Searches for dark matter at ATLAS

2022 International conference on Neutrinos and Dark Matter

Guglielmo Frattari on behalf of the ATLAS collaboration

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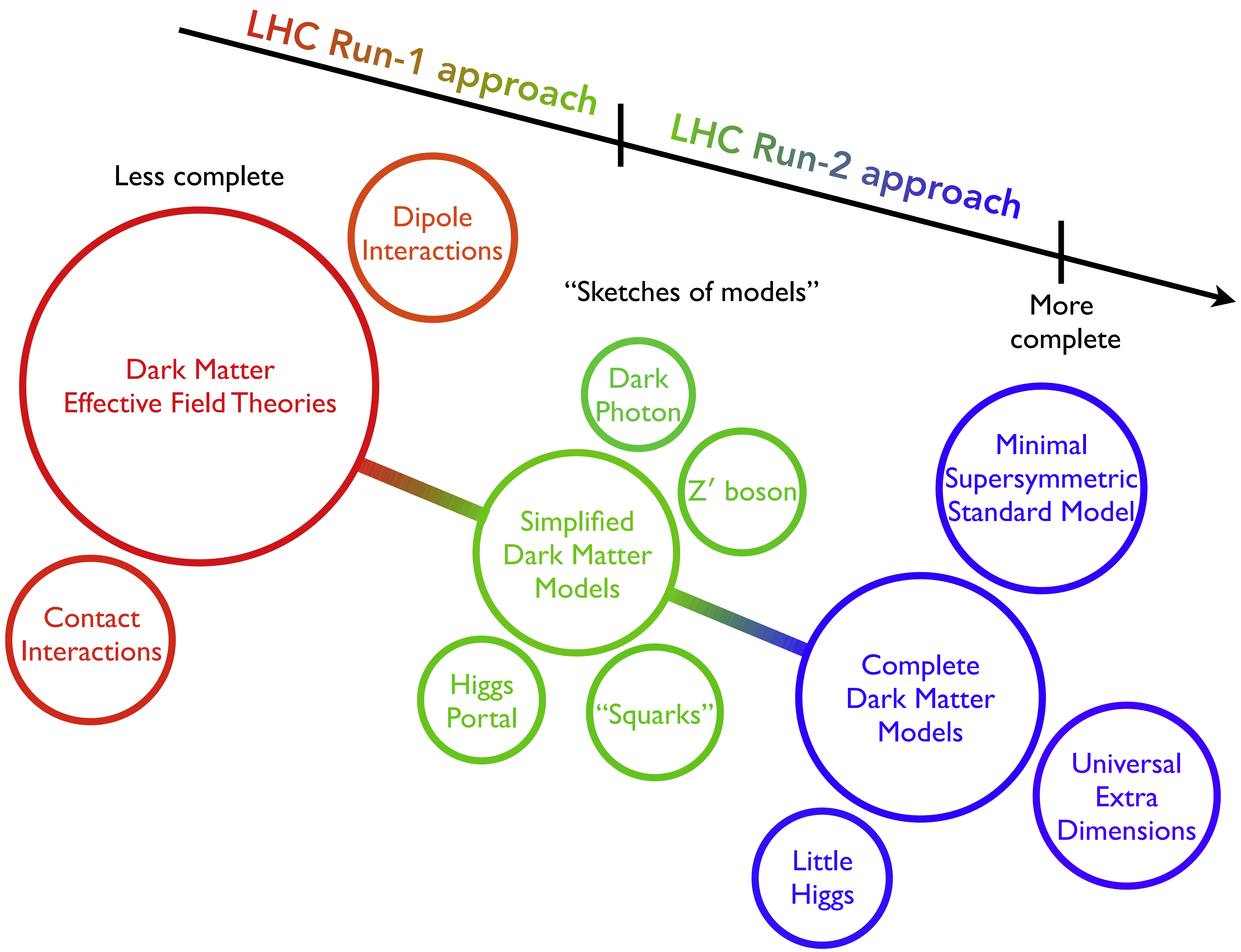
Brandeis University

ATLAS Experiment

Introduction

- dark matter searches approach at LHC evolved between Run-1 (< 2012) and Run-2, 2015-2018
  - exploring richer kinematics & phenomenology



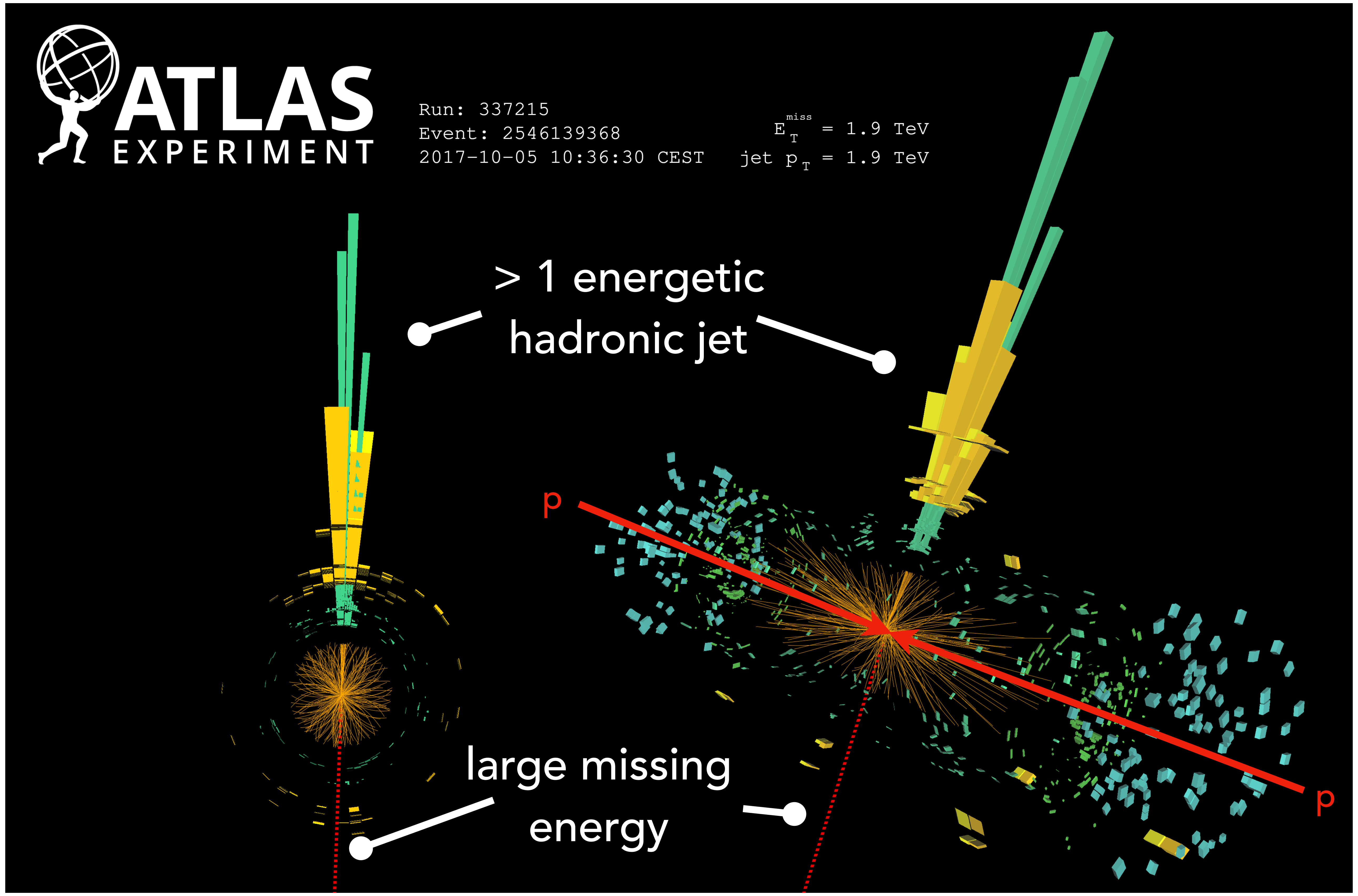
Results discussed in this talk cover:

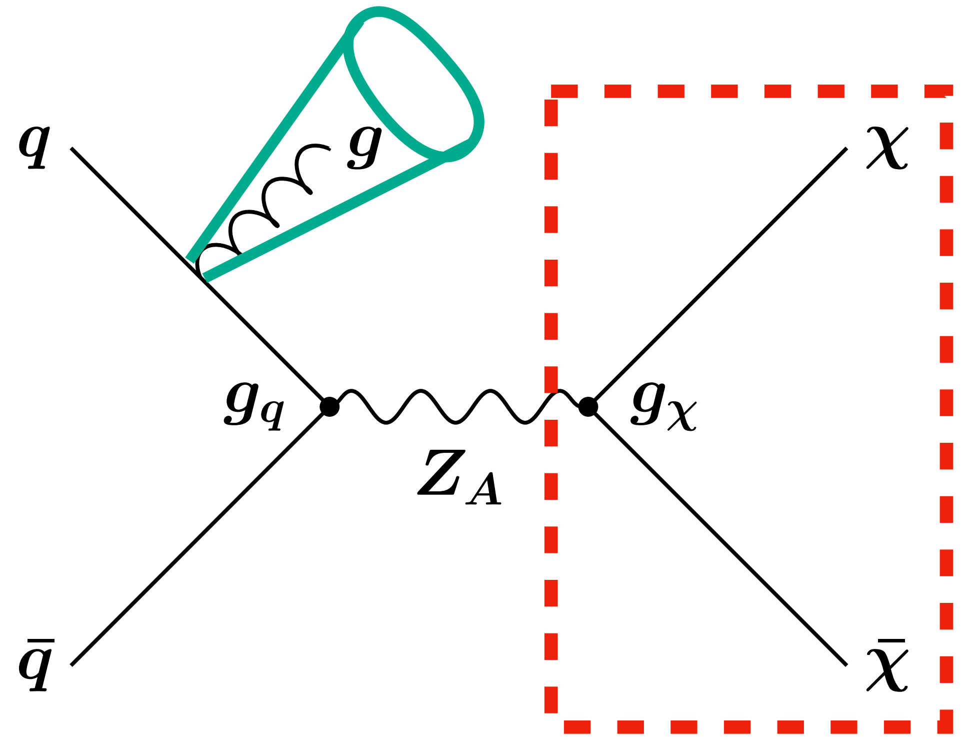
- Simplified dark matter models
  - LHC DM WG white paper arXiv:1507.00966
- 2HDM+a model: arXiv:1810.09420
- Dark Higgs model: JHEP 04(2017)143
- Higgs to invisible decays searches

Phys. Rev. D 103 (2021) 112006

Monojet analysis overview

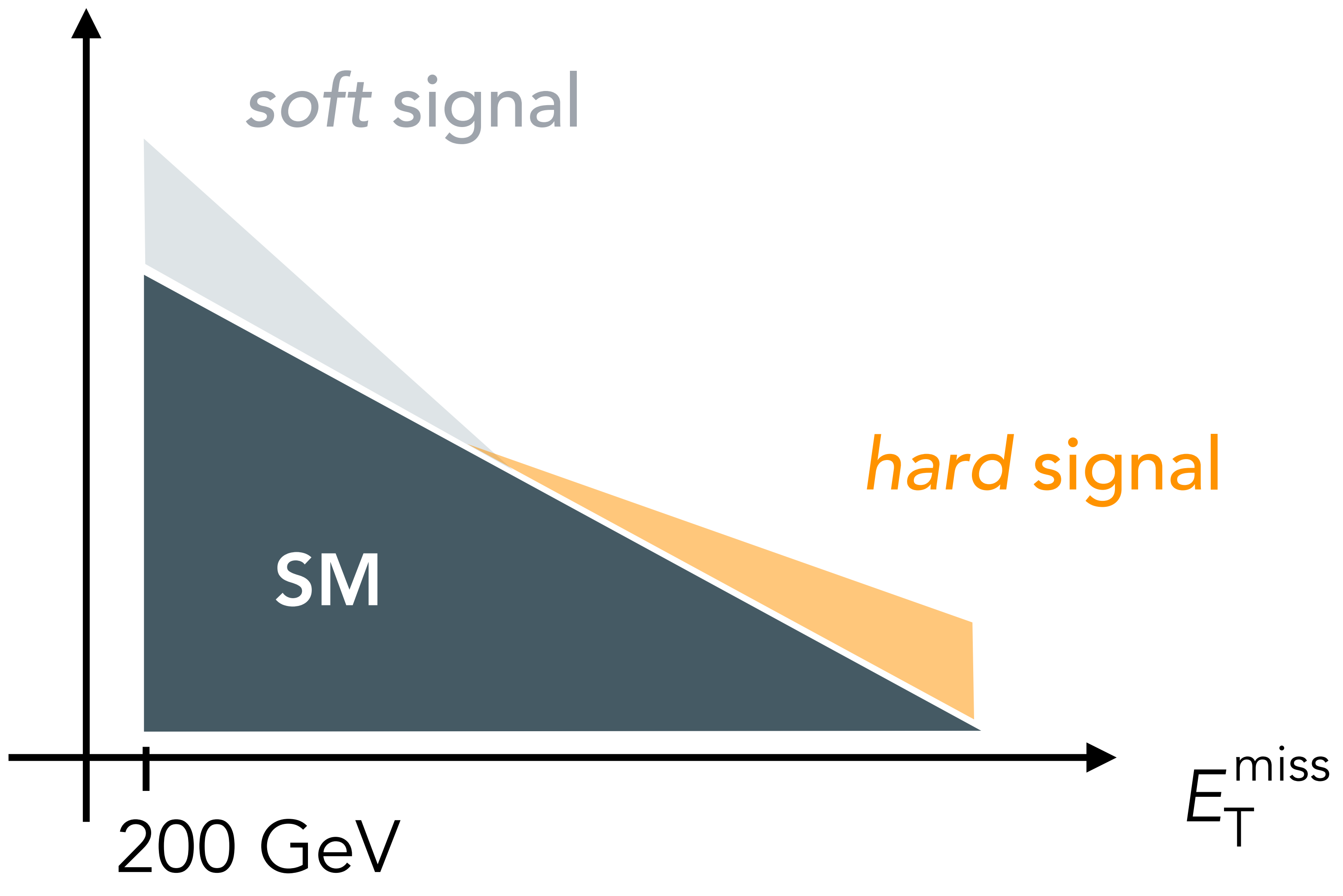
- golden channel to look for dark matter at the LHC





DM particles invisible to the ATLAS detector

- look for deviations from SM in the E_T^{miss} distribution



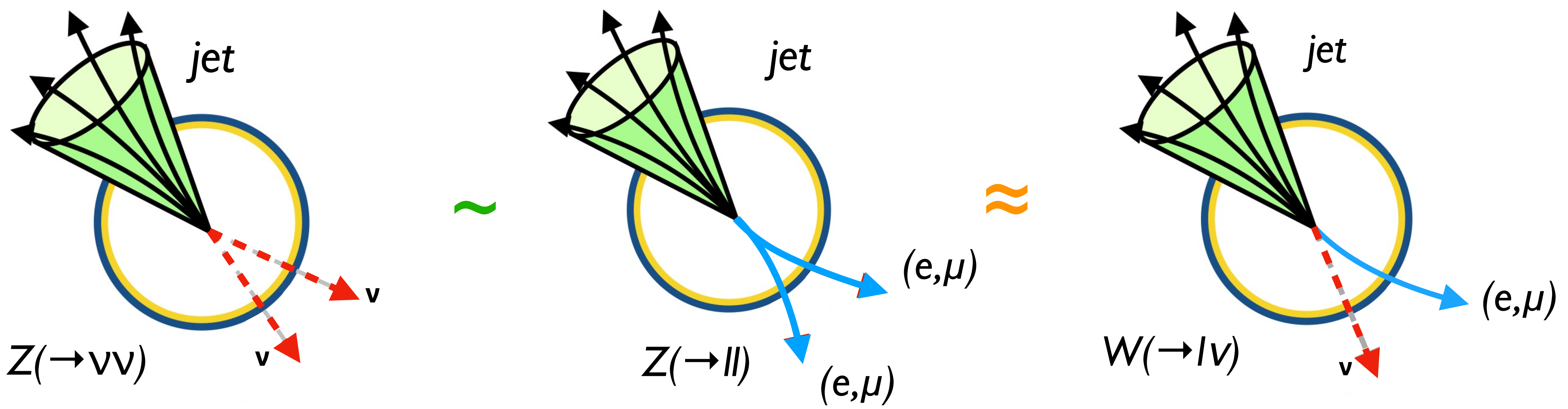
- crucial to control the uncertainty on background predictions:
  - rely on state-of-the-art Monte Carlo simulations + use data in control-regions to correct simulation

[Phys. Rev. D 103 (2021) 112006]

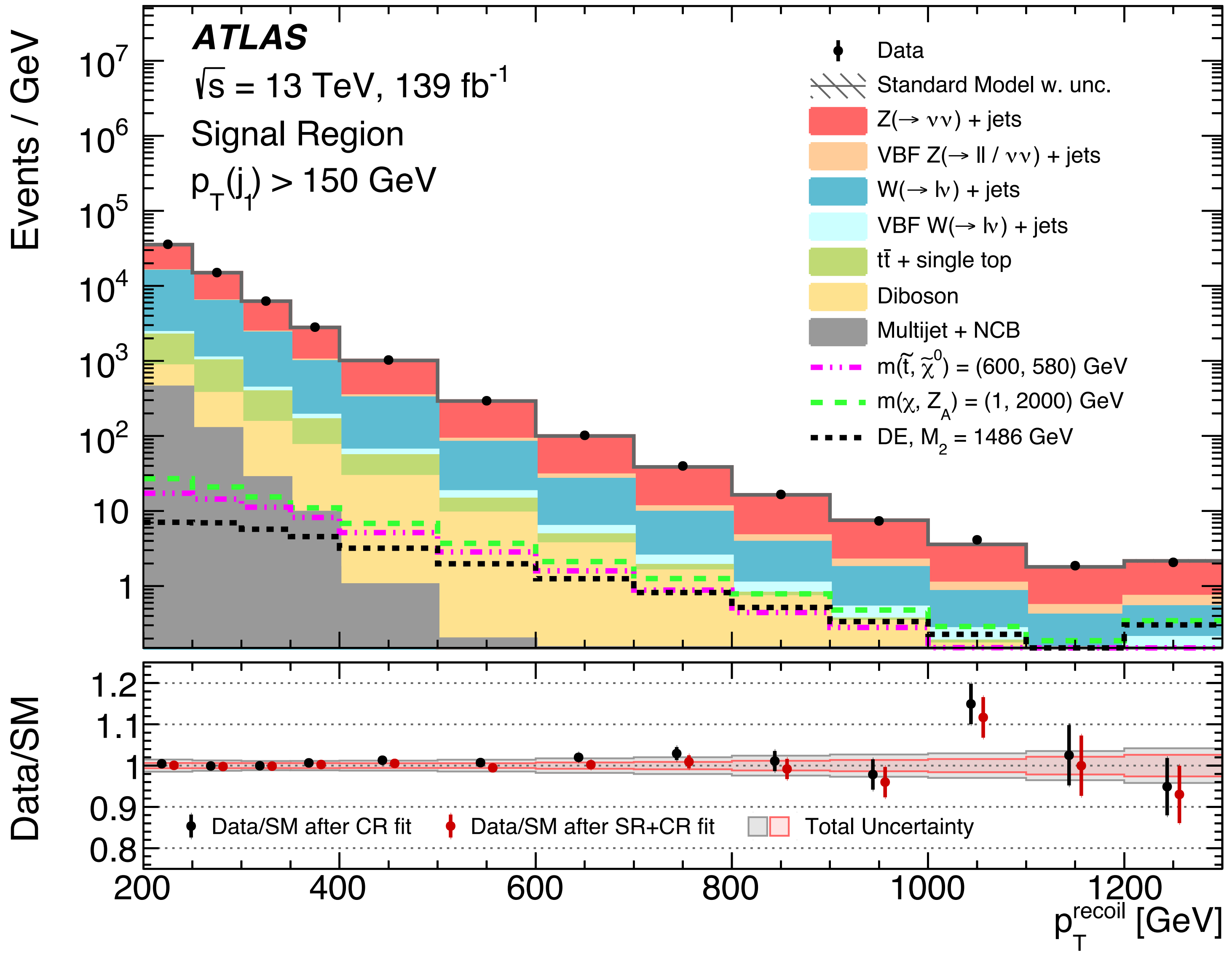
Background estimation

- simultaneous fit to Signal + Control Regions (CRs)
  - CRs: same topology of the SR inverting lepton veto

