UNIVERSITY OF CAMBRIDGE

ATLAS EXPERIMENT

Searches for boosted resonances (non-diboson) with the ATLAS detector

Lars Henkelmann on behalf of the ATLAS collaboration,

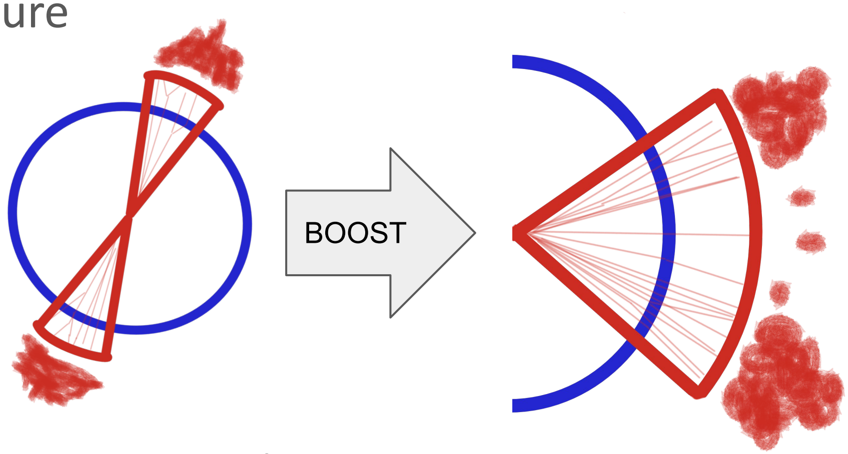
BOOST2022 @ Hamburg

15. 08. 2022

✨Exotic✨ jet substructure for exotic ATLAS searches

Many BSM hypothesis predict TeV-scale resonances decaying into light(er) (B)SM resonances which are highly boosted and themselves decay into light SM fermions.

Identifying the intermediate resonance requires resolving the boosted, thus collimated, light SM radiation → Jet Substructure



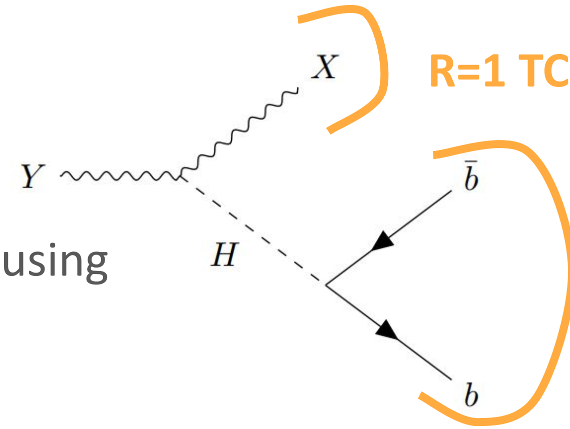
- BSM examples in this talk
  - Exotic vector bosons
  - Exotic quarks
  - Exotic decays into dark matter +X
- Watch out for:
  - **Customised higgs tagging** (there is a large variety)
  - **Creative jet reconstruction** for BOOSTed jet substructure resolution
  - **Higgs/W/Z/top tagging for more than SR purity**
    - Taggers that BOOST analyses by defining control regions

ATLAS-CONF-2022-045

$Y \longrightarrow X\ h$ resonance search

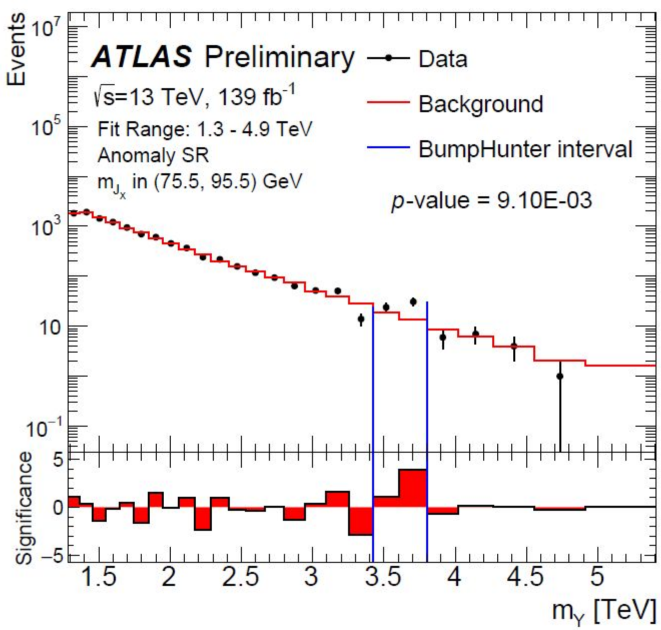
See also the poster by S. Auricchio tomorrow!

- Generic search
  - **Any hadronically decaying X**
  - **Unsupervised anomaly detection** using Variational Recurrent Neural Net operating on **sequence of jet constituents**
  - large-R jets unlock highest Y masses …
    - Up to O(5) TeV!
  - … and avoid assuming particular substructure (cf. small-R jet multiplicity)
- **Complemented by two-prong- targeting signal regions** (SRs) tuned for $X \longrightarrow qq$ decays,
  - Merged SR where track-based $D_2 < 1.2$



R=1 TCC jet

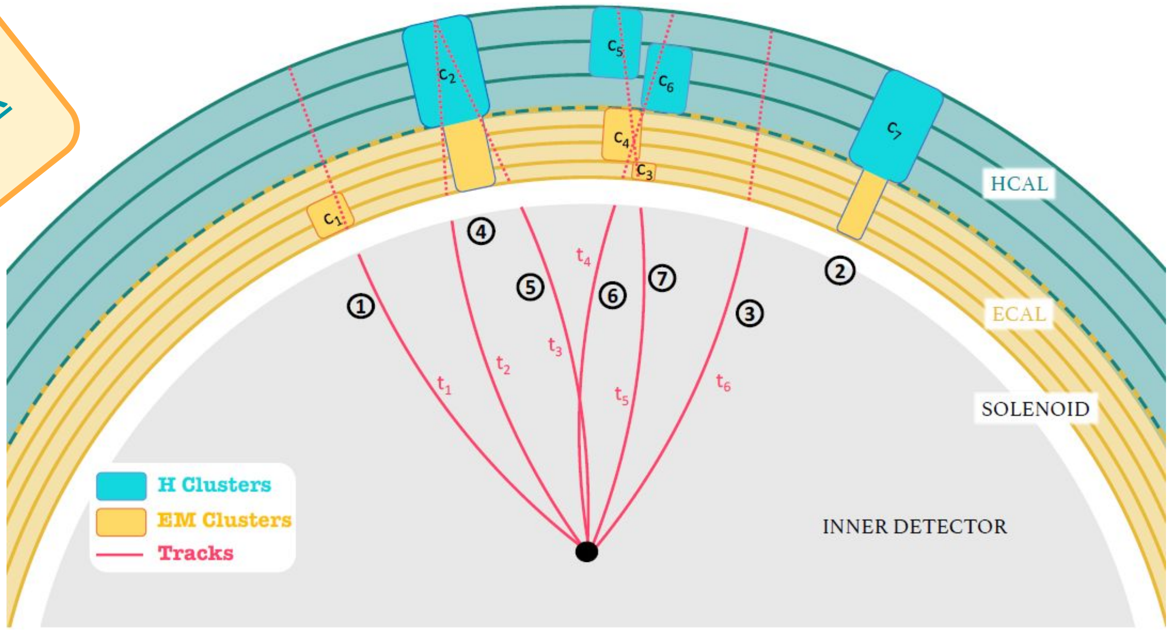
R=1 TCC jet, Higgs tagged



ATL-PHYS-PUB-2017-015

TCC jet constituents for Y → X h resonance search

Cf. N. Lalloues poster and T. Fitschens talk re. UFOs



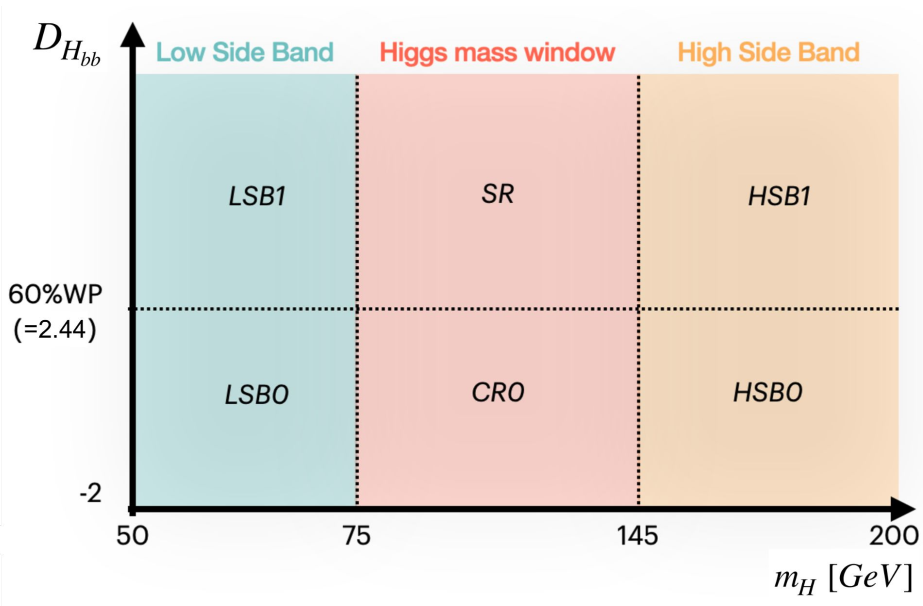
- at high p_T multiple particles contribute to same/closeby topoclusters
  - Calorimeter can not resolve due to limited granularity
- A Track-CaloCluster (TCC) object is a ΔR match* of calorimeter-only topoclusters and inner detector tracks
- Take **angular components from track** (η,ϕ) - best granularity & ang. resolution
- Take **transverse momentum from topocluster** - best energy resolution
- **p_T -fraction-proportional energy sharing** in case of multiple matches
- Cluster the R=1 jet from TCC objects, trim, calibrate

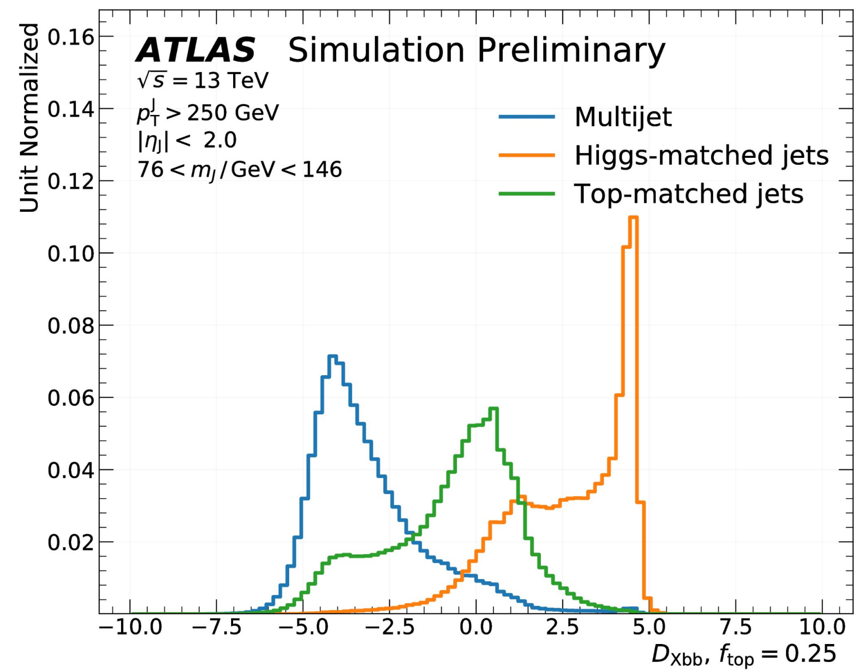
ATLAS-CONF-2022-045, ATL-PHYS-PUB-2020-019

DNN Higgs tagging for Y → X h search

See also the poster by S. Auricchio tomorrow!

- takes large-R jet eta and pT as well as **b-tagging DNN scores of up to three ghost-matched variable-radius track jets**
- **Assigns probability scores** that jet originates from top-quark, higgs-boson, or QCD
  - Higgs vs. not-higgs score: $D_{H_{bb}} = \ln \frac{p_{\text{Higgs}}}{f_{\text{top}} \cdot p_{\text{top}} + (1 - f_{\text{top}}) \cdot p_{\text{multijet}}}$
  - Train neural net to reweight events from anti-tagged to predict tagged sample

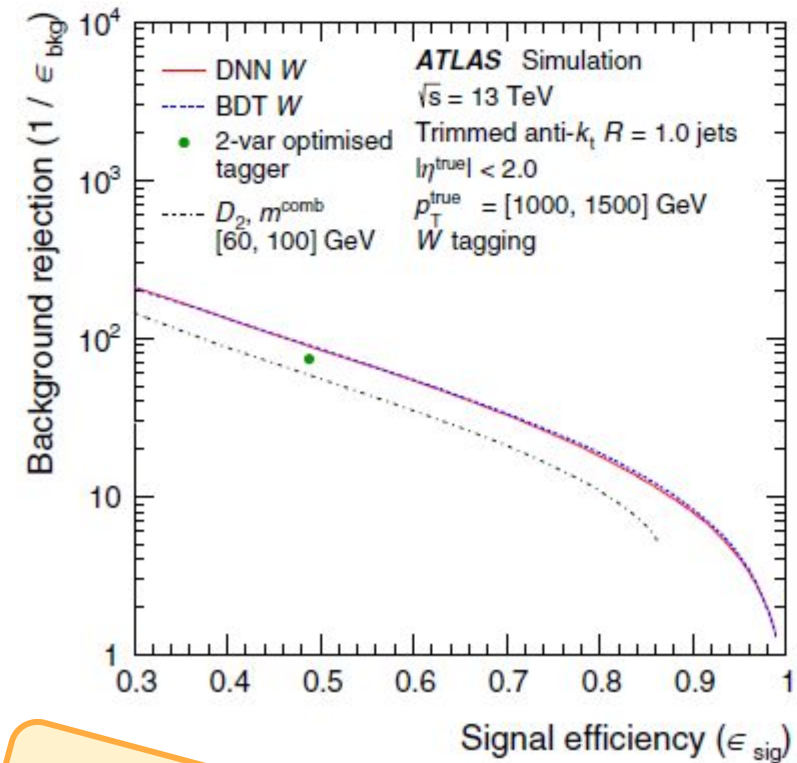




EPJC 79, 375 (2019)

DNN Top tagger in ATLAS for run 2

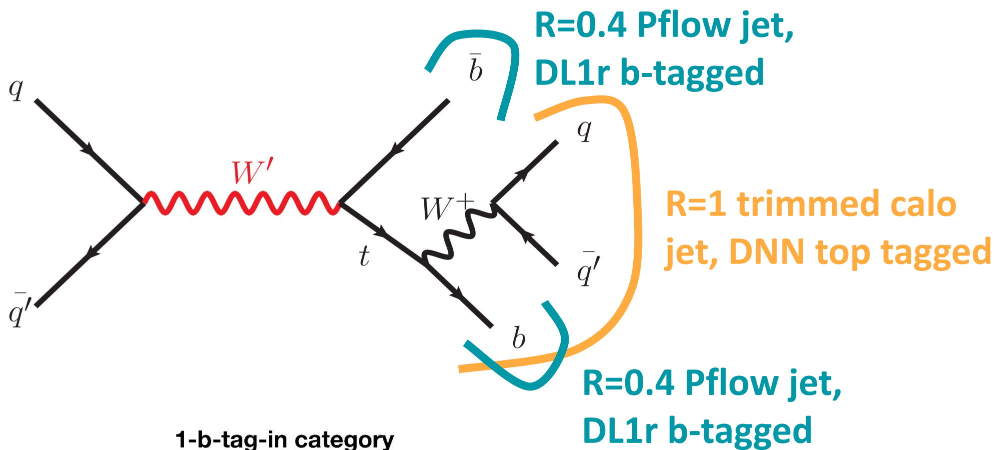
c.f. T. Fitschens talk on Wednesday on tagging UFO jets

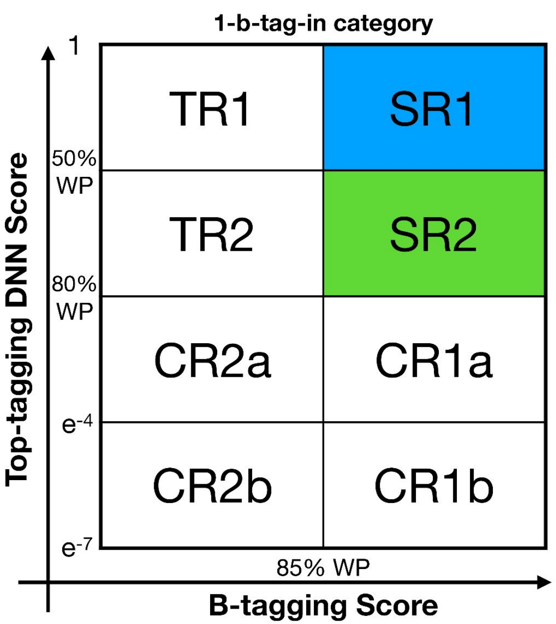


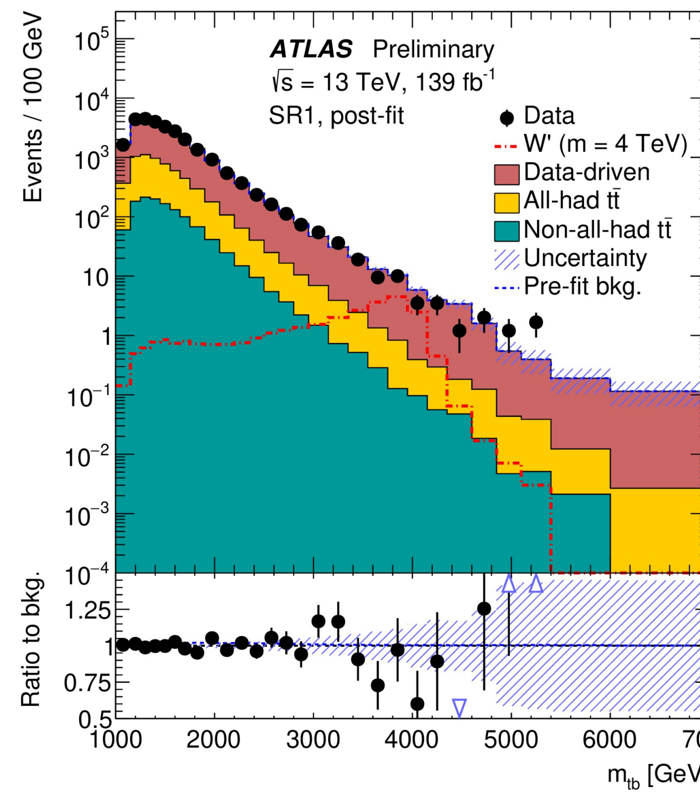
- Inputs: jet shape/substructure observables of R=1 trimmed calo jets
- Train deep neural net (DNN) to distinguish truth-labeled top jets from others
- Outperforms input jet moments 🥳
- Used to tag tops in a variety of analyses
  - High mass di-top hadronic resonance search (not covered here)
  - Boosted mono-top for DM/VLQ (not covered here) new!
  - W' → tb resonance search
  - All-hadronic single vector-like T quark search
  - SM measurements & EFT constraints using multi-top resonances
    - See next talk by K. Sedlaczek

for constituent-level top tagging, see K. T. Greifs Poster

DNN top tagging application: W’ ⟶ t b

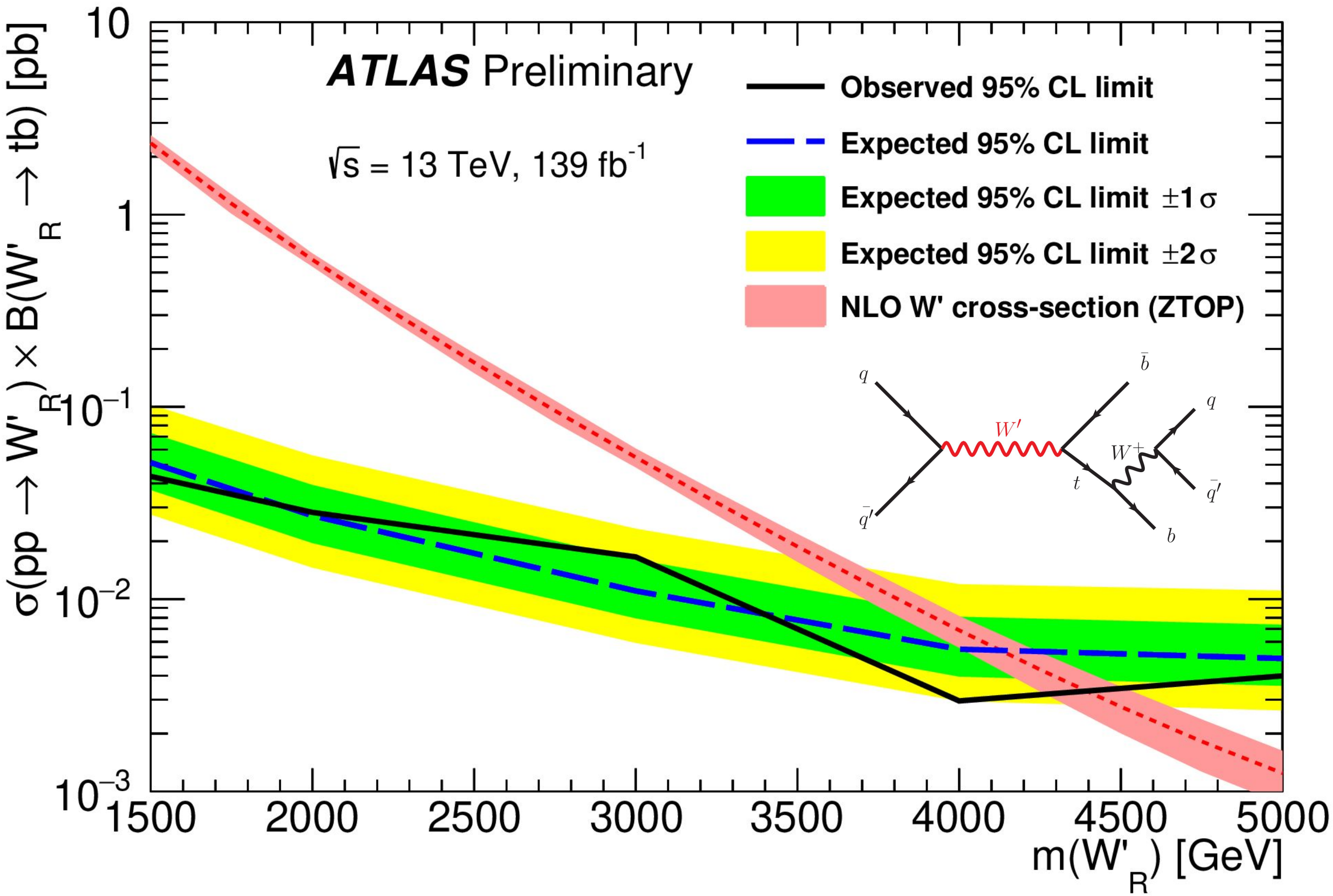






- DNN top tag for signal selection
- 4 separate DNN score thresholds for CR definition
- Dominant BKG (multijet) challenging to simulate
    - estimated from data in CRs
    - **Leveraging DNN top tagger for BKG estimate**

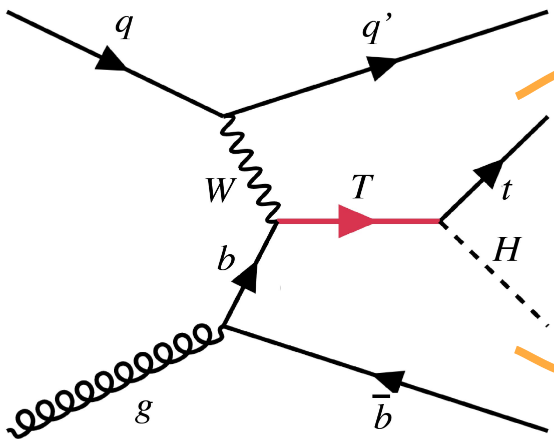
DNN top tagging application: W’ → t b



PRD 105, 092012 (2022)

DNN top tagging application: VLT → h t

See also the poster by S. Singh tomorrow!



