Search for dark matter produced in association with a dark Higgs boson in the $b\bar{b}$ final state using pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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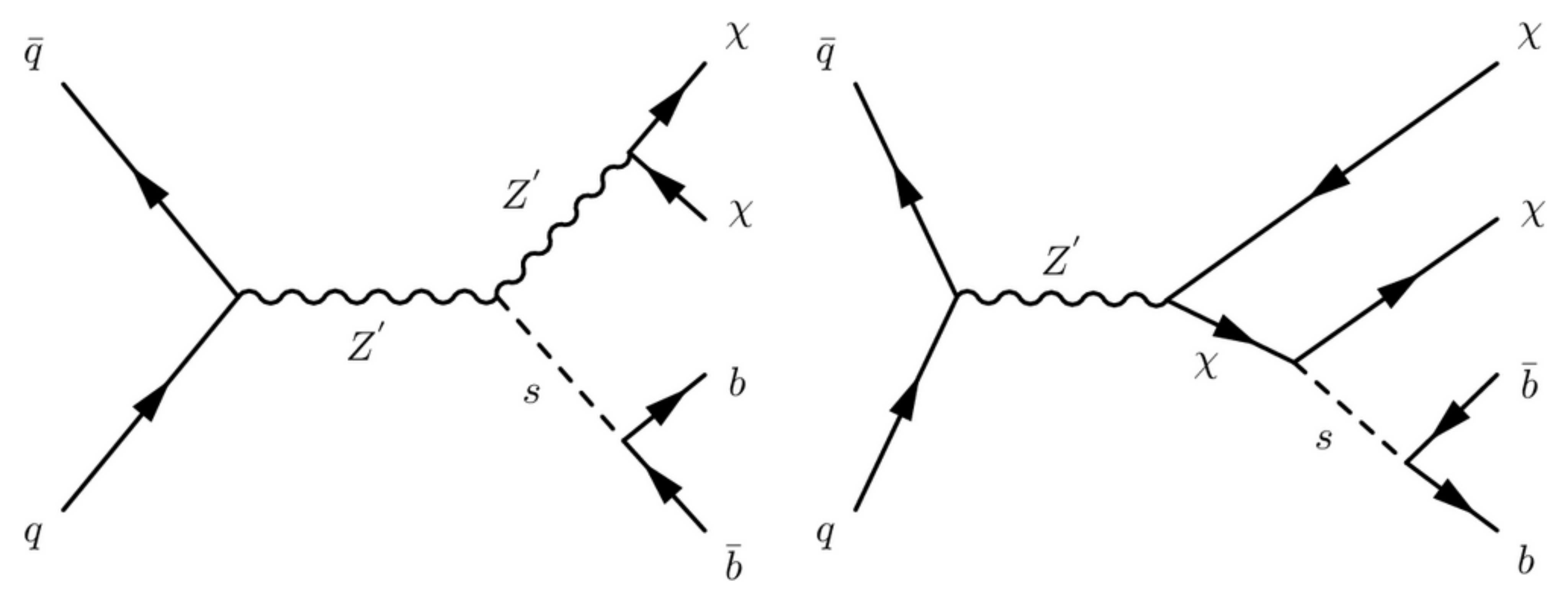
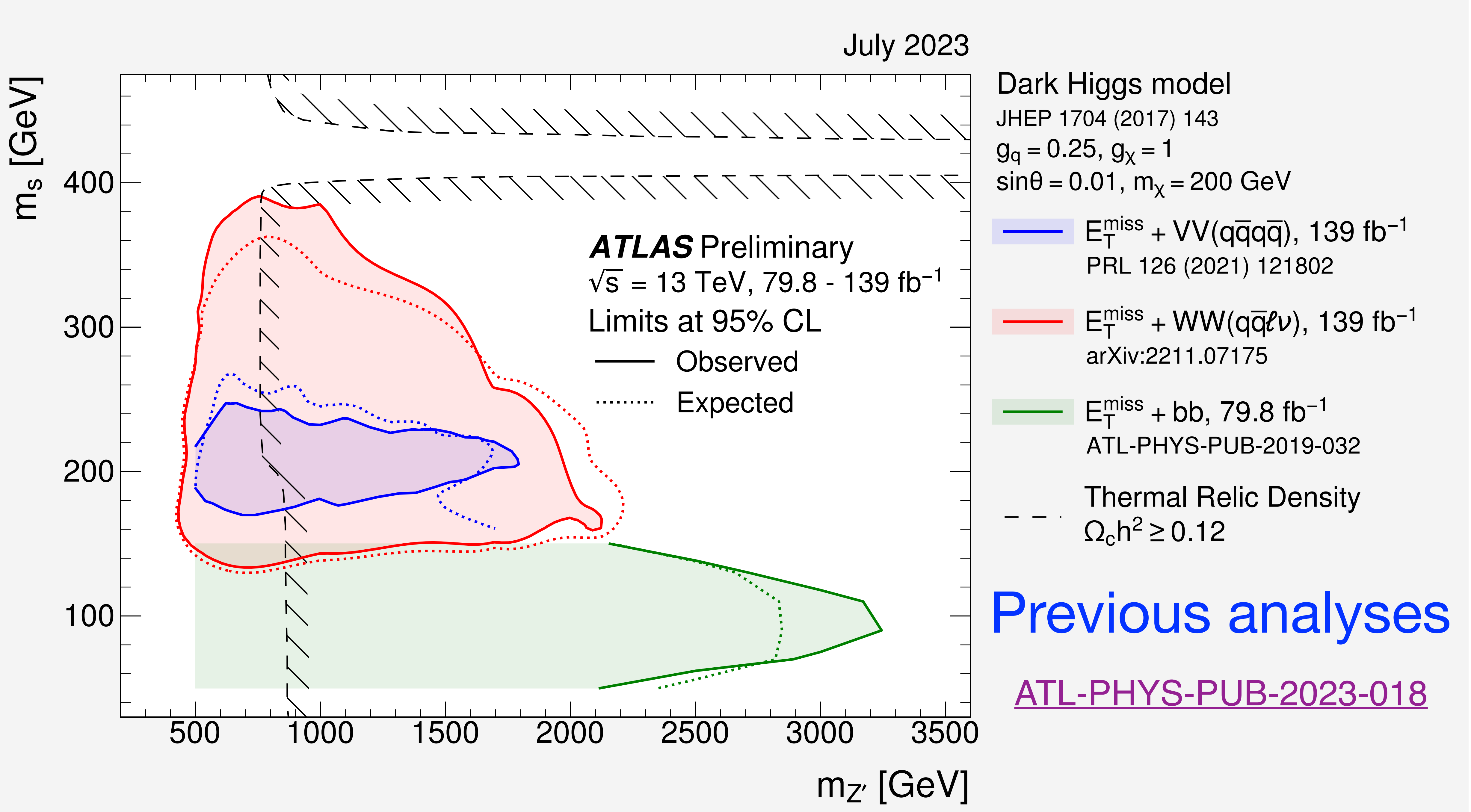
Analysis Overview

- Targets Two-Mediator DM (2MDM) model JHEP 04 (2017) 143
  - Introduces both a vector mediator (Z′) and a dark Higgs (s)
  - s mixes with SM Higgs through angle θ → allows $s \to b\bar{b}$ decay. (dominant decay for low m_s)

Particle Masses		Couling Constants	
DM mass	m_χ	Dark-sector coupling	g_χ
Z’ mass	$m_{Z'}$	Quark-Z’ coupling	g_q
Dark Higgs mass	m_S	Higgs mixing angle	θ



Two b-jets + large missing transverse momentum E_T^{miss}



Previous analyses

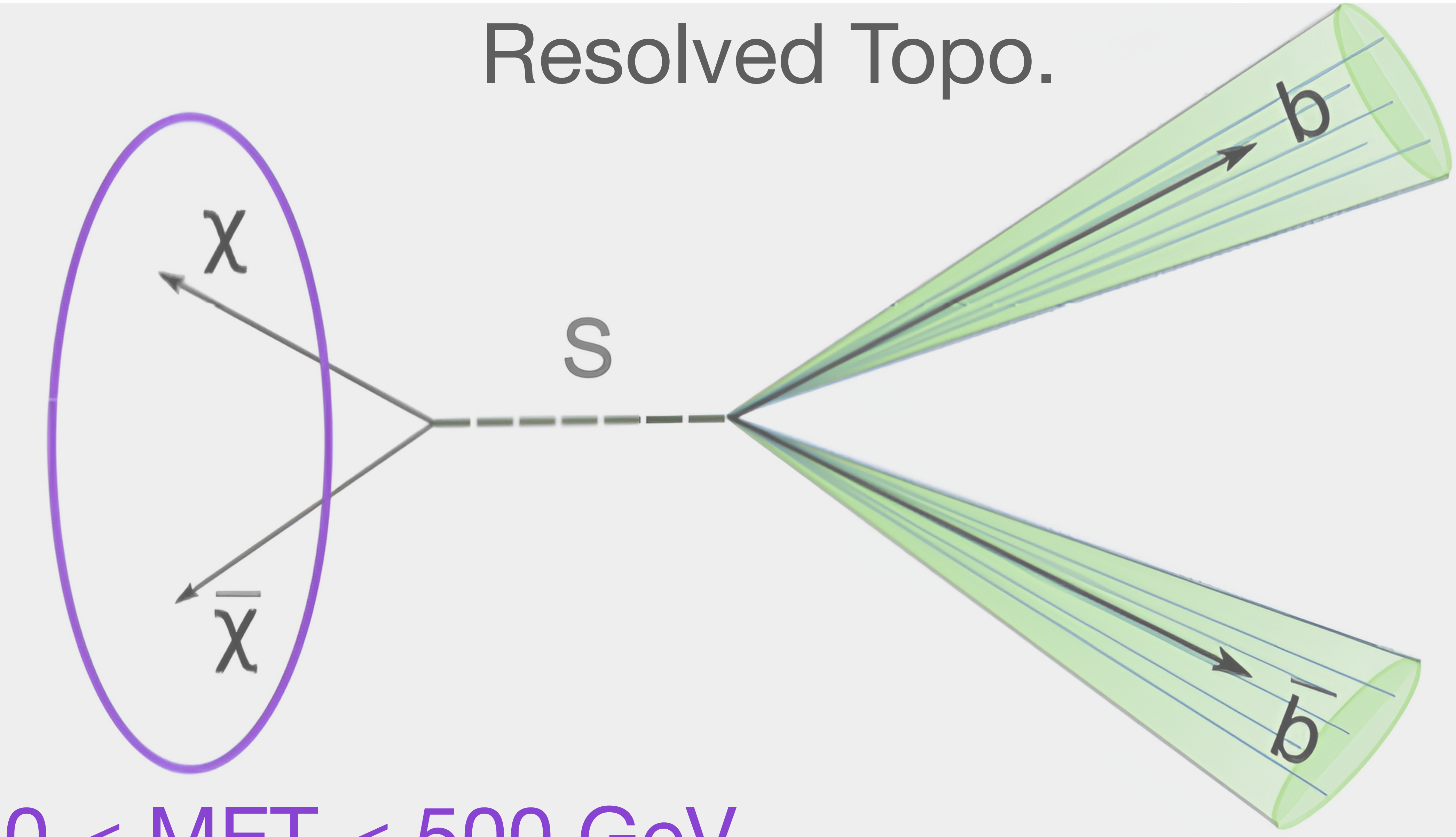
ATL-PHYS-PUB-2023-018

This analysis targets the s→bb decay with **full Run-2** datasets.

Signal Reconstruction I

- Signal event triggered by E_T^{miss} (MET) trigger
- Reconstruction strategy based on m/p_T of s→b$\bar{b}$, and p_T reflected by MET

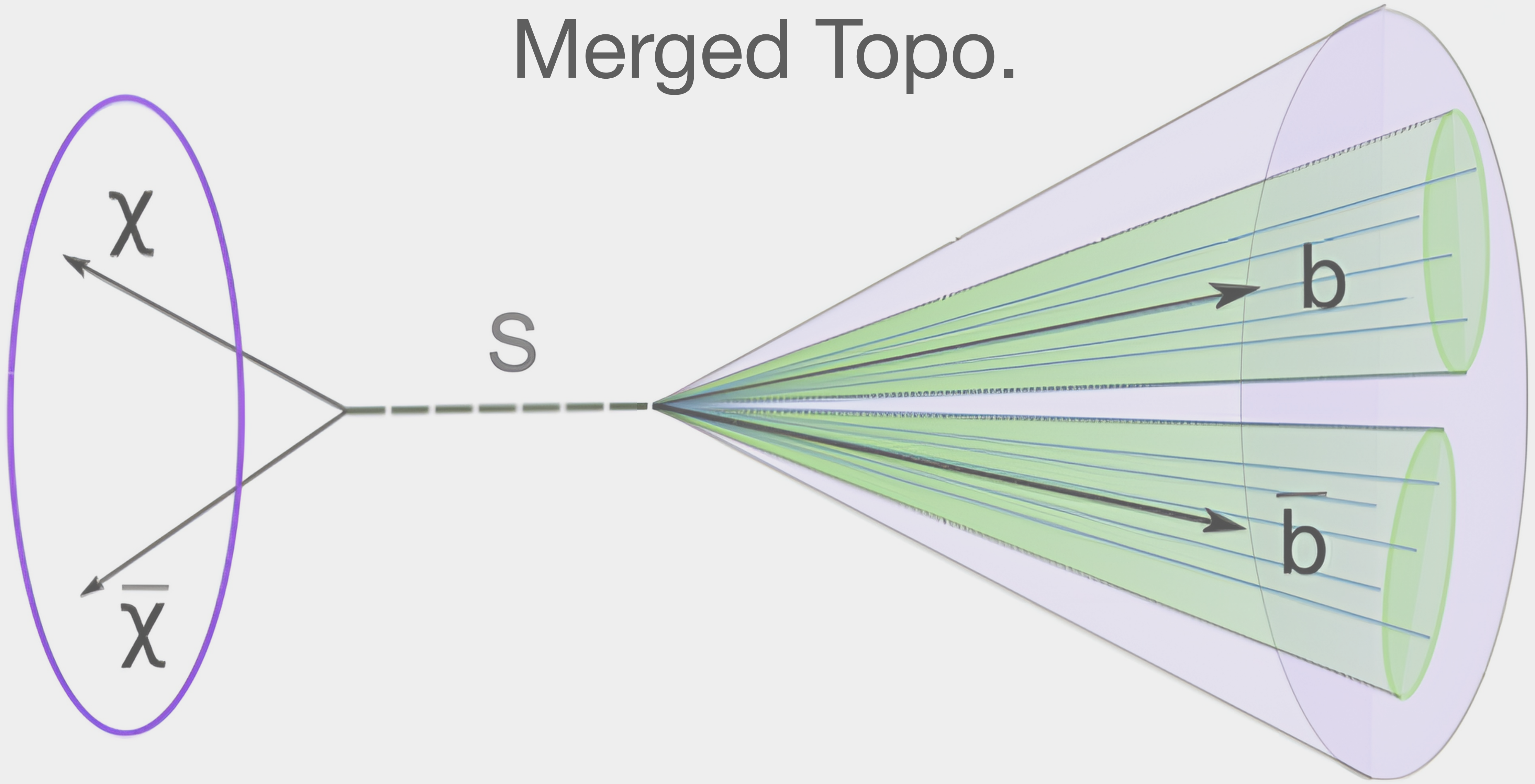
Resolved Topo.



150 < MET < 500 GeV

- 2 R=0.4 Particle Flow jets
  - Tagged by DL1r tagger @ 77% working point (wp)

Merged Topo.



