Searches for dark matter with the ATLAS and CMS detectors

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on behalf of the ATLAS and CMS collaborations

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DM at LHC

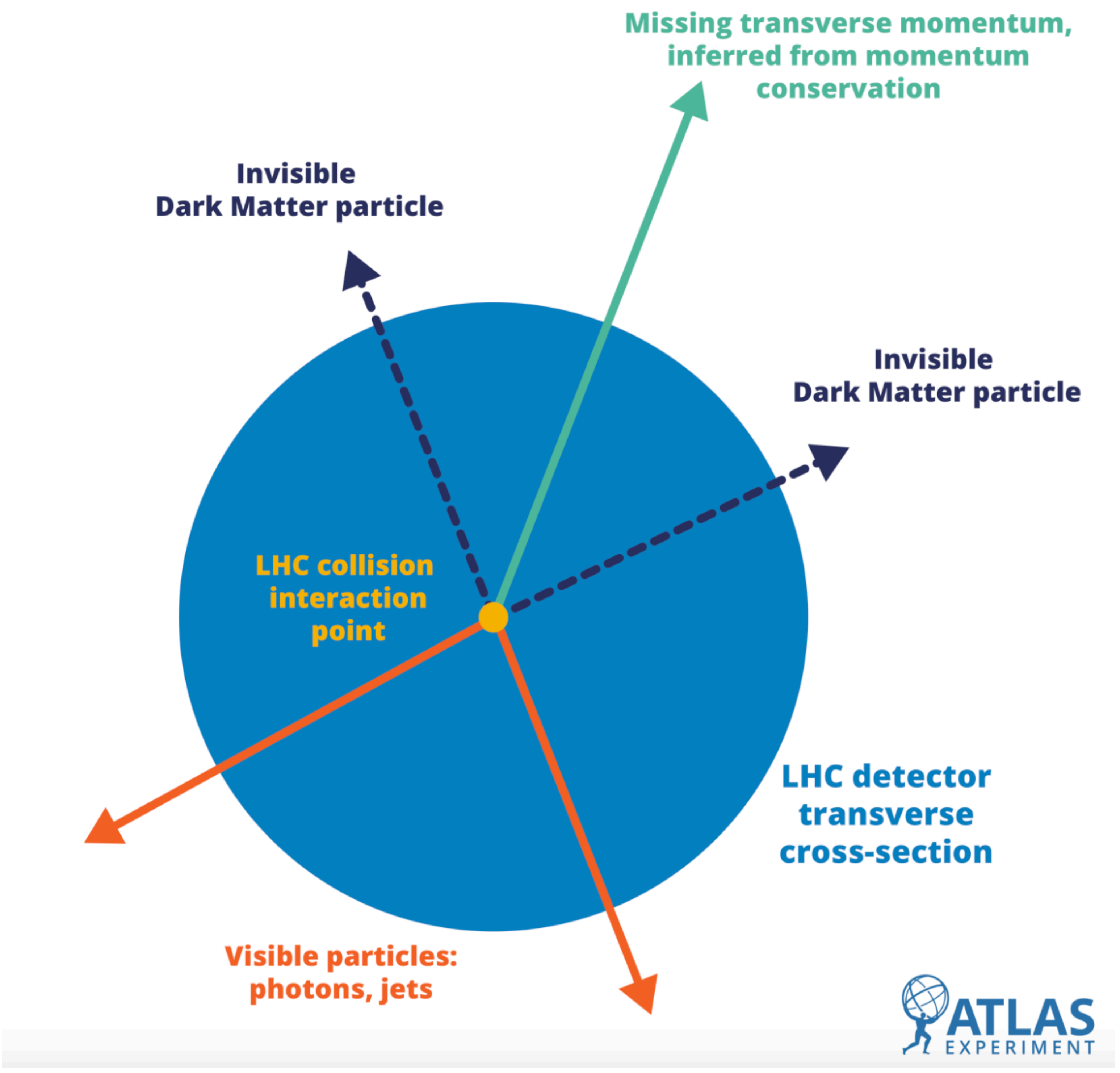
- Dark Matter (DM) is being thoroughly probed in both ATLAS and CMS collaborations
  - Covering a large amount of models, final states and parameter space….

- Dark matter particles cannot not be detected directly at the LHC

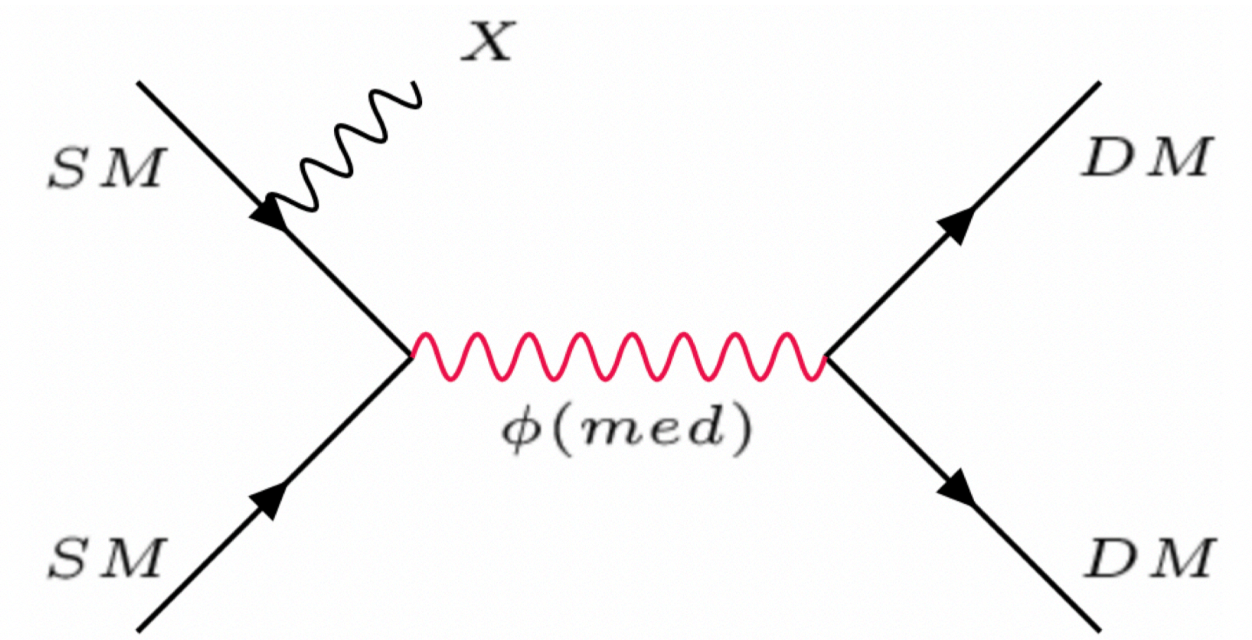
  (DM particle flux) × (interaction probability) just too low

  Instead: p_T miss = imbalance of detected particles

  Additional tag particles needed for detection



DM at LHC

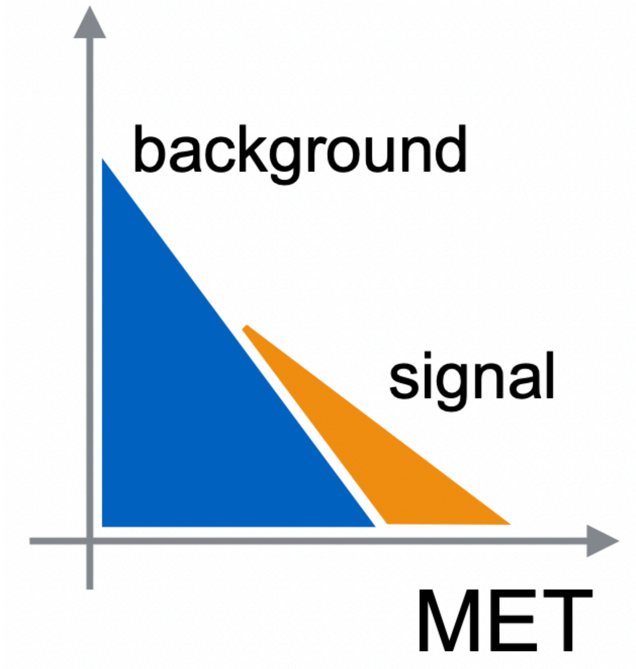


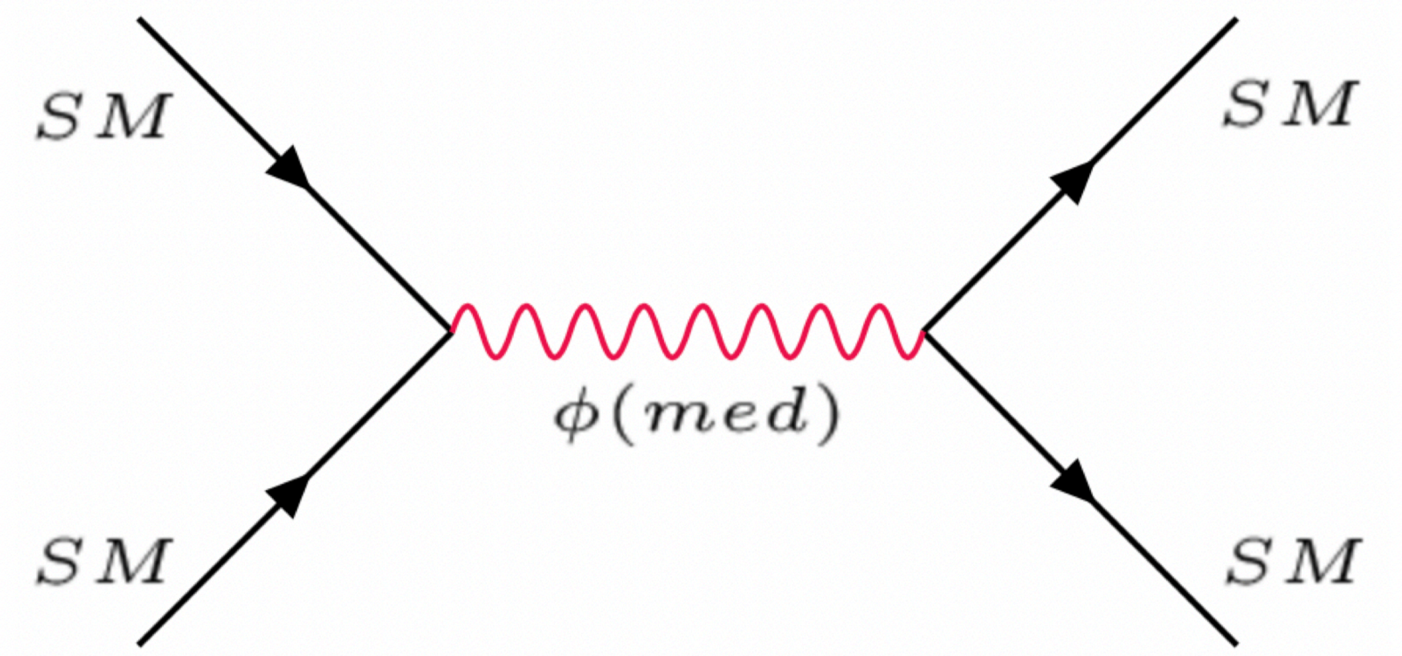
mono-X search

SM particles (jet, Z, γ, h) recoil against missing energy.

Tag from radiation or associated production.

Expect signal in the tail of missing energy distribution over the standard model background.

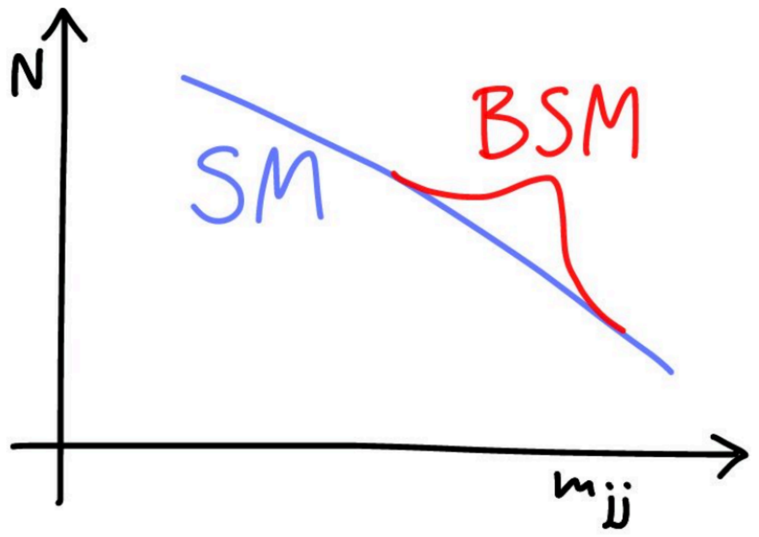




Resonance search

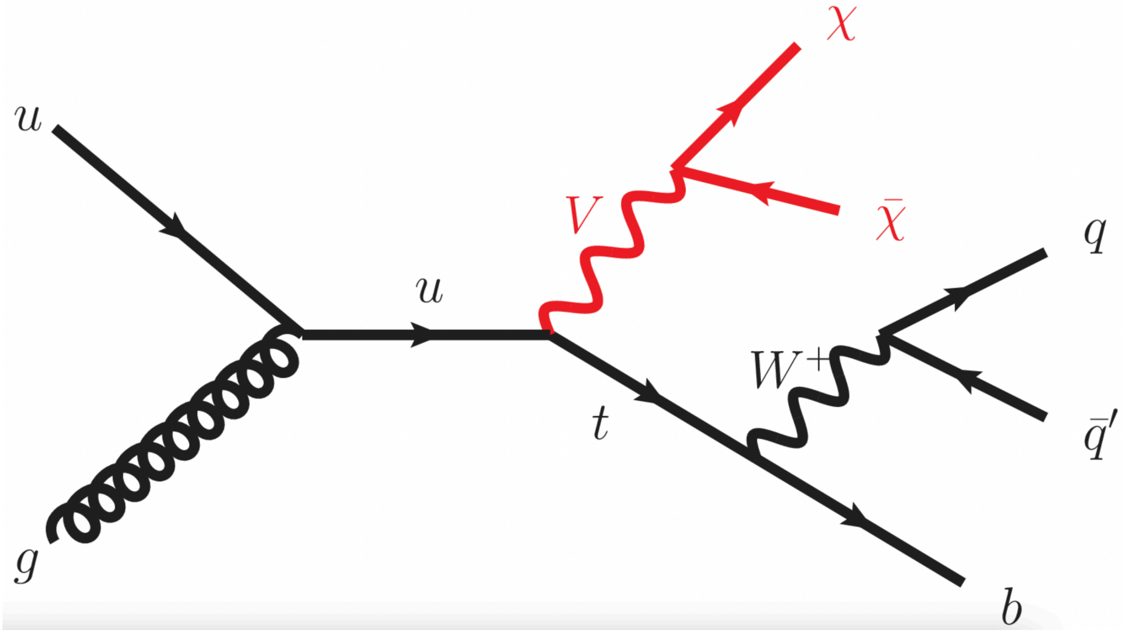
Mediator decays to visible SM particles.

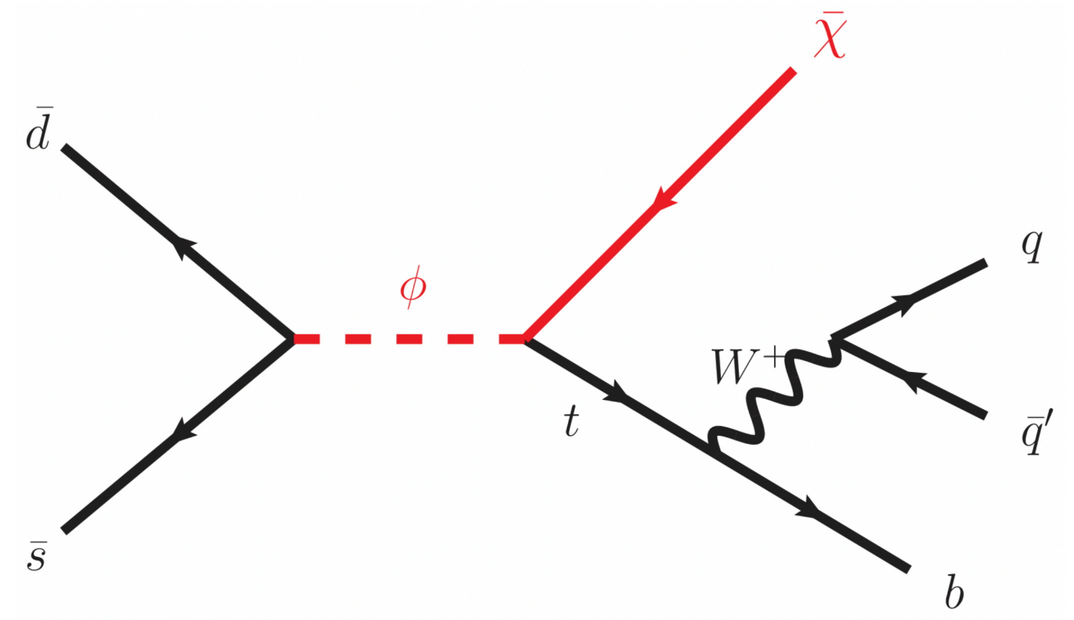
Expect signal peak in invariant mass of two visible final sate particle above the standard model background.



ATLAS: Mono-top

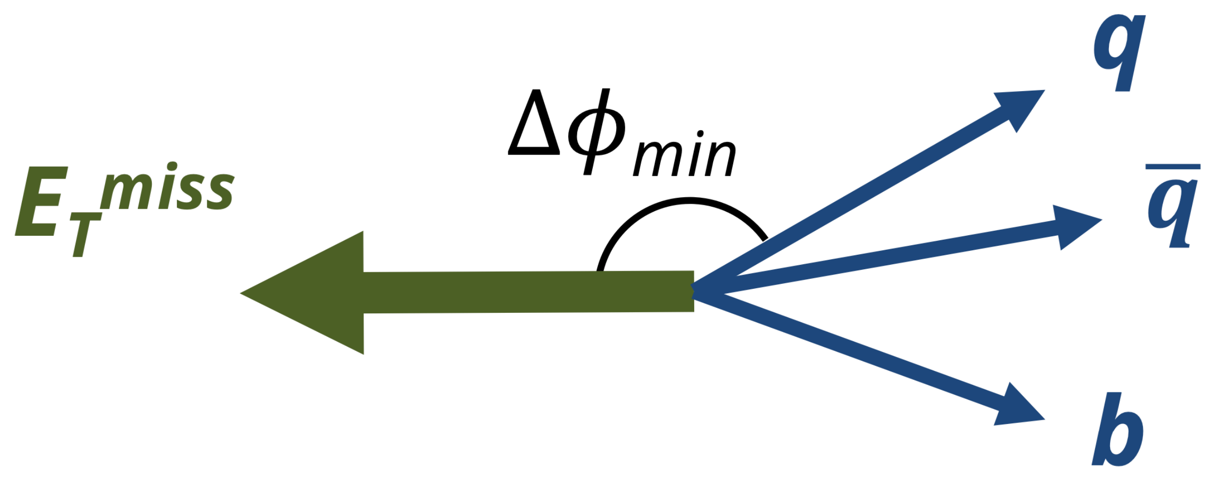
ATLAS-CONF-2022-036





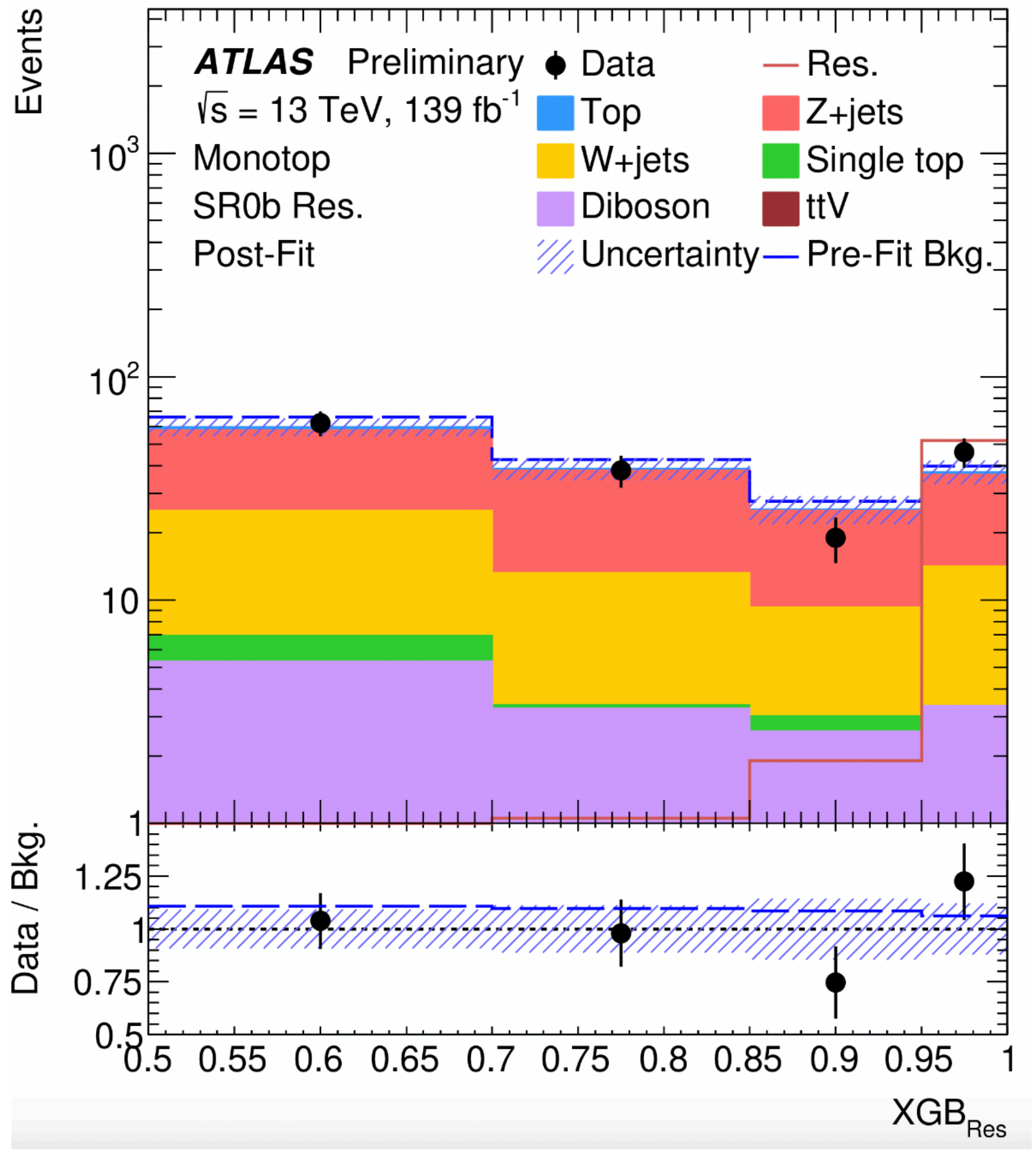
- Resonant and Non-Resonant DM production.
- $E_T^{miss} \geq 250$ GeV
- Exactly zero leptons (hadronic channel)
- At least one boosted large-R jet associated to the top quark → use top-tagging for S/B separation!
- Minimum angular distance in the transverse plane between the E_T^{miss} and any small-R jet $\Delta\phi_{min}$ is required to be larger than 0.2

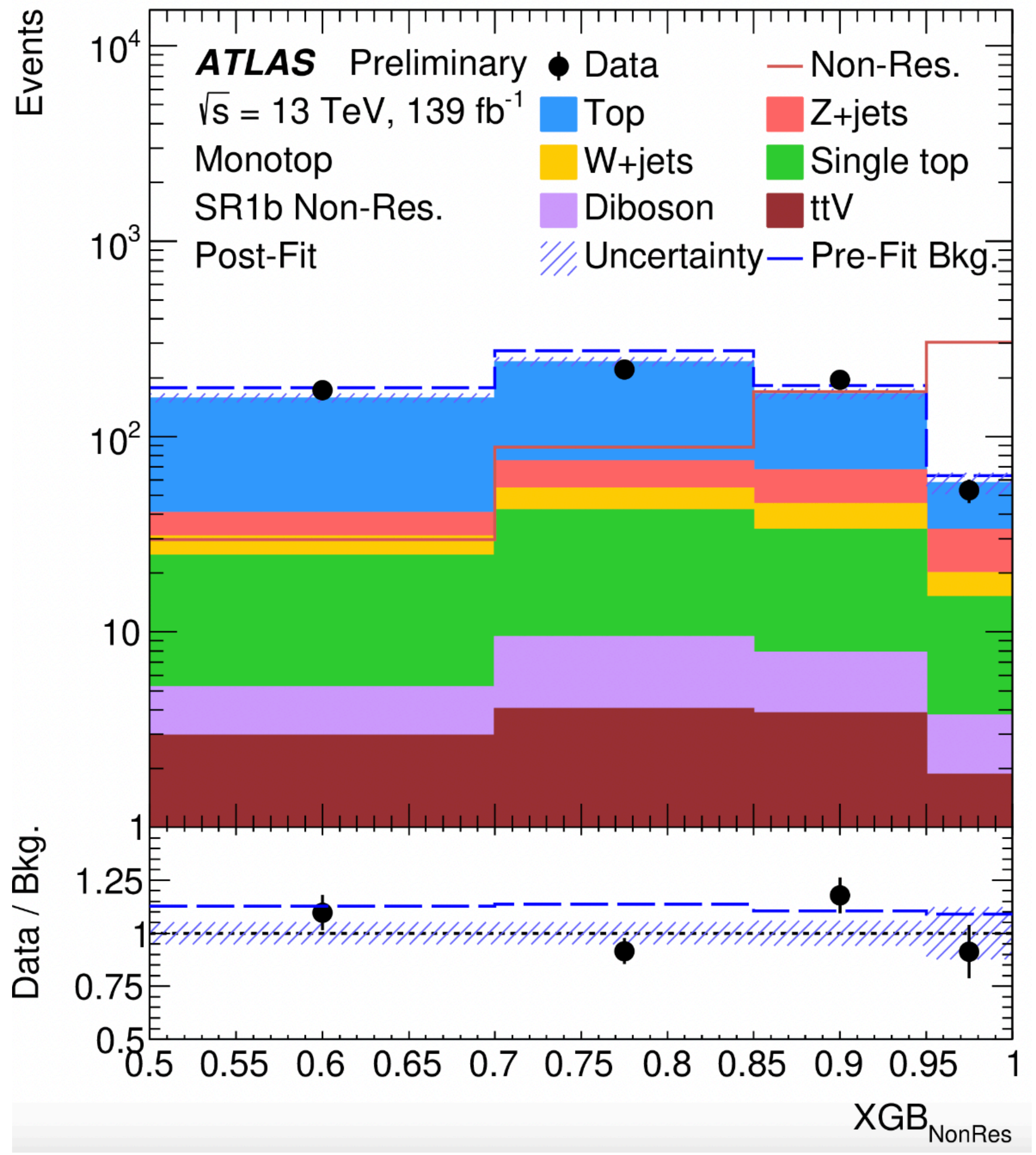
- Main backgrounds: ttbar and Z/W+jets →constrained in the control regions.
- A Multivariate Analysis (MVA) approach to discriminate signal (*XGBoost*): E_T^{miss} based variables and ΔR_{max} among the most important features in the training.

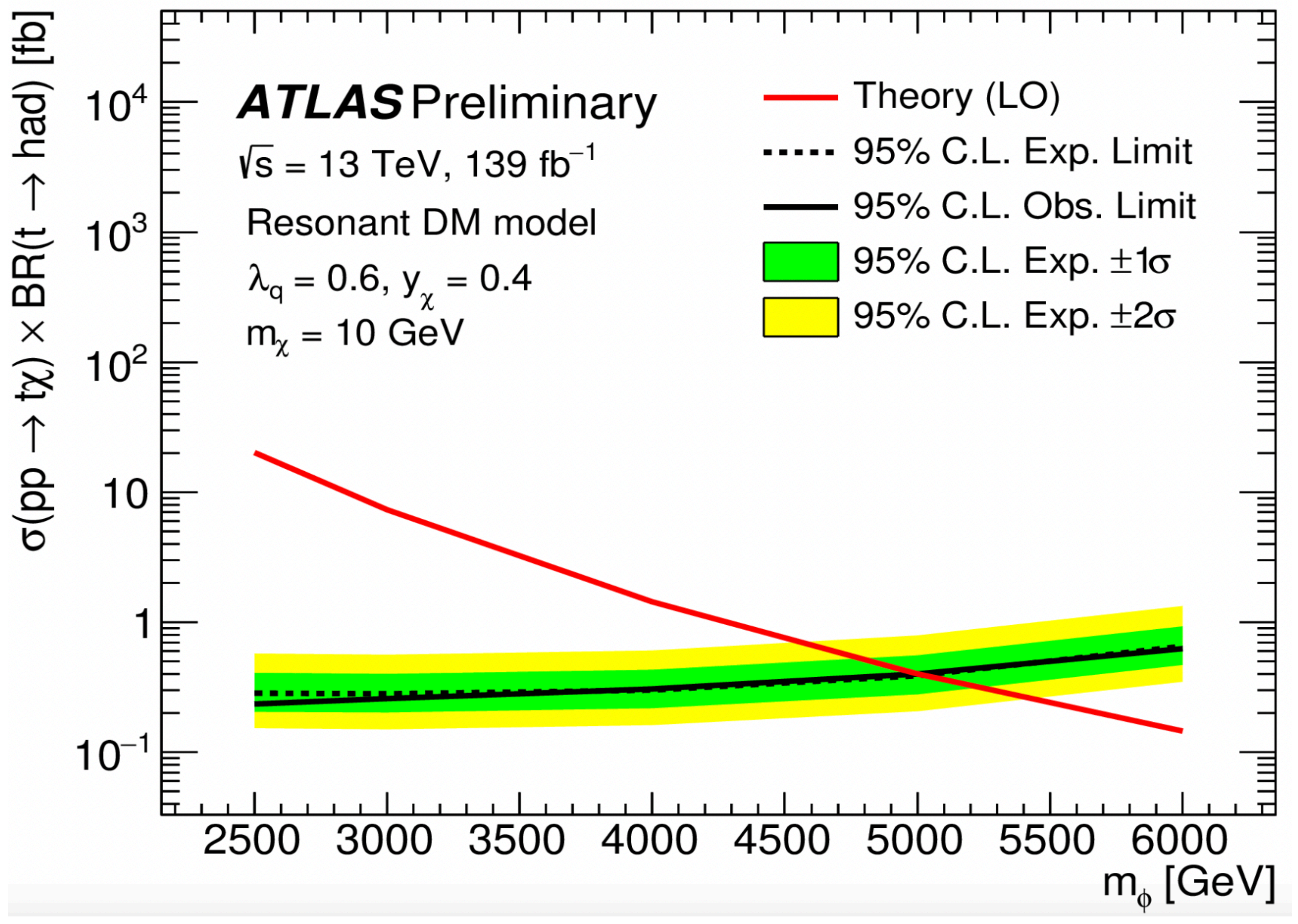


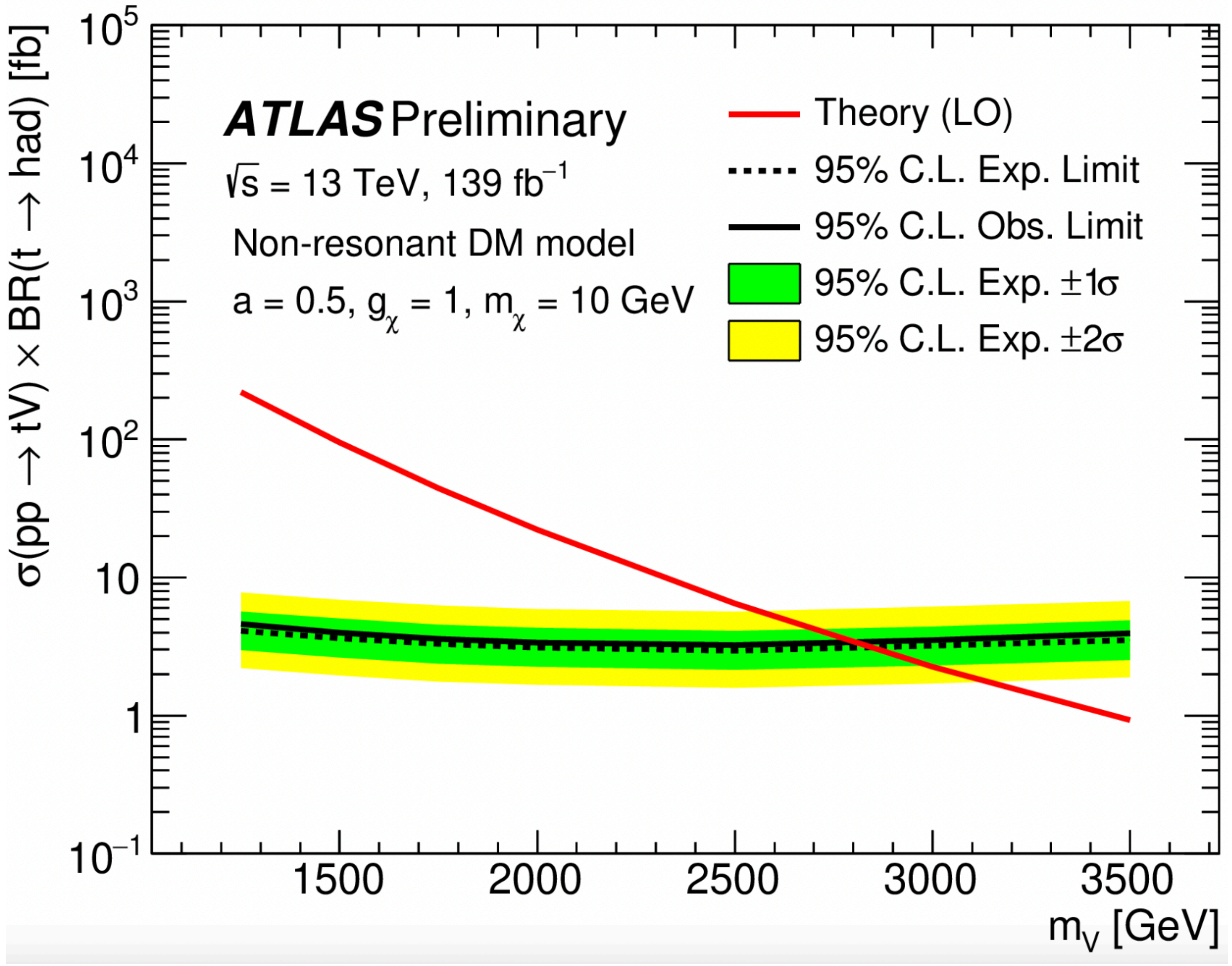
ATLAS: Mono-top Results

- No significant excess above the SM expectation is found in any of the resonant or non resonant DM model signal regions
- Expected and observed upper limit on the signal cross section