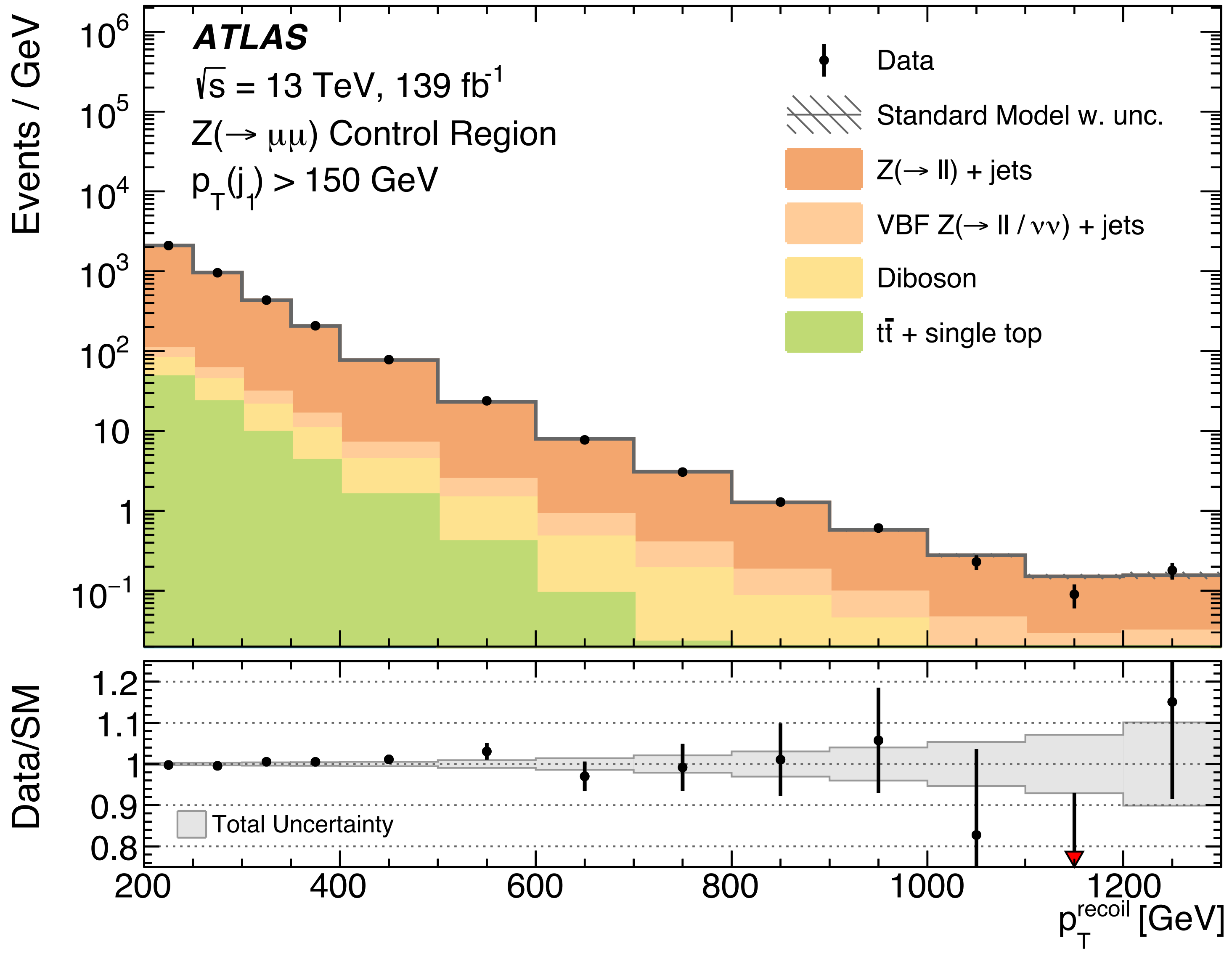
    leptons = invisible particles: $E_T^{miss} \rightarrow p_T^{recoil}$



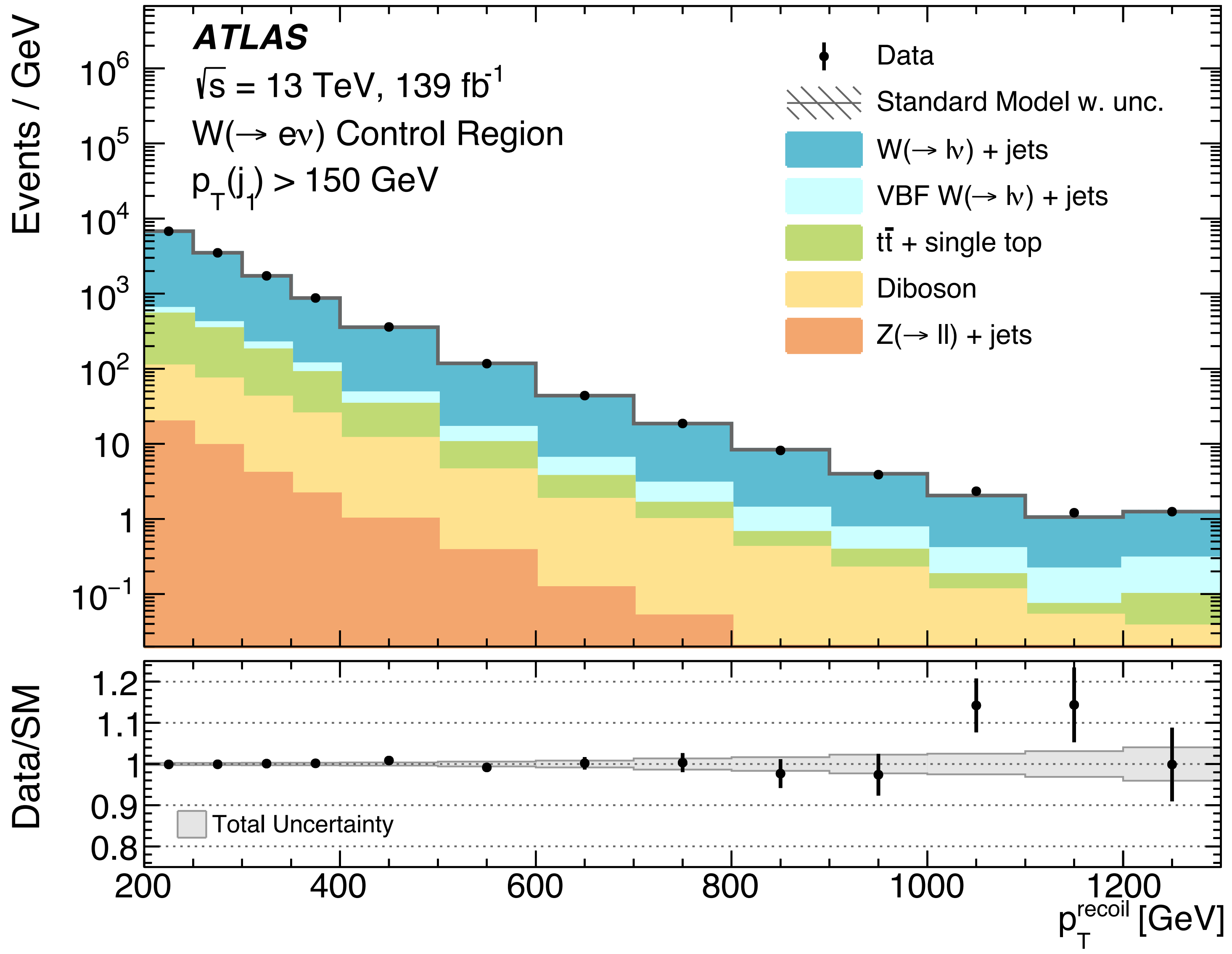
- NNLO QCD & nNLO EW correction to V+jets processes following Eur. Phys. J. C 77, 829 (2017)



Signal region



2 lepton CRs

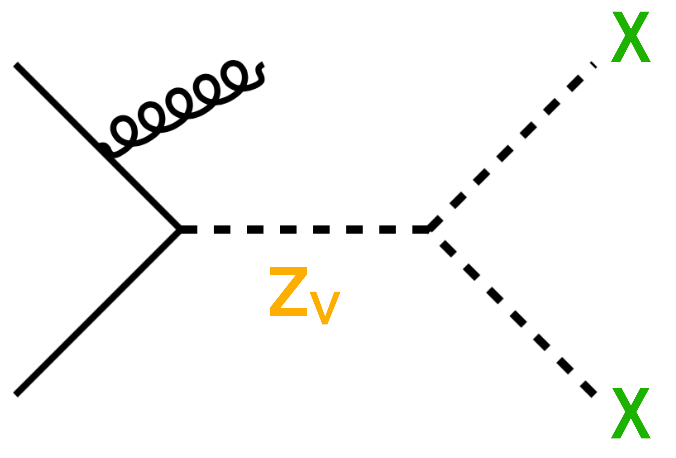


1 lepton CRs + 1 b-tag CR

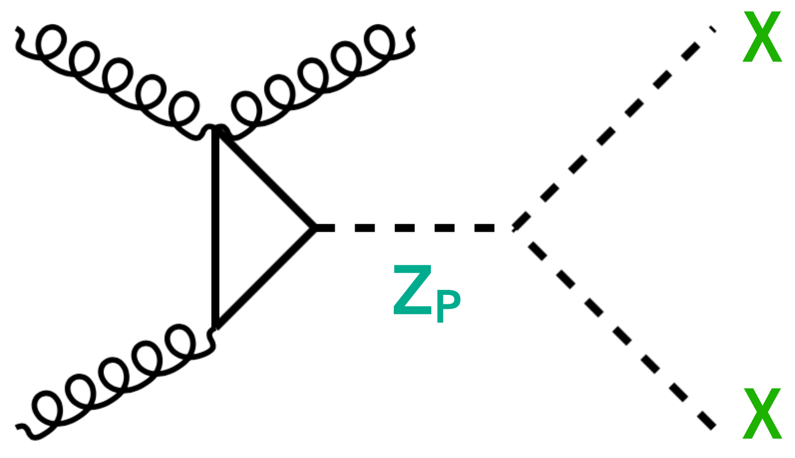
Dark matter interpretations

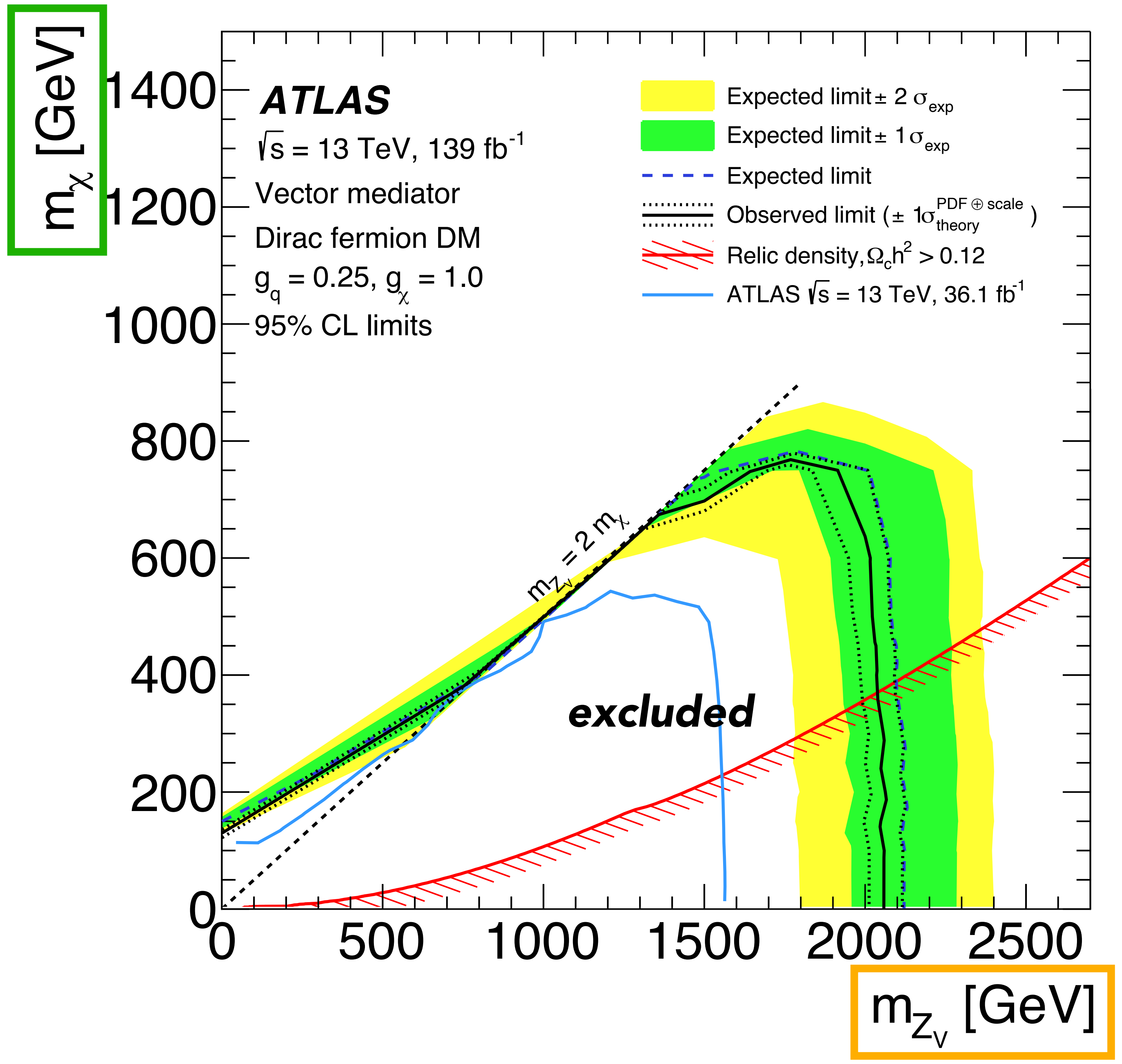
Simplified dark matter models: 5 parameters, {m_X, $m_{Z'}$, g_q, g_X} + minimal mediator width Γ