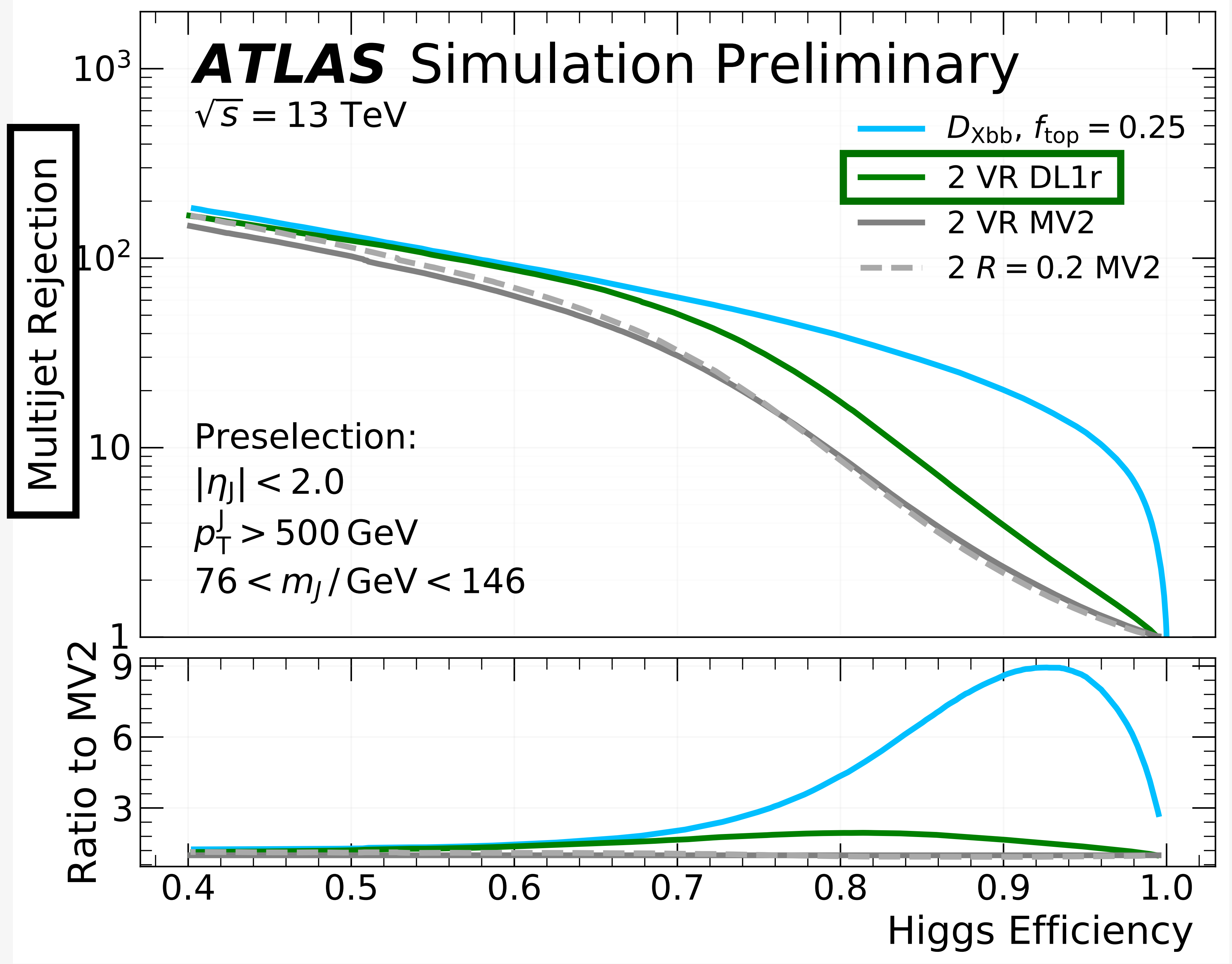
MET > 500 GeV

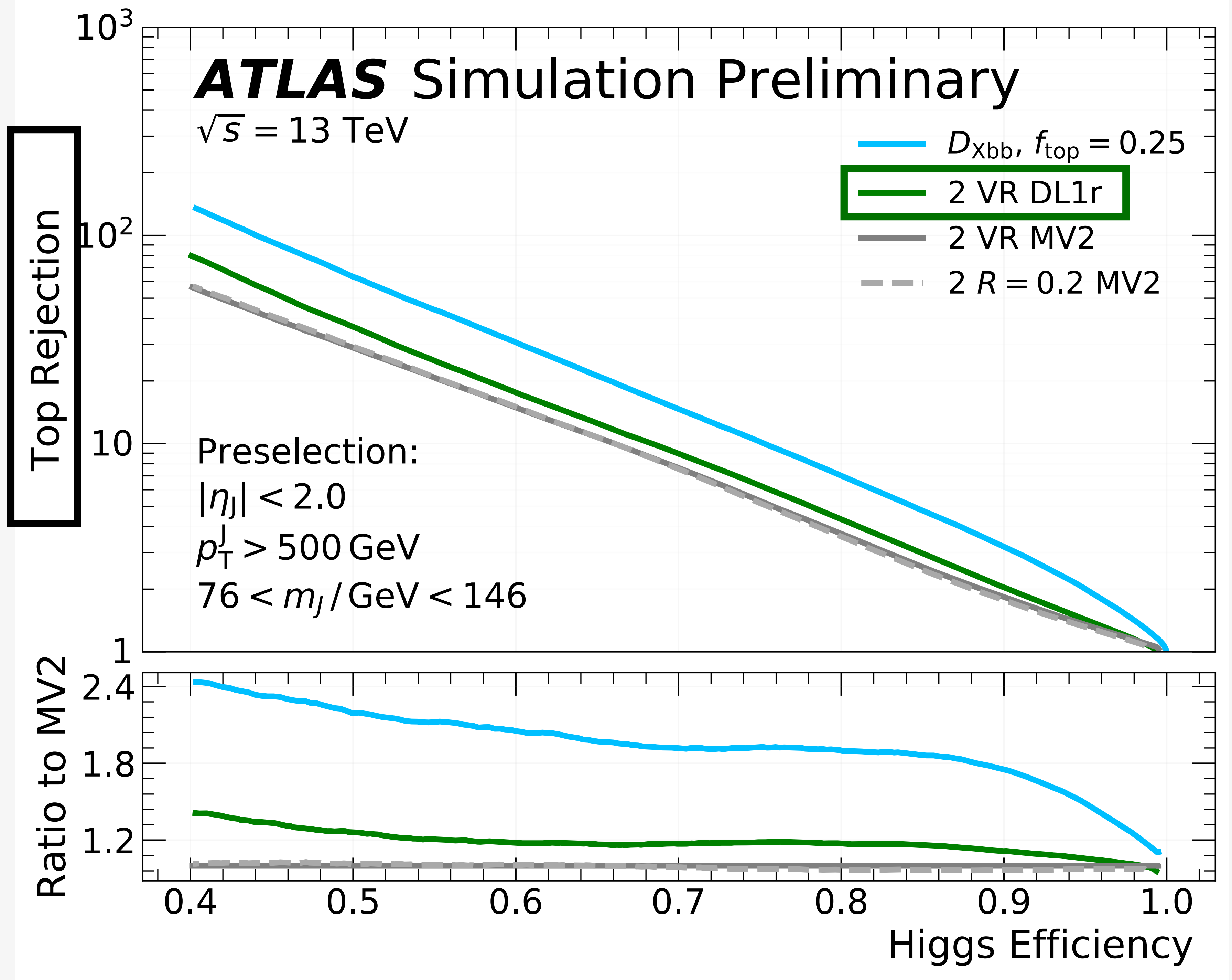
- 1 Reclustered R=1.0 jets (RC jets)
  - Tagged by DXbb tagger @ 50% wp
  - Tagged with conventional double b-tagging

Boundary at 500 GeV is optimized for search sensitivity

DXbb Tagger

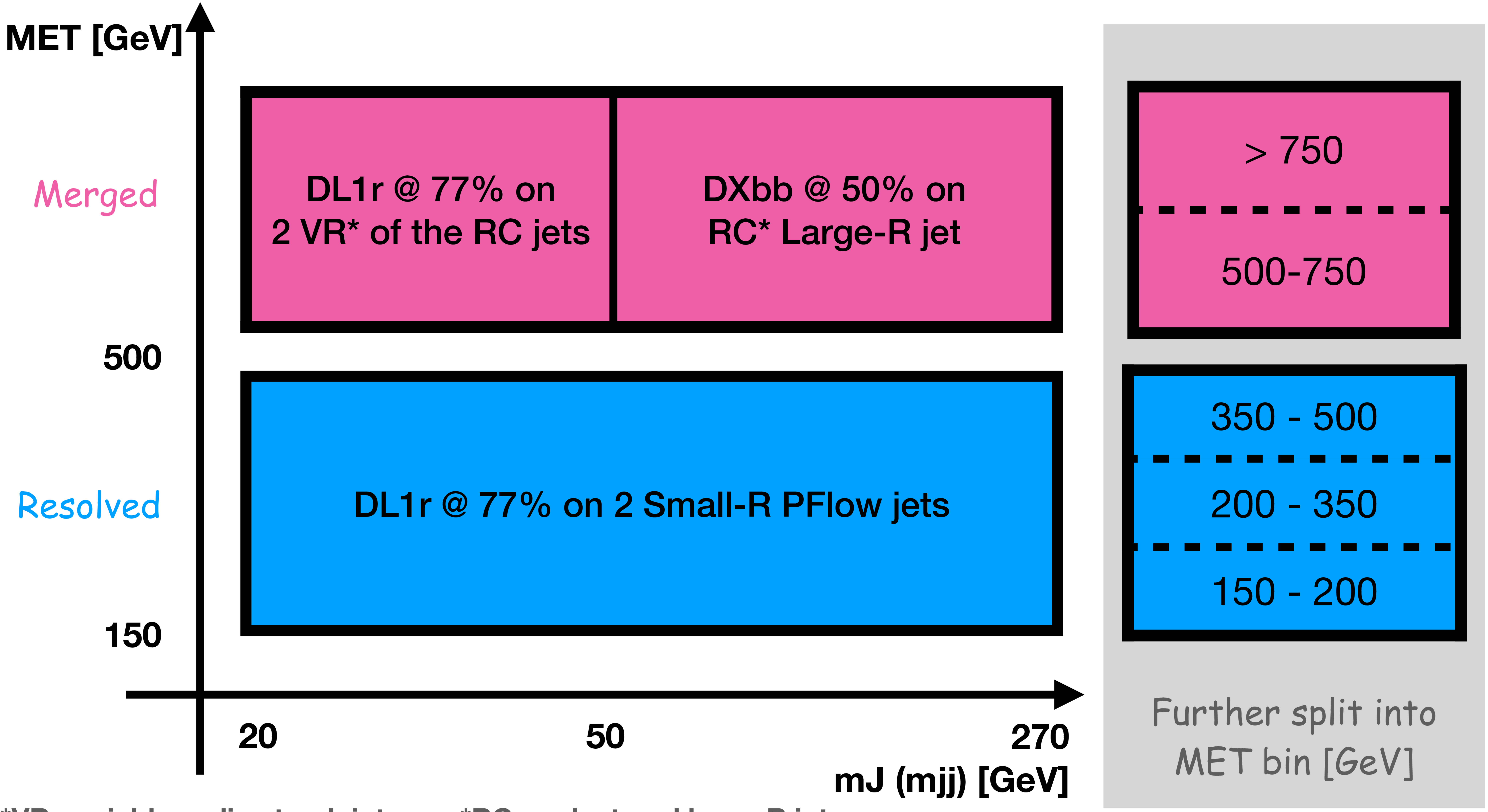
- Conventional large-R jets: tagging their associated variable radius (VR) track jets
- Advanced tagger, *DXbb*, based on a feedforward NN, better performance





- Advantage of *DXbb* tagger w.r.t the conventional double b-tagging
  - Tagging large-R jet as a whole instead of two isolated objects
  - Stable tagging efficiency vs jet mass → crucial when m_s varies

Tagging Strategy and Event Categorization



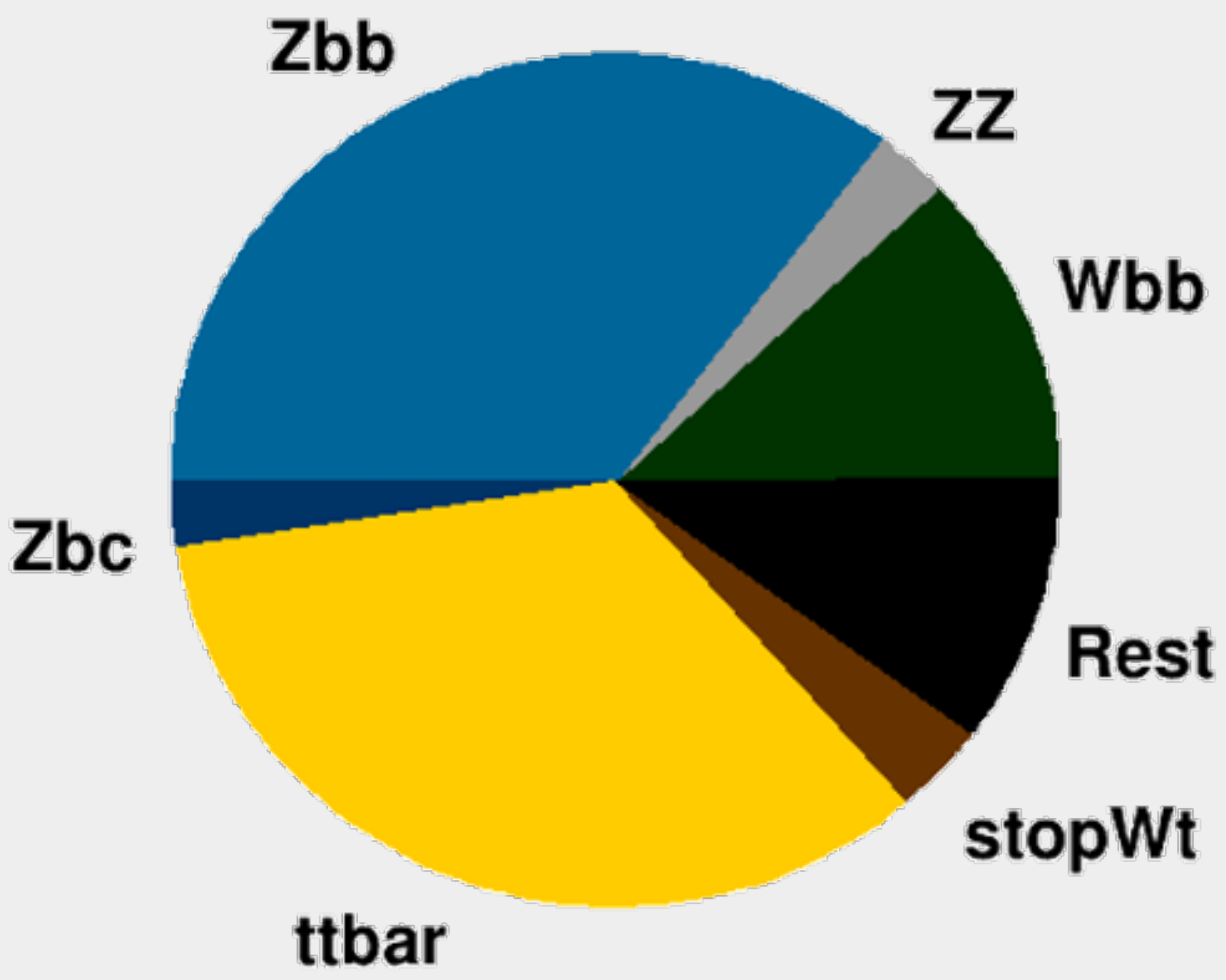
*VR: variable-radius track jets

*RC: reclustered large-R jets

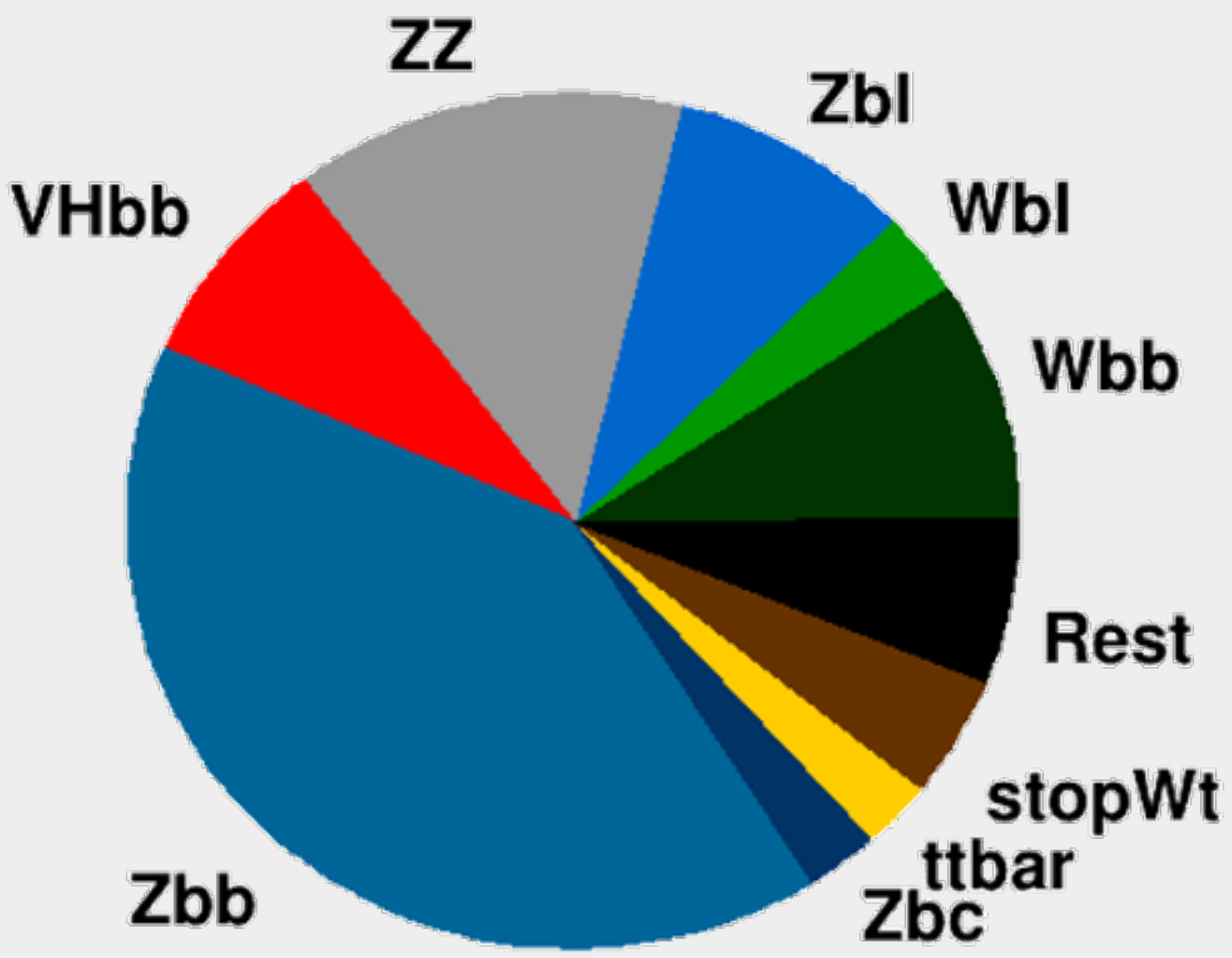
mjj also denoted as m_{bb} in this talk

Main Background and Control Region

- Main background are W+jets, Z+jets and ttbar



150 < MET < 200 GeV



MET > 750 GeV

1 muon CR introduced to constrain W+jets and ttbar:

- Same trigger as SR
- Exactly 1 muon
- MET proxy: p_T(muon) set invisible in MET calculation