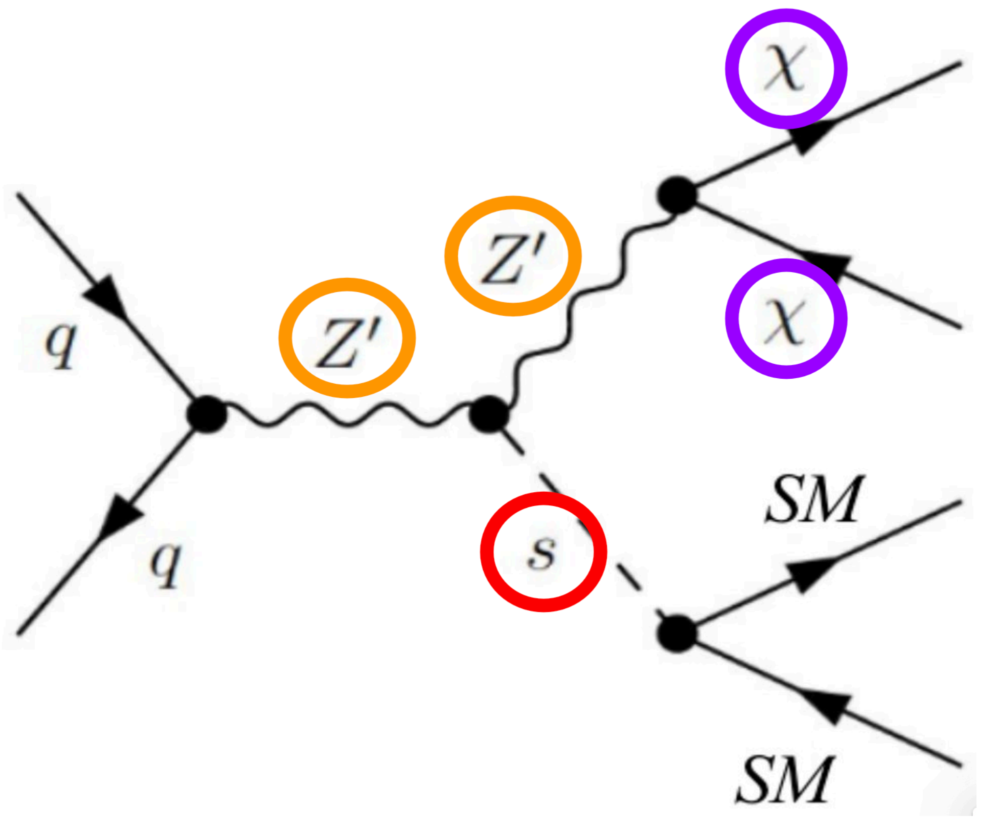






ATLAS/CMS: Mono-S(VV)

ATLAS-CONF-2022-029, CMS-PAS-EXO-20-013



Resonant pair of SM particles + E_T^{miss}

ATLAS s→WW(qqlν)

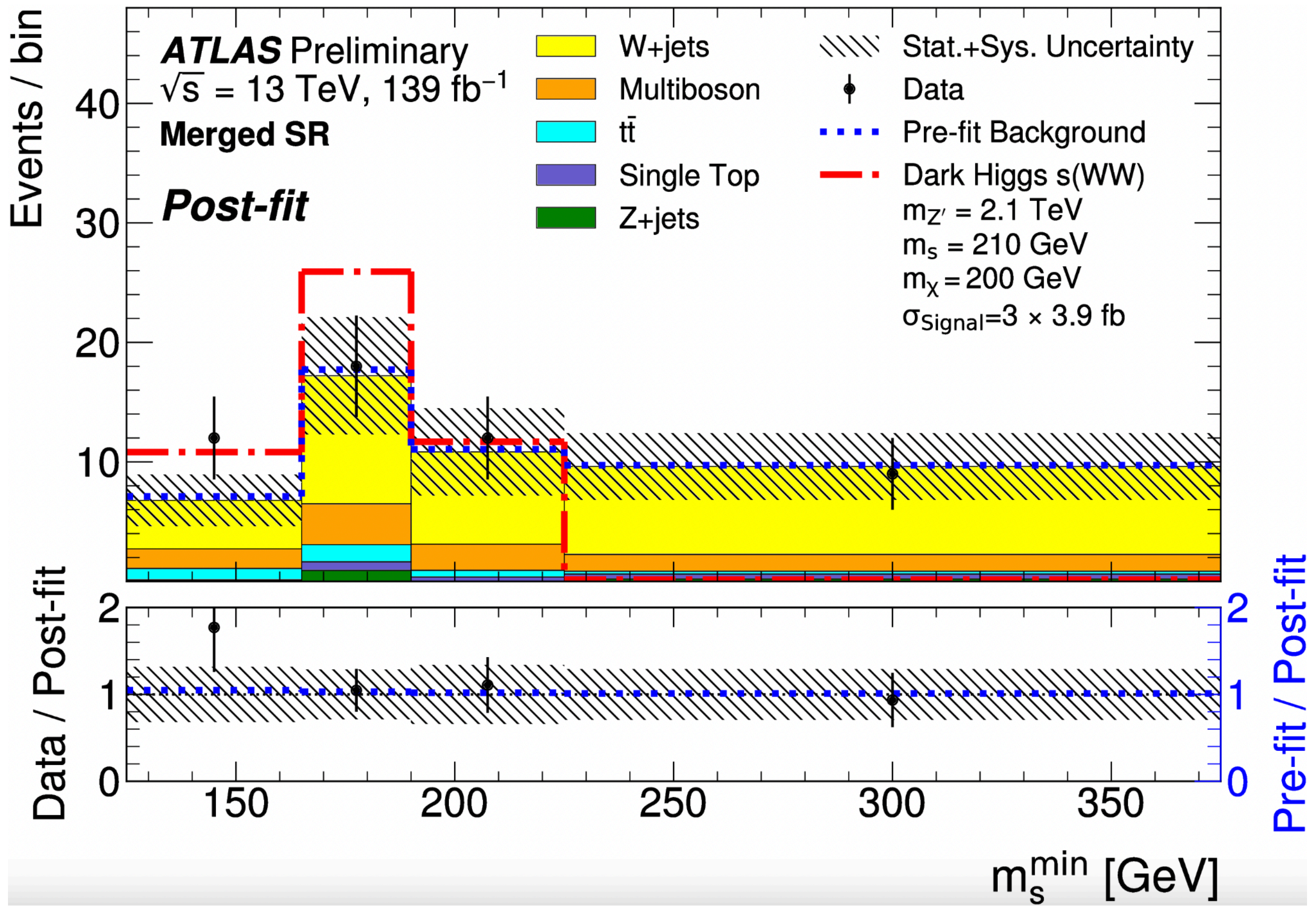
- Requiring 1 lepton + high E_T^{miss}
- Analysis in 2 categories:
  - Merged category: large-*R* jet (*R*=1) using Track-Assisted Reclustering (TAR) to deal with dense environment with hadronic activity + close-by lepton
  - Resolved category: two small-*R* jets
- Dedicated control regions for dominant *W+jets* and *tt* backgrounds.
- Fit $m_{S,min}$ (≡approximate dark Higgs reconstruction considering invisible neutrino) distribution to data.

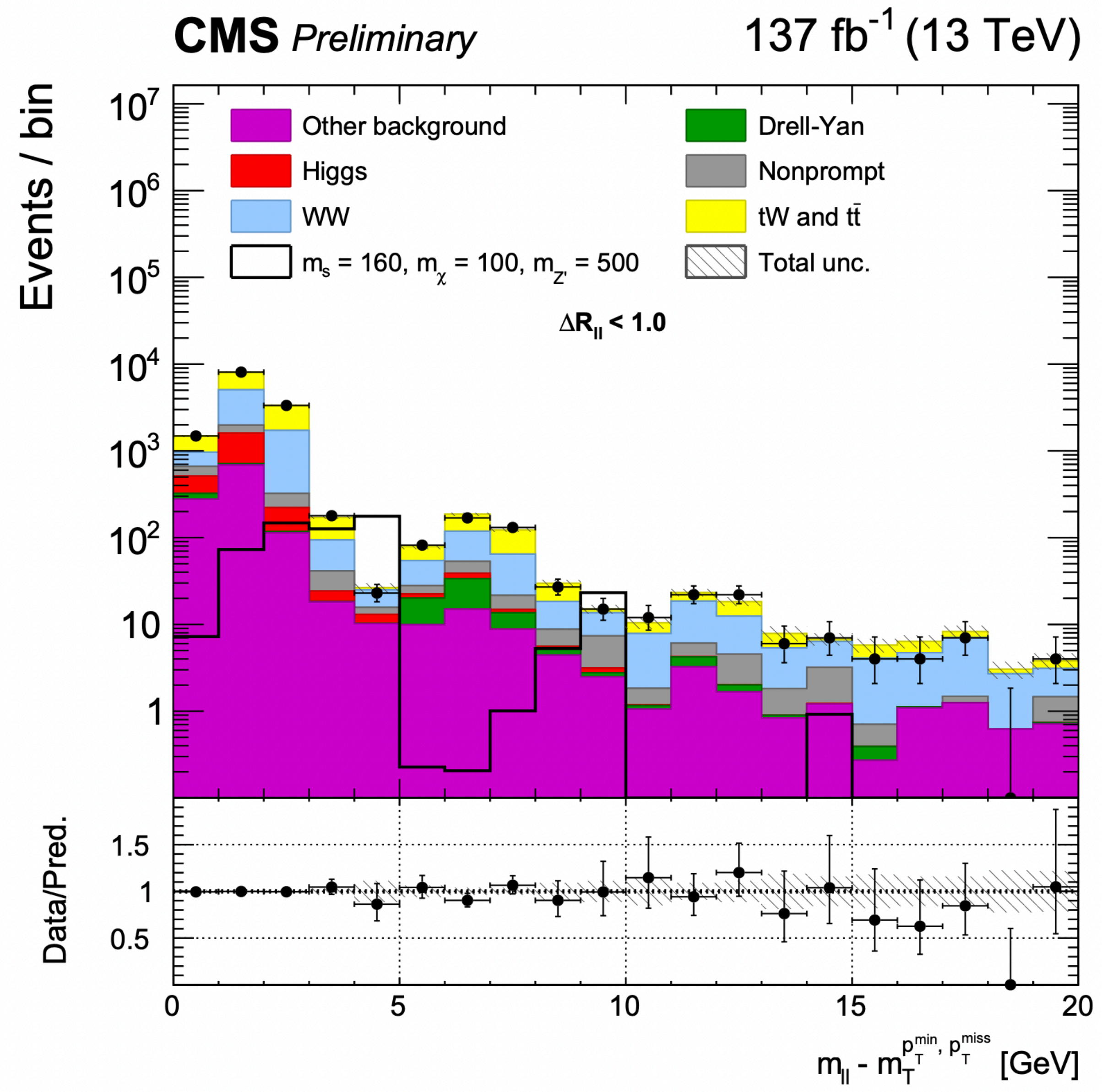
CMS s→WW(lνlν)

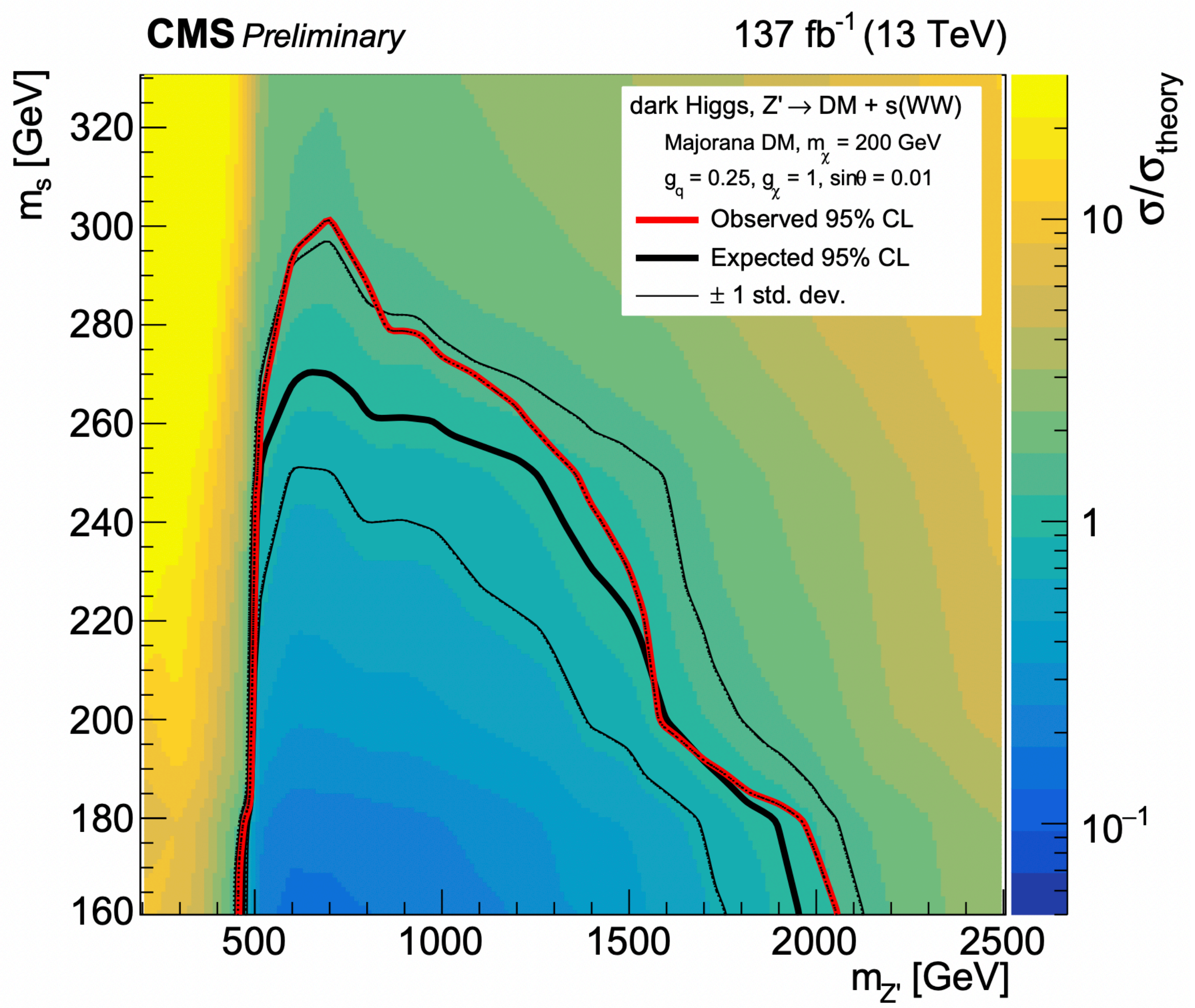
- Requiring opposite flavor, opposite charge leptons
- ttbar & qq→WW: normalization, constrained in CRs (inverting b-tag and ΔR(ℓℓ))
- non-prompt leptons: data-driven
- 3-dimensional fit performed using ΔR, m_{ll} and m_T

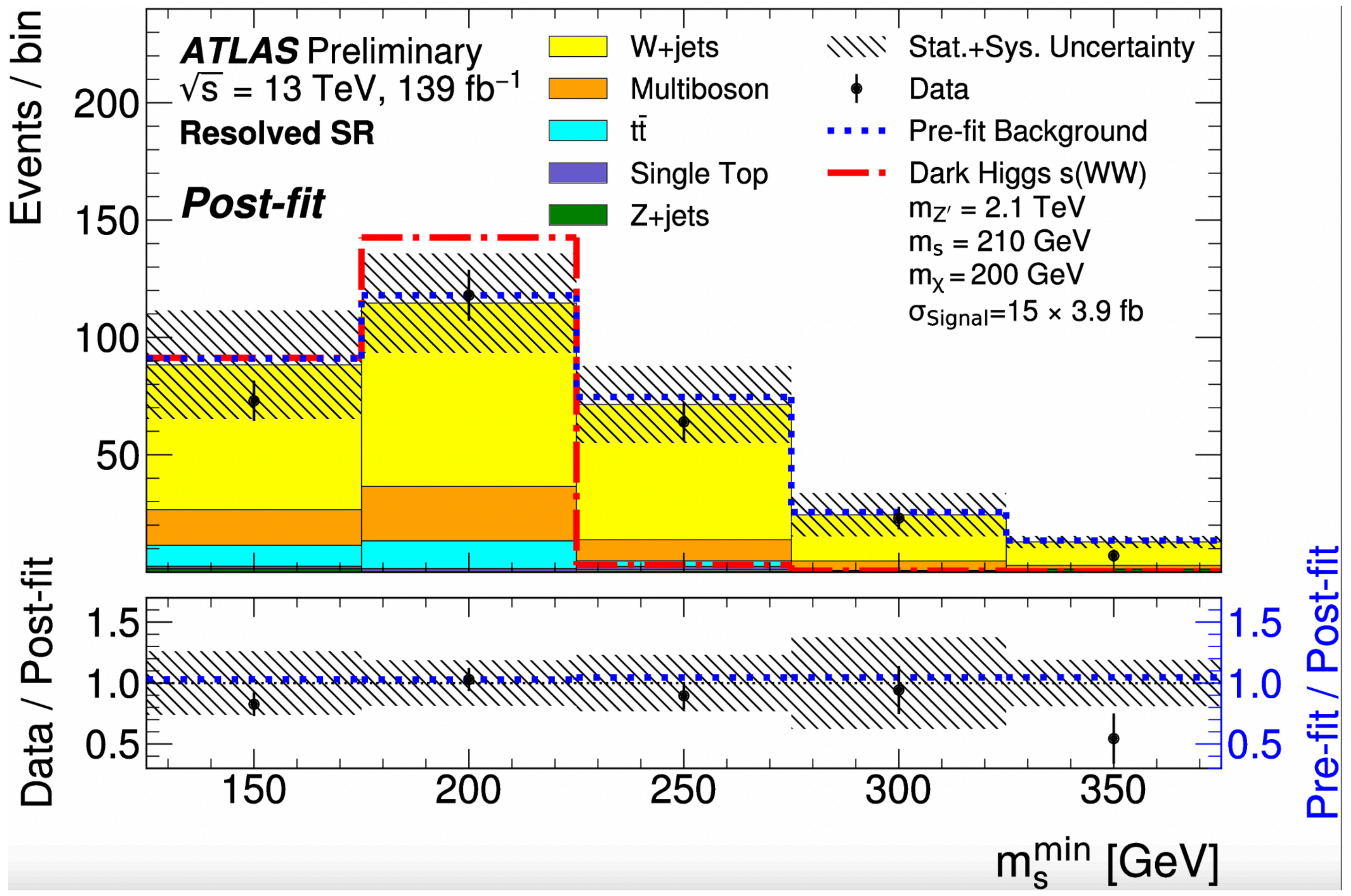
$$m_T^{\ell\,\min, p_T^{miss}} = \sqrt{2 p_T^{\ell\,\min} p_T^{miss} \left[1 - \cos\Delta\phi(\vec{p}_T^{\,\ell\,\min}, \vec{p}_T^{\,miss})\right]}$$

ATLAS/CMS:Mono-S(VV) Results

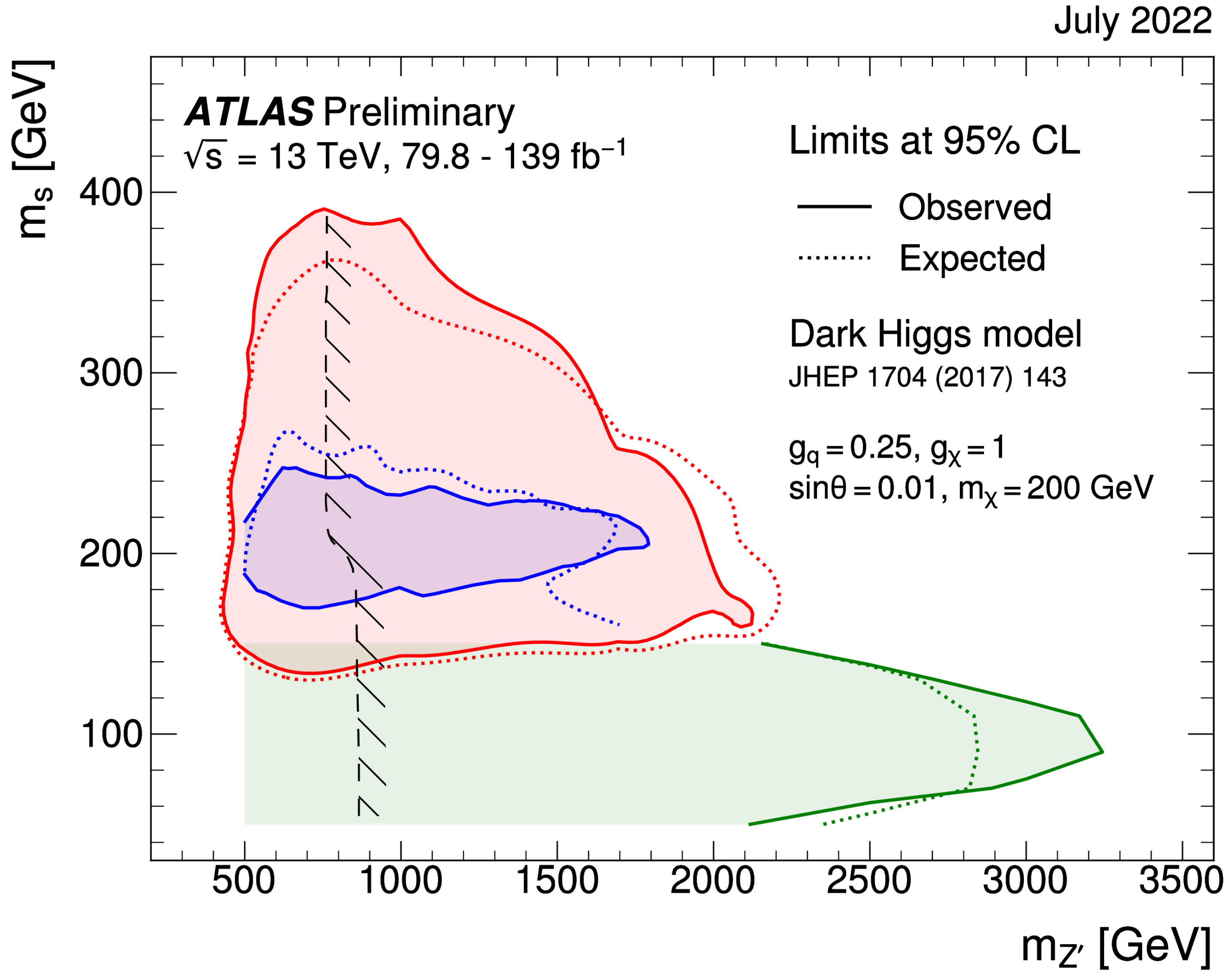


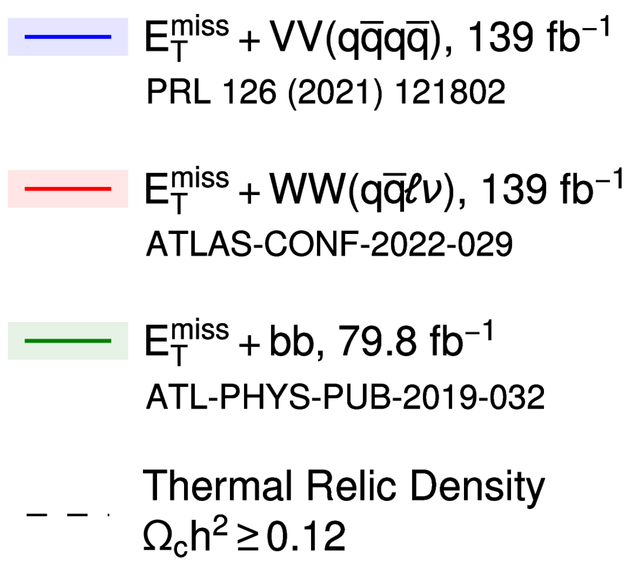






- No significant excess of events observed.
- Exclusion in $(m_{Z'}, m_s)$ plane



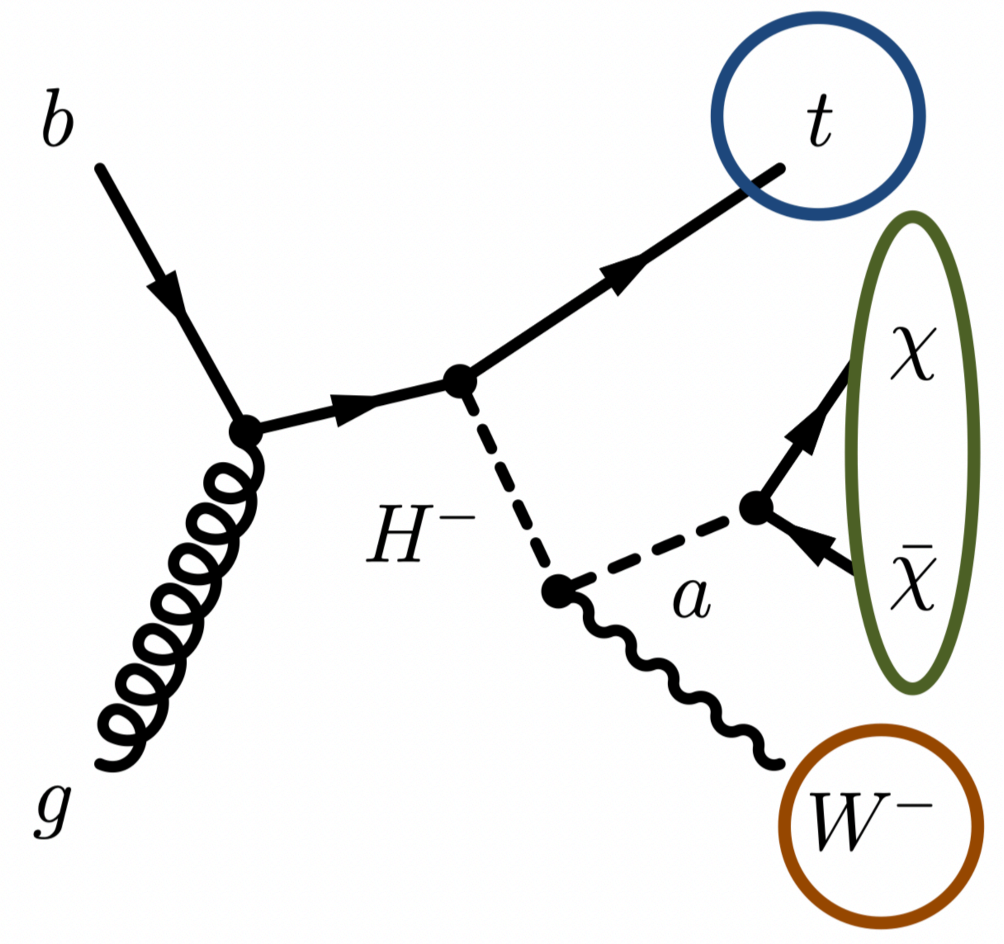


Combined with other searches targetting different decay channels of the new scalar

ATLAS: tW+MET

ATLAS-CONF-2022-012

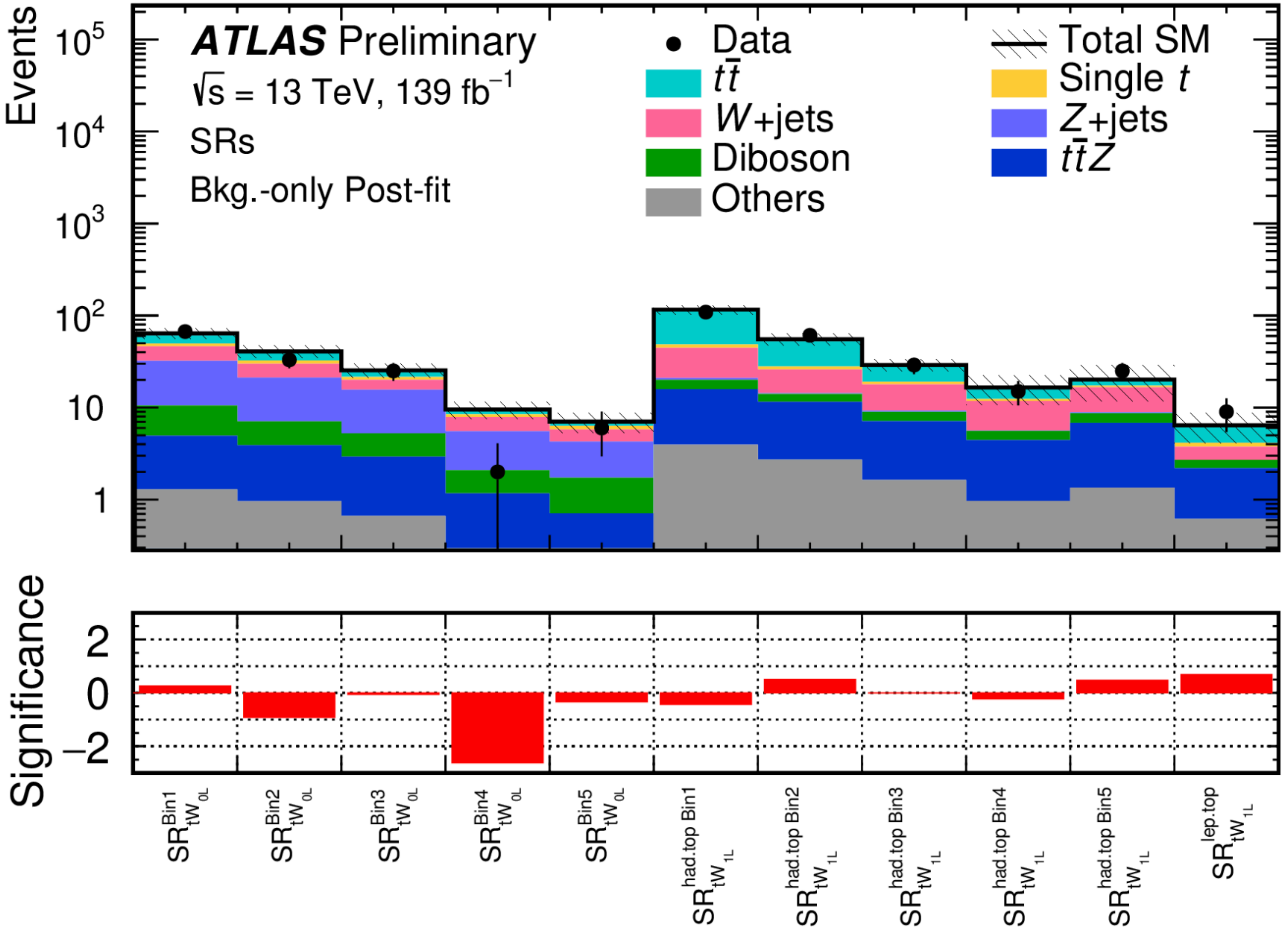
- Targetting scenario with a singletop quark and a high p_T W boson, motivated by 2HDM+*a* model.
  - $E_T^{miss} \geq 250$GeV
  - 1 b-jet (from top decay)
  - Channels with 0-1 electrons/muons
- Large-*R* jets with W-tagging or two small-R jets for hadronic *W* candidate.
- Main backgrounds: ttbar , *Z/W*+jets and *ttZ* - constrained in the control regions.
  - Fit to data under the background-only hypothesis yields to measure the normalization of the main backgrounds.
- Look for excesses in E_T^{miss} + other distributions.