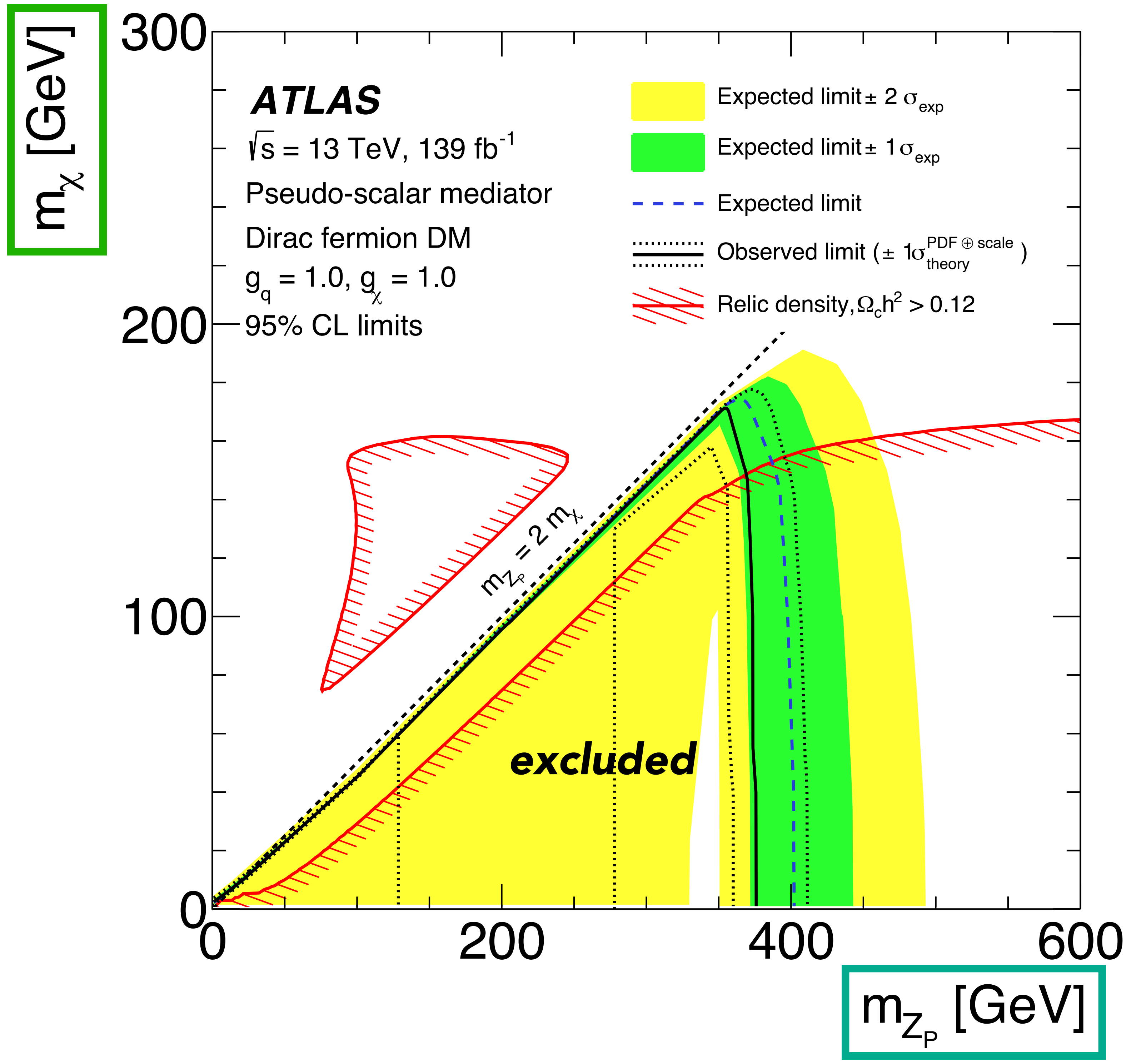
Spin 1



Spin 0







see backup for many more interpretation of the results

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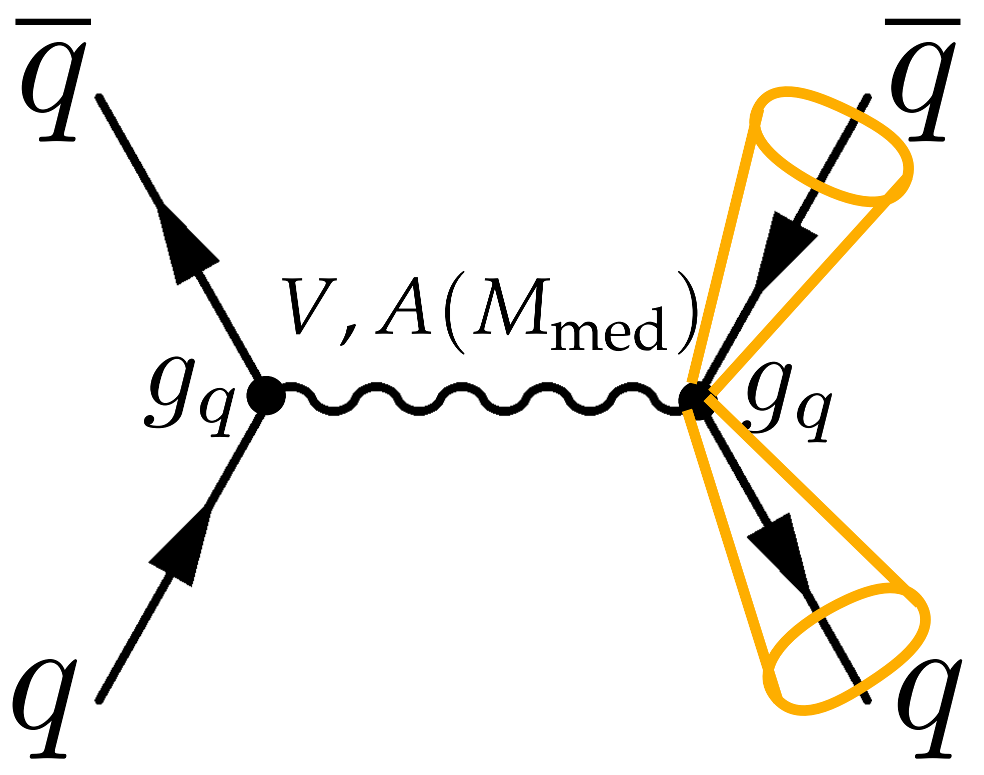
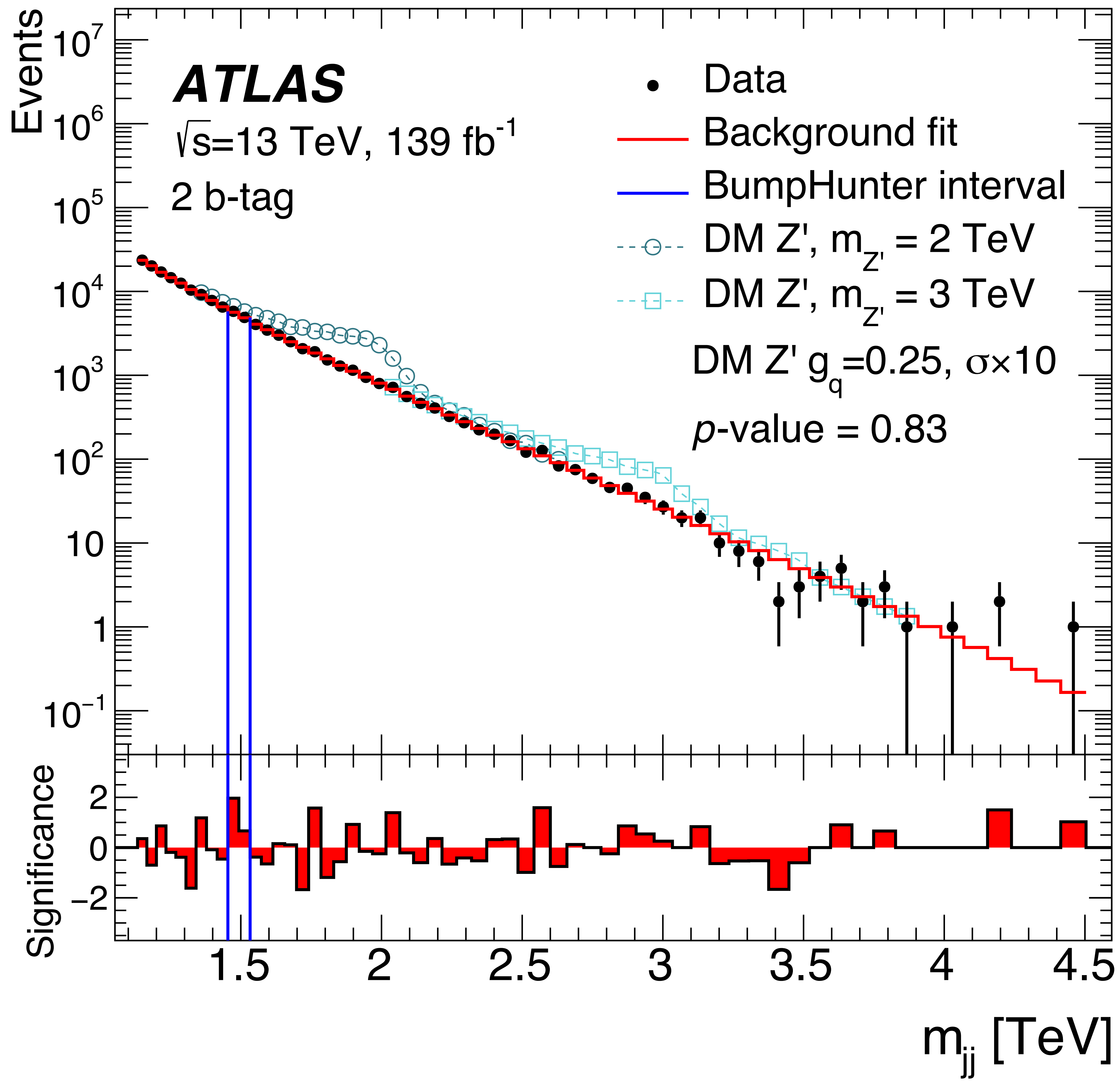
Di-jet resonance searches

- bump-hunting the mjj spectrum, both inclusive & b-tagged jets only



- fully efficient triggers ~ $m_{jj} > 1$ TeV
- target s-channel interactions with a cut on Δη of leading jets



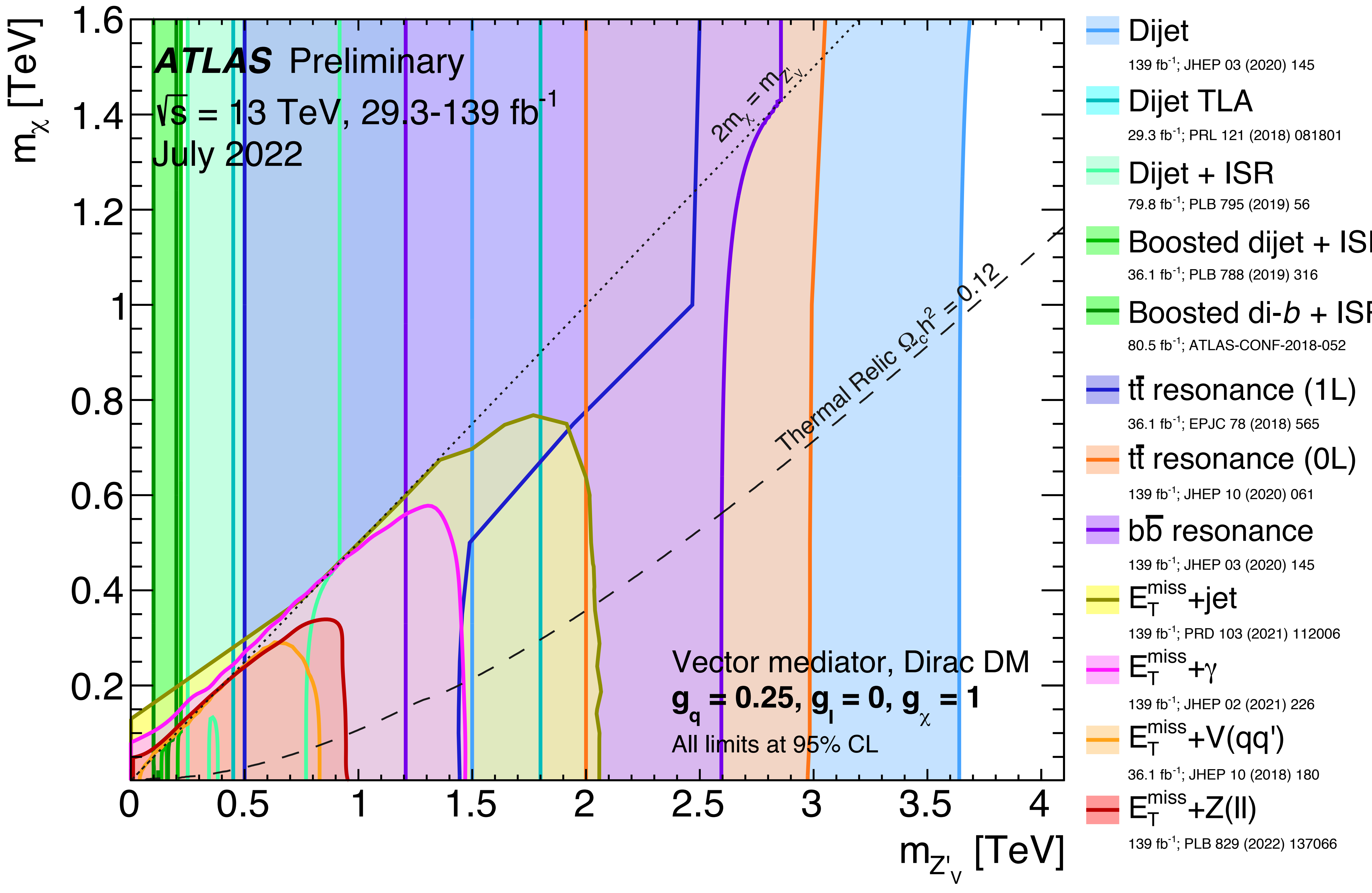
Background estimation

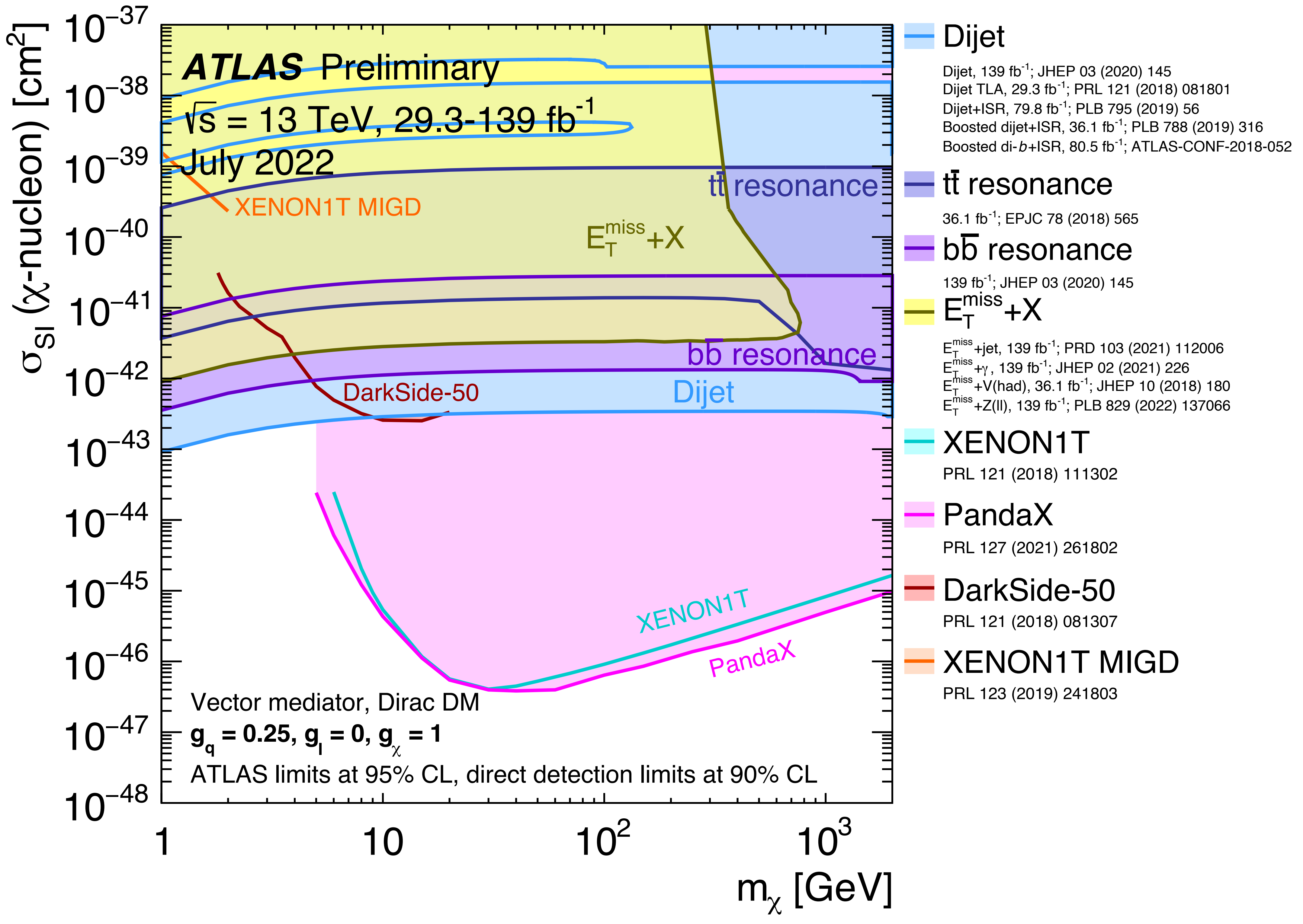
- Sliding WIndow FiT method tuned on pseudo-data
  - uncertainty from function choice: ~10% at high m_{jj}

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x} \qquad x = m_{jj}/\sqrt{s}$$

Spin 1 mediator searches summary

- broad ATLAS search program yielding complementary sensitivity to direct detection experiment results
  - results provided for both Vector & Axial vector mediators following LHC DM WG recommendations on g_q / g_χ

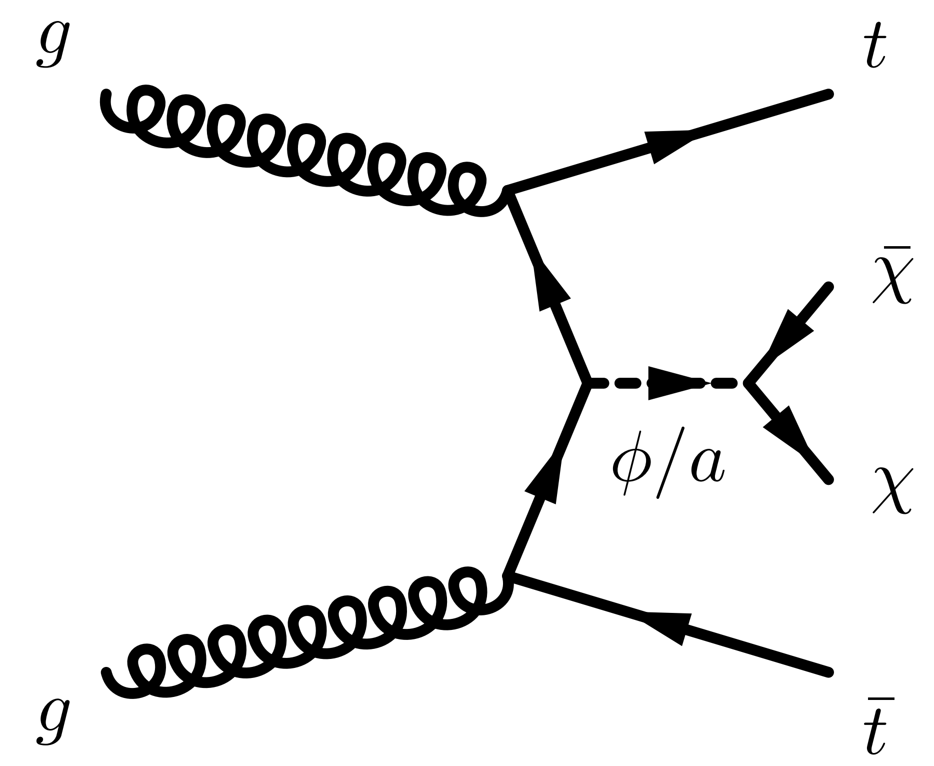




$$\sigma_{\mathrm{SI}} = \frac{f^2(g_q) g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4}$$

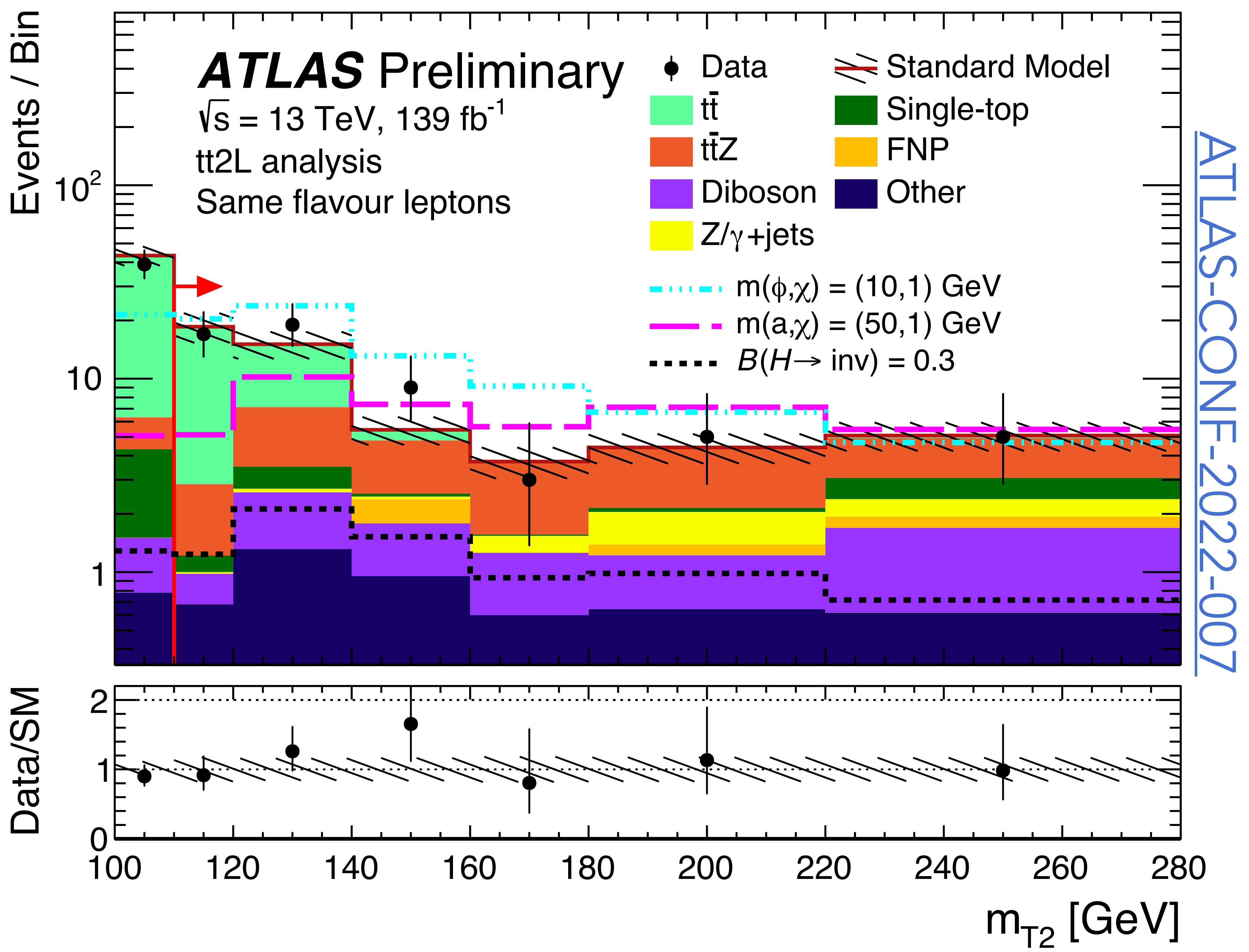
Hunting for scalar mediators in tt+E_T^{miss} final states

- scalar mediators → Yukawa-like coupling with SM particles : sensitivity driven by 3rd generation



- tt+E_T^{miss} search provides three independent channels based on # of charged leptons
  - E_T^{miss}, leptons & b-jet triggers
  - large E_T^{miss}, large jet multiplicities, ≥ 1 b-tagged jets
  - main background processes: tt, ttZ, Z(νν)+jets

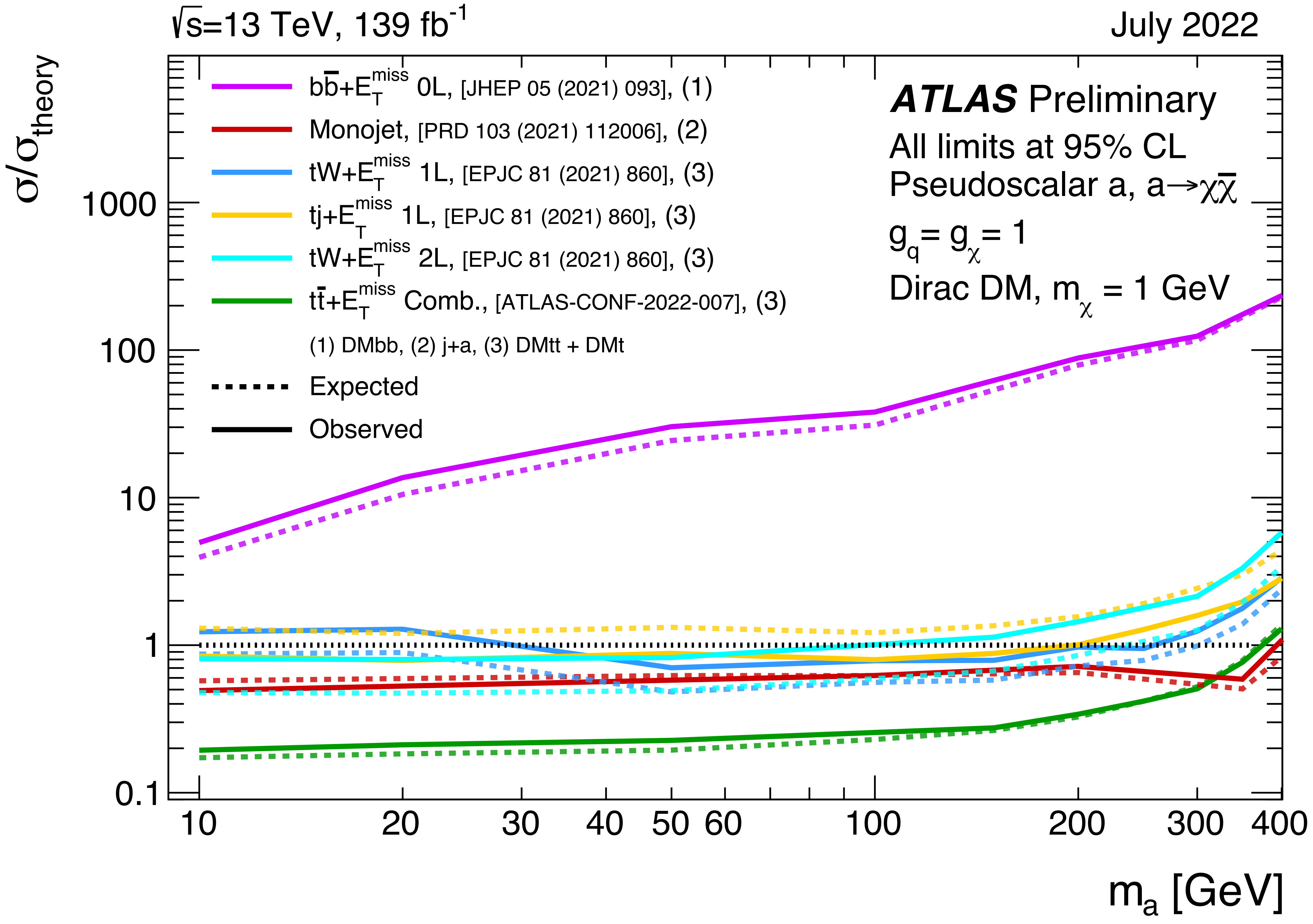
- custom variables to reconstruct ttbar system
  - stransverse mass, m_{T2}
  - large radius jets with R = 1.0 or variable-R in 1 lepton



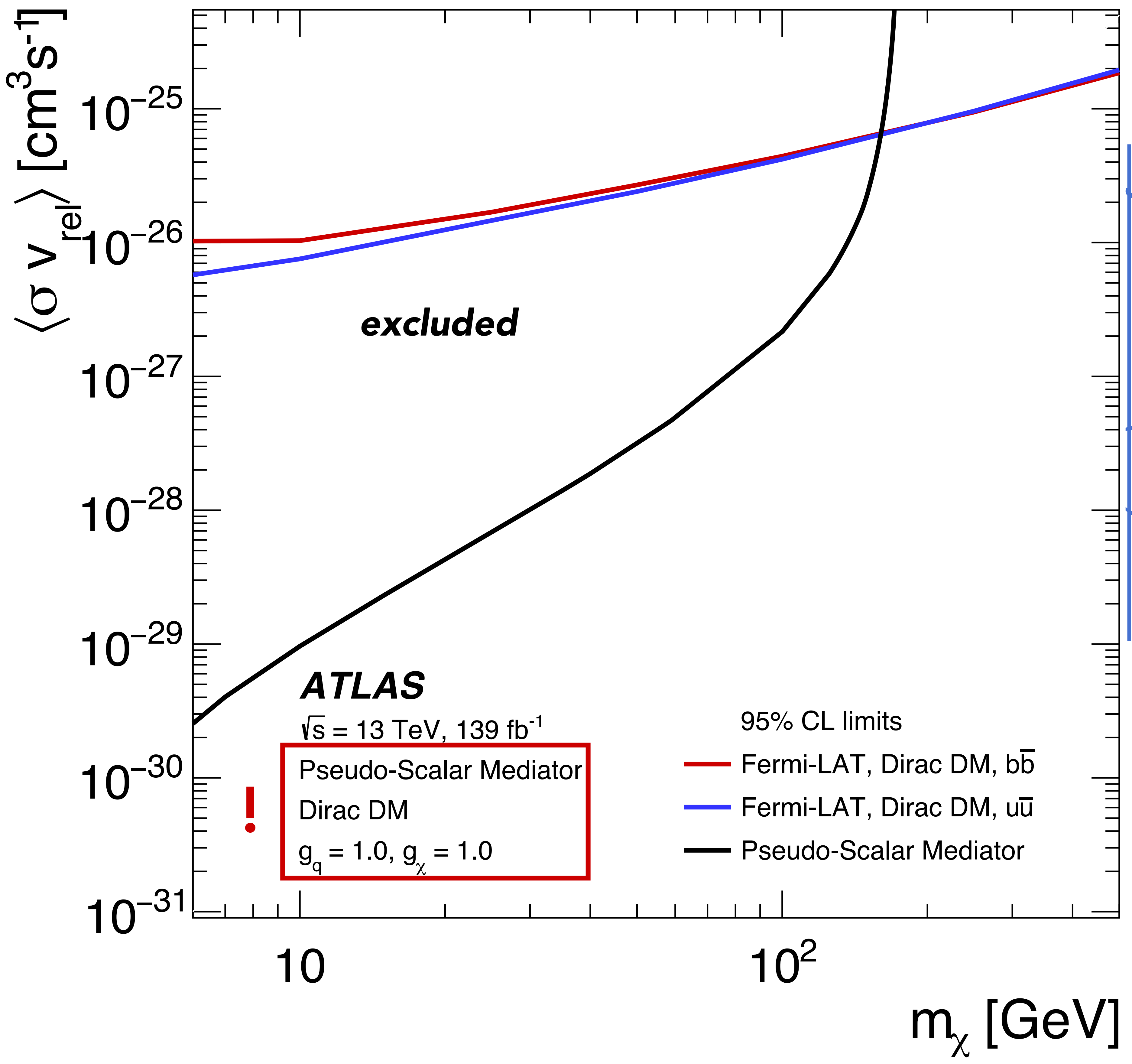
- all channels combined in ATLAS-CONF-2022-007

Spin 0 mediator searches summary

- multiple complementary channels explored
  - sensitivity driven by tt+E_T^{miss} 0+1+2 lepton channel combination



ATLAS ***monojet*** vs ID searches results



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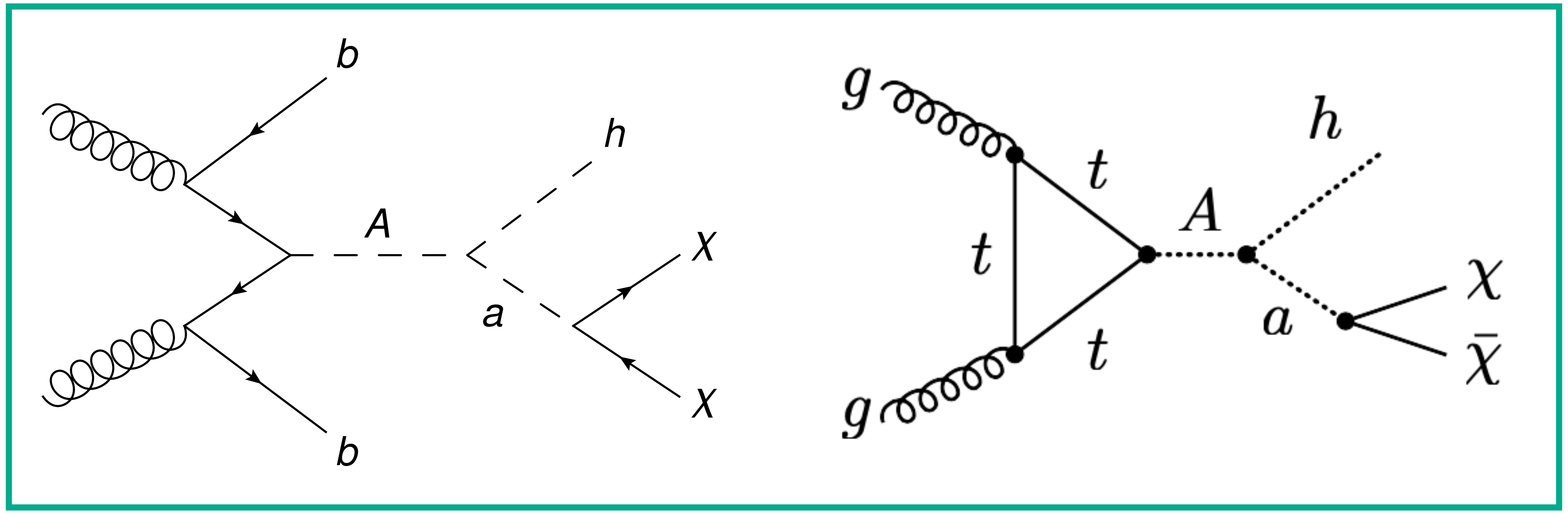
The Higgs boson as a portal to the dark sector

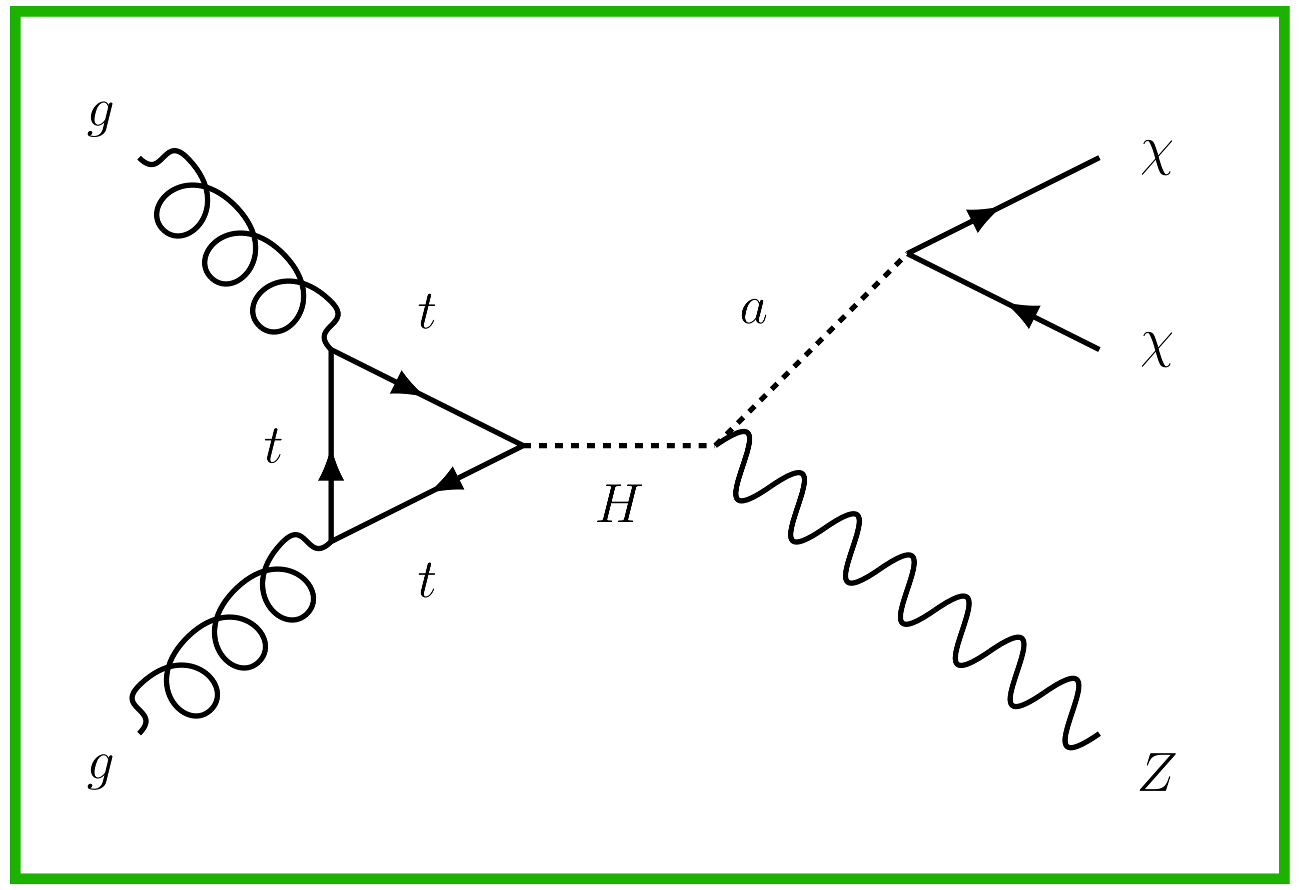
- two possible classes of models:
  1. extended Higgs sector portal models → DM produced in association with the Higgs boson
  2. SM Higgs portal models → invisible decay modes of the Higgs boson

1. Benchmark model: **2HDM+a** Phys.Dark Univ. 27 (2020) 100351
   - type II two-Higgs doublet model, including 5 new fields **h**, **H⁰**, **H±**, **A** + additional pseudo-scalar **a**
   - 14 free parameters, mostly constrained by EW measurements - assumptions can reduce those to 7 or 8

Mono-H



Mono-Z



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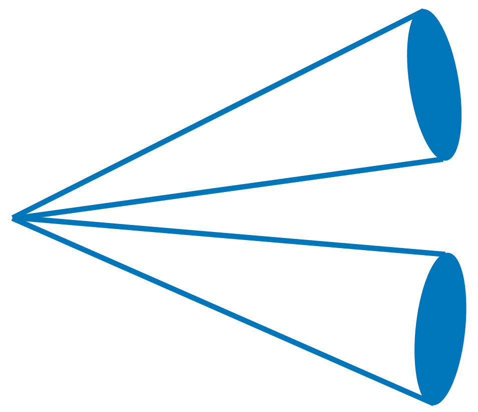
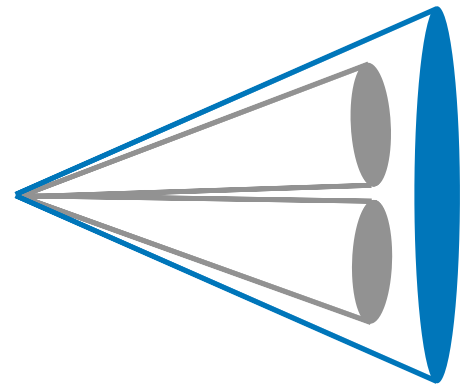
Dark matter + H(bb) production search

- target similar final states of the monojet analysis: H(bb) recoiling against large E_T^{miss}
  - $E_T^{miss} > 150$ GeV, 2 or 3 jets in the final states to be b-tagged, forming H→bb candidate
  - 0 lepton final states SR, 1 & 2 lepton events used to correct background predictions (CRs)



