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ATLAS Dark Higgs Search in the VV Channel

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Dark Higgs model

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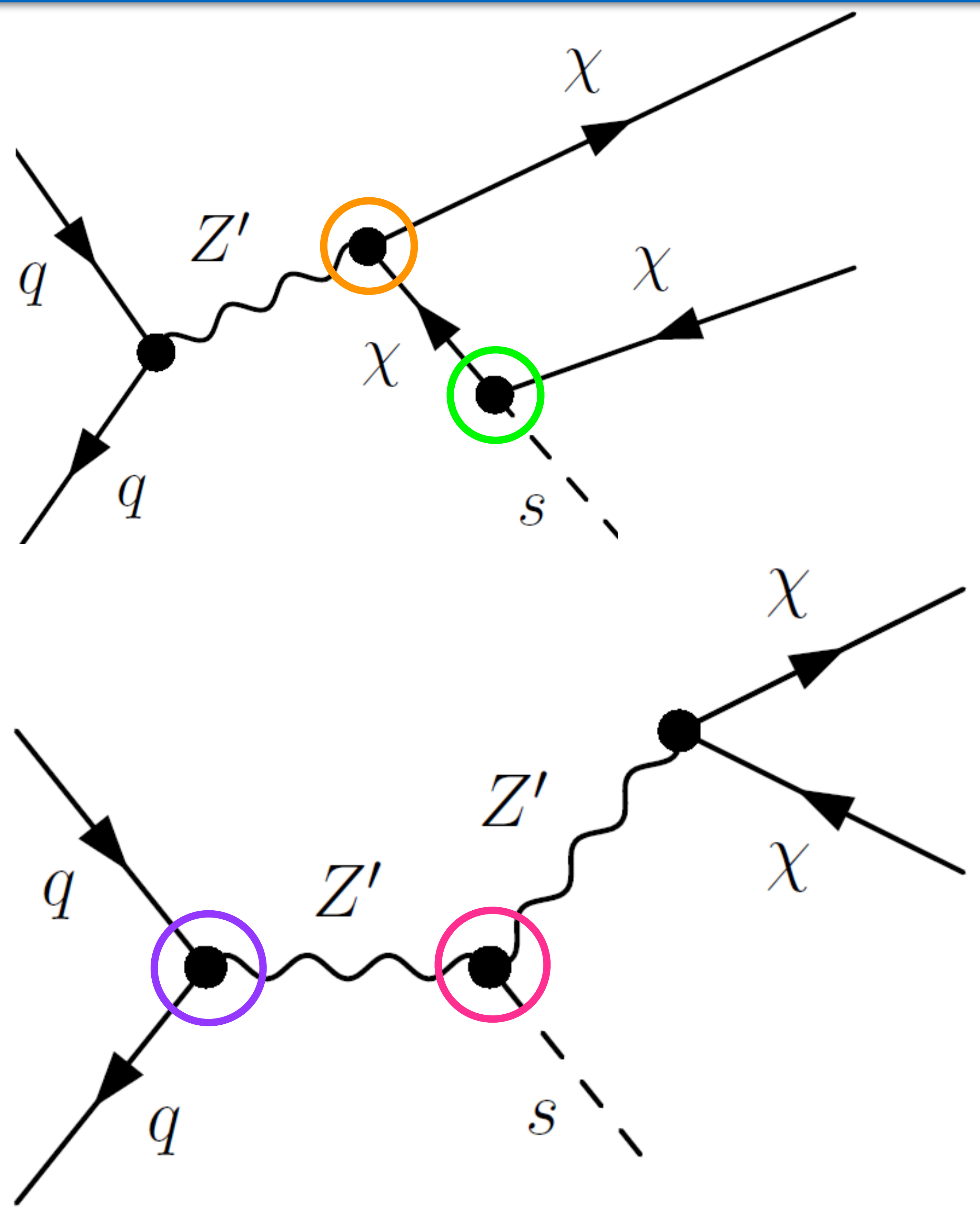
- Simplified model for DM production at the LHC, extends spin-1 mediator models of LHC DM WG
  - Majorana DM (X) interacts with two different mediators:
    - massive vector boson Z' and a dark Higgs s



Interactions:

SM Quarks $\mathcal{L}_\chi = -g_q Z'^\mu \bar{q}\gamma_\mu q$

Dark Sector $\mathcal{L}_\chi = -\frac{1}{2} g_\chi Z'^\mu \bar{\chi}\gamma^5\gamma_\mu\chi - g_\chi \frac{m_\chi}{m_{Z'}} s\bar{\chi}\chi + 2\, g_\chi\, Z'^\mu Z'_\mu \left(g_\chi\, s^2 + m_{Z'} s\right)$

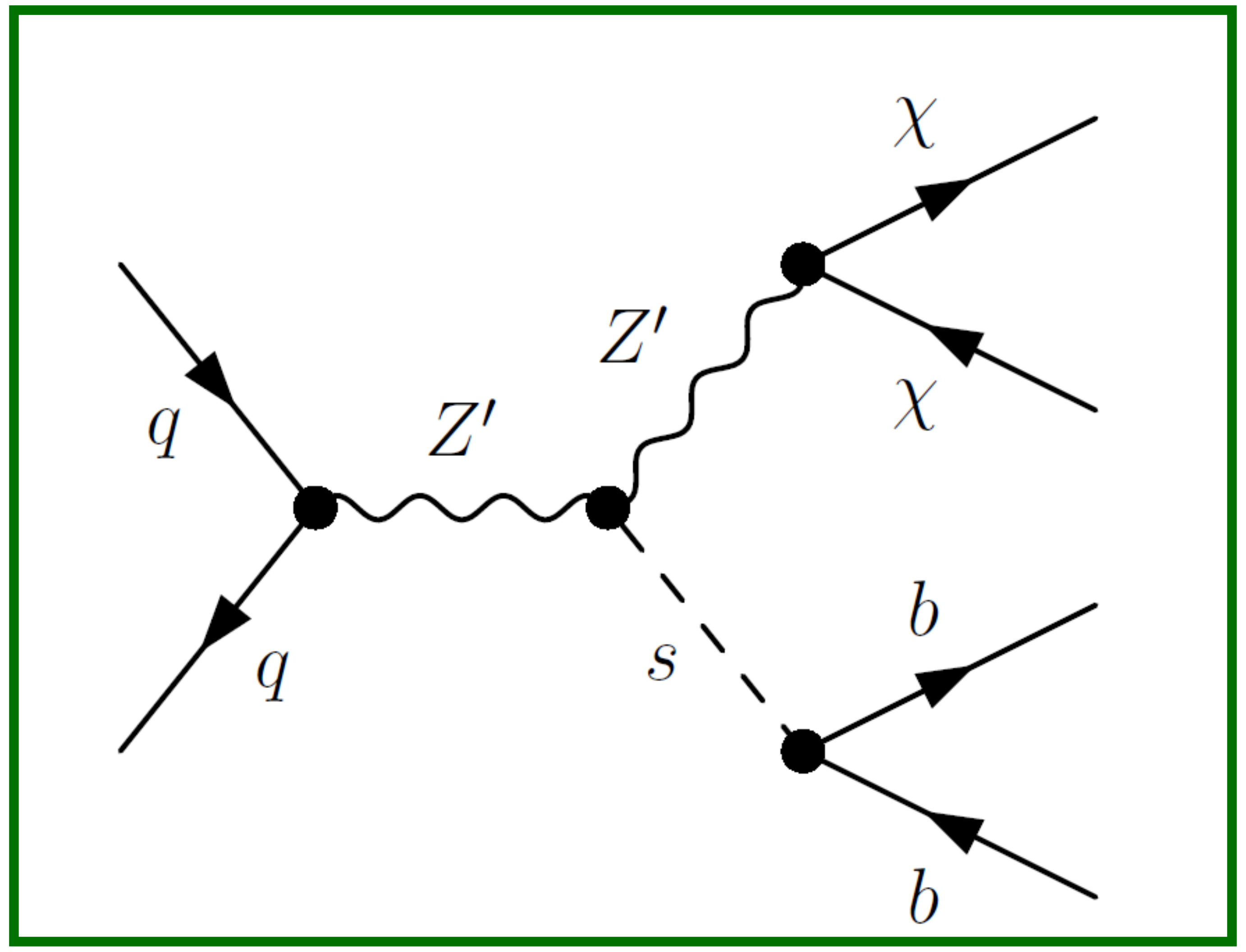
Model Parameter

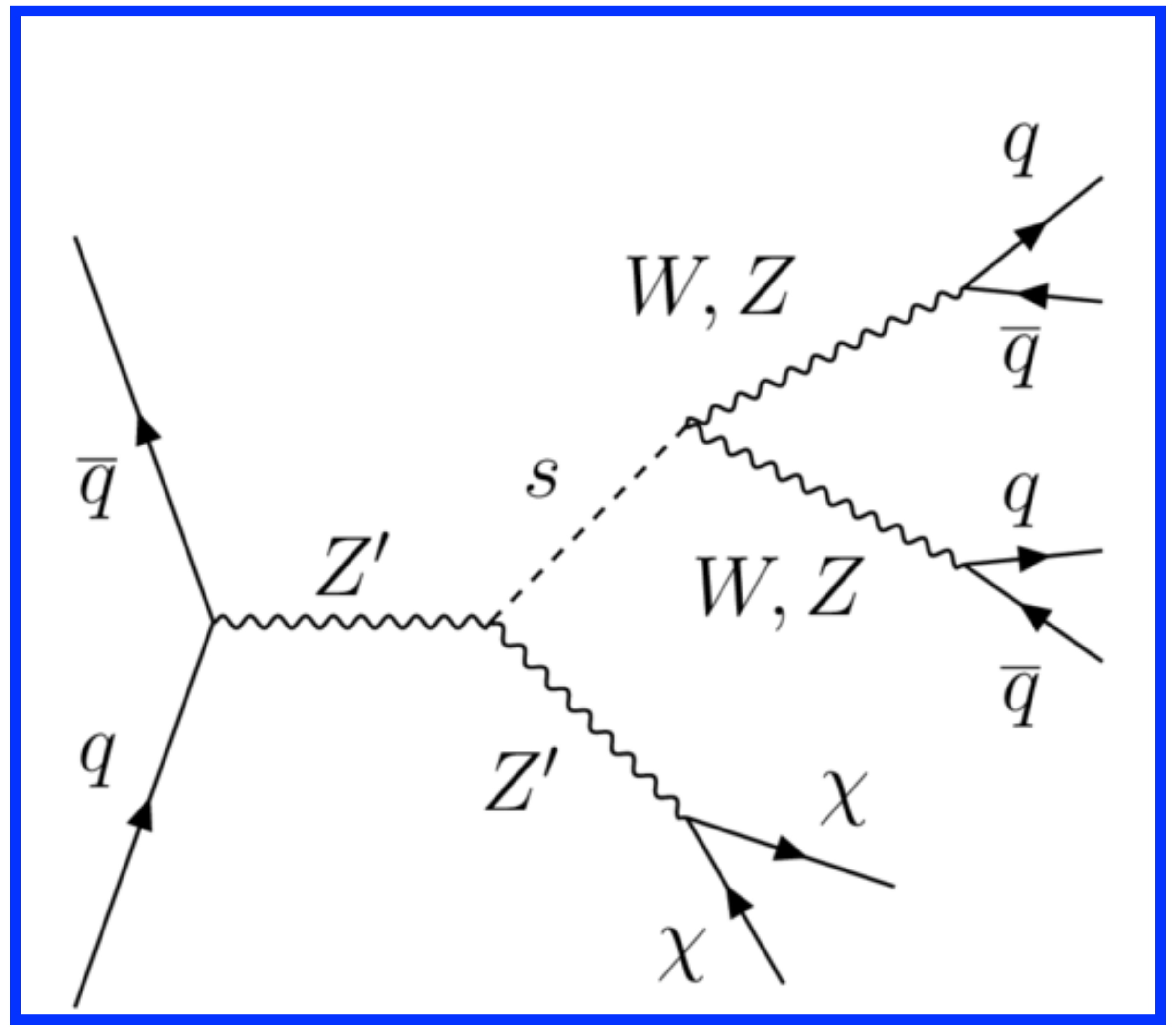
Particle Masses		Couling Constants	
Majorana DM mass	m_{χ} = 200 GeV	Dark-sector coupling	g_{χ} = 1.0
Z' mass	$m_{Z'}$	Quark-Z' coupling	g_q = 0.25
Dark Higgs mass	m_S	Mixing angle with SM Higgs	θ = 0.01

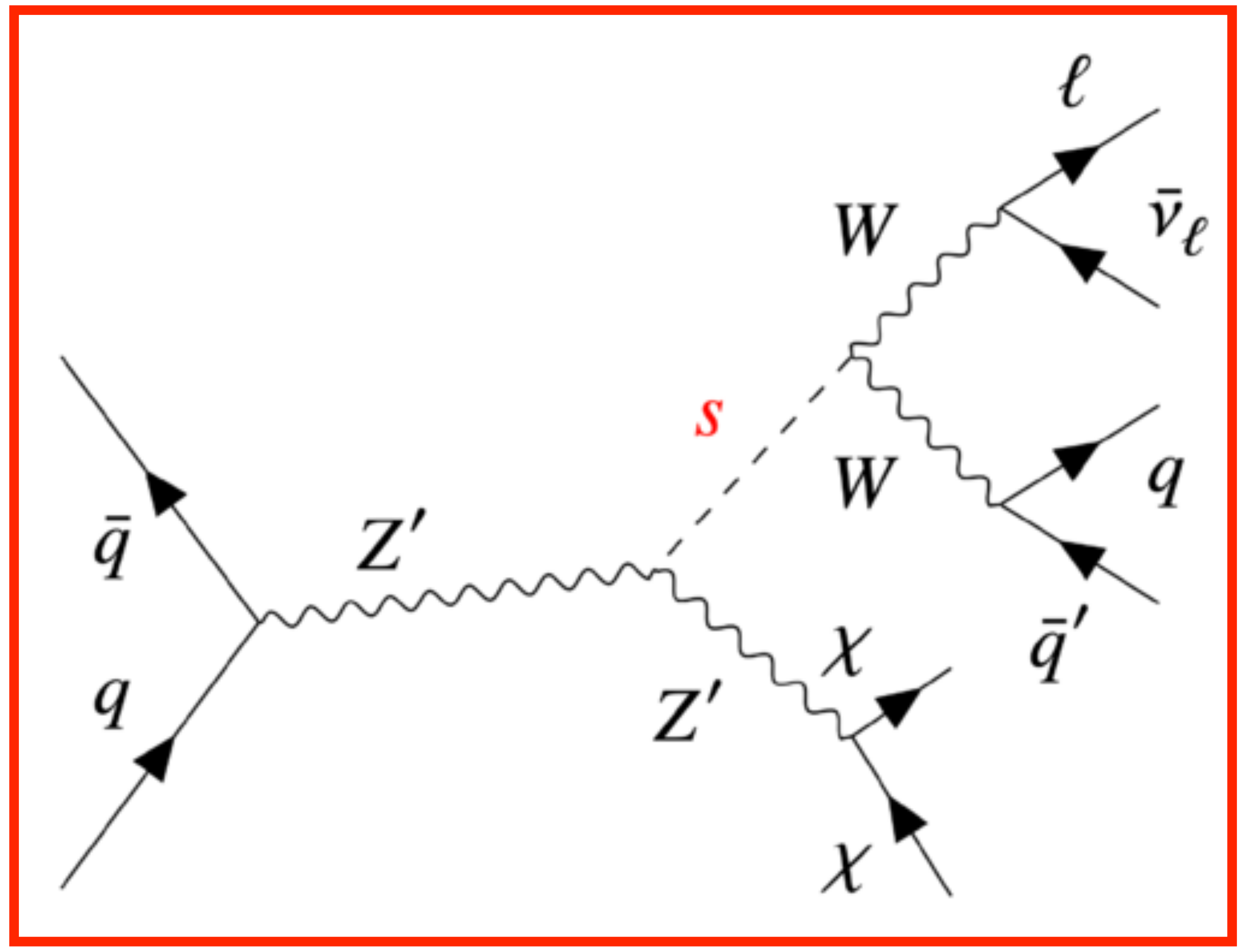
- Parameters and their recommended value from LHC DM WG
- Non-Zero mixing between the dark Higgs and the SM status
  - ensure s is unstable even if it is the lightest state in dark sector
  - s decays into SM states with a negligible lifetime, $s \rightarrow WW/ZZ$
- θ must be so small to avoid any other observable effects, eg. monoHiggs
- Scan in $m_{Z'}$ and m_S is of interest

Analysis at LHC

- Various analysis at LHC target such model with different s decays:
  - CMS-PAS-EXO-20-013: s→WW→lvlv
  - ATLAS PUB-2019-032: s→bb, recast of the monoH analysis
  - ATLAS EXOT-2018-40: s→VV→qq'qq' denoted as Mono-S to VV (had)
  - ATLAS EXOT-2020-04: s→WW→lvqq' denoted as Mono-S to VV (Semilep)



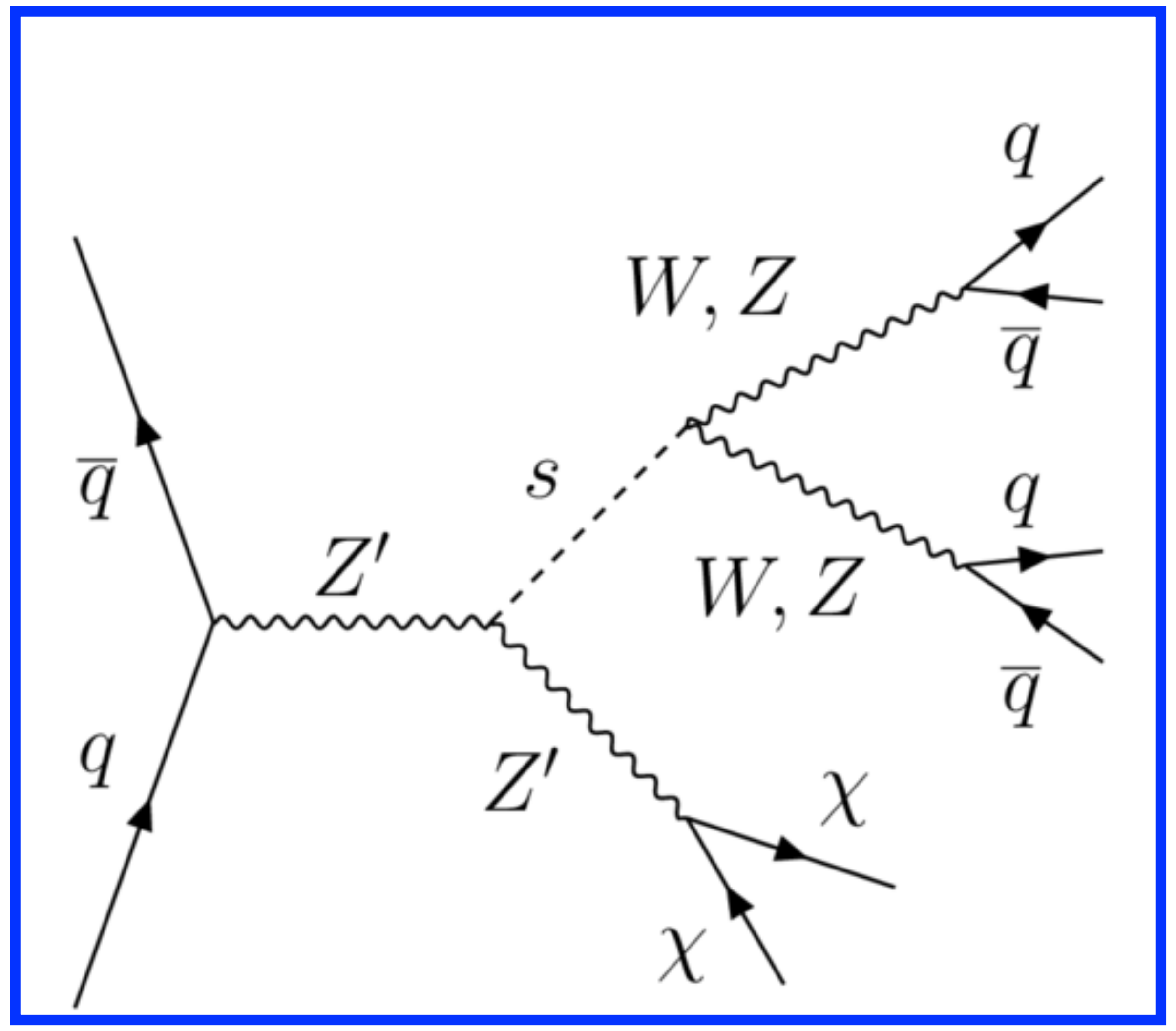


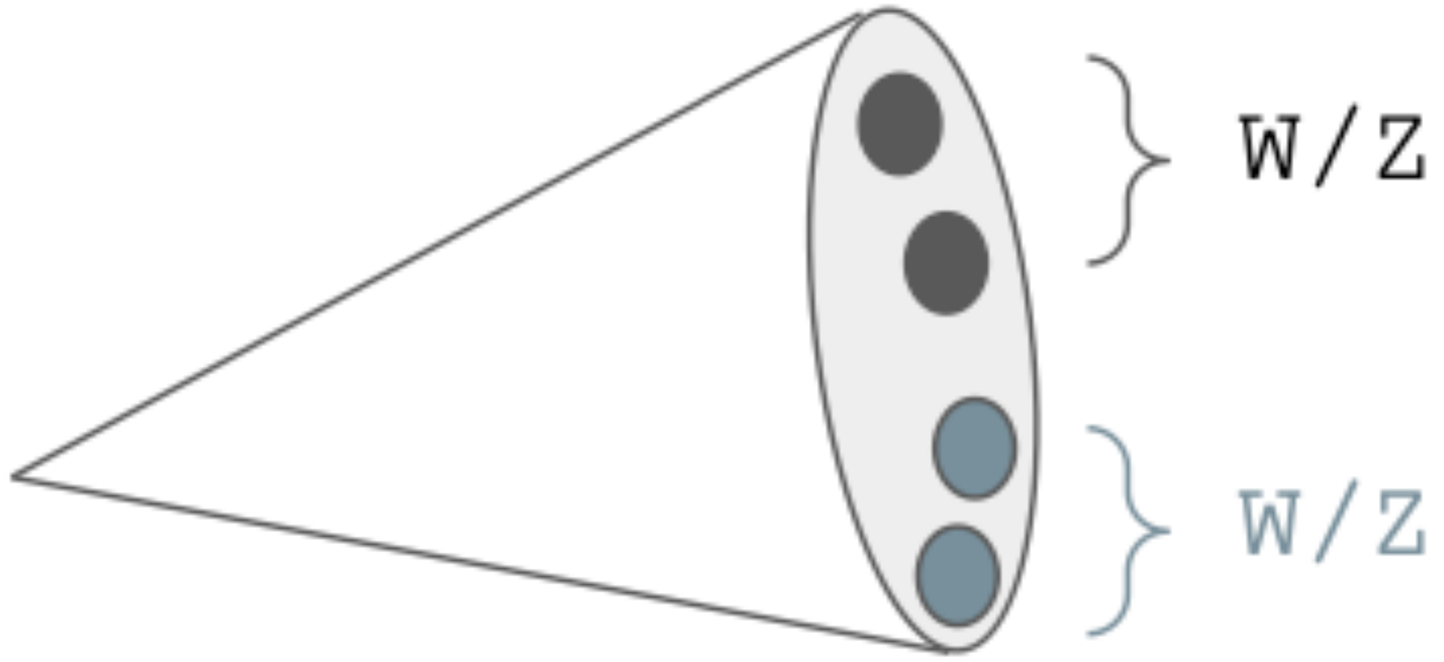


Today's focuses

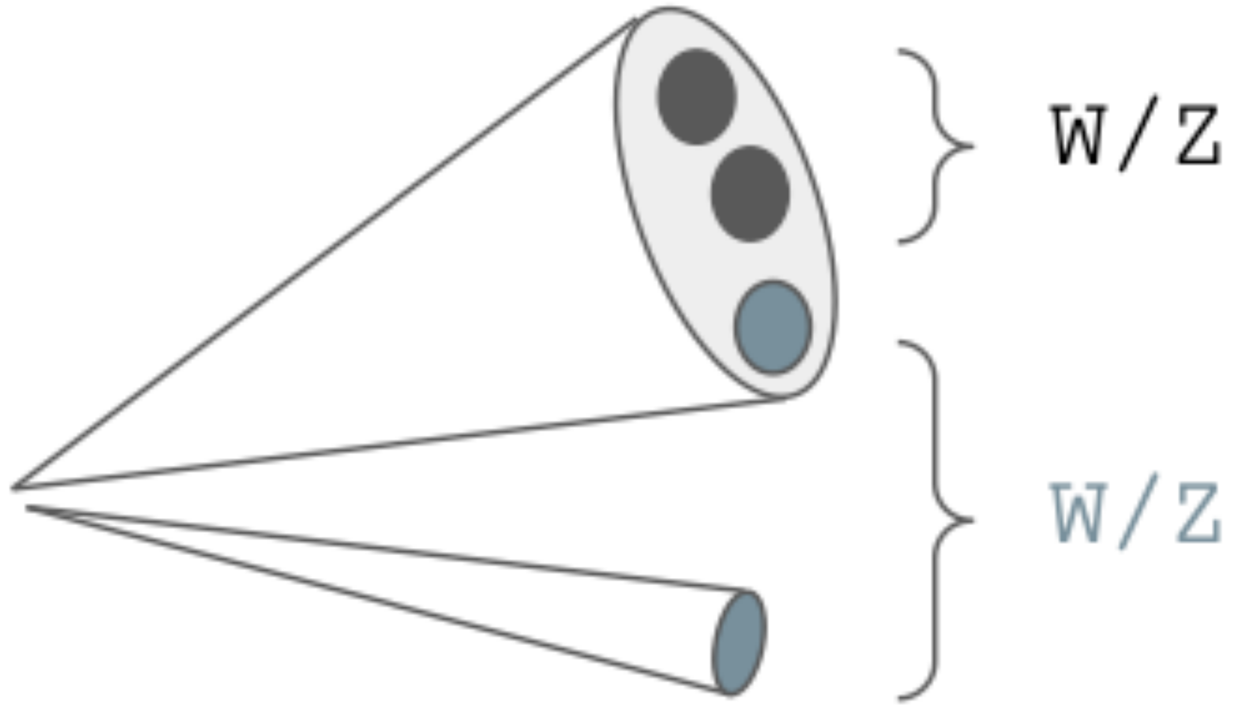
Mono-S to VV (had): Signal Reconstruction

- Signature: high missing ET (MET) + no lepton + busy final states
- MET > 200 GeV, lepton veto and N (small-R jets) ≥ 2
- $s \rightarrow VV \rightarrow qq'qq'$ reconstruction: conventional R=1.0 jets are good
  - Track-assisted-reclustering (TAR) jets are better: substructure computed from tracks associated to R=0.4 jets within TAR jet can help to improve the sensitivity up to 2.5





Merged: R=0.8 TAR
MET > 300 GeV



Intermediate: TAR + 1-2 R=0.4 jets
MET > 200 GeV

Mono-S to VV (had): Signal Reconstruction

Merged:

- ≥ 1 R=0.8 TAR jet
- p_T(TAR jet) > 300 GeV
- N-subjettinss comb.: 0. < τ_{42} < 0.3
- N-subjettinss comb.: 0. < τ_{43} < 0.6
- 100 GeV < m(TAR jet) < 400 GeV

Intermediate:

- R=0.8 TAR jet containing 2-3 prongs
  - + 1-2 R=0.4 jets
- s candidate:
  - TAR + Comb
- 100 GeV < m(TAR + Comb) < 400 GeV

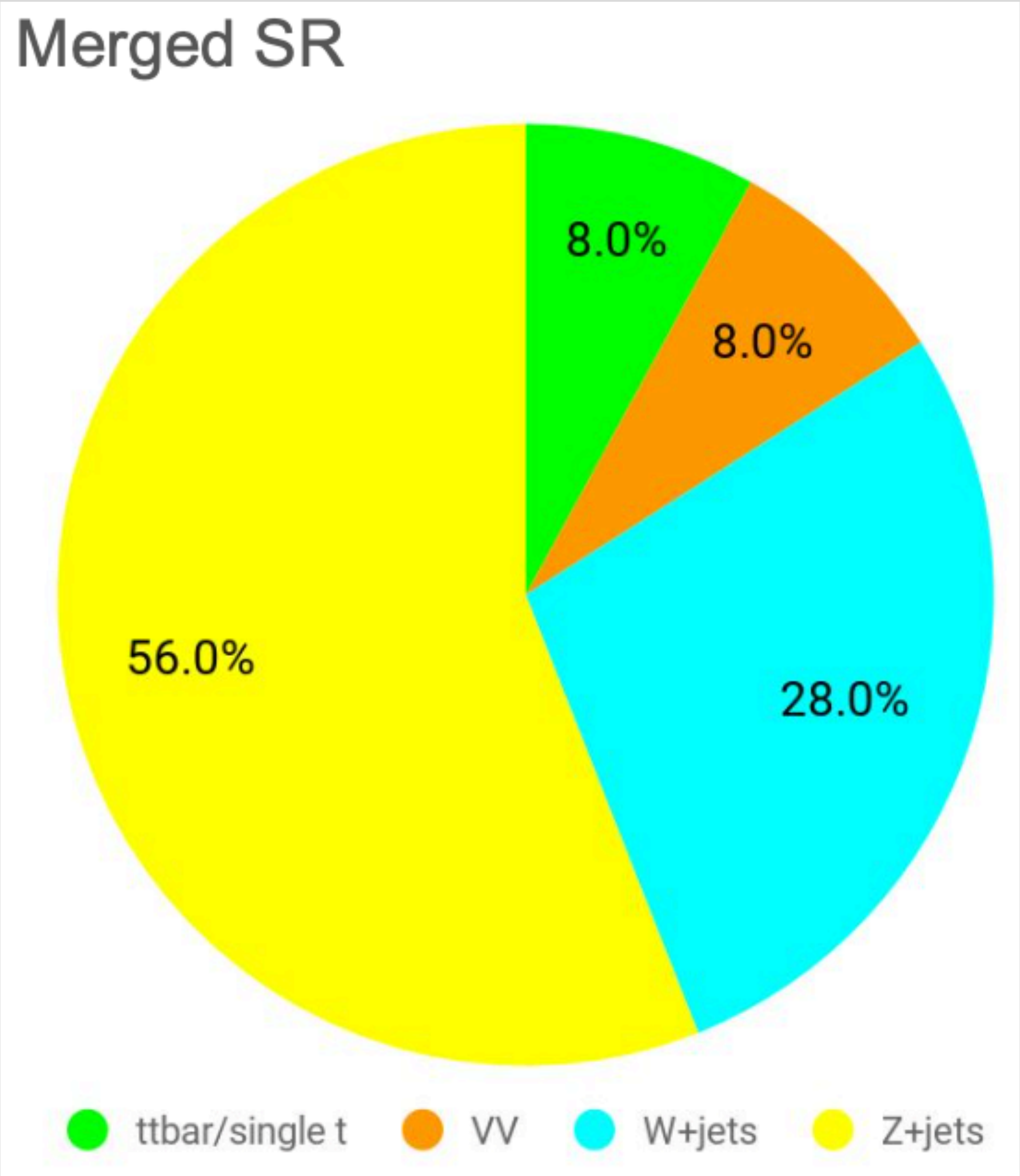
Priority	200-300 GeV	300-500 GeV	500+ GeV
1		merged	merged
2	intermediate		

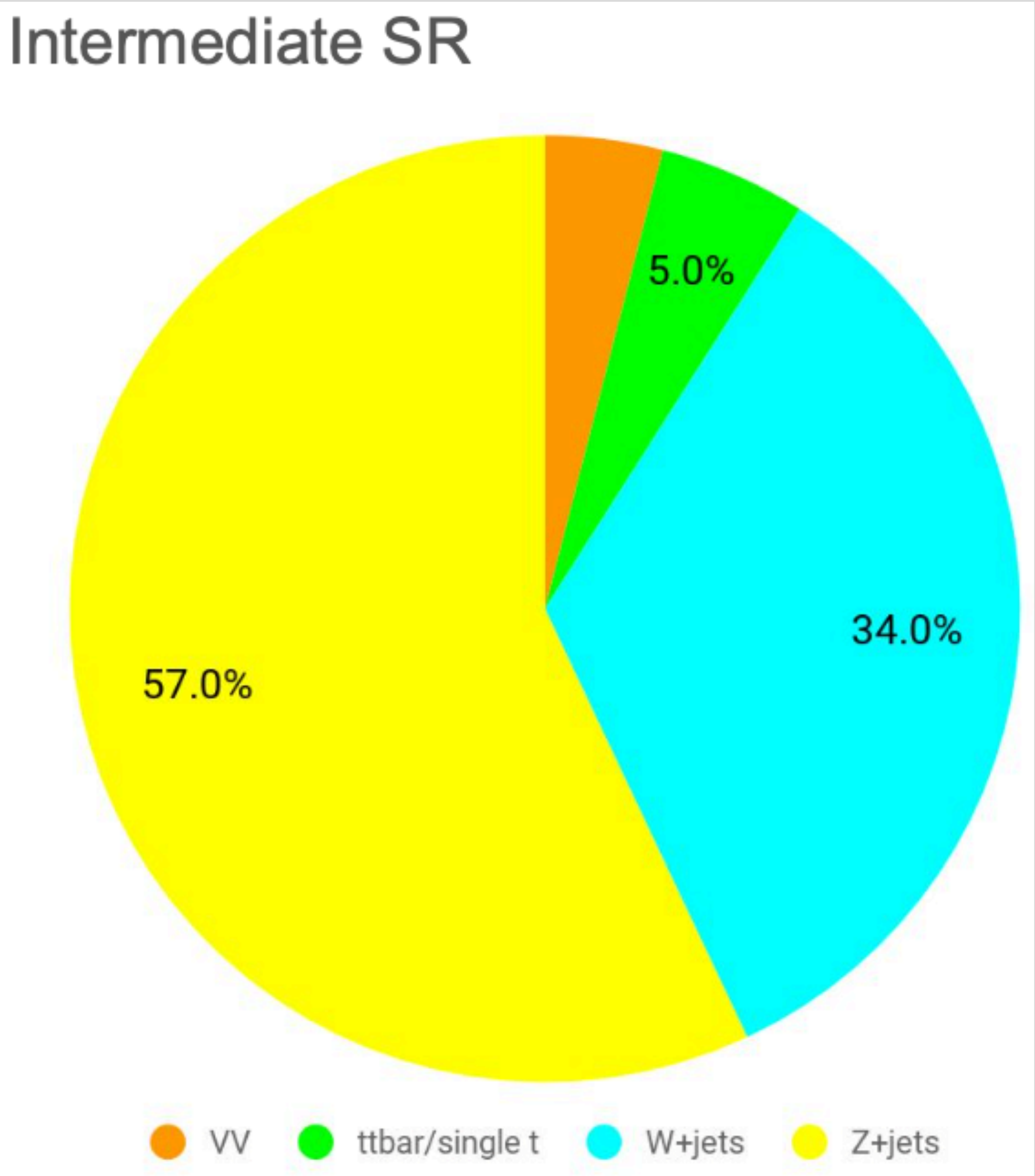
Mono-S to VV (had): Control Regions

Main backgrounds:

$Z \rightarrow \nu\nu$ + jets

W + jets





Constrained by the dedicated control regions (~90% purity)

- W + jets by 1-muon control region, MET proxy: $(E^{miss}+p^{\mu})_T$
- Z+jets by ee / $\mu^+\mu^-$ control region, MET proxy: $p(ll)_T$

Mono-S to VV (had): statistical analysis

- Profile likelihood fit on reconstructed mass
  - m(TAR jet) in the Merged
  - m(TAR + Comb) in the intermediate

0 lepton

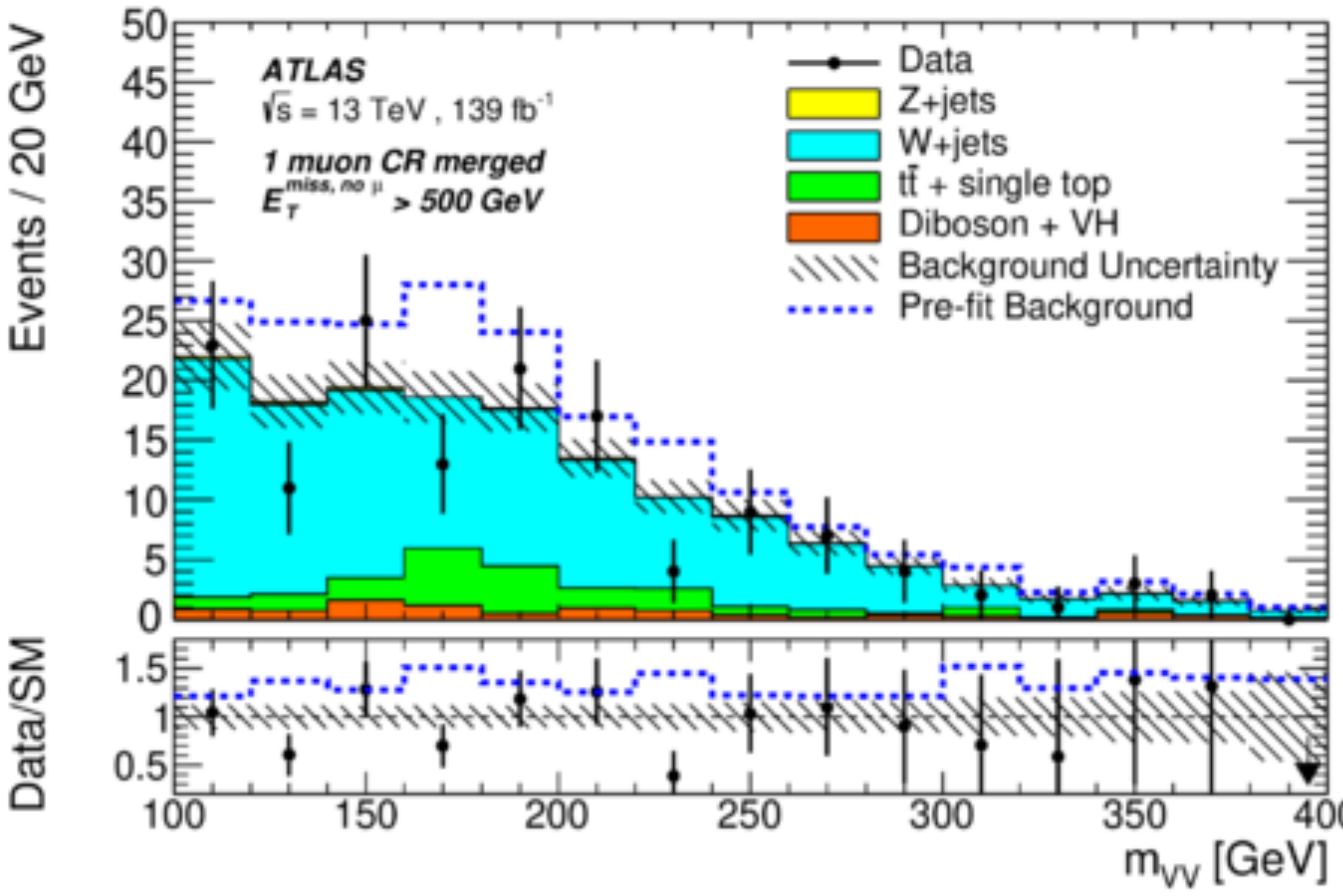
SR category	200 < MET < 300	300 < MET < 500	MET > 500
Merged	---	20 GeV mass bins	20 GeV mass bins
Intermediate		10 GeV mass bins	

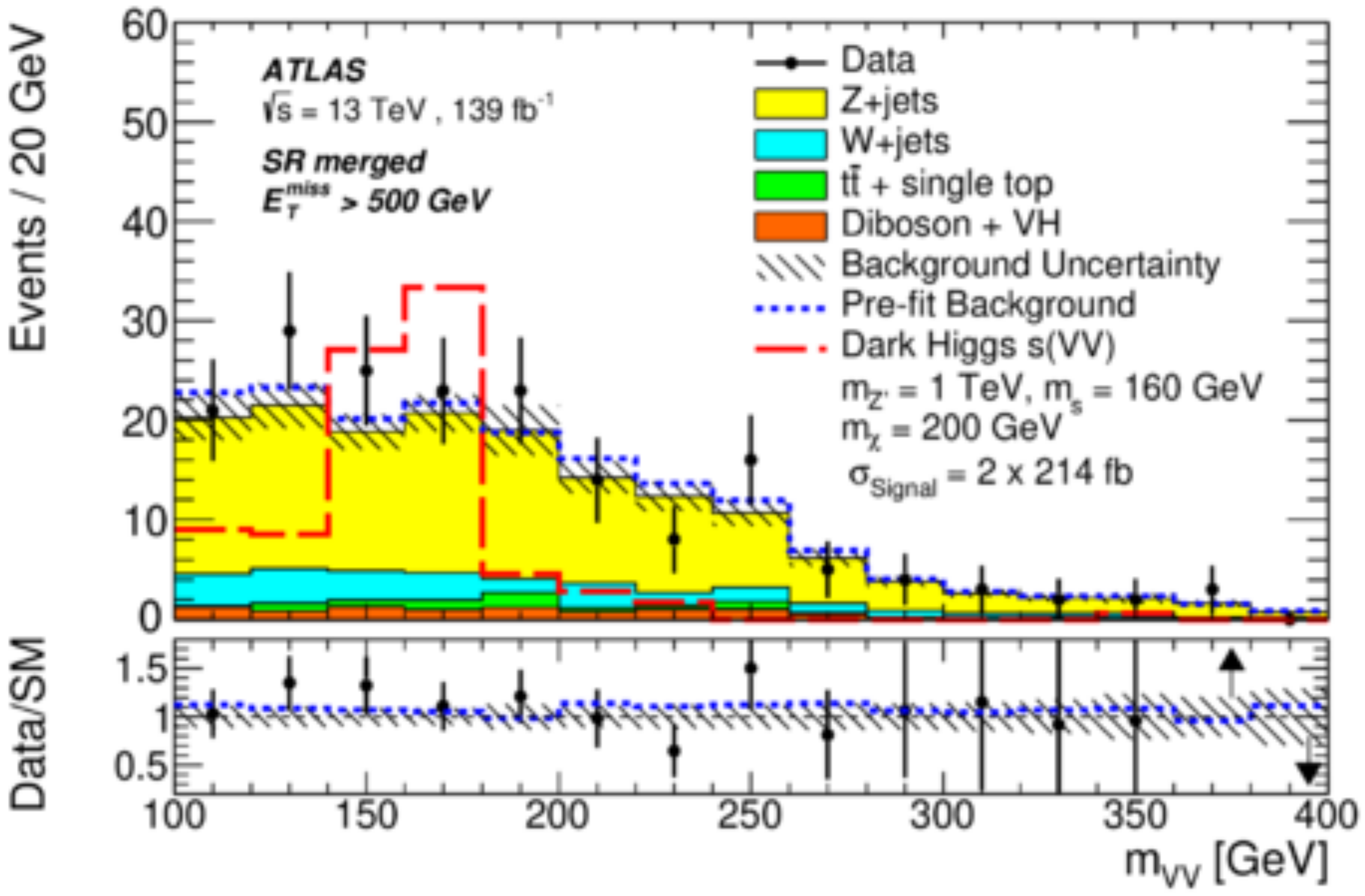
1 lepton

2 lepton

CR category	200 < MET proxy < 300	300 < MET proxy < 500	MET proxy > 500
Merged	---	1 bin	1 bin
Intermediate		1 bin	

Mono-S to VV (had): post fit m_{VV}





1 muon CR Merged
METproxy > 500 GeV

SR Merged
MET>500 GeV

Mono-S to VV (had): Systematics impact

(a) (b) (c)

s(VV) signal with $m_{Z'}$ = 1 TeV, m_s = 160 GeV, 235 GeV, 310 GeV

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

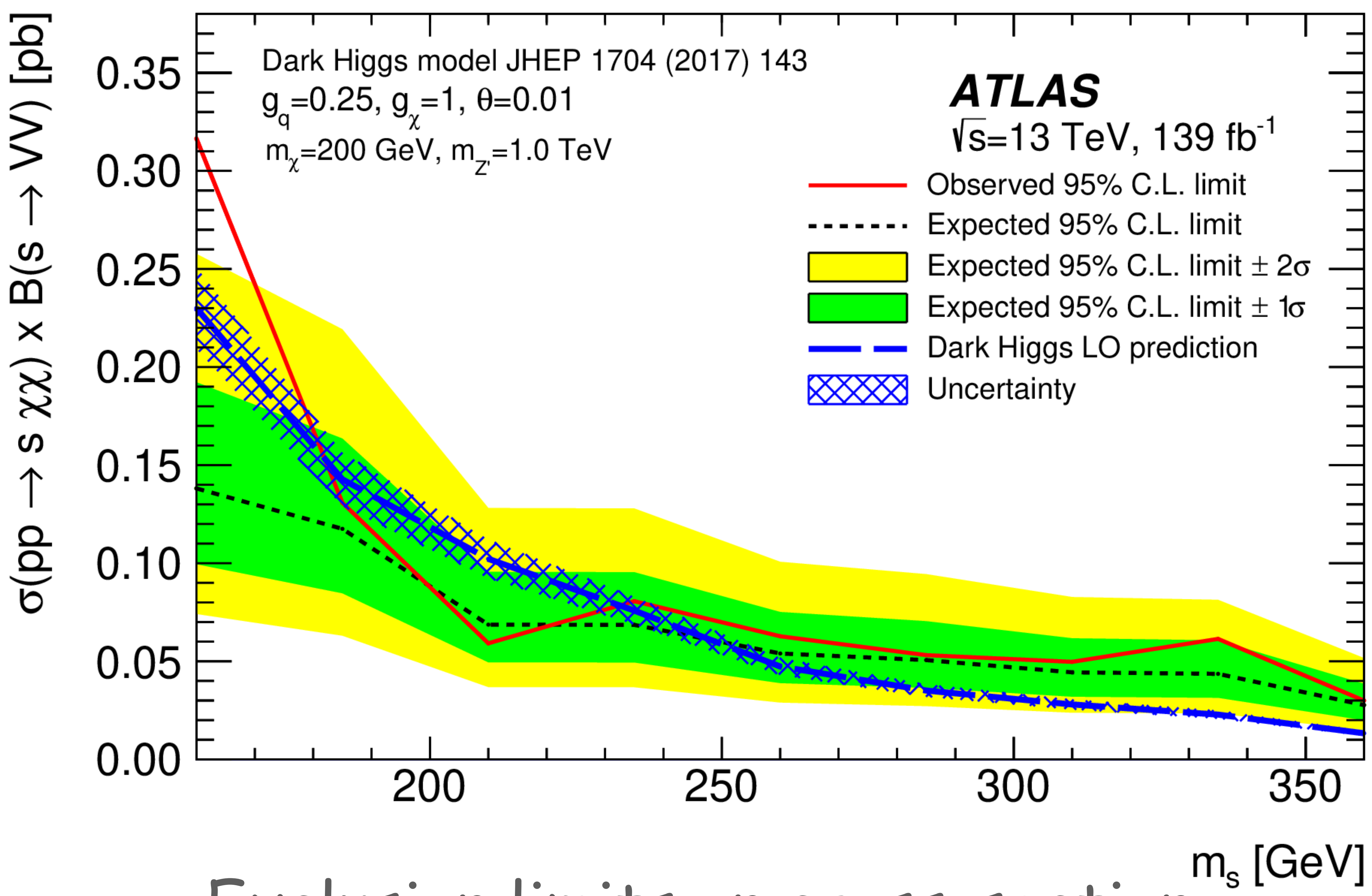
Impact on the above points

- Dominant:
  - JET
  - Signal modelling
  - V+jets modelling

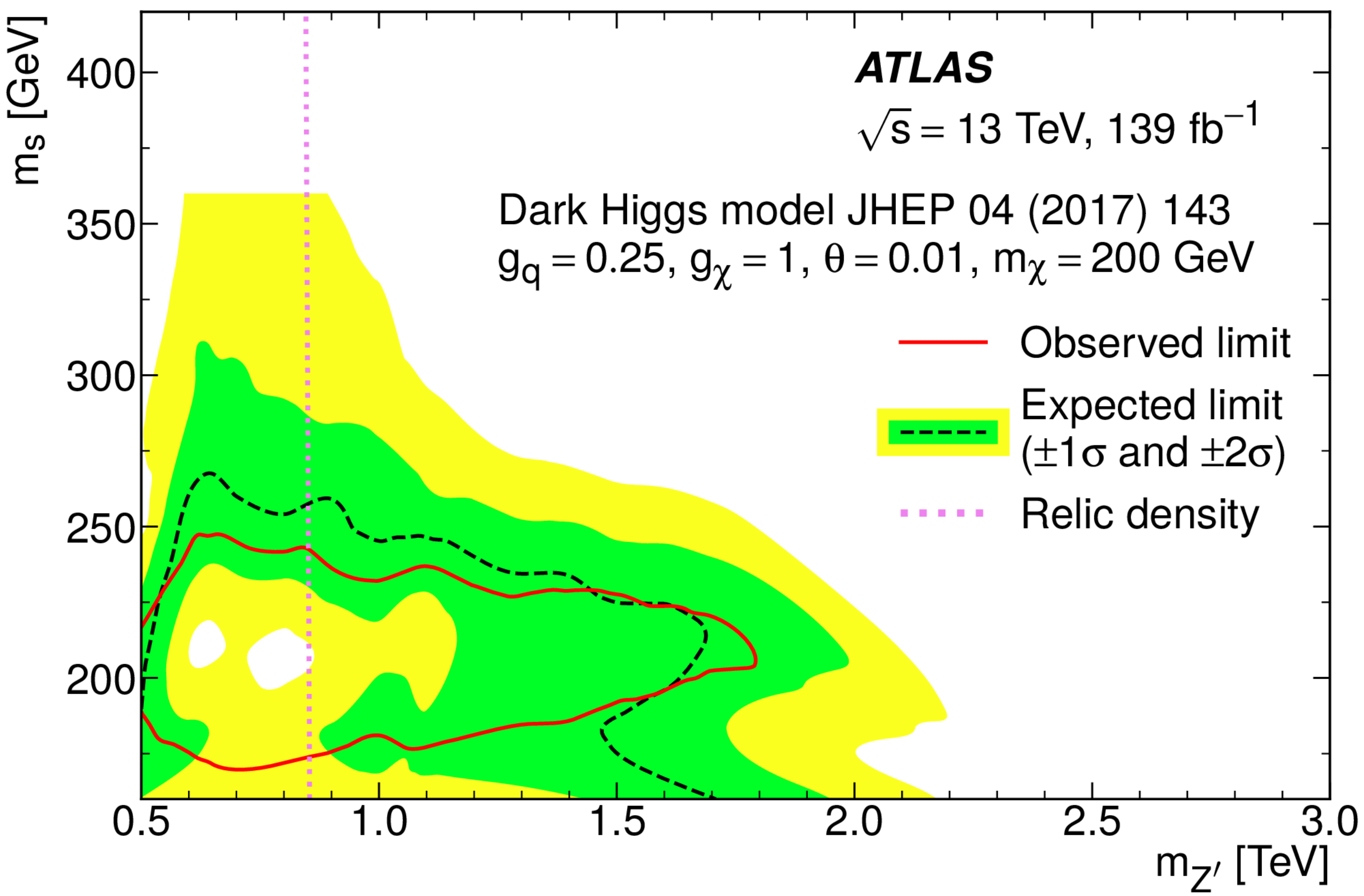
Analysis is systematics dominated

Mono-S to VV (had): Results

- Dark Higgs decaying to pair of hadronically decaying vector bosons investigated for the first time at the LHC, TAR technique used for the fist time at ATLAS



Exclusion limits on cross-section

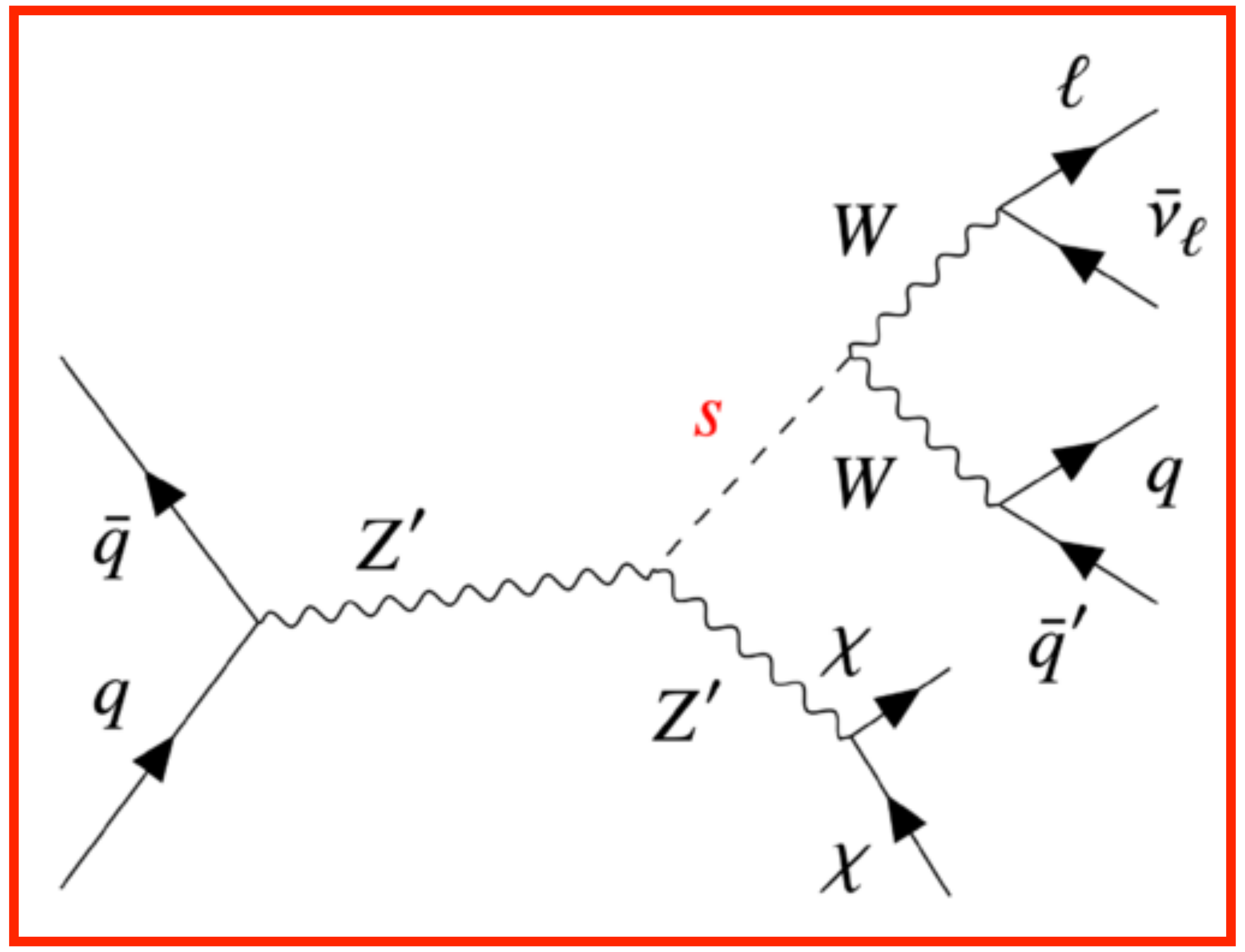


Limit contour for dark Higgs signals on $m_{Z'}$ - m_S plane

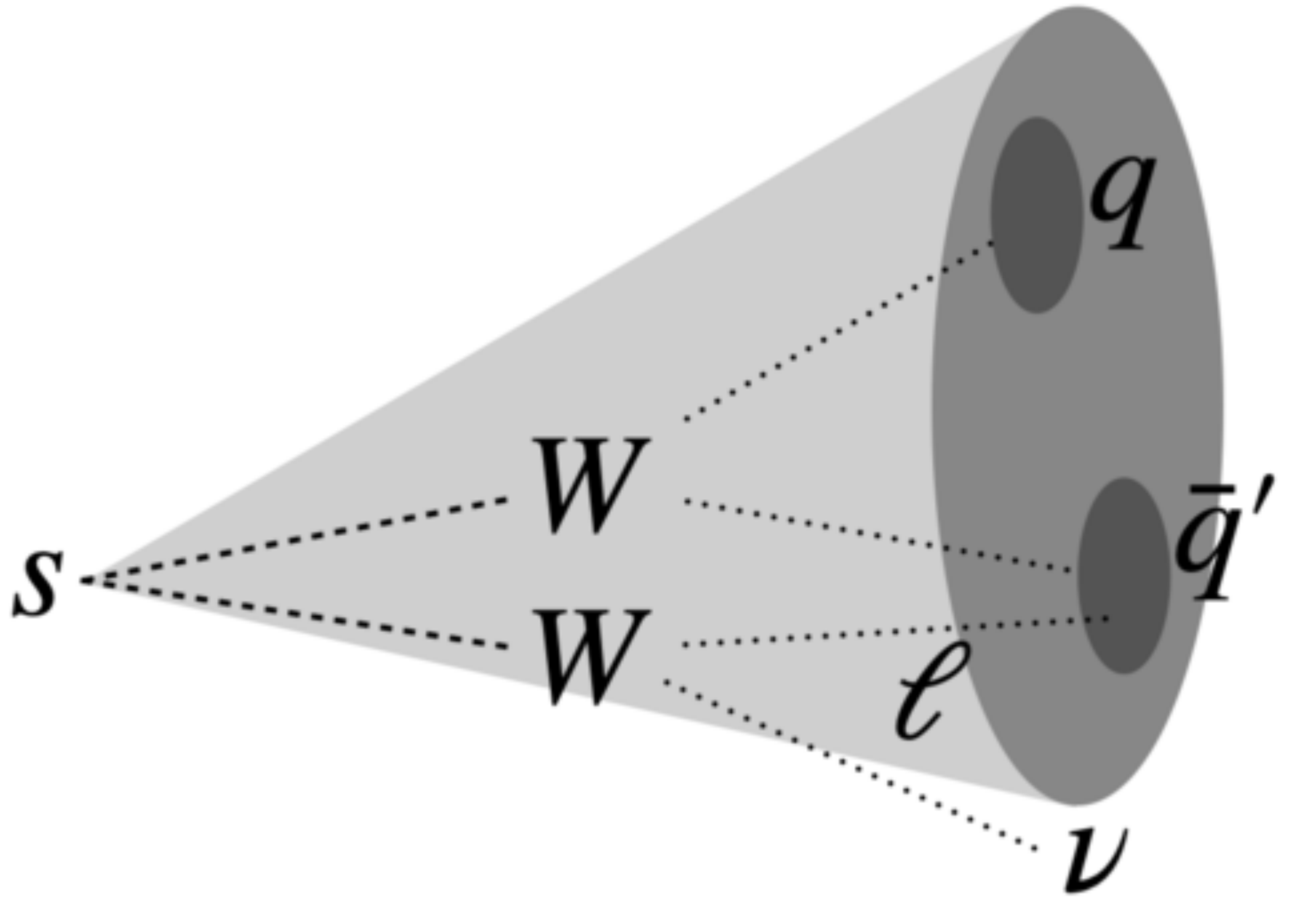
Mono-S to VV (Semilep): overview

Semileptonic channel

- Advantages:
  - Higher cross-section than fully-leptonic
  - cleaner signature than fully-hadronic

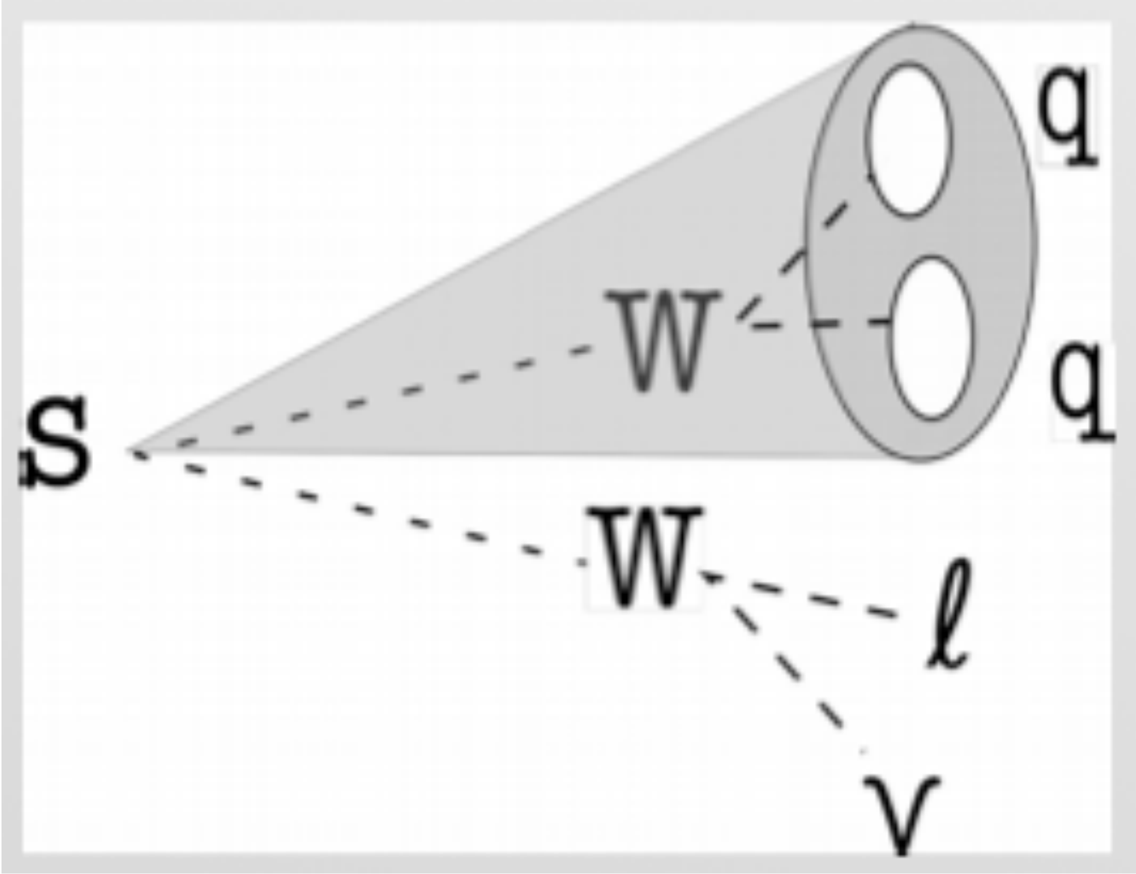


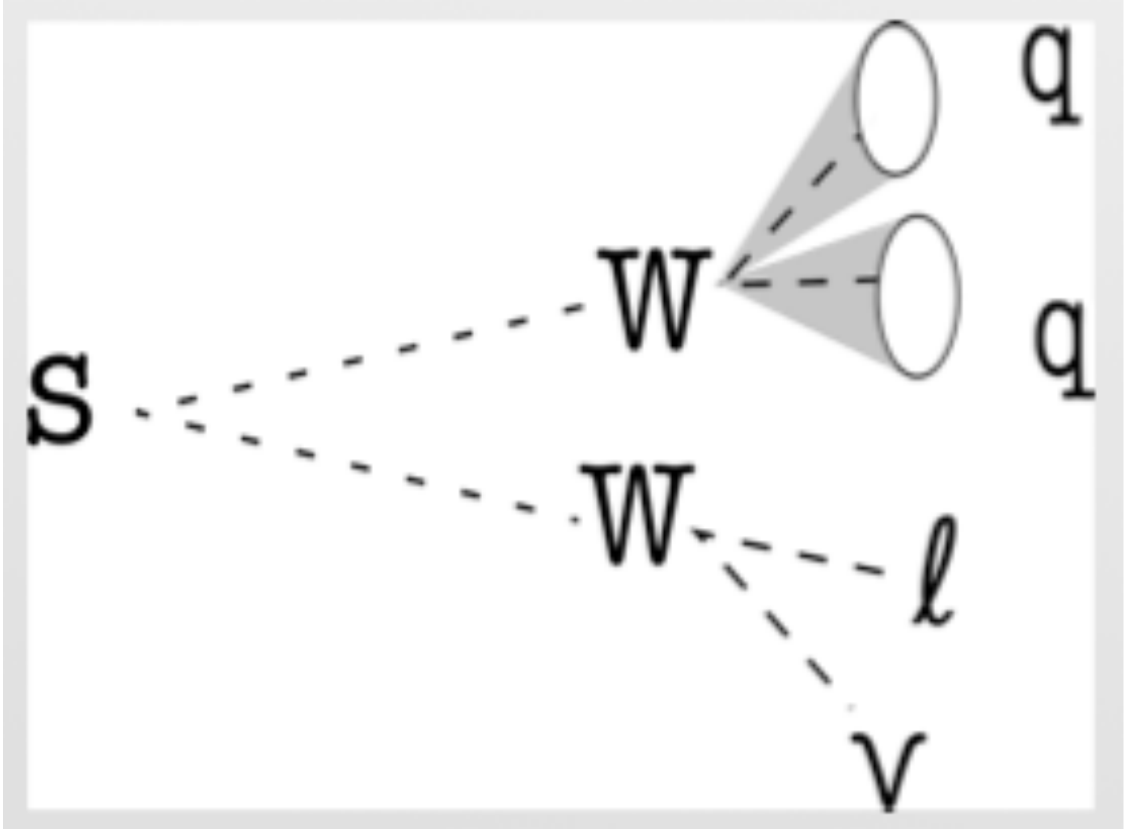
- Challenges:
  - 3 invisible particles, no possible for direct reconstruction
  - challenging W_{had} candidate reconstruction due to overlap with leptonic W decay products



Mono-S to VV (Semilep): Reconstruction

- Merged: dominantes the sensitivity
  - W_{had} candidate: TAR jet
  - TAR jets:
    - R=0.2 LC (R-scan) jets as input
    - R=1.0 AntiKt Algorithm
- Resolved: supporting role
  - W_{had} candidate: two R=0.4 jets with mjj closest to m_W
  - Only consider events for the resolved category if they fail the merged criteria for the resolved category
- W+jets, diboson and ttbar are the dominant Bkg
  - The dedicated CR, W+jets CR and ttbar CR

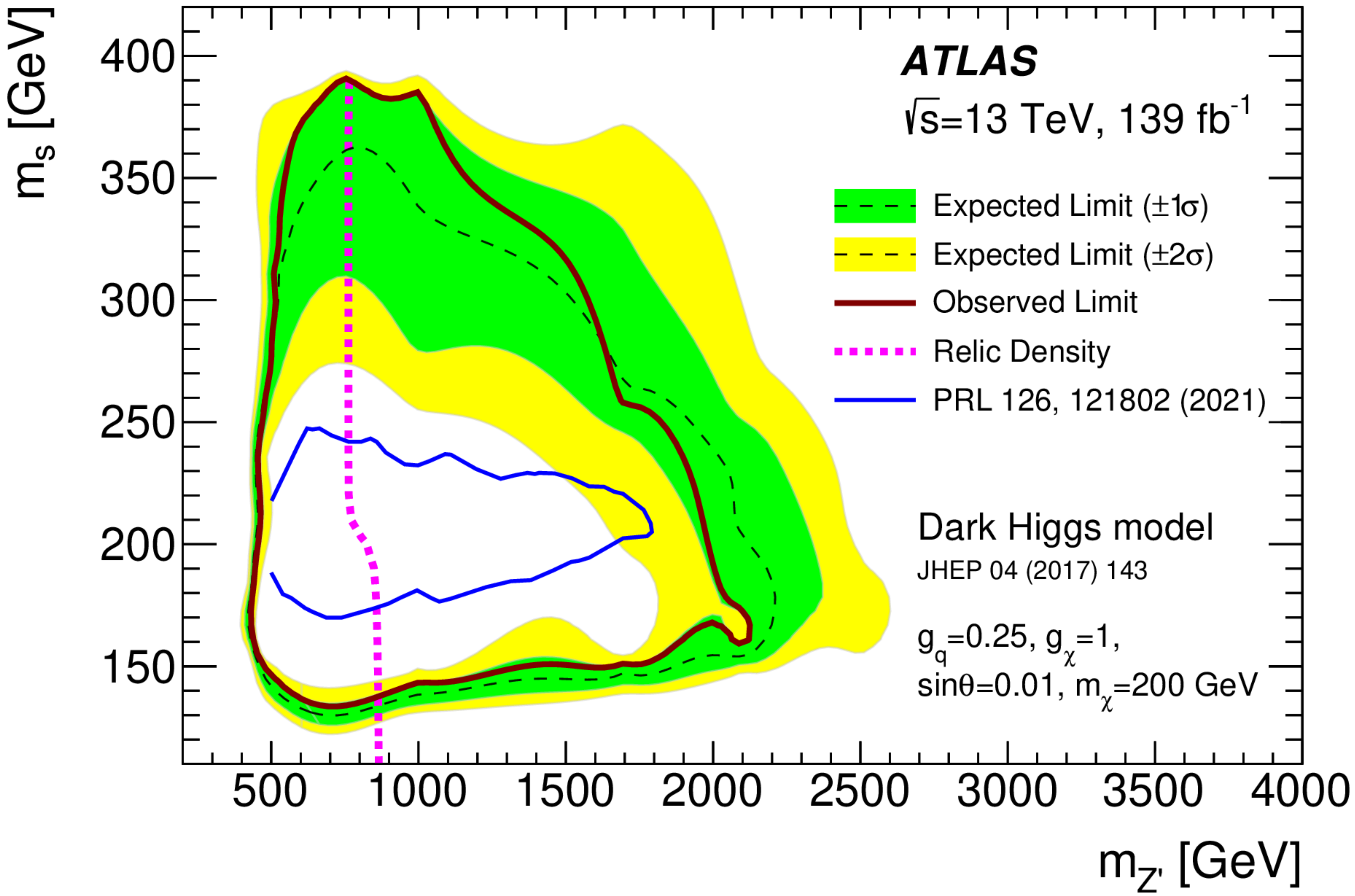




Mono-S to VV (Semilep): Results

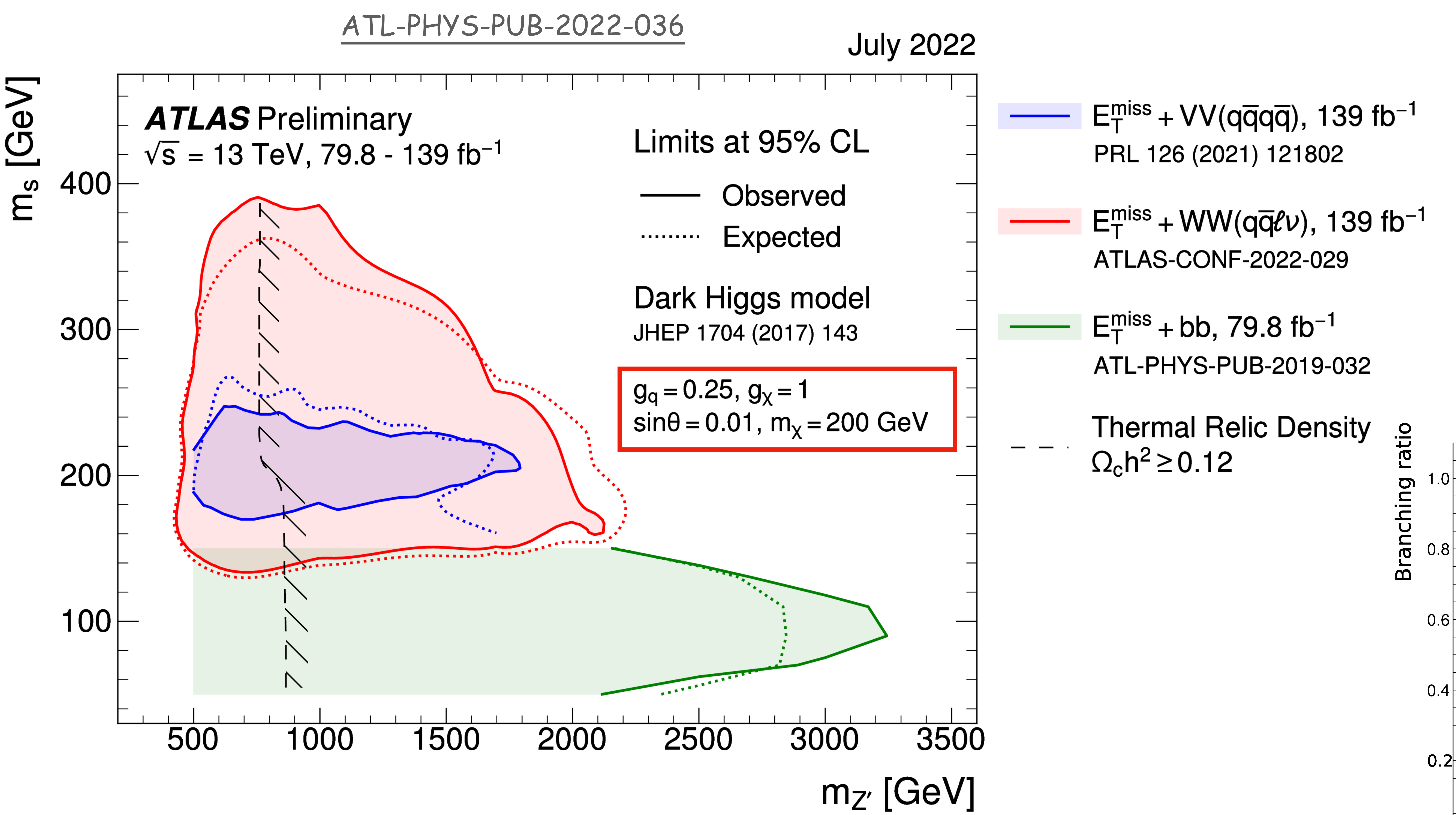
- MC stat. (mostly W+jets) and jet uncertainties are the leading systematics

- Total Syst. uncertainty (incl. MC stat.) is comparable in size to statistical uncertainty

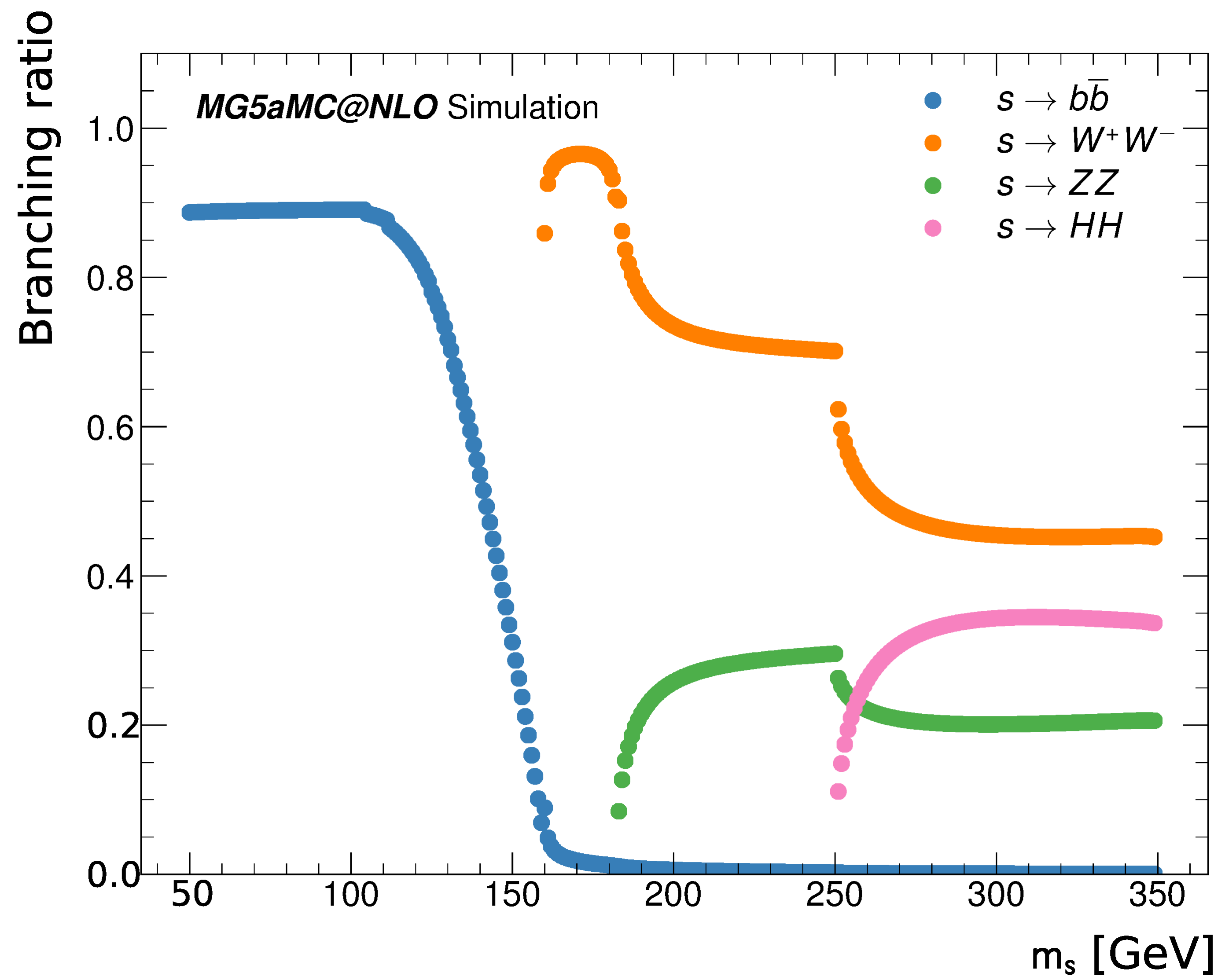


- The limits can be extended for high and low dark Higgs masses compared to the previous one

Beyond mono-S to VV



- Mono-S to VV (had)
- Mono-S to VV (Semilep)
- Mono-S to bb
  - dominate in low m_S



- ATLAS has an on-going monoSbb analysis with full Run-2 data

Drawbacks of the current interpretation

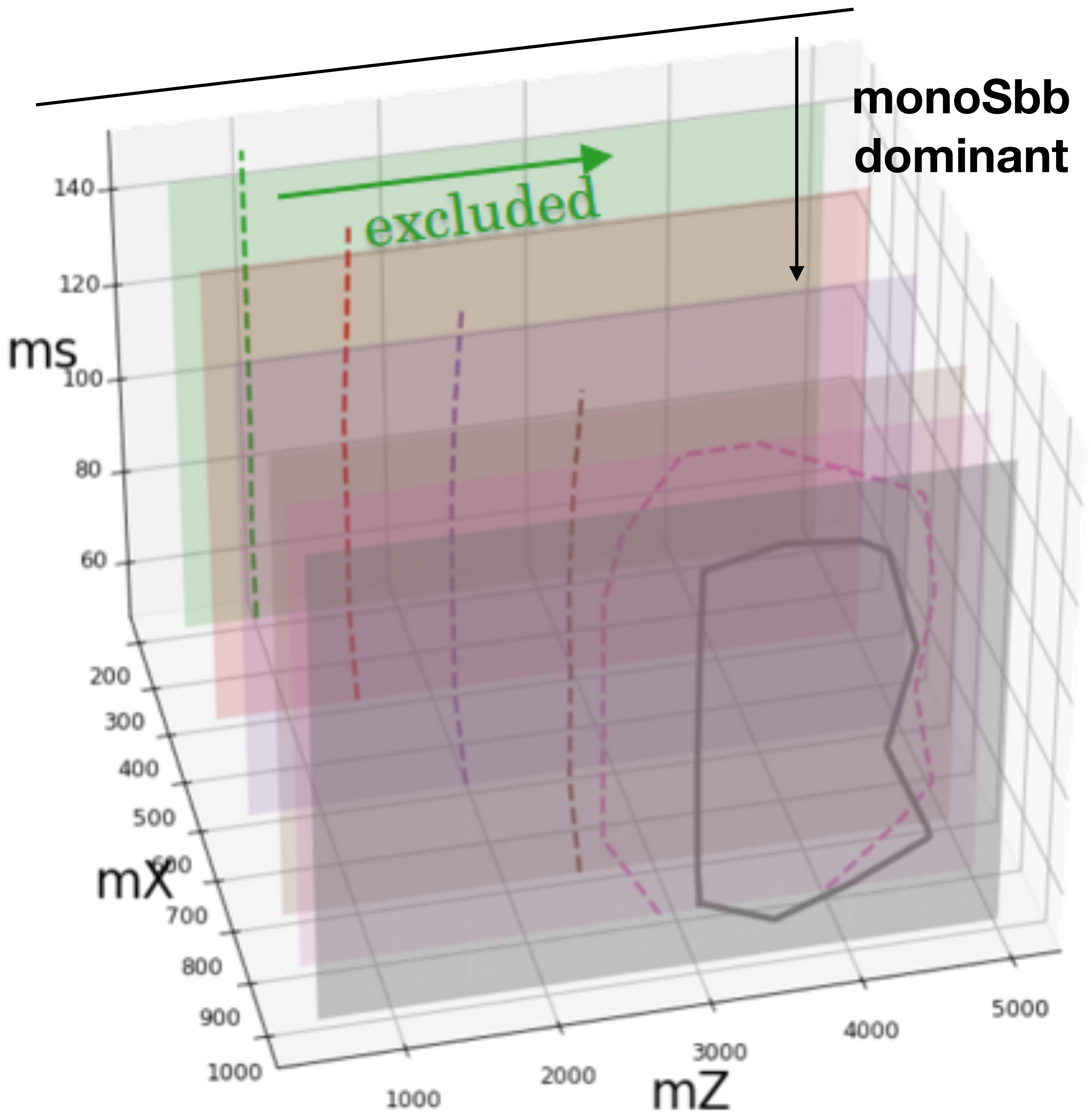
- We have limited ourselves when fixing
  - g_q = 0.25 and g_χ = 1.0

- This has important drawbacks:
  1. The observed DM relic abundance only reproduced for certain combination of the masses of the particles in the dark sector

  2. The couplings combination adopted so far is excluded by di-jet resonances for a wide range of Z' masses

Reproduce the thermal DM relic abundance

- Could adjust the coupling and the masses to make the predicted relic abundance from thermal freeze-out to agree with observations $\Omega h^2 \approx 0.12$, DM should not be overproduced
- g_q fixed 0.25
- g_X calculated from micrOMEGAs v4.2.5
- Update to the consistent coupling setup, the impact on the exclusion power is studied with monoSbb:
  - Background template from the existing analysis
  - Signal points generated with the MadAnalysis
- The mX should be increased to 900 GeV to have a close circle in current m_S, $m_{Z'}$ range.
- This introduces an additional interpretation
  - Still on m_S, $m_{Z'}$ plane with observed relic abundance consist g_X



Interpretation on mX-mZ'

- Proposed by the pheno. paper, has unique sensitivity
- Also tested with the approach introduced before (right)

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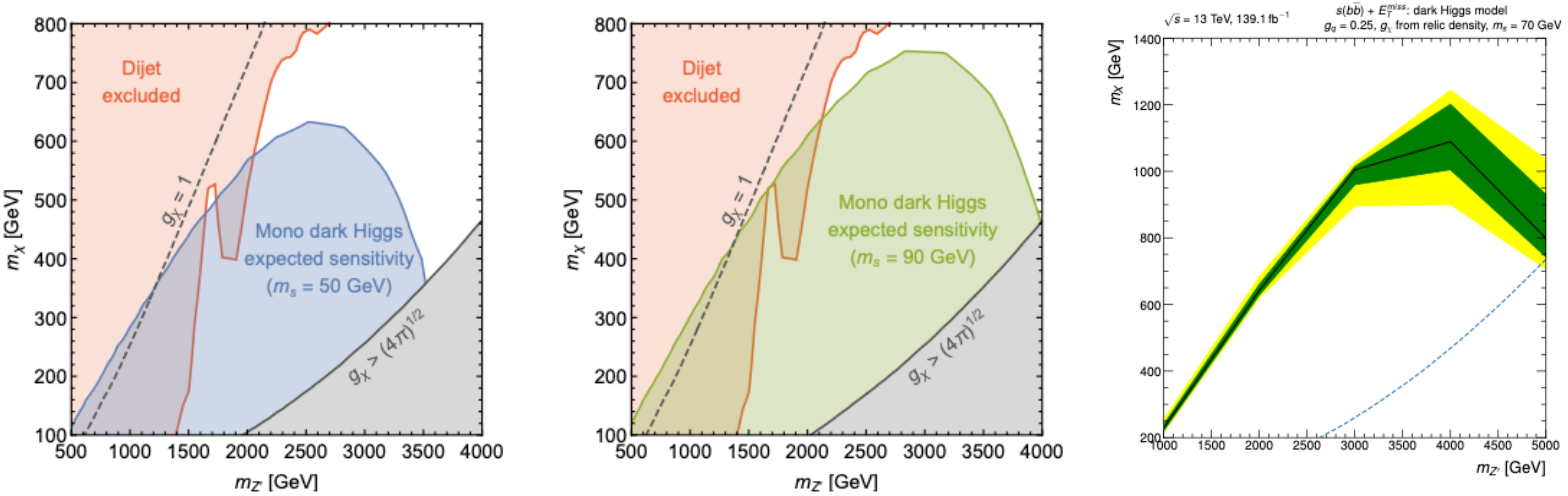
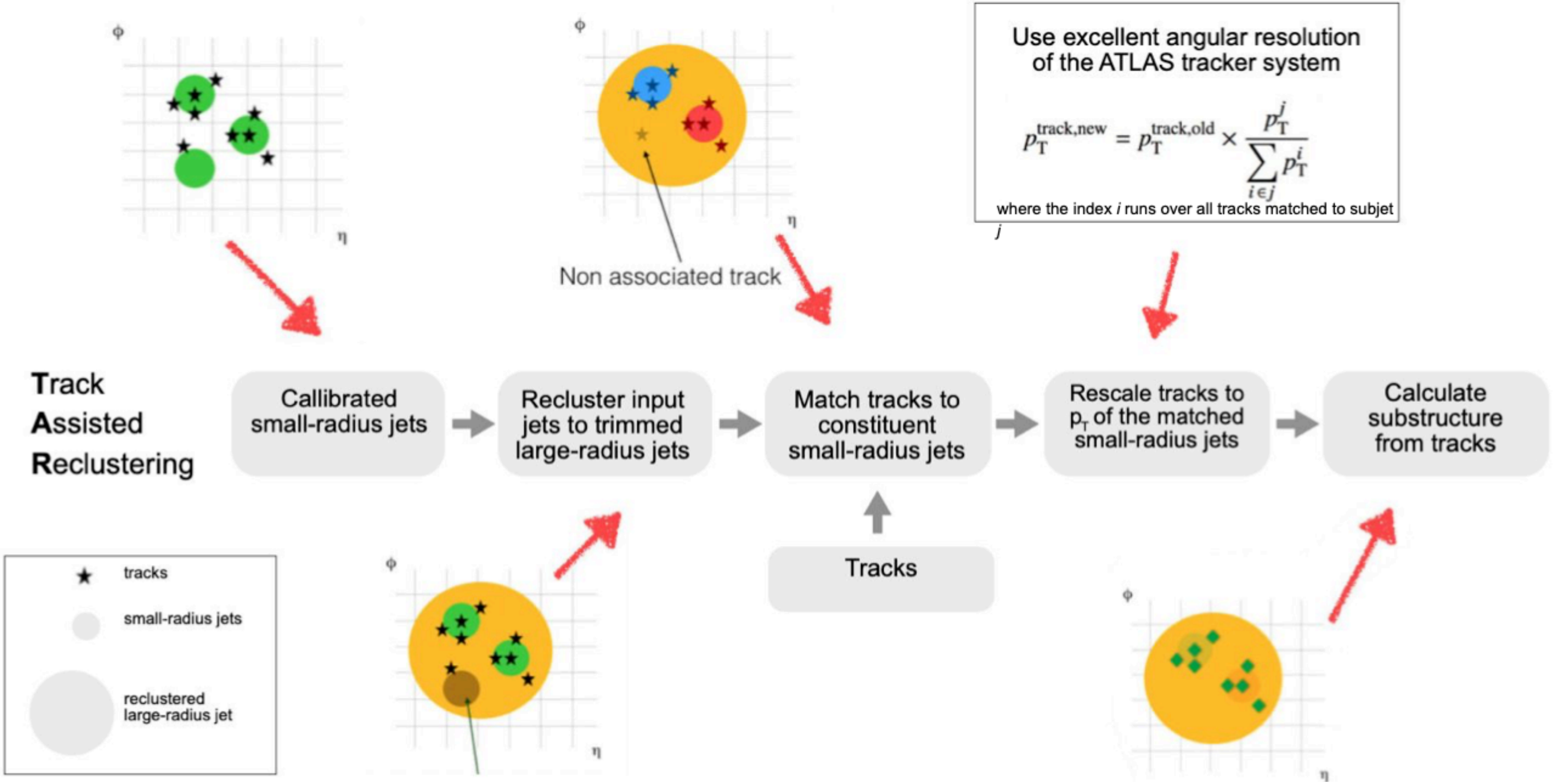


- Both two additional interpretations will be studied in the on-going full Run-2 monoSbb

backup

TAR jets: flexible jets with precise jet substructure



SL8 of Philipp's talk

Analytical solution of S->WW->qqlv system

- Find minimum ms consistent with observed Whad and lepton momenta and mW = 80.4 GeV constraint.

- Use a rotated frame of reference with lepton along z-axis and hadronic W in x-z plane.

- m_s^{min} occurs at $\varphi_\nu=0$
- Solve numerically for $\theta_{l\nu}$ subject to $m_{l\nu}$ constraint