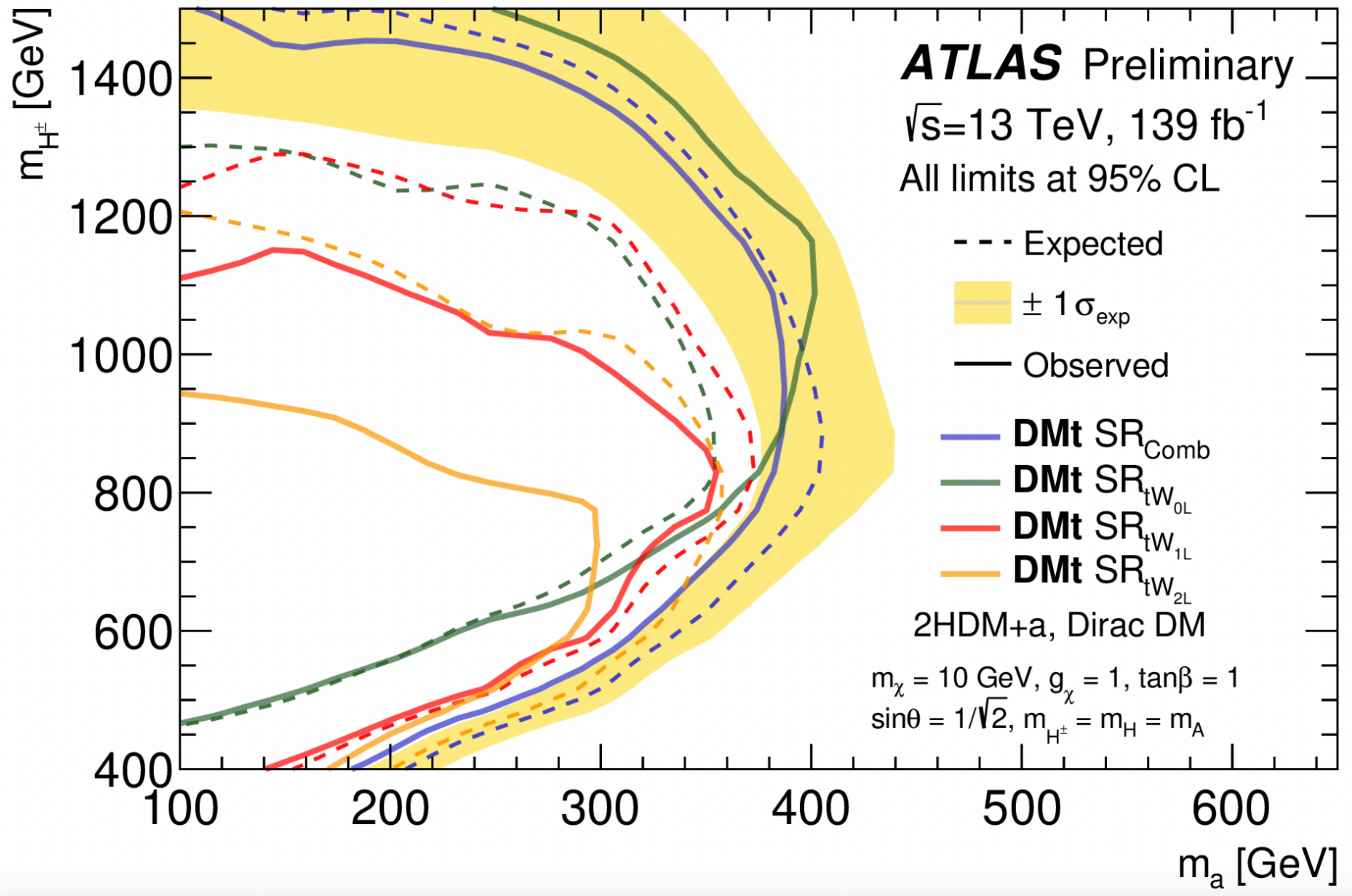
sin(θ) = 1/ √2
enhances resonant H±

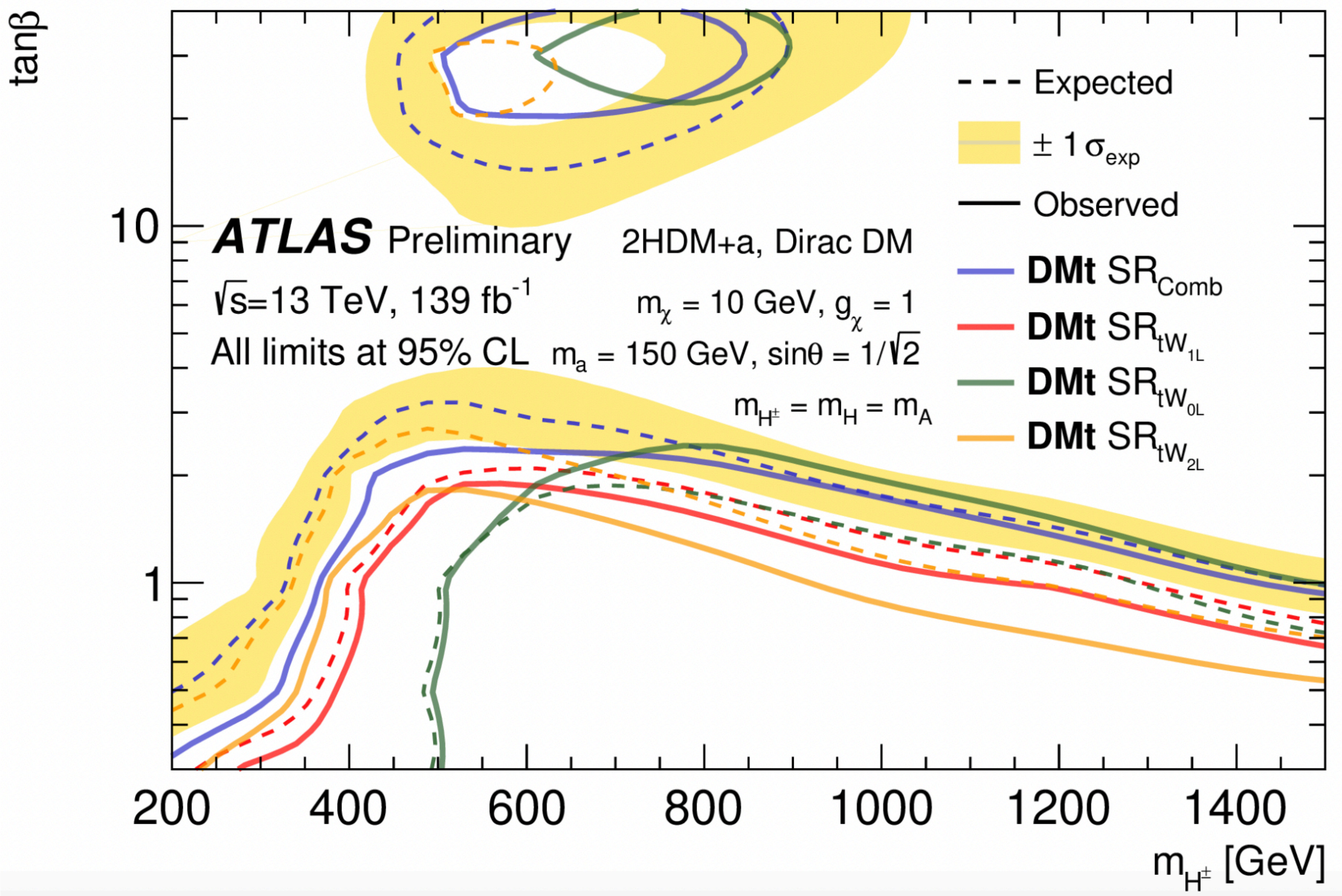
ATLAS: tW+MET Results

- No significant excess above the SM expectation found
- Model excluded up to m_a = 350 GeV and $m_{H^\pm}$ = 1500 GeV



Also include results from 2ℓ region

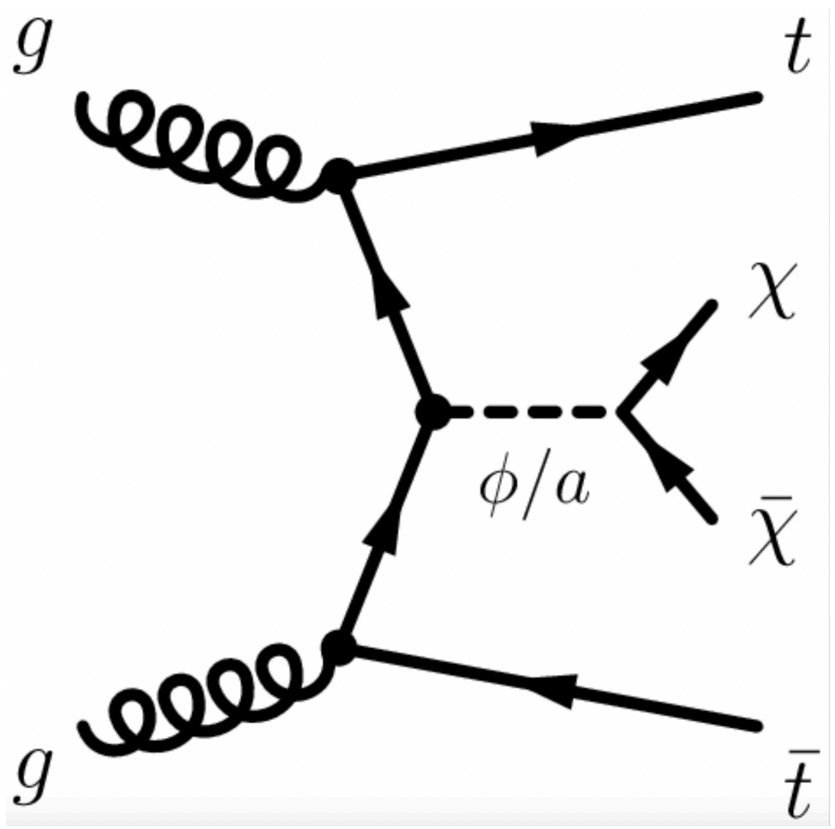


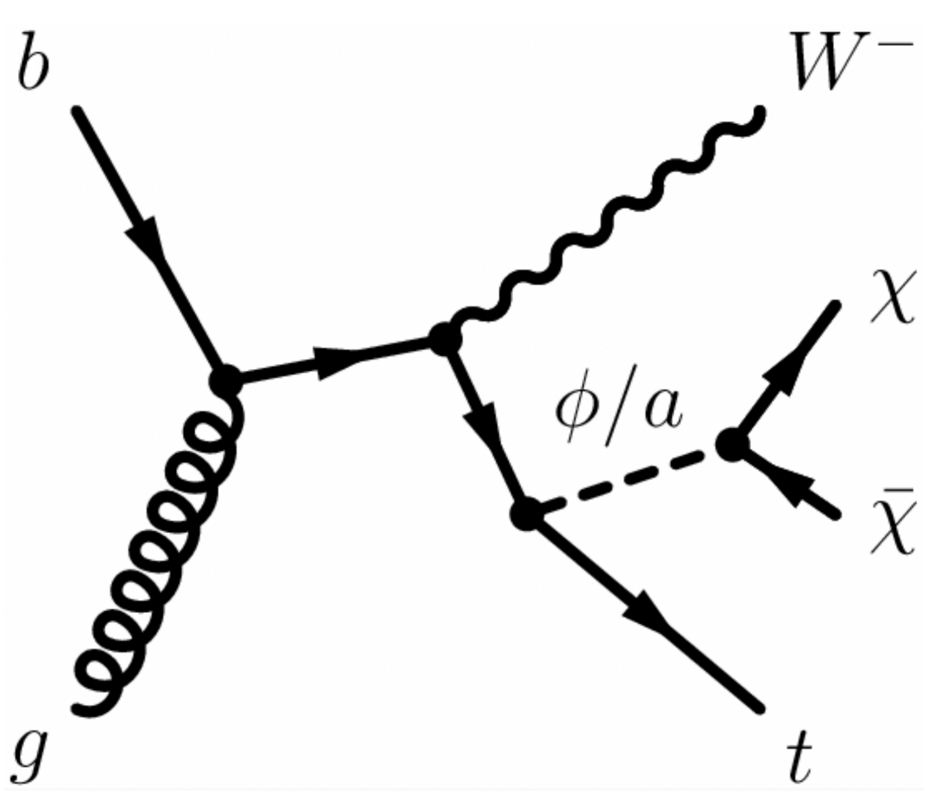


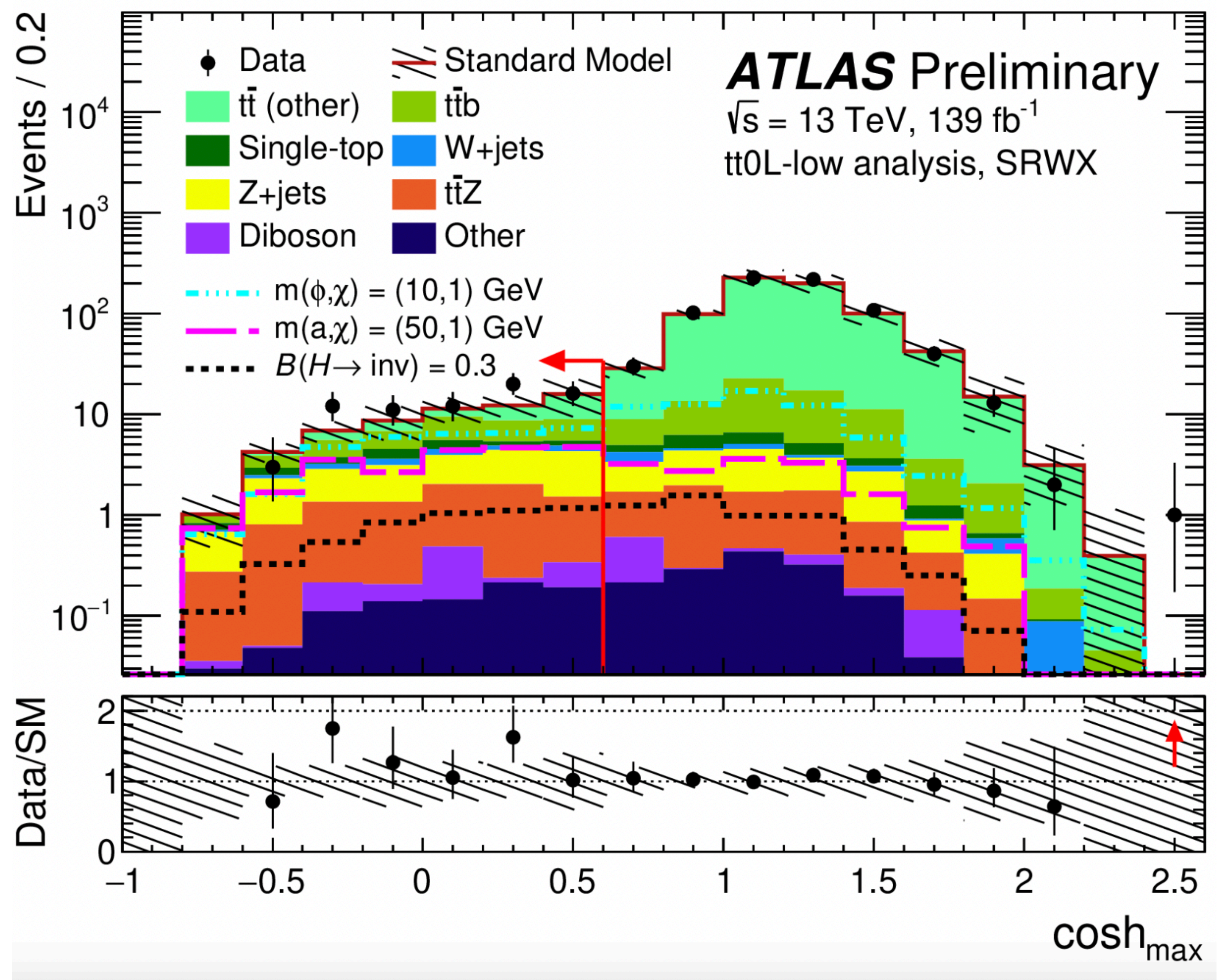
ATLAS: ttbar+MET

ATLAS-CONF-2022-007

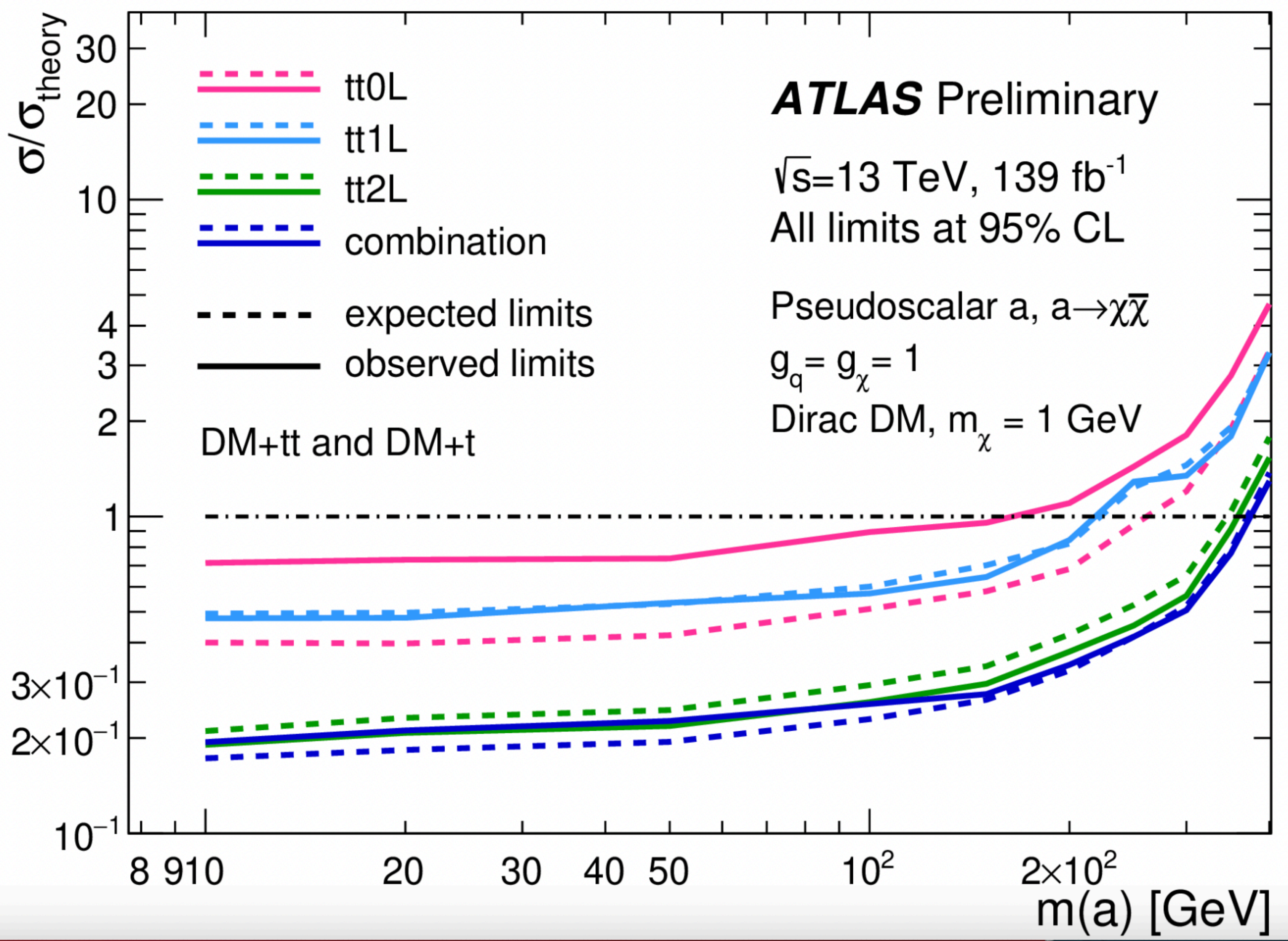
- spin-0 mediator under minimal flavour violation hypothesis → Yukawa-like couplings







- Combination of $tt + E_T^{miss}$ analyses with 2, 1 and 0 leptons.
  - *New* 0l low-E_T^{miss} channel, making use of b- jet triggers (extended to 160 GeV)
- Targetting scalar and pseudoscalar mediators.
- Backgrounds: tt, W+jets, Z+jets, $tt+Z$ → constrained in CRs
- data compatible w/ predictions within 2σ
- 2-lepton dominates, 0-lepton extension reaches 1-lepton sensitivity at low $m_{a/\phi}$



ATLAS/CMS: Mono Jet

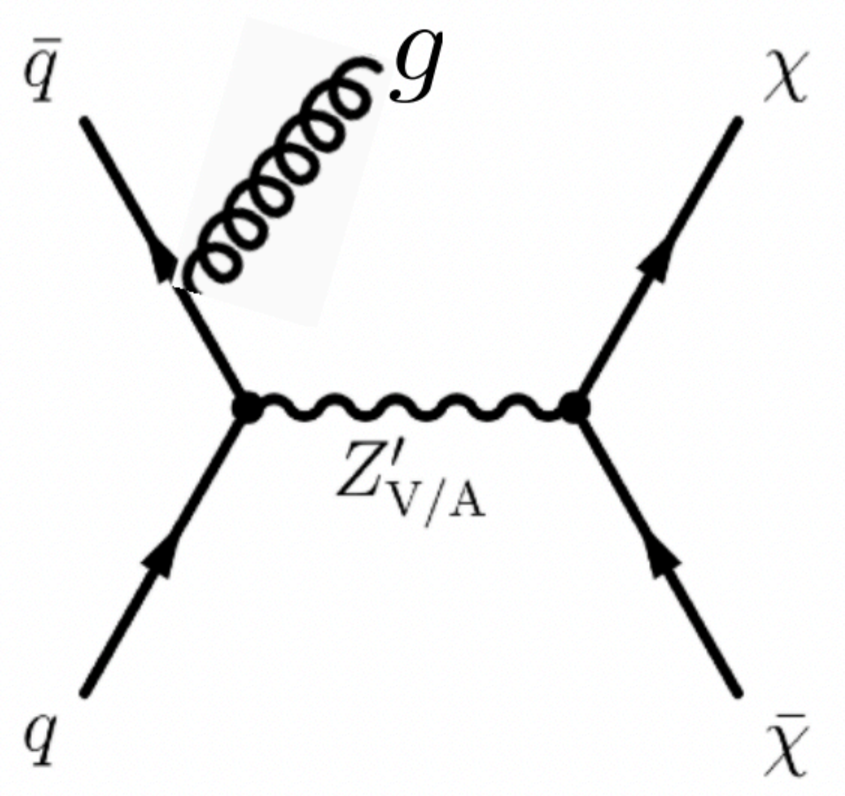
- Inclusive signature sensitive to a wide range of New Physics theories.
- Large E_T^{miss} + hadronic jets
- Trigger events based on E_T^{miss}
- $E_T^{miss} > 200$ (250) GeV for ATLAS (CMS)
- up to 4 jets well separated from E_T^{miss}
- Require jet with pT > 150 (100) GeV in ATLAS (CMS)

Main Backgrounds :

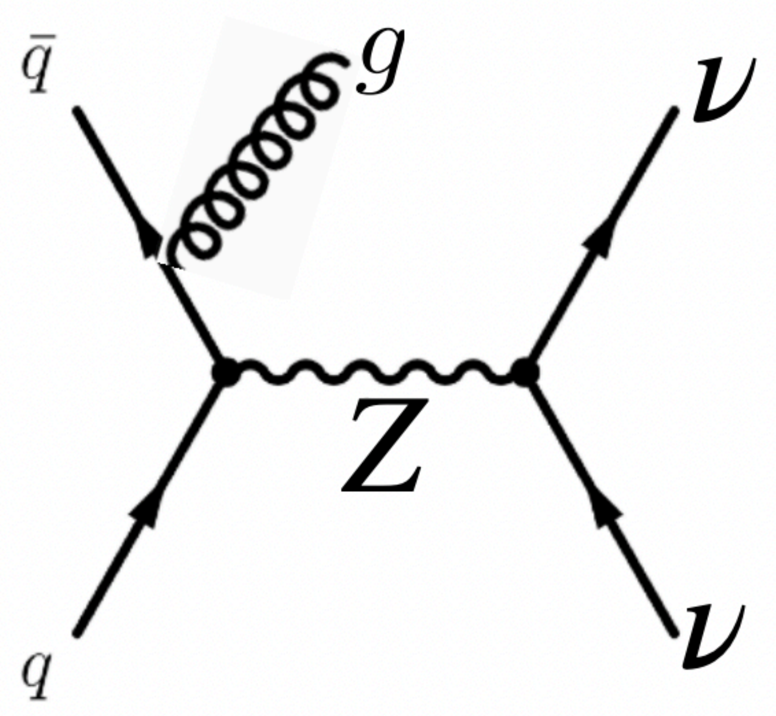
$Z(\rightarrow \nu\nu)$ +jets : basically identical to signal except for mass

$W(\rightarrow \ell\nu)$ + jets: charged lepton not always reconstructed

Signal



Background (Z+jets)

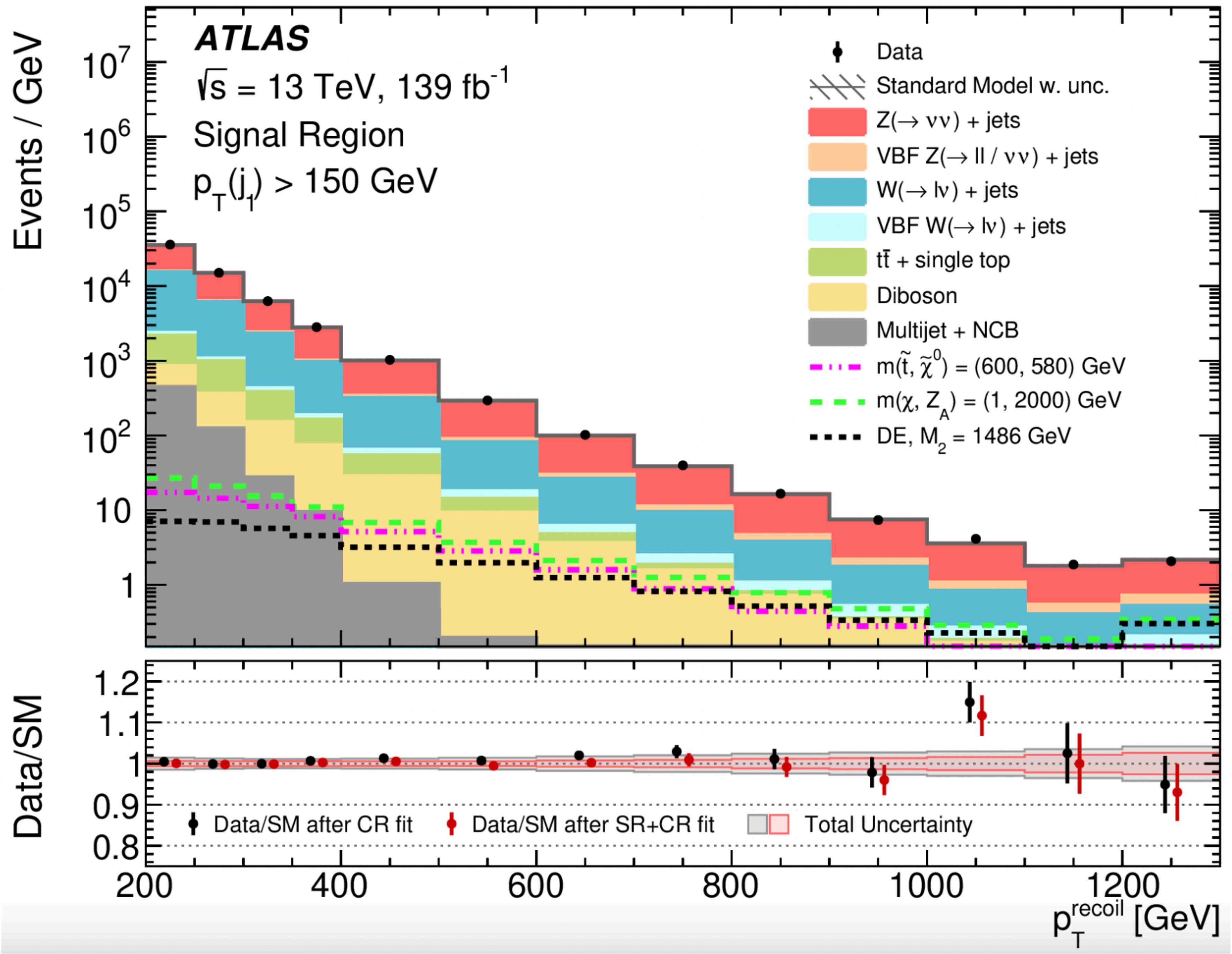


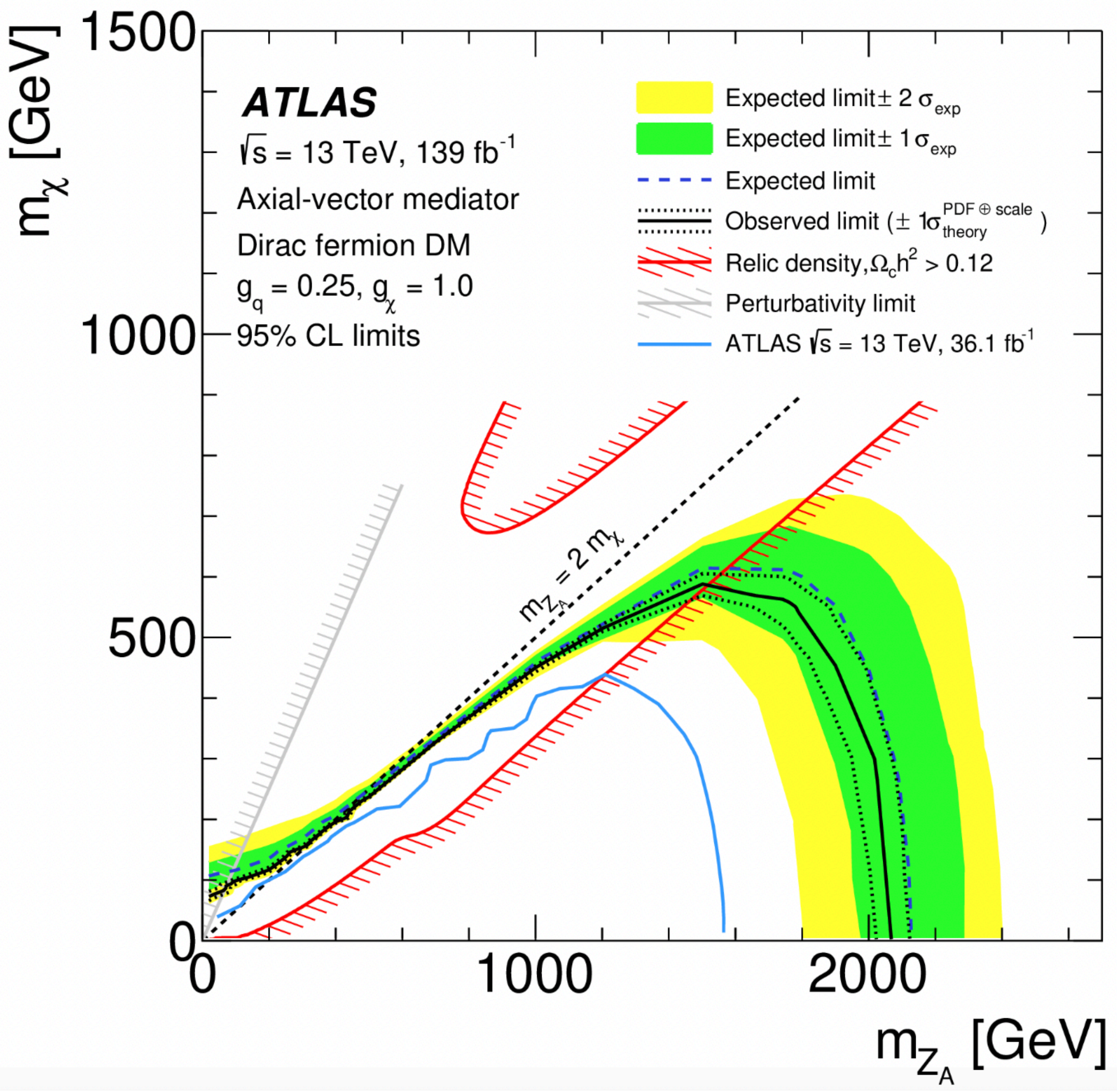
Backgrounds are estimated from 1/2-lepton Control regions

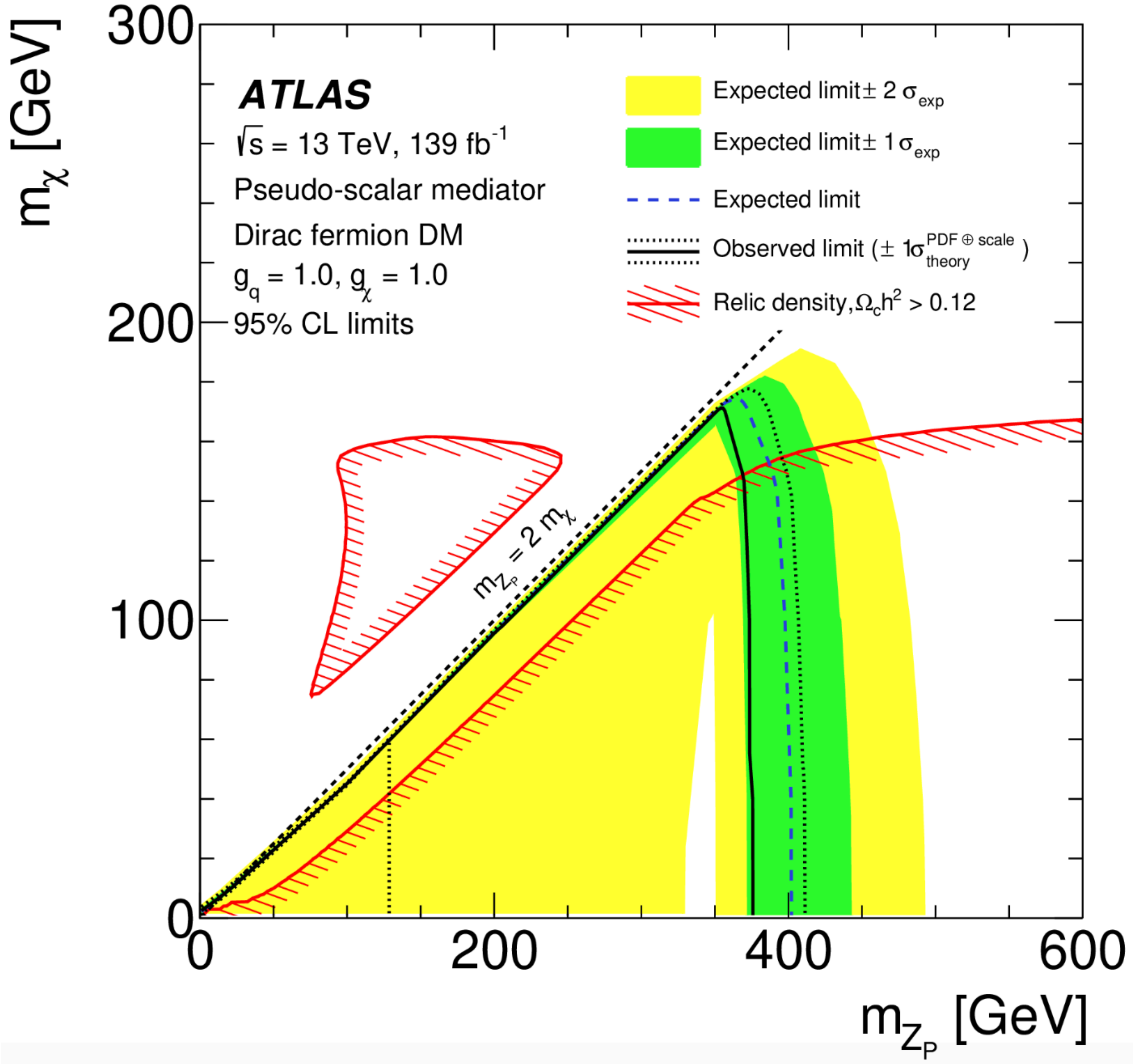
ATLAS: Mono Jet Results

Phys. Rev. D 103 (2021) 112006

Background modelling describes data in signal region well, no significant excess.







p_T^{recoil} — p_T of the system which recoils against the hadronic activity in the event.

In the CRs, $p_T^{recoil} = E_T^{miss}$ + sum of leptons p_T

In the signal region, p_T^{recoil} is equivalent to E_T^{miss}

ATLAS published model dependent & independent limits (WIMPs, squark pair production, extra dimensions, scalar dark energy).

