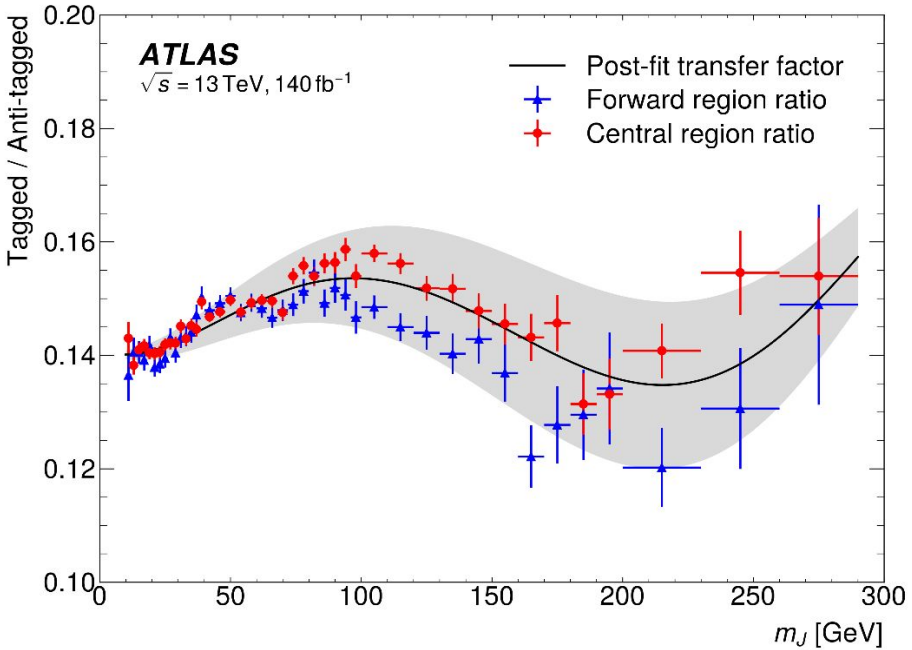
(d)

SVJ candidate

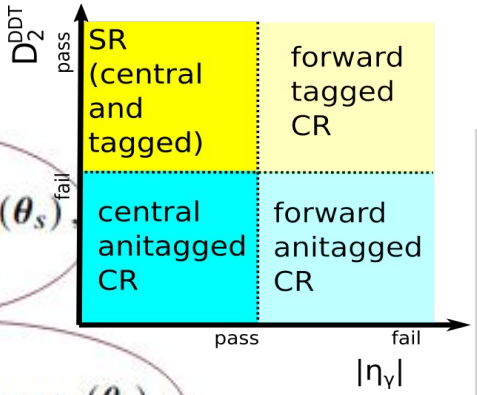


Low mass Z' - D2ddt tagger and TransferFactor



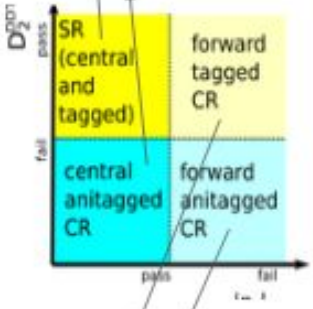


Low mass Z' - fit model



$$\nu^i_{\mathrm{SR}}(\mu,\theta) = \mu\nu^i_{\mathrm{SR,\,signal}}(\theta_{\mathrm{signal}}) + \frac{\epsilon_{\mathrm{SR}}}{1-\epsilon_{\mathrm{SR}}}\tau^i\nu^i_{\mathrm{central}\,\gamma} + \sum_{s\in\{W\gamma,Z\gamma,t\bar{t}\}}\nu_{\mathrm{SR},s}(\theta_s)\,,$$

$$\nu^i_{\mathrm{central}\,\gamma\,\mathrm{CR}}(\mu,\theta) = \mu\nu^i_{\mathrm{central}\,\gamma\,\mathrm{CR,\,signal}}(\theta_{\mathrm{signal}}) + \nu^i_{\mathrm{central}\,\gamma} + \sum_{s\in\{W\gamma,Z\gamma,t\bar{t}\}}\nu_{\mathrm{central}\,\gamma\,\mathrm{CR},s}(\theta_s)\,.$$



Signal (MC)

Tagging signal eff

Transfer factor

Resonant backgrounds (MC)

$$\nu^i_{\mathrm{fwd.}\,\gamma\,\mathrm{tagged\,CR}}(\mu,\theta) = \mu\nu^i_{\mathrm{fwd.}\,\gamma\,\mathrm{tagged\,CR,\,signal}}(\theta_{\mathrm{signal}}) + \frac{\epsilon_{\mathrm{SR}}}{1-\epsilon_{\mathrm{SR}}}\tau^i\nu^i_{\mathrm{forward}\,\gamma} + \sum_{s\in\{W\gamma,Z\gamma,t\bar{t}\}}\nu_{\mathrm{fwd.}\,\gamma\,\mathrm{tagged\,CR},s}(\theta_s)$$

$$\nu^i_{\mathrm{fwd.}\,\gamma\,\mathrm{CR}}(\mu,\theta) = \mu\nu^i_{\mathrm{fwd.}\,\gamma\,\mathrm{CR,\,signal}}(\theta_{\mathrm{signal}}) + \nu^i_{\mathrm{forward}\,\gamma} + \sum_{s\in\{W\gamma,Z\gamma,t\bar{t}\}}\nu_{\mathrm{fwd.}\,\gamma\,\mathrm{CR},s}(\theta_s)\,.$$