R=1 trimmed calo jet, DNN top tagged + mass window

R=1 trimmed calo jet, ✨custom higgs tag ✨

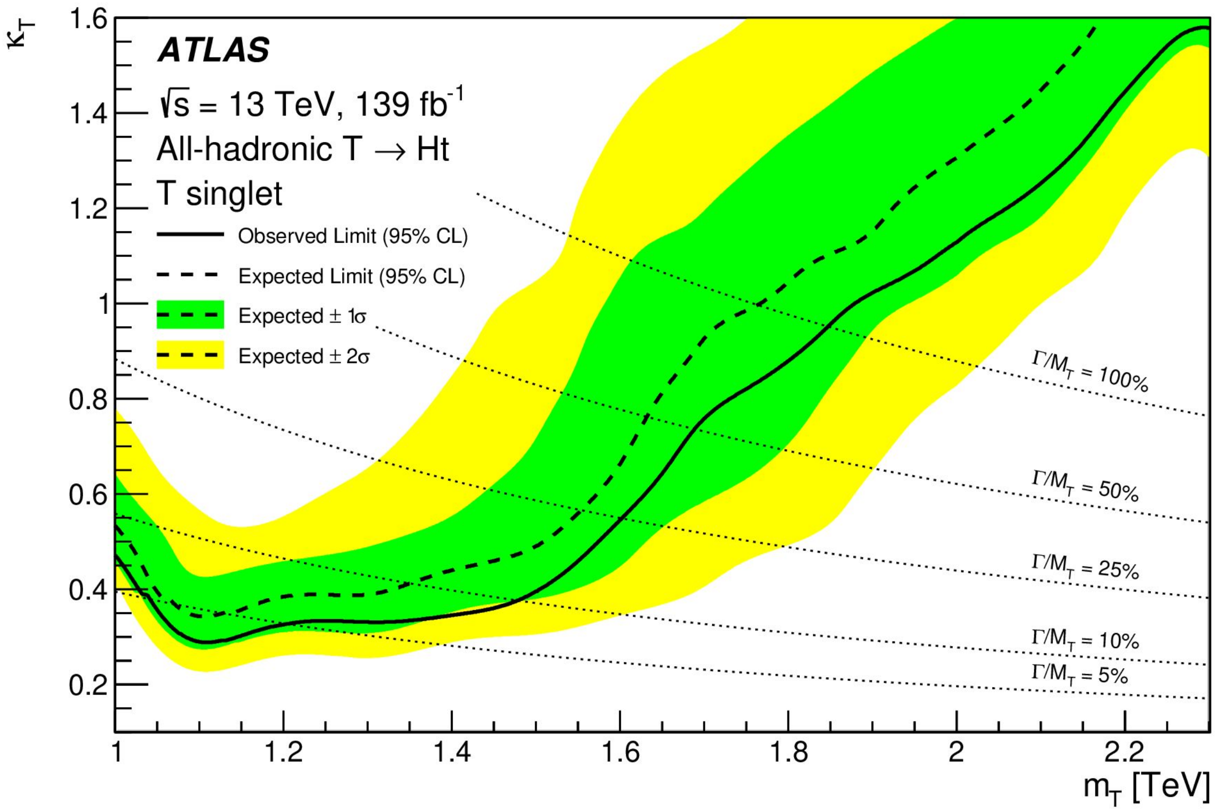
Vector-like quarks (VLQs): BSM quarks that couple non-chirally to EW bosons, avoiding constraints from e.g. Higgs measurements. Here: VLQ with top flavour (VLT)

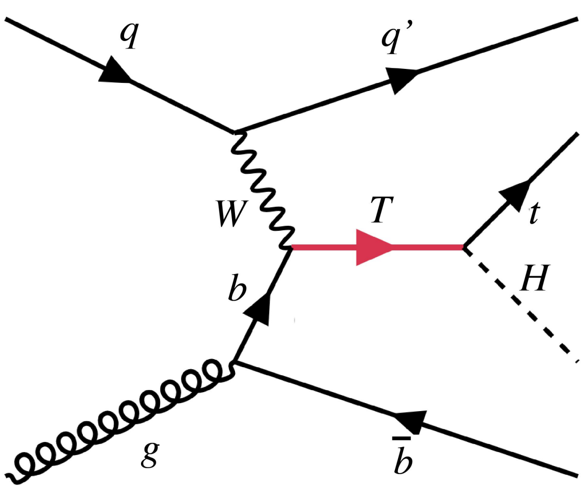
- Unique to this analysis: **Higgs-tag without b-tagging**
- Instead use a custom cut-based tagger:
  - **p_T -dependent τ_{21} cut** (such that h(bb) eff. is 70%)
  - **mass window cut**: 100 GeV < m_J < 140 GeV
- The custom tagger **allows separate use of DL1 b-tag** on variable-radius track jets for signal-/control-/validation- region splitting
- Top-candidate mass window requirement 140 GeV < m_J < 220 GeV keeps tags orthogonal

PRD 105, 092012 (2022)

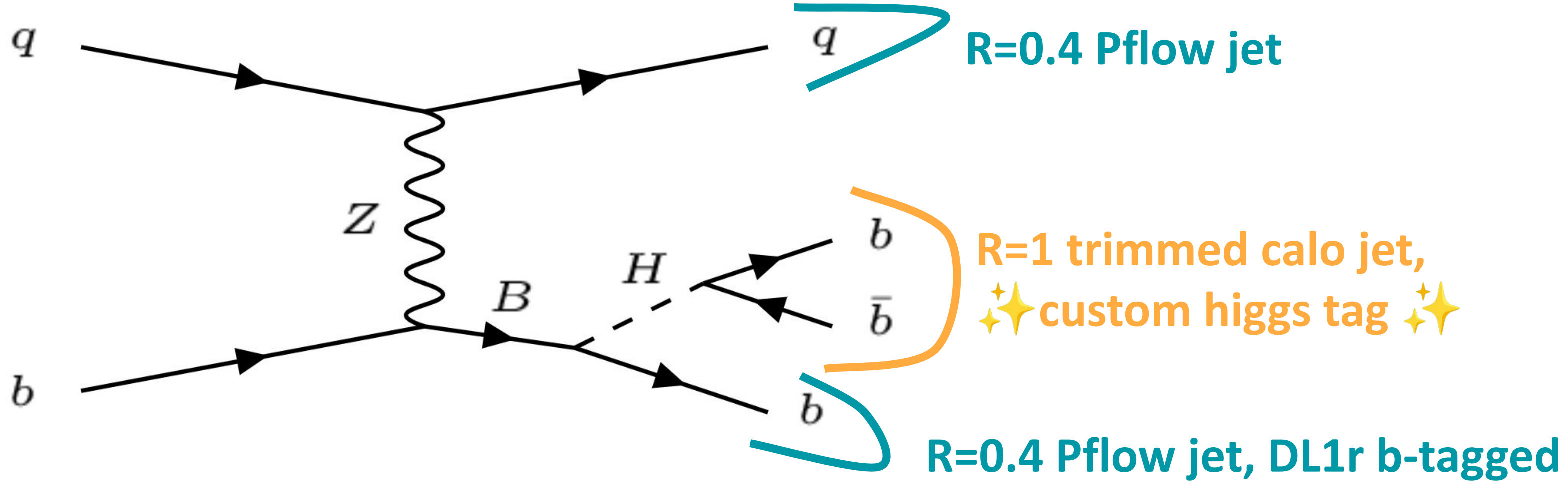
DNN top tagging application: VLT → h t

See also the poster by S. Singh tomorrow!





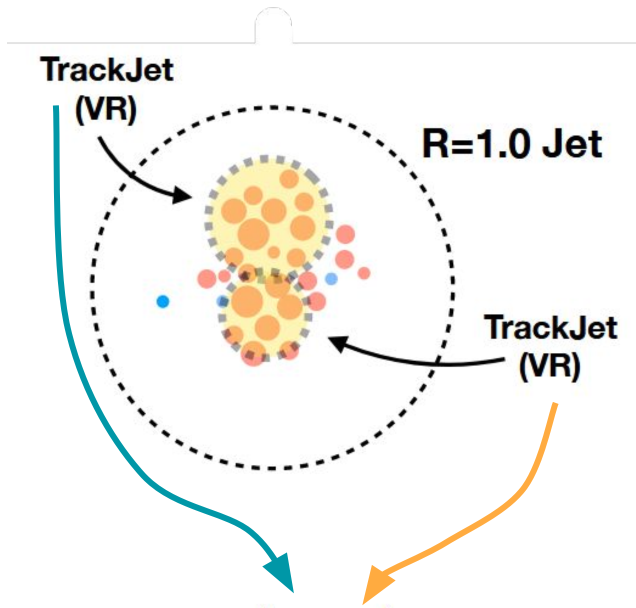
More vector-like quarks: VLB $\rightarrow$ b h(bb)



- Select boosted two-prong structure using variable radius (Reff <= 0.4) track jets:
  - require at least two VR track jets ghost-associated to R=1 jet
    - at least one of which b-tagged
  - So far, a standard h(bb) tag
- More powerful tag by **cutting on associated subjet separation**

$$\log\Delta R^* = \log\left[\frac{\Delta R\left(\mathrm{tj0}, \mathrm{tj1}\right)}{\min\left[R_{\mathrm{eff}}^{\mathrm{tj0}}, R_{\mathrm{eff}}^{\mathrm{tj1}}\right]}\right] > 0.64$$

VLB → b h(bb): custom selection on boosted Higgs



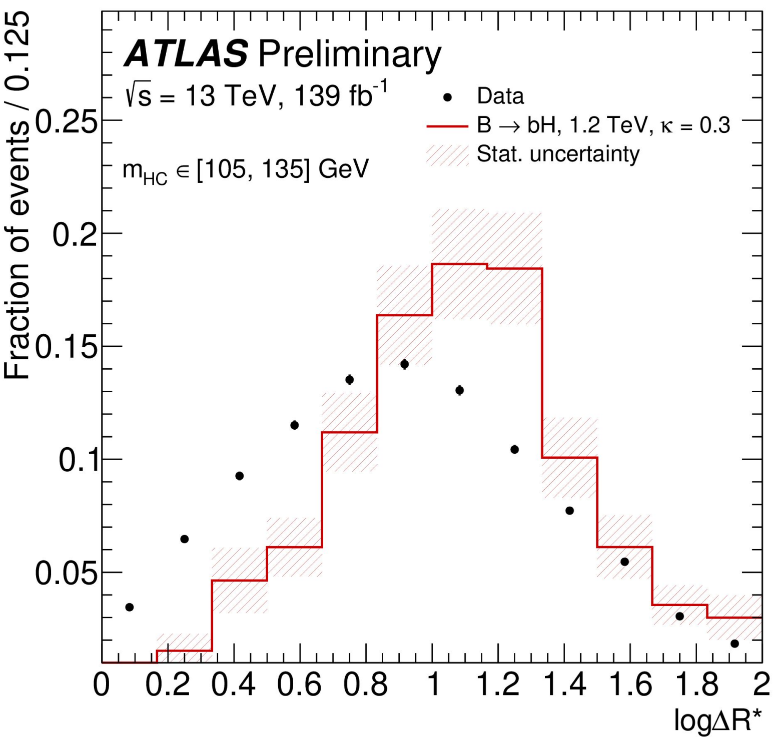
$$\log\Delta R^* = \log\left[\frac{\Delta R(\mathrm{tj0},\mathrm{tj1})}{\min\left[R_{\mathrm{eff}}^{\mathrm{tj0}}, R_{\mathrm{eff}}^{\mathrm{tj1}}\right]}\right] > 0.64$$

effective R-parameter of trackjet 0

effective R-parameter of trackjet 1

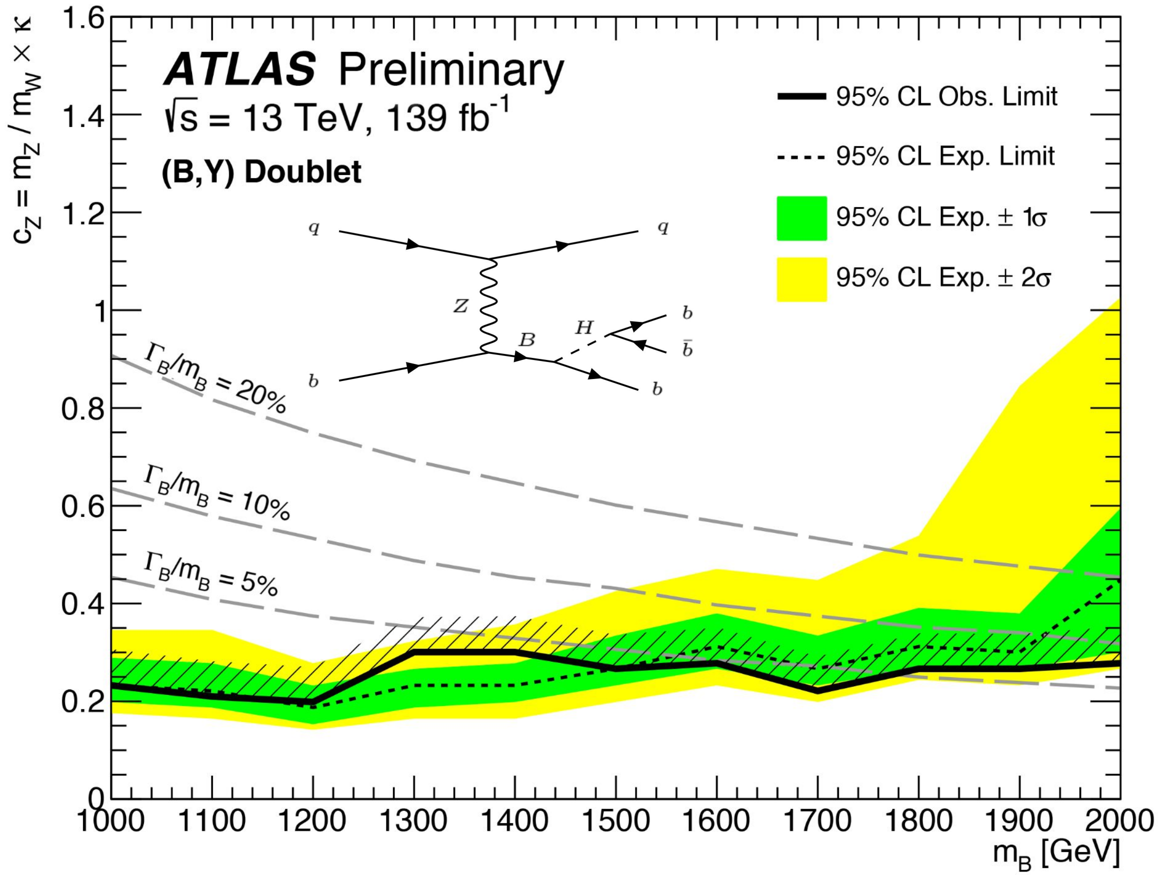
Sketch by M. Montella

stronger tag using relative separation of VR track-based subjets

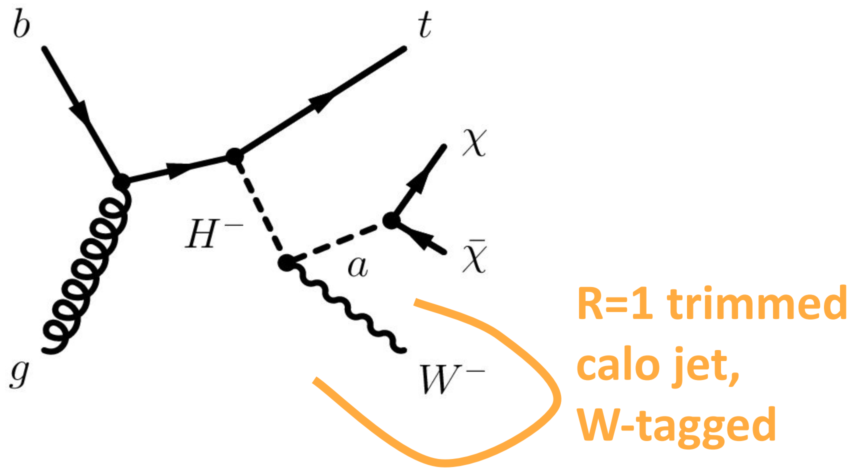


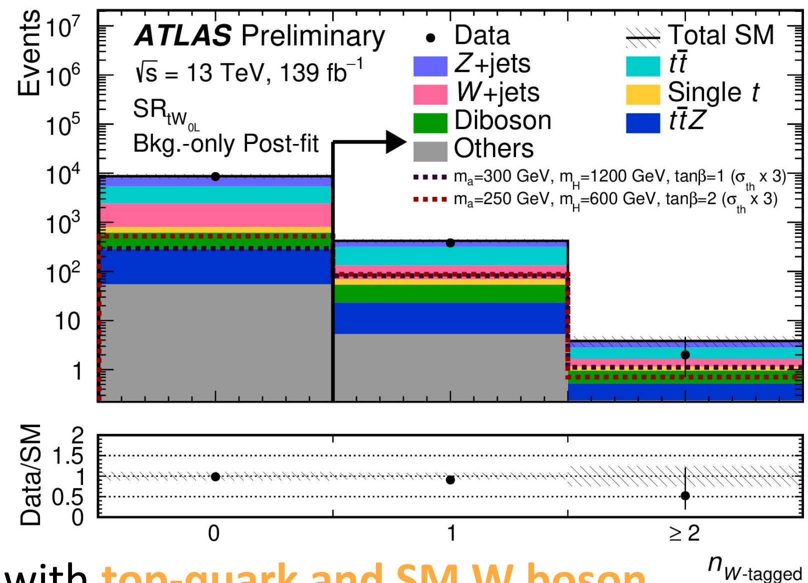
VLB ⟶ b h(bb): Result

Substructure techniques allow search to maintain sensitivity up to high VLB masses (= large boosts)



Search for DM produced with (semi-) hadronic Wt



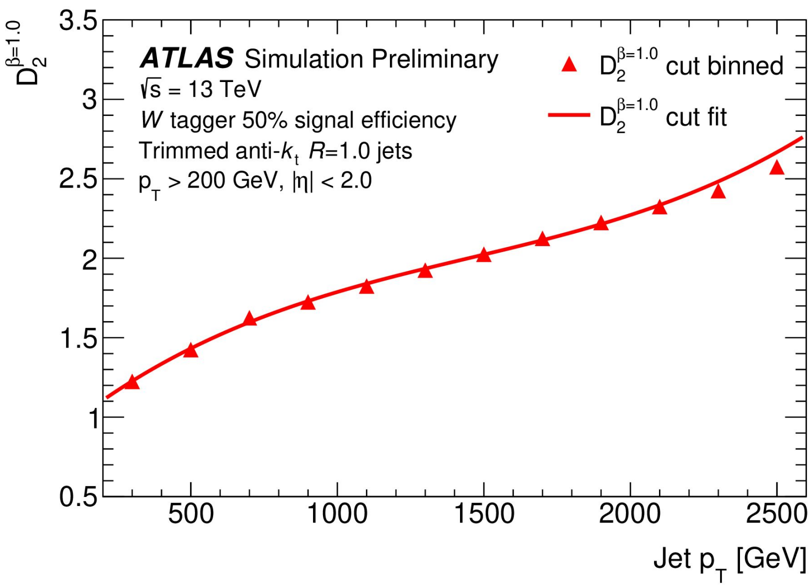


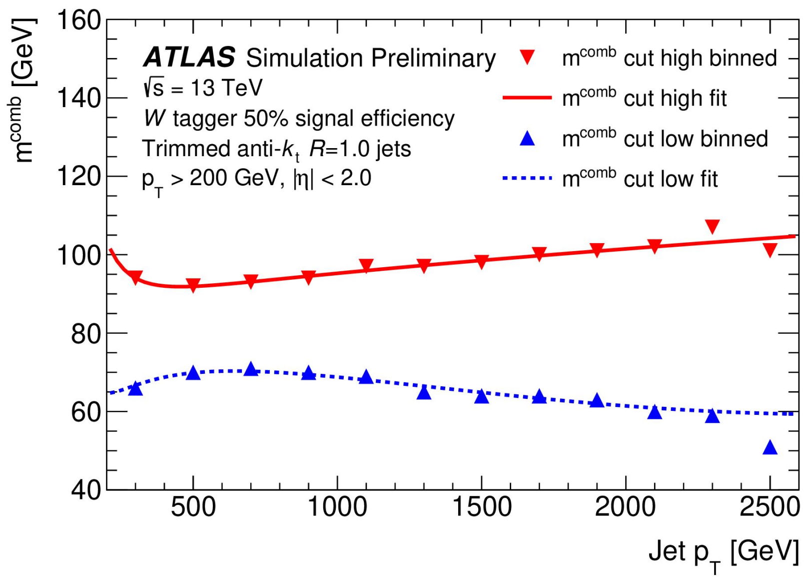
- **Dark Matter** (DM) produced in association with **top-quark and SM W boson**
  - Both **fully hadronic and semi-leptonic** channels explored
- a high H^{+-} mass can boost the SM W^{+-} substantially
  - Substructure to tag the W in the fully hadronic SR, and the leptonic top SR
- In the hadronic top/leptonic W SR, hadronic W decay is not that boosted
  - Low-boost “W-tag” using repeated reclustering of R=0.4 input jets, iteratively reducing the R of the large-R reclustered jet

W-tagging for Wt+MET DM search

cf. T. Fitschens talk on Wednesday on tagging UFO jets

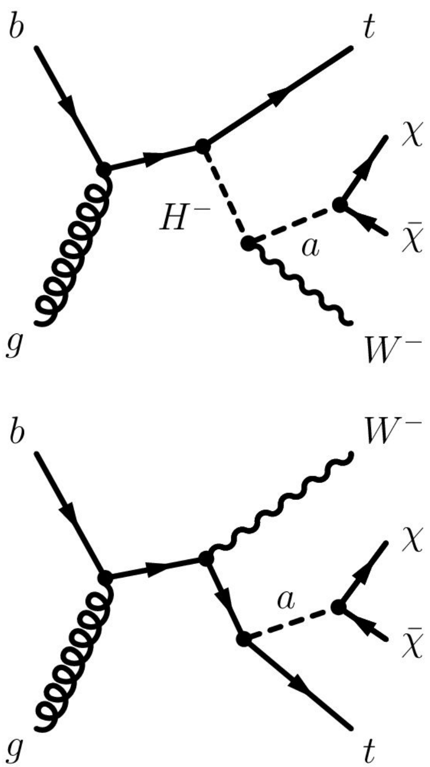
- 3-observable cut-based tagger, tuned for trimmed R=1 calo-only jets:
  - p_T -dependent, one-sided D_2 selection
  - p_T -dependent mass window cut
    - Combine track-assisted and calo-only mass for better resolution
  - track multiplicity: $n_{trk} \leq 26$