CMS: Mono Jet Results

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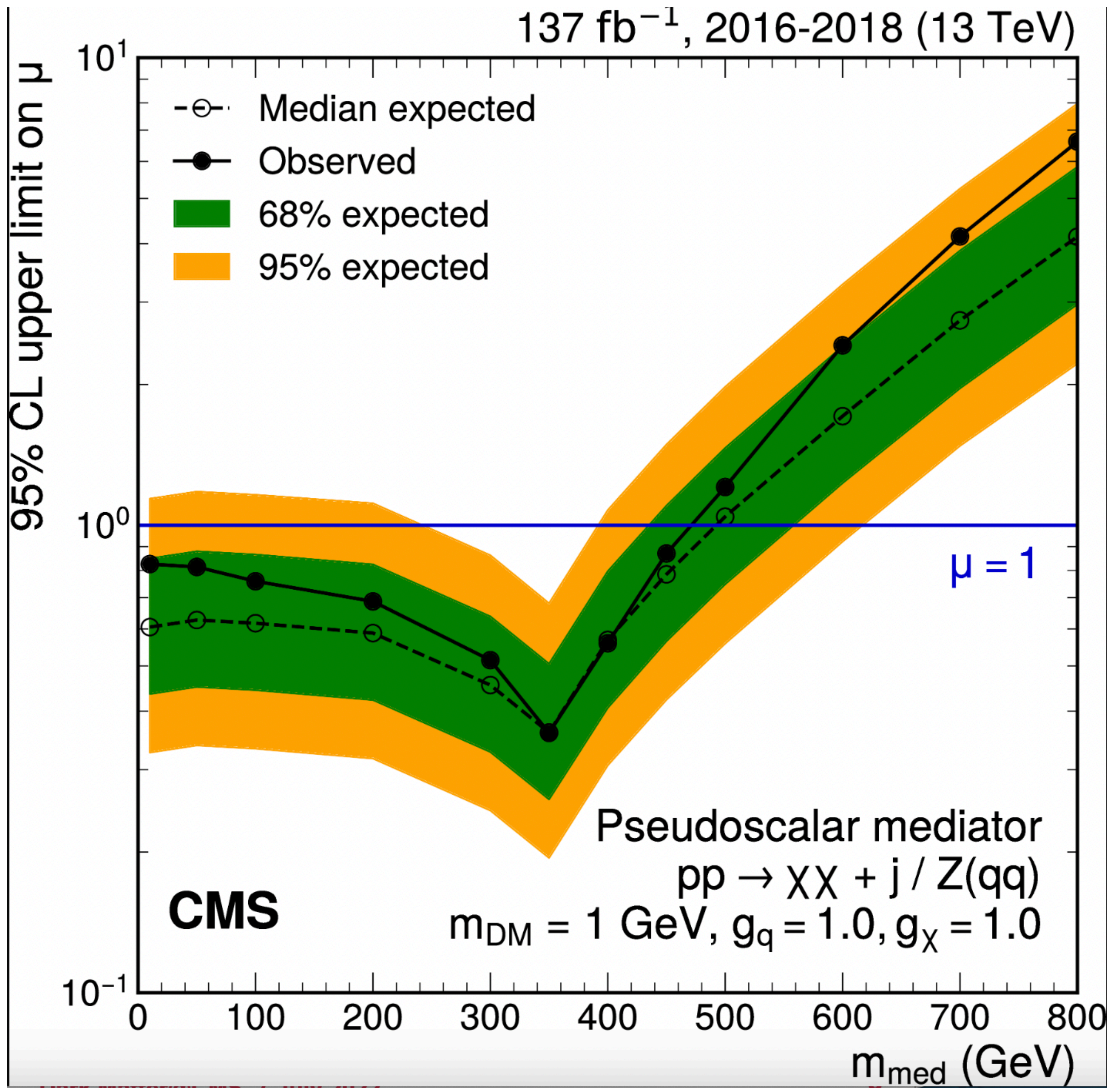
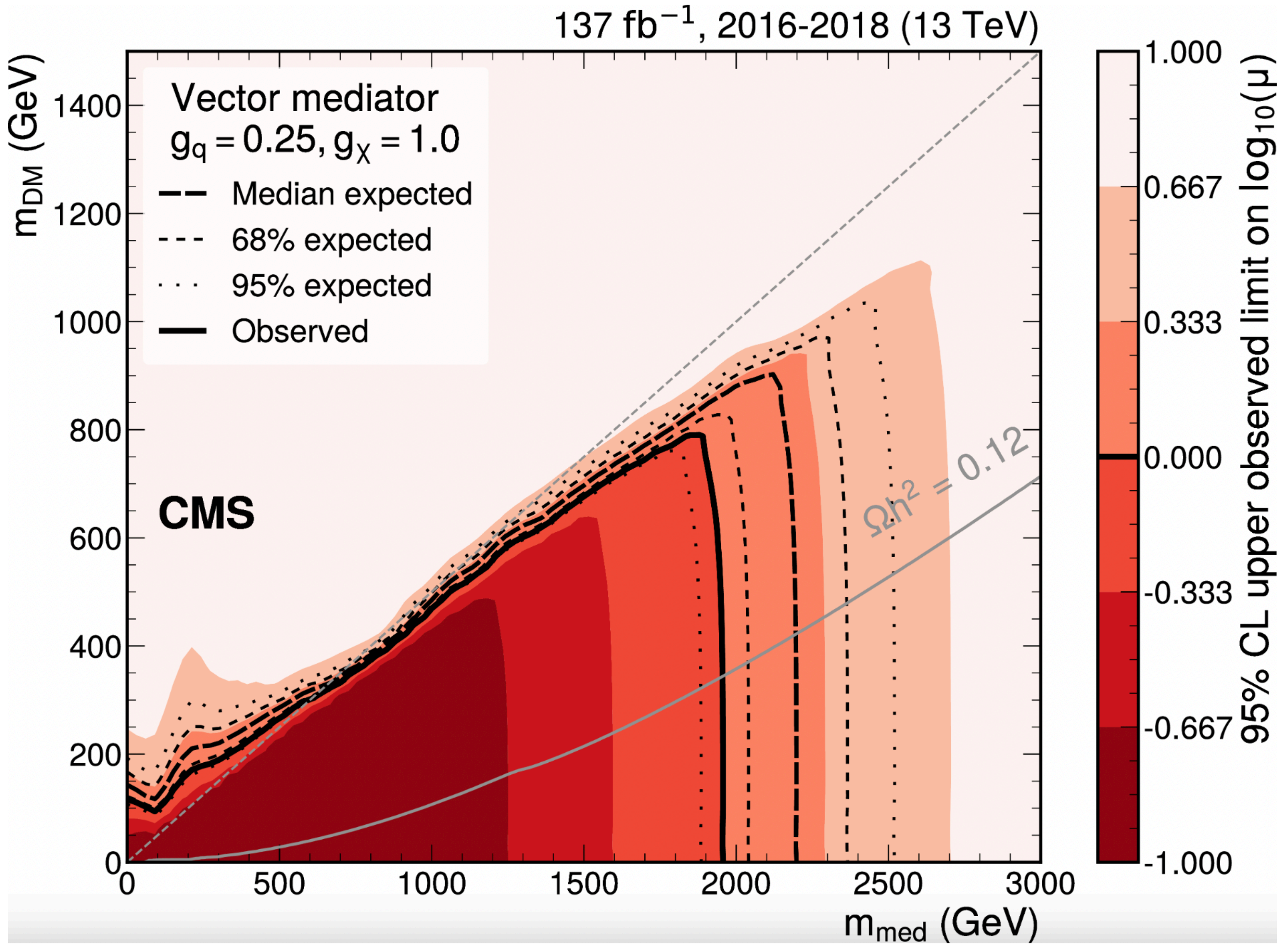
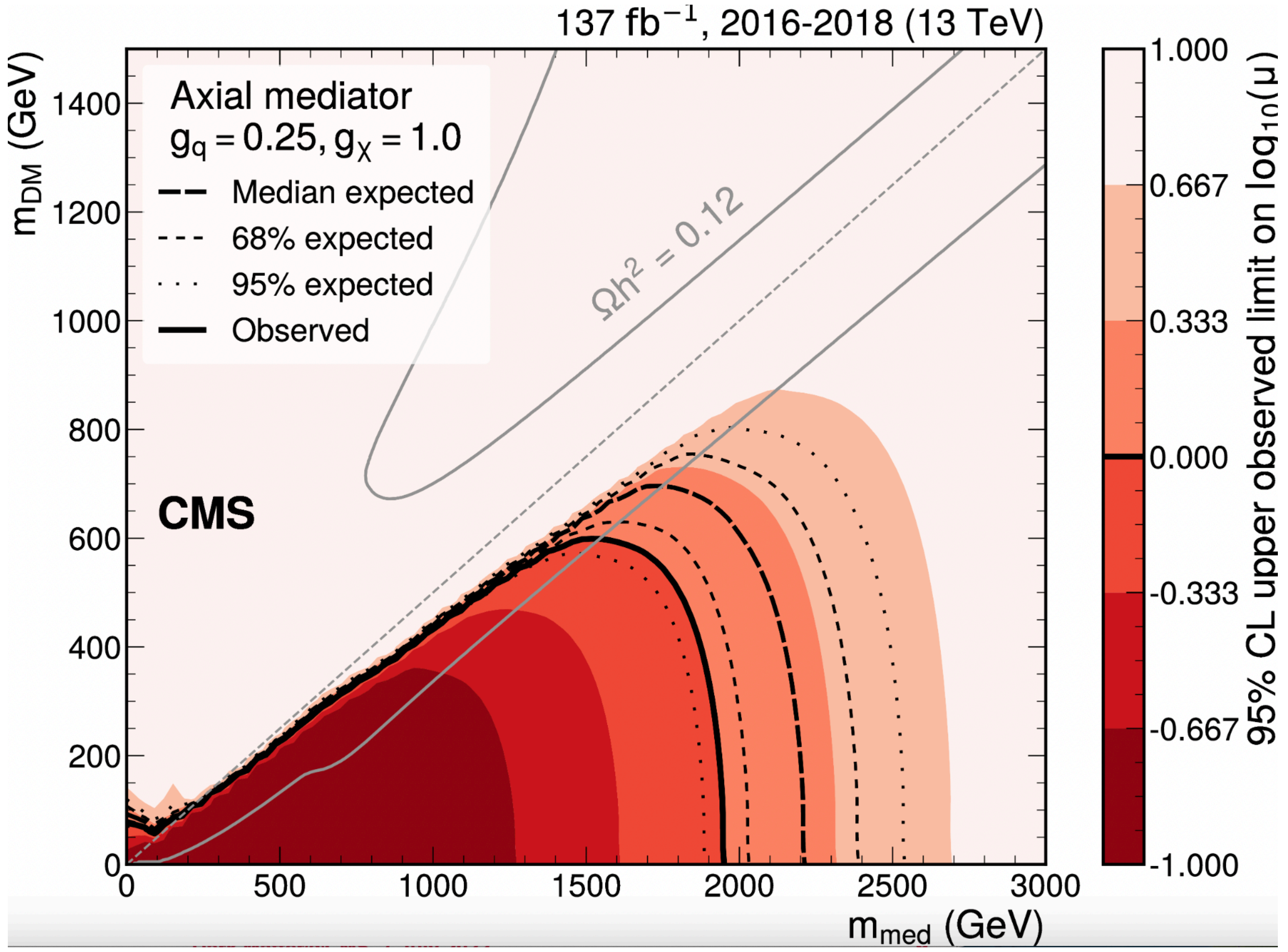


- Mono Jet and Mono-V results combined for CMS
- Limits on dark matter particle production in the context of simplified models with vector mediator and axial vector mediator





- Scalar and pseudo-scalar mediator Interpretations

CMS: Semi-visible jets

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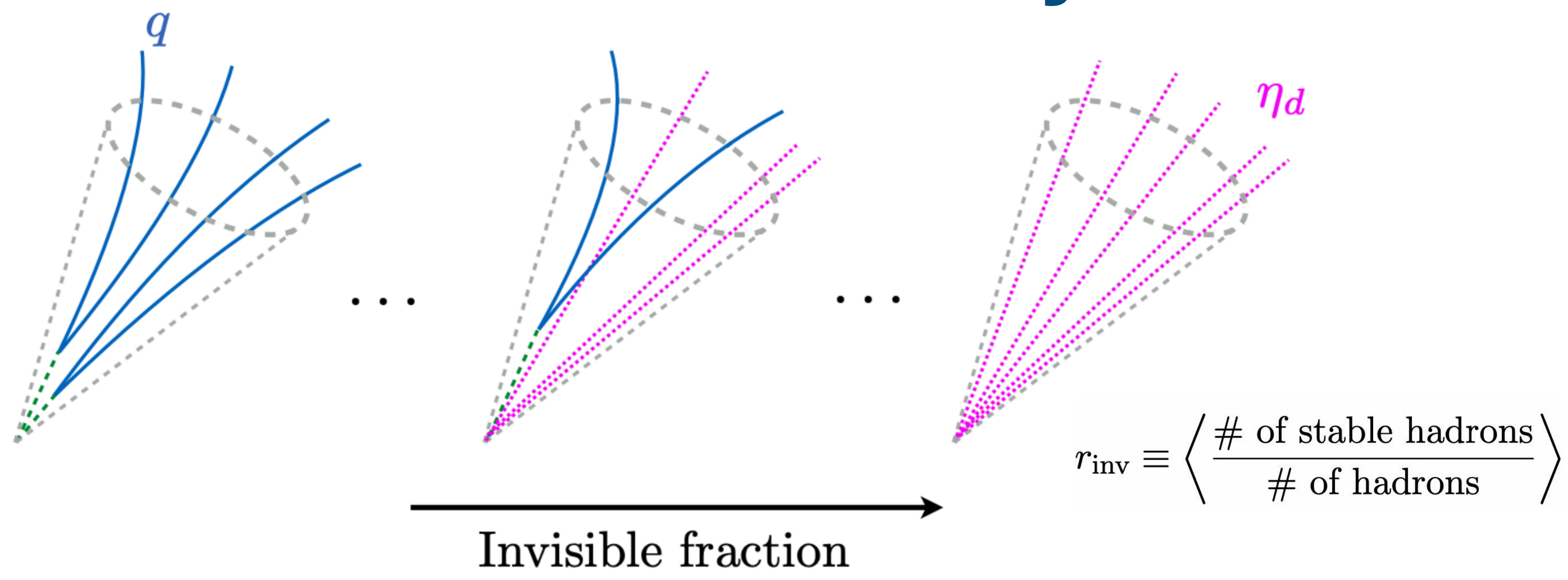
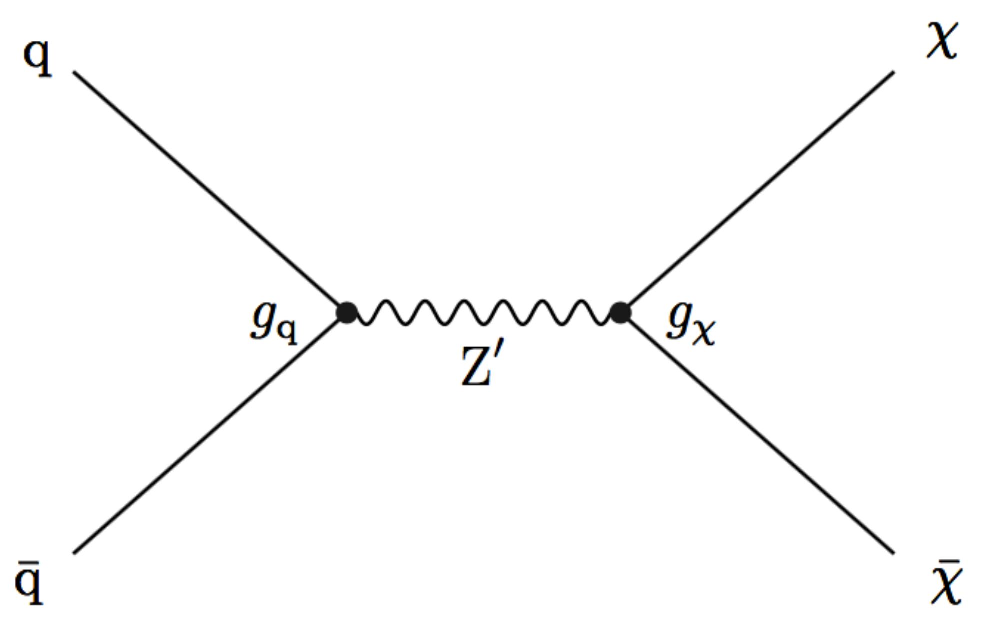
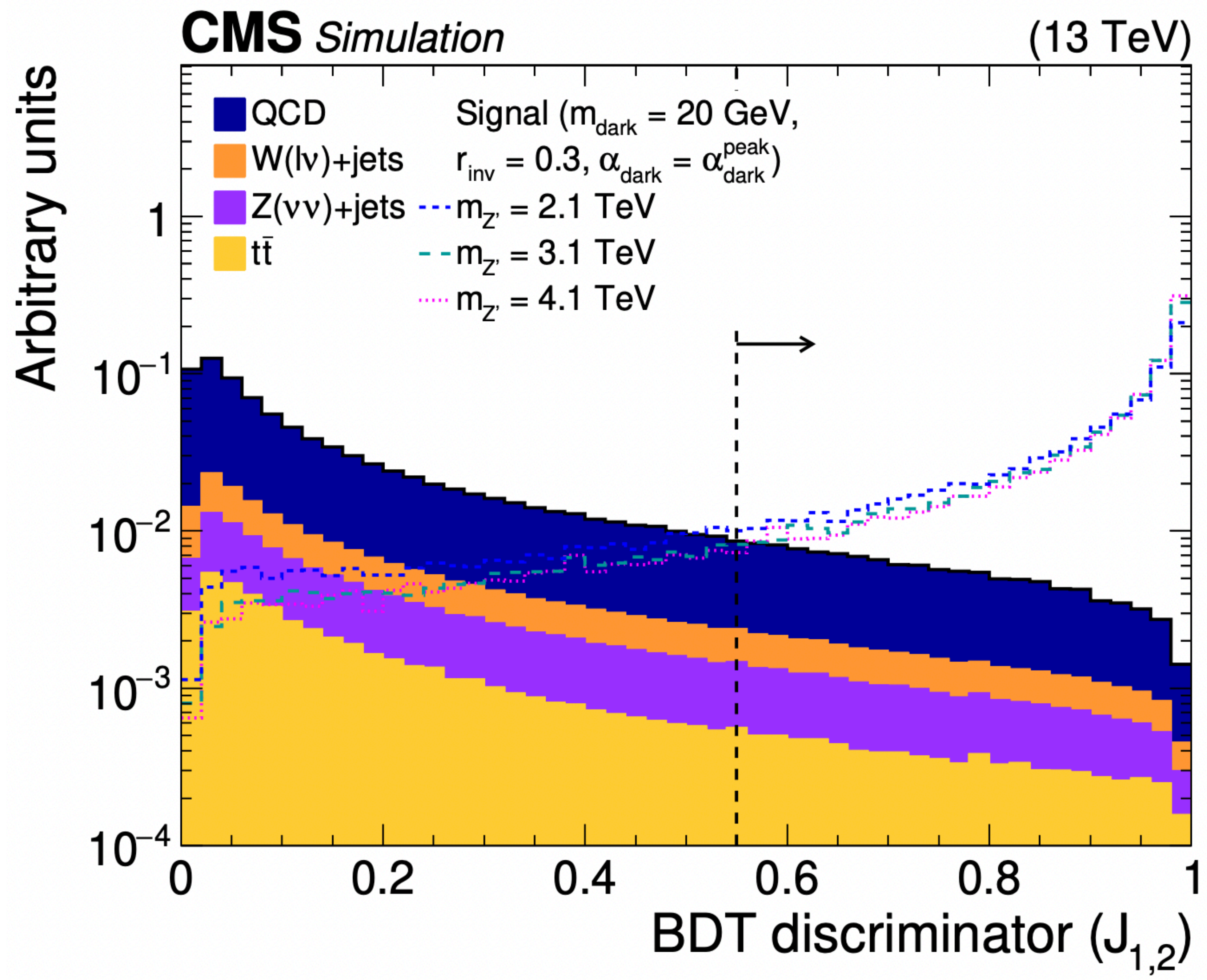




MET aligned with jets, not back-to-back → Previous searches for jets+MET not sensitive

- Dark showering process after leptophobic Z' → $q_D q_D$
- Some dark hadrons stable → Visible states interspersed with dark hadrons
- A jet-level BDT used to tag semivisible jets and define a high-purity category.
- Sensitive variable: dijet transverse mass m_T and E_T^{miss}
  - selection categorised in $R_T (= p^{miss}/m_T > 0.15)$



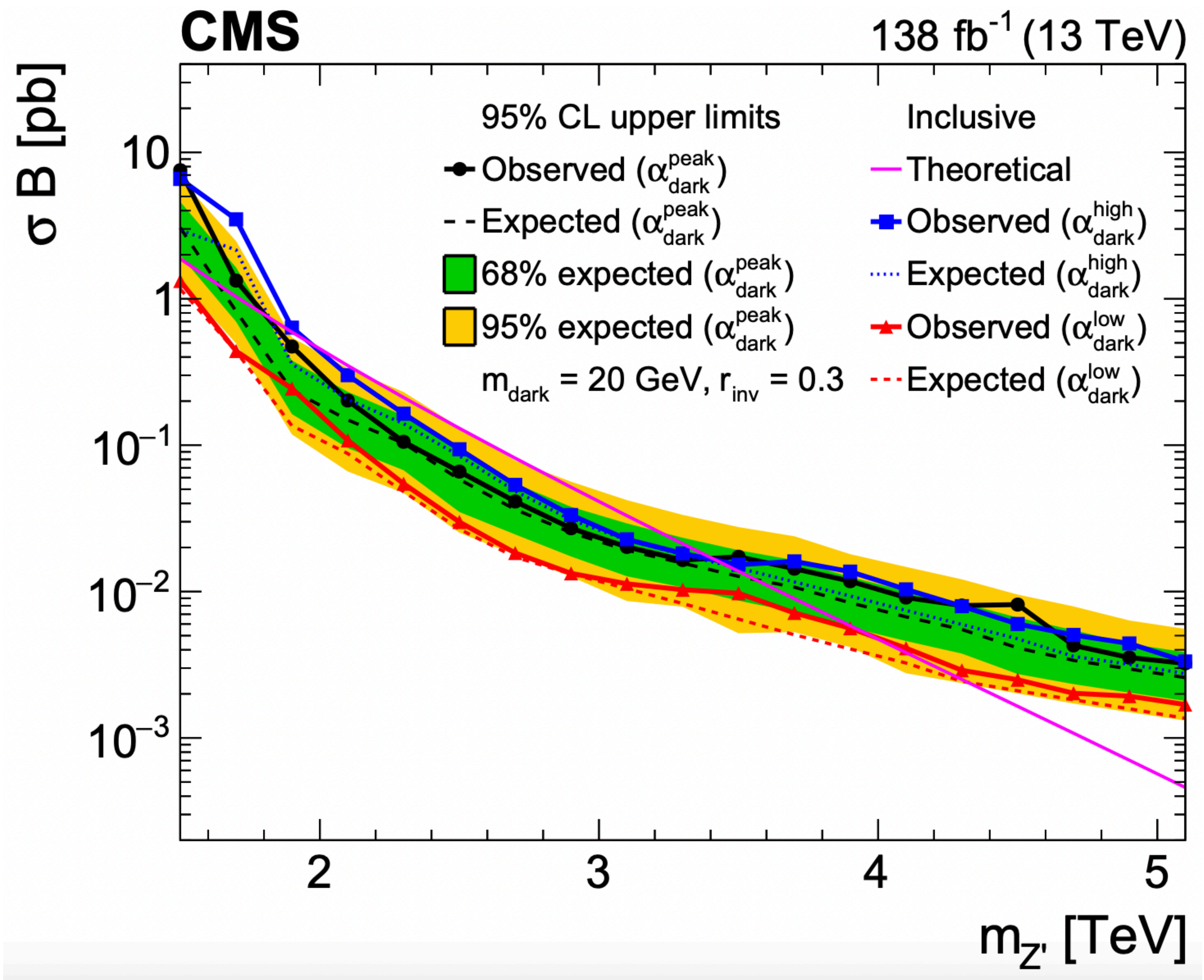
CMS: Semi-visible jets

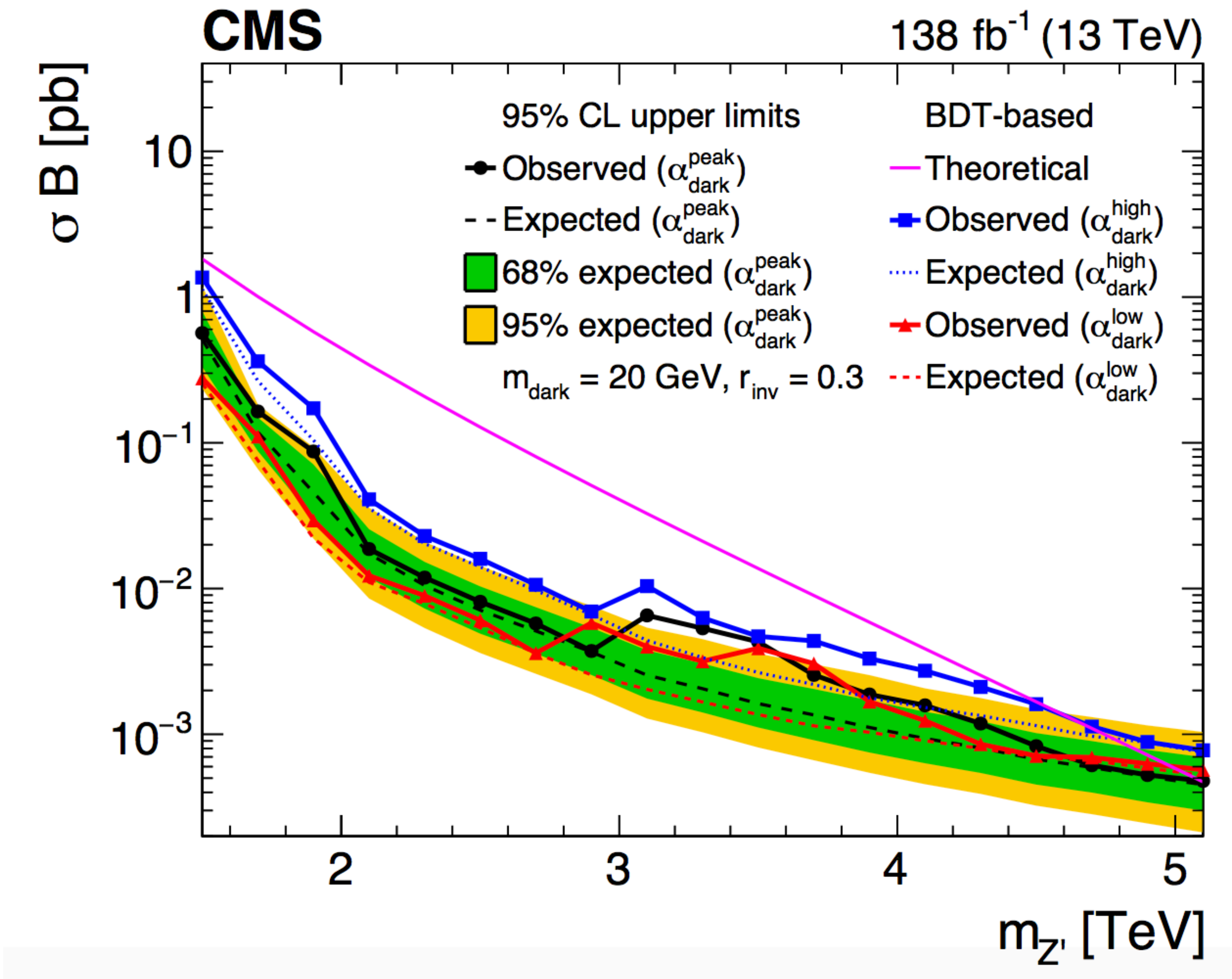
- Background Estimation: Analytic smoothly falling background

$$g(x) = e^{p_1 x} x^{p_2[1+p_3 \ln(x)]}$$

  - parameters (p_i) and normalization freely floating in the final fit

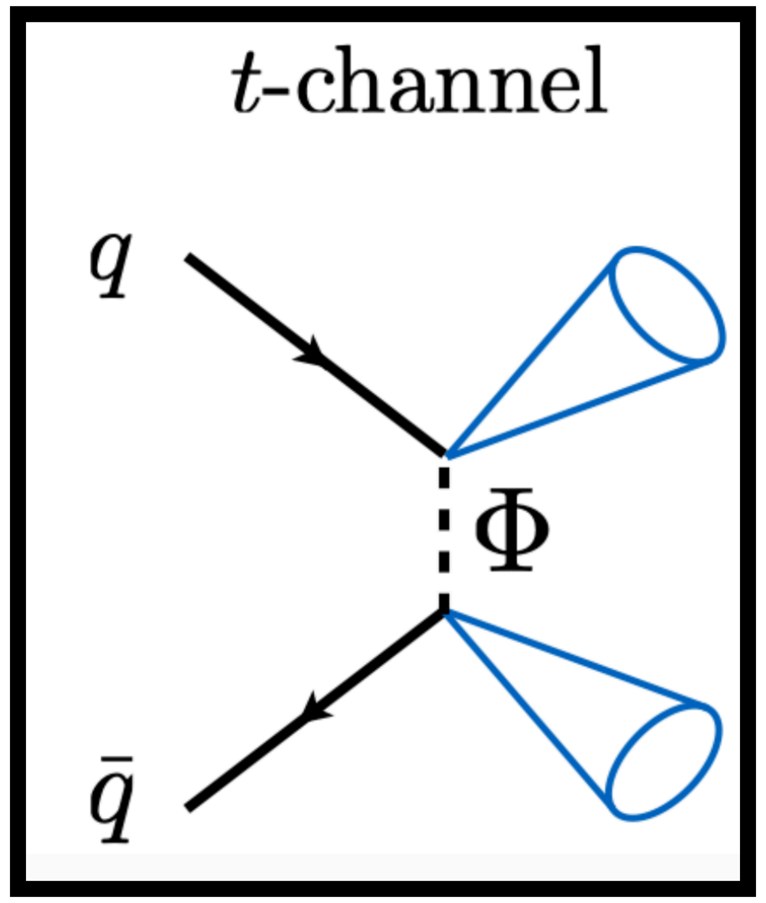
- *large improvement* ***vs*** *analysis without BDT identification of semivisible jets*
- *excluding* $1.5 \lesssim m_{Z'} \lesssim 5$ *TeV for* $r_{Inv} = 0.3$
- *excluding* $0.01 \lesssim r_{Inv} \lesssim 0.77$ *for* $m_{dark} = 20\ GeV$
- *small excess around* $m_{Z'} = 3.5$ *TeV with no real significance* ($\sim 2\sigma$ *local*)