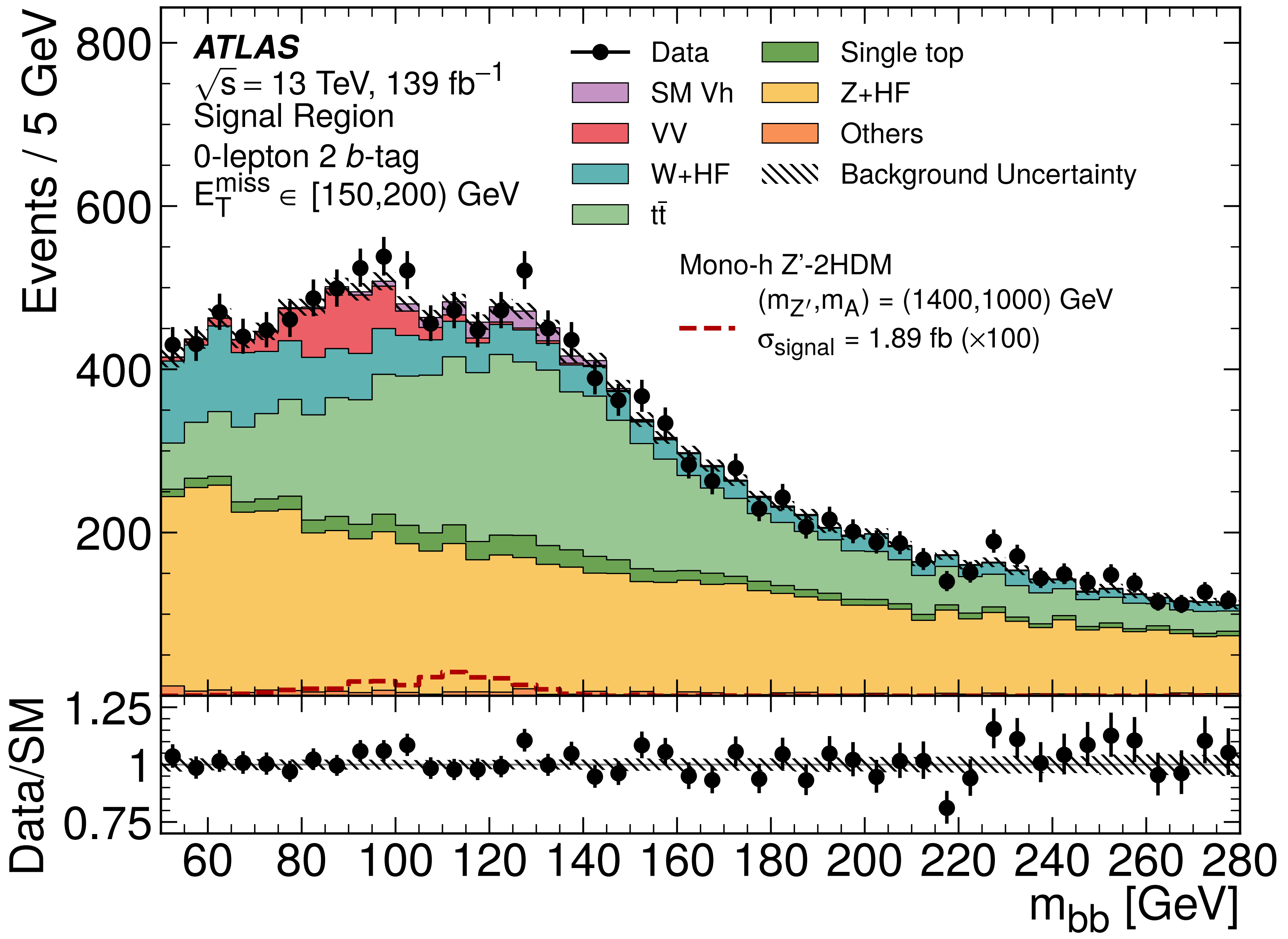
resolved topology

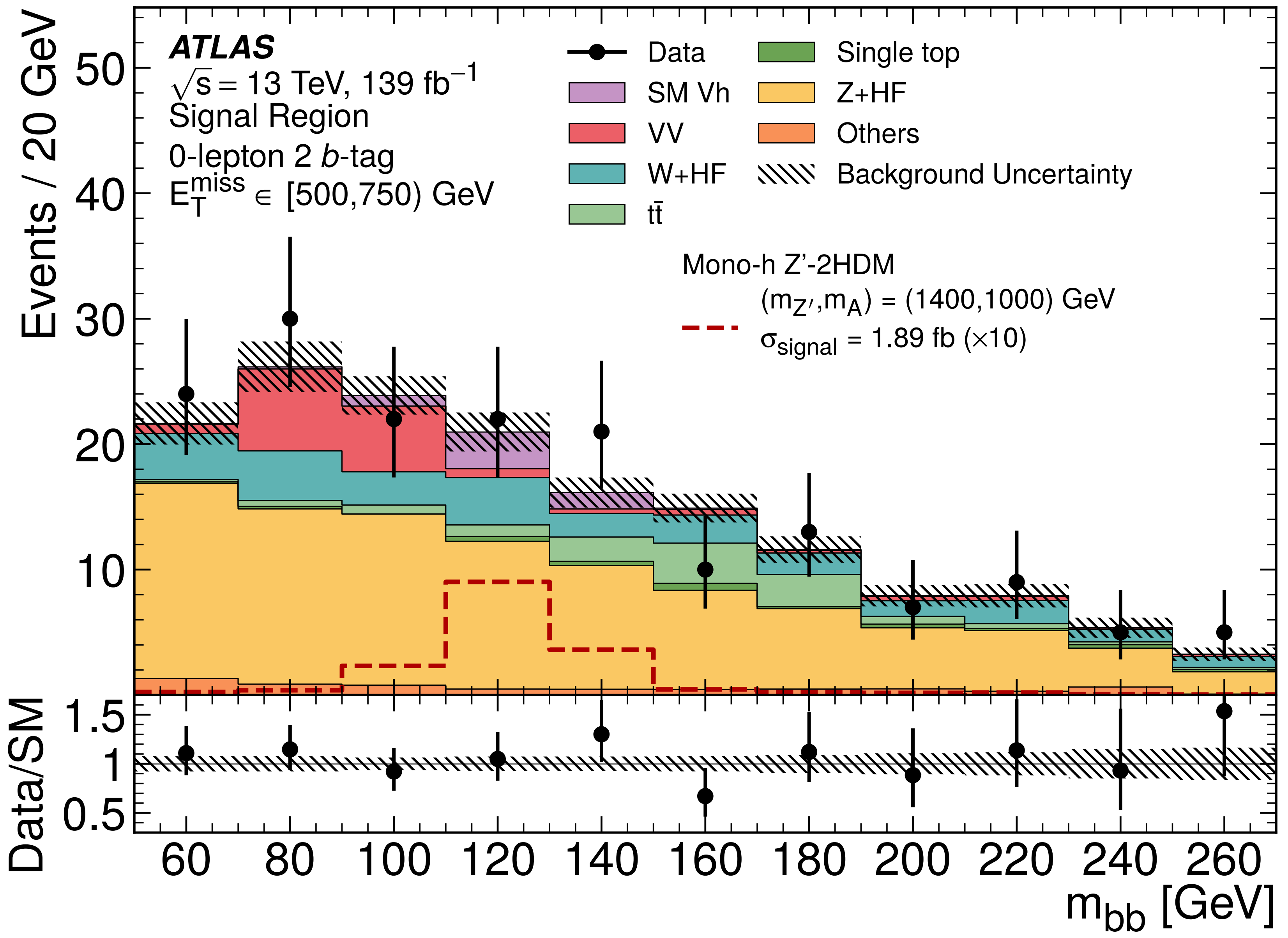
$E_T^{miss} < 500$ GeV



boosted topology

$E_T^{miss} > 500$ GeV



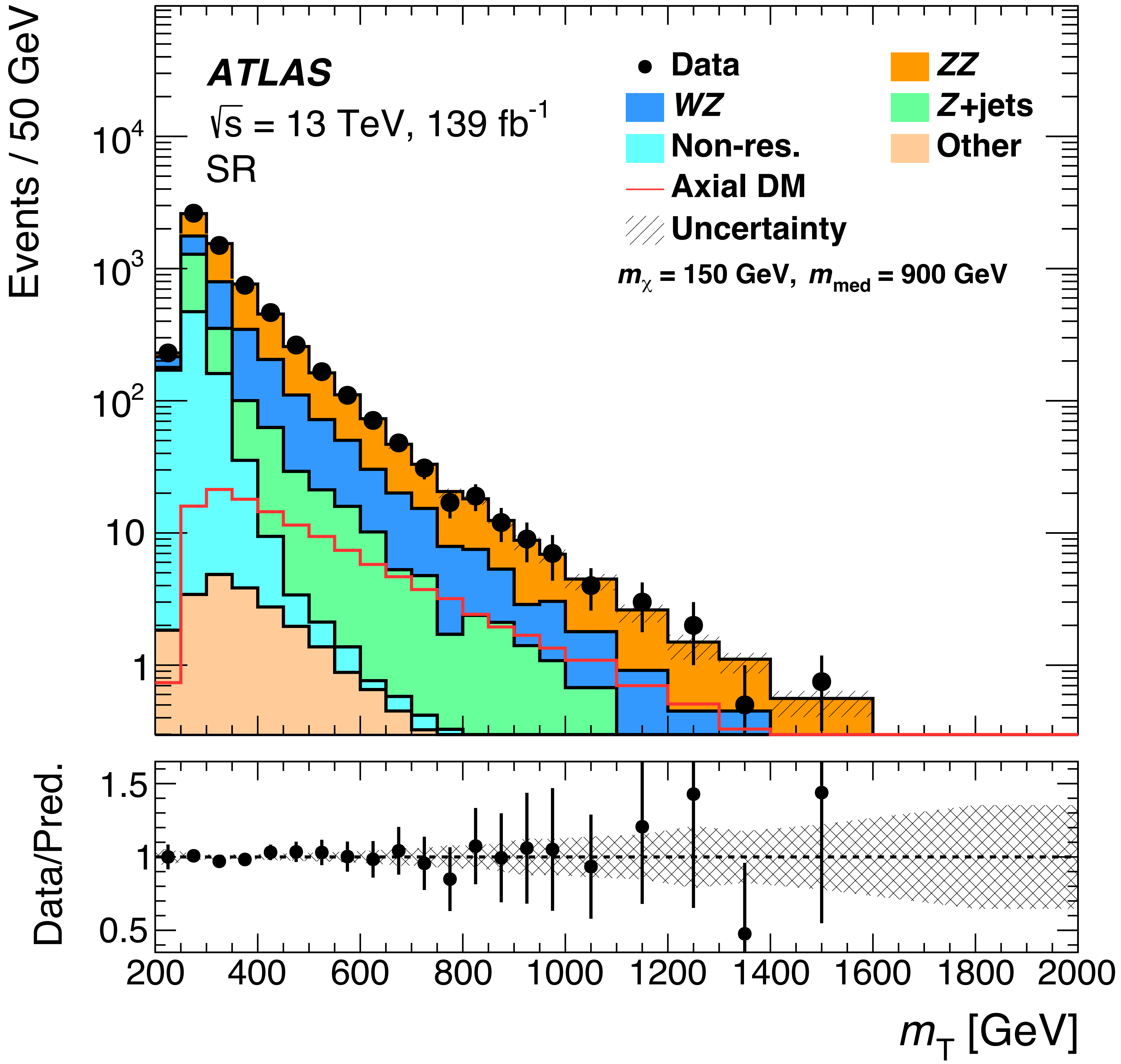


discriminant variable

Phys. Lett. B 829 (2022) 137066

Search for DM in mono-Z(ll) final states

- target events with Z(ee/μμ) candidate balancing invisible particles production: $|\, p_{T,ll} - E_T^{miss} \,| \;/\; p_{T,ll} < 0.4$
- clean final states, requiring at most 1 extra jets and large E_T^{miss}, > 90 GeV
- exploit 3-leptons and 4-leptons CRs to constrain leading WZ and ZZ backgrounds - eμ CR for top processes bkg.



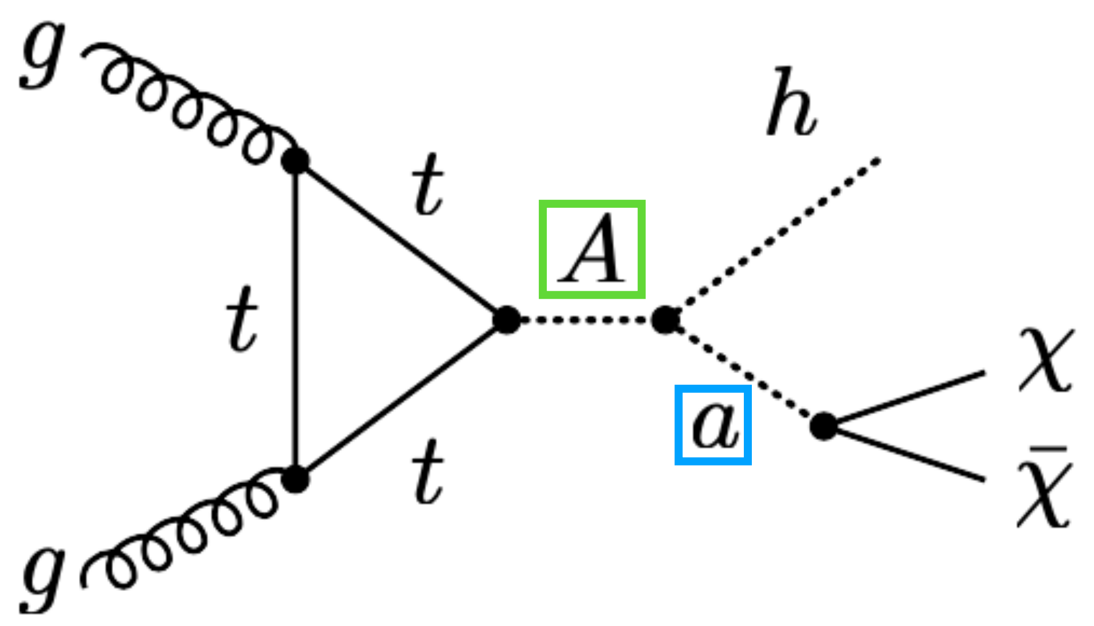
discriminant variable for 2HDM+a interpretations: transverse mass

$$m_T = \sqrt{\left[\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{miss})^2}\right]^2 - \left[\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right]^2}$$

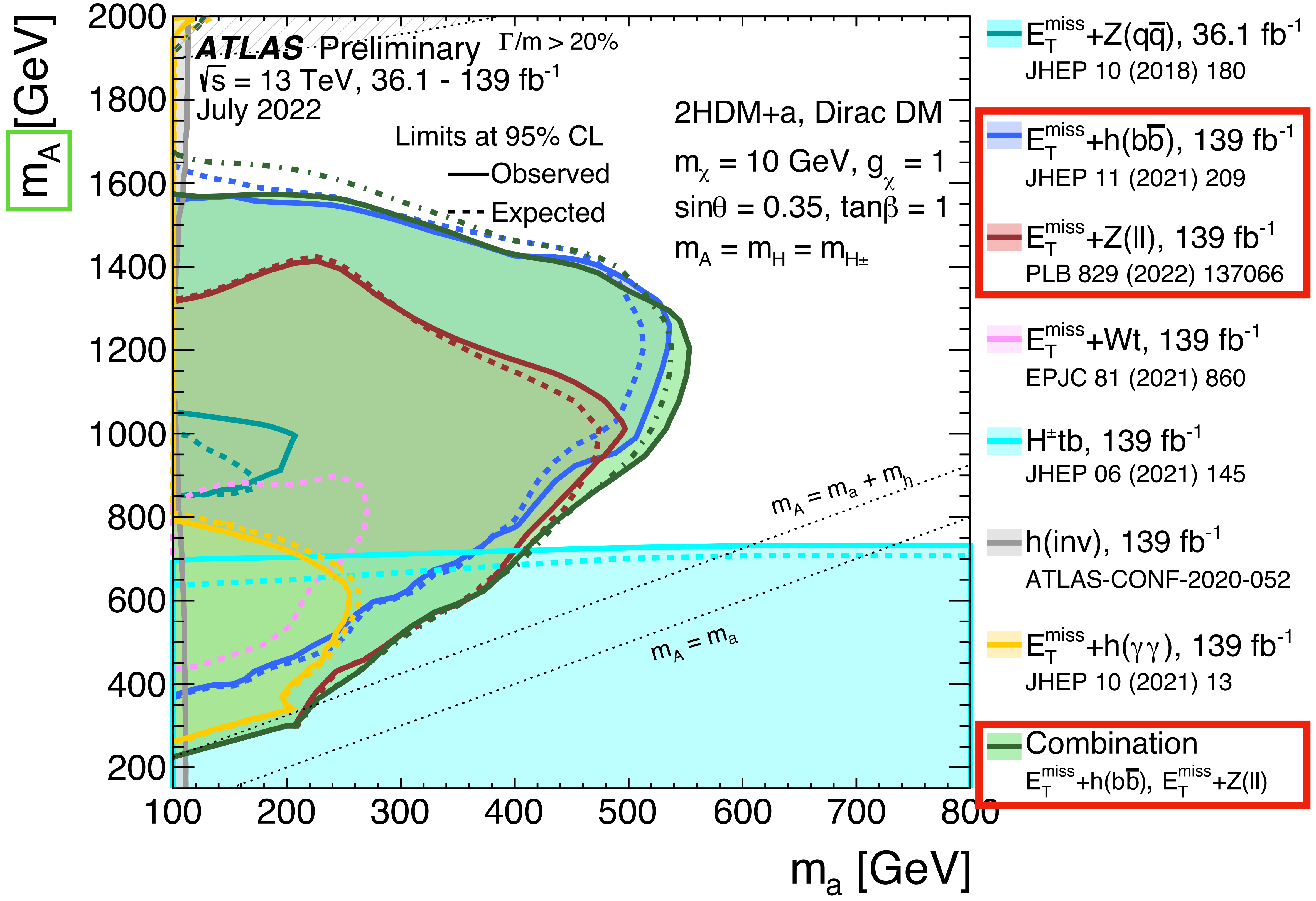
- additional interpretations:
  - simplified DM models - results included in summary plots
  - invisible Higgs decays → discussed later in this talk

→ enhanced sensitivity using BDT discriminant

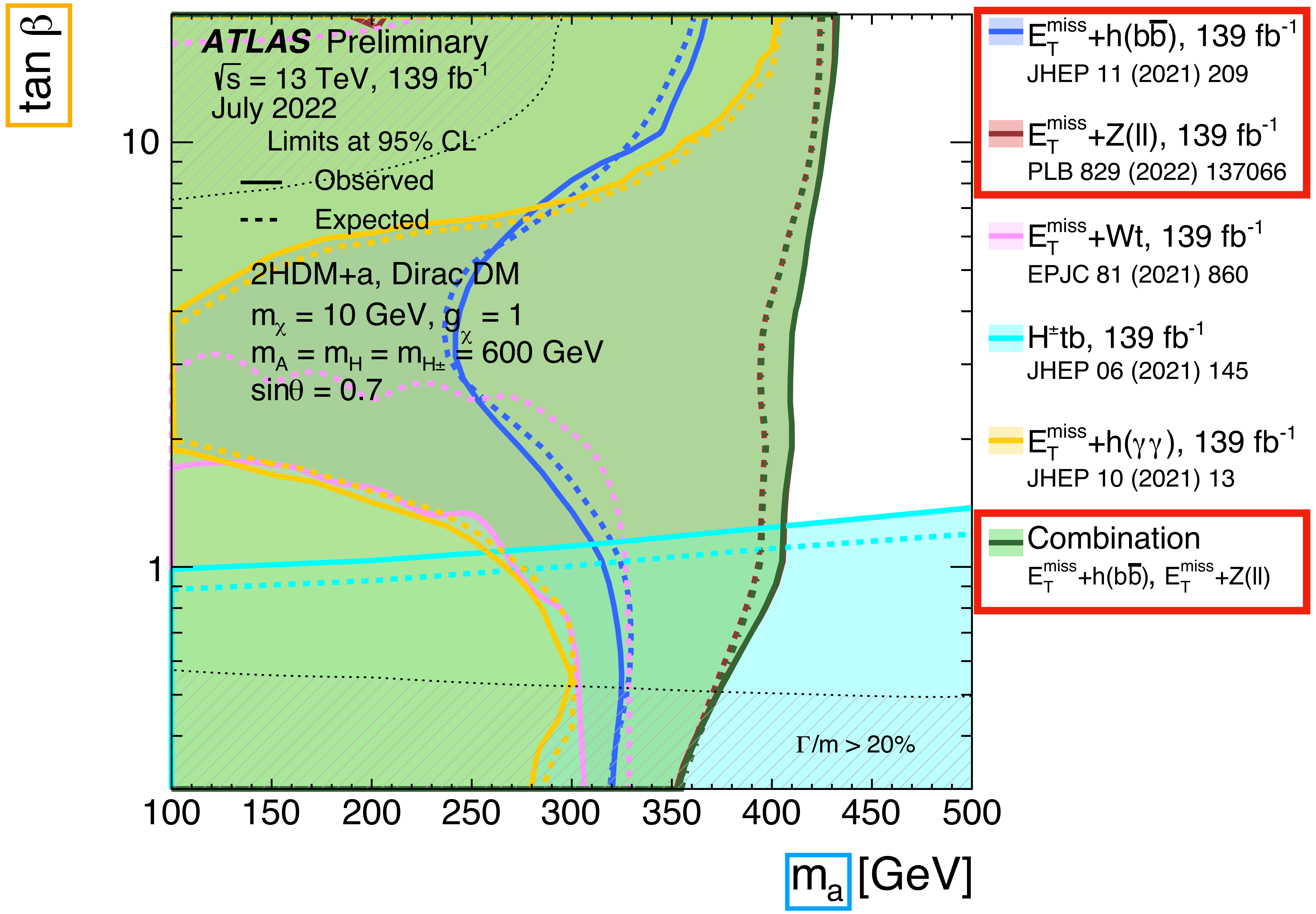
Results summary



- several scans of parameters performed
  - scan parameters agreed with LHC DM WG
  - multiple parameters scans reported in [ATL-PHYS-PUB-2022-036](#)



ratio between SM Higgs vev & extended Higgs vev

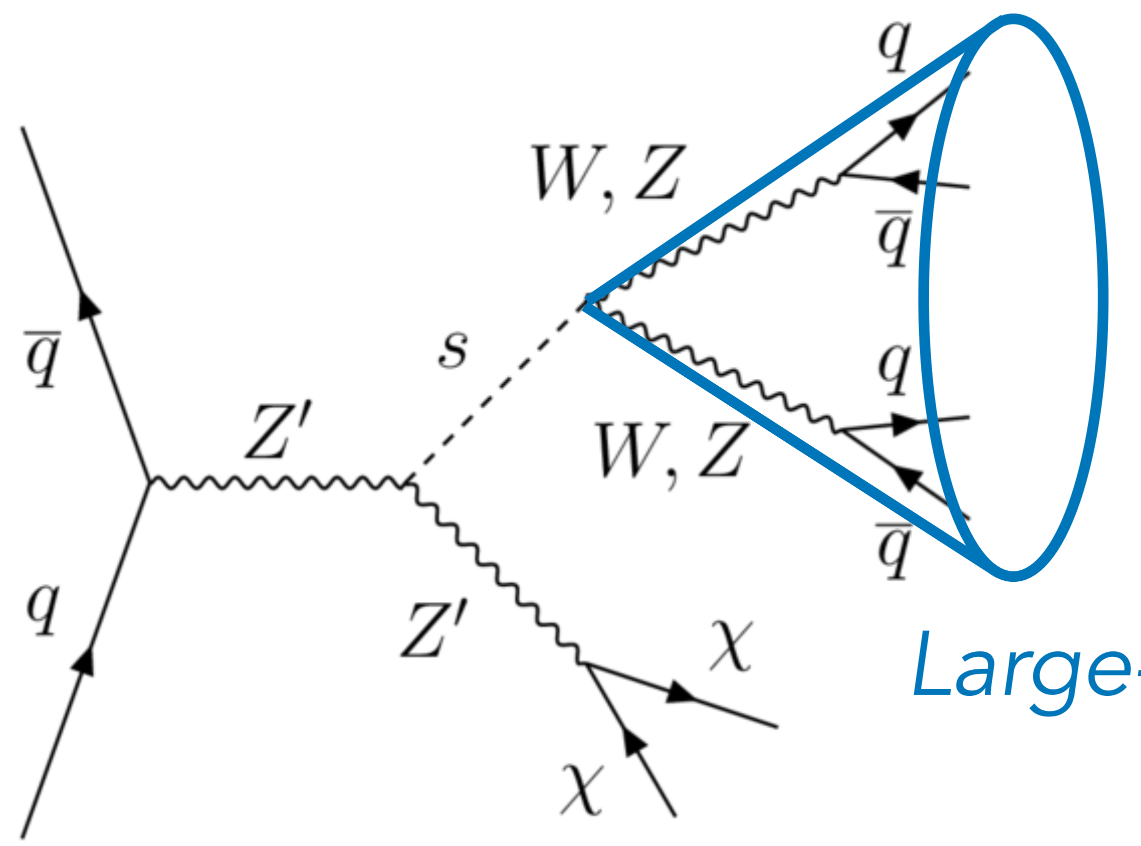


Giving mass to the dark sector

- introduce an additional scalar particle **s**, the dark Higgs boson - JHEP 04(2017)143
  - additional parameter to simplified models {m_χ, $m_{Z'}$, **m_s**, g_q, g_χ}
  - SM-Higgs-like decays: **s → WW (ZZ)** for m_S > 160 (180) GeV

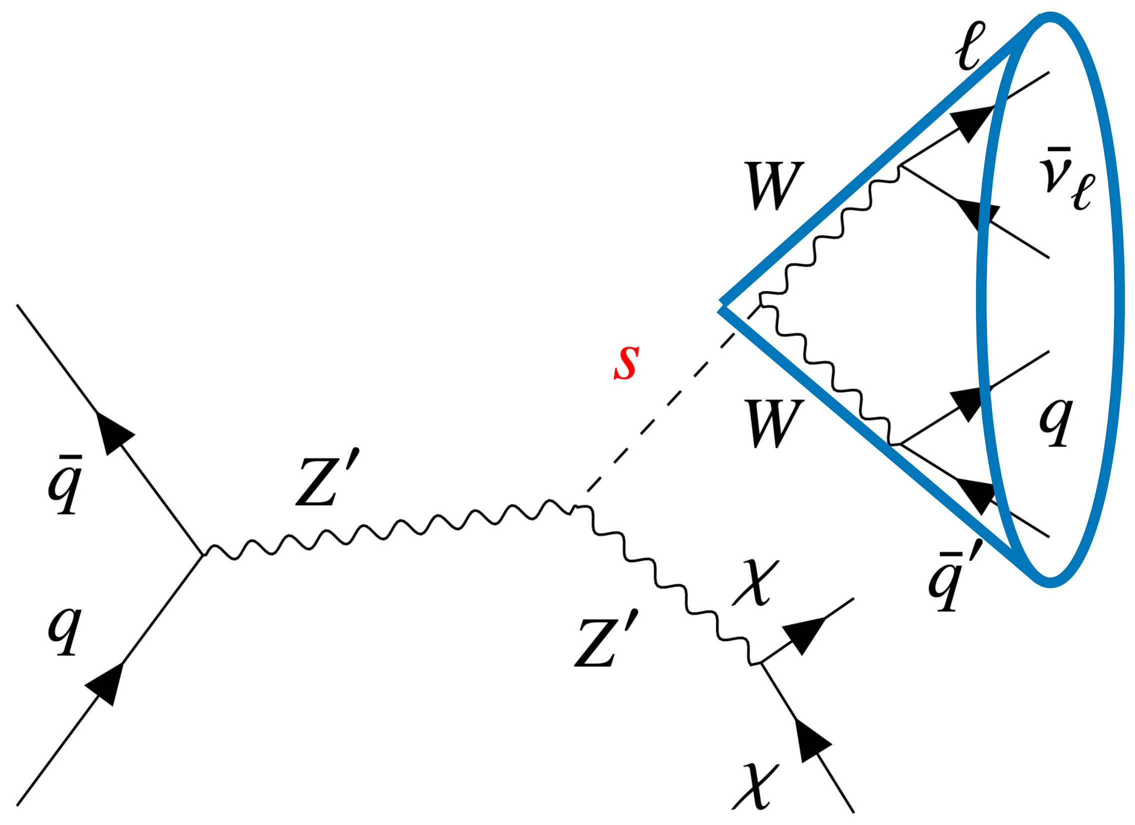
Hadronic decays - Phys. Rev. Lett. 126 (2021) 121802

- additional scalar reconstructed as large-R jet
  - exploit substructure variables to identify W candidates
- discriminant variable: m_J



Semi-leptonic decays - ATLAS-CONF-2022-029

- exploring both resolved and merged categories
- discriminant variable m_S

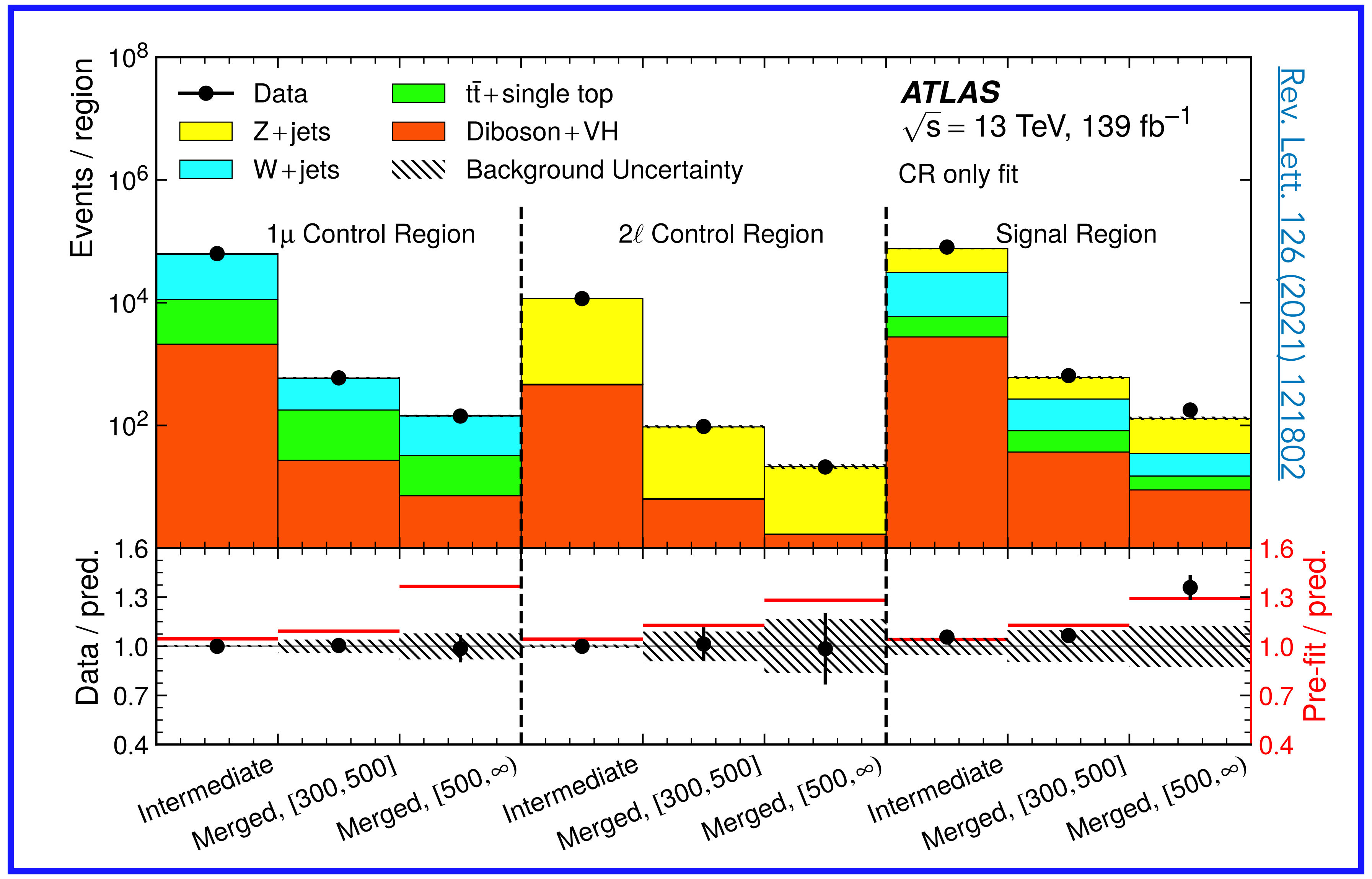


resolved: lepton + 2 jets

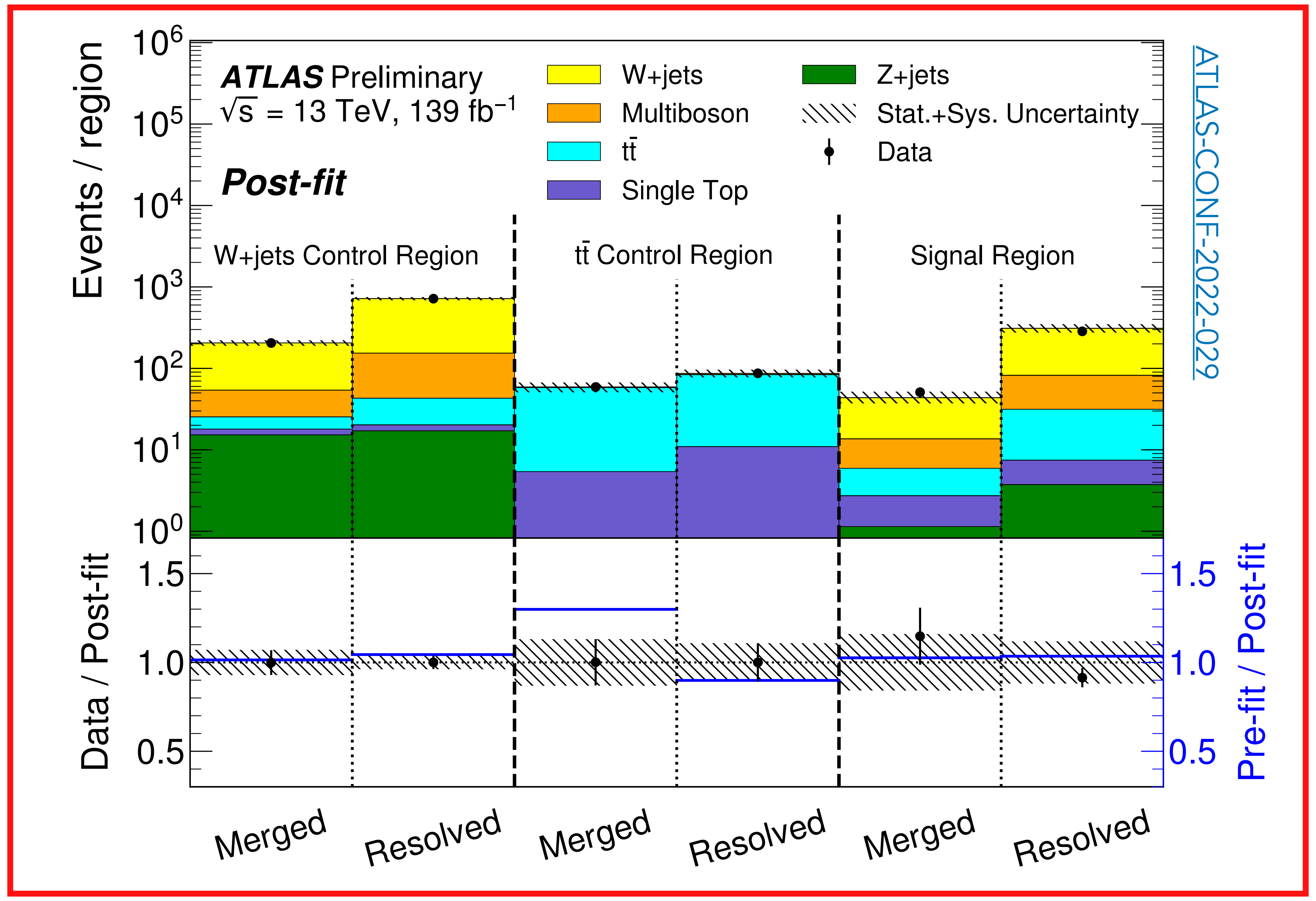
merged: large-R jet

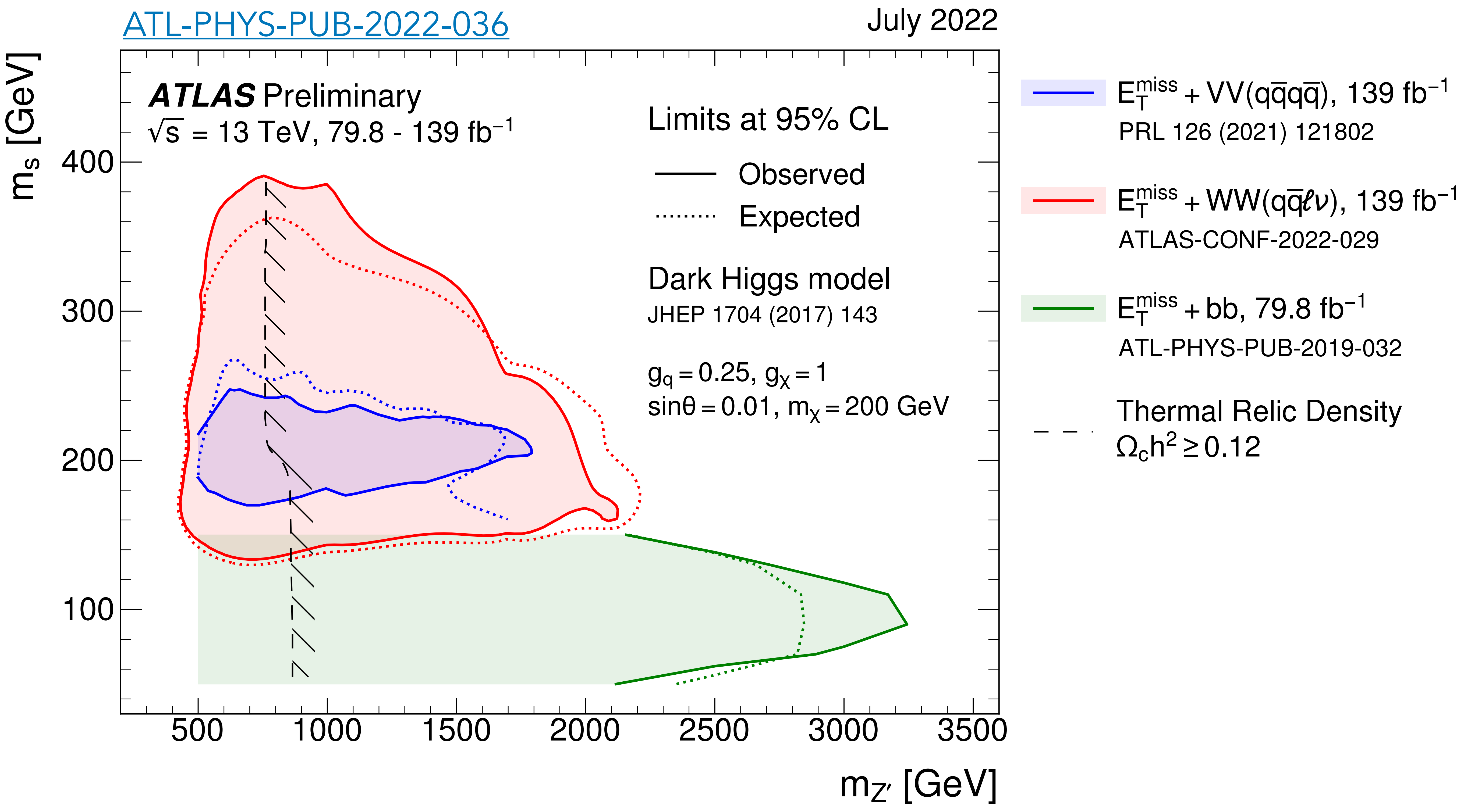
Dark Higgs summary & results

VV(qqqq)



WW(qqlv)





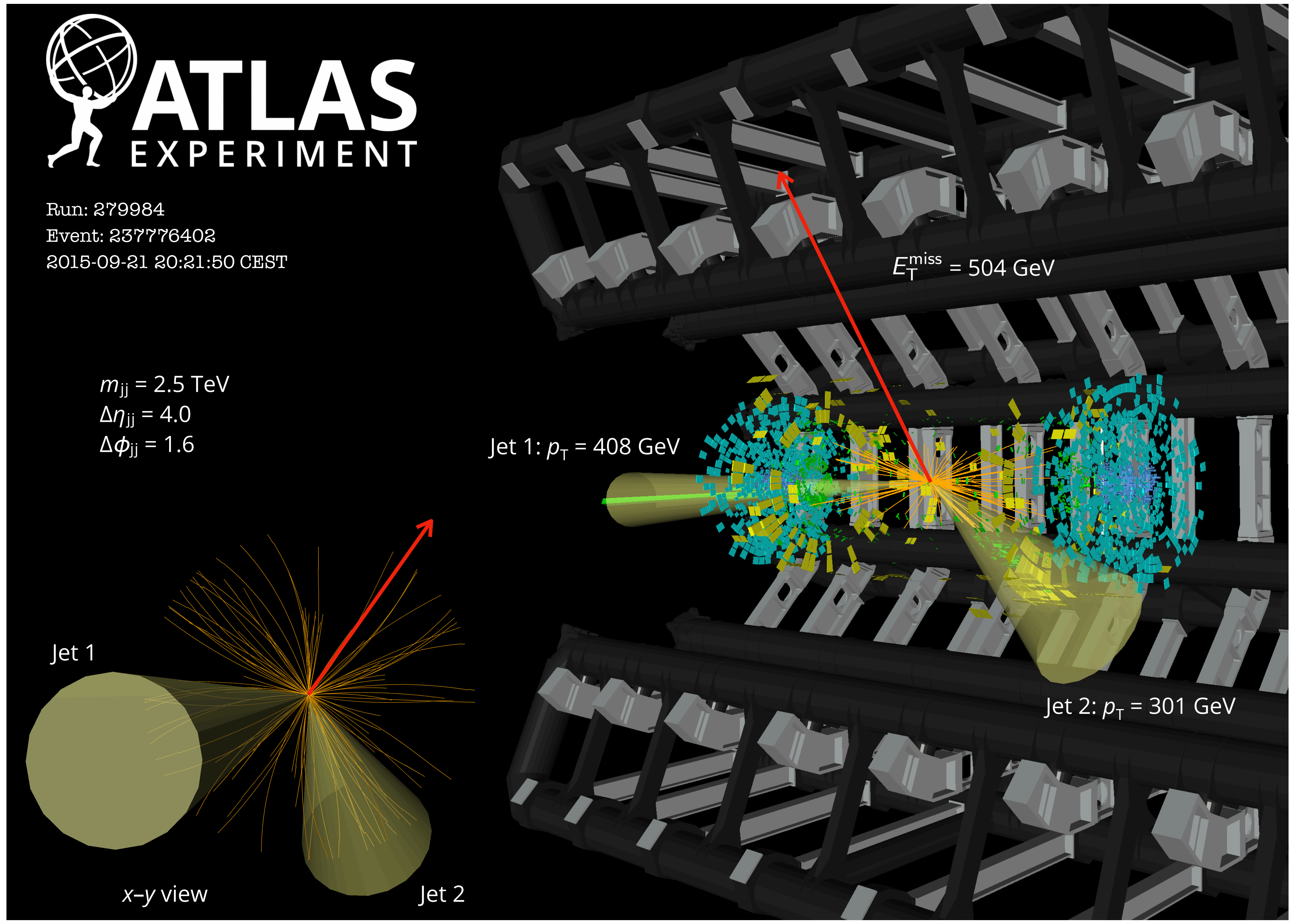
- better sensitivity for the semi-leptonic channel
- complementarity with re-interpretation of preliminary run-2 mono-H(bb) result
  - boost sensitivity in the [80,150] GeV m_{bb} range

Invisible decays of the Higgs boson

- SM Higgs boson invisible decays: H→ZZ*→4ν ~ 0.12%
  - BSM modes could lead to enhanced rates

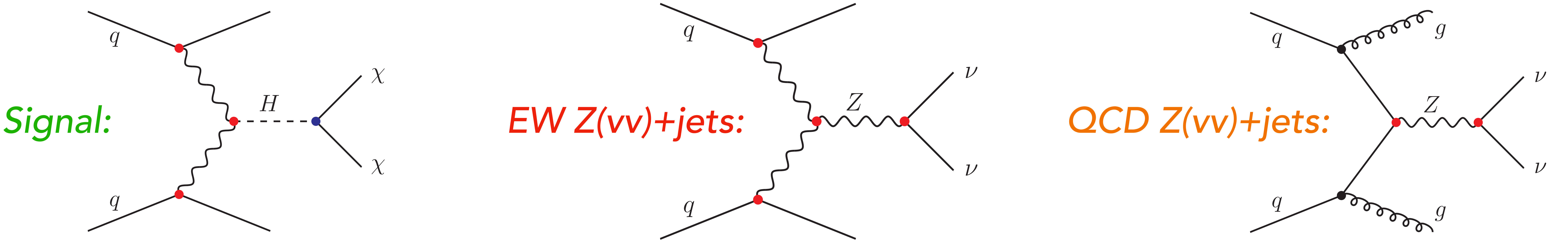
VBF production most sensitive channel:

- two forward jets with large invariant mass, mjj > 800 GeV
- large $|\Delta\eta_{jj}|$ > 3.8, small $|\Delta\phi|$, E_T^{miss} > 160 GeV
- E_T^{miss} triggers to select the events