2L CR introduced to constrain Z+jets:

- Single lepton trigger
- Exactly 2 electrons or 2 muons
- $|m_Z - m_{ll}| < 10$ GeV
- $S_{MET} < 5$ to suppress ttbar
- MET proxy: p_T(2L) set invisible in MET calculation
- Very pure Z+jets sample

Analysis Regions for Statistical Study

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	mjj / mJ	muon charge	Yield

- 9 regions in resolved
- 4 regions in merged
    - No further split at 750 GeV in CRs due to the limited statistics

Profiled likelihood fit across all 13 regions

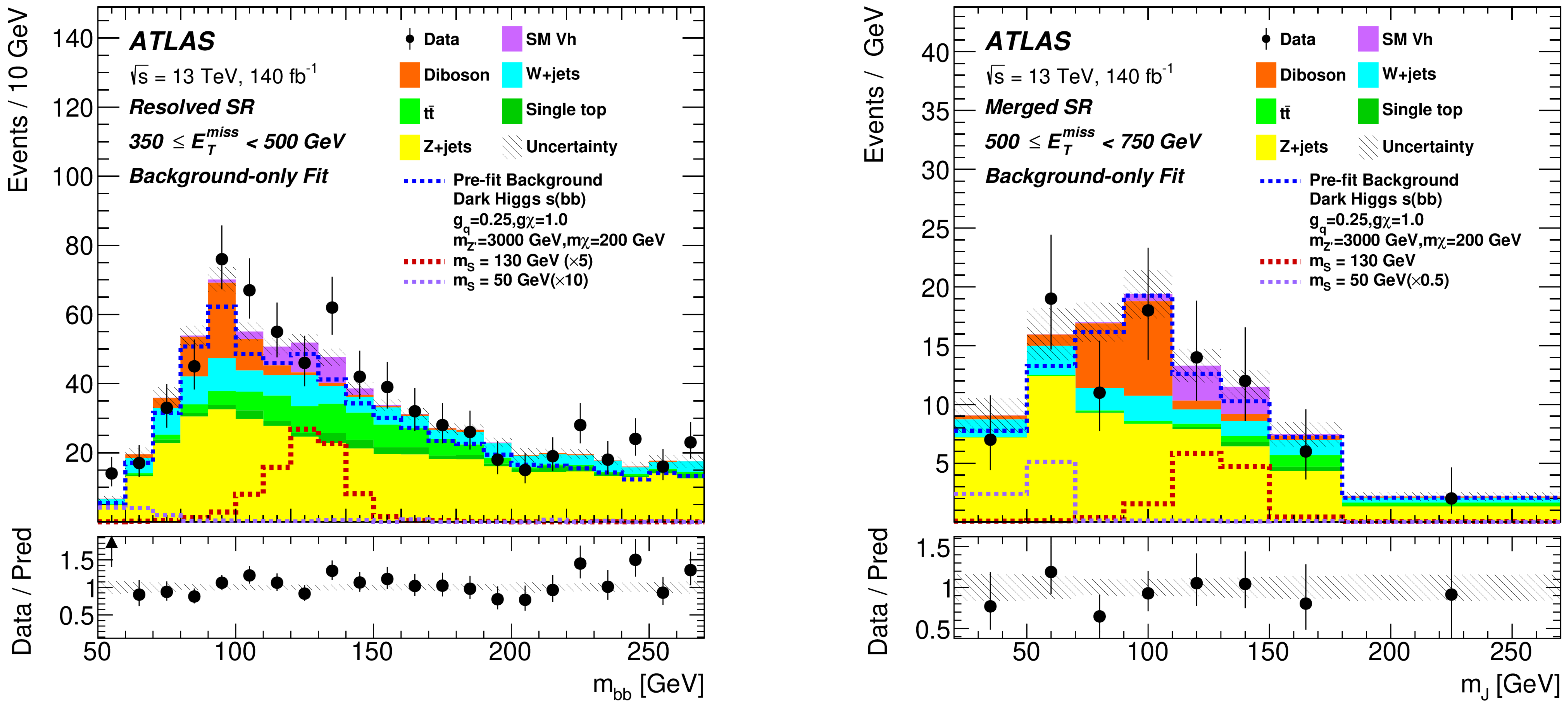
Statistical Setup

- A binned likelihood function constructed as the product of poisson terms

$$\mathcal{L}(\mu, \vec{\theta}, \vec{\gamma}) = \prod_{i \in \text{bins}} \text{Pois}(N_i | \mu s_i(\vec{\theta}) + \gamma_i b_i(\vec{\theta})) \times \prod_{\theta \in \vec{\theta}} \frac{1}{\sqrt{2\pi}} e^{-\theta^2/2} \times \prod_{i \in \text{bins}} \text{Gauss}(\beta_i | \gamma_i \beta_i, \sqrt{\gamma_i \beta_i})$$

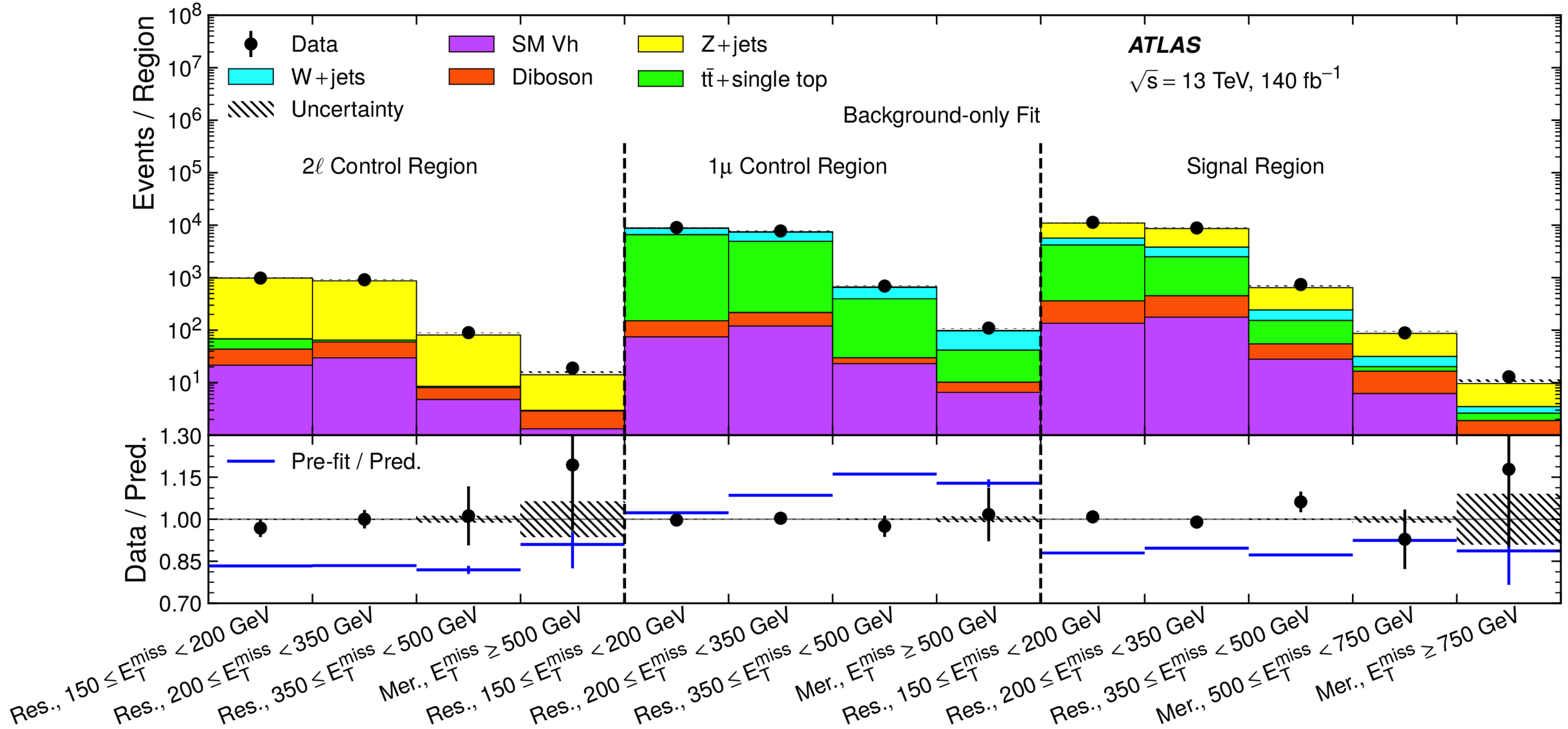
- *μ:* the product of the pp → s$\chi\chi$ production XS and branching fraction (s→b$\bar{\text{b}}$)
- *θ:* the nuisance parameters (NP), representing the systematic uncertainties.
- The norm. of Z+jets, ttbar, and W+jets are free and constrained by total yields.
- No significant evidence of a DM signal, consequently, upper limits are set on *μ:*
  - using a modified frequentist approach (*CLs*) with a test statistic based on the profile likelihood in the asymptotic approximation.

Background-only Fit to Data



The observed results in the SR indicate that the data are in agreement with SM predictions with no significant evidence of a DM signal.

Overall yields in the all CRs and SRs



Overall yields in the CRs and SRs are found to be well described by SM expectation.

Systematics Uncertainties

Source of uncertainty	Fraction of total uncertainty [%] (a)	(b)	(c)
Signal modeling	0	1	0
Z+jets normalization	41	11	11
W+jets normalization	8	13	13
$t\bar{t}$ normalization	1	7	8
Z+jets theory	16	24	25
W+jets theory	8	12	9
$t\bar{t}$ theory	3	8	11
Other background theory	10	16	22
MC statistics	15	17	18
Flavor tagging	18	47	37
Jet energy	3	7	11
Other experimental	2	4	3
Total systematic uncertainty	57	66	63
Data statistical uncertainty	82	75	77
Total uncertainty	100	100	100

Relative importance of the different sources of uncertainty for:

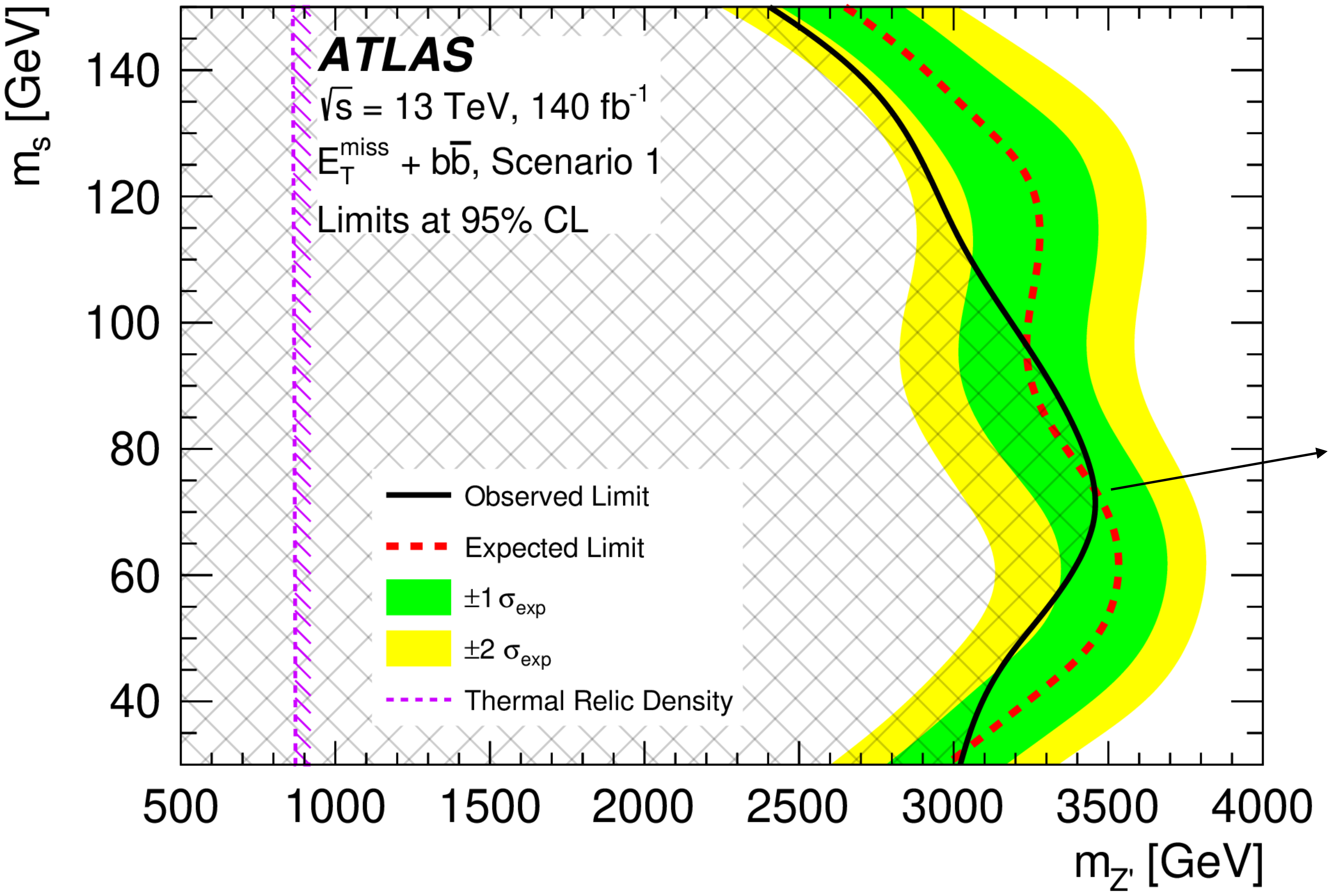
(a) $m_{Z'}$ = 3000 GeV, m_s = 50 GeV

(b) $m_{Z'}$ = 3000 GeV, m_s = 130 GeV

(c) $m_{Z'}$ = 2500 GeV, m_s = 150 GeV

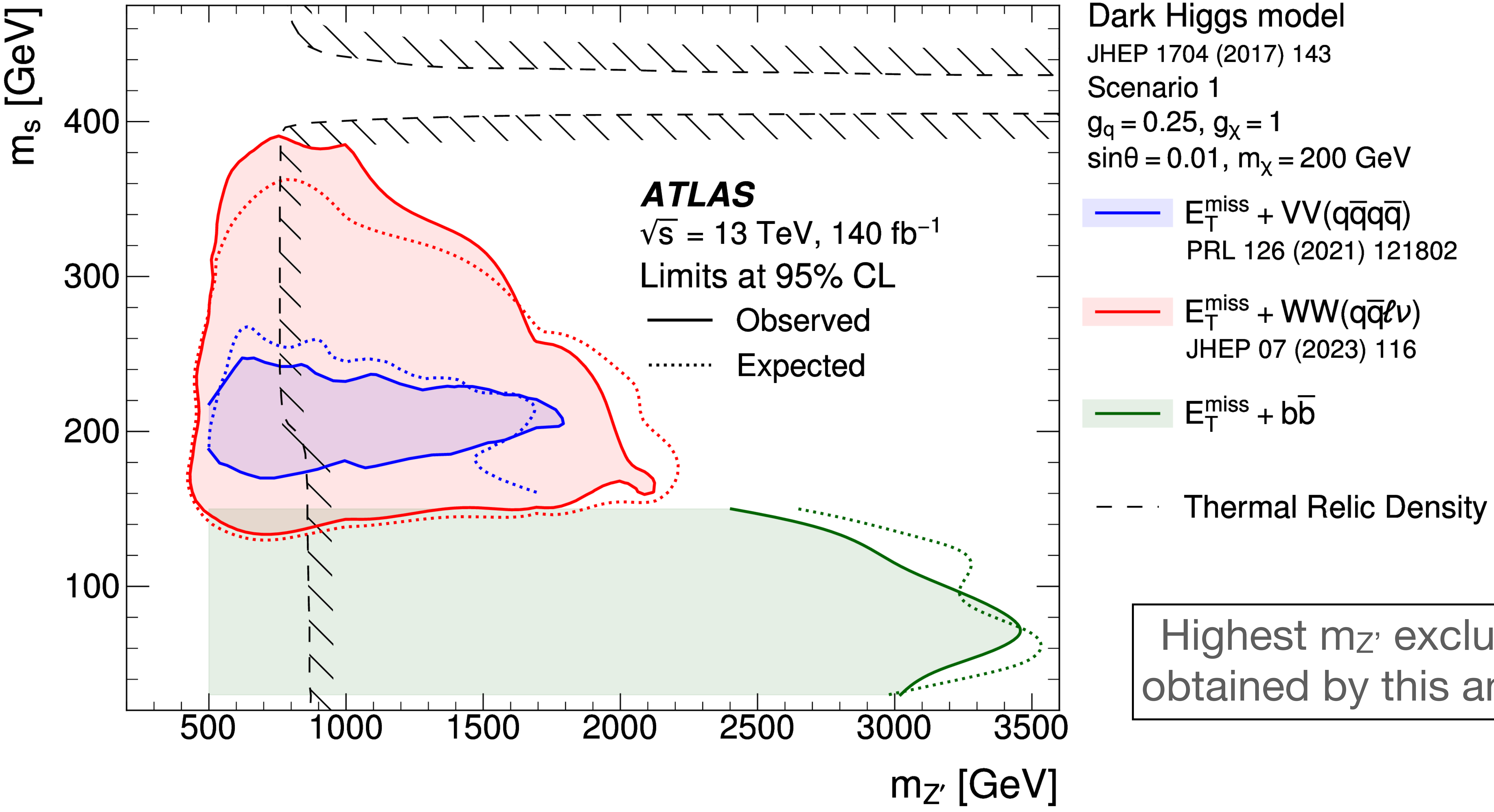
- Statistical uncertainty are the largest source of uncertainty.
- The calibration uncertainties of Large-R jet b-tagging become more important at larger p_T and $m_{Z'}$
- The modelling Z+jets processes are the largest theoretical uncertainties.
- At $m_s \approx$ 50 GeV, impact of Z+jets norm. increases.