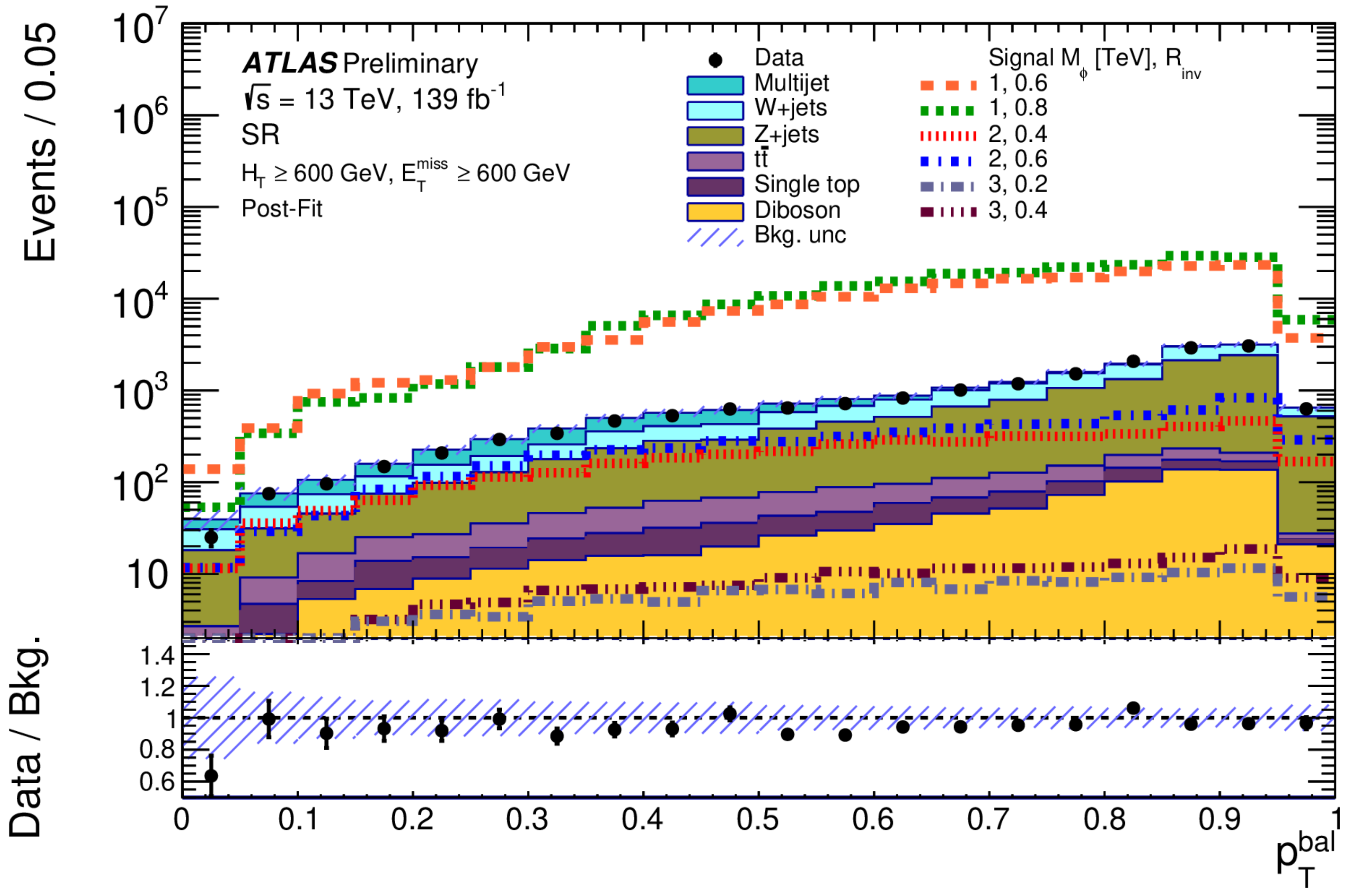


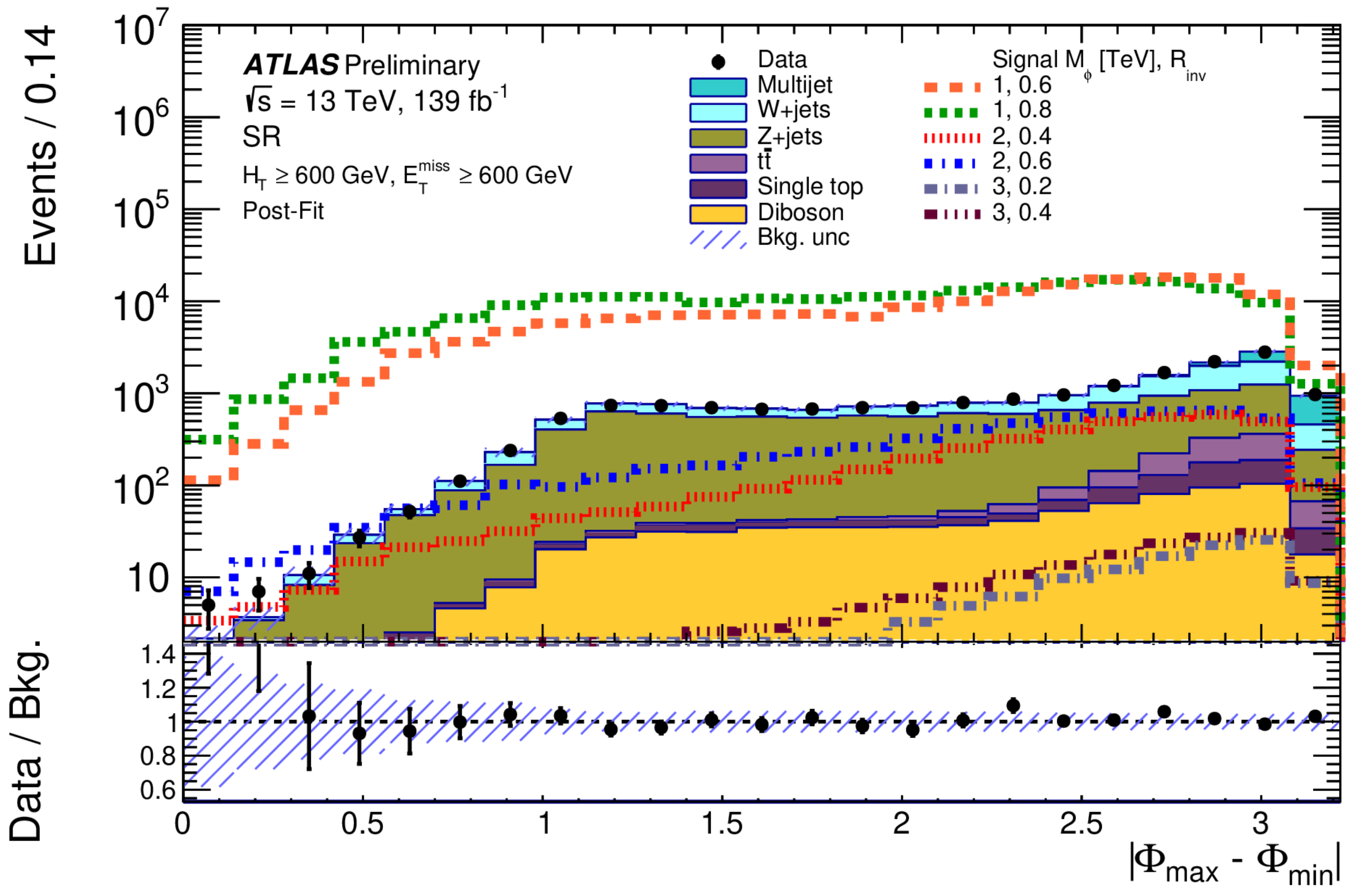
ATLAS: Semi-visible jets

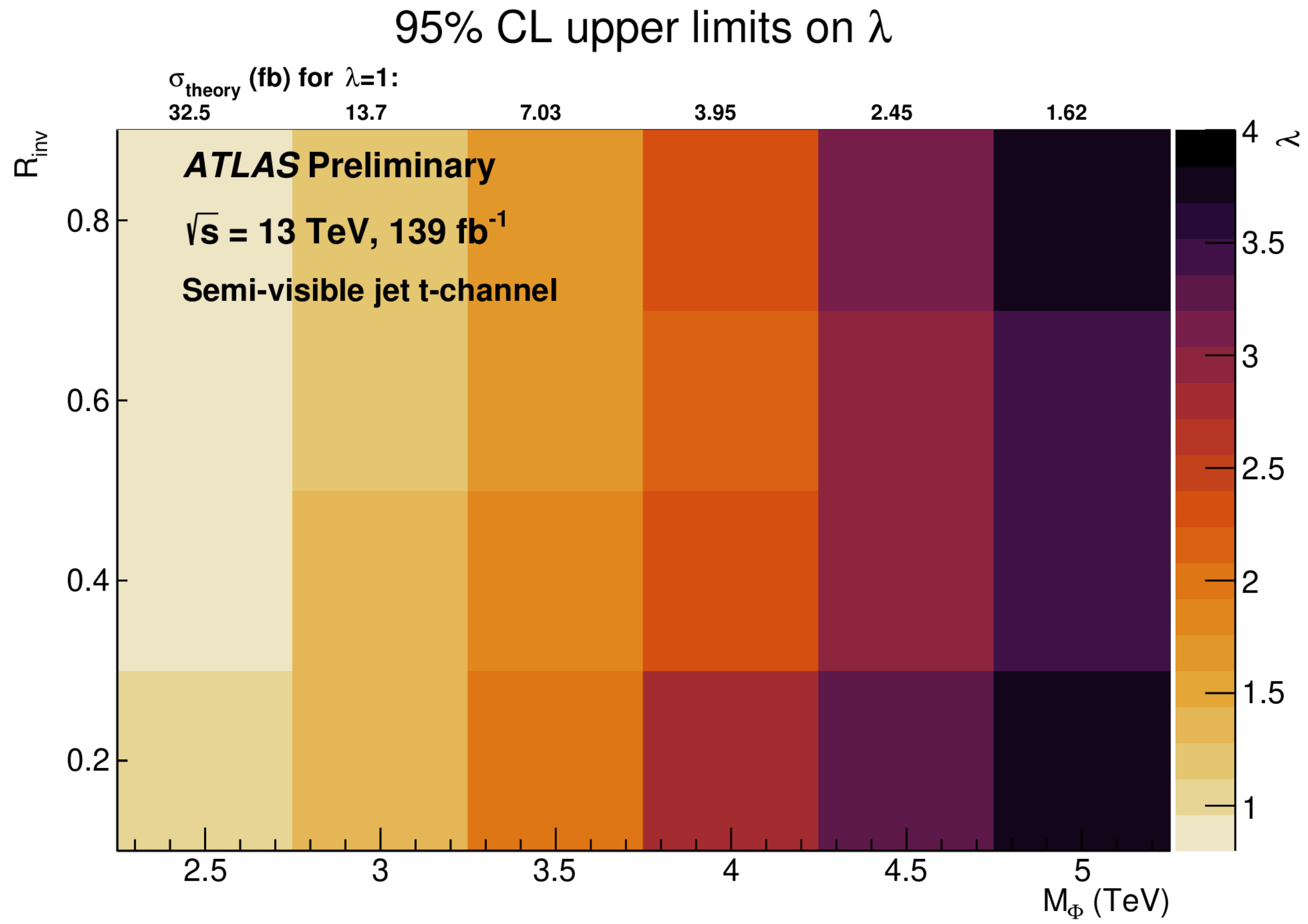
ATLAS-CONF-2022-038



- Bifundamental mediator acts as a portal!
- Two sensitive variables: p_T balance (between closest and farthest jet from MET) and $|\phi_{max} - \phi_{min}|$
- Multibin fit in the SR based on p_T balance and max-min Phi
- CR-SR Simultaneous fit with 0L, 1L(W+jets/top enriched), 2L (Z+jets) selections
  - A template fit performed in 1L1B top enriched → top SF fixed in the other fits



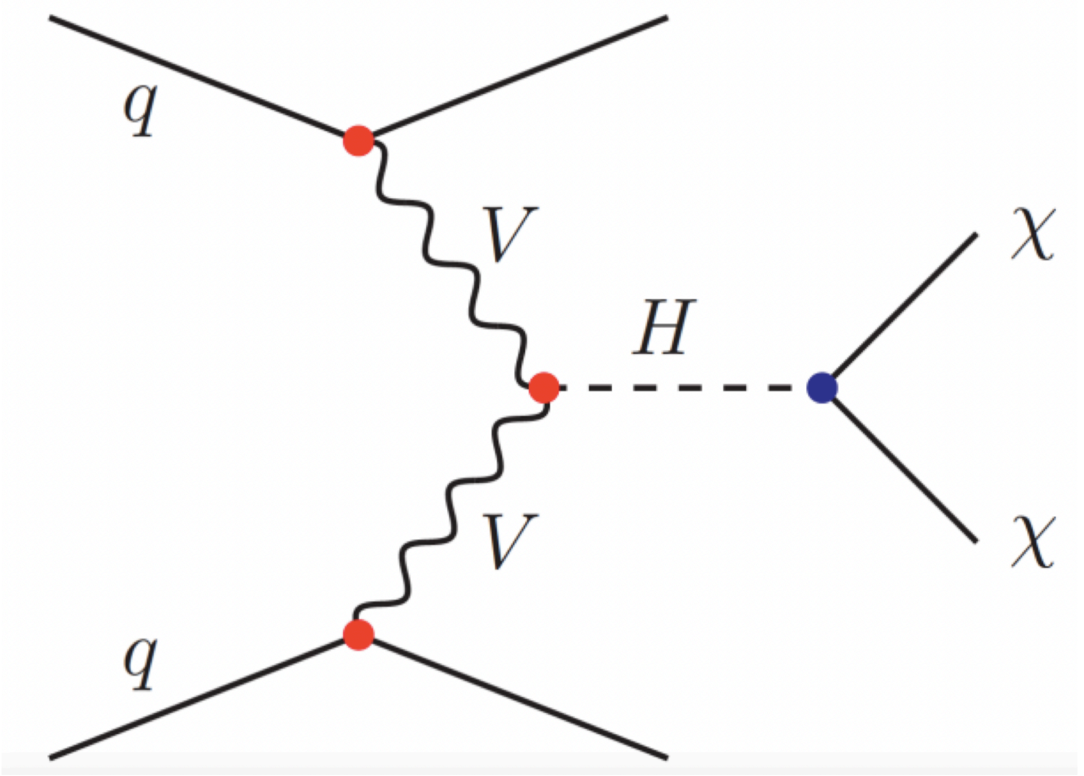




- Limits on mediator mass separately for each Rinv and limits in terms of the q-qd-ϕ vertex coupling strength λ, with the XS scaling as λ^4

ATLAS/CMS: H_{inv} VBF

- Possible coupling of the Higgs boson to dark matter
- Search for invisible Higgs boson decays produced in VBF: VBF H → inv
- Most sensitive among the H → inv direct searches
  - VBF: Second highest rate among Higgs production modes
  - Clean VBF signature



VBF signature:

- 2 jets with large η gap between leading jets
- Large dijet invariant mass
- Small $\Delta\varphi_{jj}$ and large E_T^{miss}

Main Backgrounds : $Z \to \nu\nu$, $W \to \ell\nu$, multijet

ATLAS: H_{inv} VBF Results

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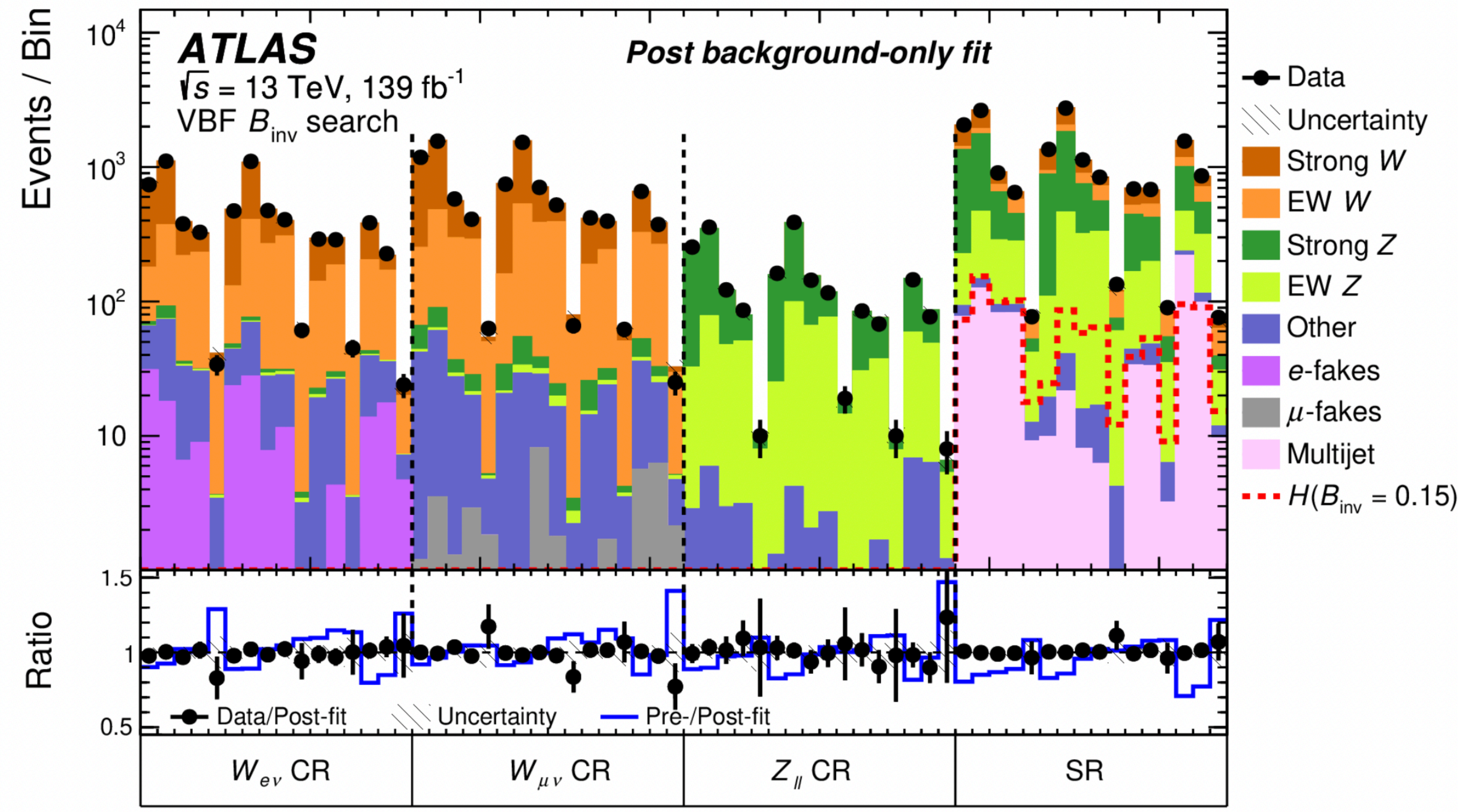
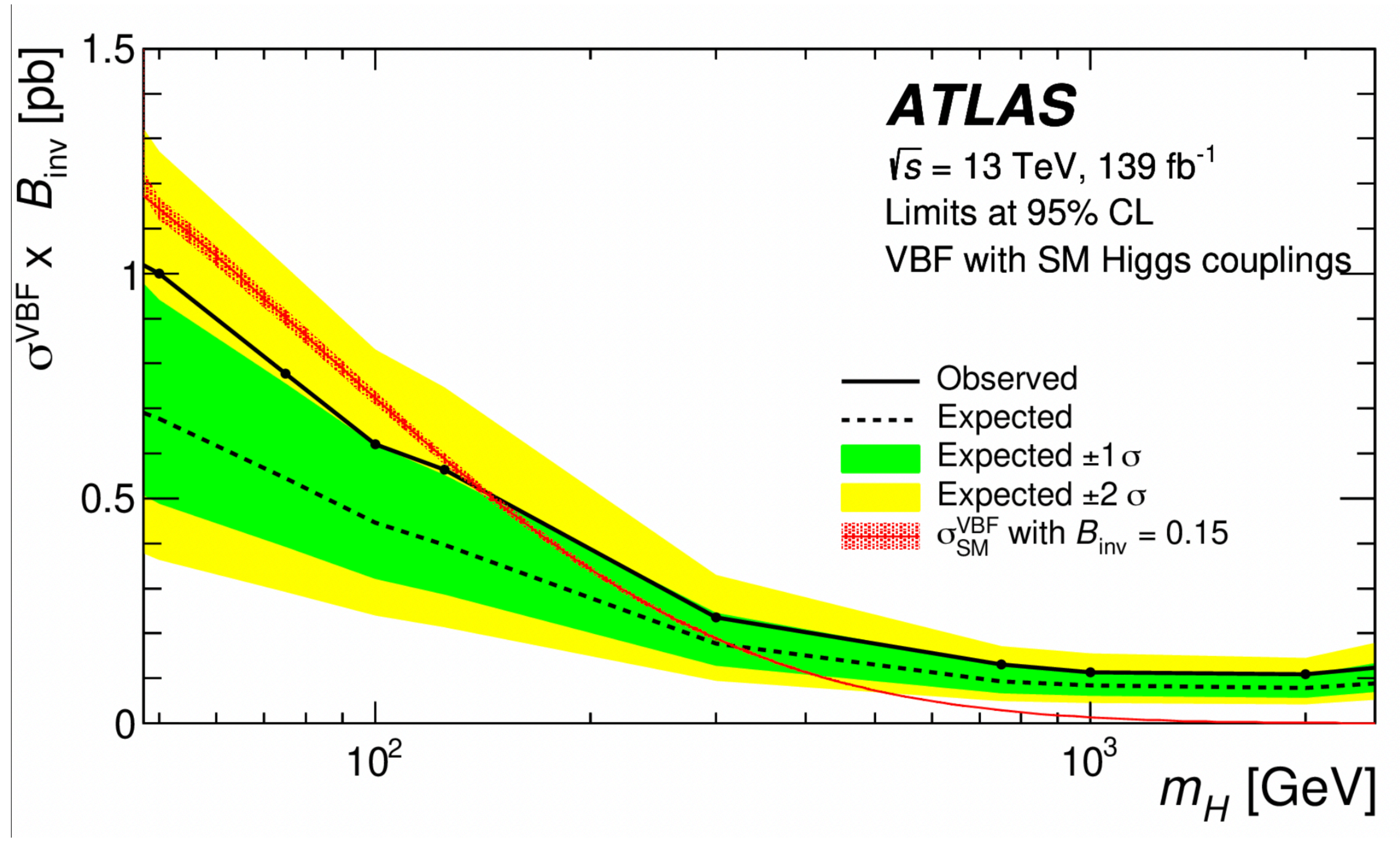
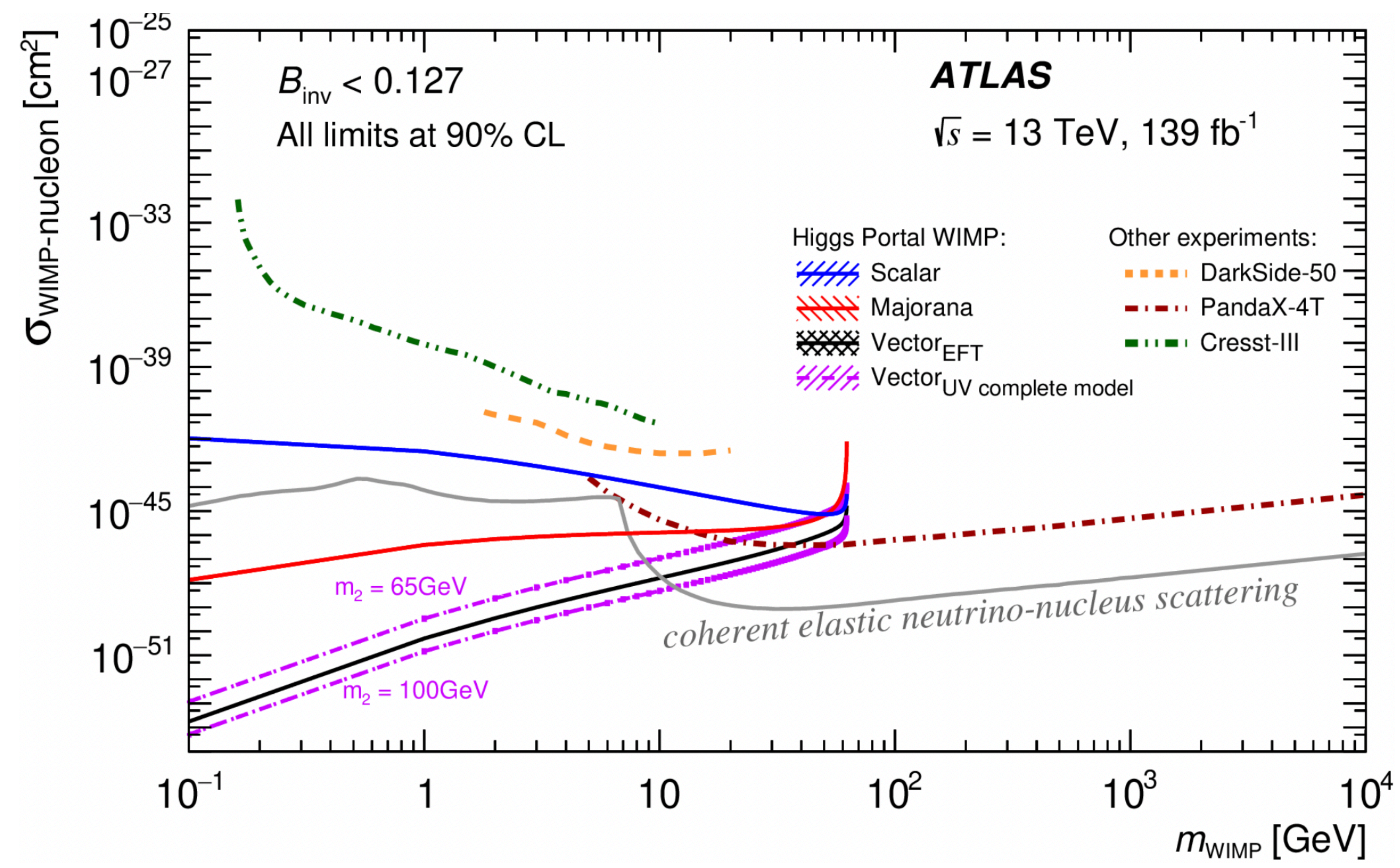
VBF + E_T^{miss} SRs & CRs : No excess over Standard Model predictions.







Upper limit on B(H→inv) at 95% C.L.

Observed	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ
0.145	0.103	0.144	0.075	0.196	0.055

CMS: H_{inv} VBF Results

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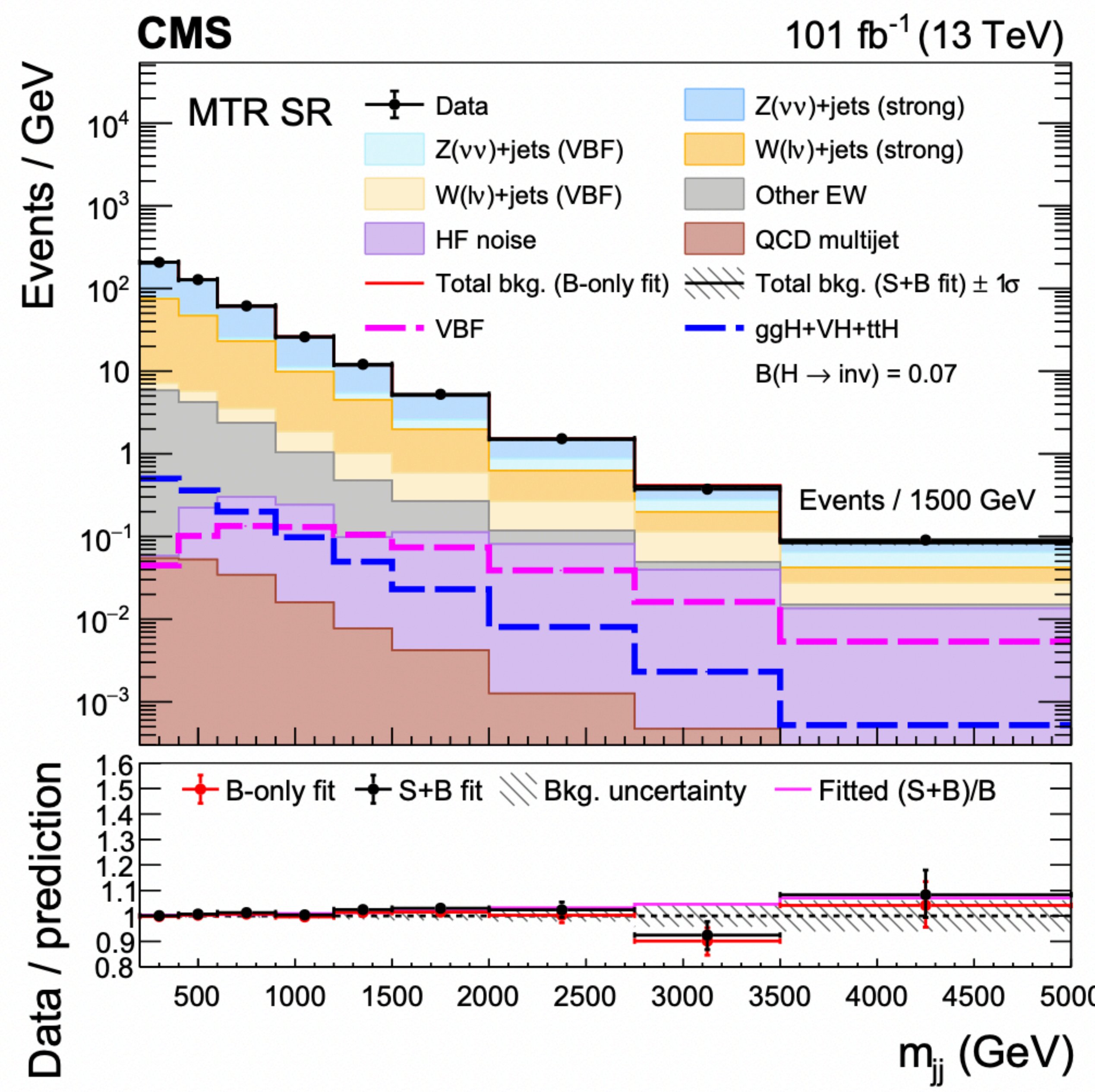
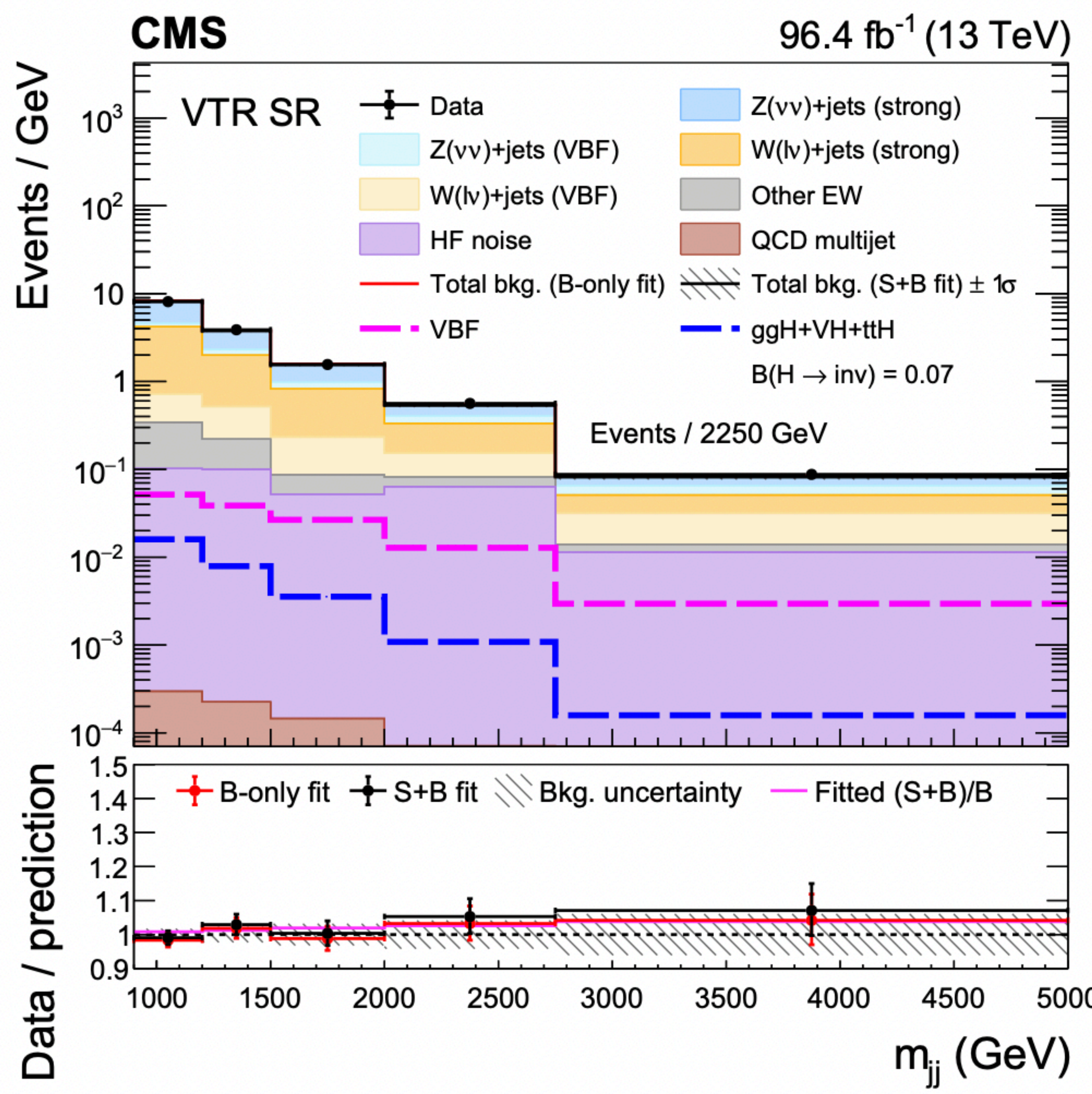
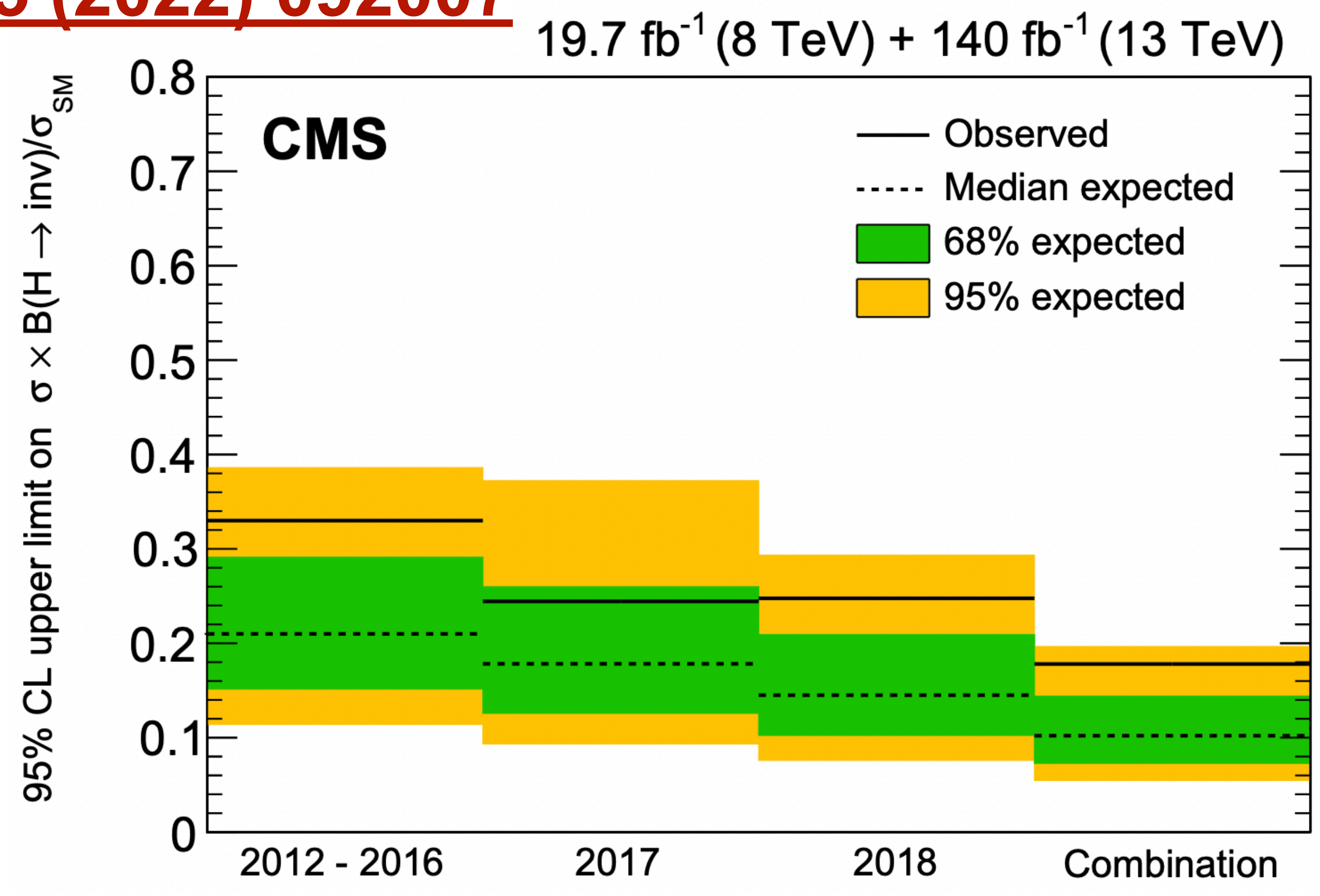
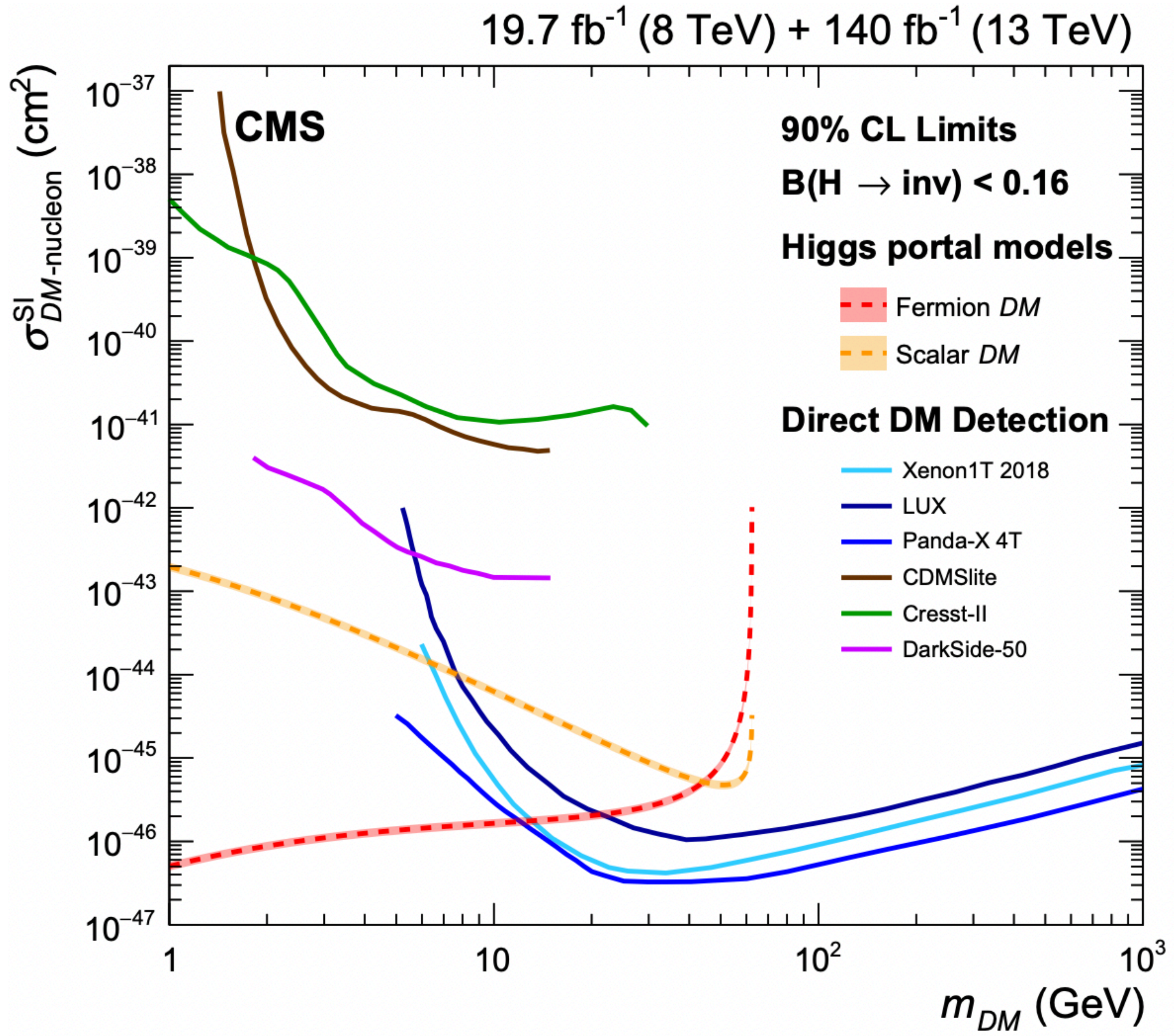