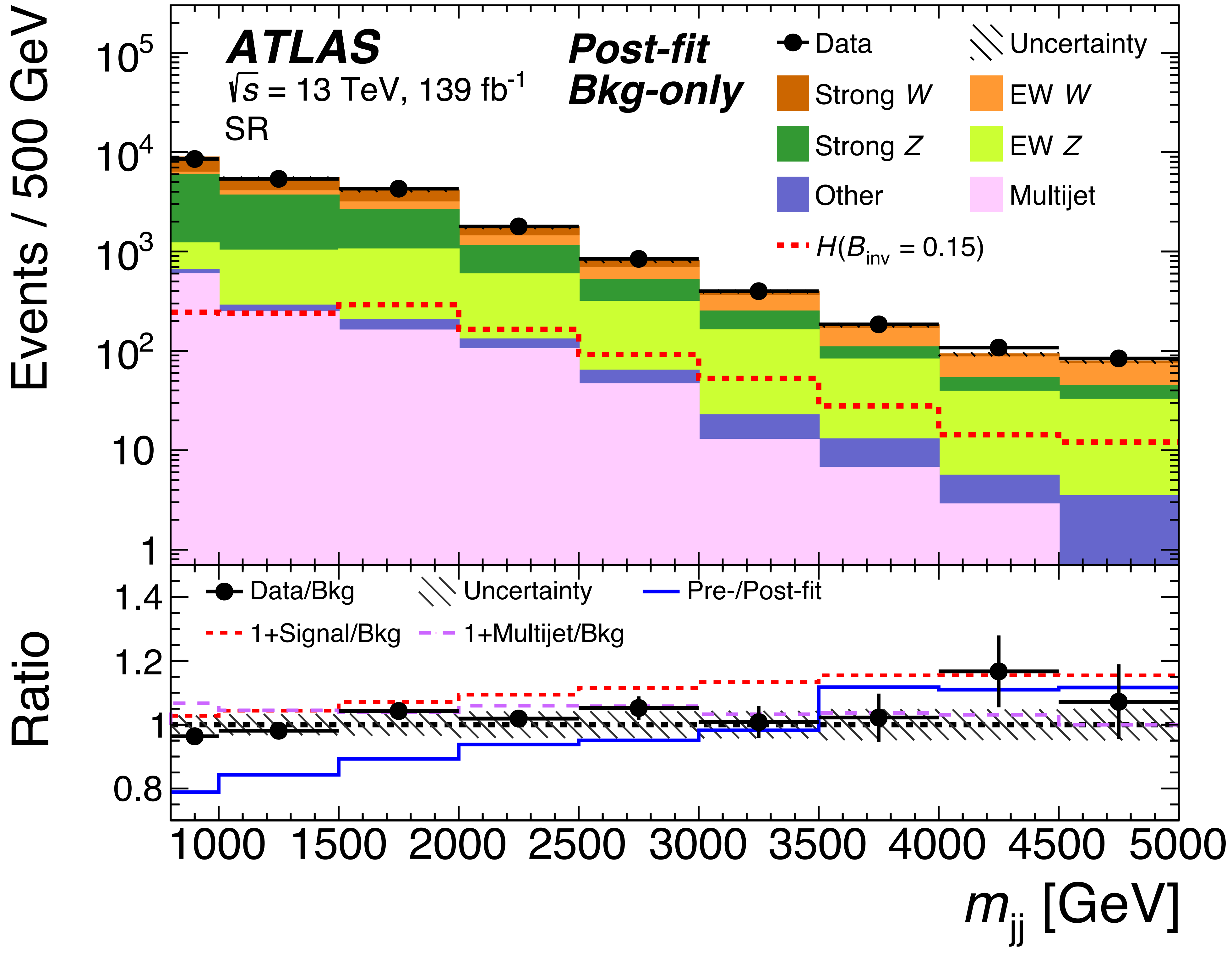
Leading backgrounds:

- EW Z(νν)+jets, QCD Z(νν)+jets, W+jets

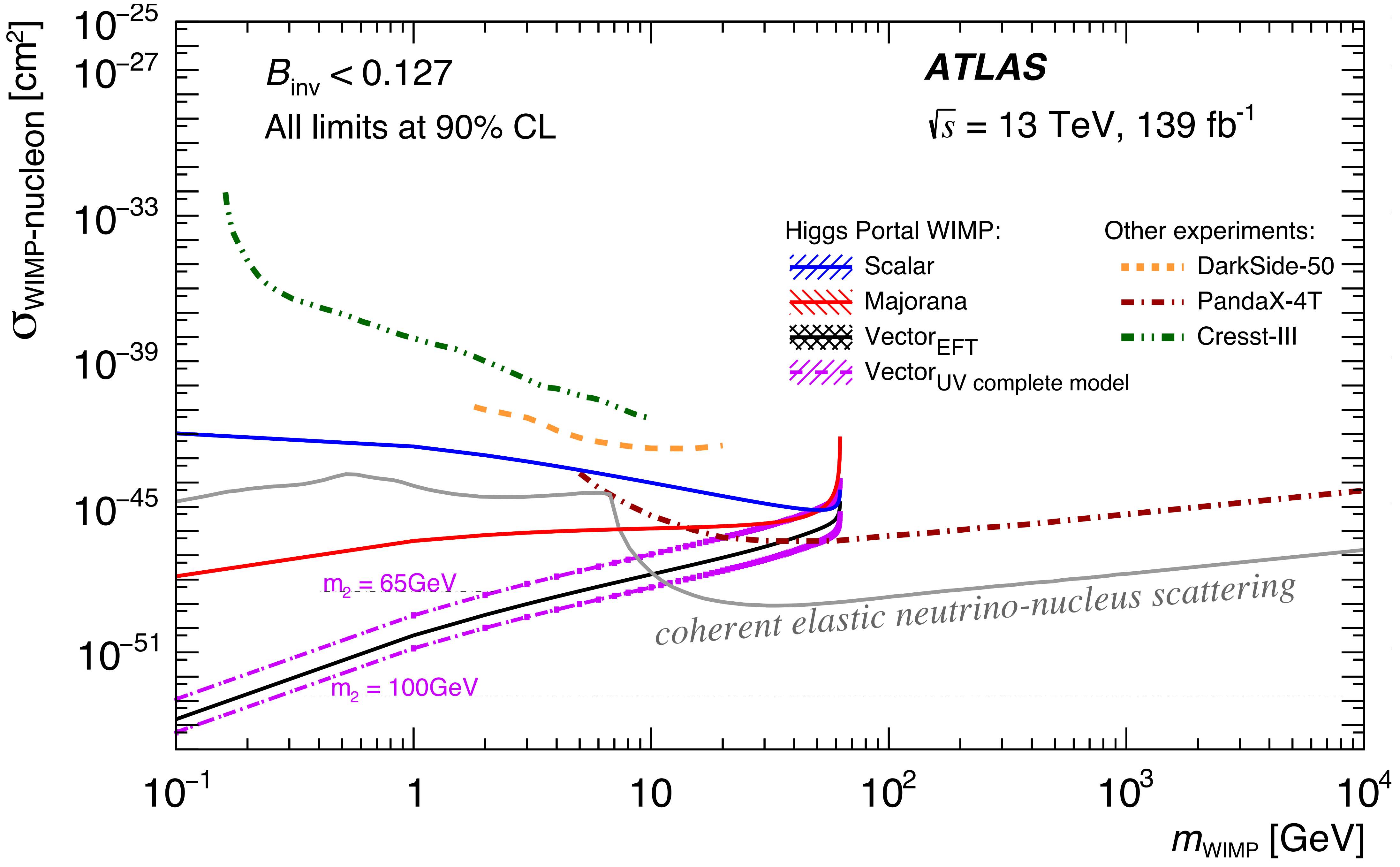


VBFH, H→invisible analysis strategy & results

- similar strategy to monojet: adopt 1 & 2 lepton CRs enriched in V+jets backgrounds
- Z to W ratio predictions @NLO QCD, NLO EW - arXiv:2204.07652 - used to constrain Z(vv)+jets with W(lv)+jets too
- discriminant variable: mjj - SR categorized in njet, Δϕjj to enhance sensitivity



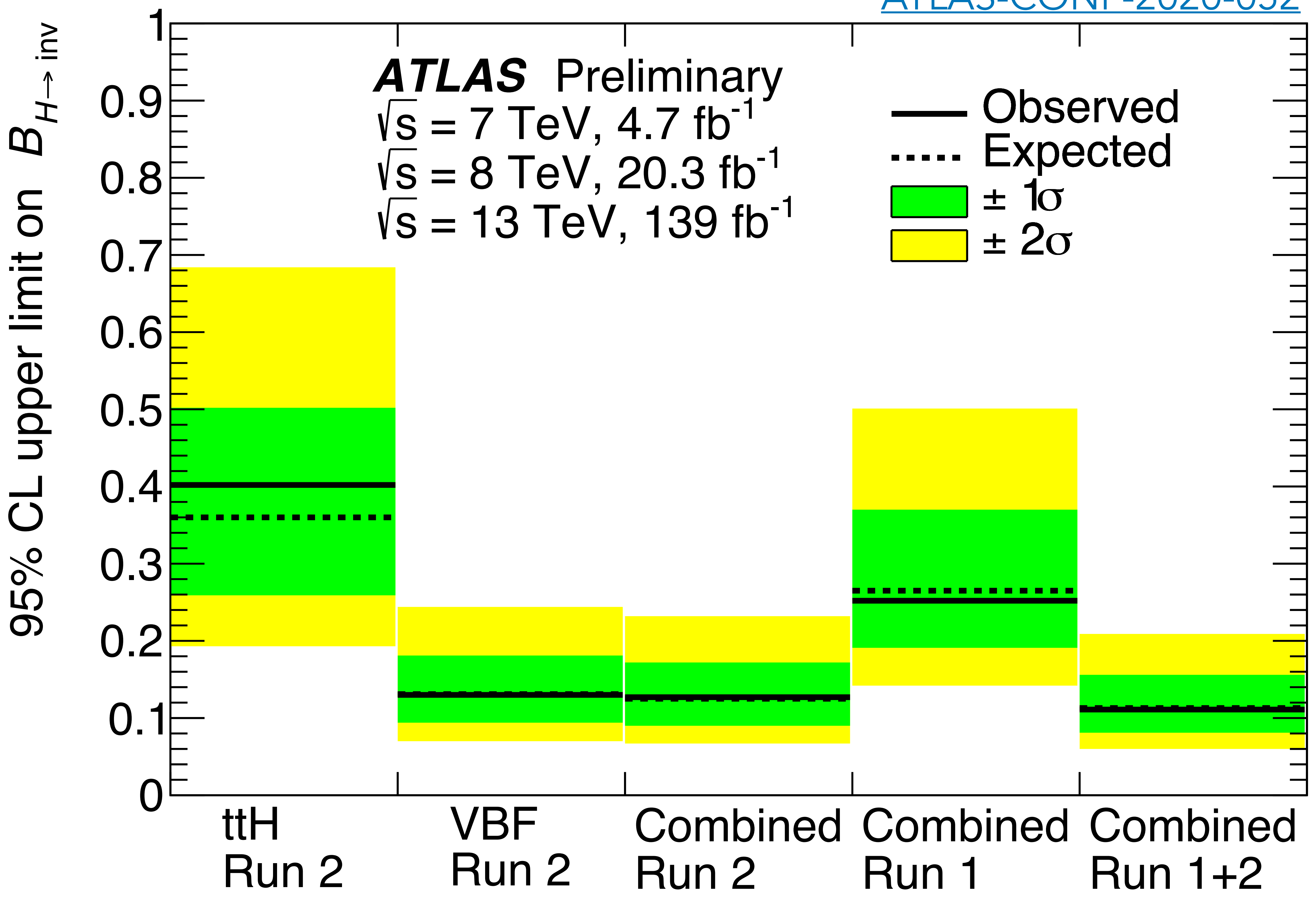
Result: **BR(H→inv.) < 14% (10% exp) @95% CL**



Higgs to invisible decays: combination

- ATLAS preliminary combination of some full run 2 results, including
  - tt + E_T^{miss} analysis, only 0 and 2 lepton channels
  - VBFH, H→invisible preliminary analysis result - not including W to Z corrections & low E_T^{miss} regime [160, 250] GeV

ATLAS-CONF-2020-052



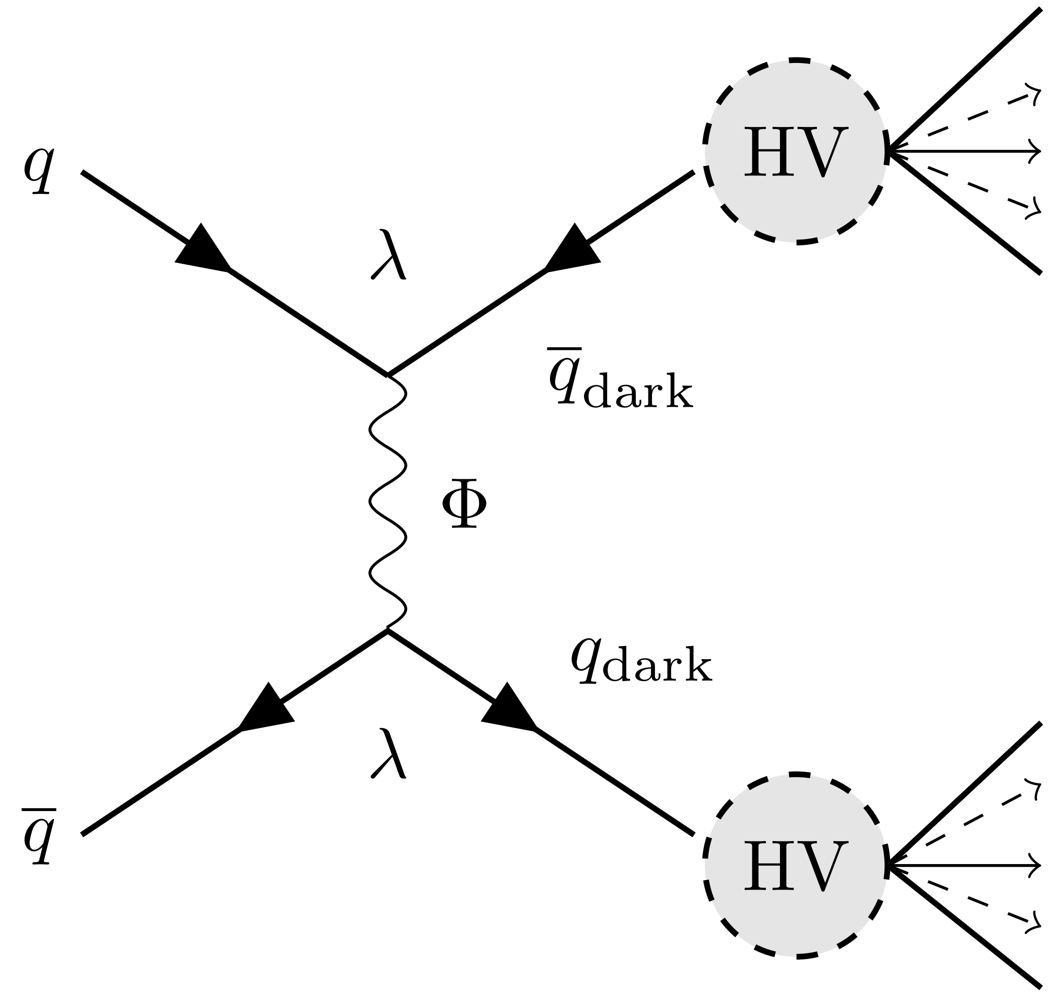
- available LHC-Run 2 ATLAS results not included in this combination - all limits @95% CL:
  - ttH+E_T^{miss} 0+1+2 lepton channels combined
  - monojet: BR(H→inv.) < 34% (39%) - obs (exp)
  - VBFH+γ: BR(H→inv.) < 37% (34%) - obs (exp)
  - mono-Z(ll): BR(H→inv.) < 19% (19%) - obs (exp)

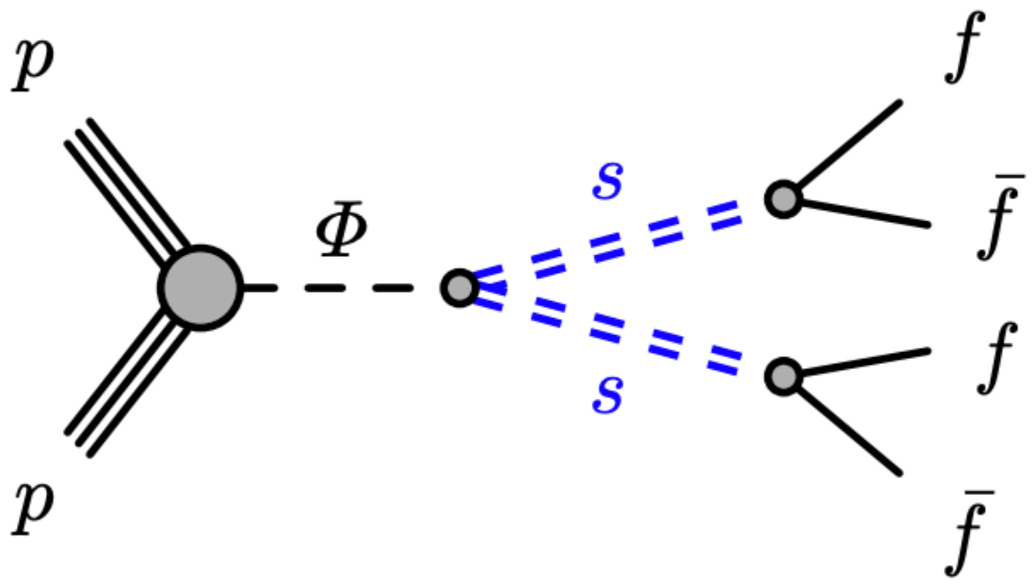
Combined upper limit: BR(H→inv.) < 11% (11% exp) @95% CL

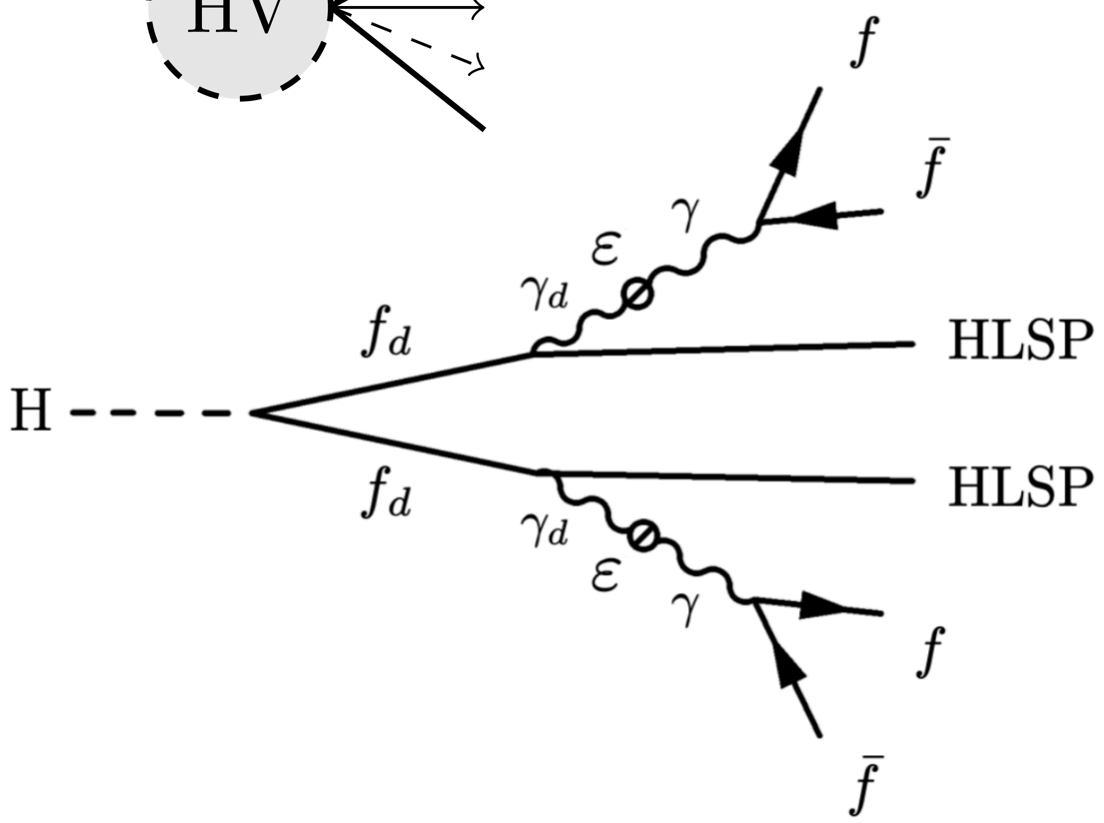
Dark matter in unconventional signatures

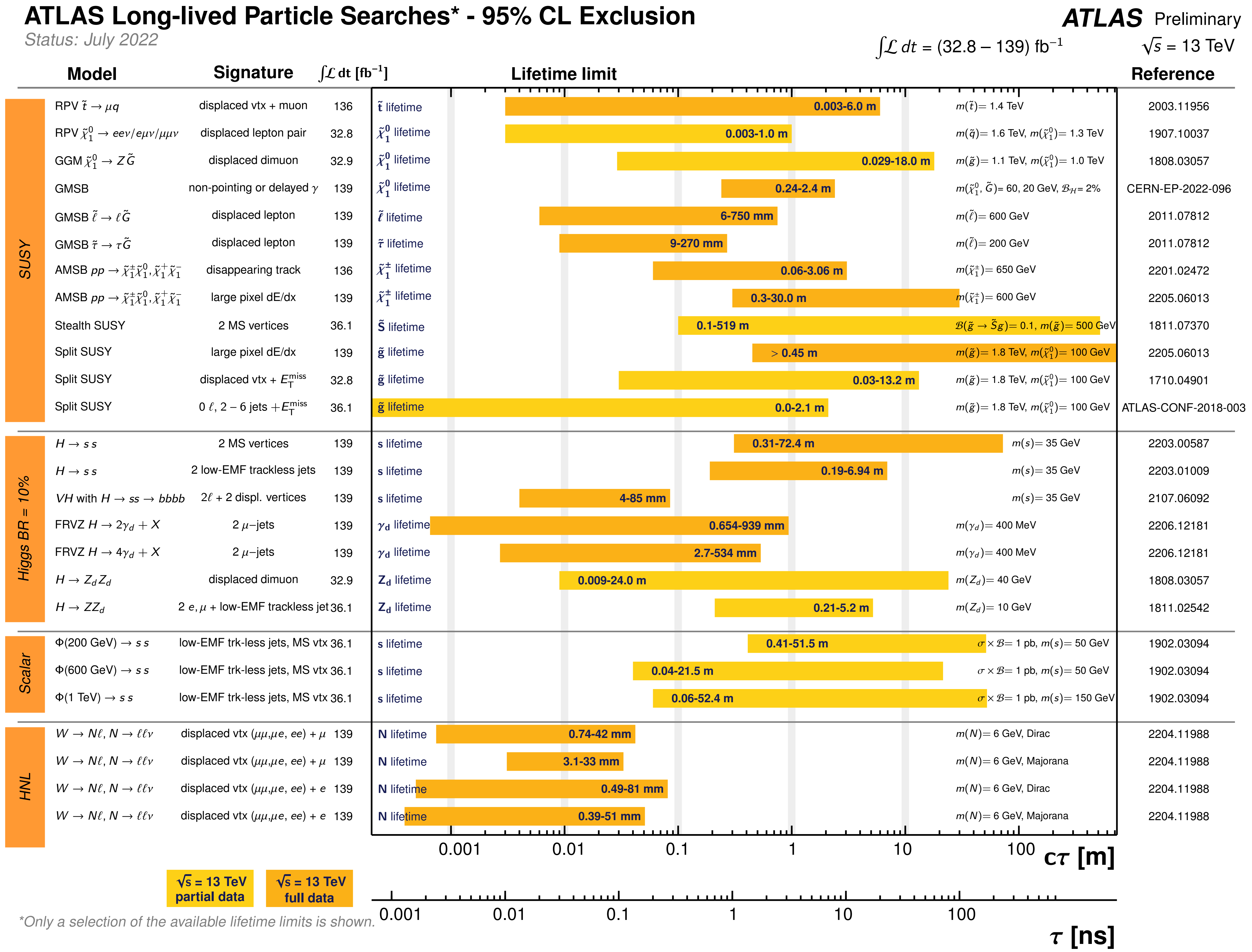
- alternative approach: search for dark matter hints in unconventional signatures
  - semi-visible jets production - [ATLAS-CONF-2022-038]
  - long-lived particles as portals to the dark sector

Very broad program covered by the ATLAS experiment!









Summary

- presented overview of broad ATLAS program on dark matter searches carried out with LHC Run 2 data-set:
  - monojet: Phys. Rev. D 103 (2021) 112006
  - dijet: JHEP 03 (2020) 145
  - tt+MET
    - 0-lepton: Eur. Phys. J. C 80 (2020) 737
    - 1-lepton: JHEP 04 (2021) 174
    - 2-lepton: JHEP 04 (2021) 165
  - mono-H(bb): JHEP 11 (2021) 209
  - mono-Z(ll): Phys. Lett. B 829 (2022) 137066
  - mono-S(VV) hadronic: Phys. Rev. Lett. 126 (2021) 121802
  - mono-S(WW) semileptonic: ATLAS-CONF-2022-029
  - VBFH, H→ invisible: JHEP 08 (2022) 104
  - H→invisible combination: ATLAS-CONF-2020-052

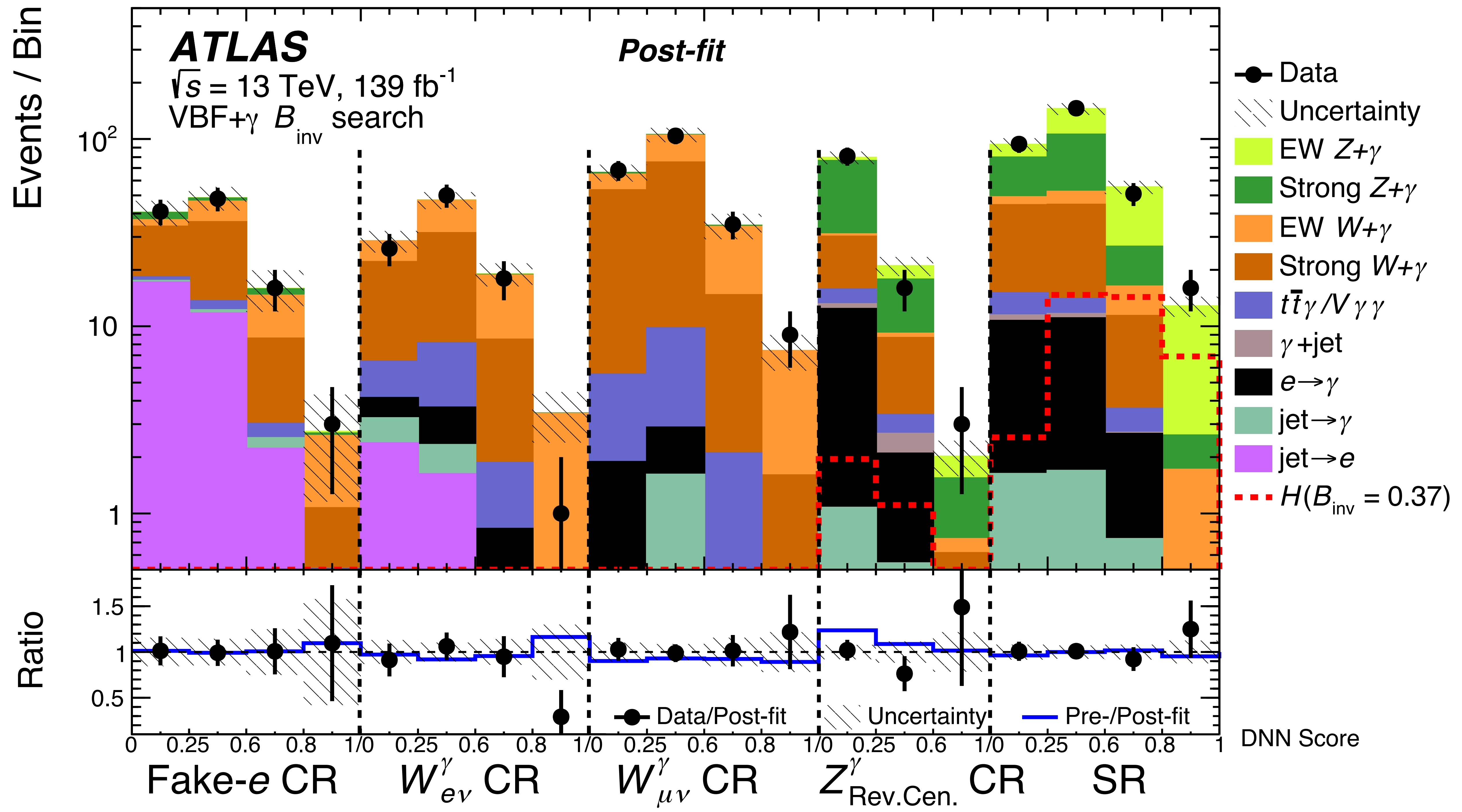
..stay tuned for new results!

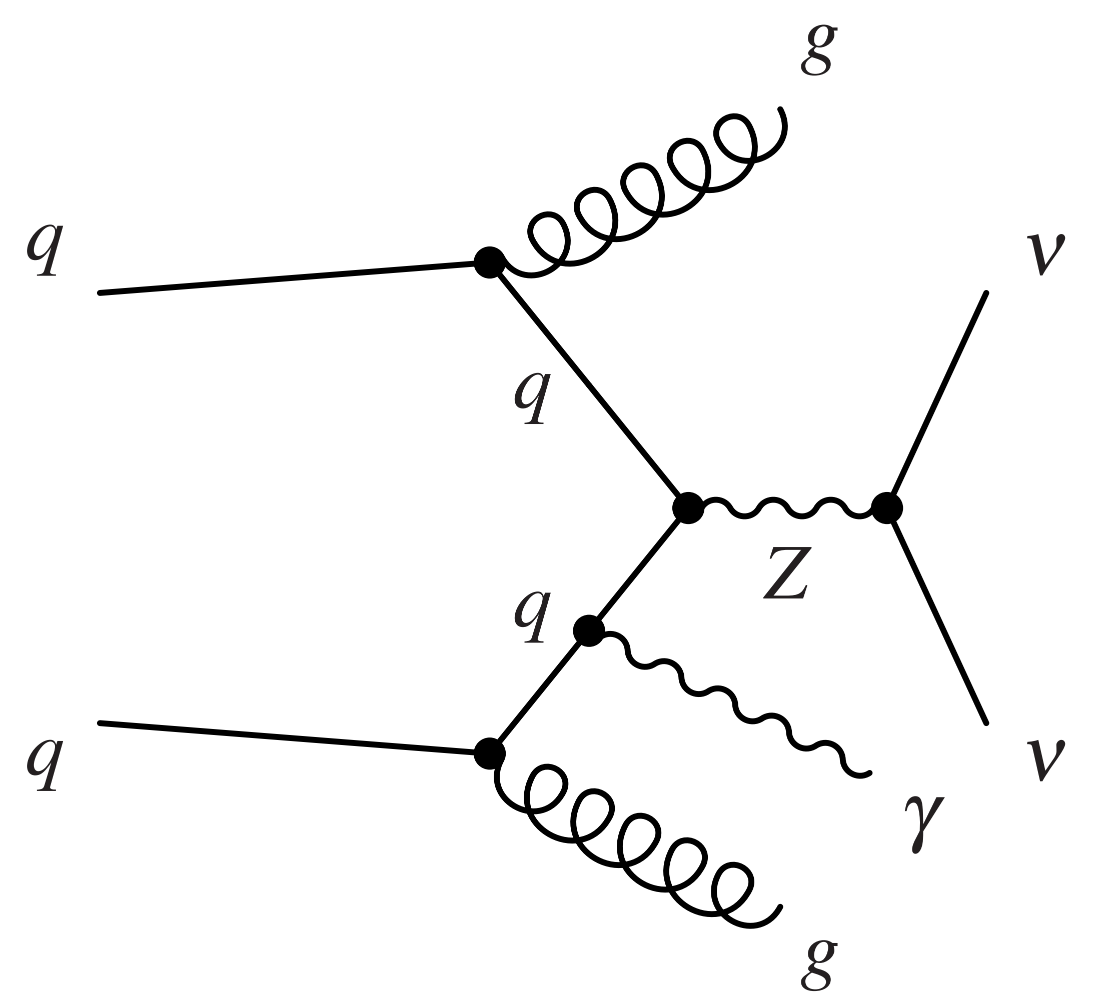
Backup

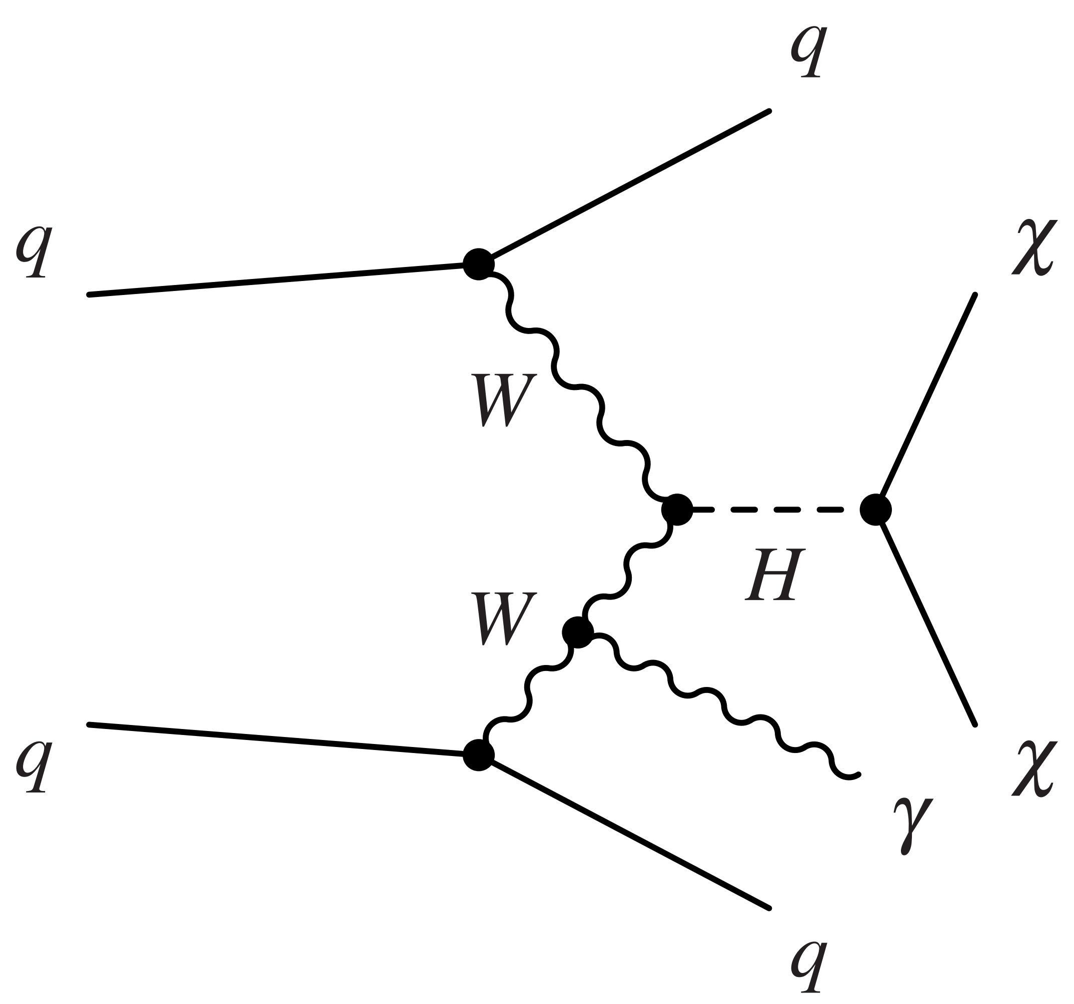
[Eur. Phys. J. C 82 (2022) 105]

VBFH + γ, H→invisible search

- enhance suppression of QCD backgrounds requiring an extra photon
- deep neural network approach to improve signal / background discrimination
  - main discriminating features: Δη, Δϕ, η_γ, jet p_T
- EW Wγ predictions corrected in dedicated CR
- no free floating normalization of EW Zγ due to degeneracy with the signal

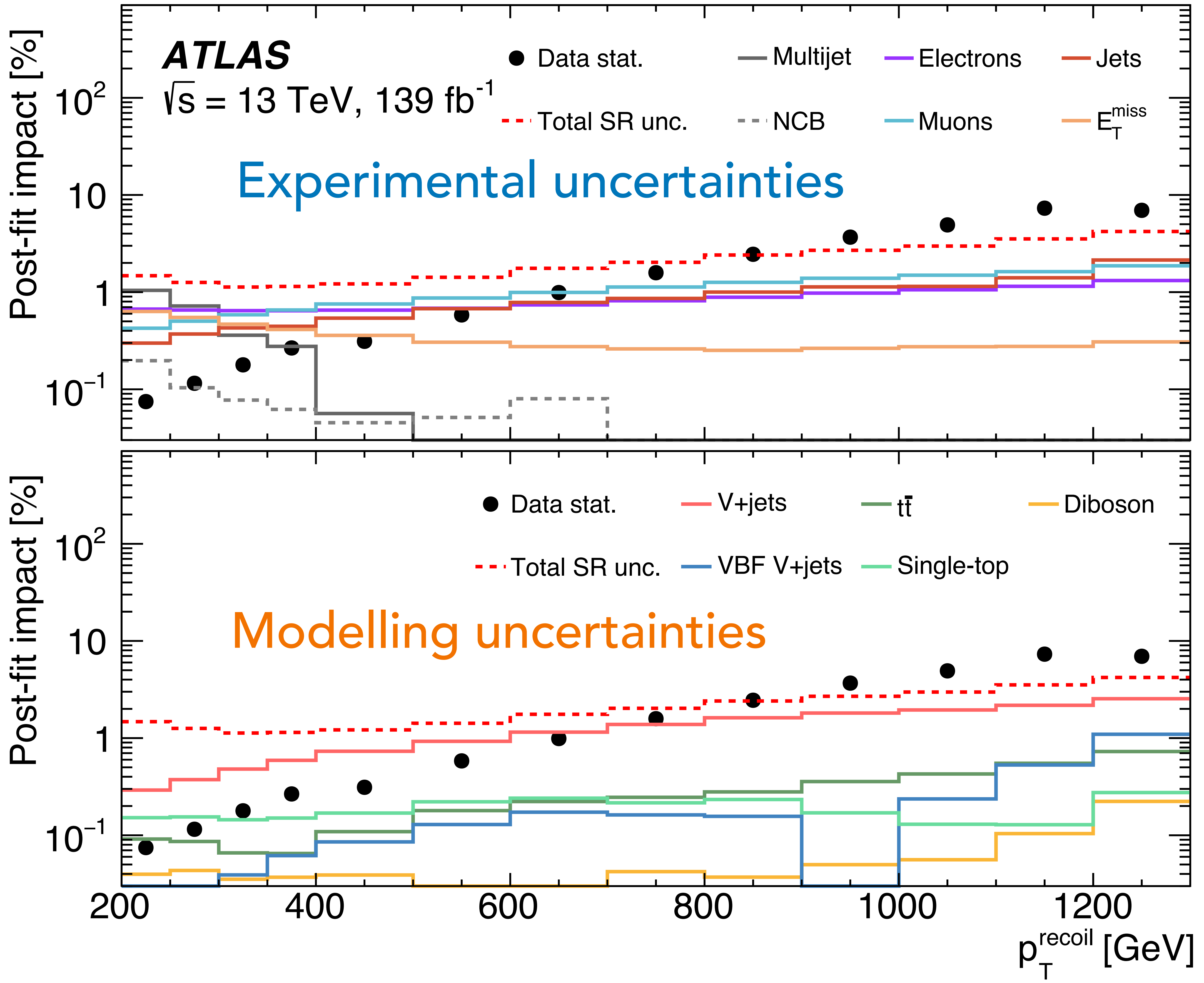






BR(H→inv.) < 37% (34% exp) @95% CL

Effect of systematic uncertainties in the monojet analysis



Leading uncertainties: V+jets processes modelling

Experimental uncertainties at % level

Effect of systematic uncertainties in the tt+E_T^{miss} analysis