Results: Exclusion Contours for Scenario 1



$m_{Z'}$ values are excluded up to 3.4 TeV at m_s = 70 GeV

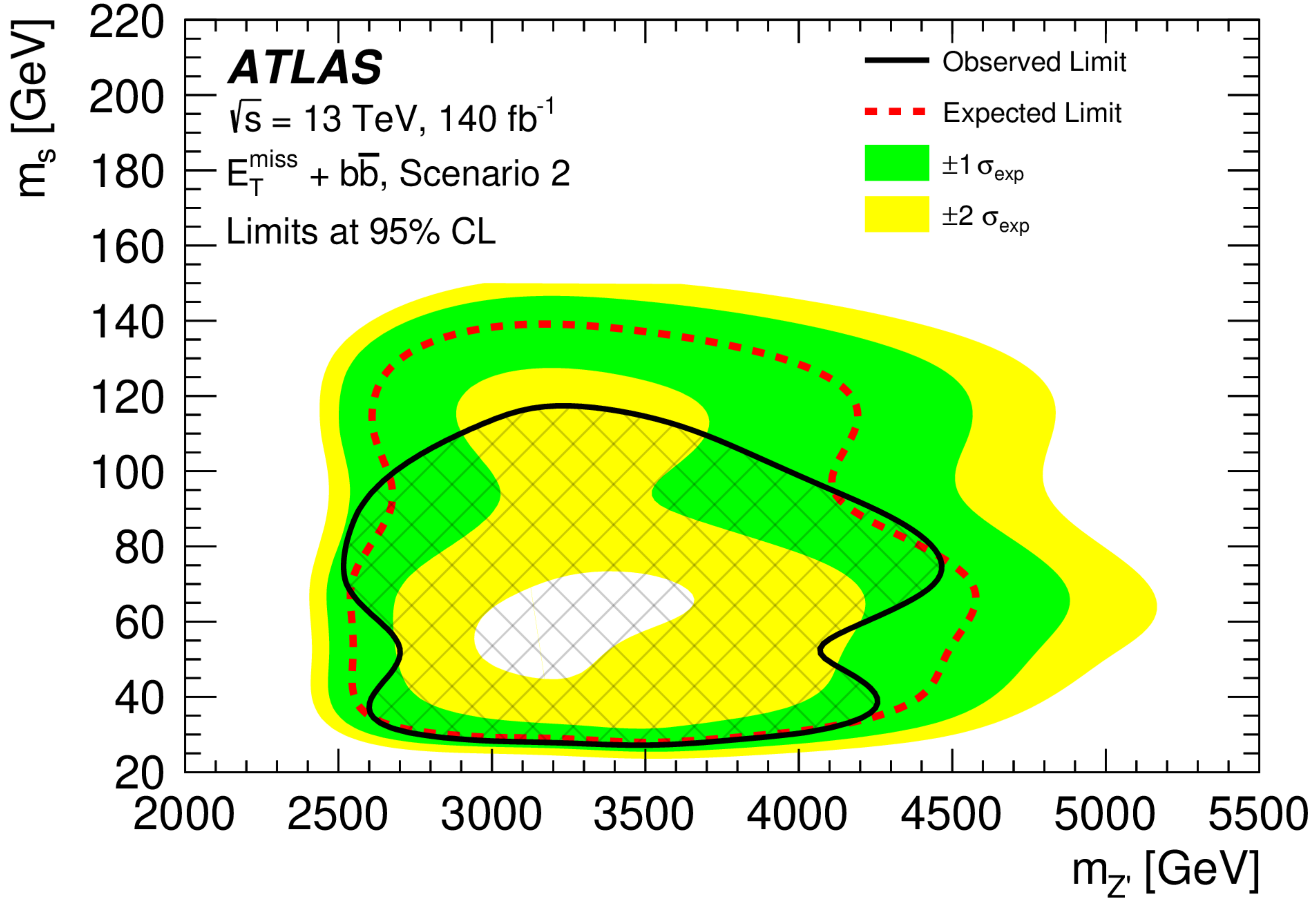
Summary of Scenario 1



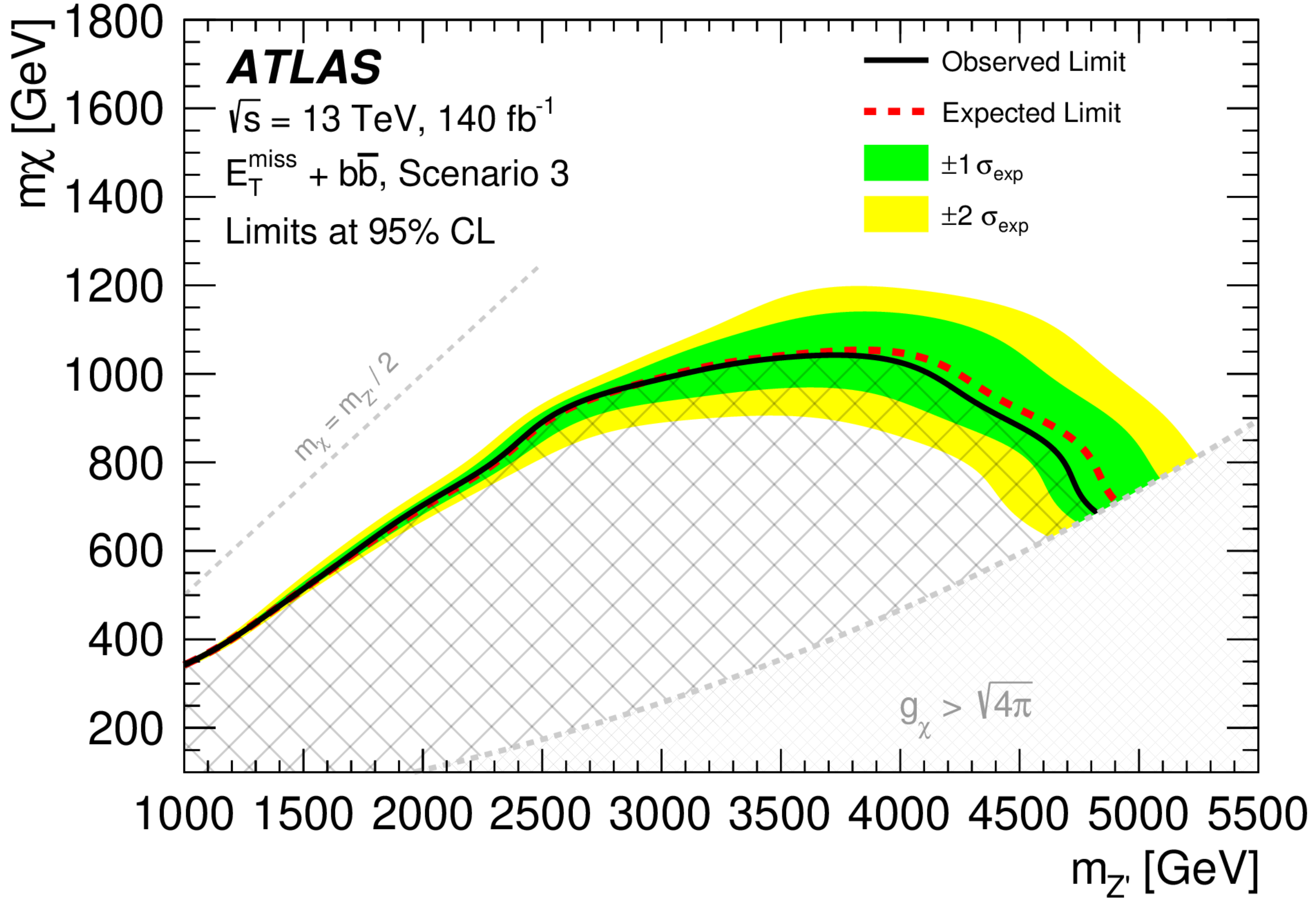
Highest $m_{Z'}$ exclusions obtained by this analysis

Results: Scenario 2 and 3

- DM coupling g_χ varies to satisfy the observed relic density throughout
- Scenario2 (m_χ = 900 GeV), exclusion contour on m_s - $m_{Z'}$ plane
- Scenario3 (m_s = 70 GeV), exclusion contour on m_χ - $m_{Z'}$ plane



$m_{Z'}$ values excluded up to 4.5 TeV for at m_s = 75 GeV



$m_{Z'}$ values up to the perturbative limit are excluded, reaching a maximum of 4.8 TeV

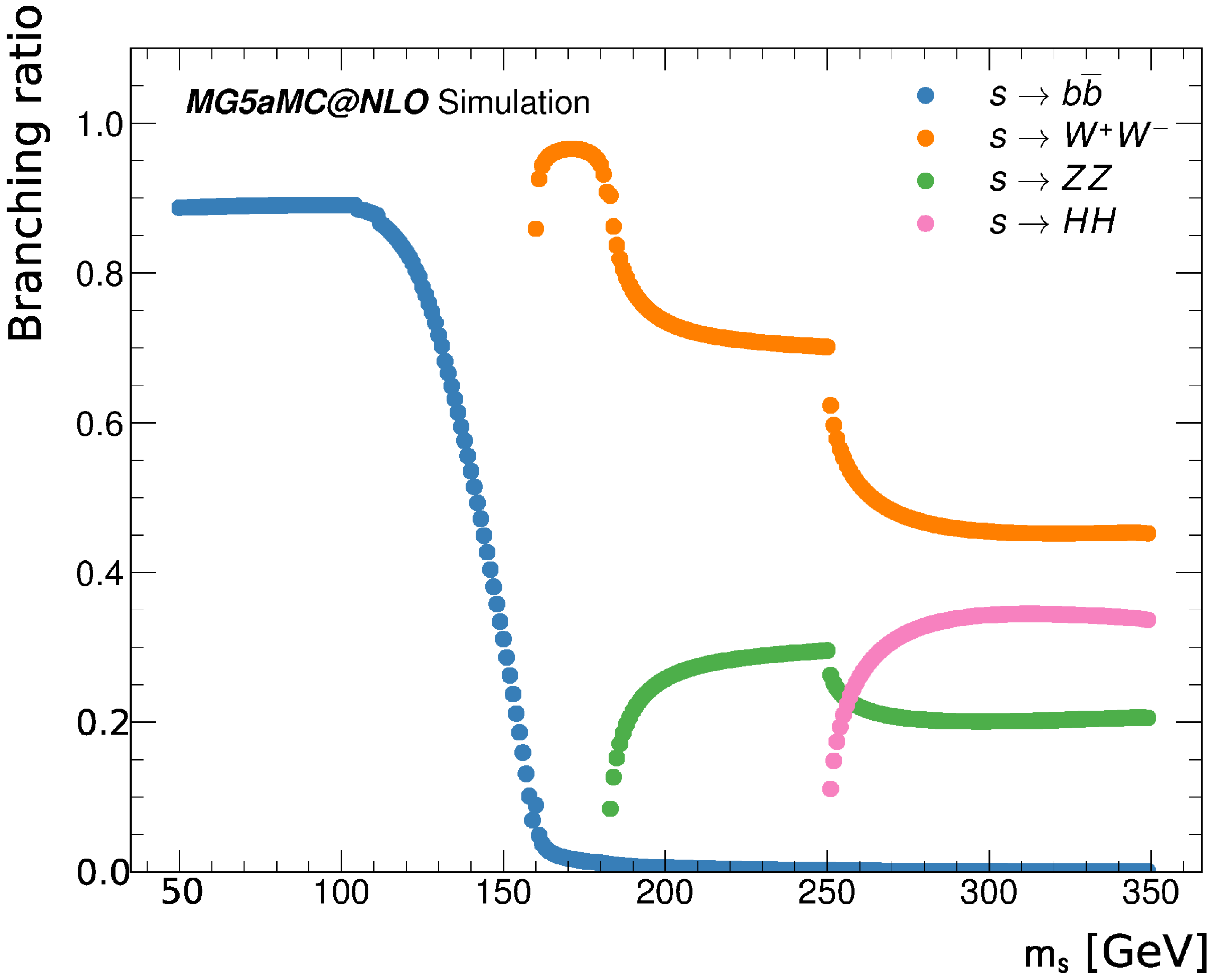
Summary

- A first dedicated search for monoSbb is reported.
  - Introduced RC-jet technique → extended reach to lower m_{bb}
  - Advanced large-R flavour tagging technique (*DXbb* tagger) used for signal identification in the merged regime → improving the overall search sensitivity
  - Observed data agree with SM background.
  - Excluded $m_{Z'}$ up to 4.8 TeV in benchmark models.
  - Published in March, 2025, Phys. Rev. Lett. 134 (2025) 121801
- Future prospects:
  - Much more statistics from Run-3 & HL-LHC
  - New/Ongoing developments in machine-learning-based large-r jet flavour tagging will further boost sensitivity.

Backup

Various final states Targeted

Non-Zero θ → unstable s and decays into SM states



m_s > 150 GeV

Dark Higgs s(VV) hadronic analysis, denoted as *monoSVV had.*

- Final states: E_T^{miss} + VV(qqqq)
- Phys. Rev. Lett. 126 (2021) 121802

Dark Higgs s(WW) semileptonic analysis, denoted as *monoSWW semilep.*

- Final states: E_T^{miss} + WW(lvqq)
- Higher cross section than fully-leptonic
- Cleaner signature than fully-hadronic
- JHEP 07 (2023) 116

$m_s \leq$ 150 GeV

Dark Higgs s(bb) analysis, denoted *monoSbb*

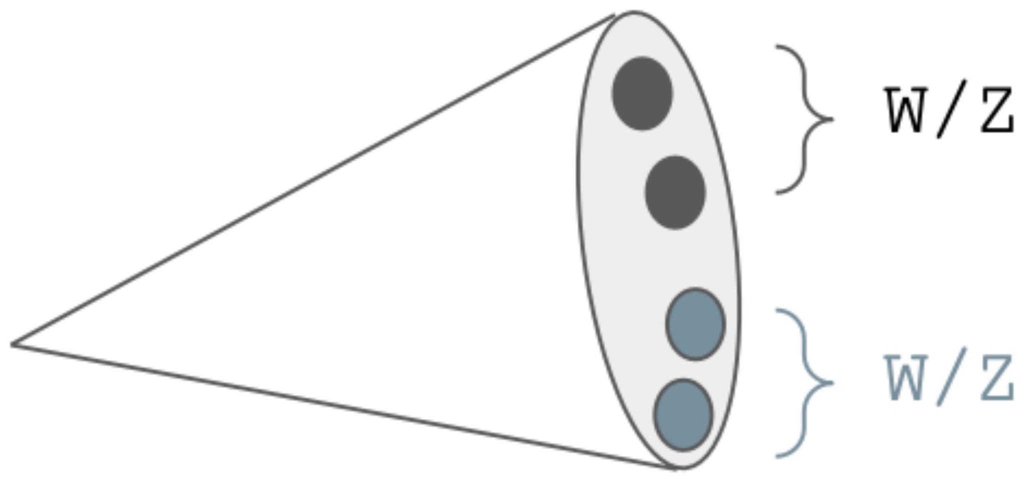
- Final states: E_T^{miss} + bb
- Dominates in low m_S
- ATLAS-CONF-2024-004

Reconstruction of the s decay

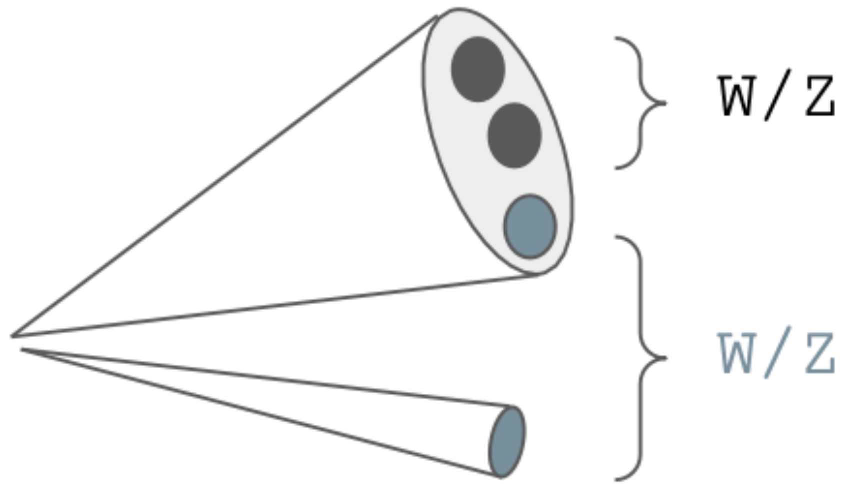
$m_s > 150$ GeV

monoSVV had.

Merged

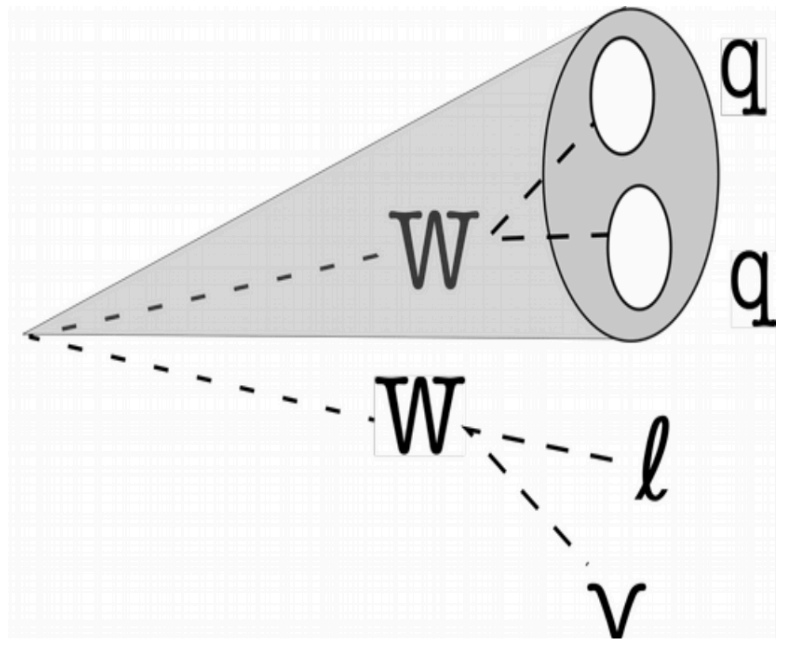


Intermediate

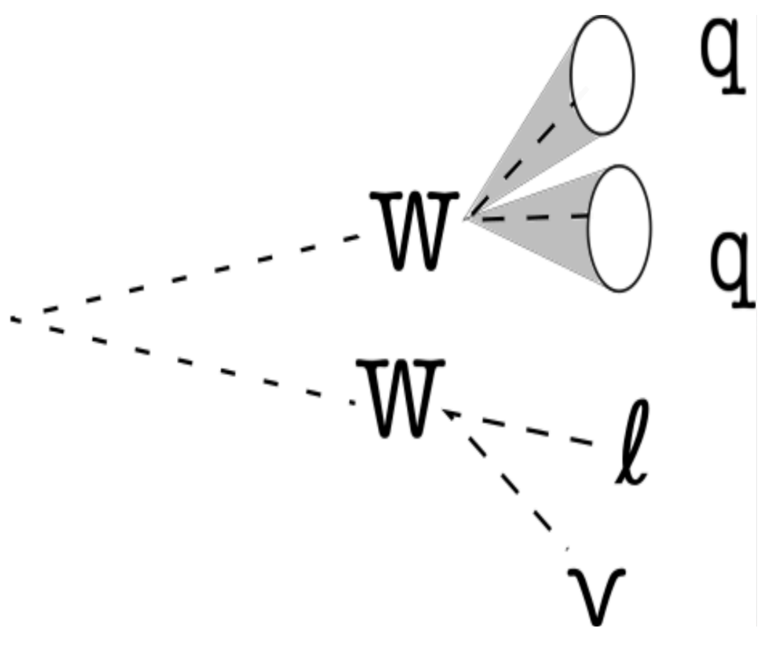


monoSWW semilep.

Merged



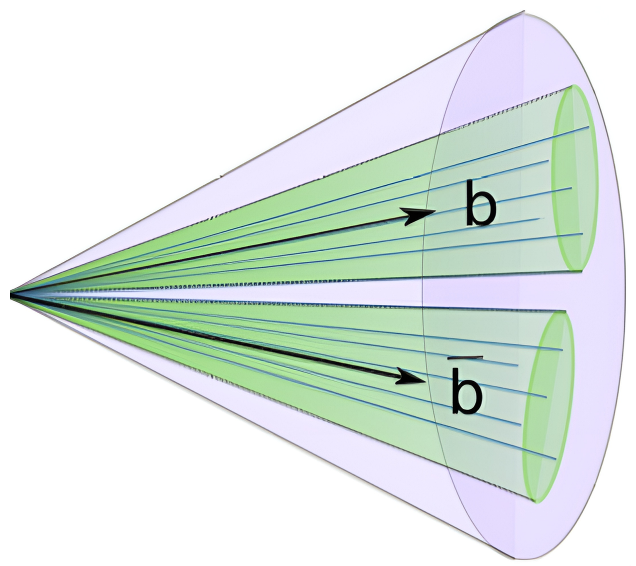
Resolved



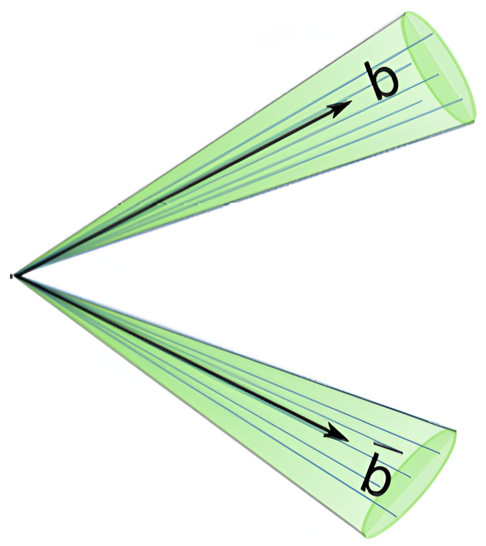
$m_s \leq 150$ GeV

monoSbb

Merged



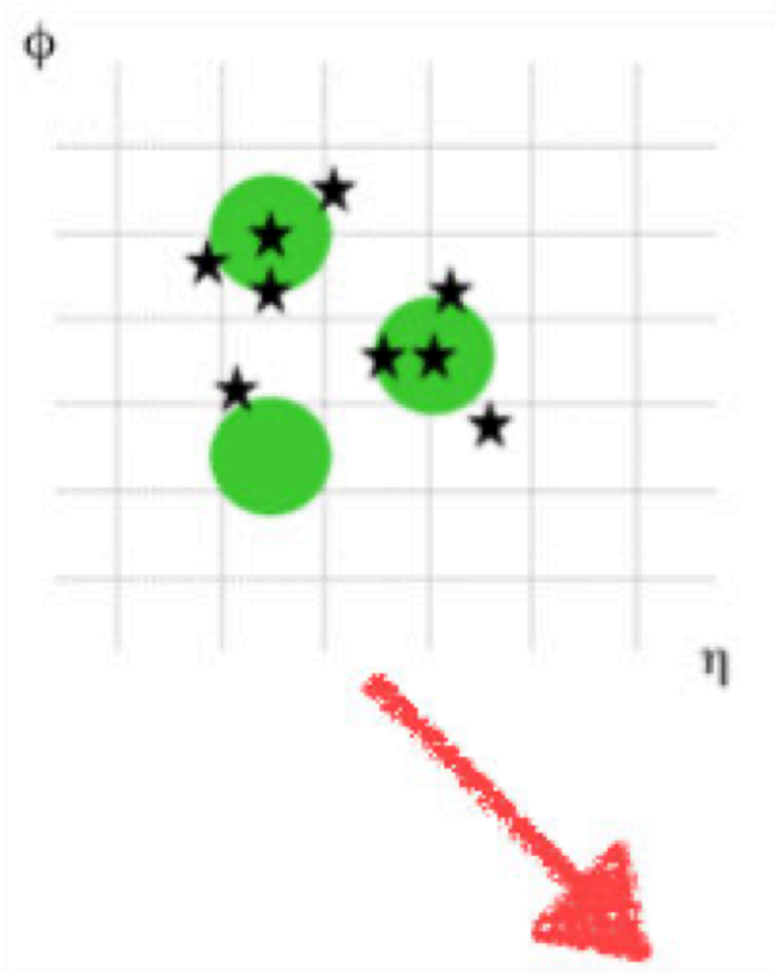
Resolved

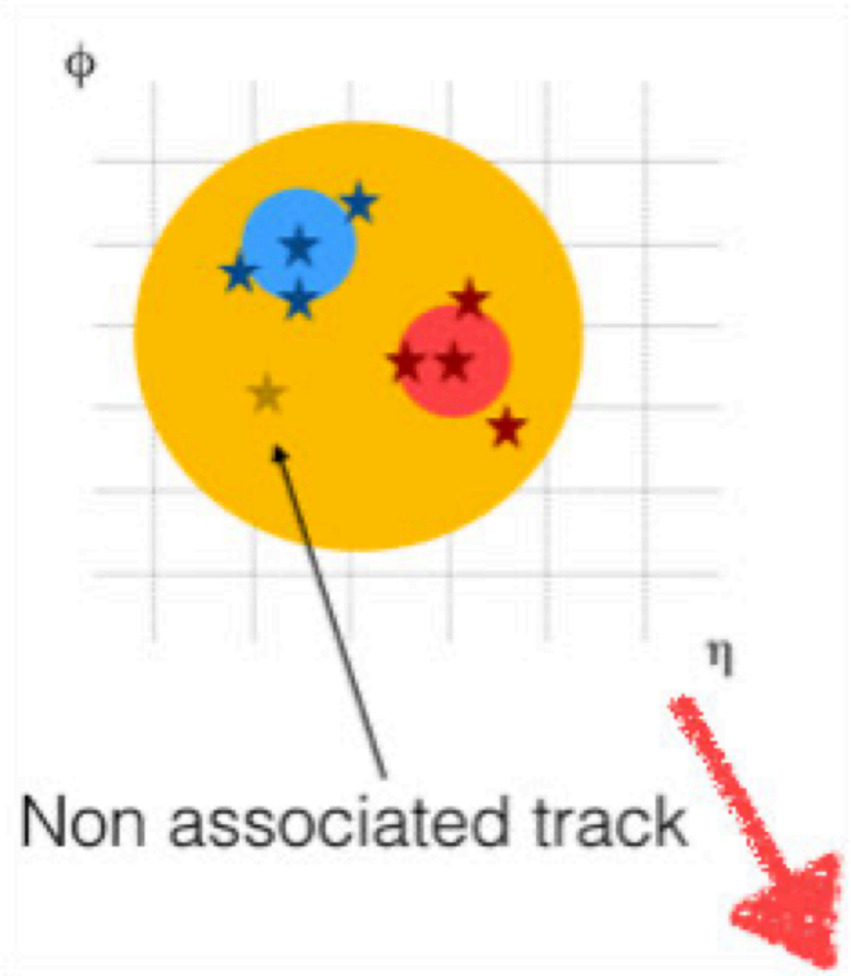


In all three analyses, Merged SR dominates sensitivity

Reconstruction techniques used in Merged / Intermediate regions	
monoSbb	*Reclustered large-R* jets (allows for exploring the low m_s)+ *Xbb* tagger
monoSVV had. / monoSWW semilep.	*Reclustered* + *track assisted large-R* jets + the cuts on the substructure variables

Reclustering and Track Assisted large-R jets





Use excellent angular resolution of the ATLAS tracker system

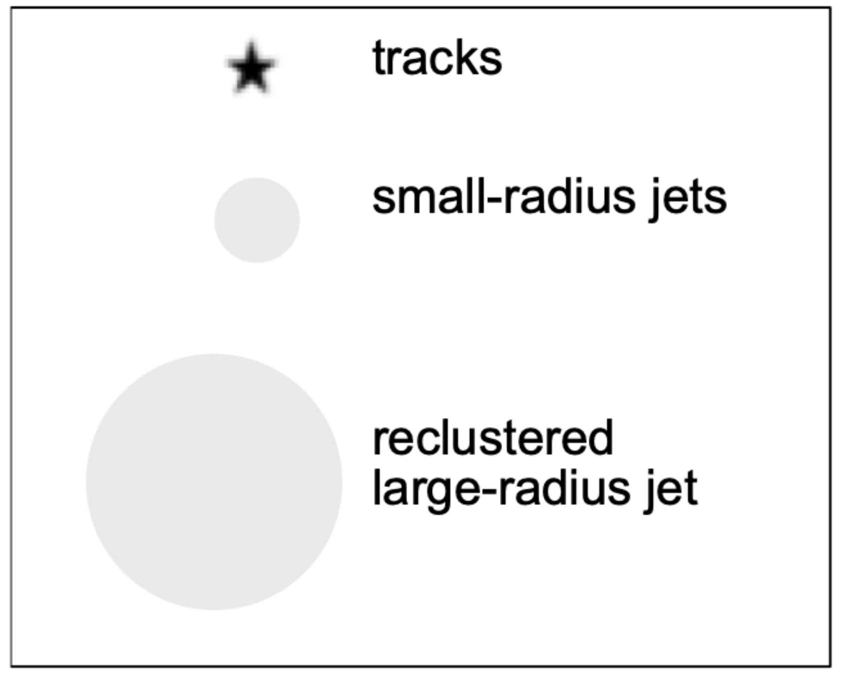
$$p_{\mathrm{T}}^{\mathrm{track,new}} = p_{\mathrm{T}}^{\mathrm{track,old}} \times \frac{p_{\mathrm{T}}^{j}}{\sum_{i \in j} p_{\mathrm{T}}^{i}}$$

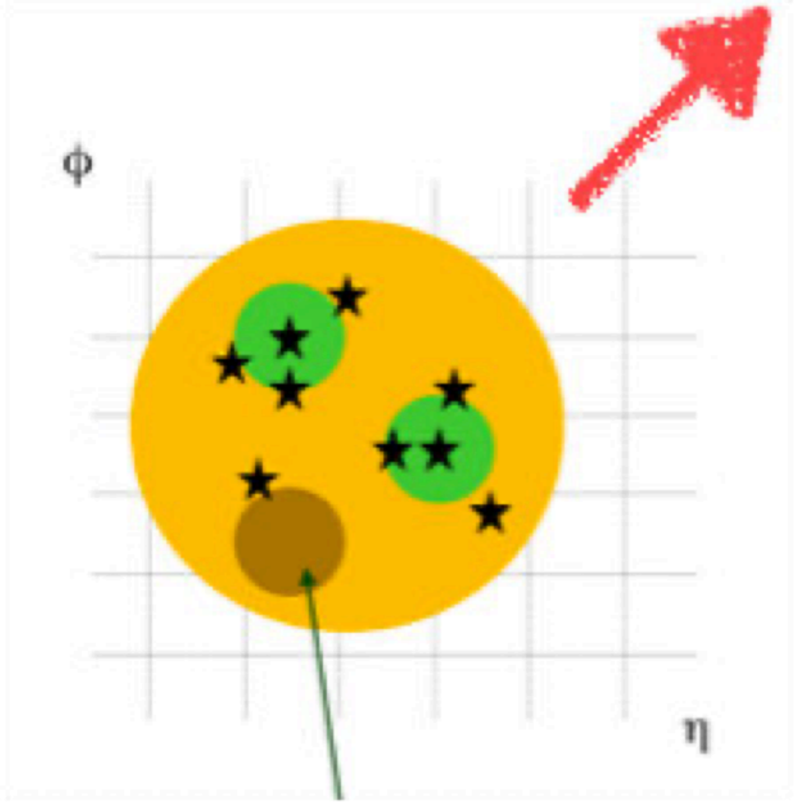
where the index i runs over all tracks matched to subjet j

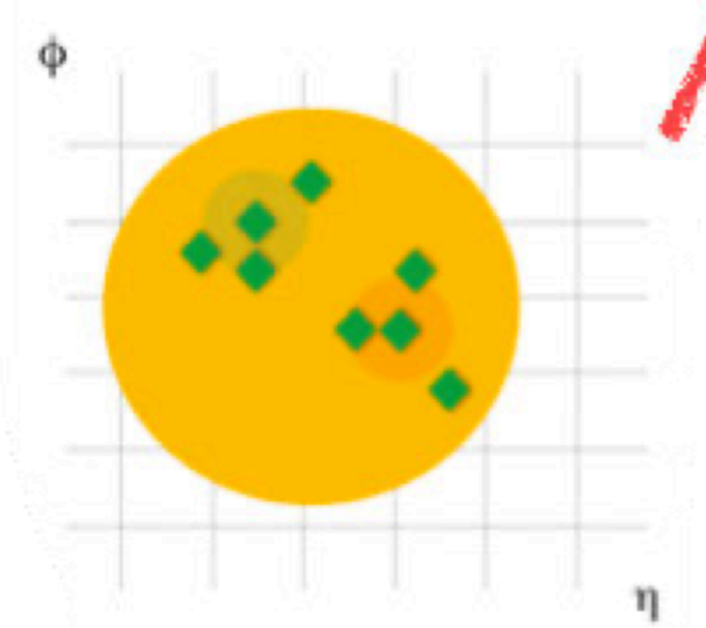
Track Assisted Reclustering

Callibrated small-radius jets → Recluster input jets to trimmed large-radius jets → Match tracks to constituent small-radius jets → Rescale tracks to p_T of the matched small-radius jets → Calculate substructure from tracks

Tracks → Match tracks to constituent small-radius jets







credit to monoSVV team

monoSbb
Analysis

Event Selection in SR

Cut	Resolved	Merged
Trigger	lowest unprescaled E_T^{miss} triggers	
Lepton multiplicity	veto on baseline electrons, muons	
τ vetoes	veto on baseline τ leptons & extended τ-veto	
$\min_{j\in\{1,2,3\}} \Delta\phi(E_T^{miss}, j)$	$> 20°$	
Jet multiplicity	$2 \leq N_{small-R\ jets}^{central} \leq 4$	$N_{large-R\ jets}^{central} \geq 1$
b-tag multiplicity	$N_{small-R\ jets}^{b-tagged} = 2$	leading large-R jet D_{Xbb}-tagged (m_J>50GeV) $N_{asso.VRTrk.jets}^{b-tagged} = 2$ (m_J<50GeV)
Non-associated b-jet veto	-	$N_{non-asso.VRTrk.jets}^{b-tagged} = 0$
E_T^{miss} significance	$\mathcal{S} > 12$	—
Top-mass proxy	$m_T^{b,min} > 170$ GeV $m_T^{b,max} > 200$ GeV	—
E_T^{miss} and $S(b\bar{b})$ recoil	$0.7 < E_T^{miss}/p_T(jj) < 1.3$	$0.7 < E_T^{miss}/p_T(J) < 1.3$
Boosted decay	-	$2m_J/p_T(J) < 0.6$
E_T^{miss}	$150 < E_T^{miss} < 500$ GeV	$E_T^{miss} > 500$ GeV

Common selection (0lepton and MET)