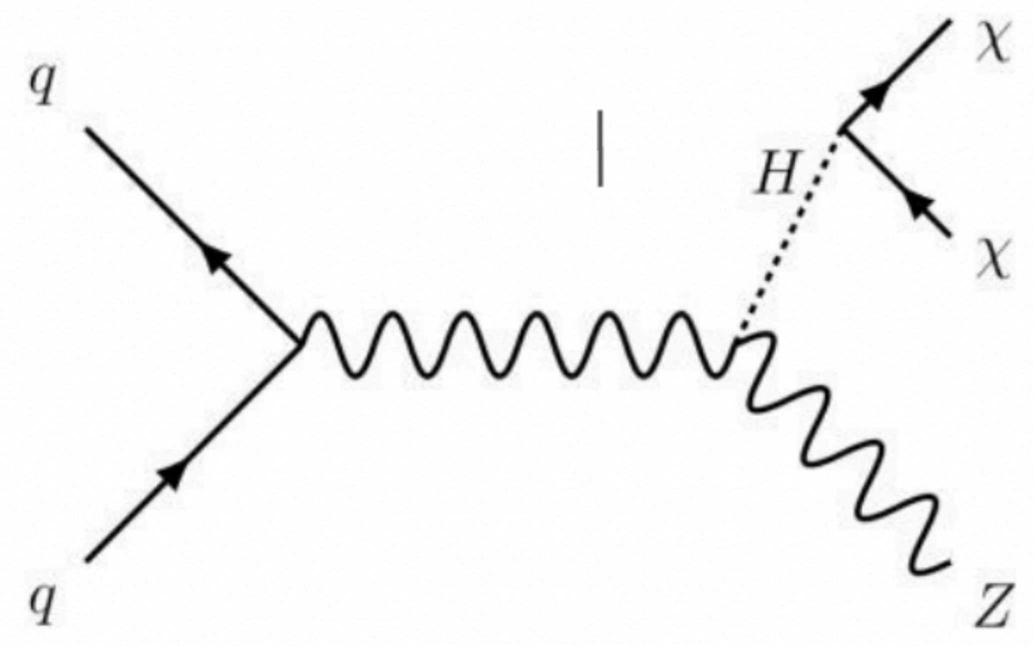




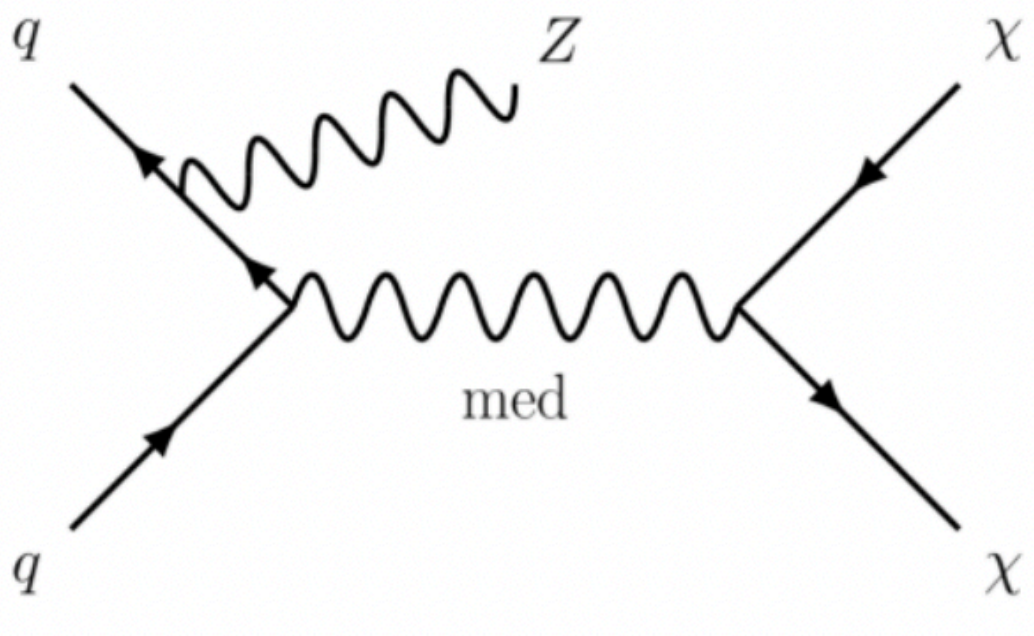
- Using two different trigger strategies (MET trigger and VBF trigger) to recover lower-MET event
- Combination of Run 1 and Run2:
  - 95% CL upper limits on **BR (H→inv) < 0.18 (0.10)**

ATLAS/CMS: Z(ll)+MET (ZH, MONO-Z)

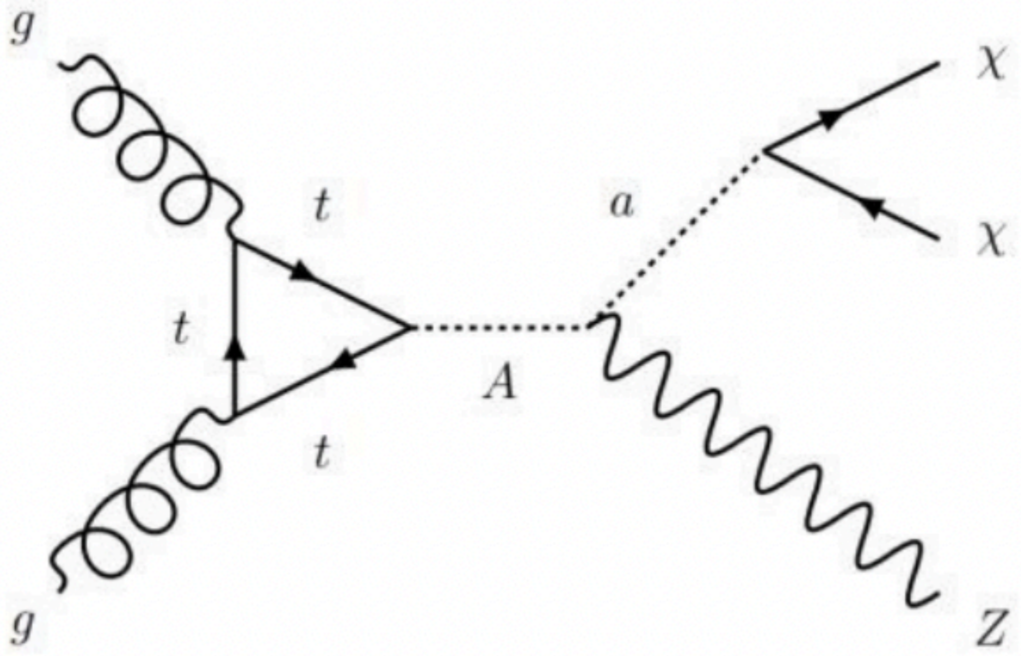
Search in the ll (from Z) + MET (from Higgs invisible or through mediators) final state:



Higgs invisible decay



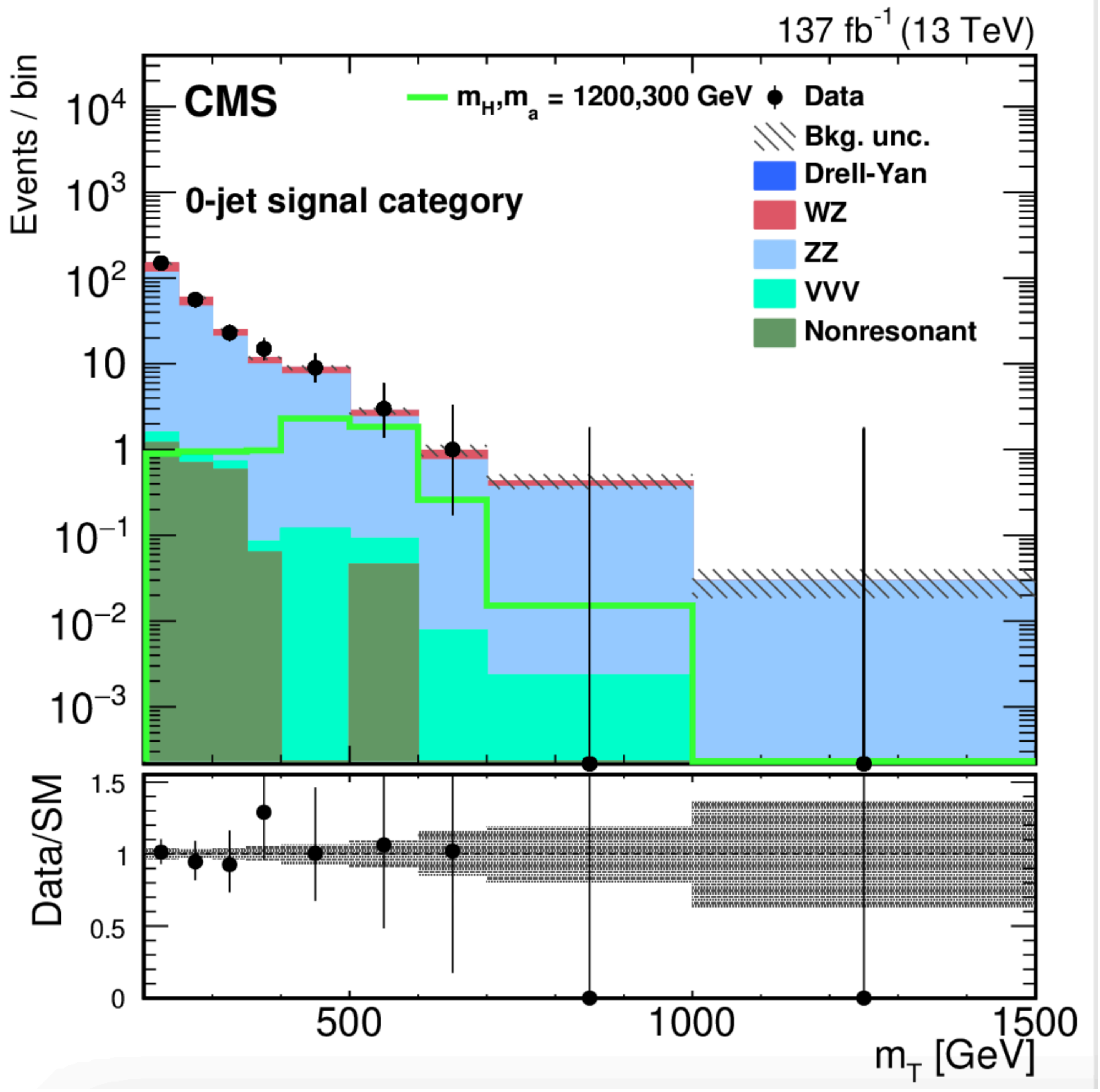
Simplified models

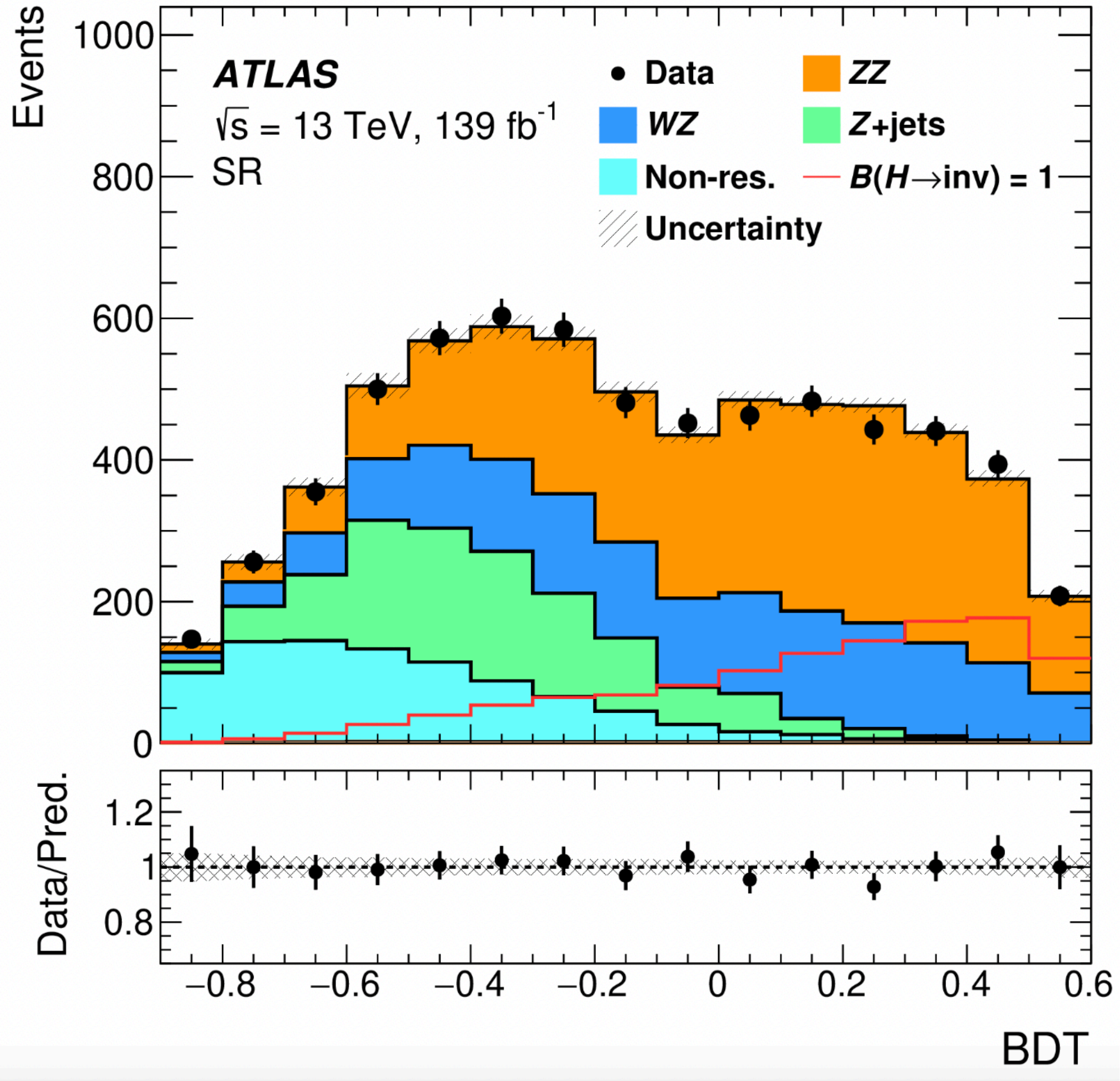


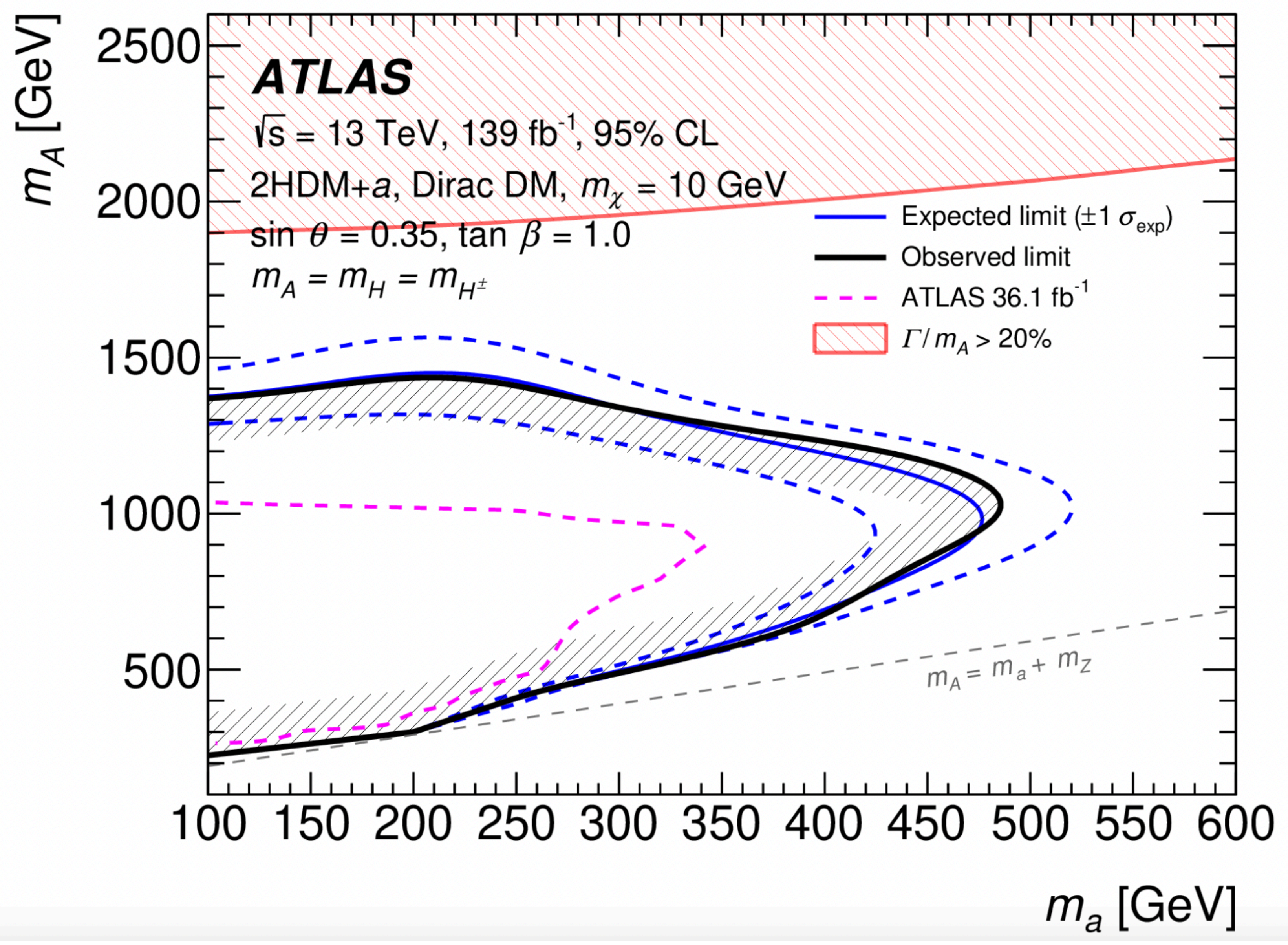
2HDM+a models

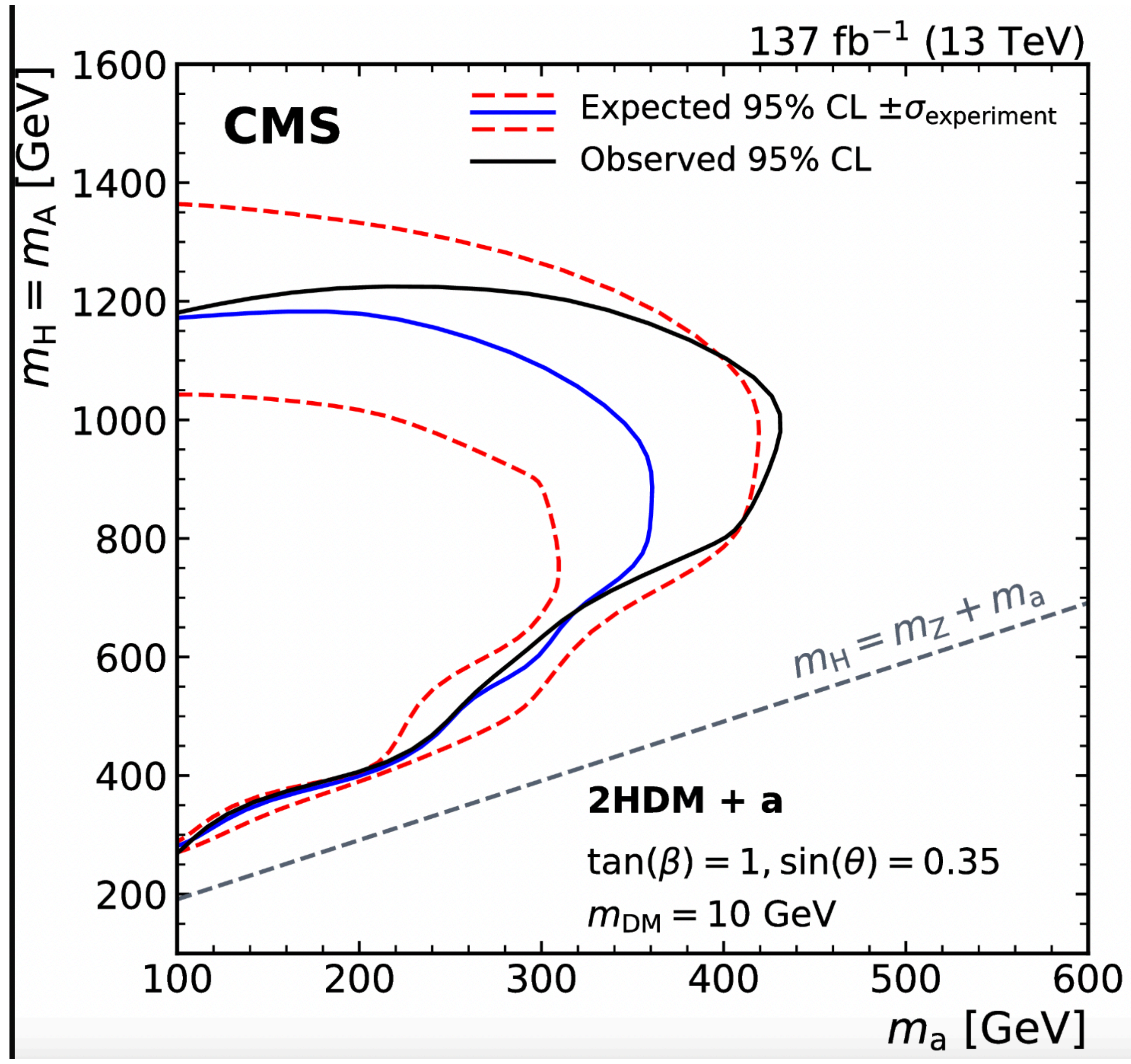
- 3l, 4l CRs used to constrain WZ/ZZ SM predictions
- Simutanous fit to E_T^{miss}, BDT score or m_T in CRs to estimate SR total background.
  - BDT used for H→invisible, E_T^{miss} / m_T used for mono-Z models
- Main background: SM qq→ZZ

ATLAS/CMS: Z(ll)+MET









Phys. Lett. B 829 (2022) 137066,

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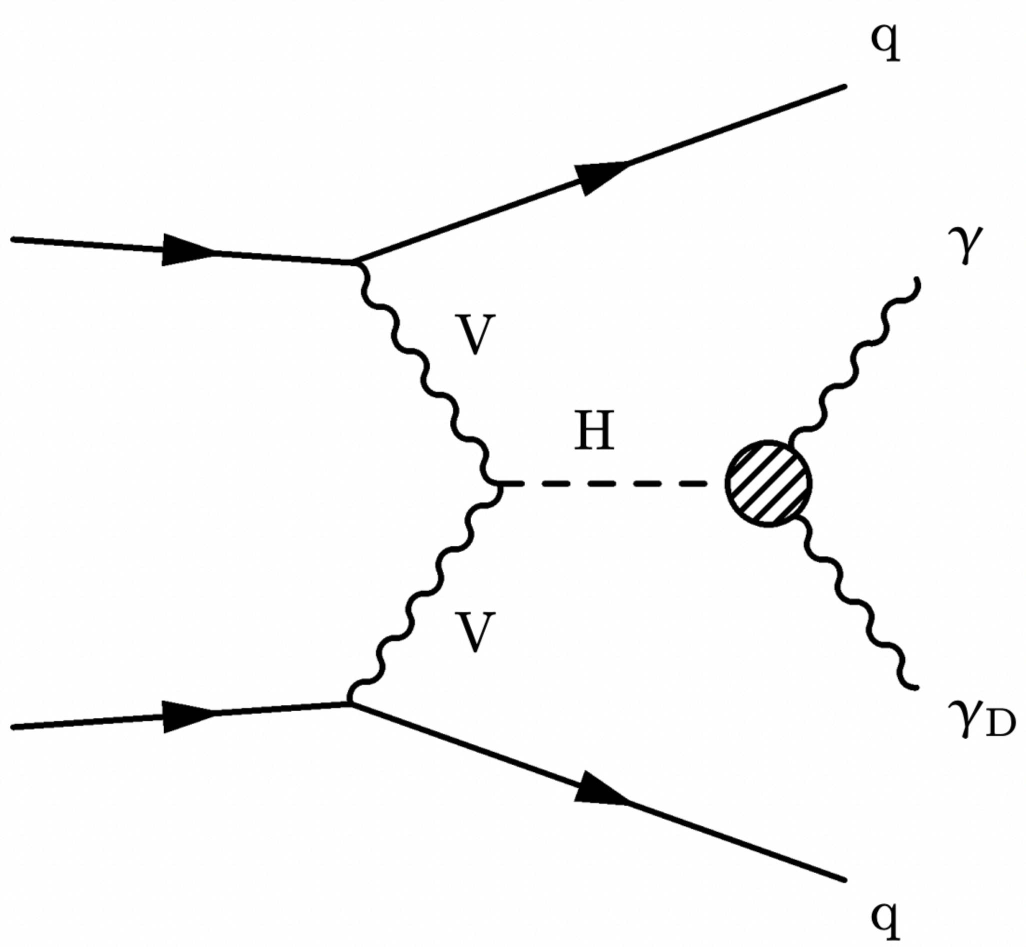
ATLAS/CMS:VBF + MET + Photon

- Search for semivisible Higgs decays → isolated photon, MET, and 2 VBF jets
- Dedicated CRs for major background: W+jets, Wγ, Zγ, γ+jets
- Simultaneous fit of SR and CRs
- M_T (γ,MET) shape analysis for γ_D in bins of m_{jj}

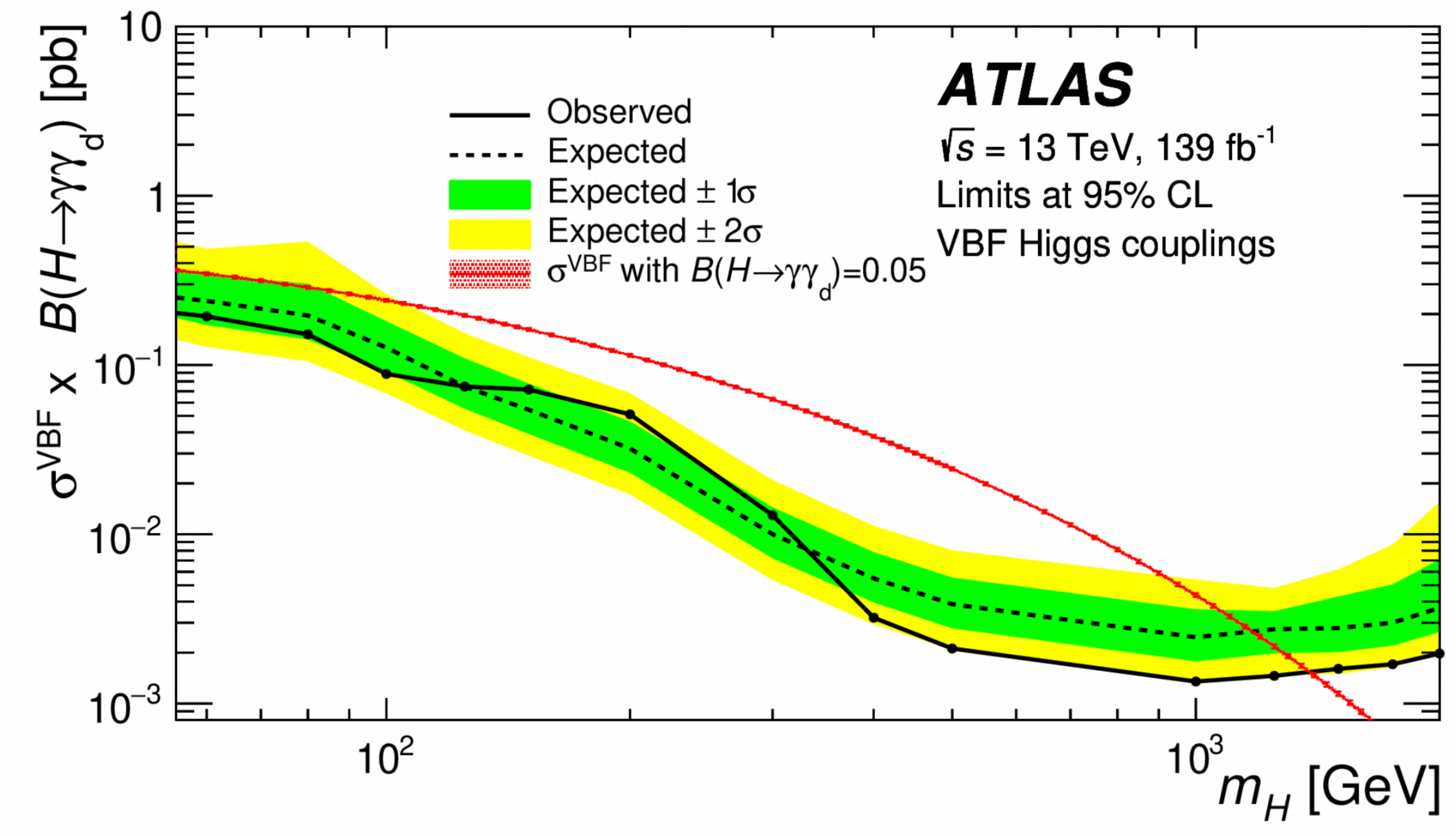


CMS

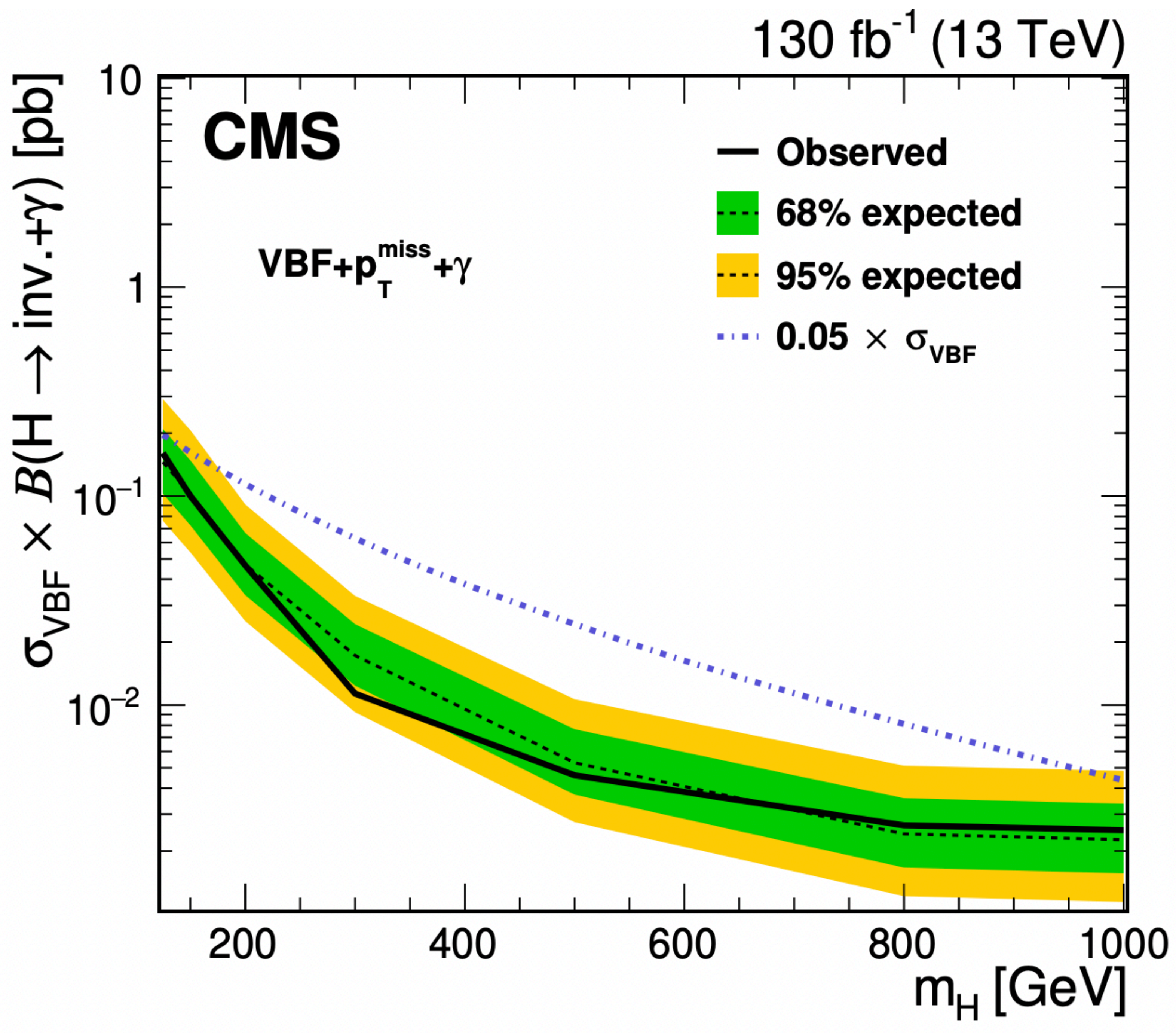
VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.5	$2.8^{+1.3}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+1.0}_{-0.7}$