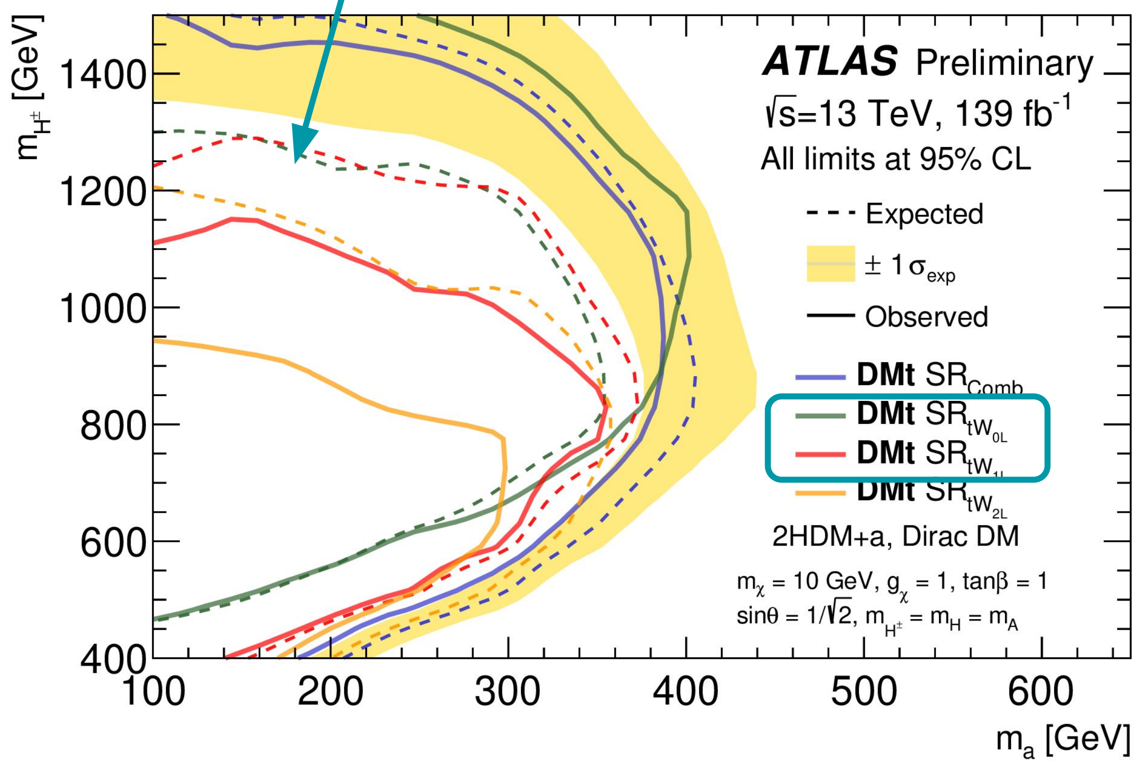




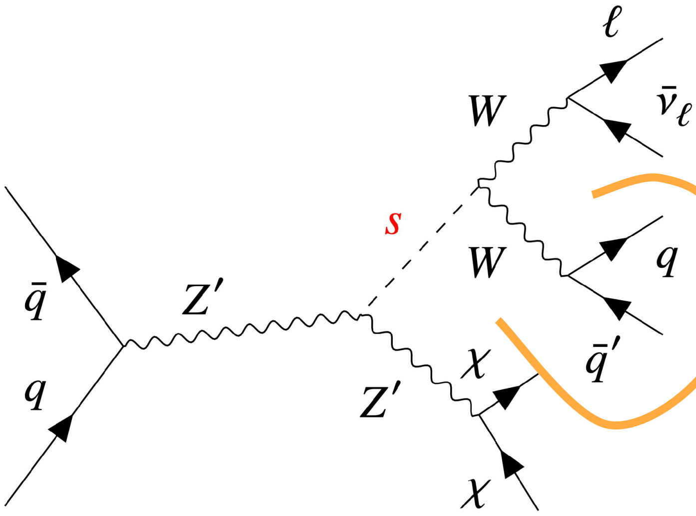
Wt + MET DM search: Result

Boosted topologies unlock sensitivity to **high charged higgs mass region** (--> high W boost)

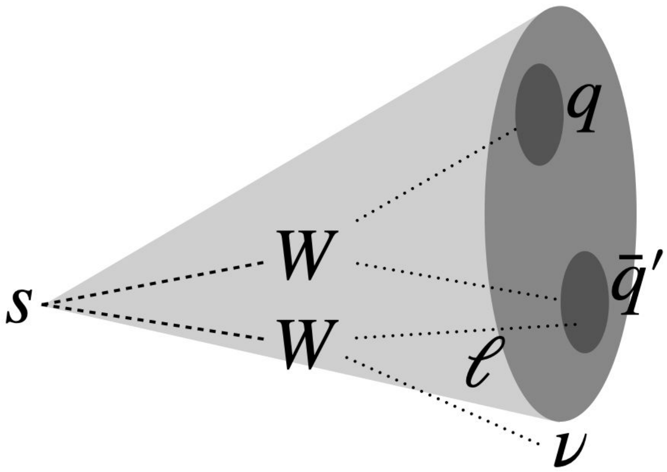




DM + dark scalar: mono-s(W^+W^-) semi-leptonic



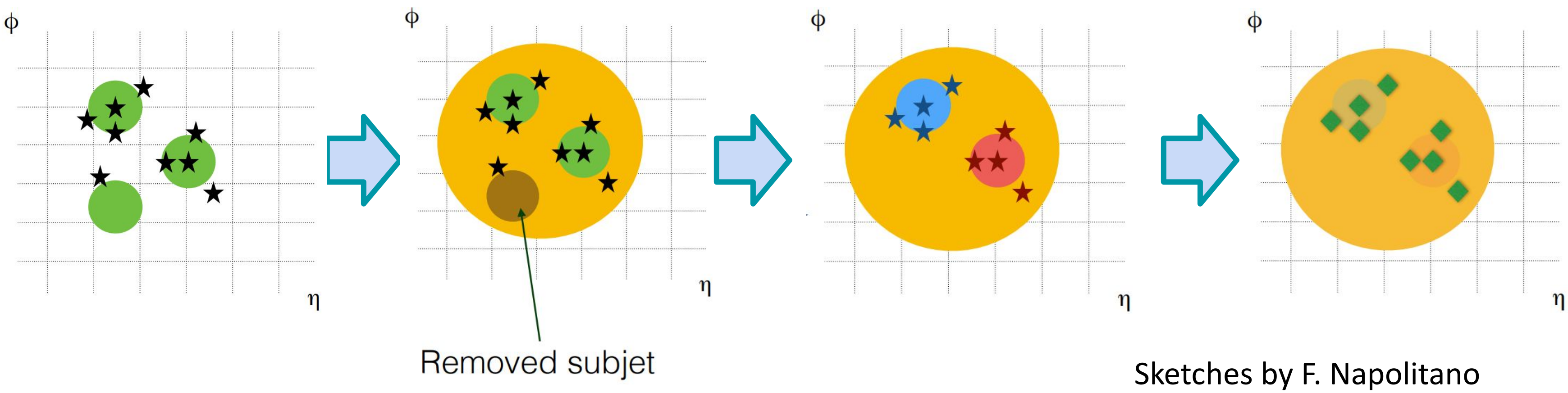
R= 1.0 track-assisted reclustered jet
(from calibrated R=0.2 and tracks)



- More granular calorimeter-based inputs: **R=0.2 jets calibrated against MC and Data**
- **W-tag the hadronic half** of the dark scalar decay: cut on $D_2 < 1.1$ and mass in [68, 89] GeV
- Remove R=0.2 jets overlapping with reco electrons
- Recover sensitivity to events failing boosted selection using two resolved R=0.4 jets in resolved region

ATLAS-CONF-2022-029, ATL-PHYS-PUB-2018-012

Mono-S(WW): Track-assisted-reclustered (TAR) jets



Sketches by F. Napolitano

TAR jets improve substructure resolution, esp. at high p_T, using fully calibrated inputs

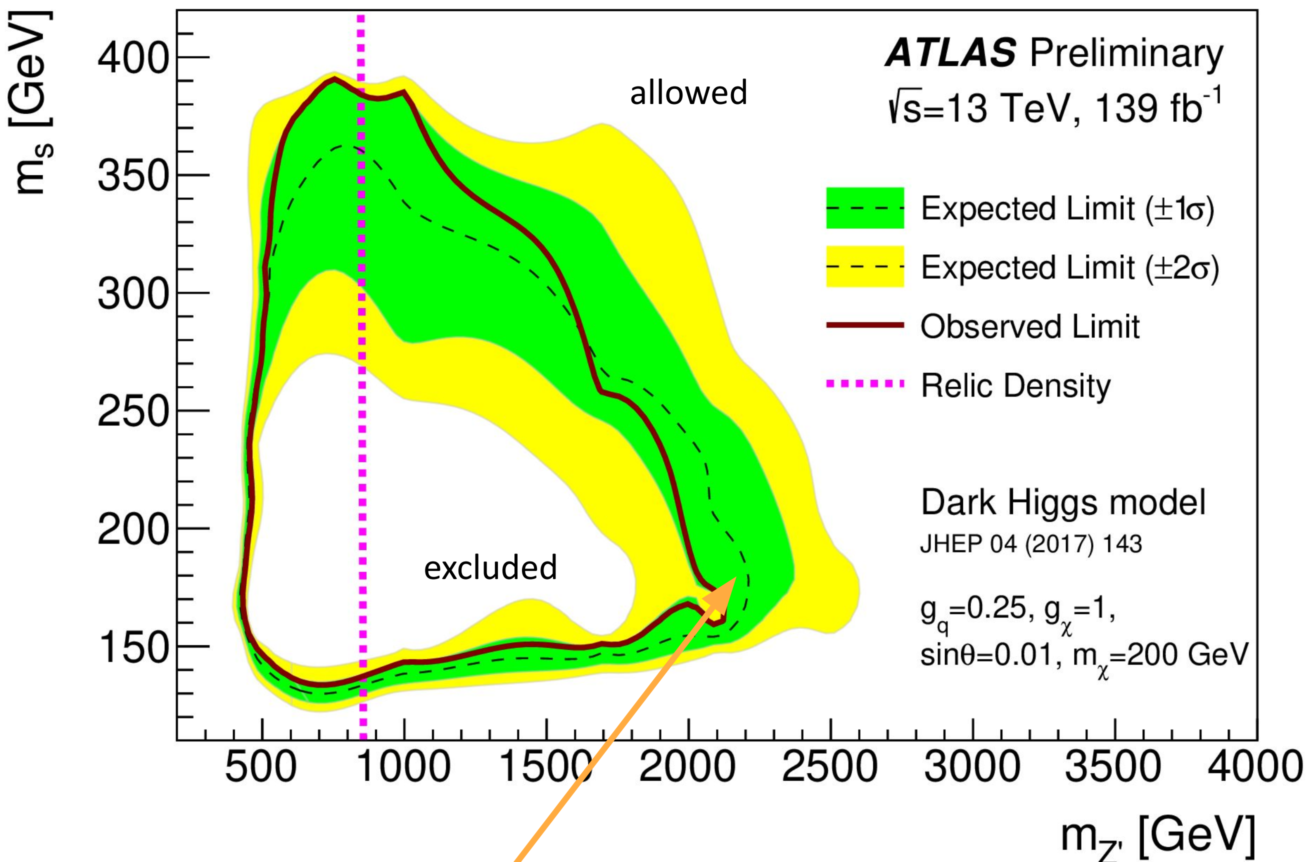
- Recluster **calibrated R=0.2** calorimeter-based jets into R=1.0 jet
- Rescale tracks using pT of associated R= 0.2 calo jet

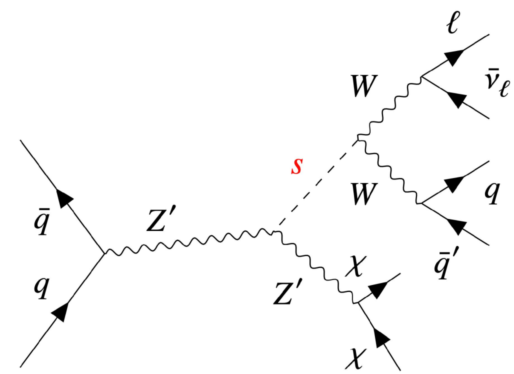
flexible choice since inputs calibrated

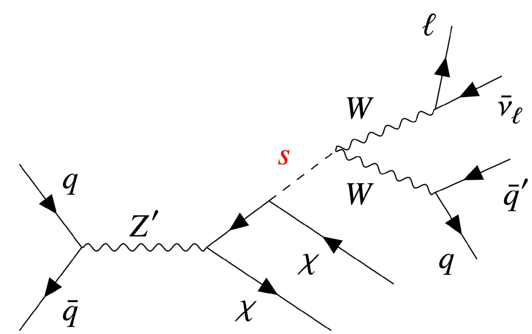
$$p_T^{\text{track, new}} = p_T^{\text{track, old}} \times \frac{p_{T,j}^{\text{subjet}}}{\sum_{i \in j} p_{T,i}^{\text{track, old}}}$$

  - Benefit from **track angular resolution**
  - Benefit from **energy resolution/neutral sensitivity of calorimeter clusters**

mono-s(W^+W^-) semi-leptonic: Result







higher mass differences (--> more boosted dark higgs decay) can be probed thanks to improved substructure resolution

Summary

- BOOSTing used in a range of searches for exotic signatures
- Tagging heavy SM particles powerful tool(s)
  - **Signal region purity** …
  - … **AND background estimation!**
- Heavy quark tagging: **a few highly-tuned tools** work well for many applications
- **Higgs tagging sees diverse solutions** employed:
- Most analyses shown here used **calo-cluster constituents** & **trimming**
  - combining calo and track data in jet reconstruction is a custom thing
    - combined mass, TAR, TCC

Thank you for your attention!
Please ask, please comment,
Boostamos!

Backup

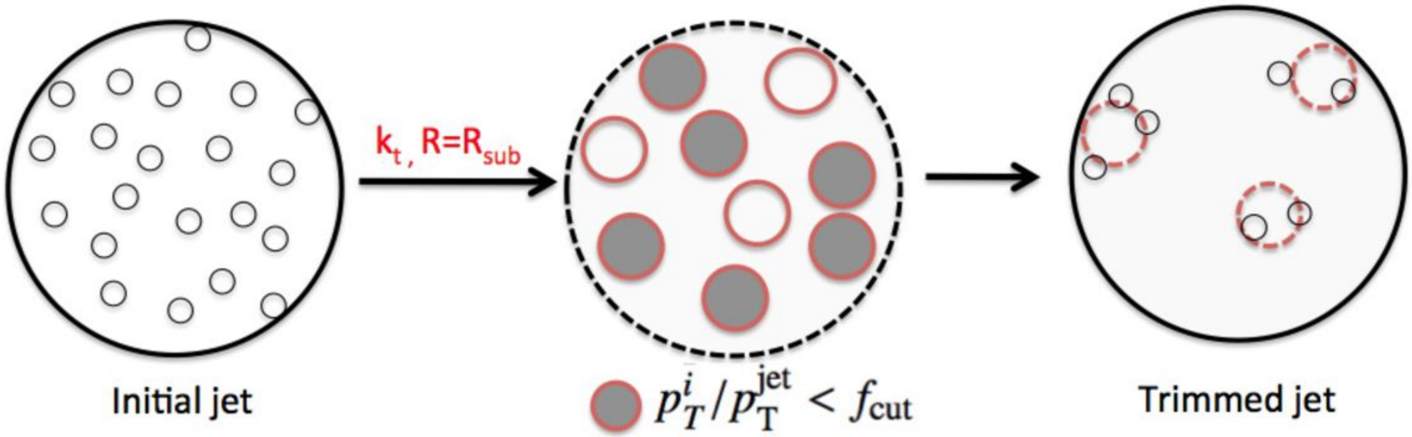
Outlook

- Most analyses shown here used **calo-cluster constituents** & **trimming**
  - combining calo and track data in jet reconstruction is a custom thing
    - combined mass, TAR, TCC
  - particle flow only for R=0.4 jets (see C. Youngs talk)
  - this will change in the future (see N. Lalloues poster tomorrow re. **UFO**s, jet reco, etc.)
    - And it will impact the performance of the tagging approaches used here (see T. Fitschens talk on Wednesday)
- Most ML taggers shown here take **analytic jet shapes as input features**
  - this too may change
    - for constituent-level top tagging, see K. T. Greifs Poster tomorrow
    - for constituent-level soft X$\longrightarrow$ bb tag, see Y. Chou's talk on Wednesday

Trimming @ ATLAS

Cf. N. Lalloues poster re. UFO-jet grooming

- Every analysis presented in this talk only uses large-R (here R=1 or R=0.8) jets that are trimmed [1] to improve resolution and resilience to additional radiation
  a. Recluster jet constituents into smaller subjets using k_T algorithm with R=0.2
  b. Reject subjets with $p_{T,\,sj} < f_{cut} * p_{T,J}$ ($f_{cut} = 0.05$)
  c. Form the trimmed jet from the remaining constituents
- In every case, though the jet reconstruction varies, the trimming procedure does not



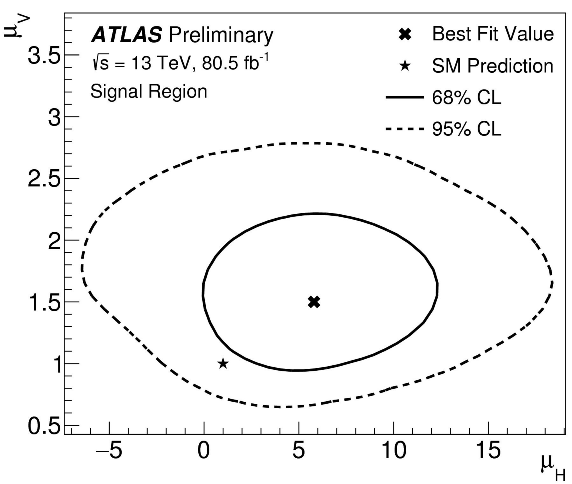
[1] D. Krohn et al., JHEP 02, 084 (2010)

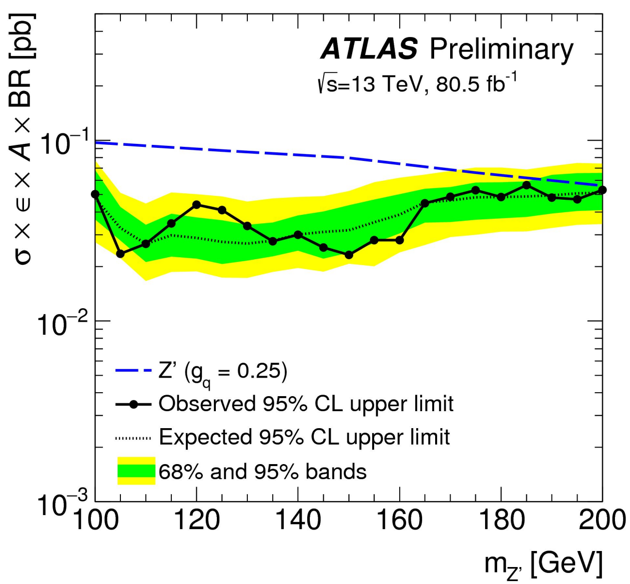
JHEP 09, 076 (2013)

$\Delta R/\min(R_{eff})$ example: low-mass b-tagged dijets search

CONF-EXOT-2018-04

- Search for low-mass BSM resonances coupling (preferentially) to 3rd gen. Quarks
- Trigger on hard ISR jet to access low masses
- Use variable track jets to b-tag resonance candidate decay products (standard)
- As part of selection require $\Delta R(j1, j2) > \min(R_{eff,j1}\ R_{eff,j2})$
  - Equiv. of $\log\Delta R^* > 0$

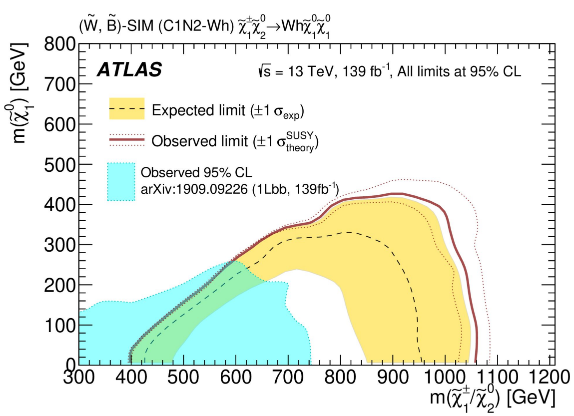


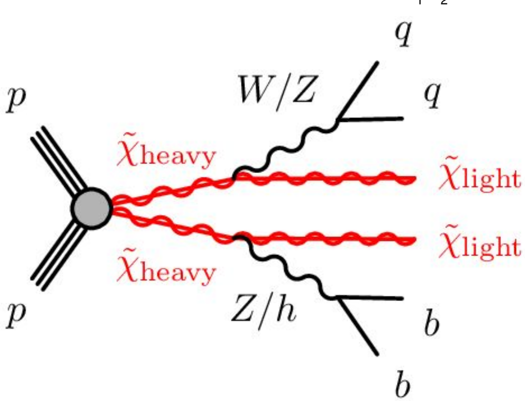


ΔR/min(R_{eff}) examples: SUSY VV/Vh and SM boosted h

PRD 104 (2021) 112010

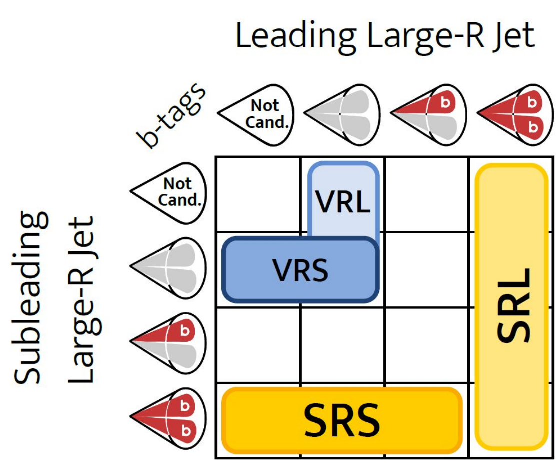
- All-hadronic bosons+LSPs search
- As part of event pre-selection require ΔR(j1, j2) > min($R_{eff,j1}$ $R_{eff,j2}$)

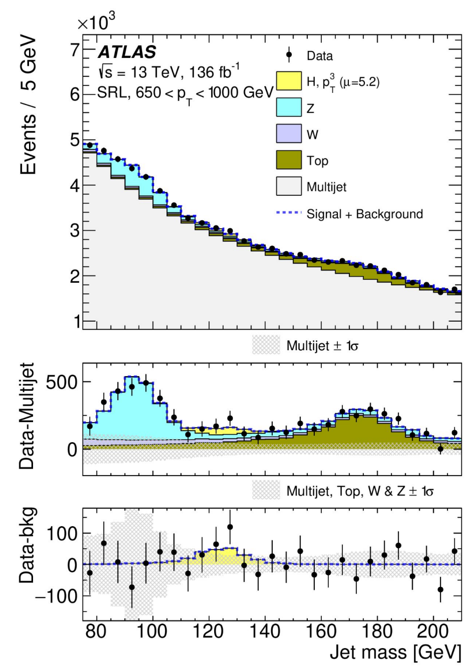




Phys. Rev. D 105 (2022) 092003

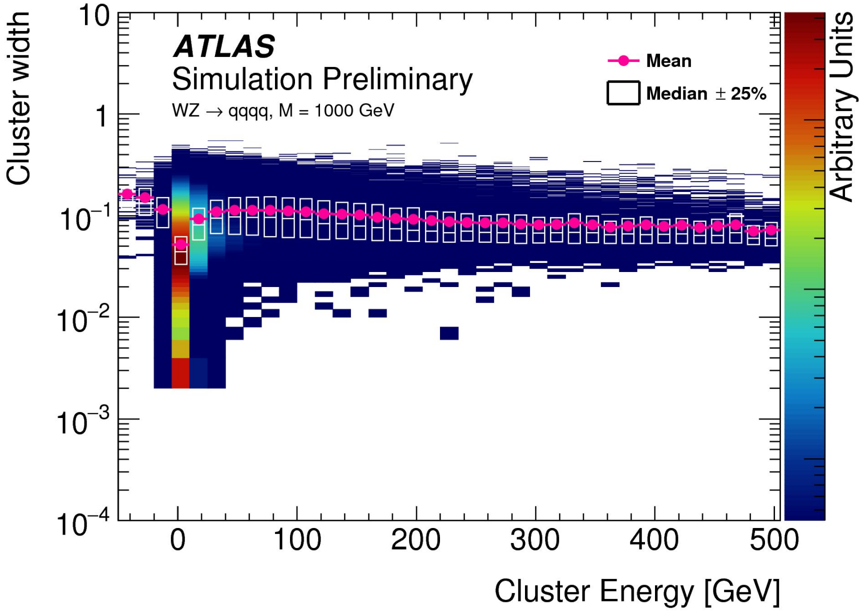
- Boosted SM h(bb) search
- Ignore VR track jet for b-tagging if ΔR(j1, j2) <= min(Reff,j1 Reff,j2)
- Implicitly means the jet may not be Higgs-tagged, since that requires 2/2 VR track jets be b-tagged

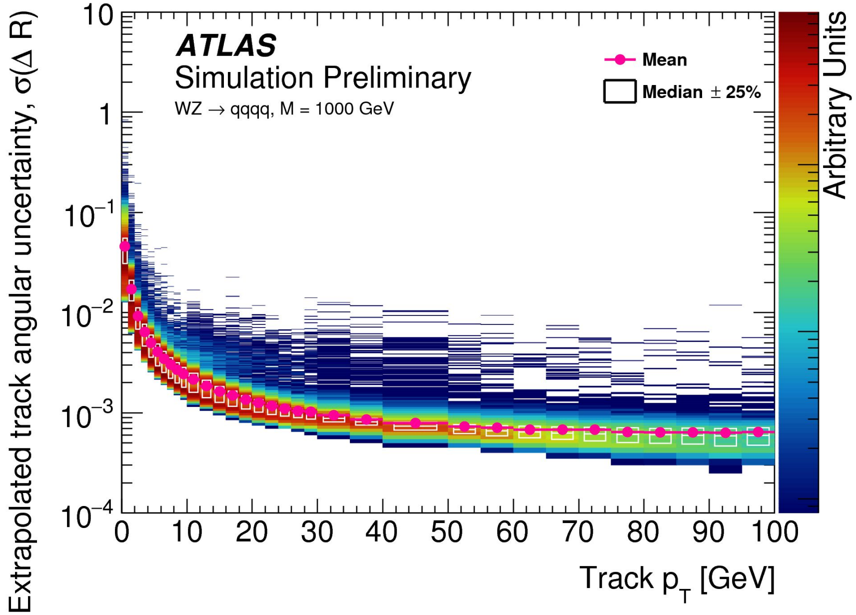




TCC: Track extrapolation vs. Cluster width

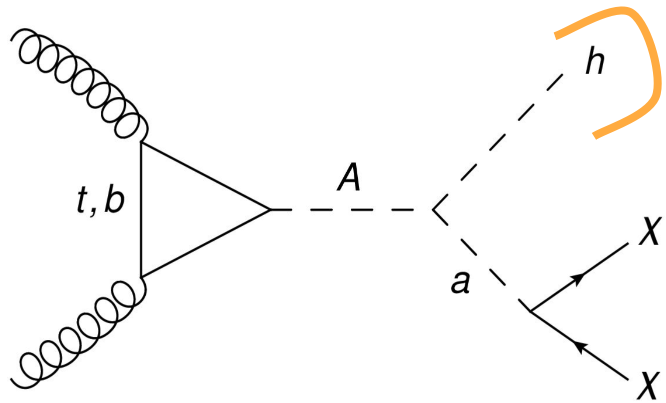
Cf. N. Lalloues poster and T. Fitschens talk re. UFOs





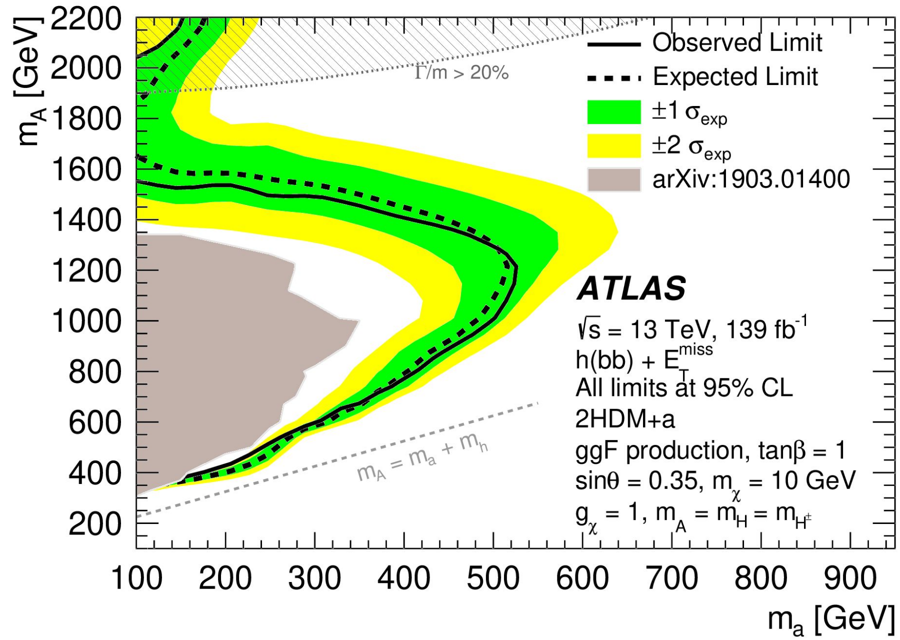
JHEP 11, 209 (2021)

A more standard ATLAS higgs tag: mono-h(bb)

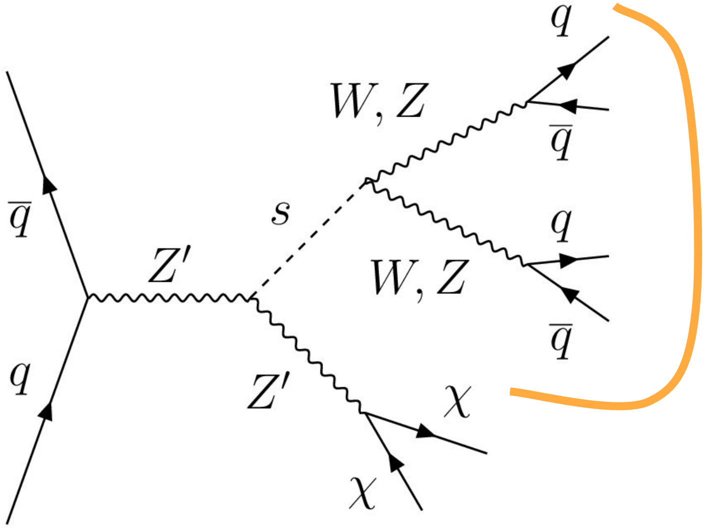


R=1 trimmed calo jet, higgs tag

- Search for dark matter produced in association with hadr. decaying 125 GeV higgs
- Merged region (MET > 500 GeV) targets boosted higgs decay, reconstruct as one large-R jet
- Tag higgs by requiring 2 ghost-associated VR track jets with b-tag

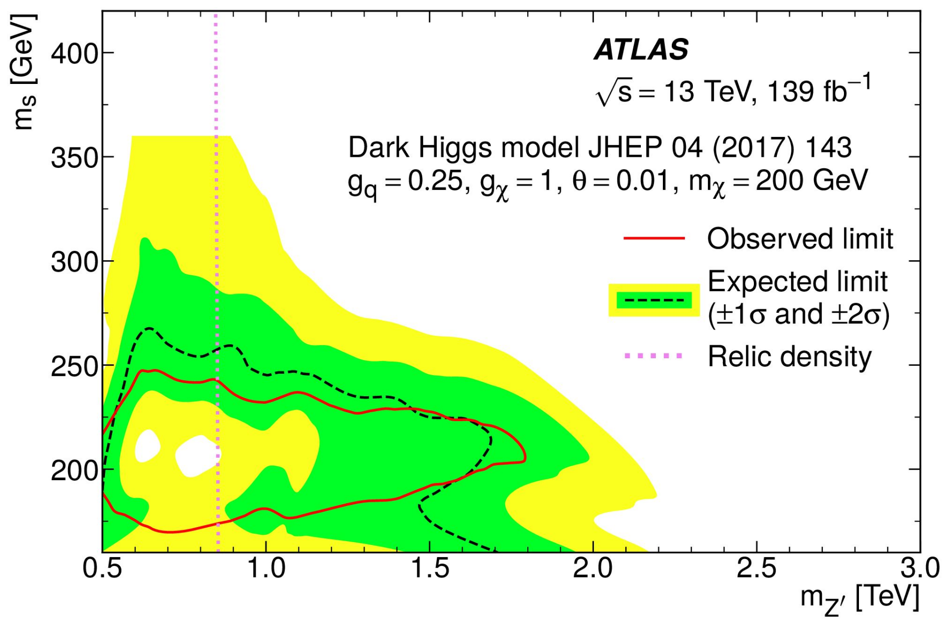


What if mono-h but heavier: mono-S(VV) hadronic



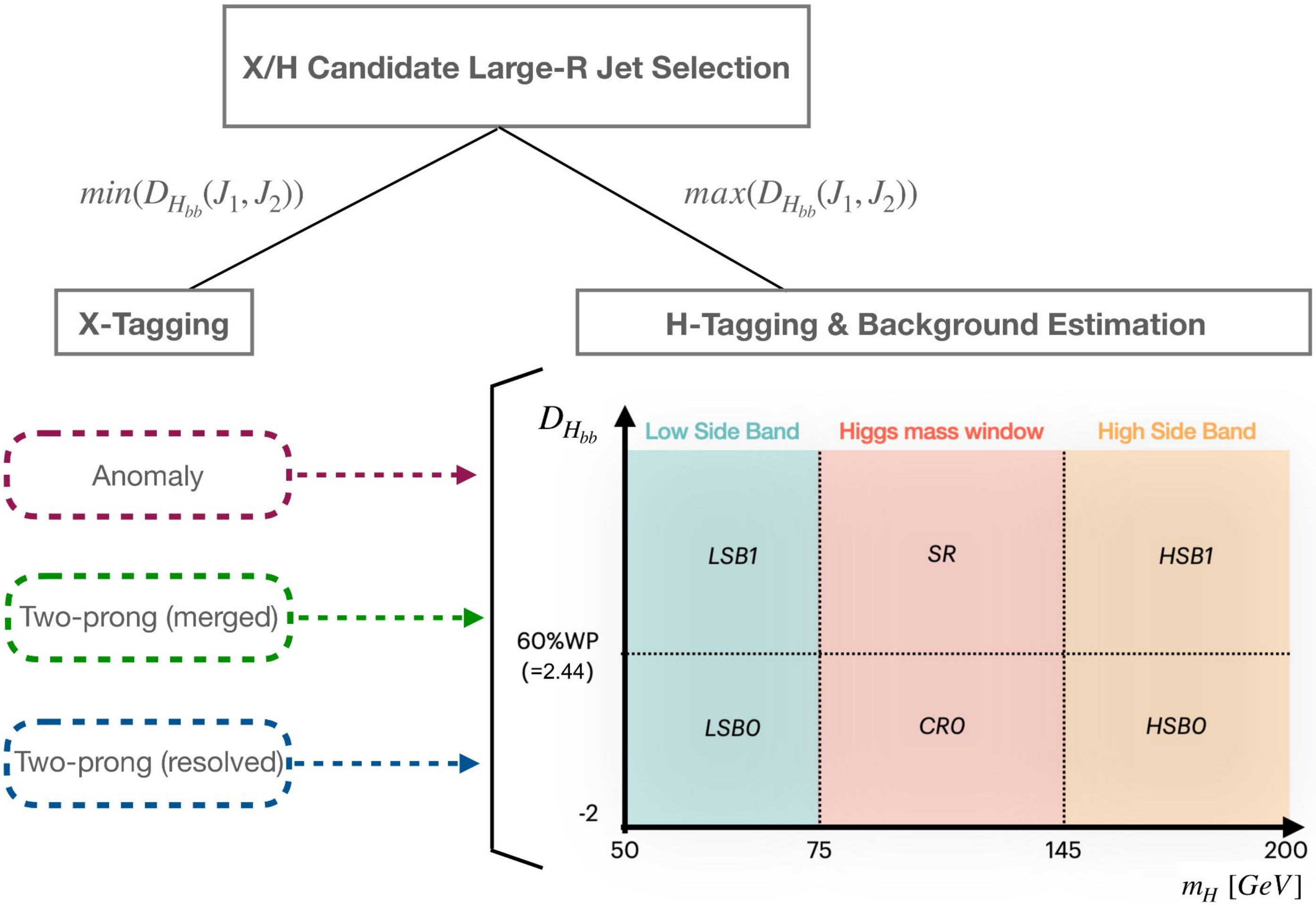
R= 0.8 track-assissted reclustered jet (from calibrated R=0.4 and tracks)

- Search for dark matter scattering off a BSM scalar which decays to a pair of EW vector bosons
- $0 < \tau_4/\tau_2 < 0.3$ and $0 < \tau_4/\tau_3 < 0.6$ to select four-prong substructure
- Target boosted topology, recover sensitivity to low-mass models using dedicated resolved region w. R = 0.4 jets



Y –> X h search additional material

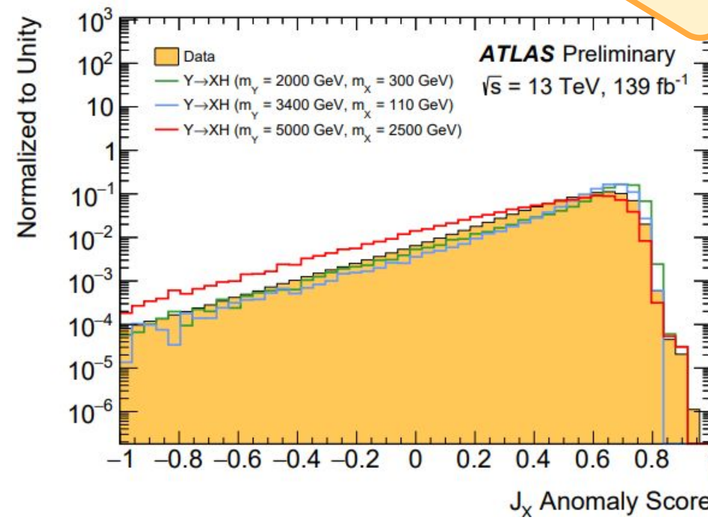
Y → X h strategy

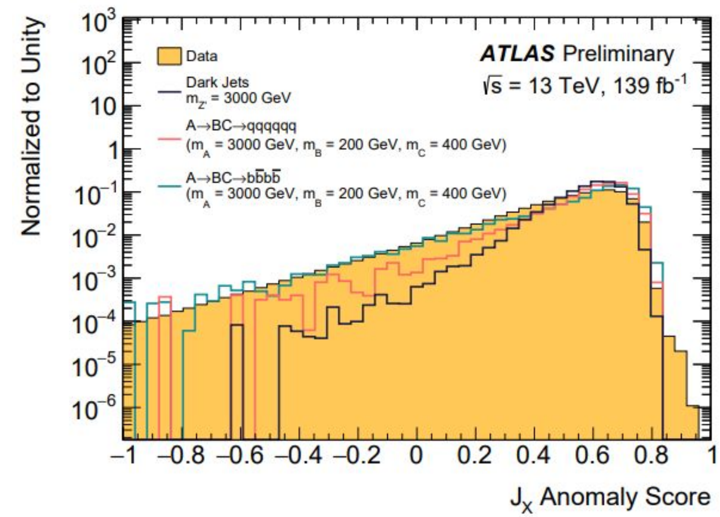


See also the poster by S. Auricchio tomorrow!

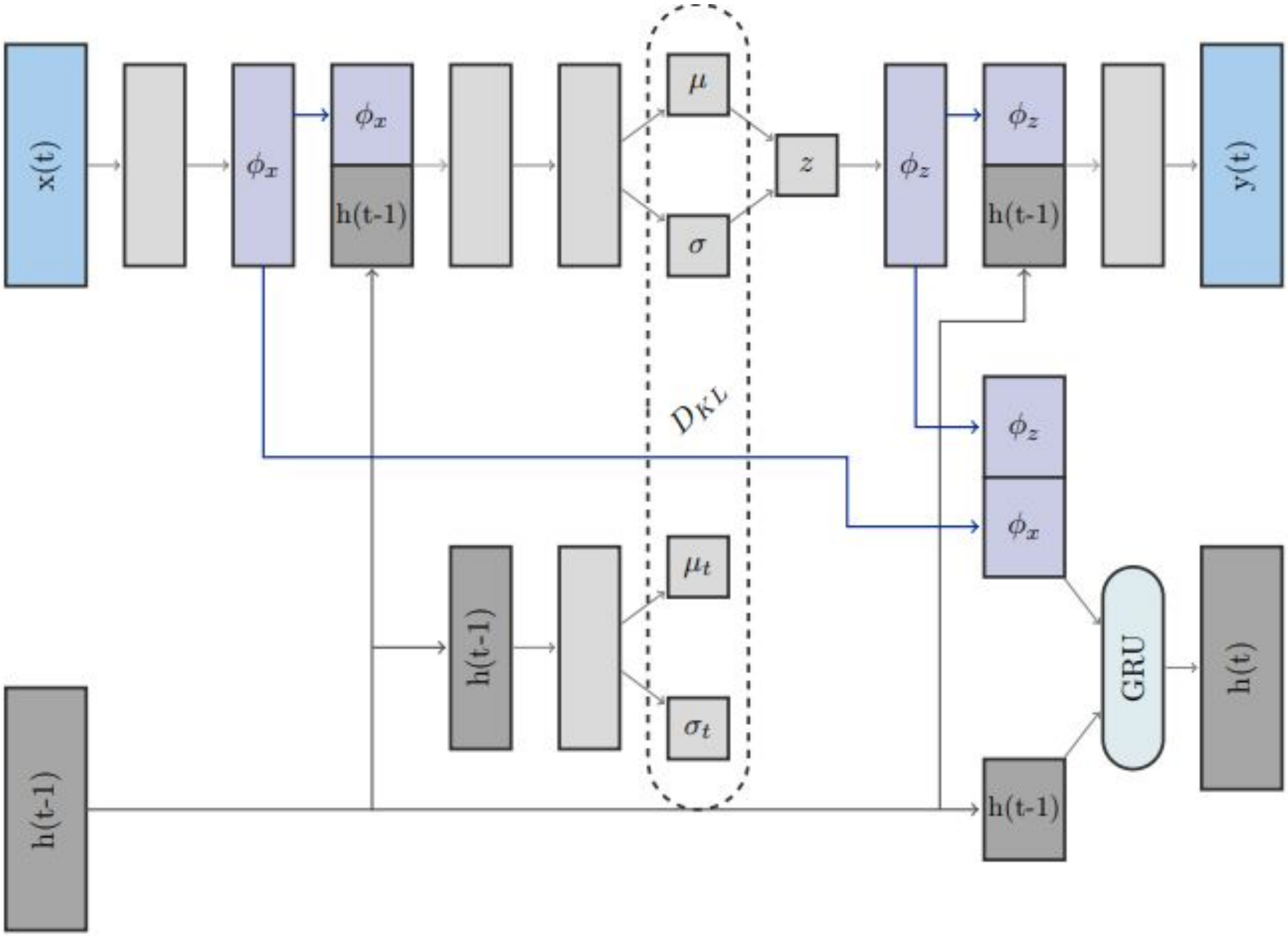
Unsupervised variational RNN for Y → Xh search

- Takes k_T - ordered sequence of jet constituent four-momenta + D_2, τ_{21}, d_{12}, d_{23}
- Trained to **compress sequence of constituents** (and conditioning high-level JSS) into sequence of latent priors, then **recover inputs from sampled results**
  - RNN structure → prior information about harder constituents accumulates in the VRNN cell as it processes a jet
- Train over run 2 data, then select sample of most anomalous jets based on VRNN loss averaged over constituent sequence
- Increase **sensitivity to wide range of anomalous jet structures**





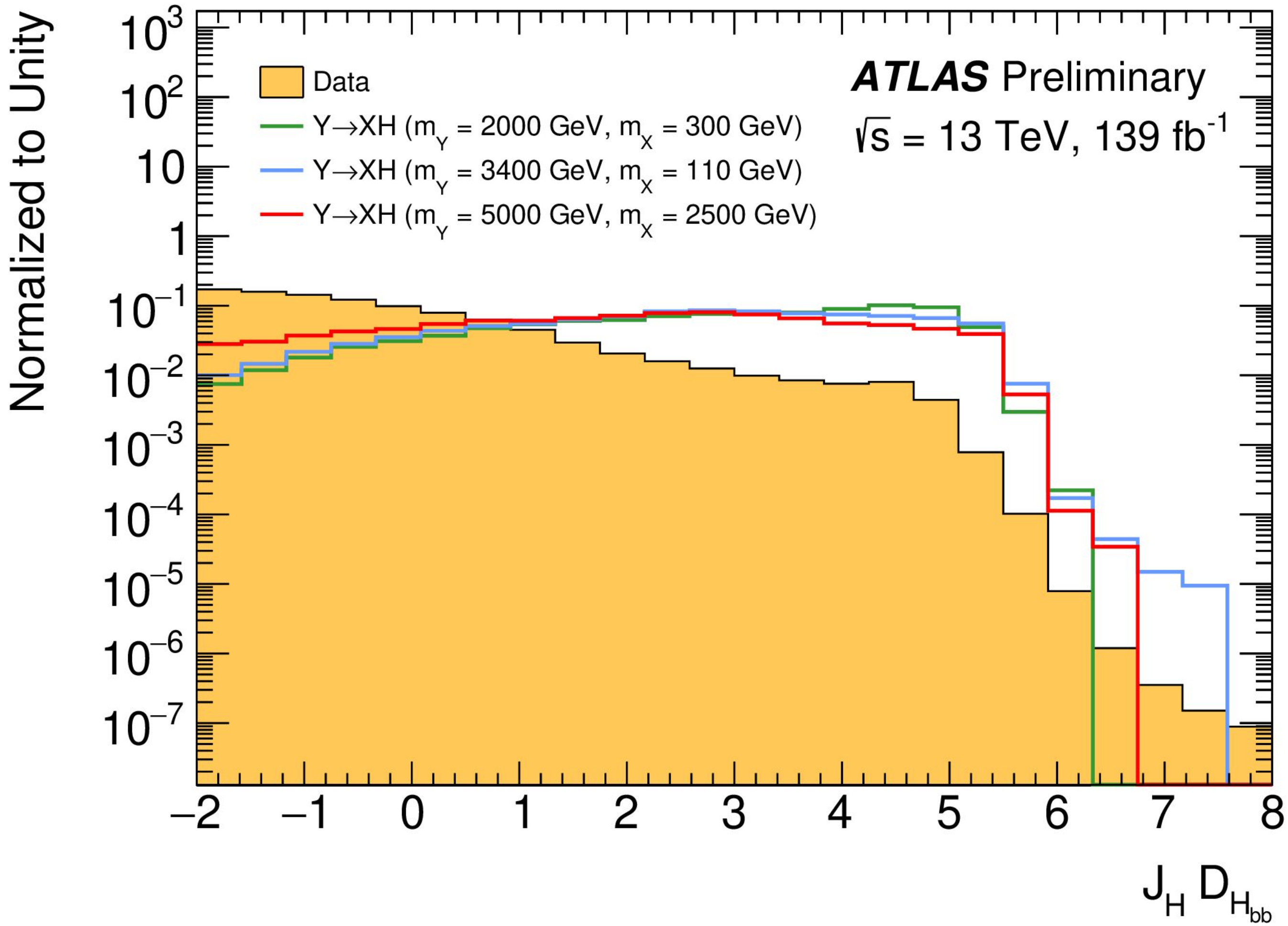
VRNN cell



x(t)
ϕ_x
ϕ_x
h(t-1)
μ
σ
z
ϕ_z
ϕ_z
h(t-1)
y(t)
D_{KL}
ϕ_z
ϕ_x
h(t-1)
μ_t
σ_t
GRU
h(t)
h(t-1)
h(t-1)

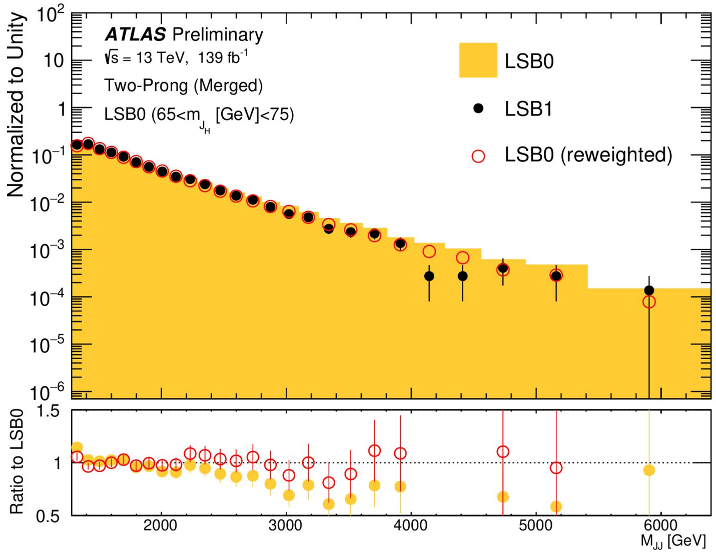
ATLAS-CONF-2022-045

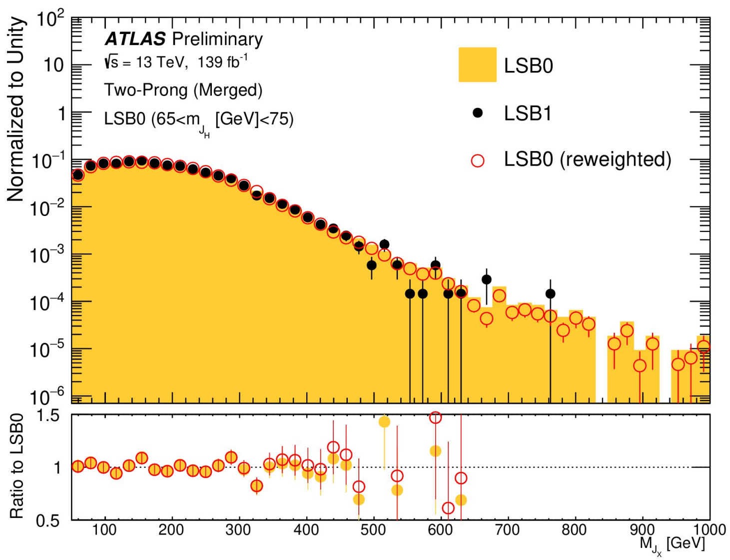
Y → X h Higgs tag scores

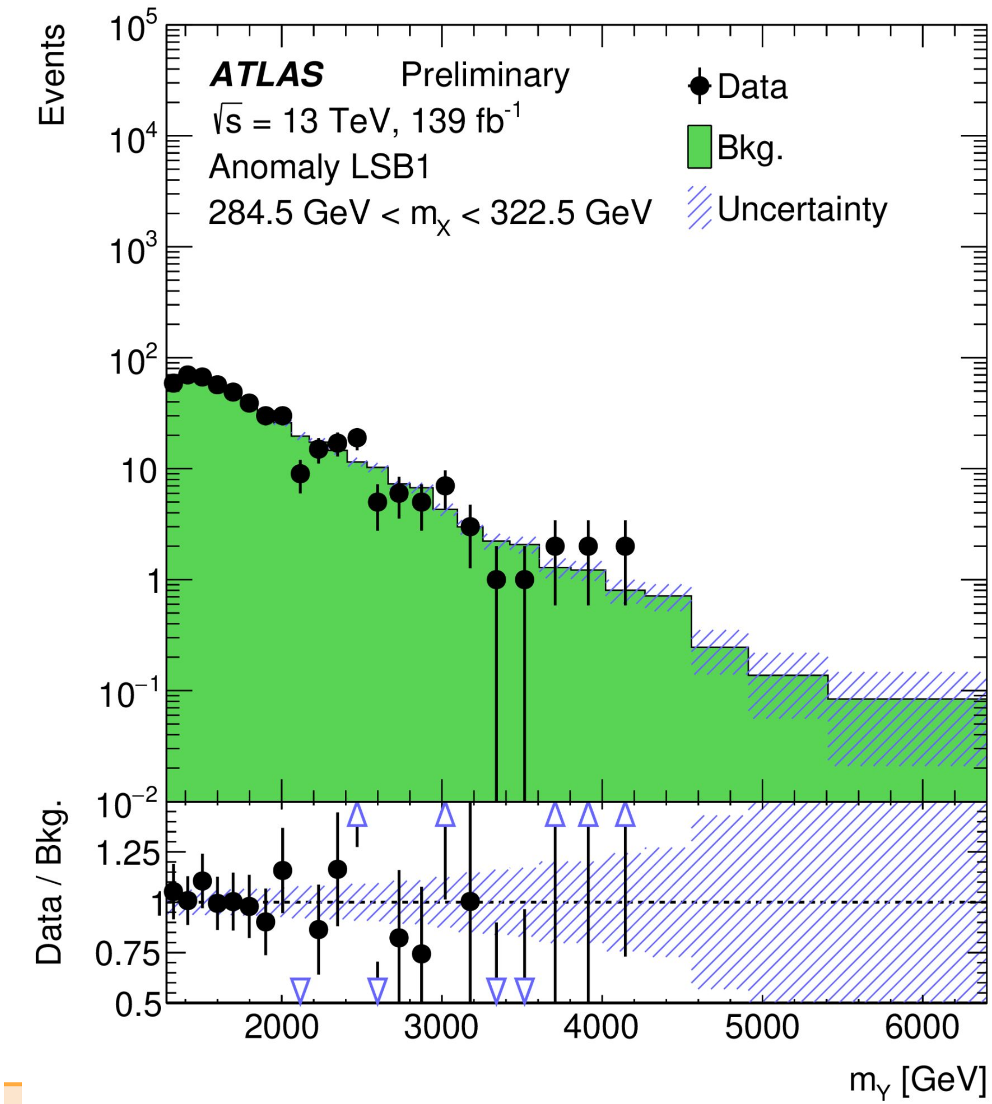


ATLAS-CONF-2022-045

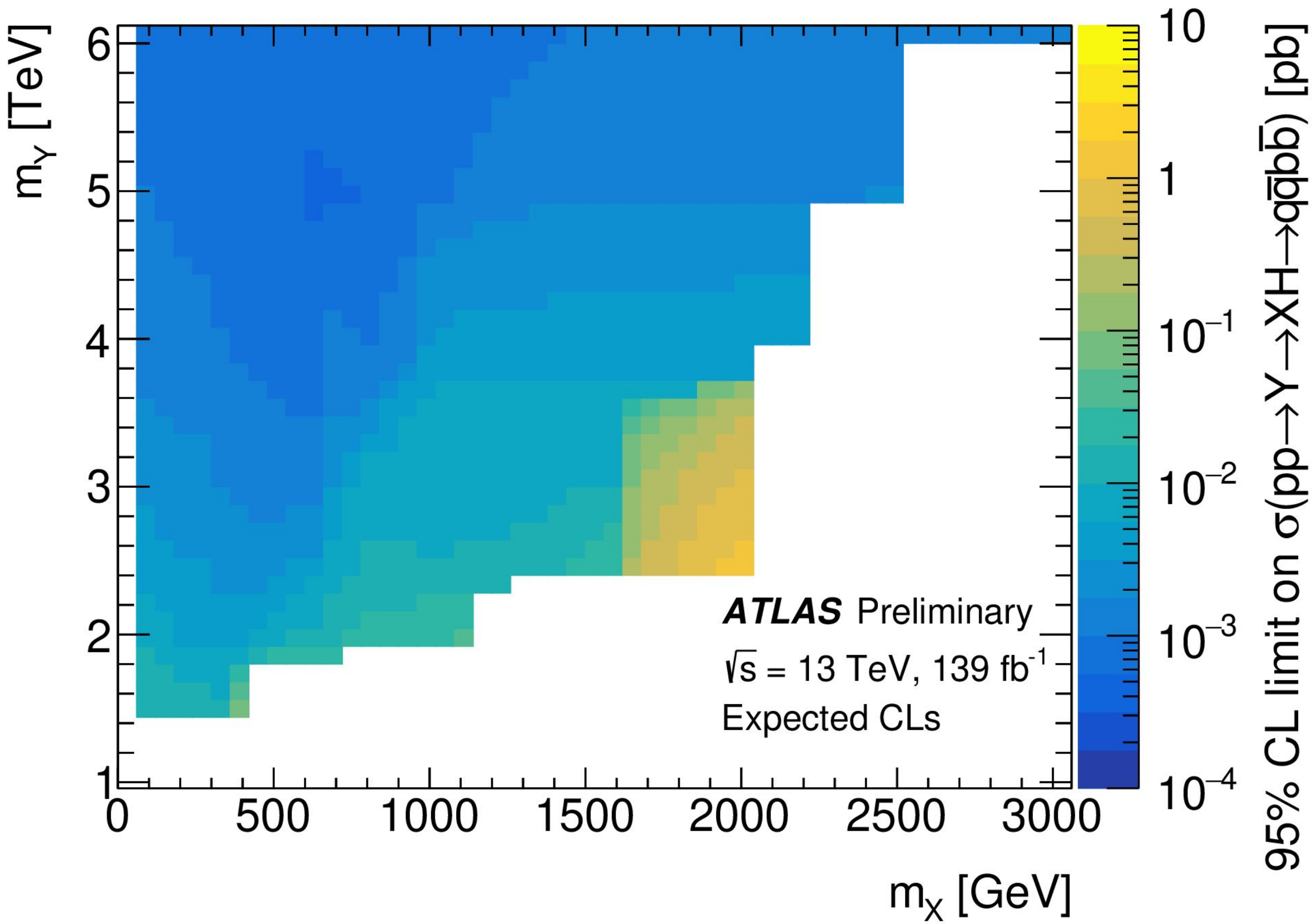
Y → X h Validation mass spectra



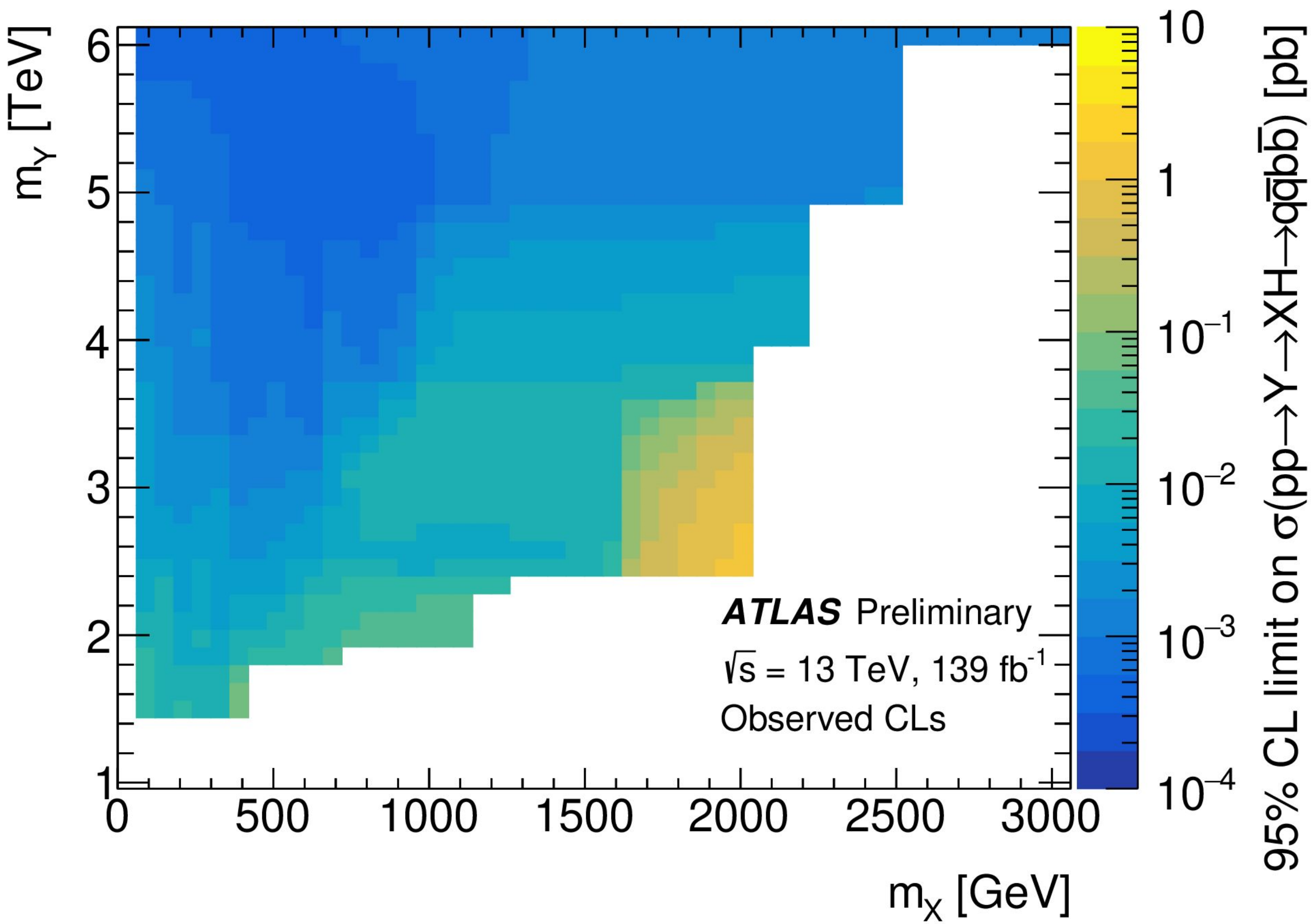




Y ⟶ X h Two-prong interpretation limits

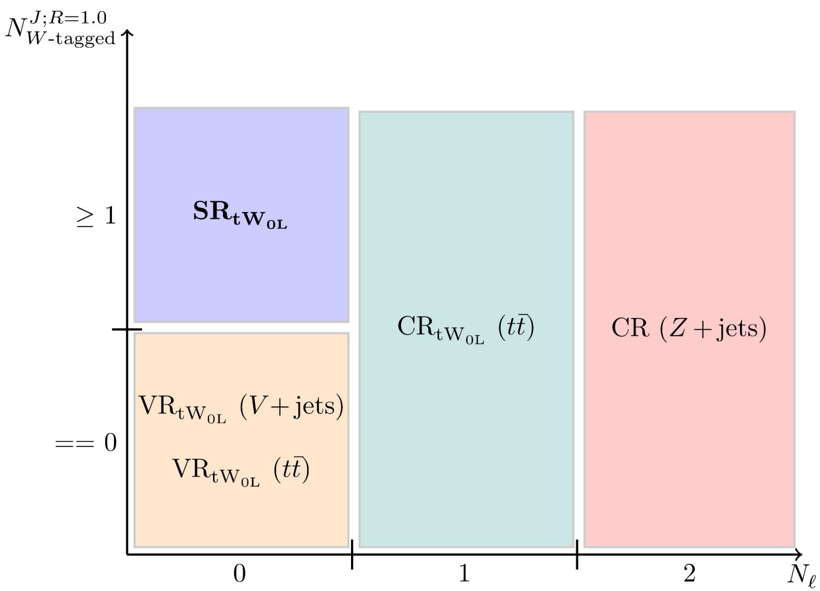


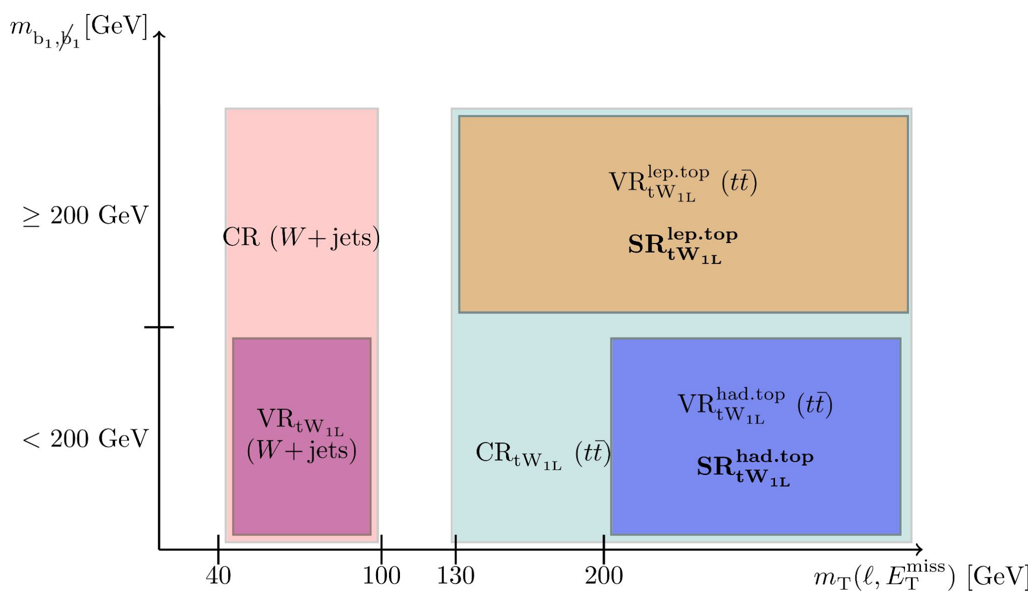
Y ⟶ X h Two-prong interpretation limits



Wt+MET DM search: additional material

Wt+MET DM search: Region definitions





ATLAS-CONF-2022-012, JHEP 06, 108 (2018)

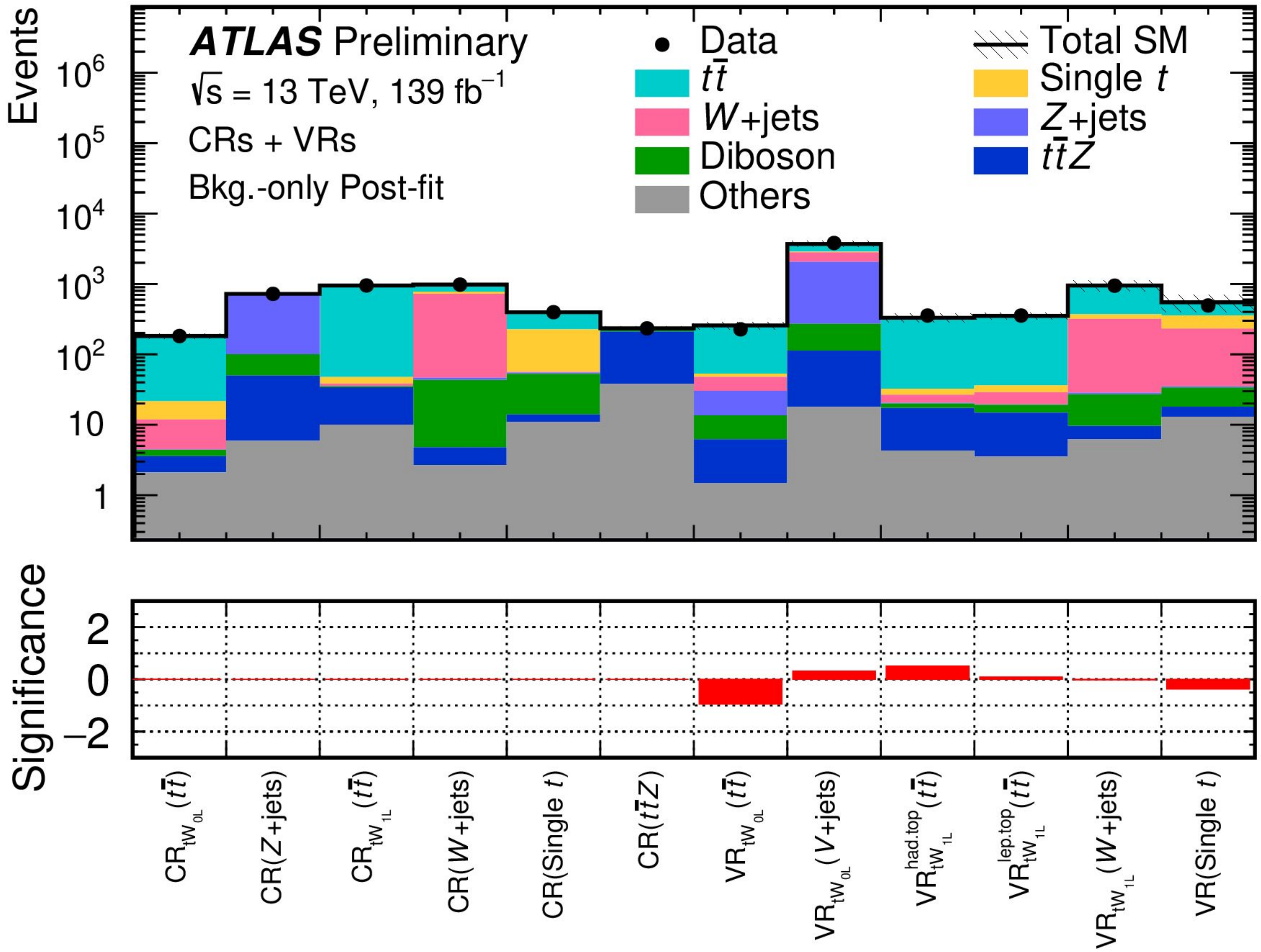
Wt+MET DM search: iteratively reclustered W mass

- Only relevant to hadronic top/leptonic W part of selection
- A kind of variable-radius jet, but starting from large radius and iteratively reducing
  - The individual iterations each perform fixed-R anti-k_T re-clustering of calibrated R=0.4 anti-k_T jets into a large-R jet
- The search keeps events with if they contain such a reclustered jet with mass >= 60 GeV

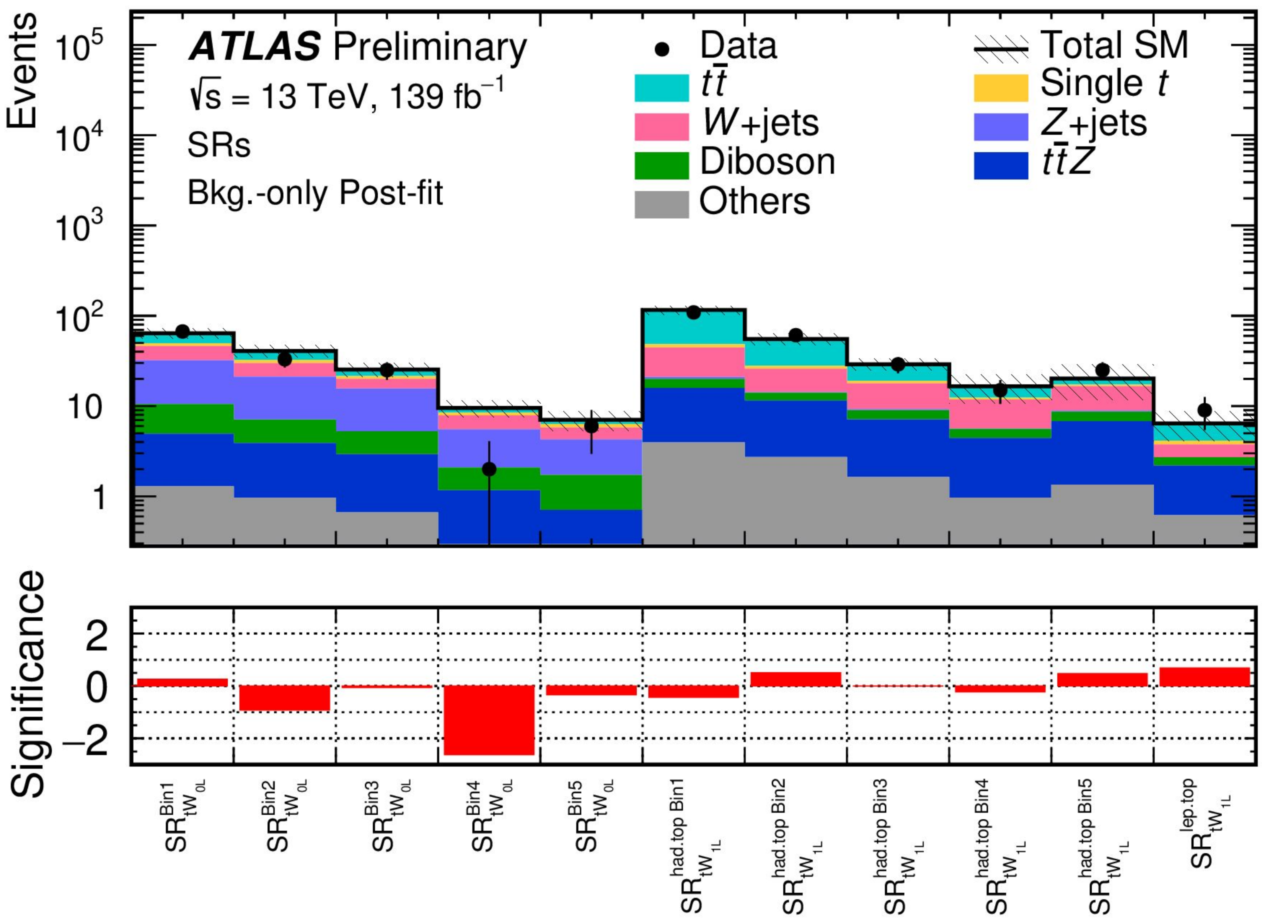
Algorithm (for each initial R= 3 jet):

```
i = 0
R_i = 3
for i → i + 1:
    p_T,i-1 = <pt of jet reclustered with anti-k_T and R=R_i-1>
    R_i = 2*m_W/p_T,i-1
    if R_i > R_i-1 +0.3:
        # discard the jet
        break
    if R_i < R_i - 0.5:
        continue
    else:
        # keep the jet for R=R_i
        break
```

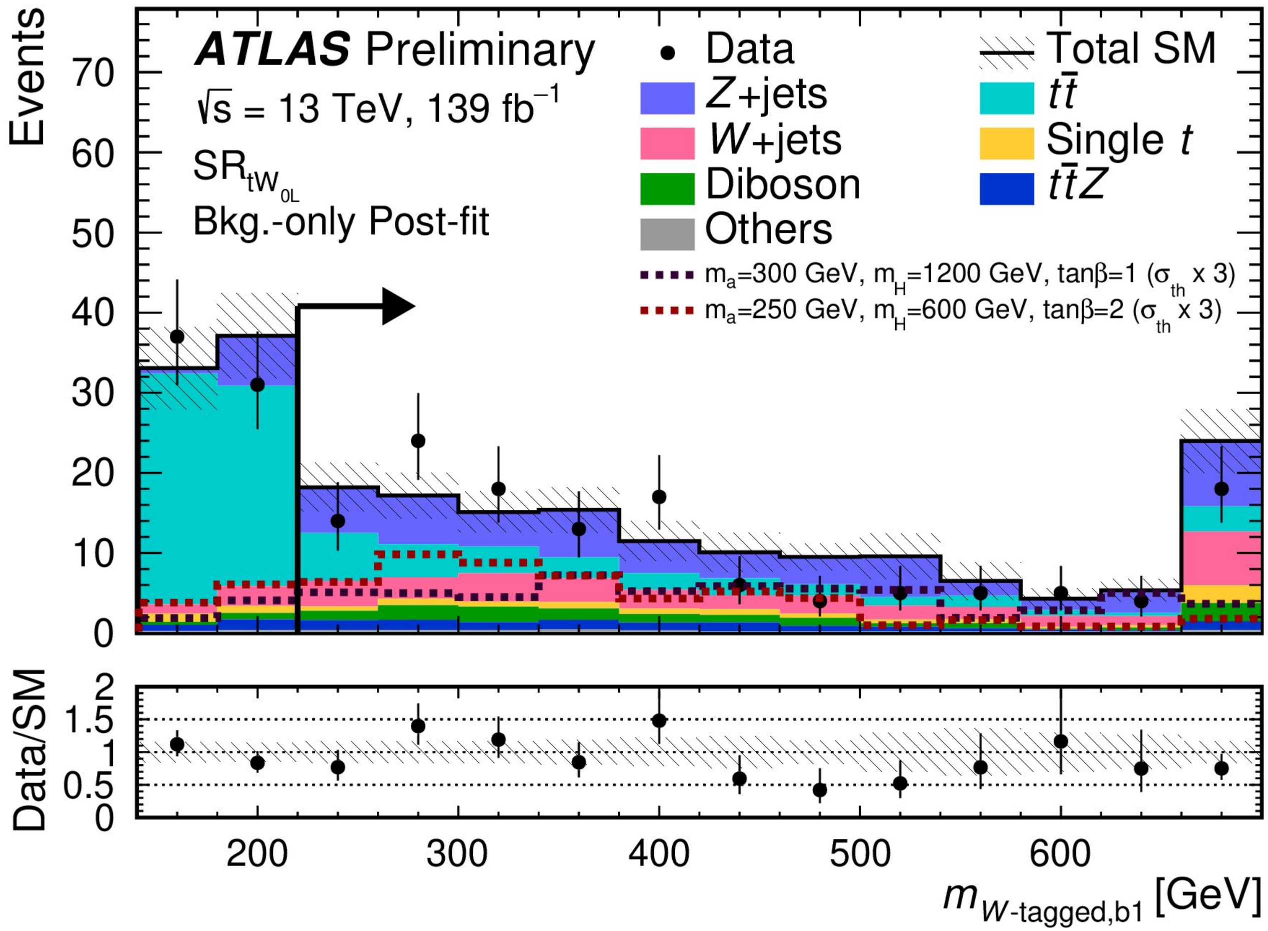
Wt+MET DM search: CR/VR yields



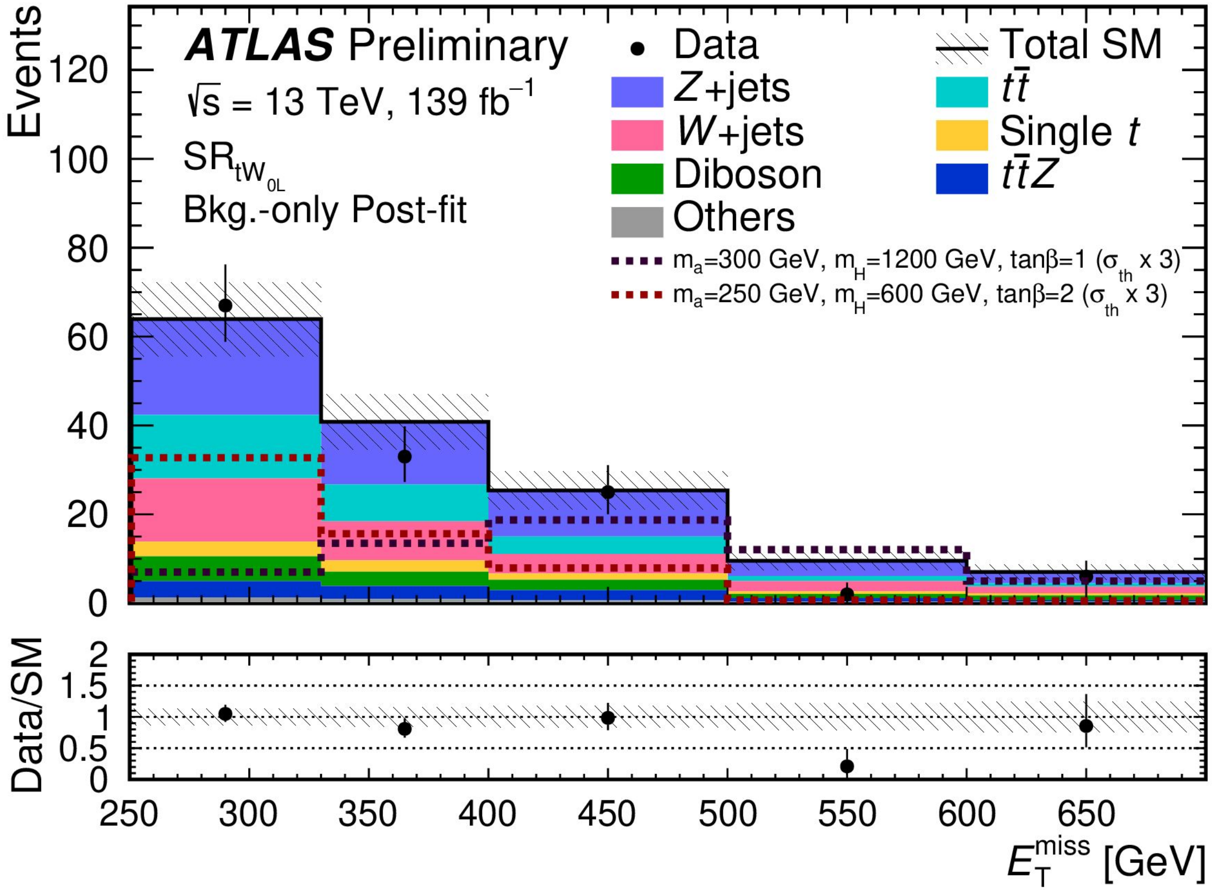
Wt+MET DM search: SR yields



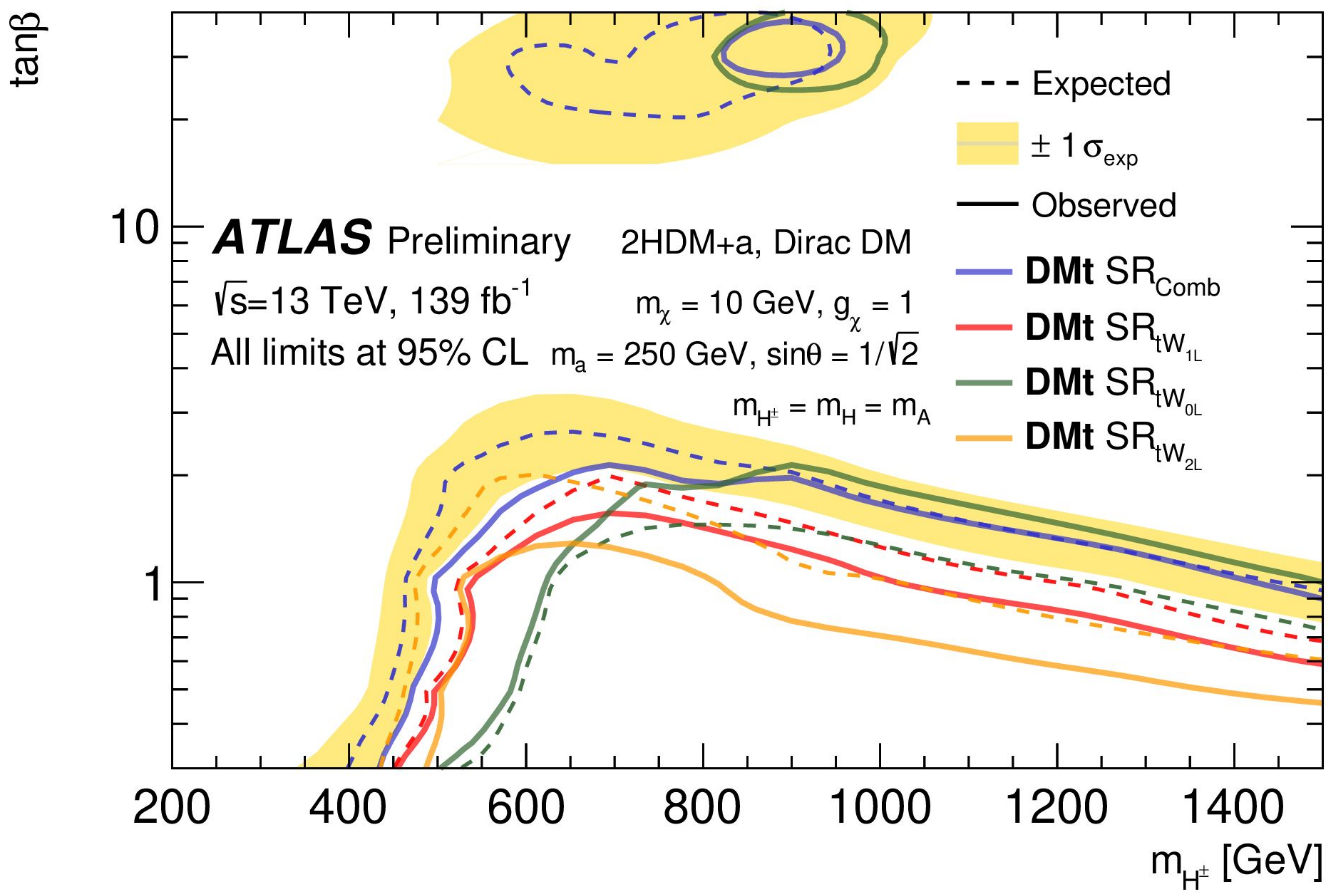
Wt+MET DM search: SR fits



Wt+MET DM search: SR fits



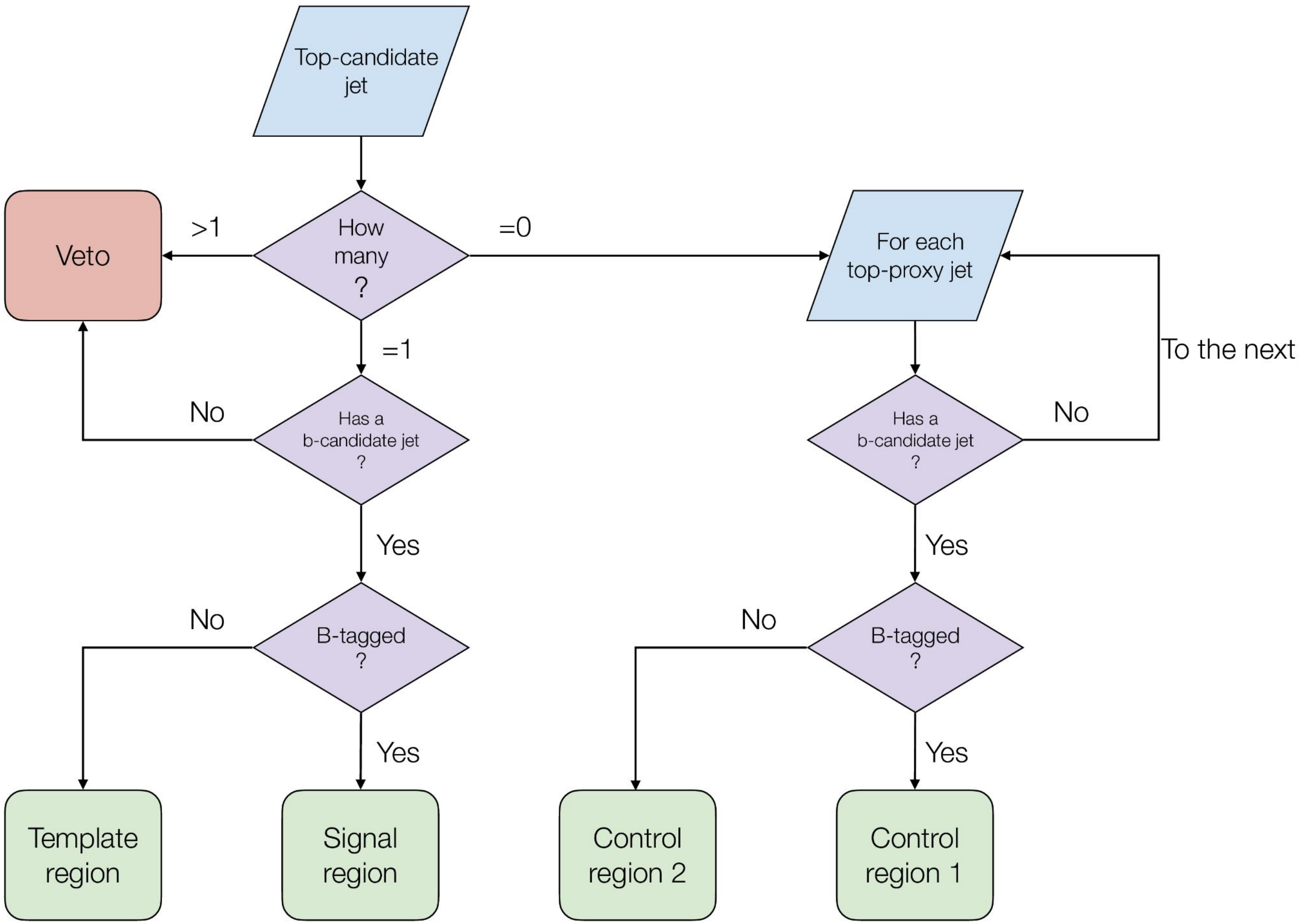
Wt+MET DM search: high-m_a limits



ATLAS-CONF-2021-043

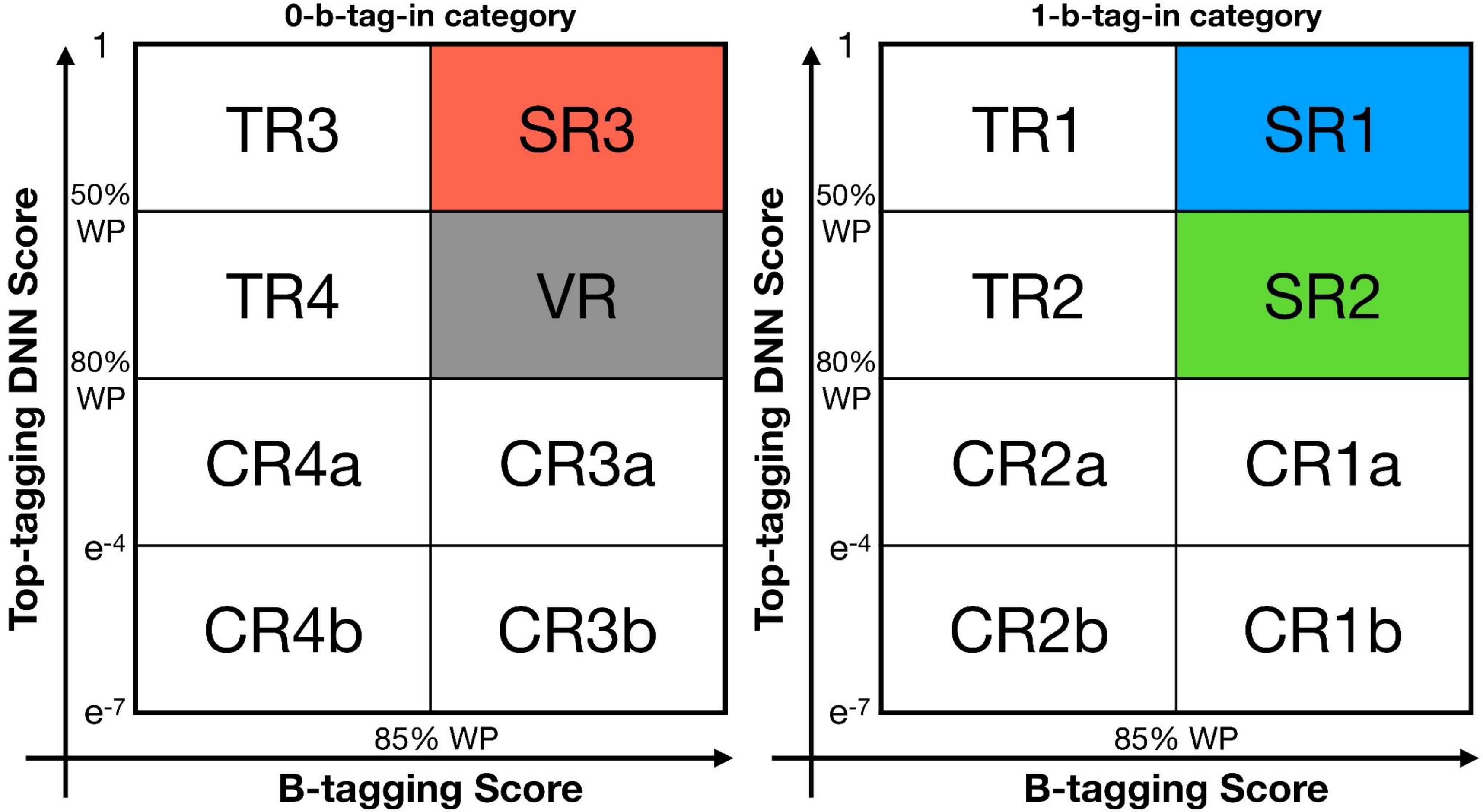
$W' \rightarrow t\,b$ additional material

W’ ⟶ t b strategy

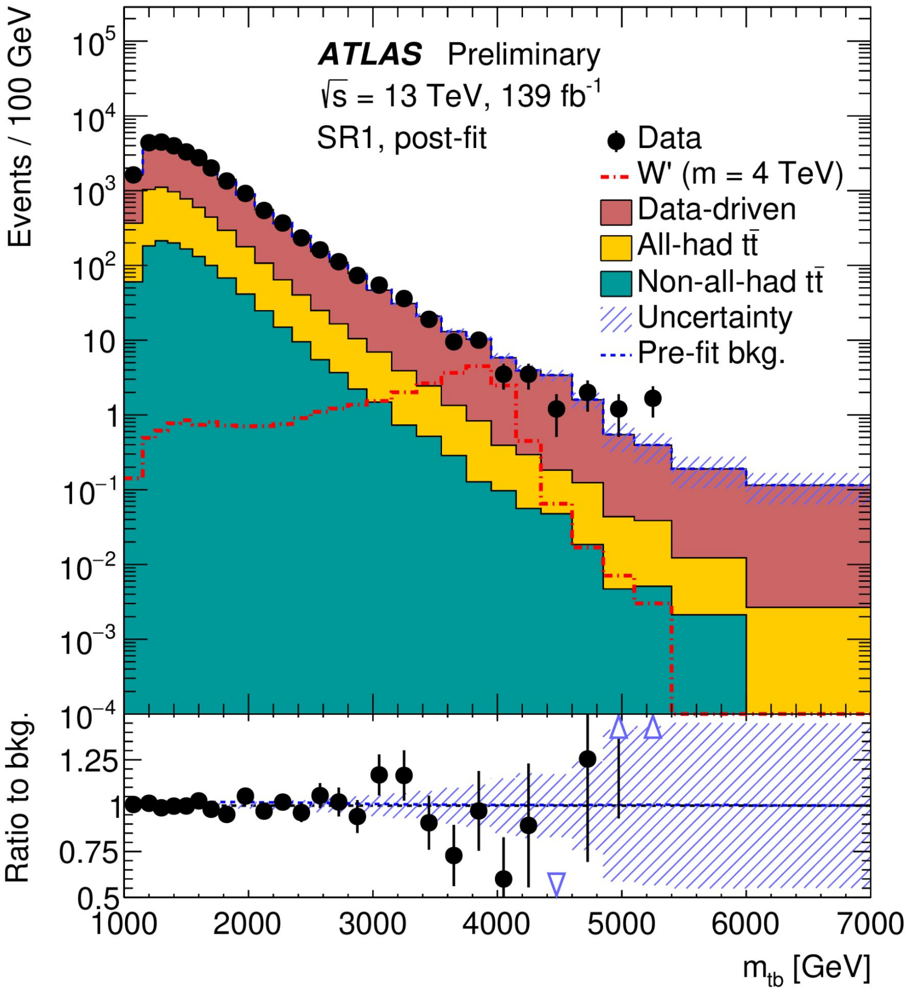


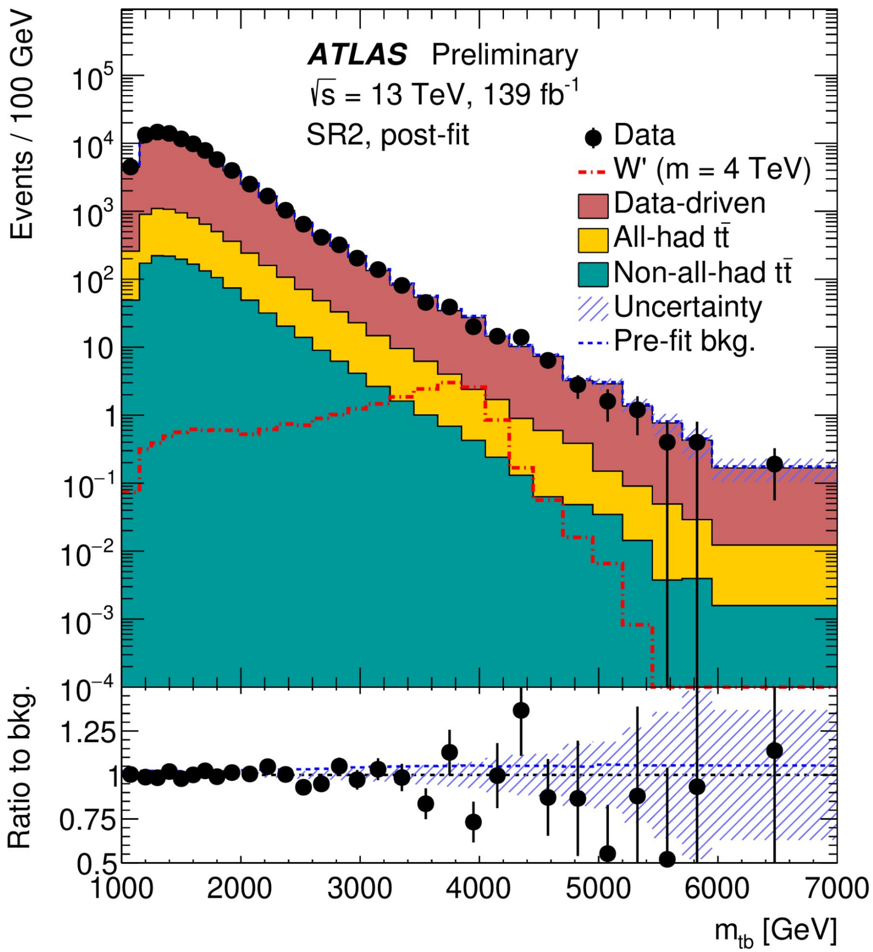
ATLAS-CONF-2021-043

W' ⟶ t b strategy



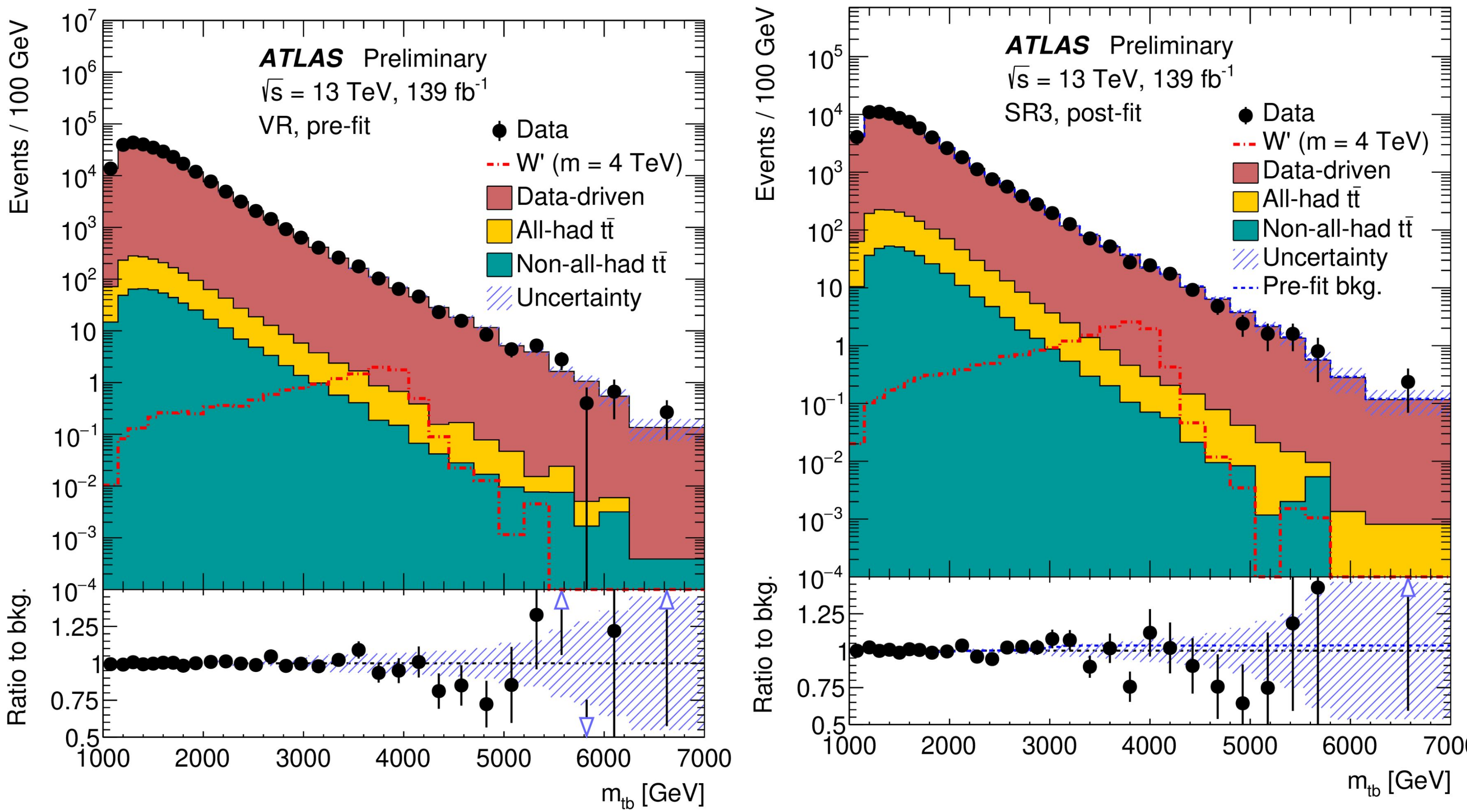
W’ ⟶ t b fitted distributions





[ATLAS-CONF-2021-043]

W' → t b fitted distributions



PRD 105, 092012 (2022)

VLT $\rightarrow$ h t additional material

PRD 105, 092012 (2022)

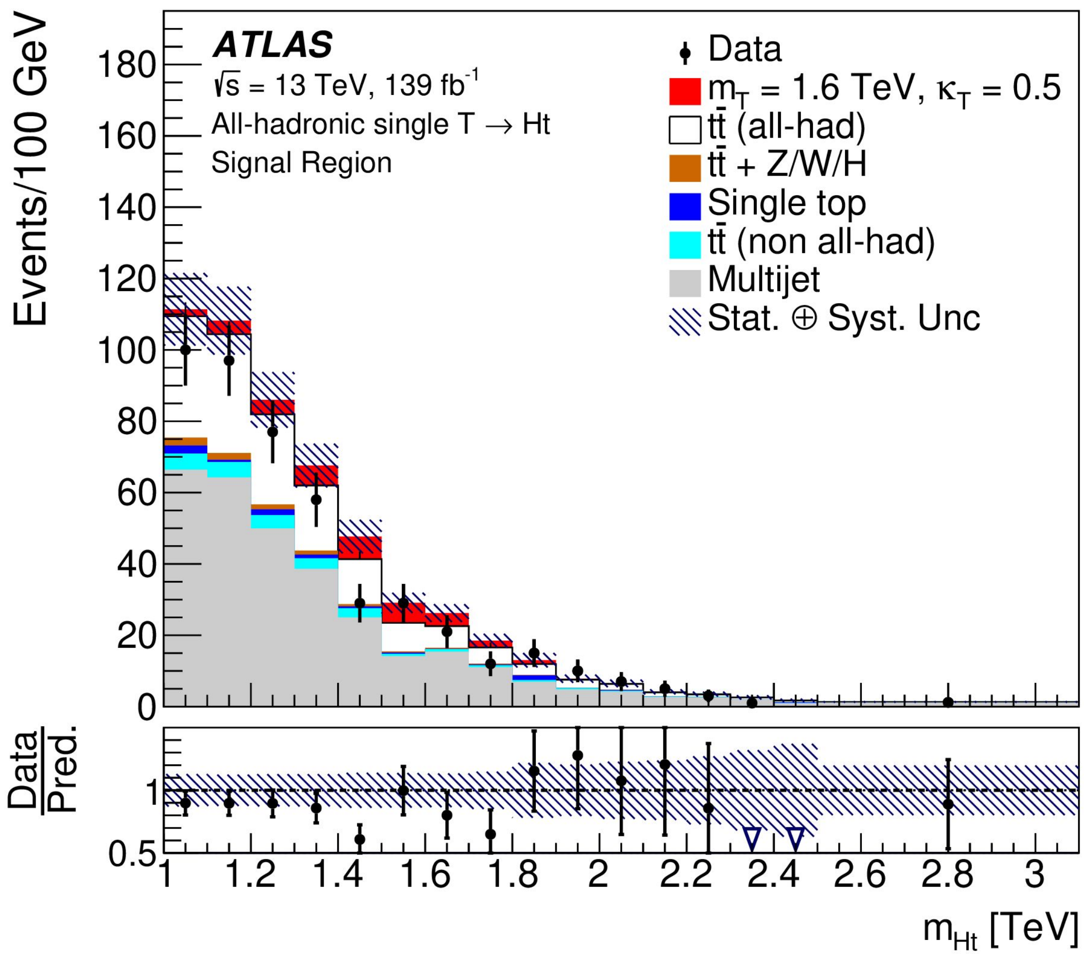
VLT → h t regions

Second-leading large-R jet tagging state

	0t 0H 0b	0t 1H 0b	1t 0H 0b	0t 0H 1b	0t 1H 1b	1t 0H 1b	0t 0H ≥2b	0t 1H ≥2b	1t 0H ≥2b
1t 0H ≥2b				VR8		NR		SR	NR
0t 1H ≥2b			VR6			SR			SR
0t 0H ≥2b									
1t 0H 1b						NR		SR	NR
0t 1H 1b						VR1			
0t 0H 1b						VR2			VR7
1t 0H 0b						VR3		VR5	
0t 1H 0b						VR4			
0t 0H 0b									

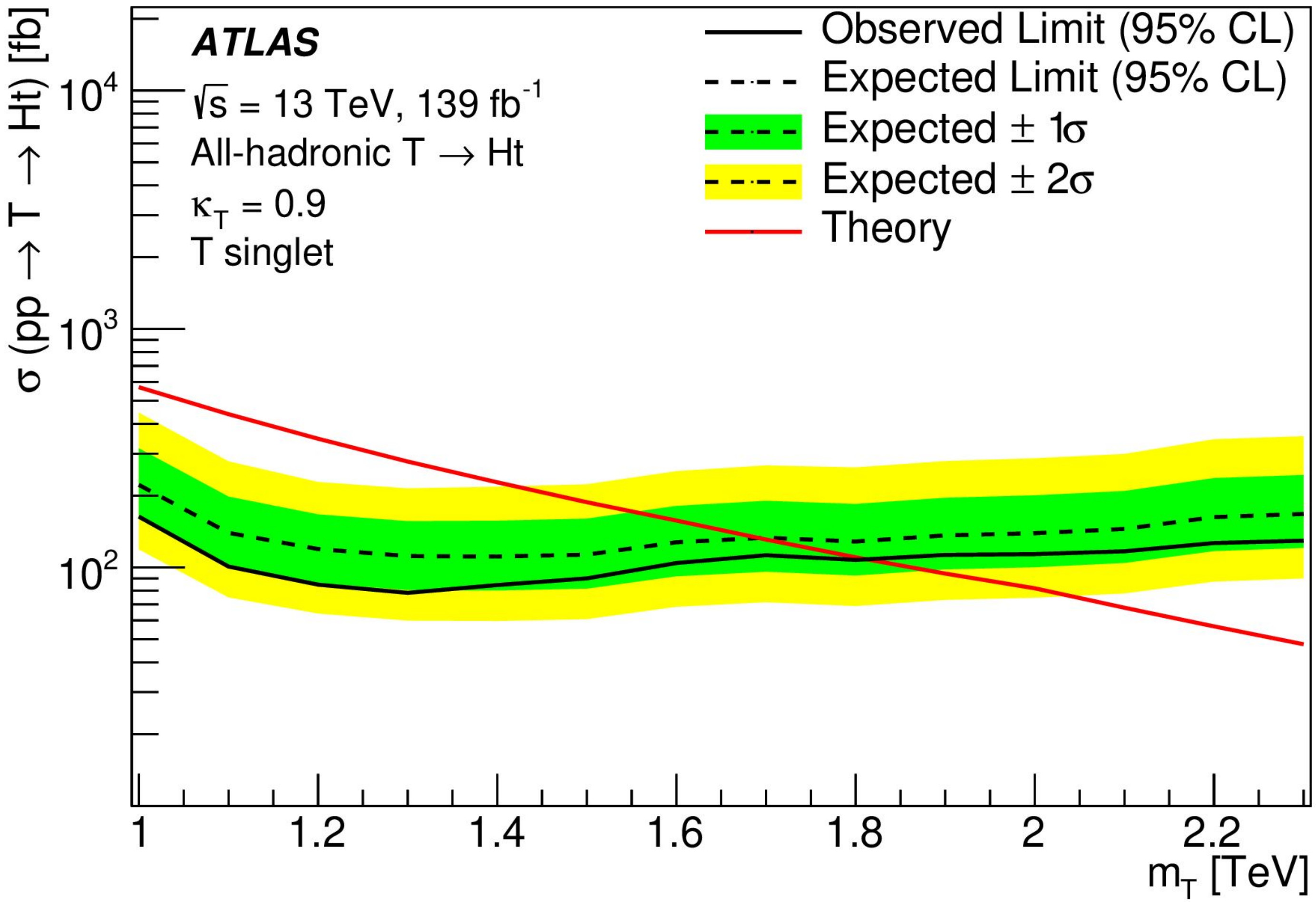
Leading large-R jet tagging state

VLT → h t SR postfit dijet mass spectrum



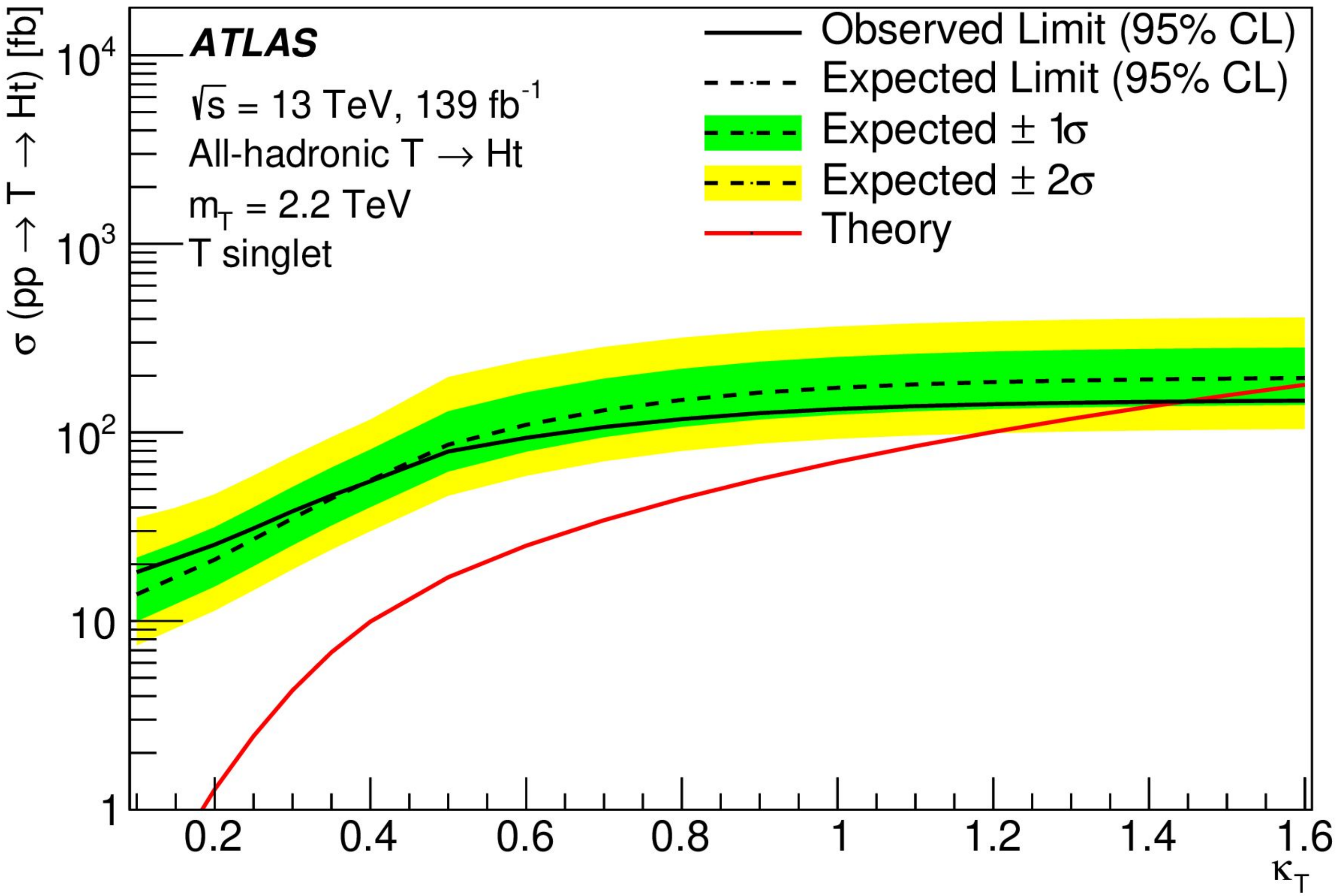
PRD 105, 092012 (2022)

VLT → h t limit in terms of xsec, mass



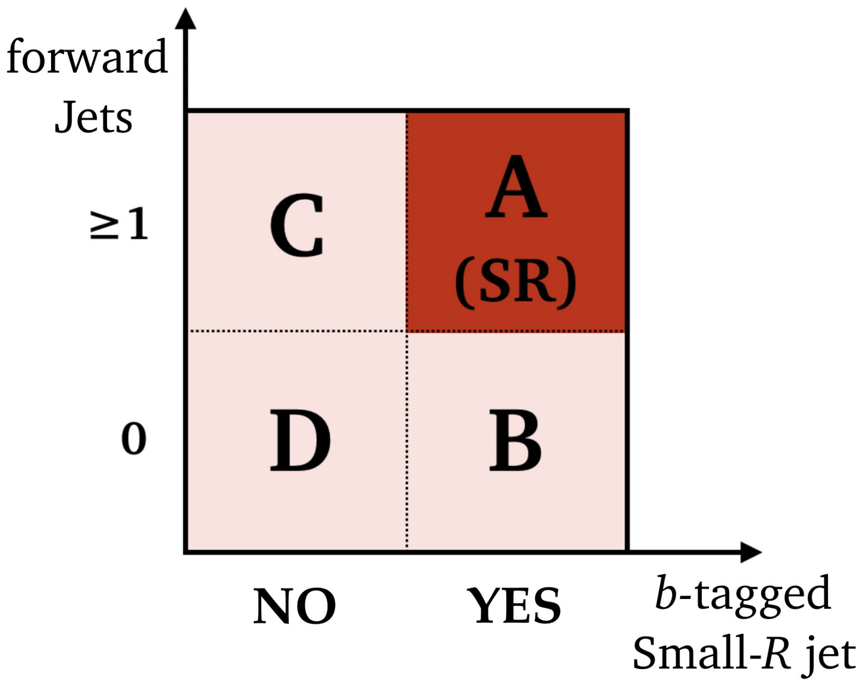
PRD 105, 092012 (2022)

VLT → h t limit in terms of xsec, coupling



VLB $\rightarrow$ h b additional material

VLB → h b strategy



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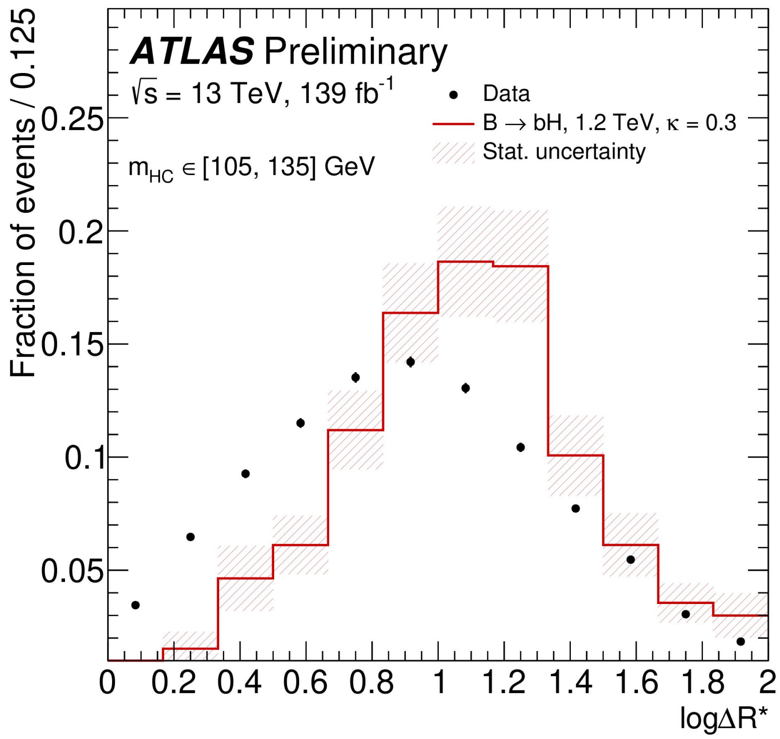
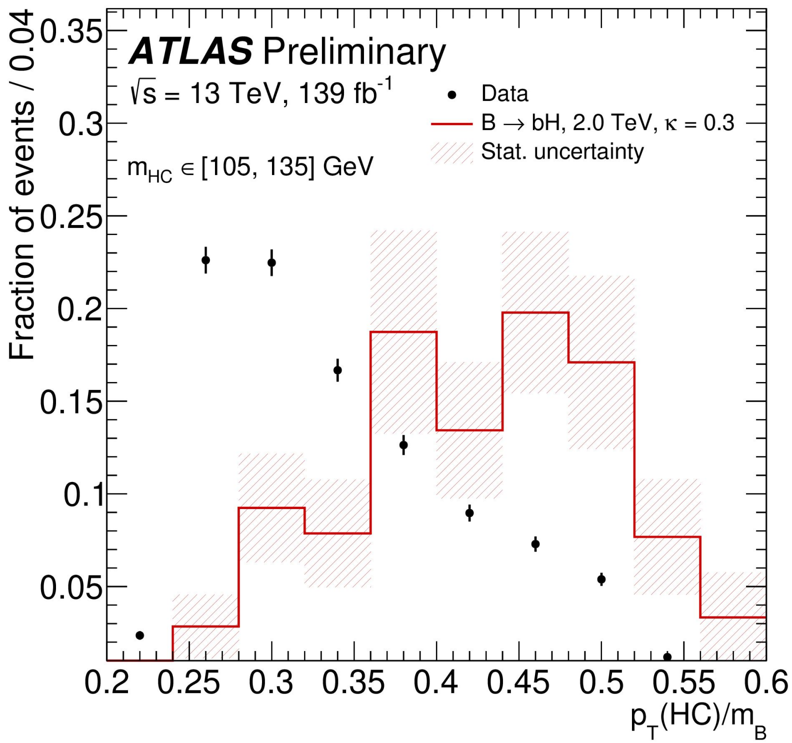
<tr><th colspan="8">Pre-Selection</th></tr>
<tr><td colspan="8">$\geqslant$ 1 large-R Jet, $p_{\mathrm{T}} > 480$ GeV</td></tr>
<tr><td colspan="8">No Leptons & no $\gamma\gamma$ pairs with $m_{\gamma\gamma} \in [105,\ 160]$ GeV</td></tr>
<tr><td colspan="8">$\geqslant$ 2 associated track jets to large-R jet, $\geqslant$ 1 b-tagged track jet</td></tr>
<tr><td colspan="8">$\geqslant$ 1 small-R jet with $p_{\mathrm{T}} > 300$ GeV</td></tr>
<tr><td colspan="8">ΔR(small-R jet, large-R jet) > 2.0</td></tr>
<tr><th colspan="8">HC Reconstruction</th></tr>
<tr><td colspan="8">Any large-R jet with $p_{\mathrm{T}} > 480$ GeV</td></tr>
<tr><td colspan="8">$\geqslant$ 2 ghost-matched track jets with $p_{\mathrm{T}} > 50$ GeV</td></tr>
<tr><td colspan="8">Pass collinear veto</td></tr>
<tr><td colspan="4">Highest b-tag multiplicity: 2 track jets</td><td colspan="4">Highest b-tag multiplicity: 1 track jet</td></tr>
<tr><td colspan="8">Select candidate with largest m_{HC}</td></tr>
<tr><th colspan="8">VLB Candidate Reconstruction</th></tr>
<tr><td colspan="8">HC + small-R jet, p_{T}(small-R jet) > 480 GeV</td></tr>
<tr><td colspan="8">ΔR(small-R, large-R) > 2.5</td></tr>
<tr><th colspan="8">Kinematic Selection</th></tr>
<tr><td colspan="8">$\log \Delta R^{*} > 0.67$</td></tr>
<tr><td colspan="8">$p_{\mathrm{T}}^{HC}/m_{B} > 0.4$</td></tr>
<tr><td colspan="8">$m_{\mathrm{HC}} \in [105,\ 135]$ GeV</td></tr>
<tr><td colspan="2">$\geqslant$ 1 Forward Jets</td><td colspan="2">= 0 Forward Jets</td><td colspan="2">$\geqslant$ 1 Forward Jets</td><td colspan="2">= 0 Forward Jets</td></tr>
<tr><td colspan="8">Small-R jet b-tagging status</td></tr>
<tr><td>Tag</td><td>No Tag</td><td>Tag</td><td>No Tag</td><td>Tag</td><td>No Tag</td><td>Tag</td><td>No Tag</td></tr>
<tr><td>SR</td><td colspan="7">Control Samples</td></tr>
</table>

VLB → b h: custom selections

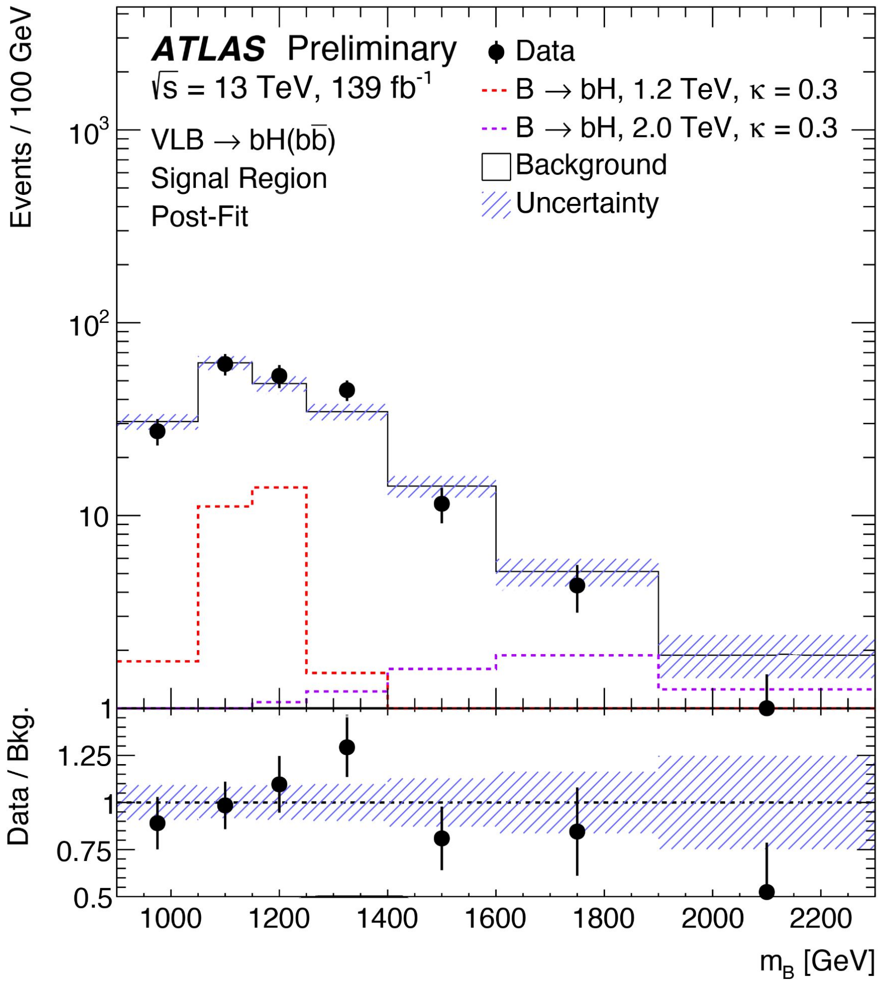
$$\log\Delta R^* = \log\left[\frac{\Delta R(\mathrm{tj0},\mathrm{tj1})}{\min\left[R_{\mathrm{eff}}^{\mathrm{tj0}}, R_{\mathrm{eff}}^{\mathrm{tj1}}\right]}\right] > 0.64$$

$p_{T,Higgs}/m_{VLB}$

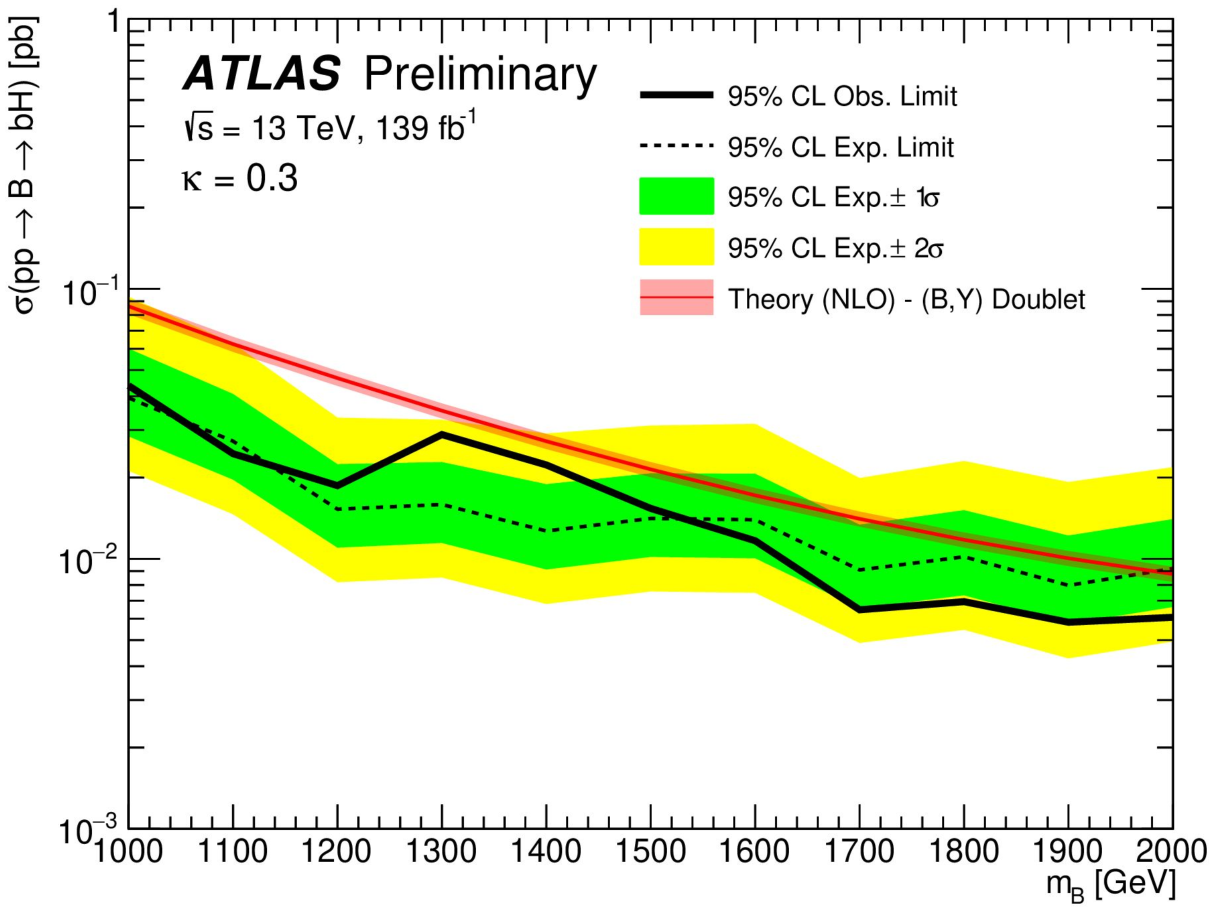




VLB ⟶ h b post-fit mass spectrum



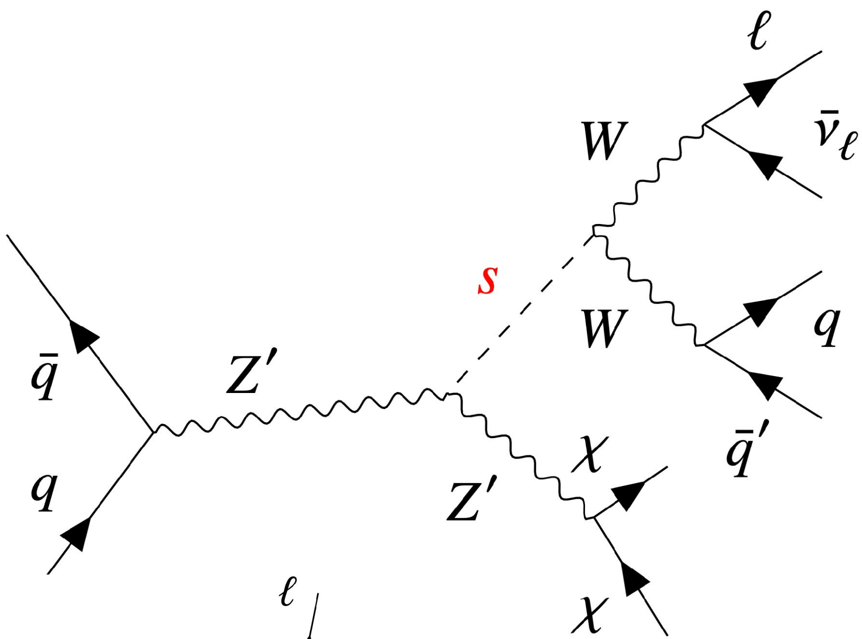
VLB → h b limit in terms of xsec

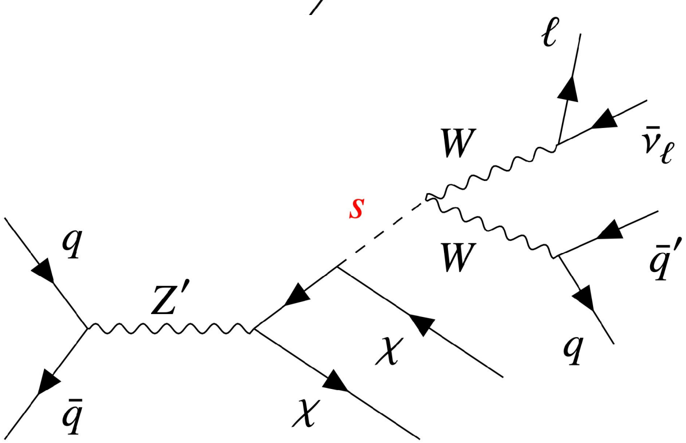


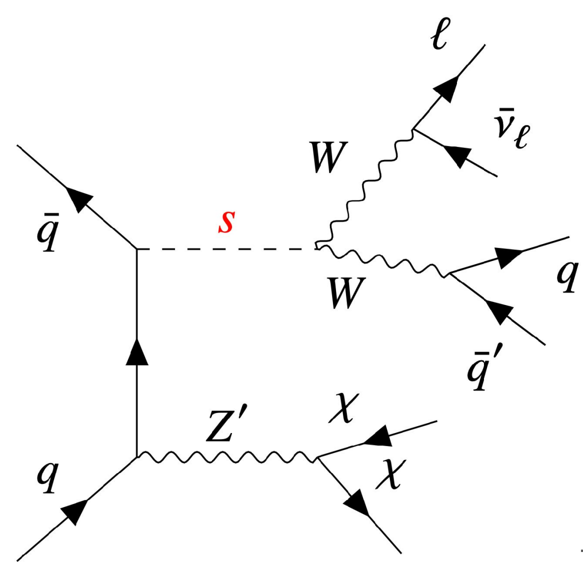
mono-s(W^+W^-) semi-leptonic additional material

[ATLAS-CONF-2022-029]

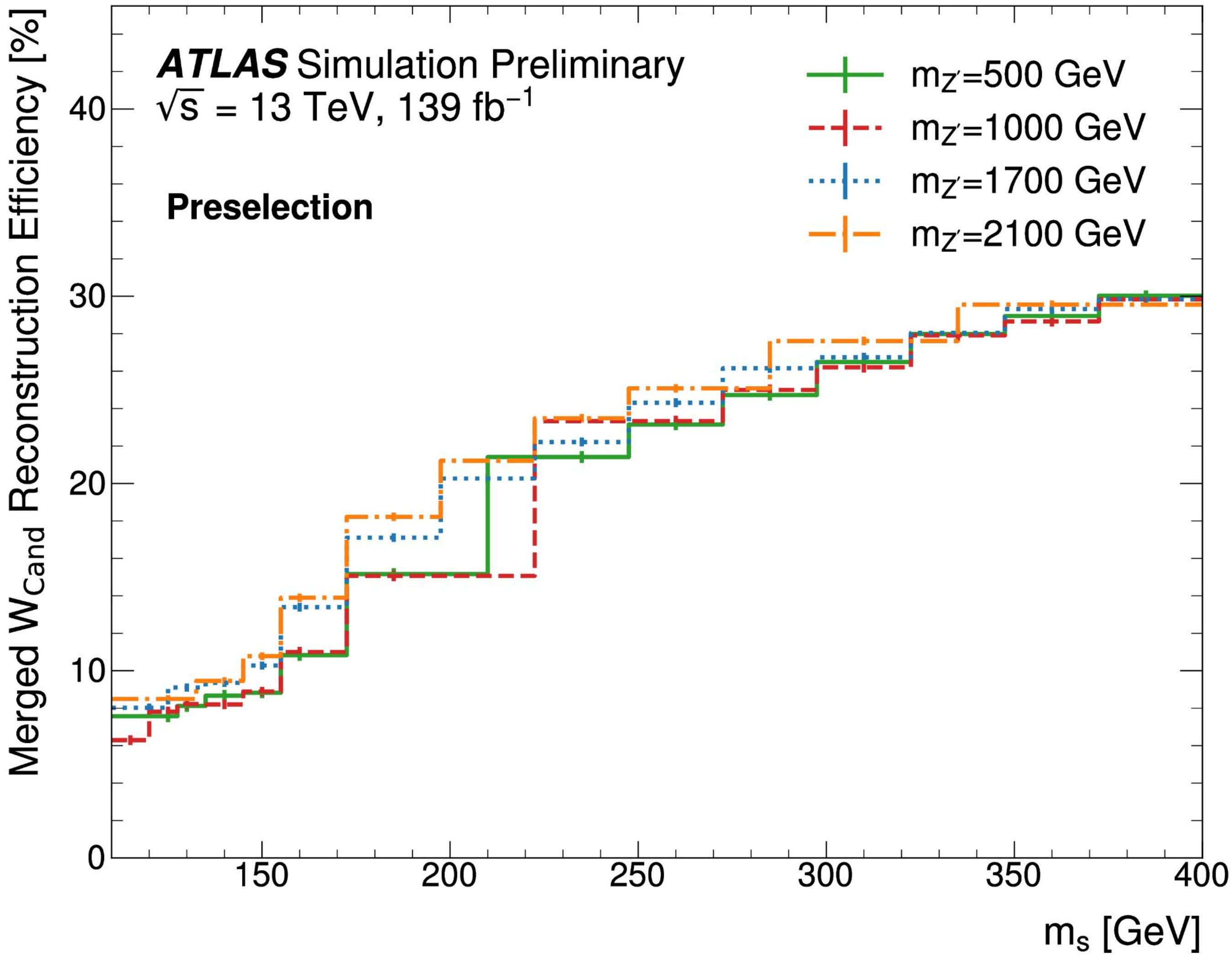
mono-s(W^+W^-) semi-leptonic: varieties of signals







mono-s(W^+W^-) semi-leptonic:merged W reco efficiency



mono-s(W^+W^-) semi-leptonic: merged selections

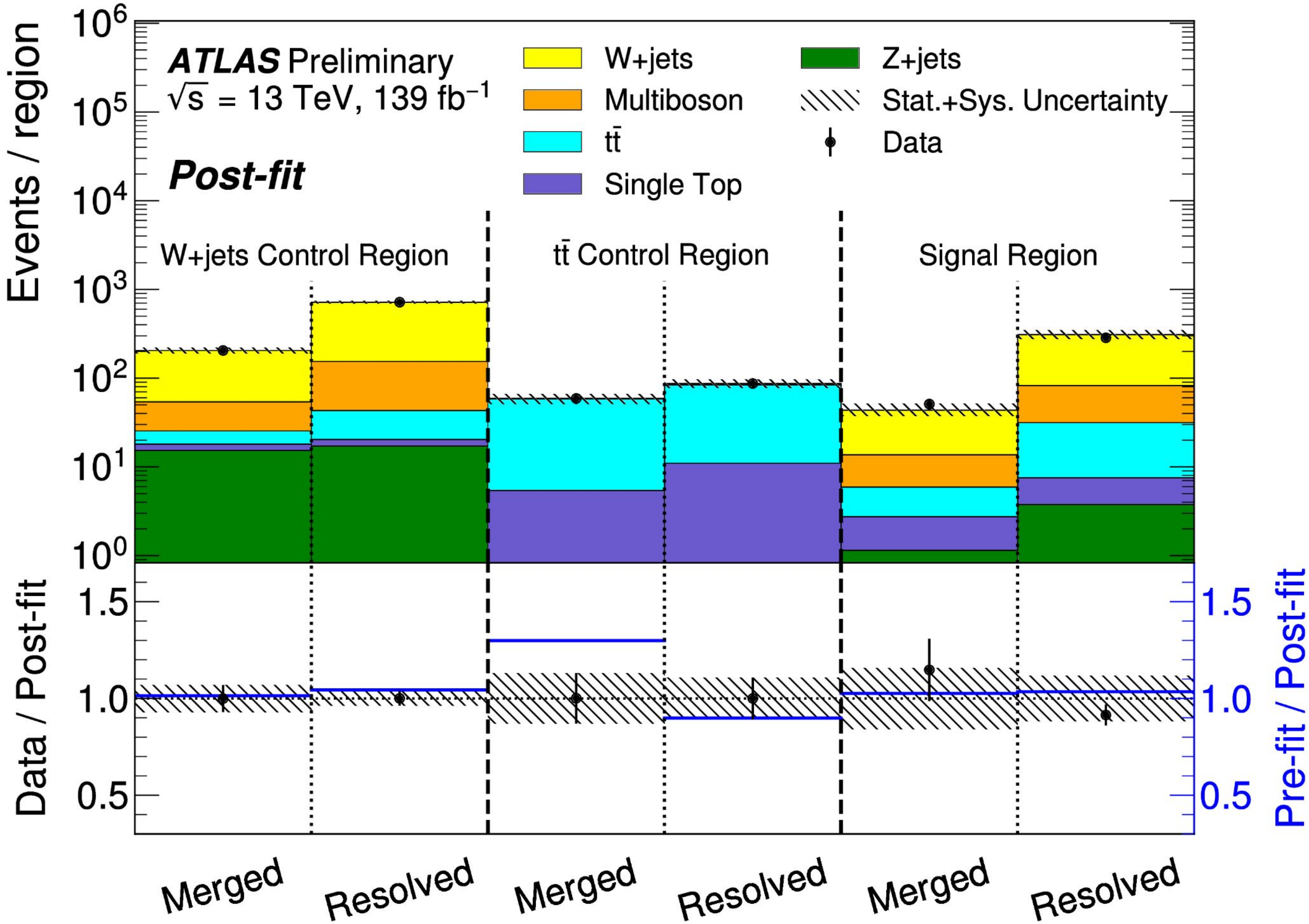
Requirement	SR	CRW	CRTT
Trigger	E_T^{miss} or single muon		
N_ℓ	$= 1$		
m_T [GeV]	> 220		
E_T^{miss} [GeV]	> 200		
$N_{b\text{-Jets}}$	0	0	≥ 2
$N_{\text{TAR Jets}}$	≥ 1		
$m_{W_{\text{cand}}}$ [GeV]	$[68, 89]$		
$\mathcal{S}$	> 16	> 12	> 12
$\Delta R(W_{\text{cand}}, \ell)$	< 1.2	> 1.8	< 1.2
$D_2^{\beta=1}$	< 1.1		
m_s^{min} binning [GeV]	$[125, 165, 190, 225, 375]$	incl.	incl.

mono-s(W^+W^-) semi-leptonic: resolved selections

Requirement	SR	CRW	CRTT
Orthogonality	Fails merged category selections		
Trigger	E_T^{miss} or single muon		
N_ℓ	$= 1$		
m_T [GeV]	> 200		
E_T^{miss} [GeV]	> 250		
$N_{b\text{-Jets}}$	0	0	≥ 2
N_{Jets}	≥ 2		
$m_{W_{cand}}$ [GeV]	$[65, 95]$		
$\mathcal{S}$	> 16		
$\Delta R(W_{cand}, \ell)$	< 1.4	> 1.4	< 1.4
$p_{T,W_{cand}}$ [GeV]	> 150		
m_s^{min} binning [GeV]	$[125, 175, 225, 275, 325, 375]$	incl.	incl.

ATLAS-CONF-2022-029

mono-s(W^+W^-) semi-leptonic: yields by region



mono-s(W^+W^-) semi-leptonic: merged SR mass spectrum