Dedicated selection (target signal signature)

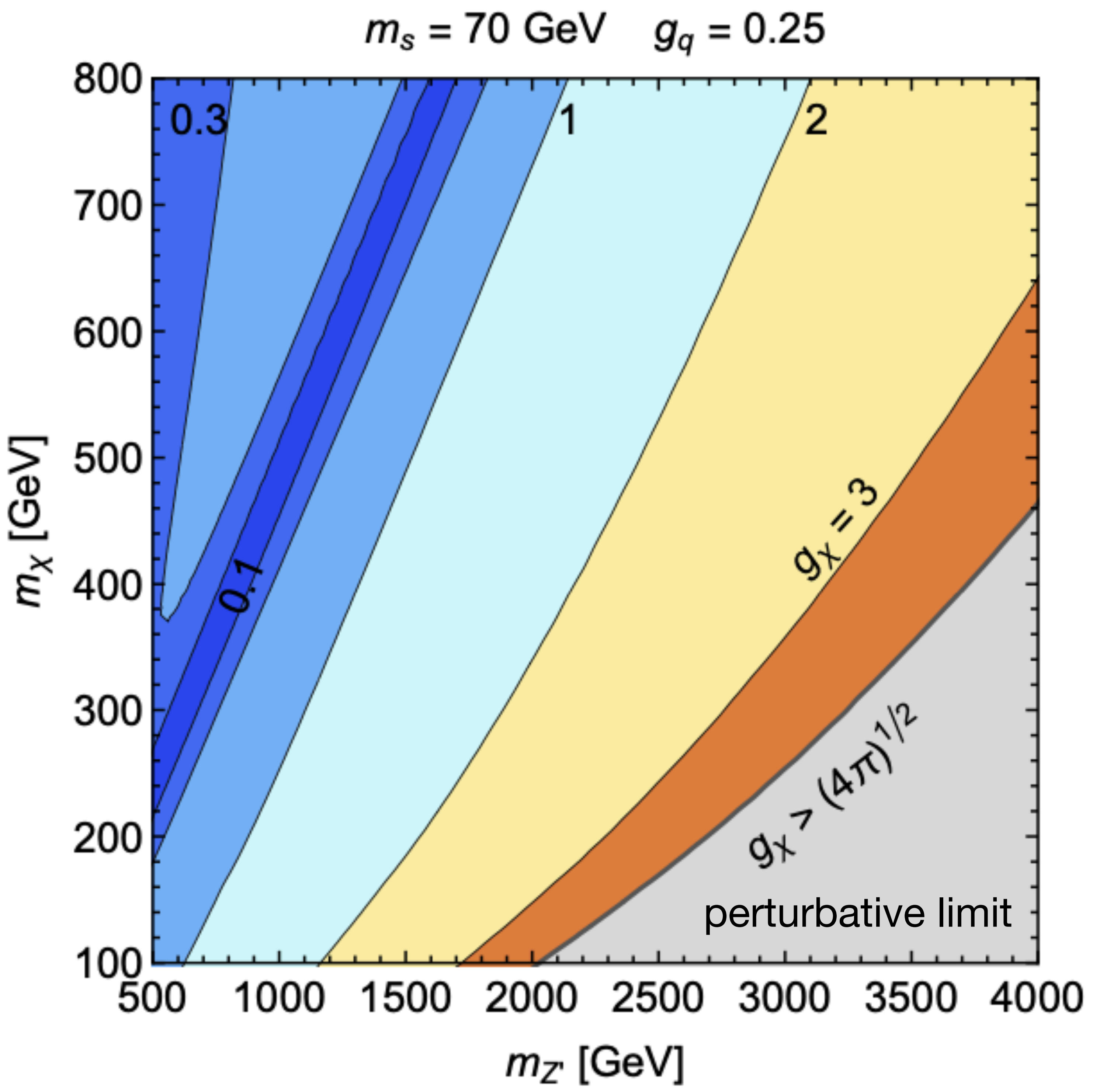
Resolved dedicated

Merged dedicated

$$m_T^{b,min/max} = \sqrt{2p_T^{b,min/max} E_T^{miss}(1 - \cos\Delta\phi(\vec{p}_T^{\,b,min/max}, \vec{E}_T^{miss}))}$$

Constraint from observed DM relic abundance

- Up to now fixing $g_q = 0.25$ and $g_\chi = 1.0$, this has important drawbacks when
  1. The couplings combination adopted so far is excluded by di-jet resonances for a wide range of Z' masses
  2. The observed DM relic abundance only reproduced for certain combination of the masses of the particles in the dark sector



values of g_X determined by the relic abundance

When constraint from the observed DM relic abundance considered (fixing g_q), possible DM annihilation processes:

- XX → Z' → qq
  - when $m_\chi \approx m_{Z'}/2$, resonantly enhanced, dominant, small g_X is sufficient to reproduce relic abundance
- XX → ss → SM
  - becomes leading when far from $m_\chi \approx m_{Z'}/2$
- Larger Z'-DM coupling also implies a larger partial decay width for Z' $\rightarrow \chi\chi$, di-jet signal rates suppressed

Experimental systematics source

Objects	**Systematics**
Luminosity	0.83% as priori
Pileup	PRW_DATASF
Small-R(0.4) jet	JES, JER, JVT, fJVT
	DL1r tagging
Small-R(0.4) jet as RC input	JES, JER, JMS (Rtrk based) propagated to RC
VR Track jet (for mJ < 50 GeV)	DL1r tagging
RC large-R jet	Xbbv3 tagging
	RC-LCTopo matching (negligible)
ET-miss	trigger efficiency
	track-based soft term
	track-in-jets scale unc.
Lepton	ID/Iso/Trigger of Elec/Muon/Tau

Theory Systematics Source

Process	Systematics
ttbar	ME, PS, muR, muF, PDF, FSR, ISR
single top	ME, PS, UE, ttbar-single top interference (DR vs DS), FSR, ISR
V+jets	muR, muF, PDF, NLO merging (CKKW), Resummation (qsf), ME/PS/merging (sherpa2.2.11 vs MGFxFx)
Diboson	muR, muF, PDF, PDFalphaS, ME/PS/Had(PowPy)
VHbb	muR, muF, PDF, PS
monoSbb signal	muR, muF, PDF

Two new scenarios proposed

	Parameters	m_S	Fixed values of the rest parameters
1	m_S - $m_{Z'}$	30 < m_S < 150 GeV	$\sin\theta$ = 0.01, m_χ = 200 GeV, g_q = 0.25, g_χ = 1.0
2	m_S - $m_{Z'}$	30 < m_S < 150 GeV	$\sin\theta$ = 0.01, m_χ = 900 GeV, g_q = 0.25, g_χ determined by relic density
3	m_χ - $m_{Z'}$	m_S = 70 GeV	$\sin\theta$ = 0.01, g_q = 0.25, g_χ determined by relic density

- In addition to the LHCDM WG recommendation, monoSbb analysis proposes:
  - Scenario2: g_χ = 1 → value determined by relic density abundance, m_χ increased to 900 GeV
  - Scenario3: g_χ = 1 → value determined by relic density abundance, m_S = 70 GeV for the largest sensitivity on m_χ - $m_{Z'}$ - plane, also proposed in paper JHEP 04 (2017) 143

Looking forward to further discussions

Normalization of the main Background

Process	Priori	Description	Applied in region
ttbar	**constrained by data**	inclusive norm uncertainty for ttbar, floated in fit	all
Zhf	**constrained by data**	inclusive norm uncertainty for Zhf, floated in fit	Resolved regions
		inclusive norm uncertainty for Zhf and correction for Xbbv3 tagging for Zhf, floated in fit	Merged regions
Whf	**constrained by data**	inclusive norm uncertainty for Whf, floated in fit	Resolved regions
		inclusive norm uncertainty for Whf and correction for Xbbv3 tagging for Whf, floated in fit	Merged regions

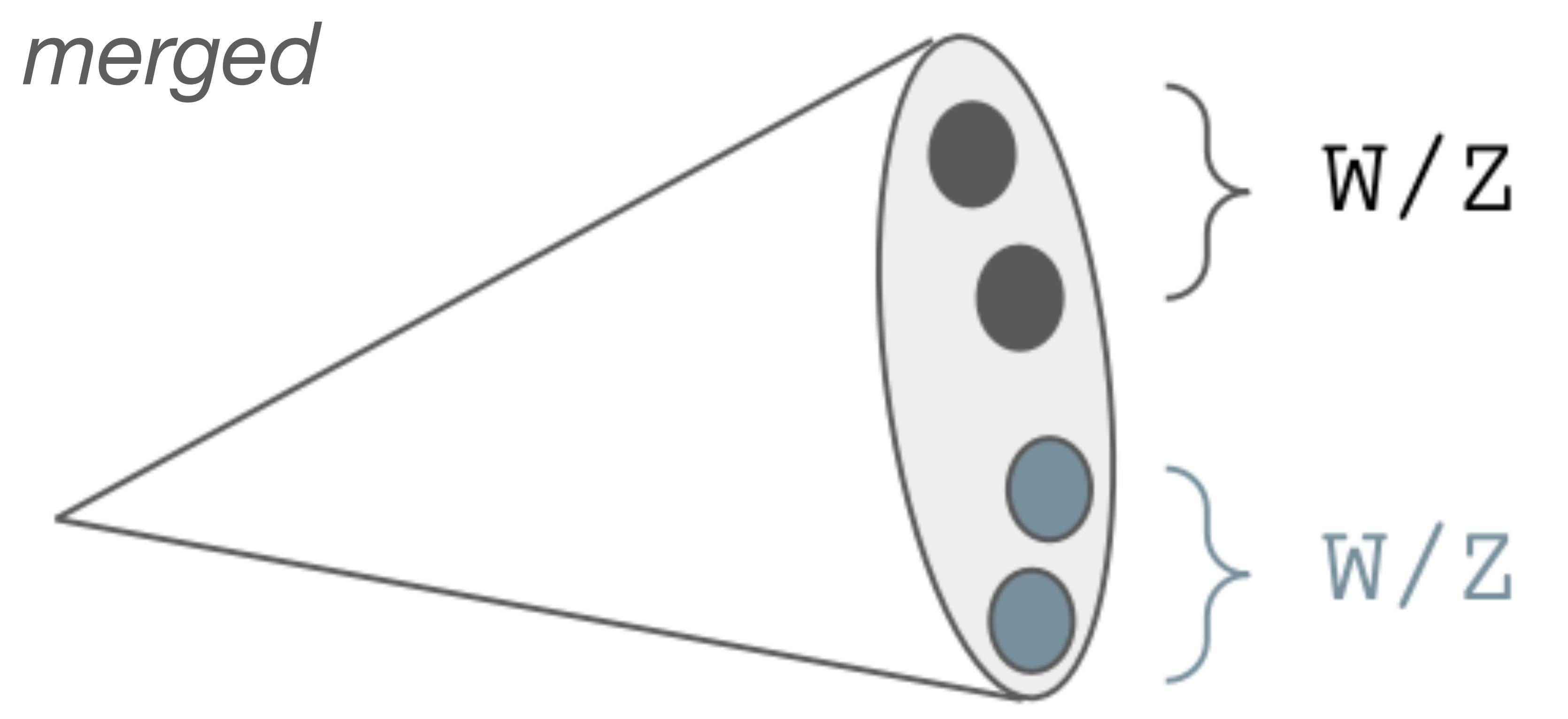
- Correction factor for Zhf and Whf in Merged Region also constrain the Xbb tagging uncertainty

Theory Systematics Impact

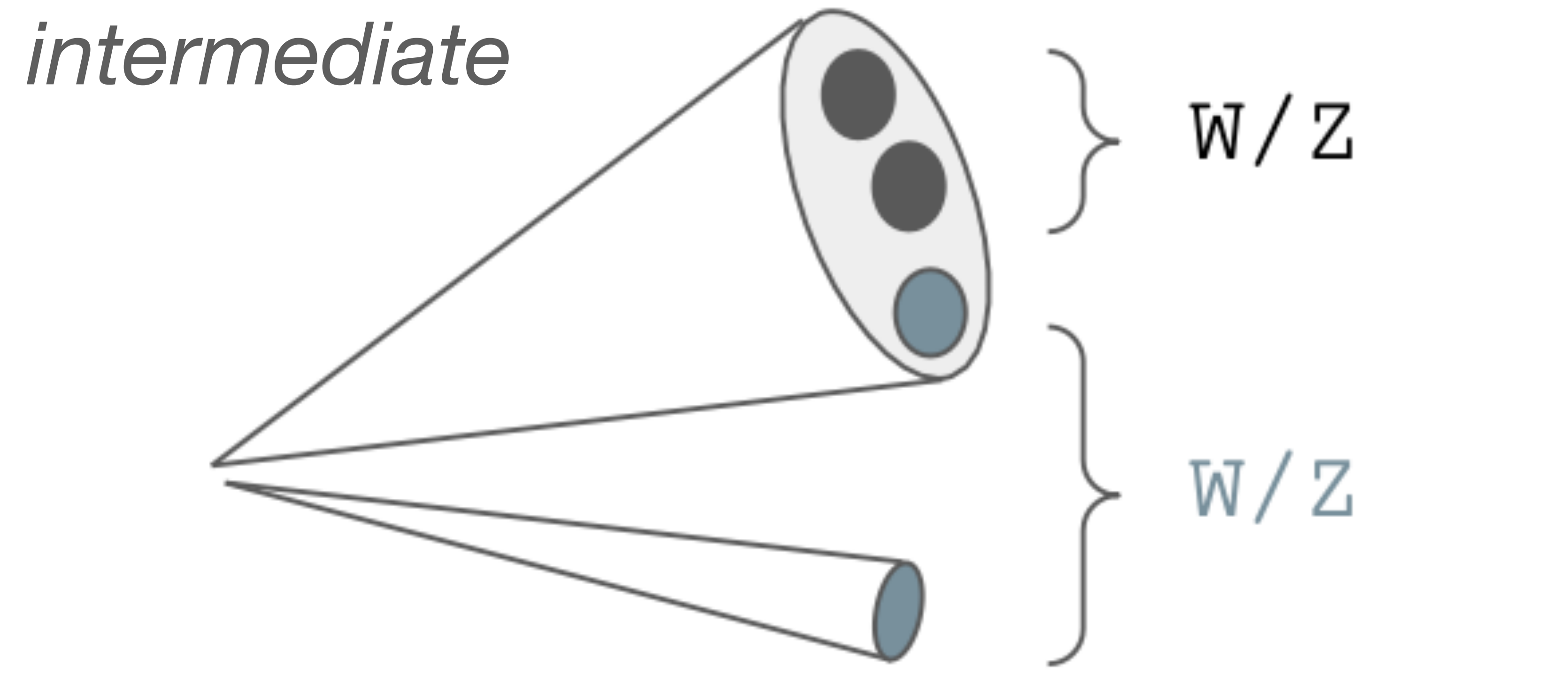
Systematics	Effect
Norm. On Bkg	Diboson (0.15) VHbb (0.05) Wcl (0.55) Single Top (0.40)
On discriminant shape	mJ (0L channel), mu_charge(1-muon channel), yields (2L channel)
Relative difference (nom. vs alt.) MET(_proxy) region to region	Applied on each MET(_proxy) region
Relative difference (nom. vs alt.) Lepton channel to channel	Applied in each lepton channel
Flavour ratios in W+hf (bb, bc, bl, cc)	bl (0.10), cc (0.59), bc (0.07)
Flavour ratios in Z+hf (bb, bc, bl, cc)	bl (0.20), cc (0.46), bc (0.13)

monoSVV had. Analysis

Overview



R=0.8 TAR jet with highest pt with τ_{42}<0.3 and τ_{43}<0.6 $m_{VV} = m_{TAR}$



R=0.8 TAR jet with 1-2 small-radius jets $m_{VV} = m_{TAR+COMB}$

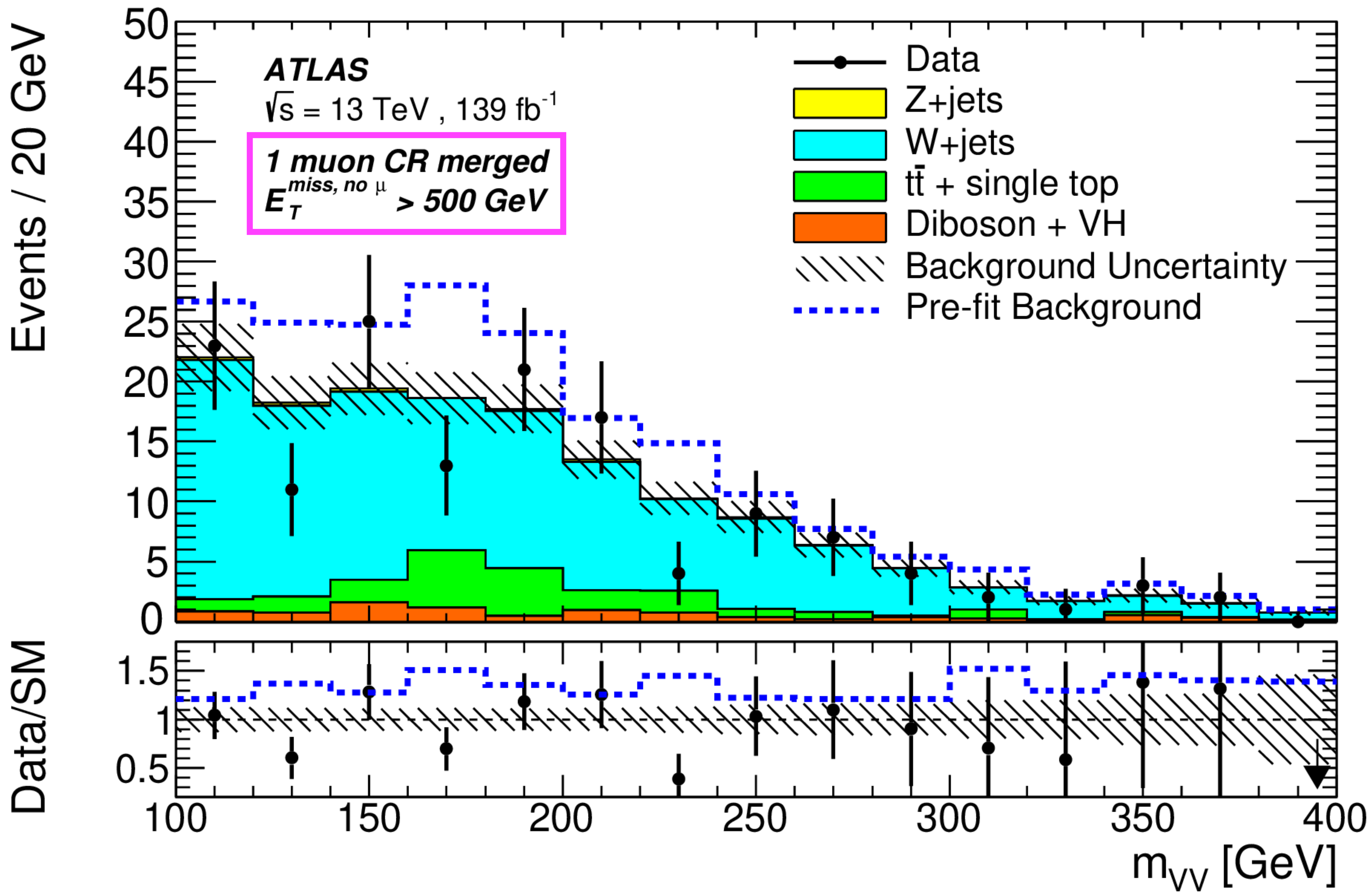
✖

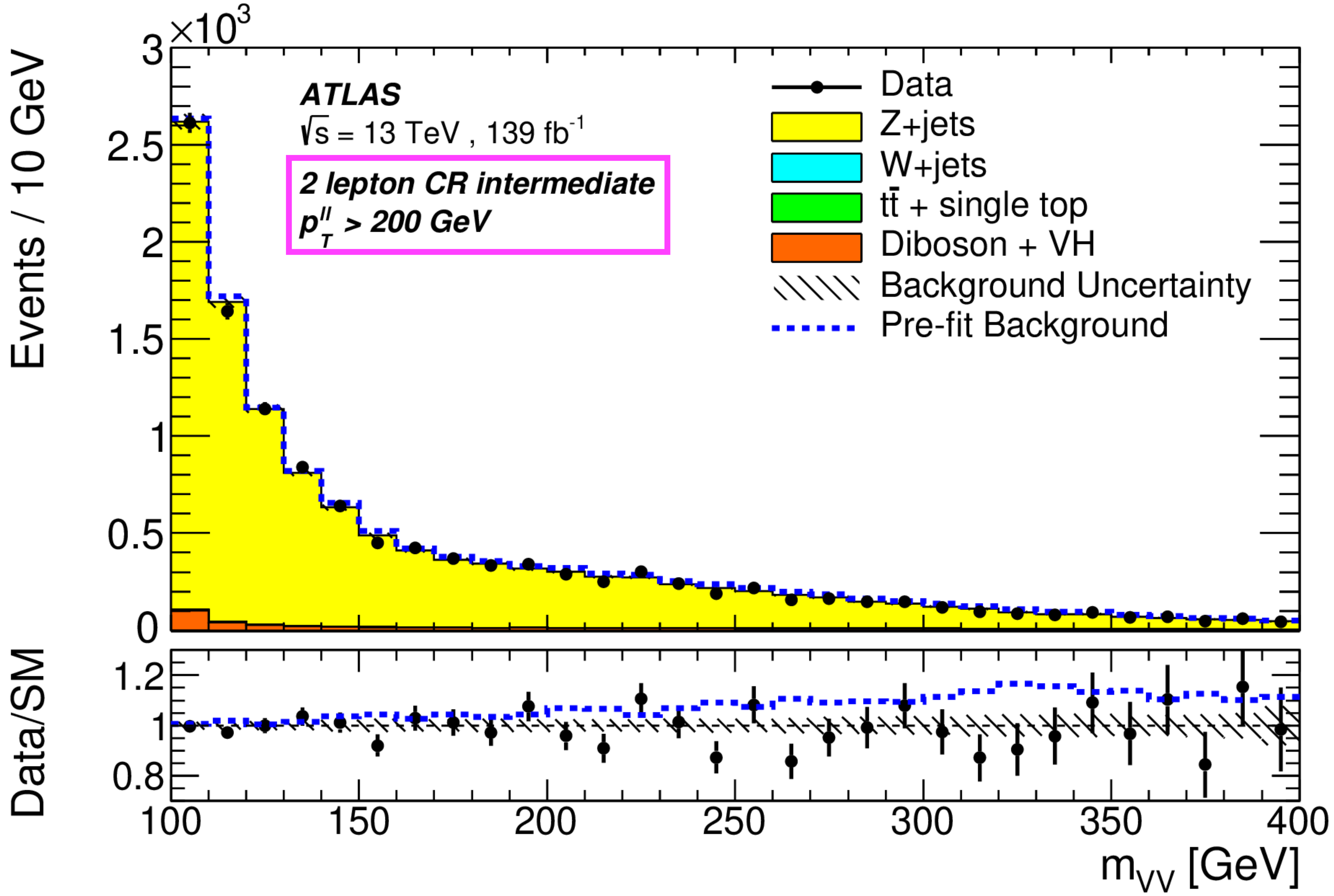
0 lepton	1 μ	2 lepton
signal region	W+jets control region	Z+jets control region
E_T^{miss} bins	E_T^{miss} proxy = $(E^{miss} + p^{\mu})_T$ bins	E_T^{miss} proxy = $p_T(ll)$ bins

- E_T^{miss} triggers used in 0 lepton and 1 μ channel, combination of single lepton triggers in 2 lepton channel
- N(small-R jets) ≥ 2, dedicated # of lepton for each channel, E_T^{miss}(or E_T^{miss} proxy) > 200 GeV
- anti-QCD cuts, tau veto, b-tag veto

Reconstructed m_{VV} in CR

E_T^{miss}	200 - 300 GeV	300 - 500 GeV	> 500 GeV
merged	not considered	prioritized	prioritized
intermediate	prioritized	not prioritized	not prioritized

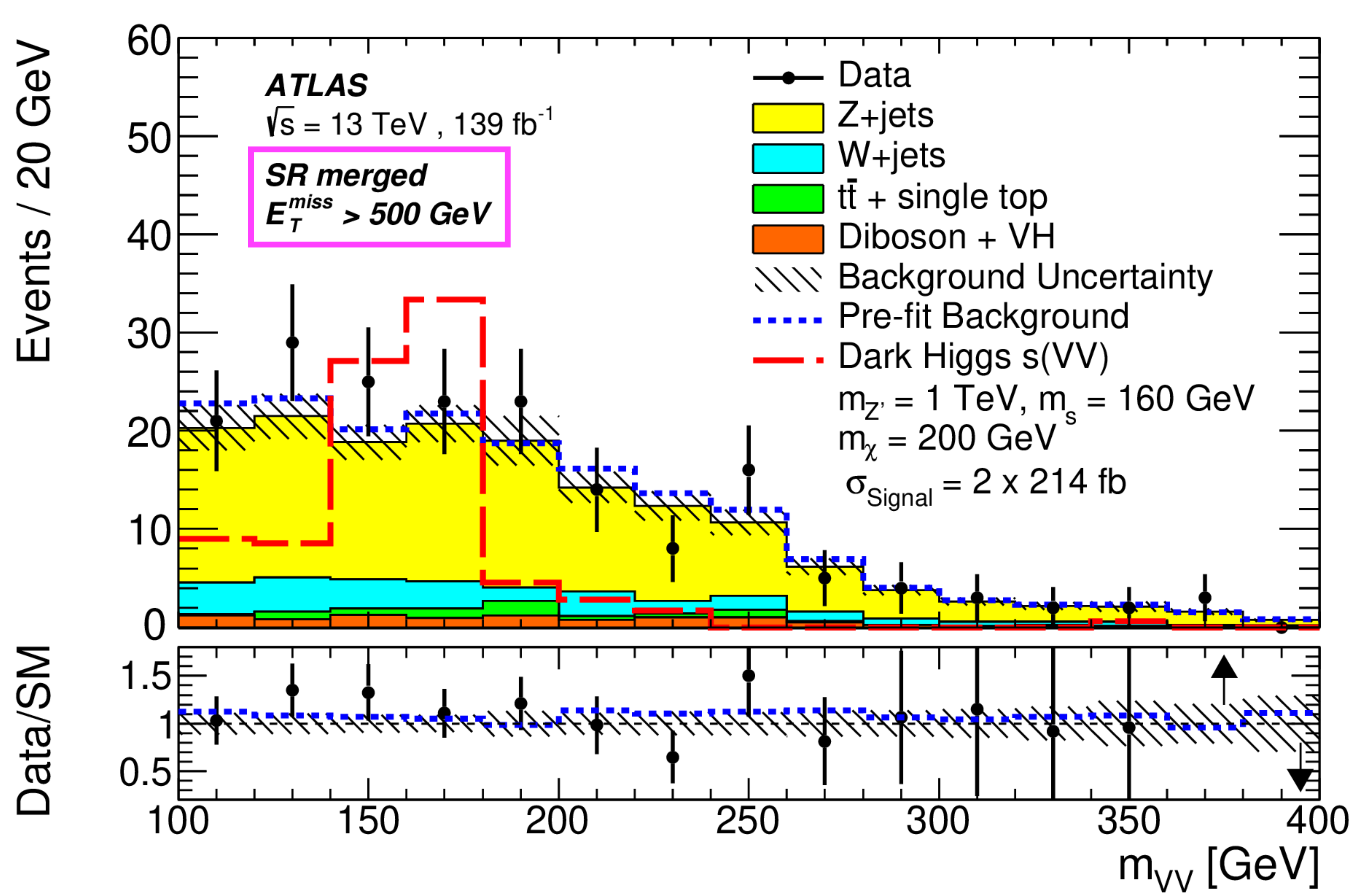


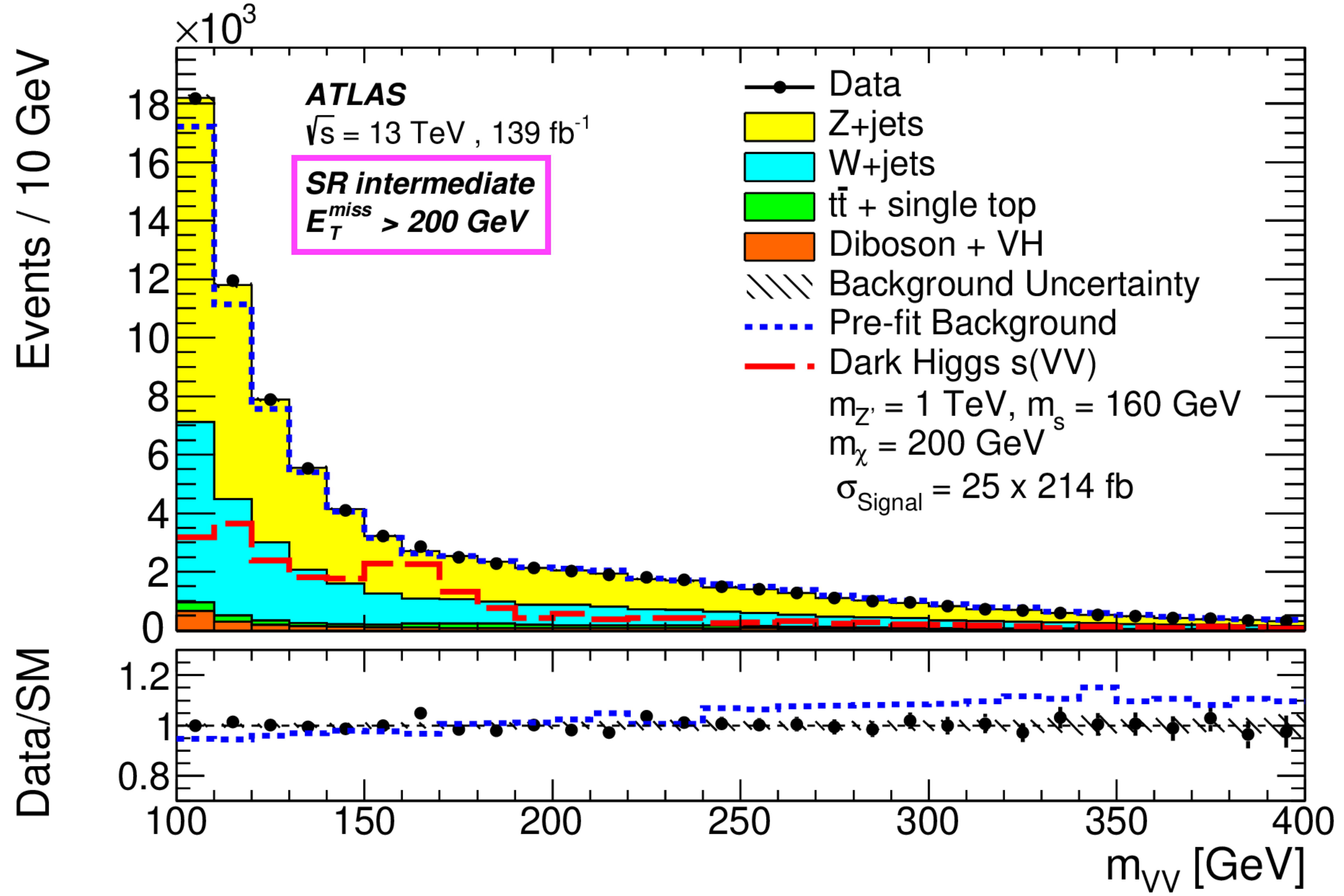


A good modelling of the mVV observed, only yield information in CRs used in fit, shape not

Reconstructed m_{VV} in SR

E_T^{miss}	200 - 300 GeV	300 - 500 GeV	> 500 GeV
merged	not considered	prioritized	prioritized
intermediate	prioritized	not prioritized	not prioritized





fit on m_{VV} shape in the SRs

Dominant Sources of Uncertainty

Source of uncertainty	Uncertainty [%] (a)	(b)	(c)
Signal modeling	11	10	10
W+jets modeling	9	21	14
Z+jets modeling	7	12	13
MC statistics	11	14	23
Jet energy scale	8	17	24
Jet energy resolution	11	18	15
Lepton reconstruction	8	9	5
Track reconstruction	6	7	5
Systematic uncertainty	30	42	55
Statistical uncertainty	16	25	50
Total uncertainty	34	49	74

3 selected signals

	$m_{Z'}$ [TeV]	m_s [GeV]
a	1	160
b	1	235
c	1	310

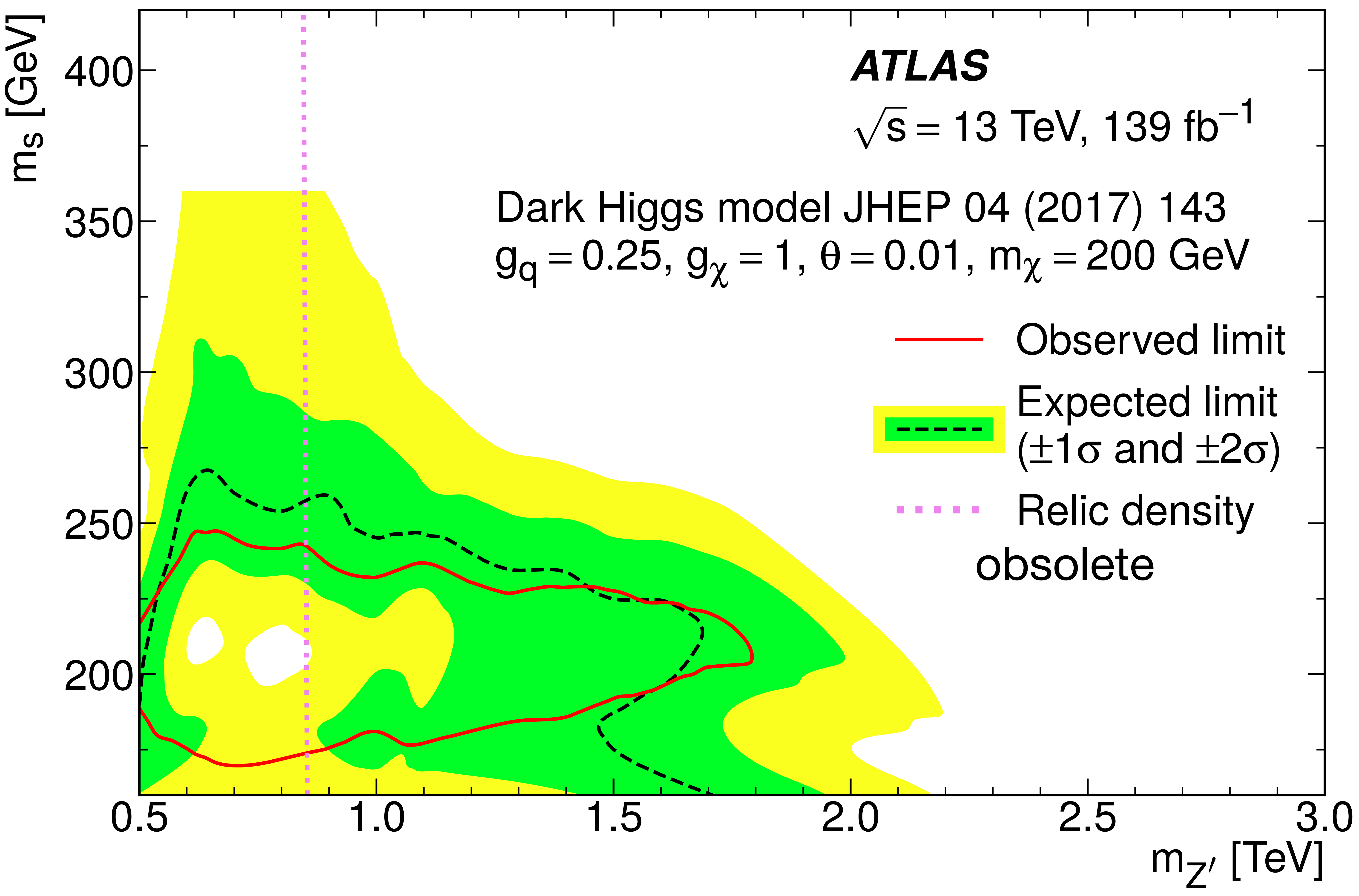
Strongest impact on theory predicted signal strength from:

- W/Z+jets modelling
- Jet systematics
- signal modelling

systematics dominated

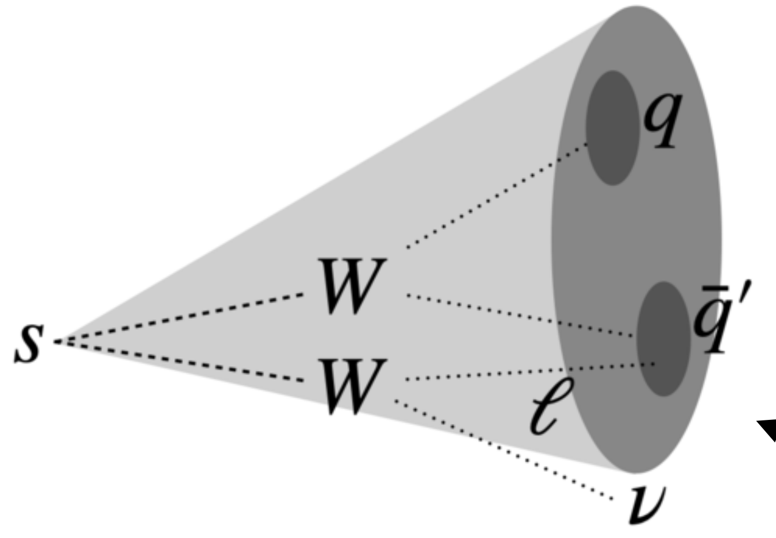
Limit Contours in $m_{Z'}$-m_S-plane

- TAR jet can improve the sensitivity up to 2.5 compared to conventional large-R jet

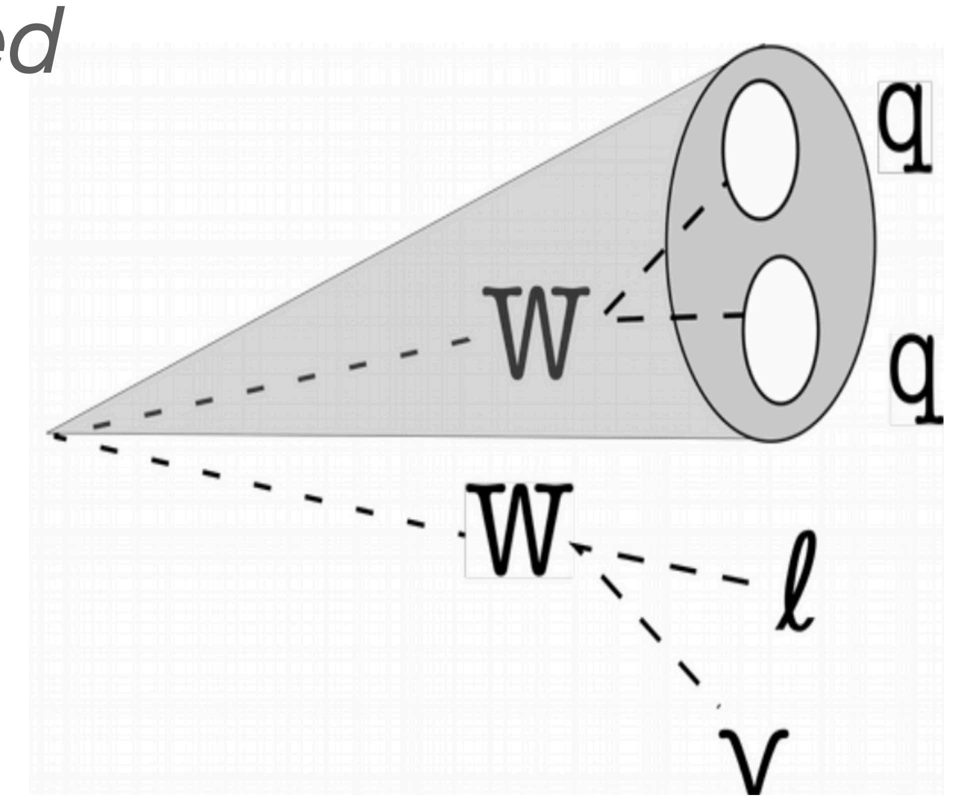


monoSWW semilep. Analysis

Overview



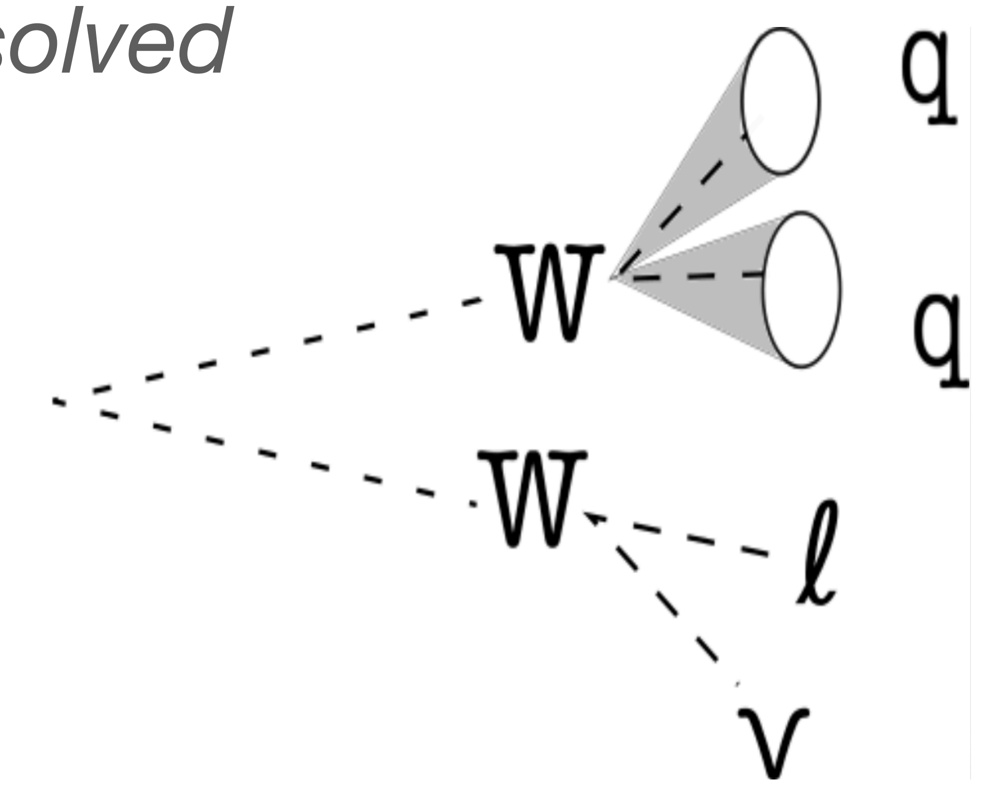
merged



W_{had} candidate: R=1.0 TAR jet

lepton disentanglement and $D_2^{\beta=1} < 1.1$

resolved



W_{had} candidate: 2 R=0.4 jets with

m(j,j) closest to W mass

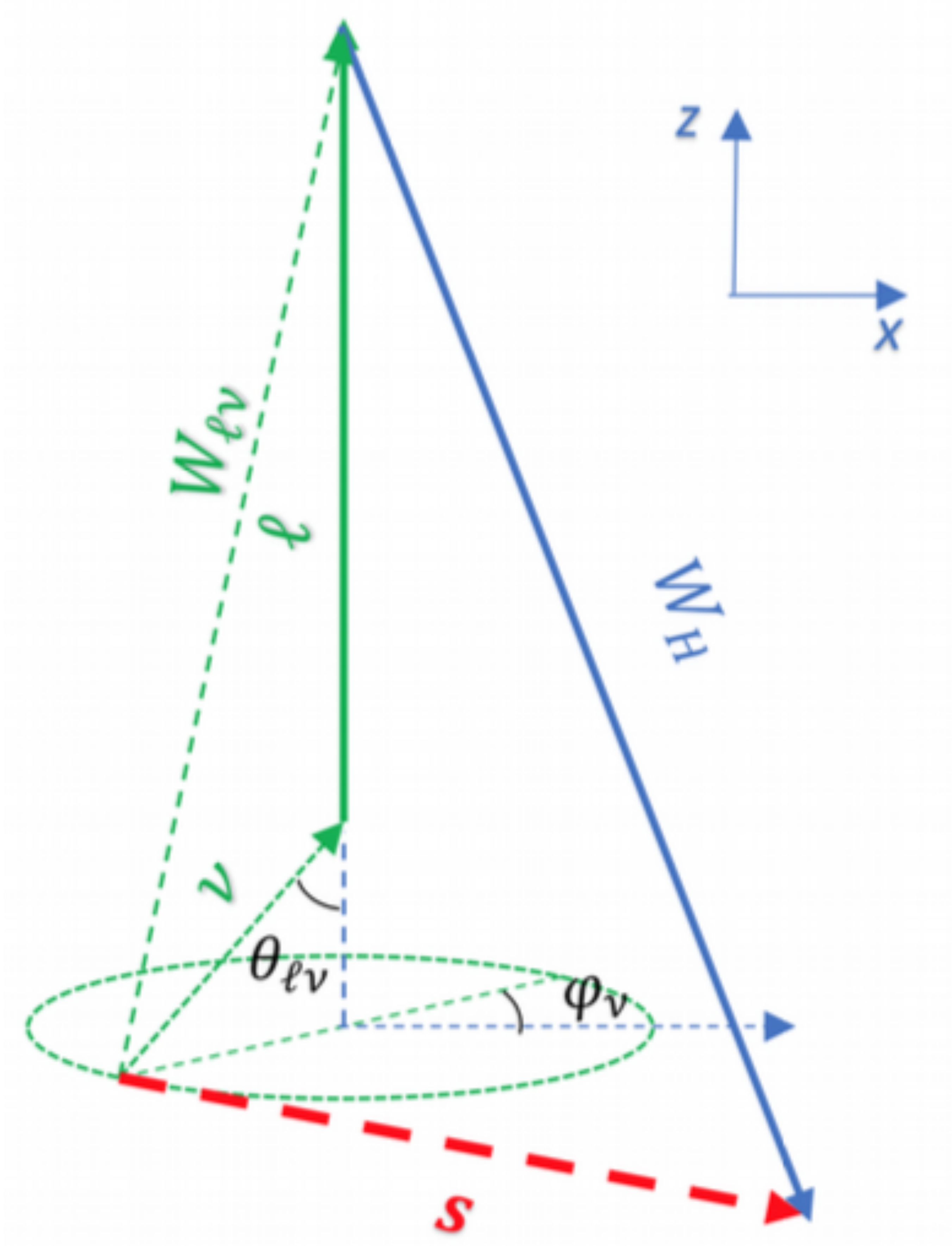
✖

	SR	W+jets CR	ttbar CR
$N_{b\text{-}jet}$	0	0	≥ 2
$\Delta R(W_{can.}, lep)$	<1.2	>1.8	<1.2

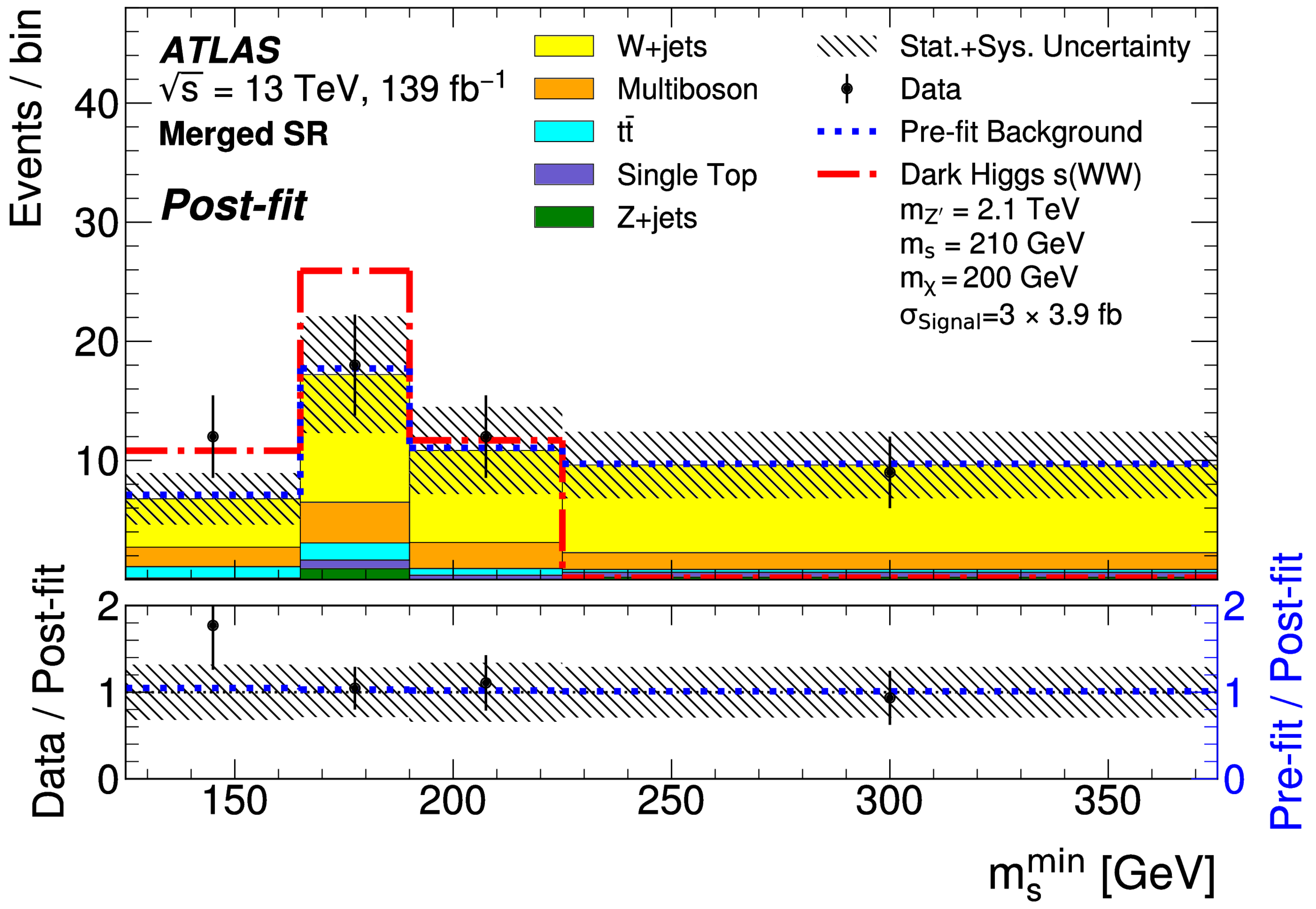
- passed E_T^{miss} trigger or single muon trigger, N(lep) = 1, high E_T^{miss} and high $m_T(lep, E_T^{miss})$
- E_T^{miss} significance cuts, window cut on $m_{Wcand.}$
- Recycling strategy: Only consider events for the resolved category if they fail the merged criteria

Analytical solution of s→WW→qqlv system

- 3 invisible (neutrino + 2 DM) particle in the decay products → direct dark-Higgs reconstruction impossible
- Used a rotated frame of reference with lepton along Z-axis and W_{had} in X-Z plane.
- Find minimum m_s (m_s^{min}) consistent with W_{had} and lepton momenta and m_W constraint. details in backup



credit to monoSWW team



fit on m_s^{min} shape in the SRs + yield in CRs simultaneously

Dominant Sources of Uncertainty

Source of uncertainty	Uncertainty [%]		
	(2100, 210)	(1000, 140)	(1000, 360)
W+jets modelling	4	5	2
Diboson modelling	5	4	1
$t\bar{t}$ modelling	7	4	1
Single top modelling	9	5	11
Signal modelling	1	3	0
Statistical uncertainty of MC	26	15	29
$R = 0.4$ jet energy scale	11	12	14
$R = 0.4$ jet energy resolution	9	4	7
$R = 0.2$ jet energy scale	9	9	14
$R = 0.2$ jet energy resolution	13	10	16
$E_{\mathrm{T}}^{\mathrm{miss}}$	7	1	7
Track reconstruction	5	2	2
Lepton reconstruction	2	3	1
Systematic uncertainty	38	28	40
Statistical uncertainty of data	38	32	37
Total uncertainty	53	43	55

($m_{Z'}$, m_s)

Strongest impact on fitted signal strength from:

- MC statistics (mainly W+jets)
- Jet uncertainties

systematic uncertainty (incl. MC statistics) is comparable to statistical uncertainty

Limit Contours in $m_{Z'}$-m_S-plane