Eur. Phys. J. C 82 (2022) 105,

JHEP 03 (2021) 011

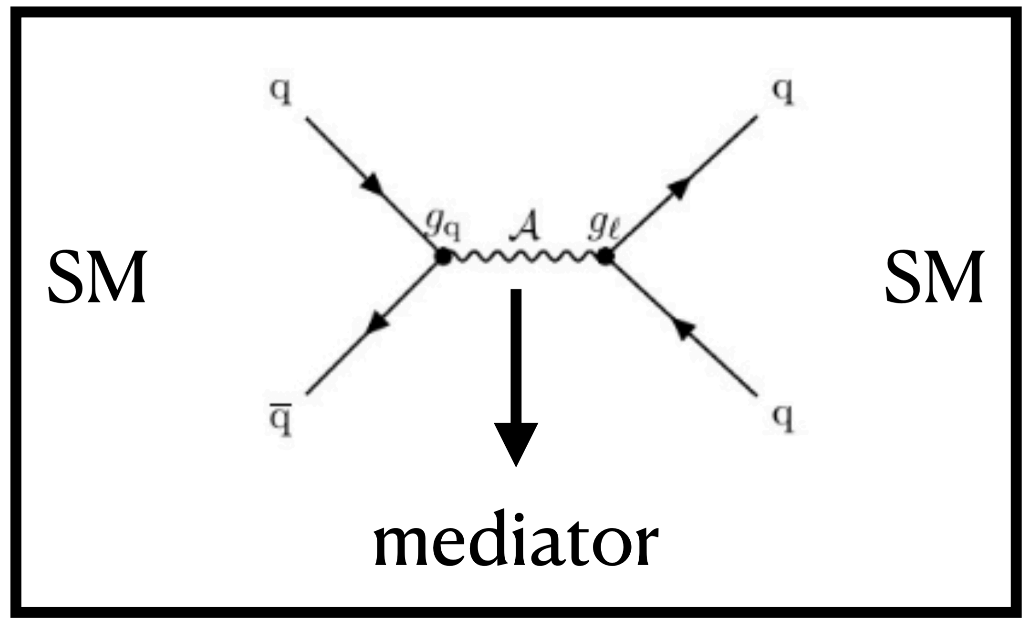


Observed (Expected) upper limit on BR(125 GeV):
ATLAS: 1.8% (1.7%),
CMS: 2.9% (2.1%)

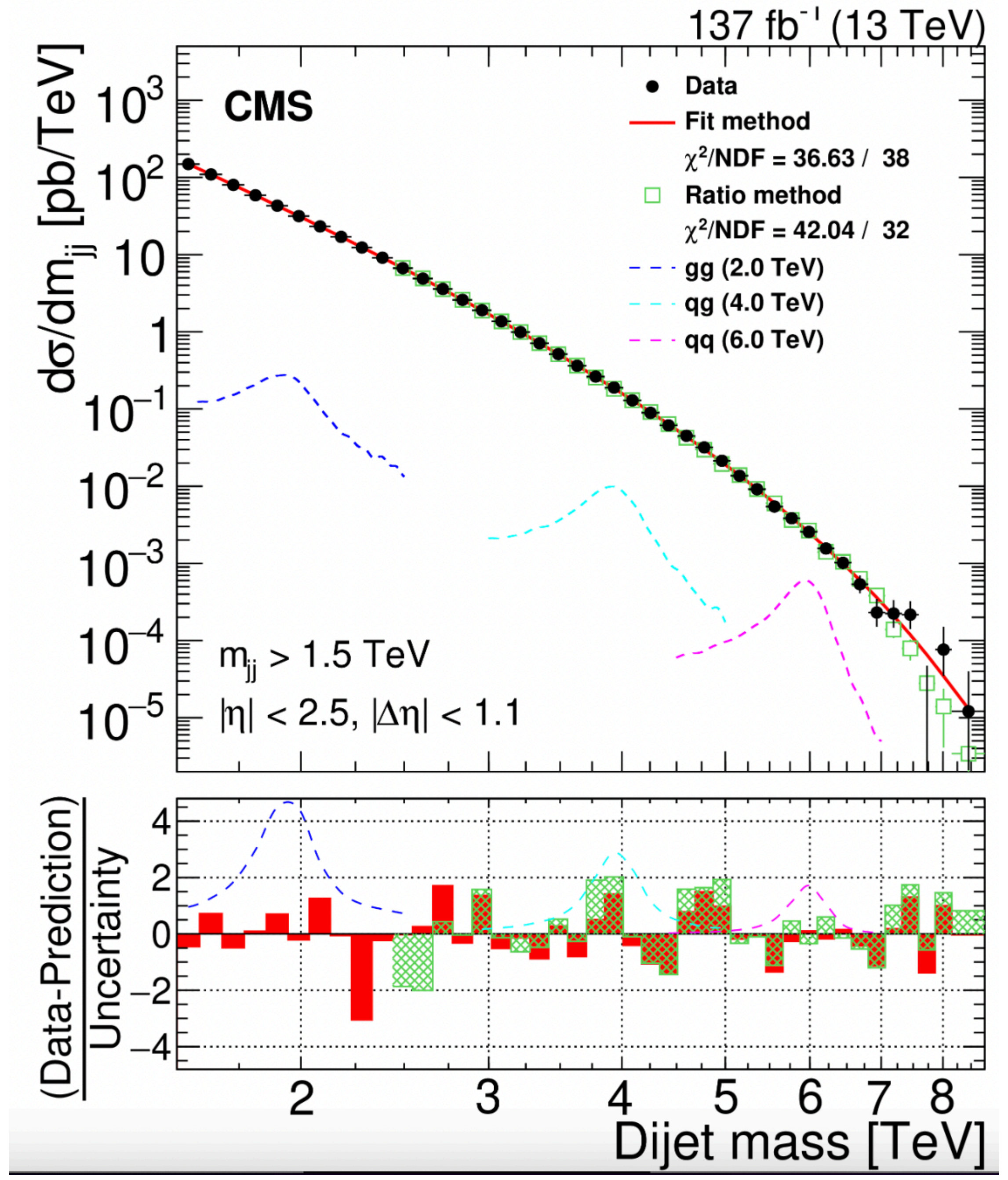


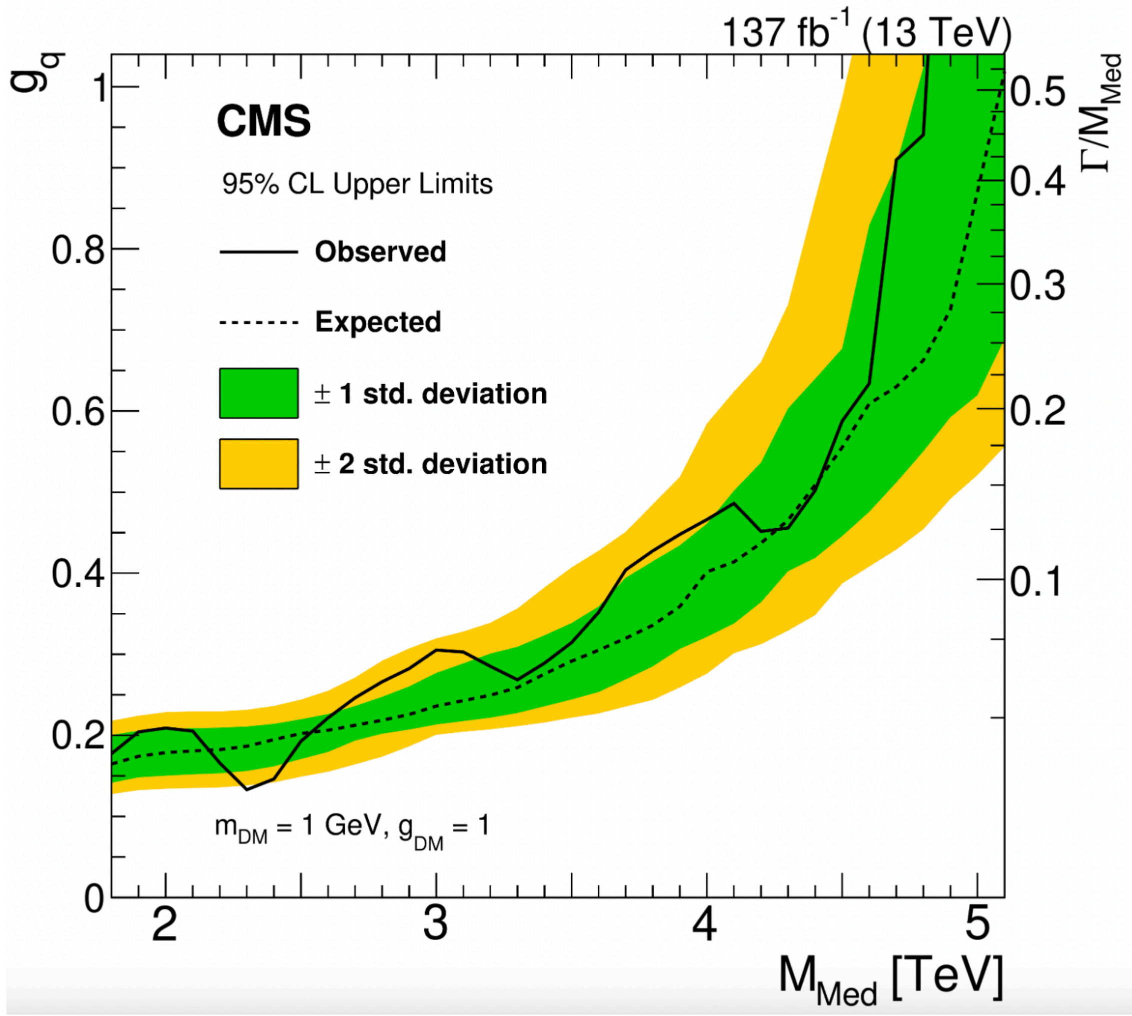
ATLAS/CMS:Dijet resonances

- Direct search for mediator particle in dijet mass spectrum
- Look for bump over smoothly falling background (fit)
- Sensitivity at low mass limited by trigger threshold
- For low mass: dijet TLA, di-jet+lepton/jet with trigger on jet / photon / lepton
- No excess observed with respect to the SM background expectations.

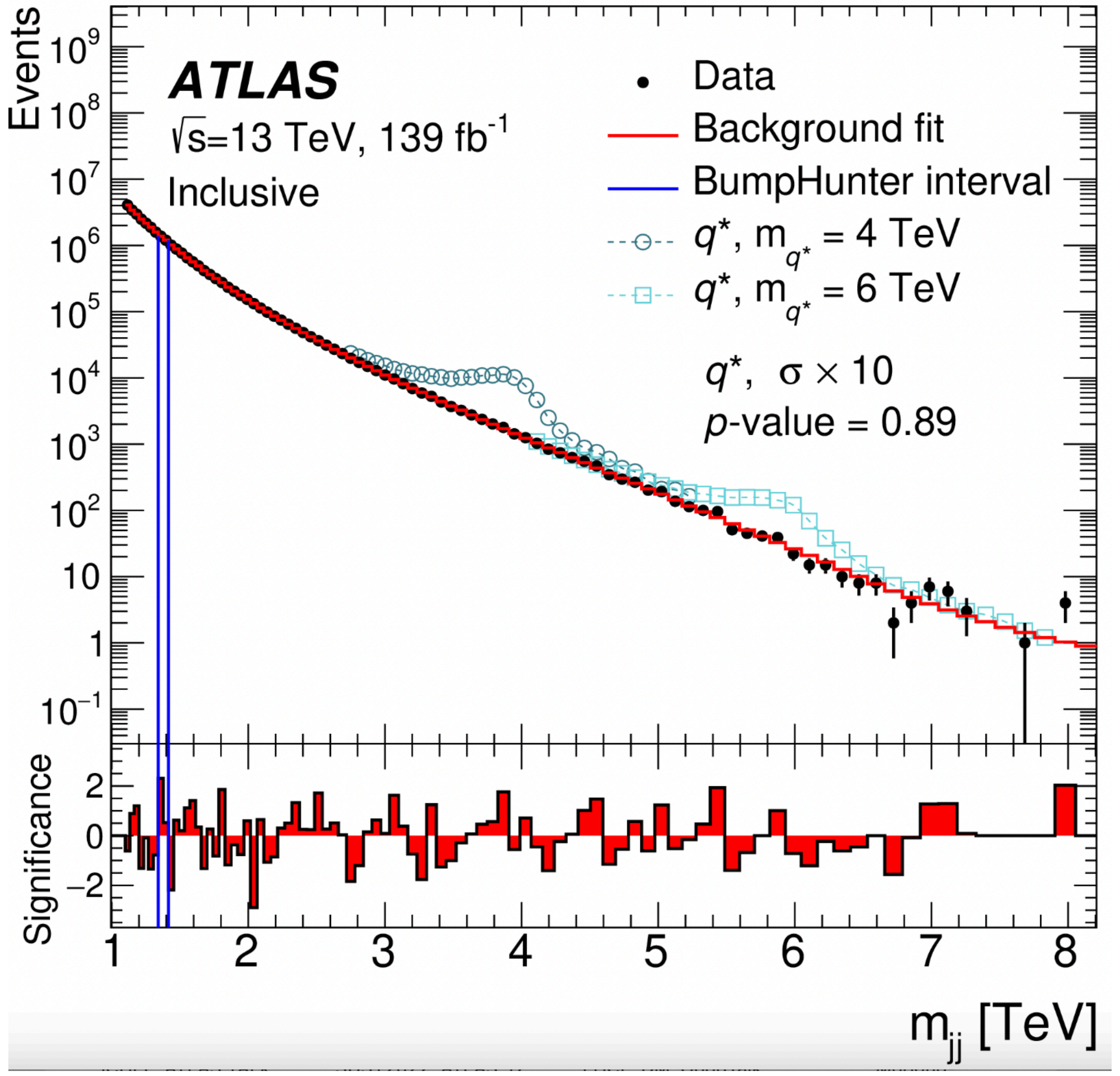


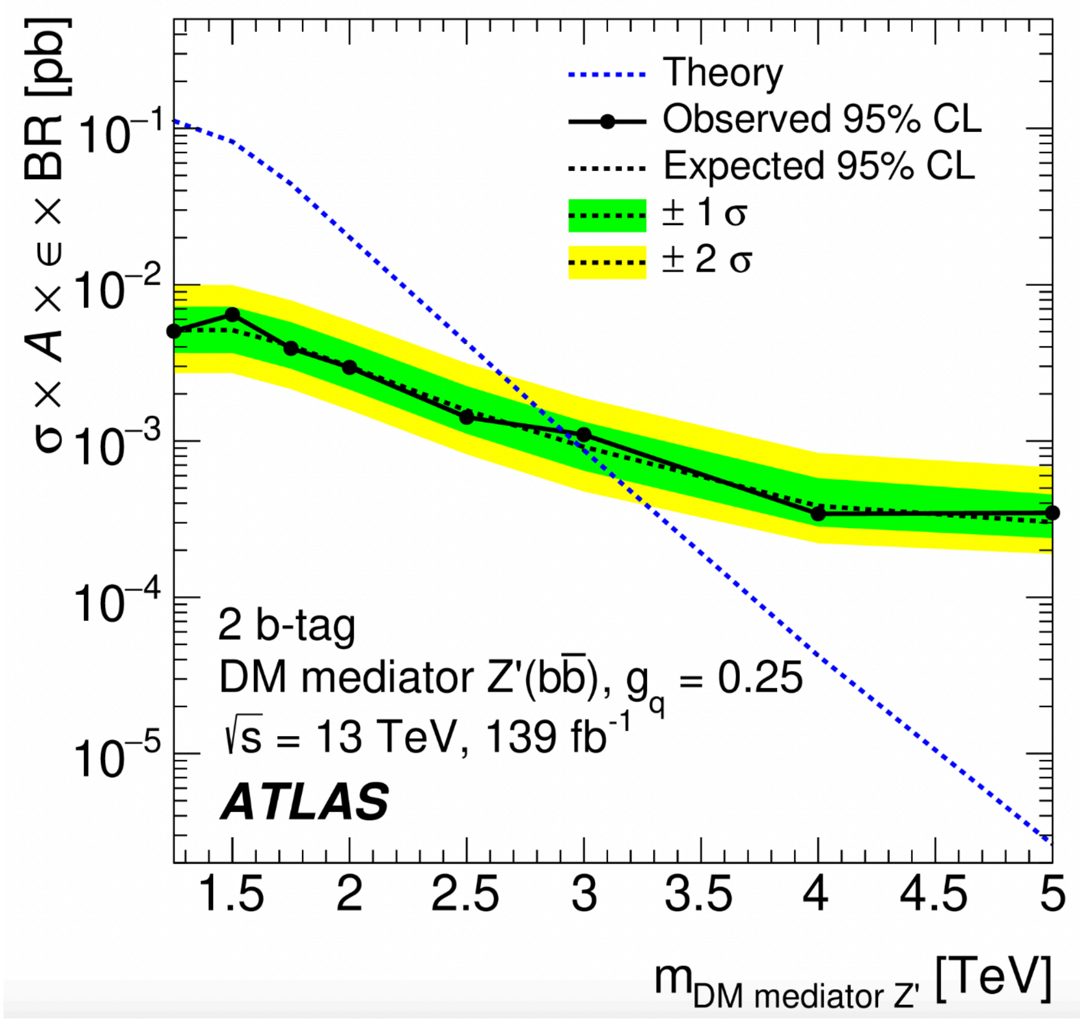
JHEP 05 (2020) 033





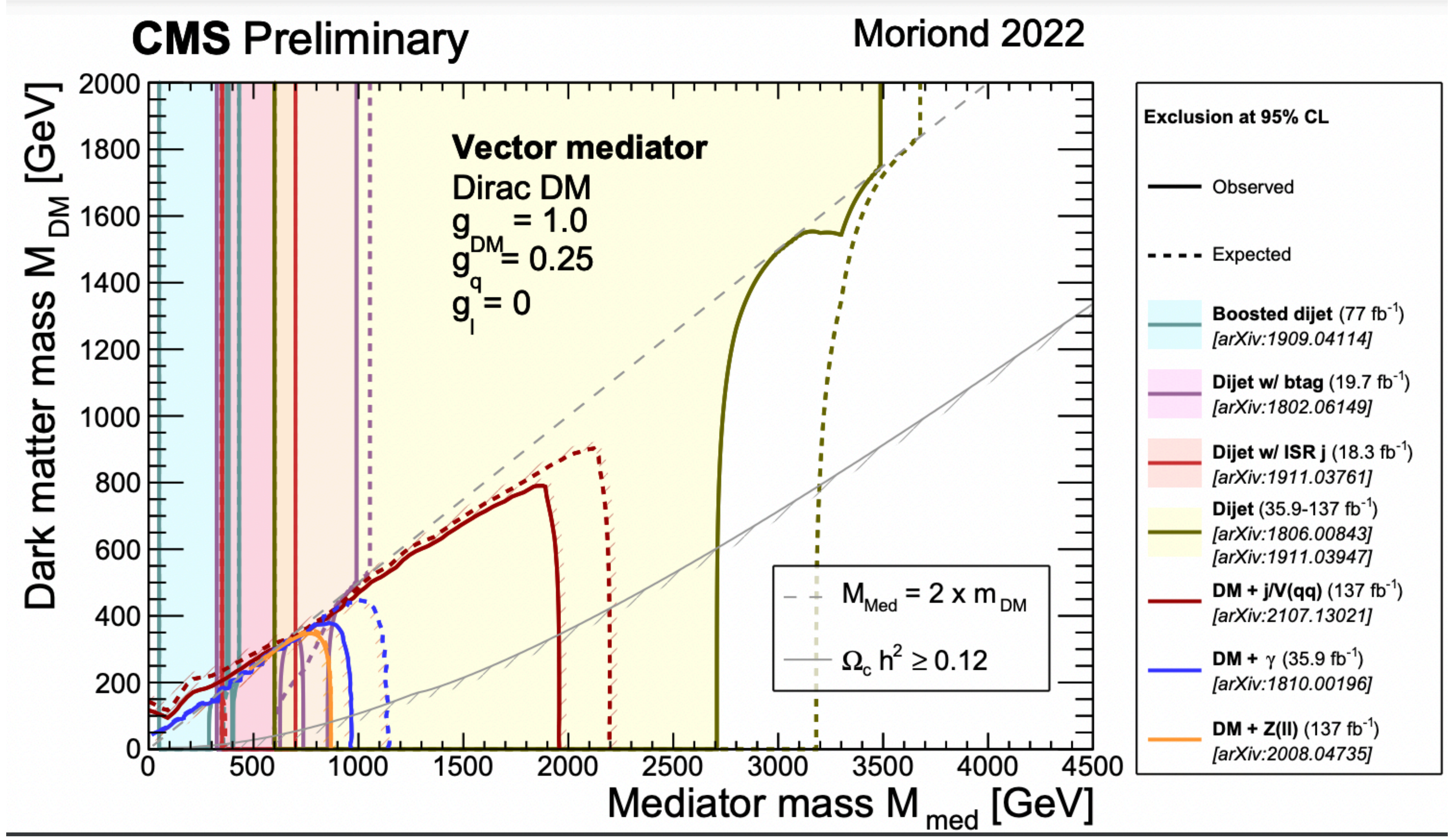
JHEP 03 (2020) 145

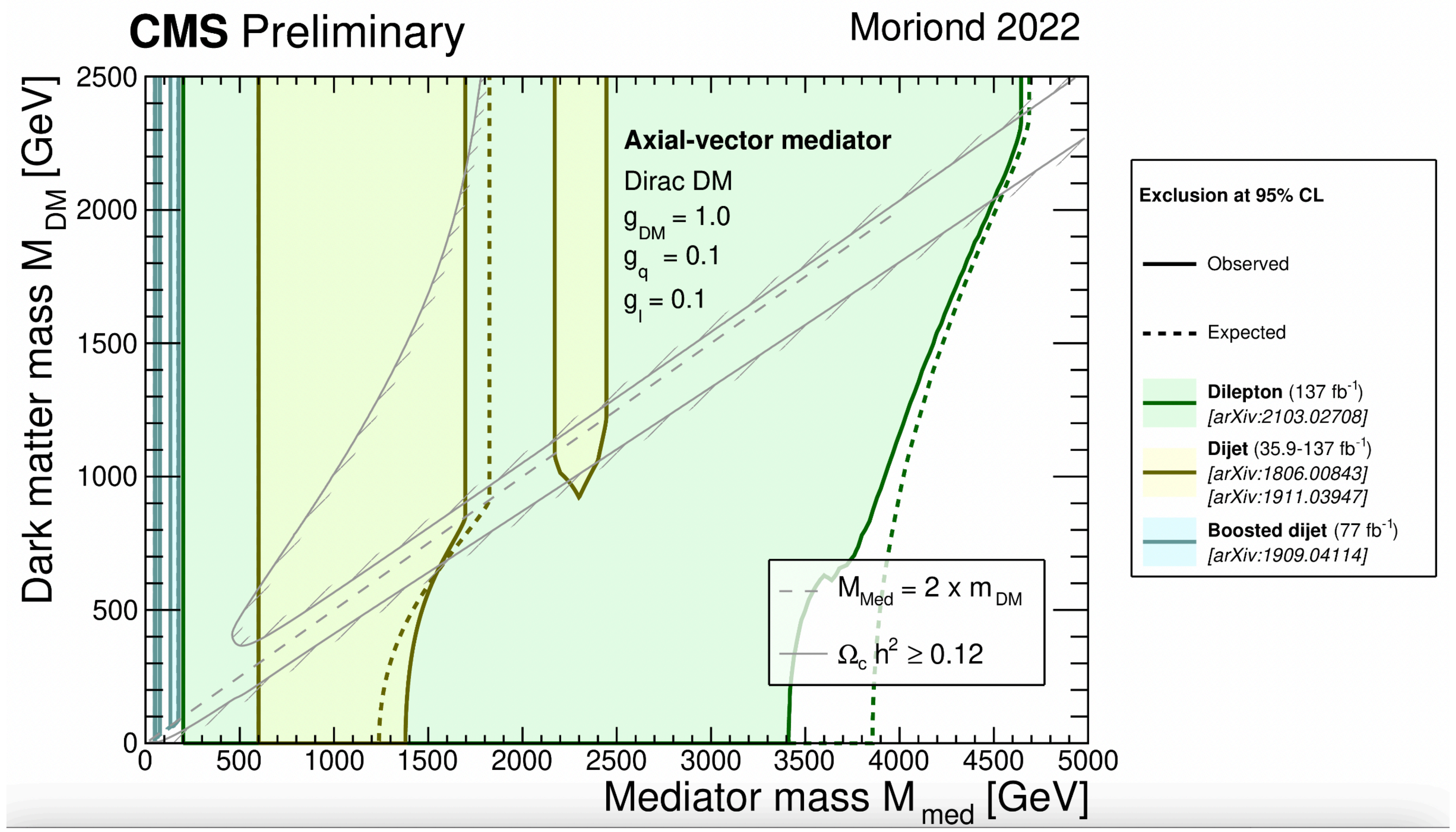




CMS: DM Summary Plots

DM Summary Plots

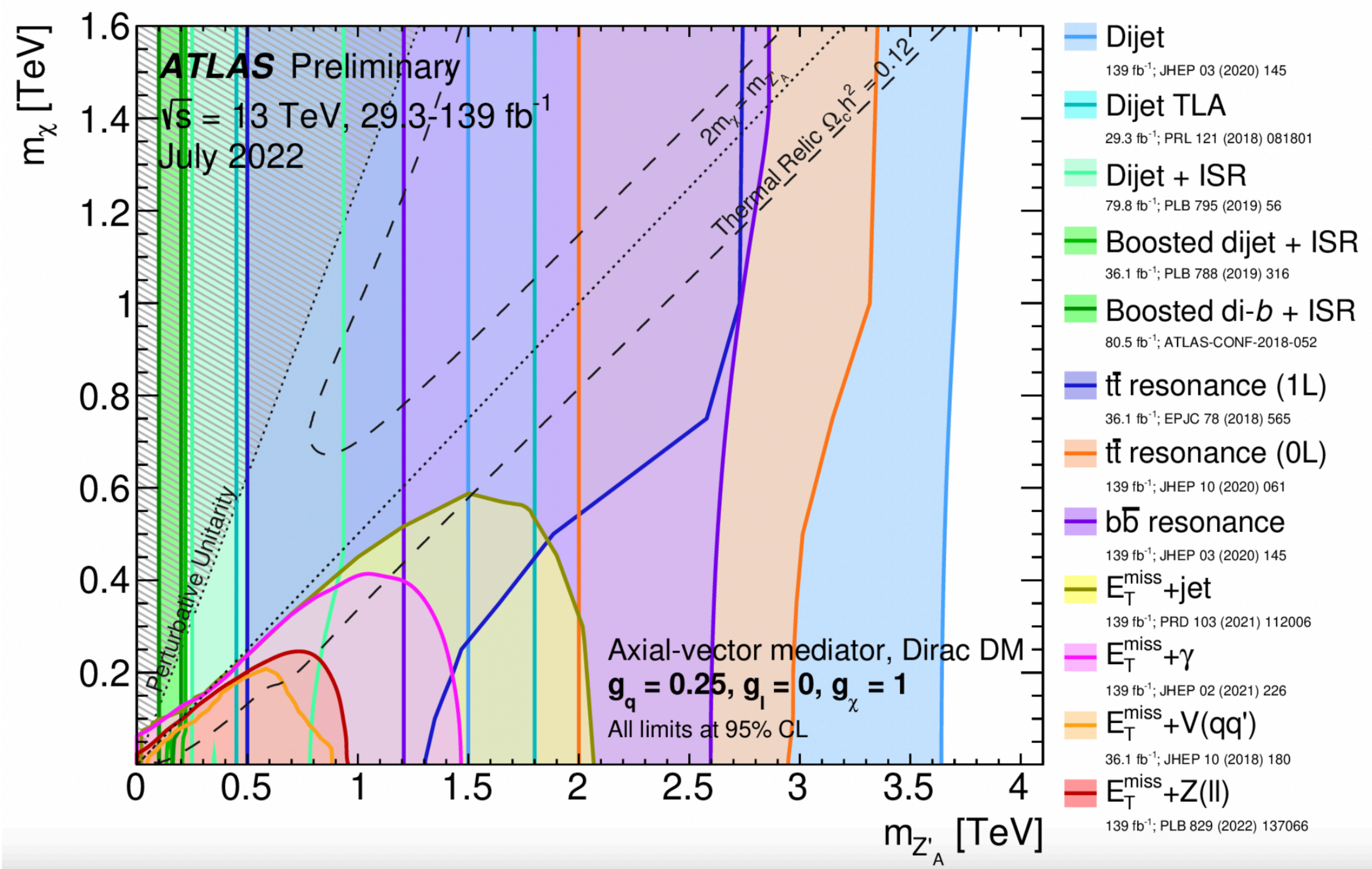


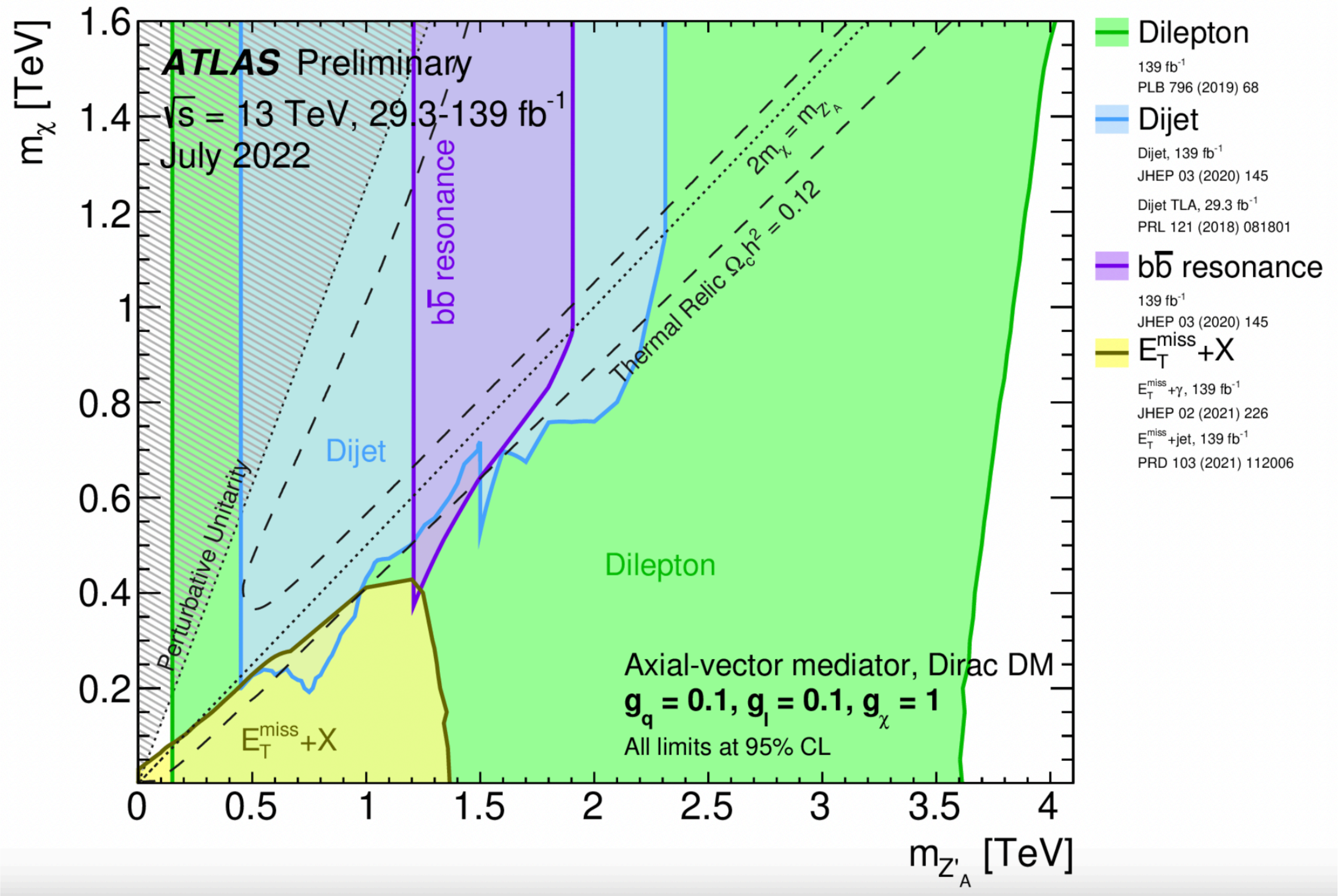


s-channel spin-1 mediator summary plots, including both monoX and resonance search channels

ATLAS: DM Summary Plots

ATL-PHYS-PUB-2022-036

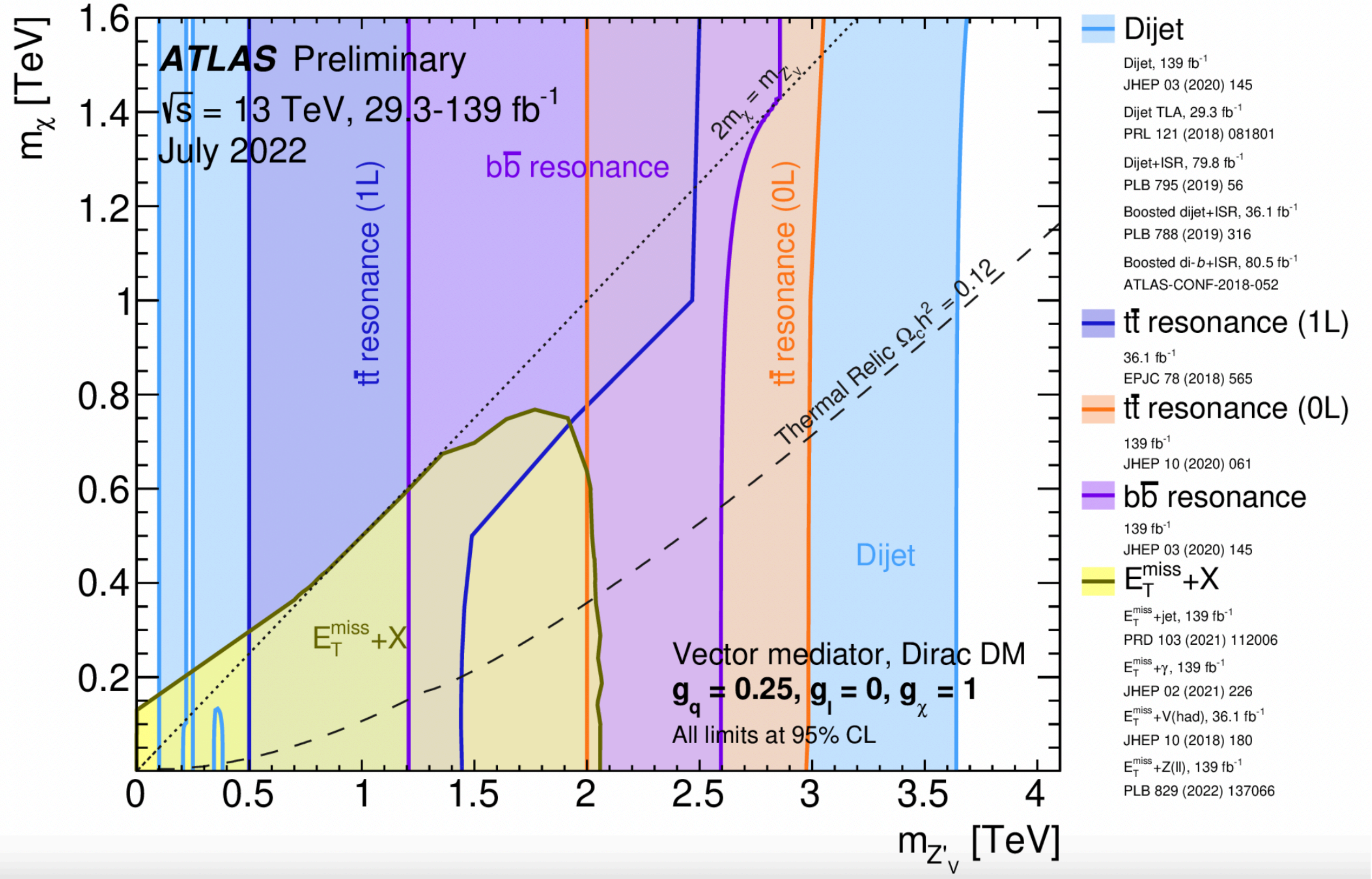


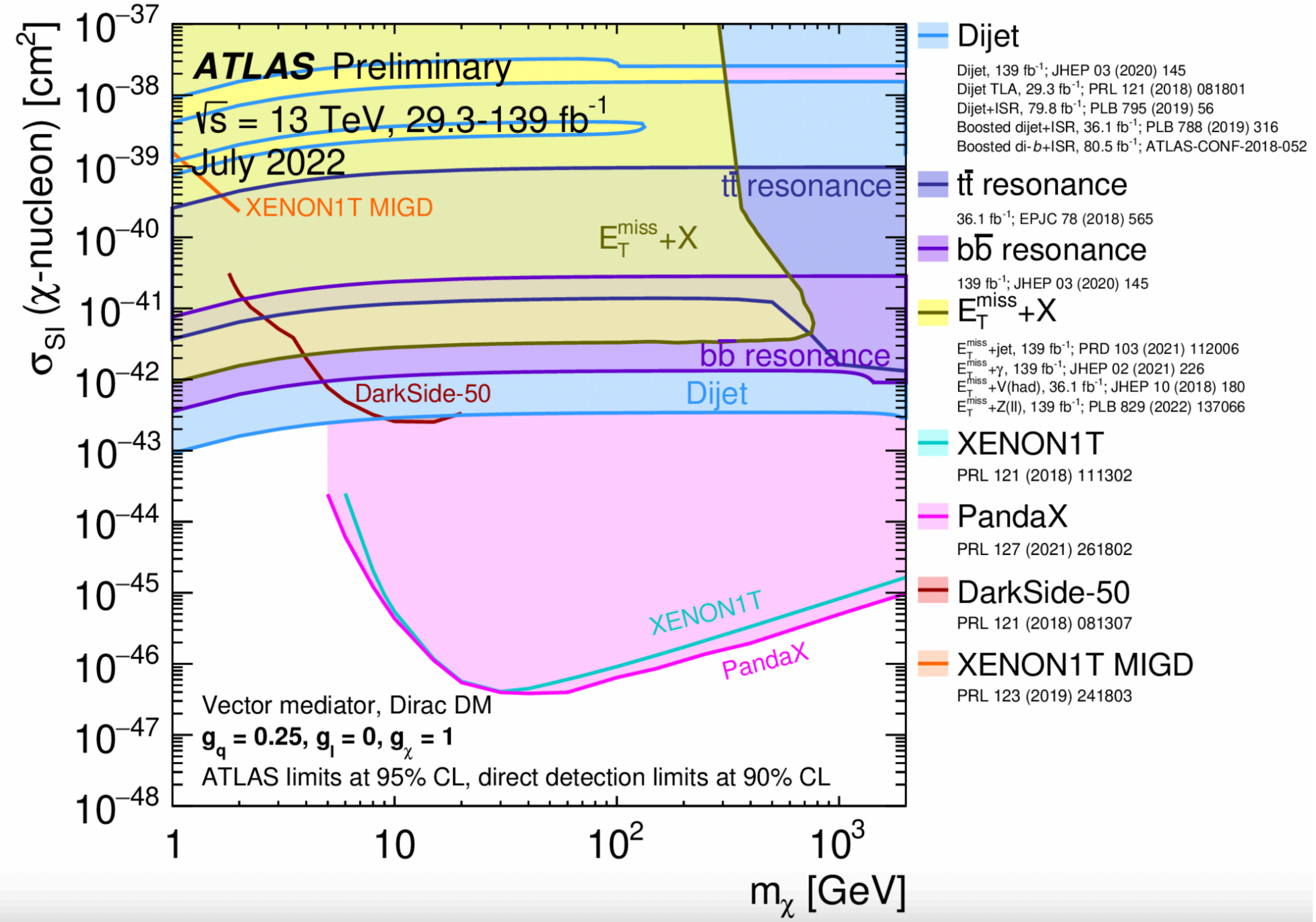


s-channel spin-1 mediator summary plots, including both monoX and resonance search channels

Comparison to Direct Detection

ATL-PHYS-PUB-2022-036





LHC and Direct Detection provide complementary constraints
Comparison to direct detection strongly dependent on coupling assumption

ATLAS/CMS:Hinv combination

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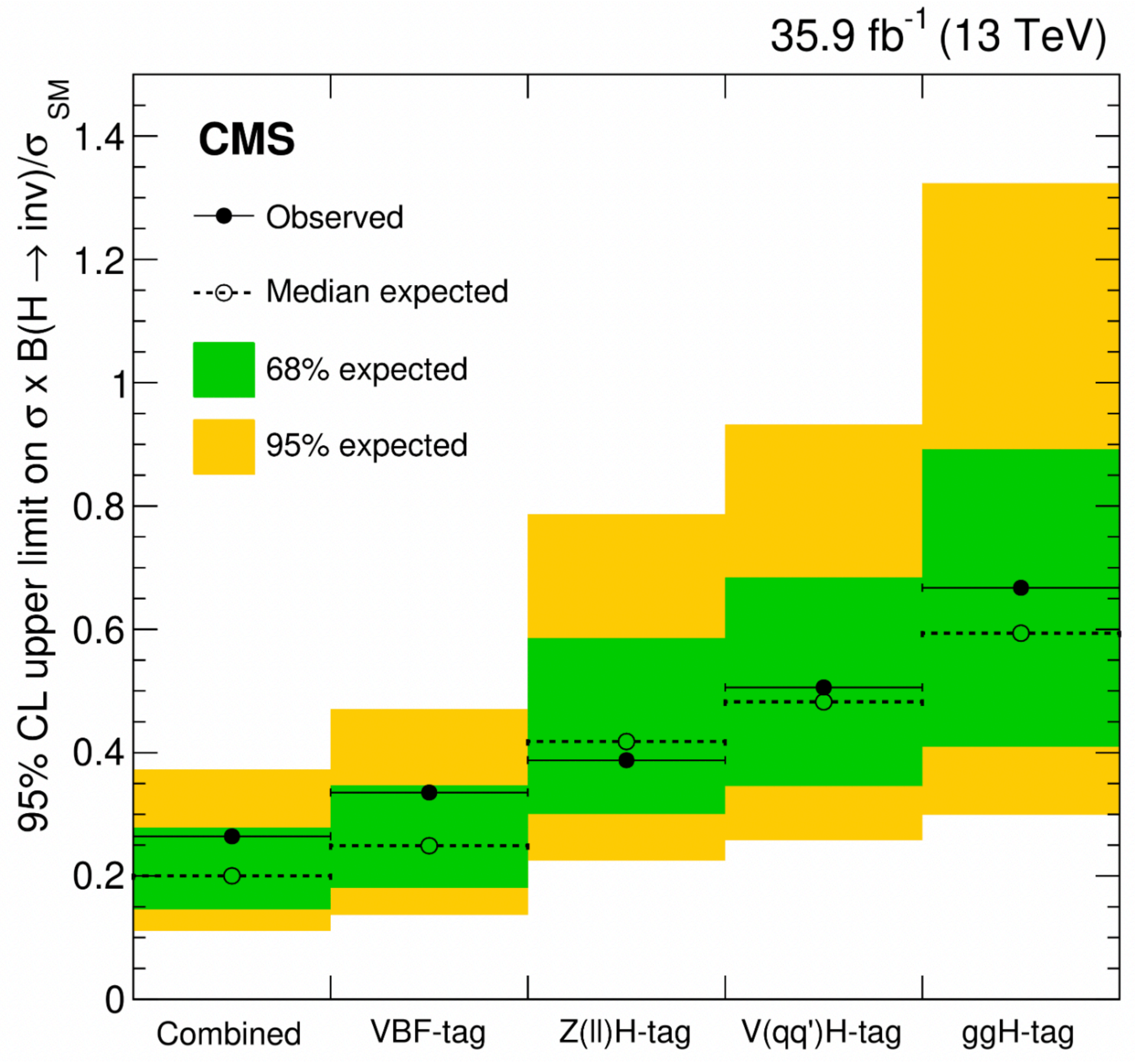
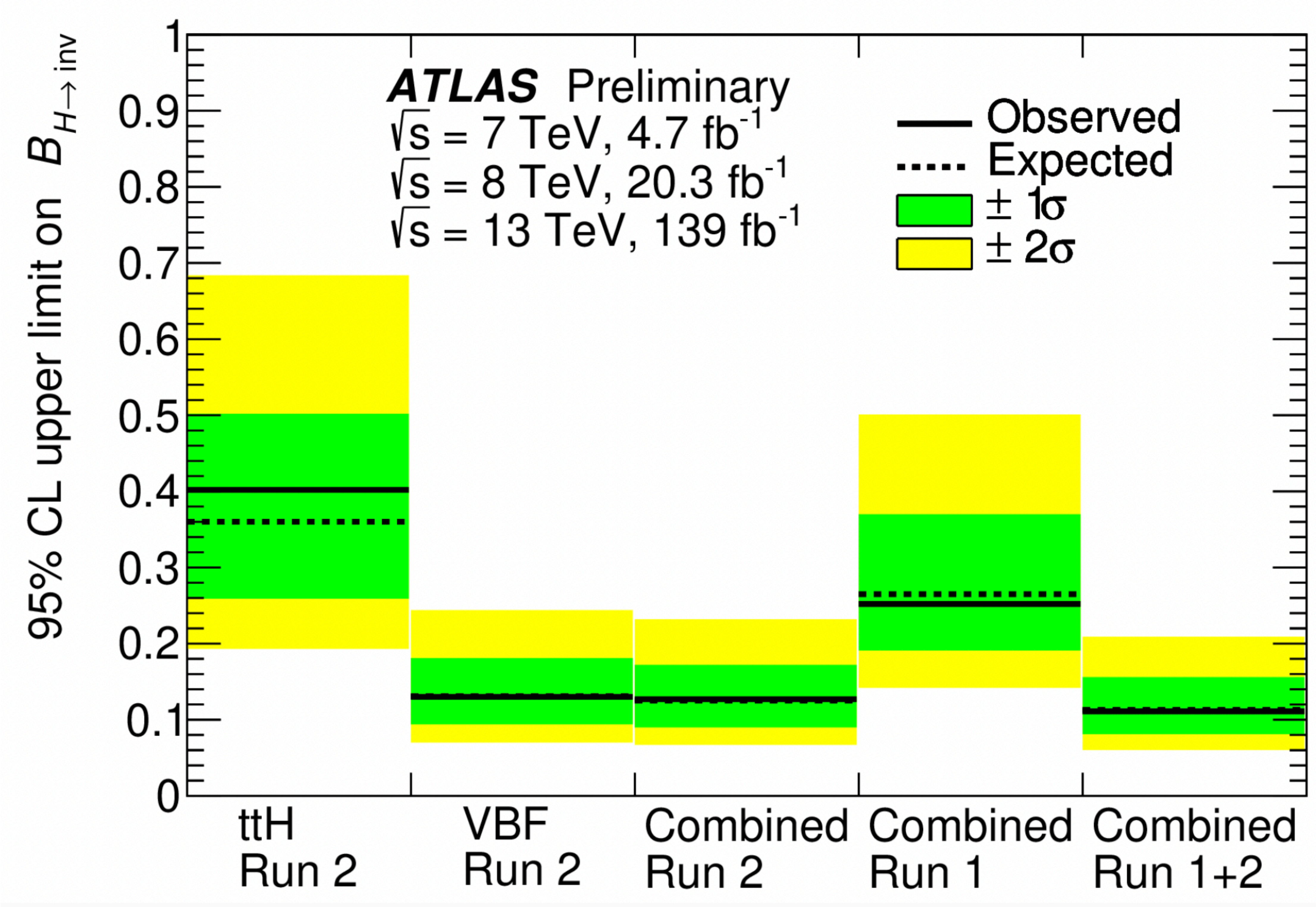


ATLAS-CONF-2020-052



CMS 2015 + 2016 data : BR(H→ inv) < 19% (15% exp)

Full Run-2 data H_{inv} VBF : BR (H→inv) < 18% (10%)

ATLAS full Run-2 data:

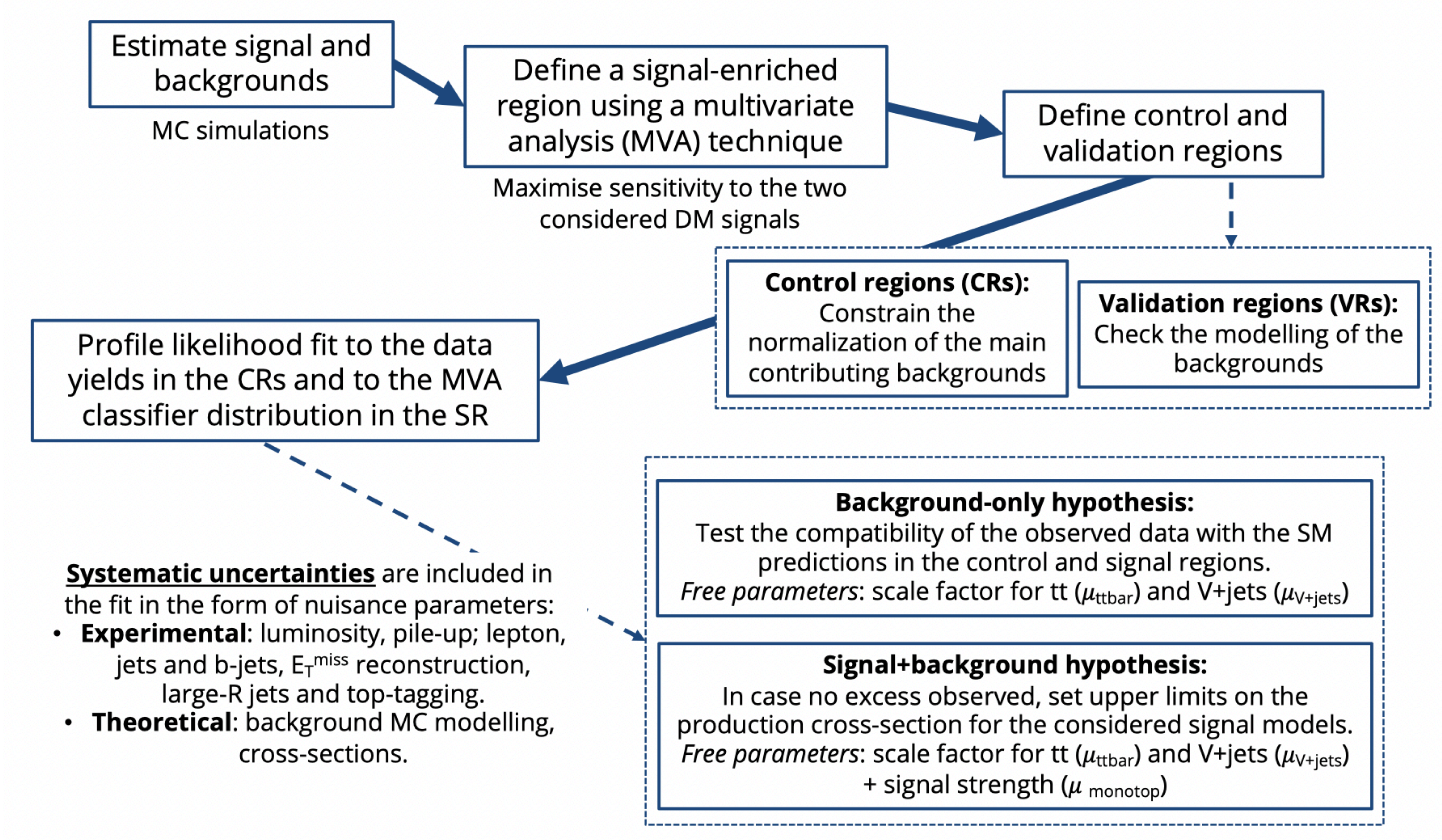
BR(H→ inv) < 11 % (11% exp)

Summary

- The Run 2 programs at both ATLAS and CMS covers a wide range of parameter space.
  - Interpretation in view of many different DM models with many different signatures.
- No significant deviations from SM found so far.
- Observed complementarity with non-collider DM searches.
- We are getting ready for Run-3. Stay Tuned!

Back-Up

Mono-top Analysis Strategy

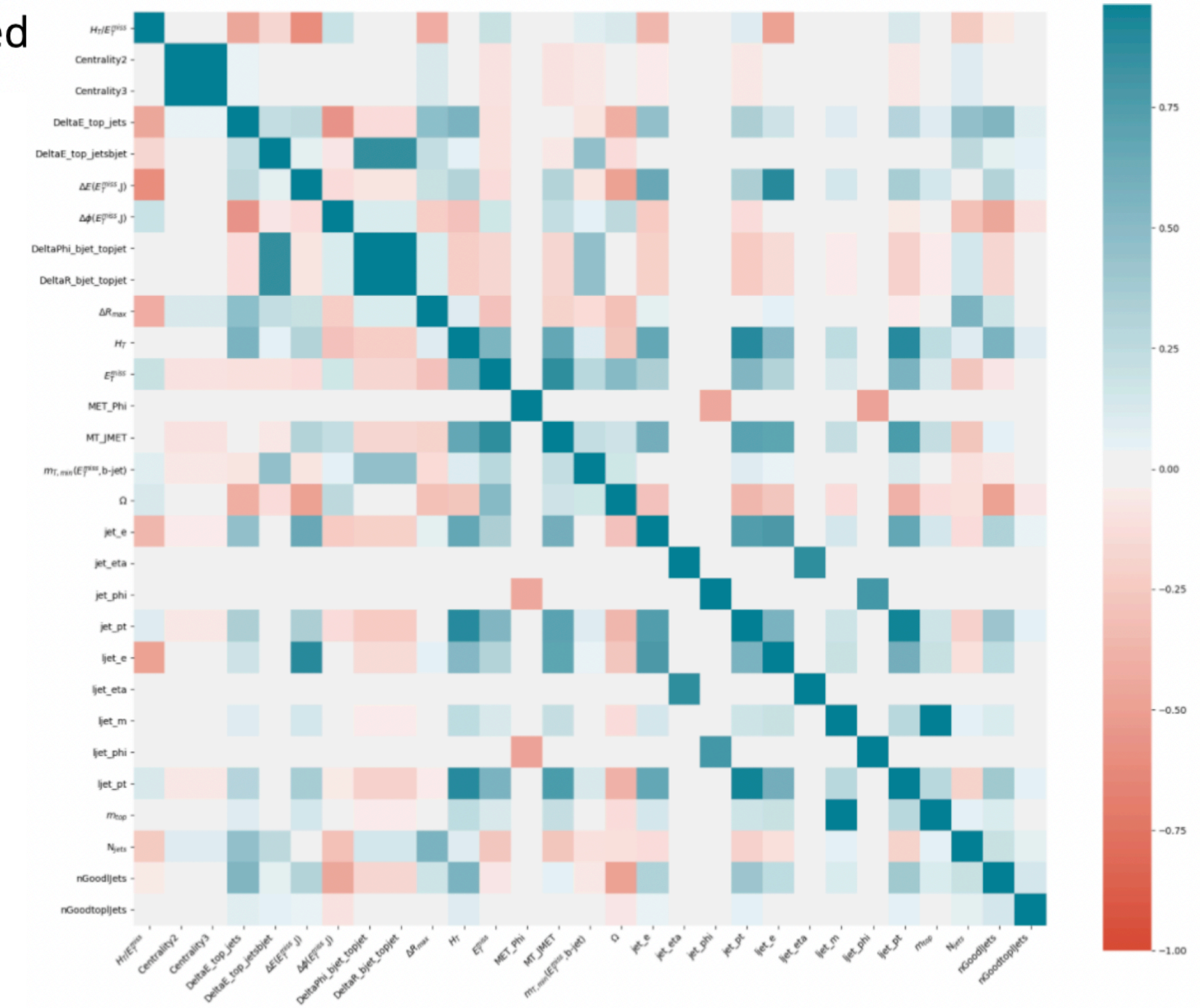


Mono-top MVA

- Several techniques are being studied: BDT (default), NN, Autoencoder,...
- Using preselection as the training region.
- Training with the most relevant signal and background samples.
- Variables that didn't improve significantly the performance (by more than 0.001 in terms of area under the ROC) or had a correlation coefficient larger than 0.8 were pruned

Variable	Resonant DM model	Non-resonant DM model	VLQ
E_T^{miss}	✓	✓	✓
Δp_T (J,jets)	✓	✓	
Ω^*	✓	✓	✓
N_{jets}	✓	✓	✓
ΔR_{max}	✓	✓	✓
$m_{T,min}(E_T^{miss}$,b-jet)	✓	✓	✓
m_{top}	✓		
H_T/E_T^{miss}		✓	✓
$\Delta E(E_T^{miss}$,J)		✓	✓
$\Delta\phi(E_T^{miss}$,J)		✓	✓
H_T		✓	✓
$p_T(J)$			✓
$m_T(E_T^{miss}$,J)			✓
$\Delta\phi$(b-jet,J)			✓
$m(J)$			✓

$$^*\ \Omega = \frac{E_T^{miss} - pT(top)}{E_T^{miss} + pT(top)}$$



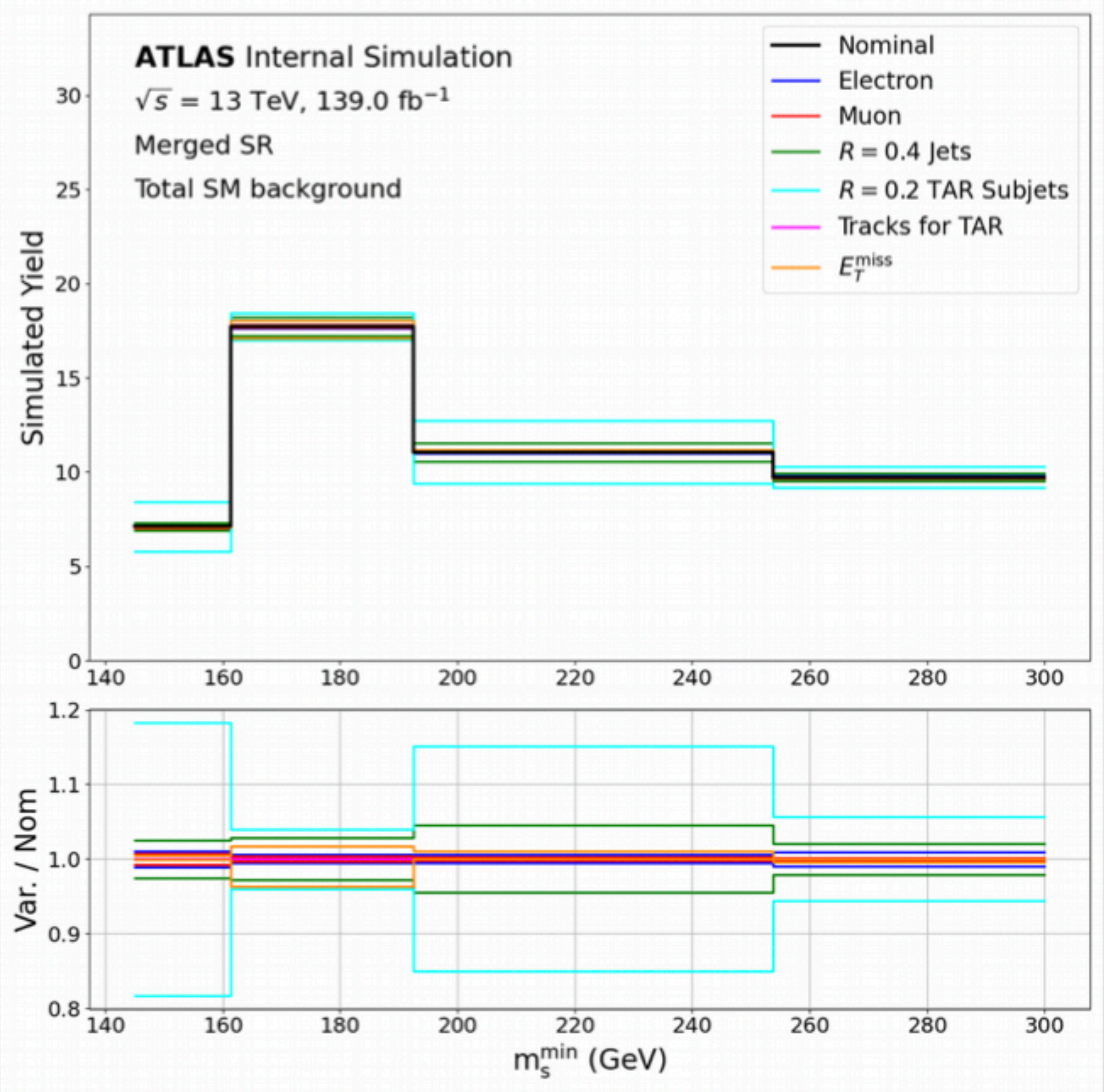
Mono-S(VV)

- Electrons:
  - $|\eta|<2.47$, $p_T > 7$ GeV
  - ID: MediumLLH, Iso: FCLoose
  - veto additional electrons:
    ID: LooseAndBLayerLLH, Iso: FCLoose
- Muons:
  - $|\eta|<2.5$, $p_T > 7$ GeV
  - ID: Medium, Iso: TightTrackOnly_VarRad
  - veto additional muons:
    ID: Loose, Iso: -
- R=0.4 PFlow jets
  - $|\eta|<2.5$, $p_T > 20$ GeV
  - JVT: Tight
  - b-tagging: DL1r 77% efficiency
- TAR jets
  - track-assisted reclustering, using tracks and calibrated R=0.2 LCW (R-scan) jets as input
  - lepton disentanglement: remove tracks associated with electrons/mouns, and R=0.2 jets within $\Delta R<0.2$ of an electron from input
  - jets are reclustered with R=1 AntiKt
  - tracks are associated to R=0.2 jets and rescaled to jet p_T
  - mass and substructure of TAR jets are calculated from tracks, making use of superior tracking resolution
- $E_{T,miss}$: Calculated from electrons, muons, PFlow jets, and track-based soft term
- Photons and hadronic tauons are not considered

Mono-S(VV) Systematics

Considered experimental systs:

- Luminosity
- Electron and muon efficiency, resolution, scale
- MET
- PRW
- Flavour tagging
- R=0.4 jets
  - JES: CategoryReduction
  - JER: FullJER
- TAR jets
  - Tracking (TRK)
  - Jet systematics for R=0.2 input jets
    - JES: CategoryReduction
    - JER: FullJER



- All JES/JER NPs treated as uncorrelated between R=0.4 and R=0.2 jets
  - Impact of correlating JES was found to be negligible

tW+MET

Baseline objects			
Jets	**Large-R jets**	**$e^{\pm}$**	**$\mu^{\pm}$**
$p_T >$ 20 GeV	$p_T >$ 200 GeV	$p_T >$ 4.5 GeV	$p_T >$ 4 GeV
$\lvert\eta\rvert < 4.5$	$\lvert\eta\rvert < 2.0$	$\lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.7$
		ID: LooseAndBLayerLLH	ID: 1 (medium
		$Z_0 sin(\theta) <$ 0.5mm	
Signal objects			
Jets	**b-jets**	**$e^{\pm}$**	**$\mu^{\pm}$**
$p_T >$ 30 GeV	$\lvert\eta\rvert < 2.5$	$p_T >$ 4.5 GeV	$p_T >$ 4 GeV
PFlow jets	$Tagger: DL1r$	$\lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.7$
JVT > 0.5 (Default)	WP: 77%	ID: MediumLLH	ID: 1 (medium
		FCLoose	Loose_VarRac
Large-R jets		$Z_0 sin(\theta) < 0.5mm$	
$Tagger: SmoothedWTagger$		$\lvert d_0/\sigma_{d_0}\rvert < 5$	$\lvert d_0/\sigma_{d_0}\rvert < 3$
WP: 50%			
E_T^{miss}		**Derivation: PHYS**	
Jet WP: Tight			
Additional event cuts			
BadMuon(q/p)	Cosmic muons	Jet cleaning	
0.4	$Z_0 < 1.0$	LooseBad	
0.4	$d_0 < 0.2$		

Reject	Against	Criteria
electron	electron	shared track, $p_{T,1} < p_{T,2}$
tau	electron	None
tau	muon	None
muon	electron	is calo-muon and shared ID track
electron	muon	shared ID track
photon	electron	None
photon	muon	None
jet	electron	$\Delta R < 0.2$ if not a b-jet
electron	jet	$\Delta R < 0.4$
jet	muon	Not a b-jet and NumTrack < 3 and (ghost-associated or $\Delta R < 0.2$)
muon	jet	$\Delta R < 0.4$
jet	tau	None
photon	jet	None
fat-jet	electron	$\Delta R < 1.0$
fat-jet	muon	$\Delta R < 1.0$
jet	fat-jet	None

VBF Hinv

- lowest unprescaled E_T^{miss} **triggers** *(see next slide)*
- require at least **2 jets** with p_T>25 GeV, passing JVT
- **p_T(j1) > 80 GeV** & **p_T(j2) > 50GeV**

VBF topology:

- **veto** any **third jet** with p_T> 25 GeV and passing JVT
- require the two jets to be in an **opposite hemisphere**
- **$\Delta\eta_{jj}$> 4.8**
- 3 bins in **M_{jj} > 1 TeV:**
  - bin1: 1.0 < Mjj<1.5 TeV
  - bin2: 1.5 < Mjj<2 TeV
  - bin3: Mjj>2 TeV

suspress W and top bkg:

- **lepton veto**
- **E_T^{miss} > 180 GeV**

reduce QCD bkg:

- **$\Delta\Phi_{jj}$<1.8**
- $\Delta\Phi$(j1, E_T^{miss})>1 and $\Delta\Phi$(j2, E_T^{miss})>1
- **MHT(noJVT) > 150 GeV** *(see later)*

in a sketch: