LHC anomalies: where ATLAS and CMS searches see tension with the Standard Model

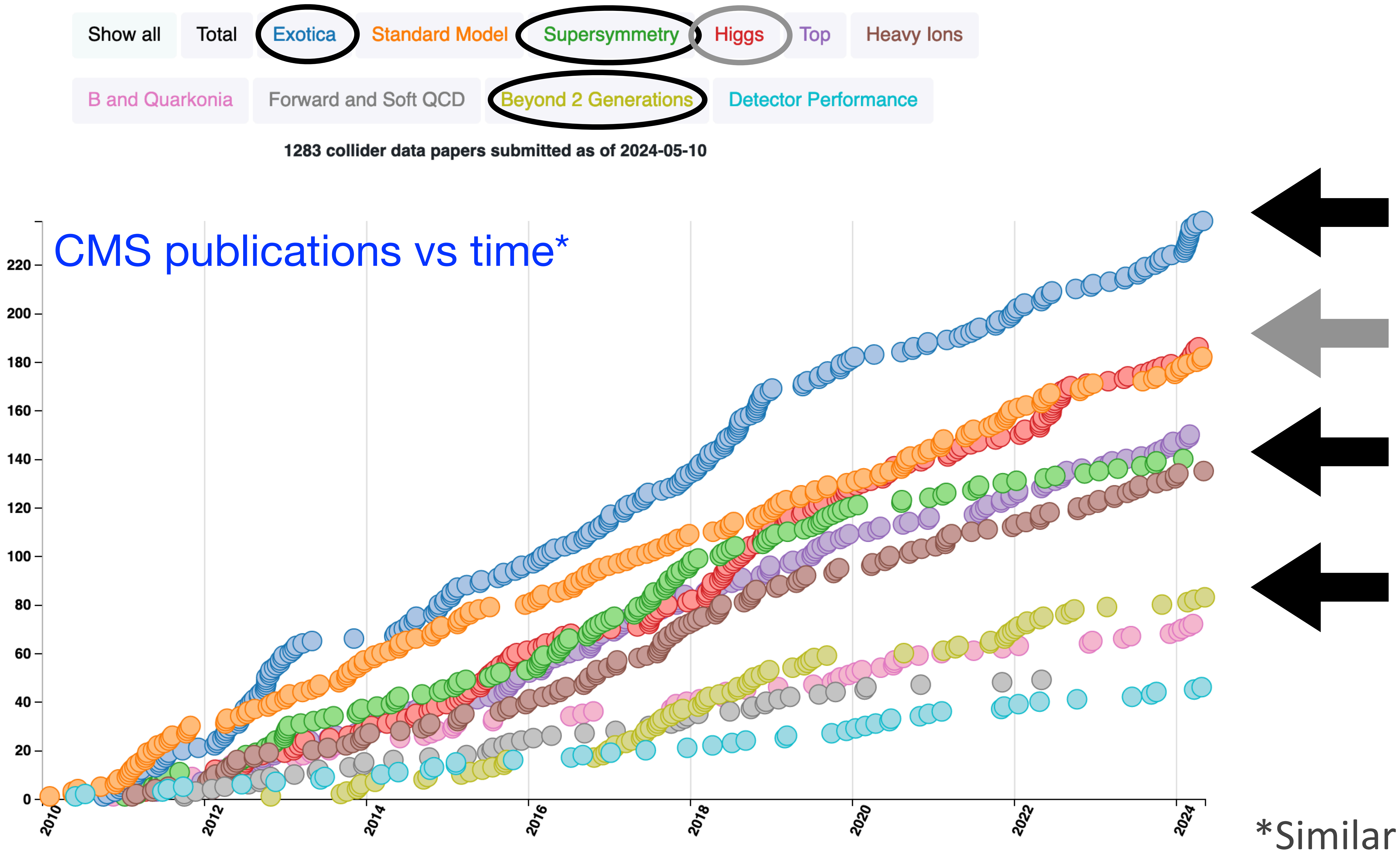
DPF-Pheno 24

May 17, 2024

Valentina Dutta

Carnegie Mellon University

Huge search program at the LHC!

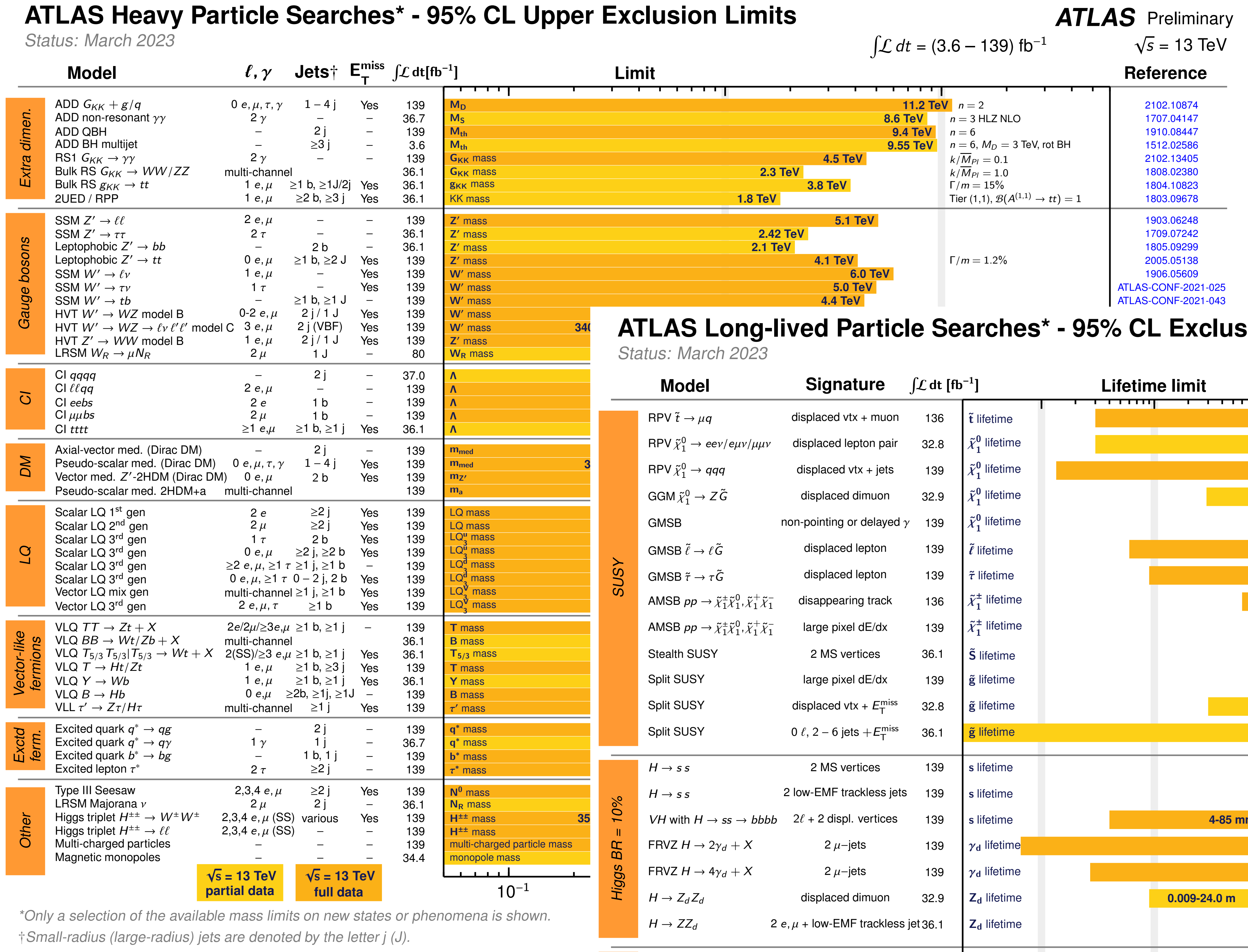


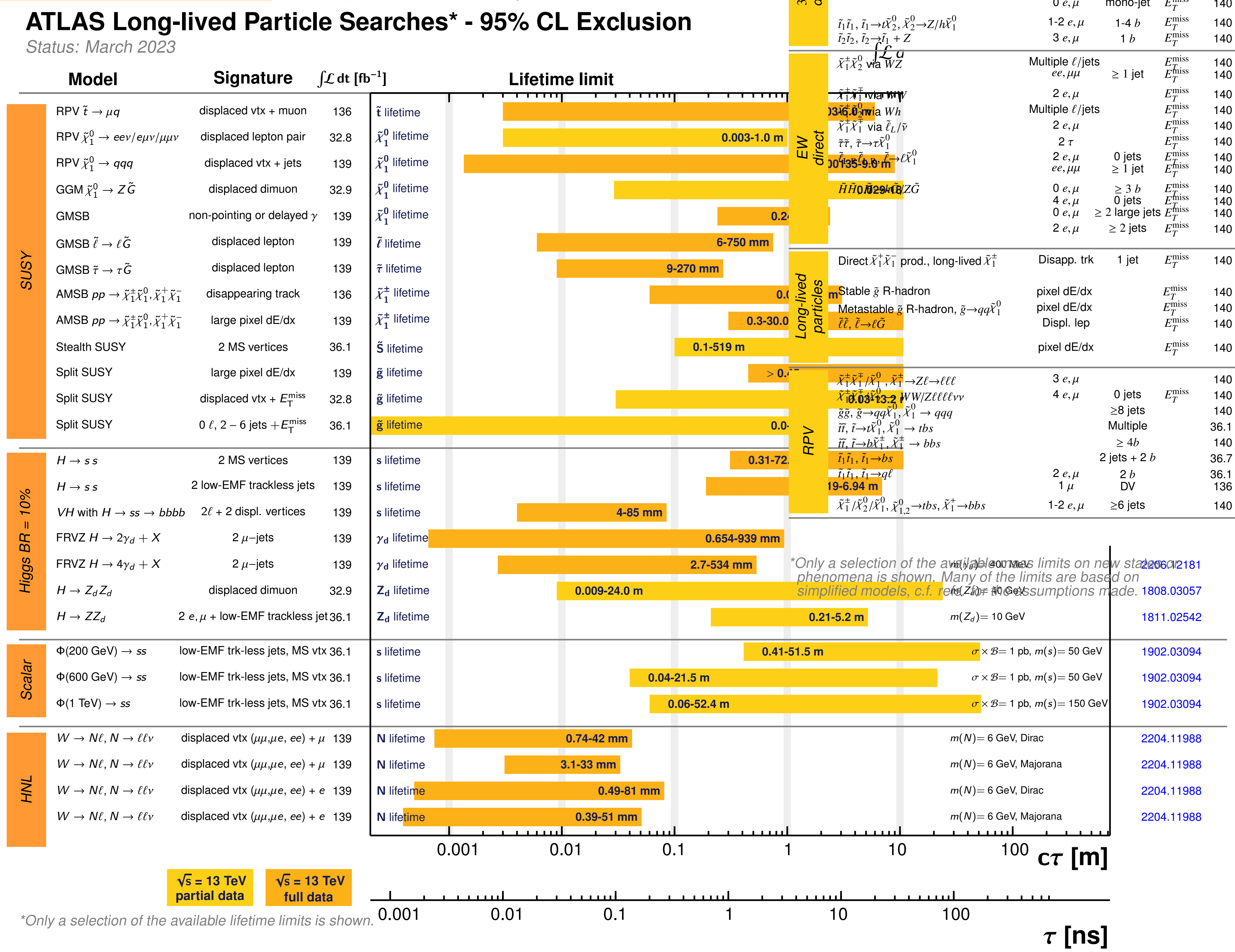
*Similar for ATLAS!

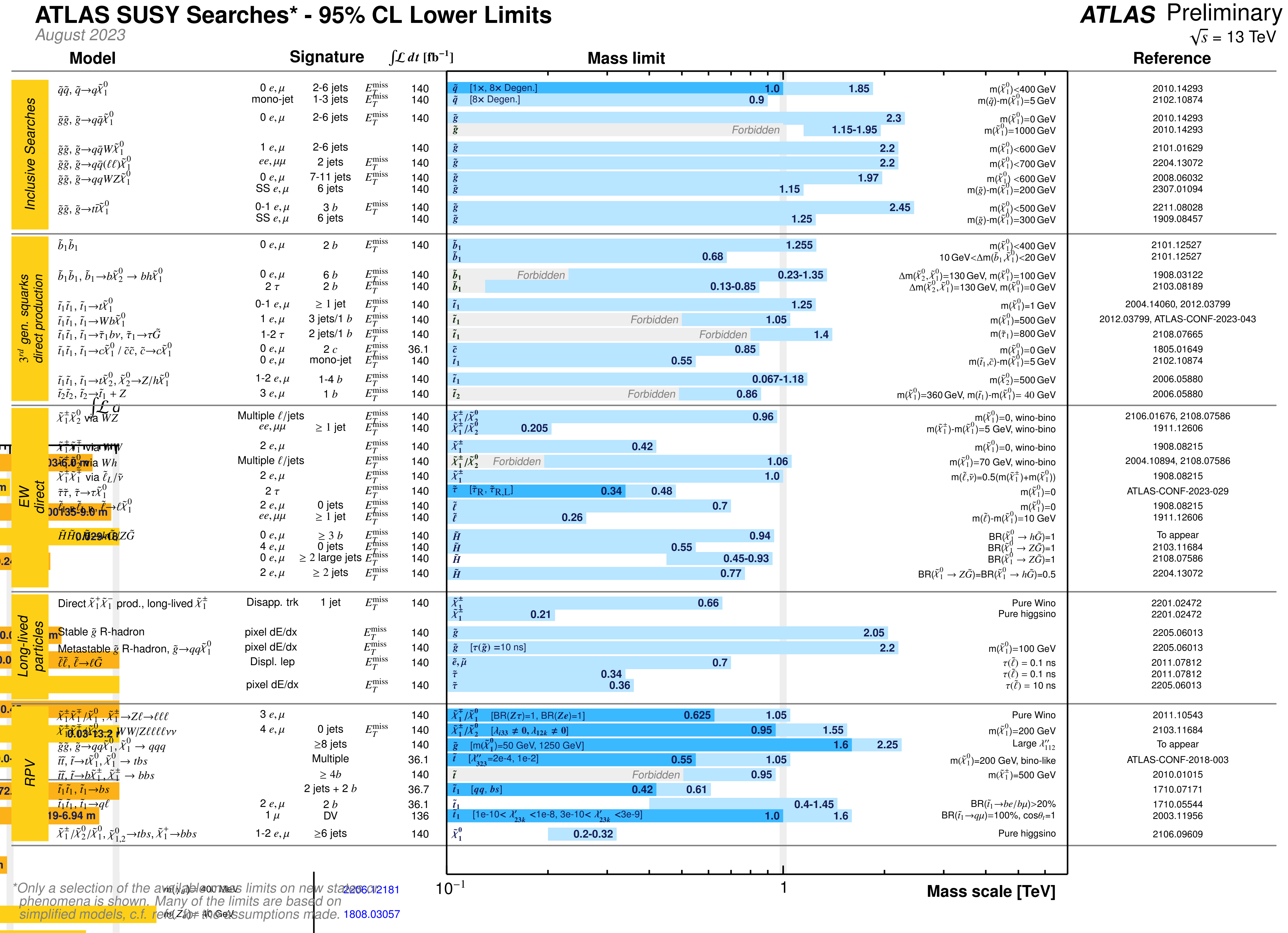
Exploring all directions in searches for new physics …

- dark sector
- Dark Matter
- Invisible decays
- heavy neutrinos
- Extra dimensions
- compositeness
- contact interactions
- resonances
- Long Lived Particles
- Highly ionizing particles
- Leptoquarks
- Axions
- WIMPS weakly interacting massive particles
- Supersymmetry
- vector like quarks

Covering vast range of new physics signatures

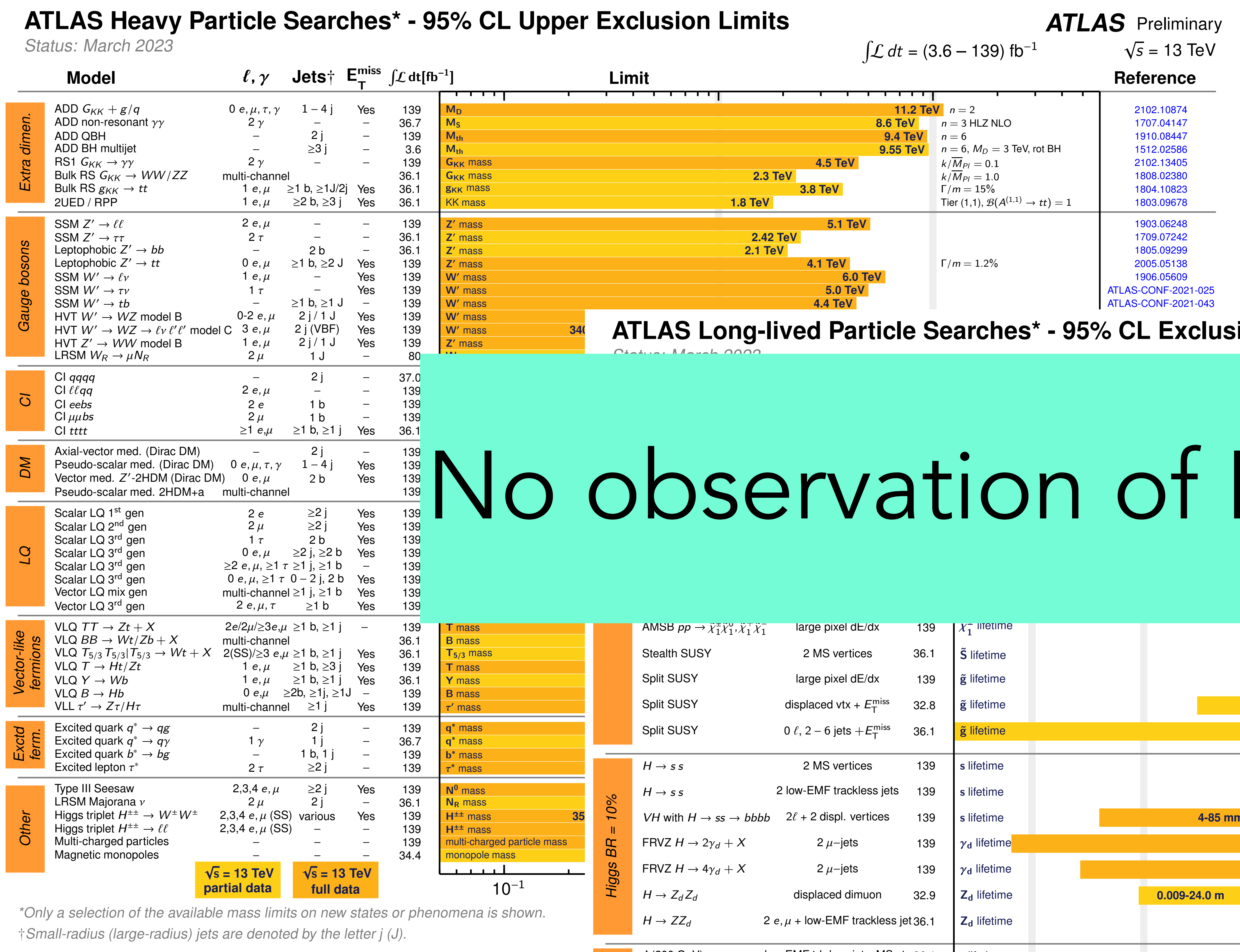


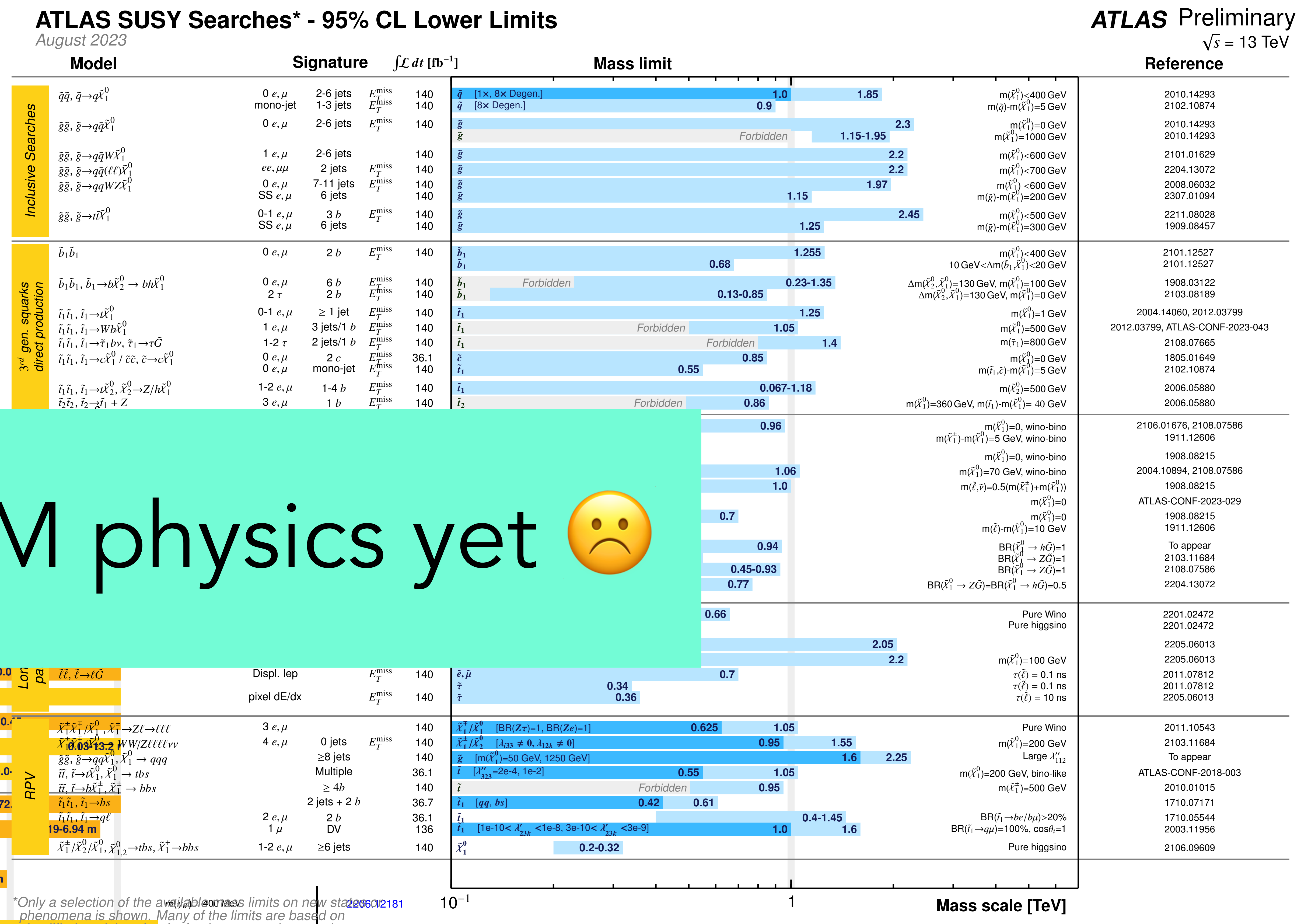


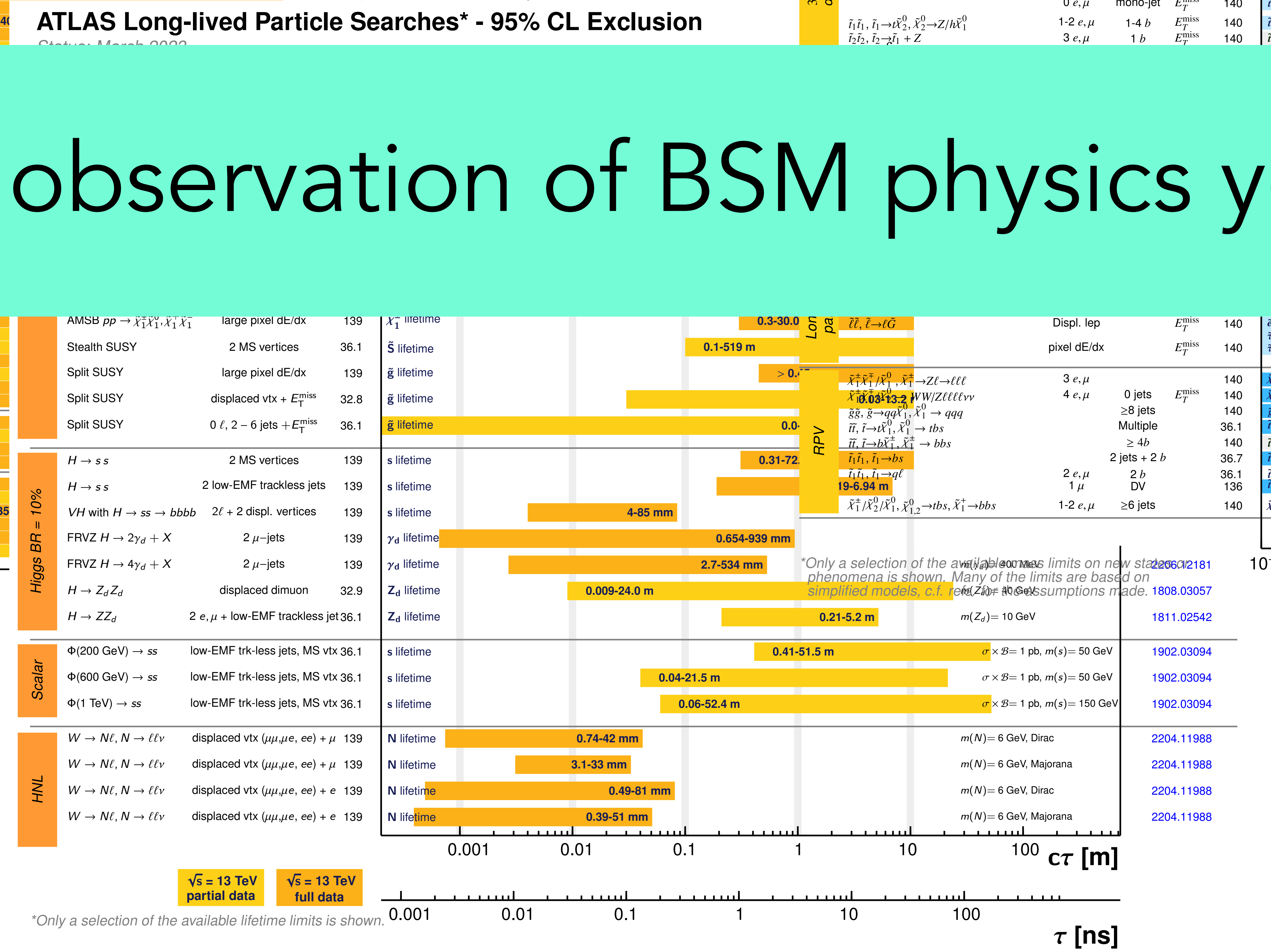


Limits set on BSM physics in many, many scenarios …

Covers vast range of new physics signatures







No observation of BSM physics yet ☹

Limits set on BSM physics in many, many scenarios …

Any hints or anomalies??

Any hints or anomalies??

This talk:

- A <u>selection</u> of results from ATLAS and CMS with intriguing excess of events observed with respect to the SM: especially where excess appears to be observed in multiple channels / searches or interesting in the light of other anomalies … cases worth following up with more data / additional searches
- Compare ATLAS and CMS where available
- Results with full LHC Run 2 data set (~140 fb^{-1} at $\sqrt{s}$ = 13 TeV) except where noted
- Caveat: by the nature of this talk, results shown are highly cherry-picked!

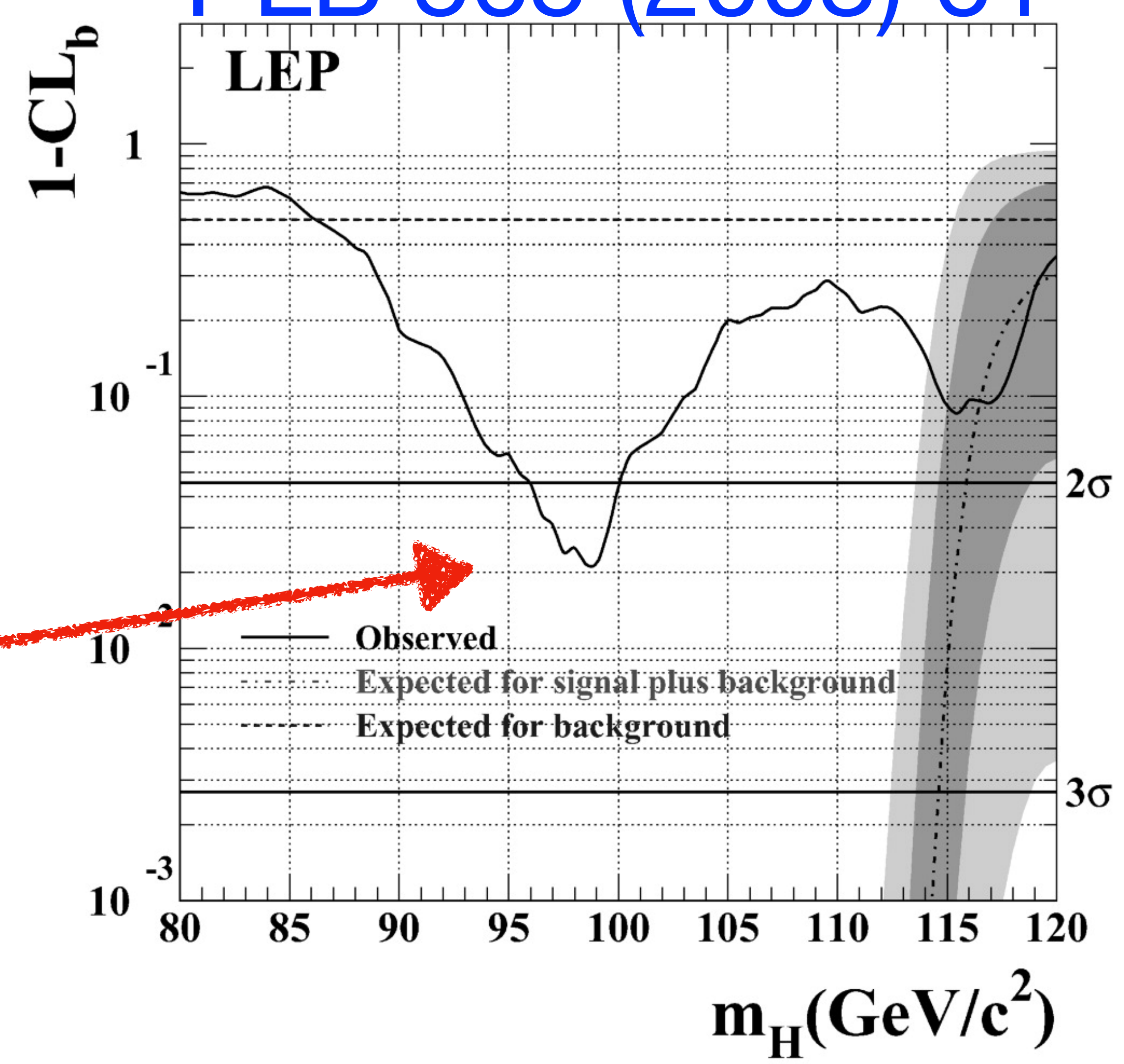
Searches for low- or high-mass resonances

Low mass di-photon search

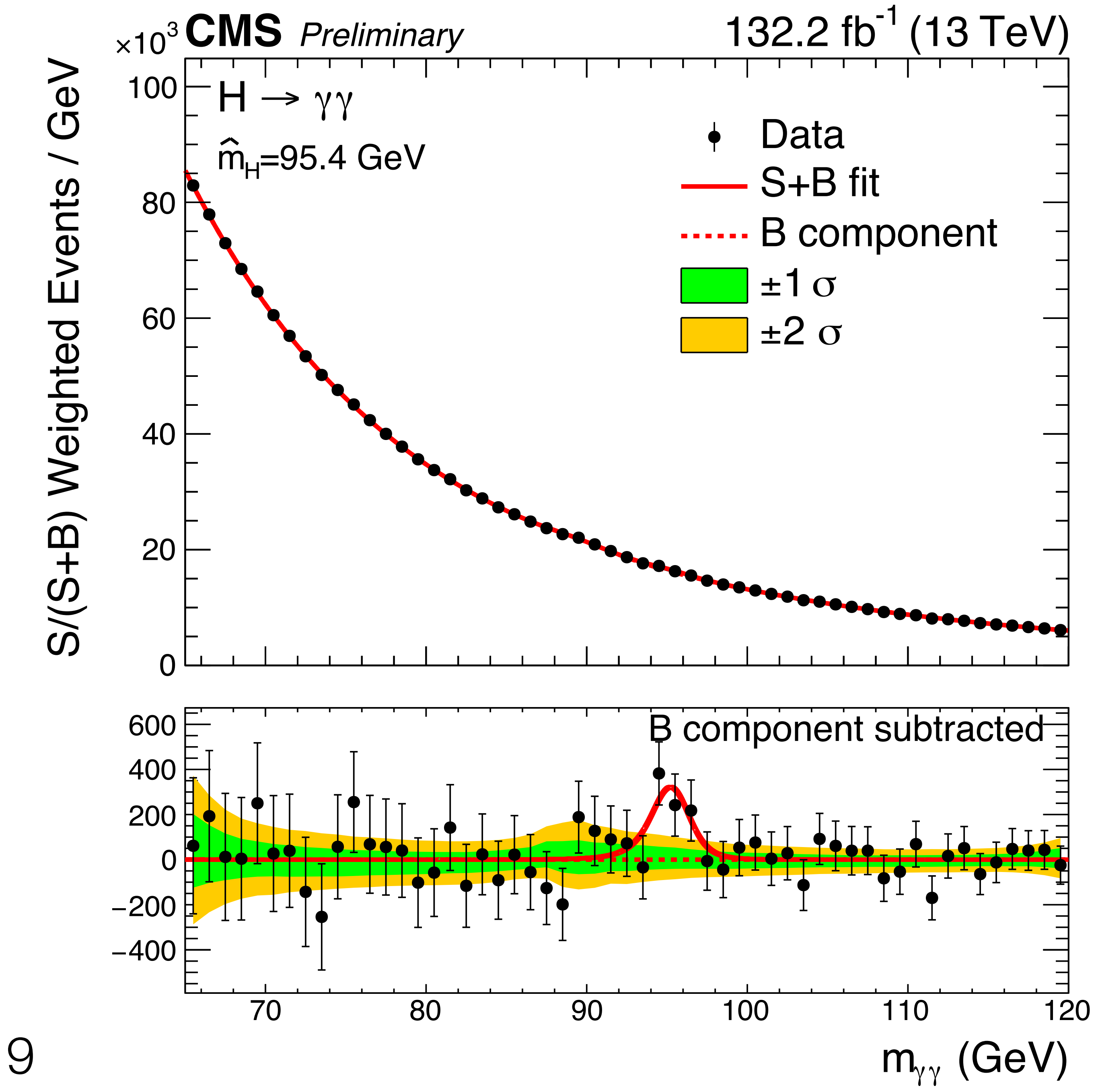
Search in 70 < $m_{\gamma\gamma}$ < 110 GeV from CMS

- Following up on previous search with $\sqrt{s}$ = 8 and 13 TeV data from 2012+2016 that observed local (global) significance of 2.8 (1.3) σ (PLB 793 (2019) 320) at 95.3 GeV
- LEP saw a small excess of events (~2σ) at m_H = 98 GeV in $H(b\bar{b})$
- In addition to continuum γγ background, contends with additional background from Drell-Yan → e^+e^- with electrons faking photons
- Kinematic diphoton BDT used for signal selection

PLB 565 (2003) 61

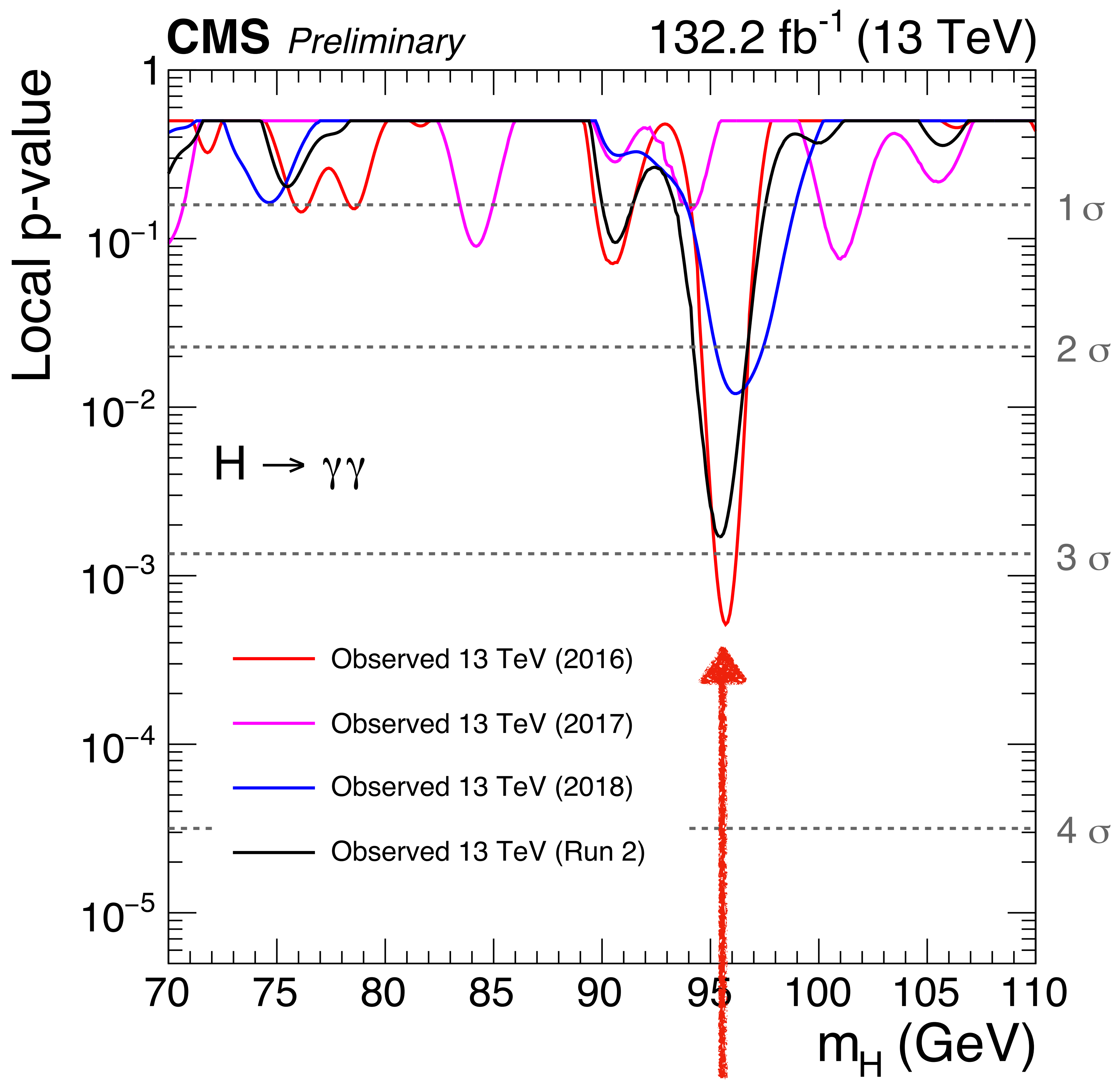


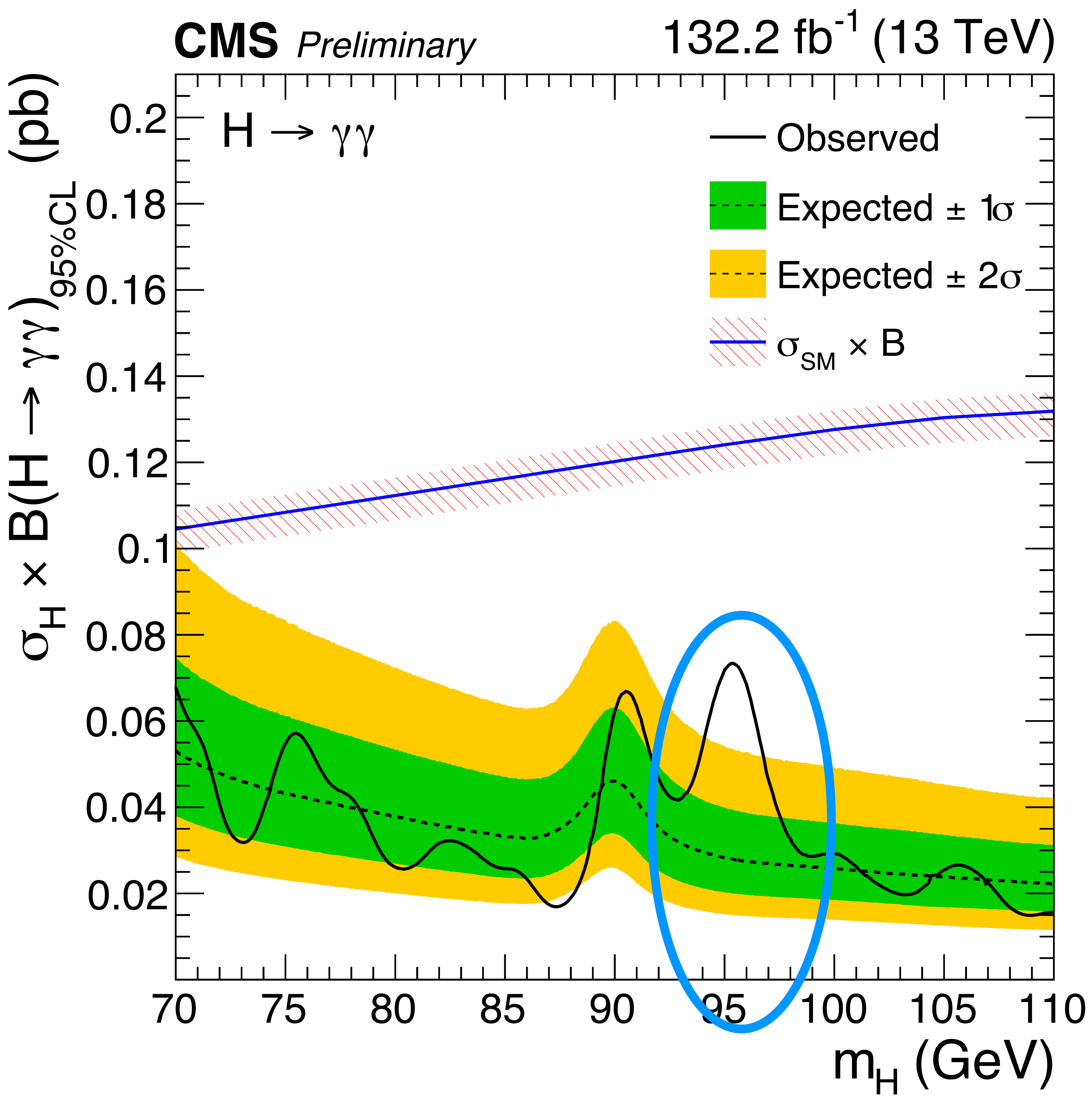
CMS-PAS-HIG-20-002



Note: LEP excess only for E_{CM}=189 GeV

Low mass di-photon search





Excess previously seen in 2016 data persists, combined 2.9 (1.3) σ local (global) significance at **95.4 GeV**

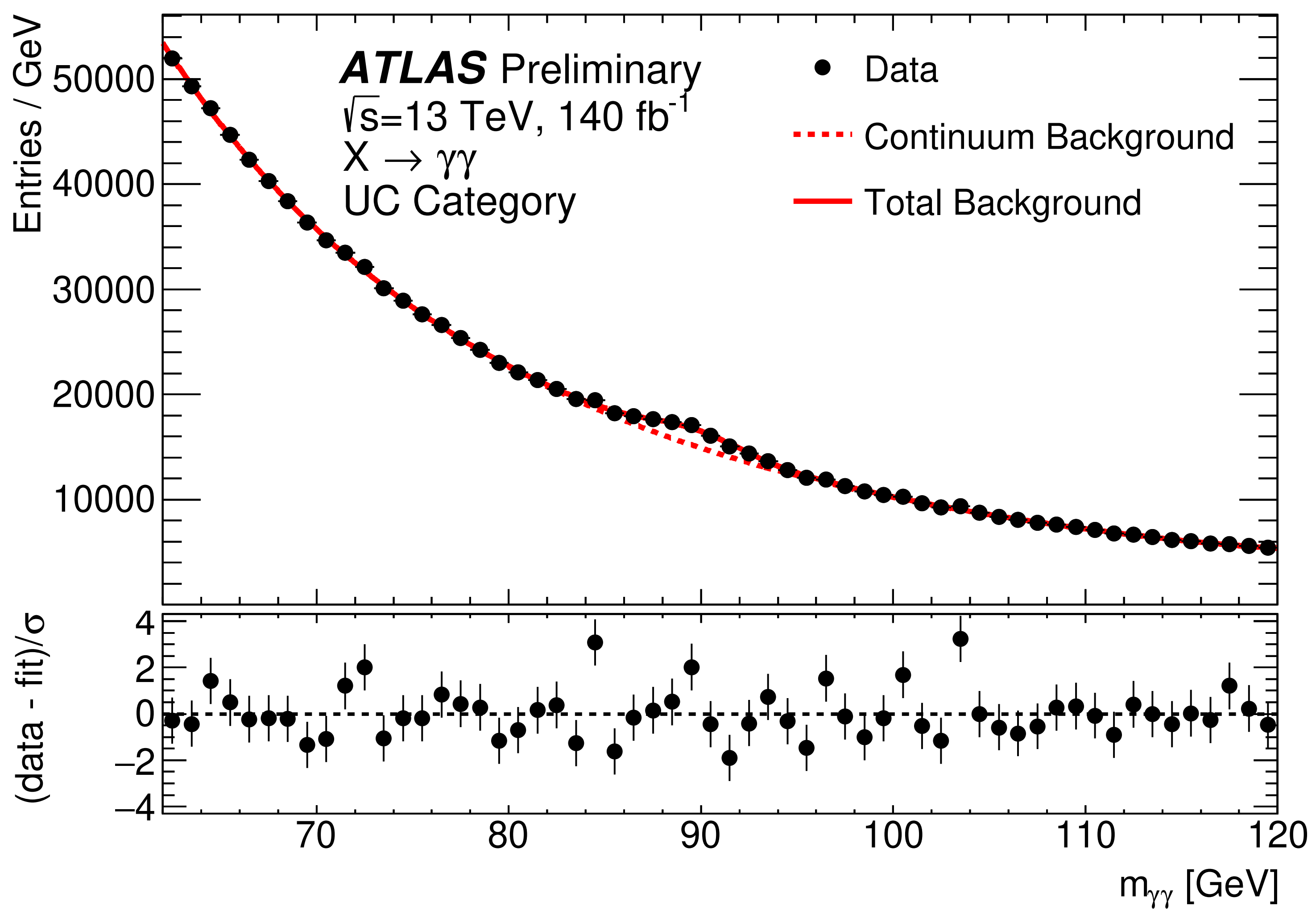
Limits also set on σ_H x B(H→γγ) for additional SM-like Higgs boson

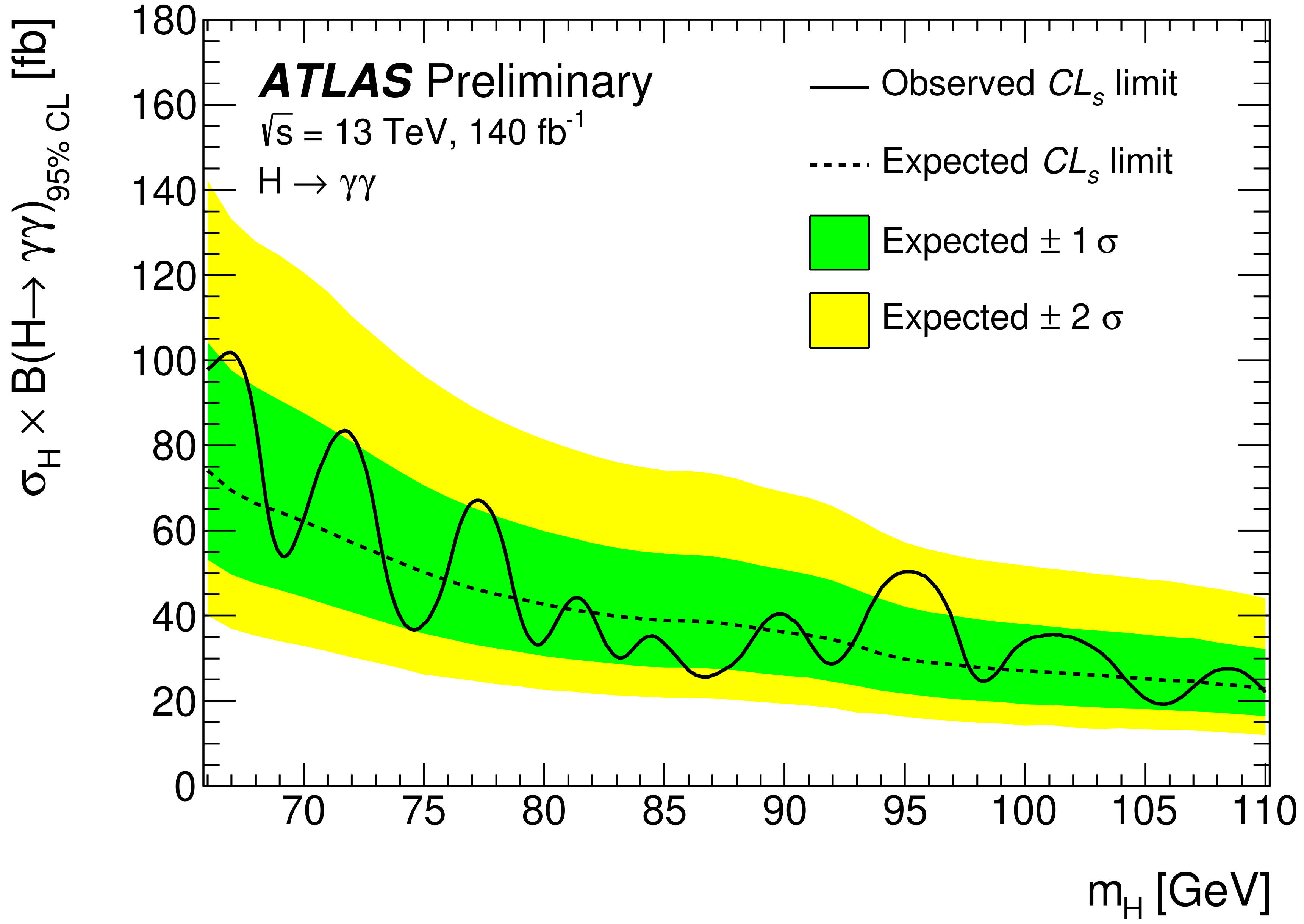
Low mass di-photon search

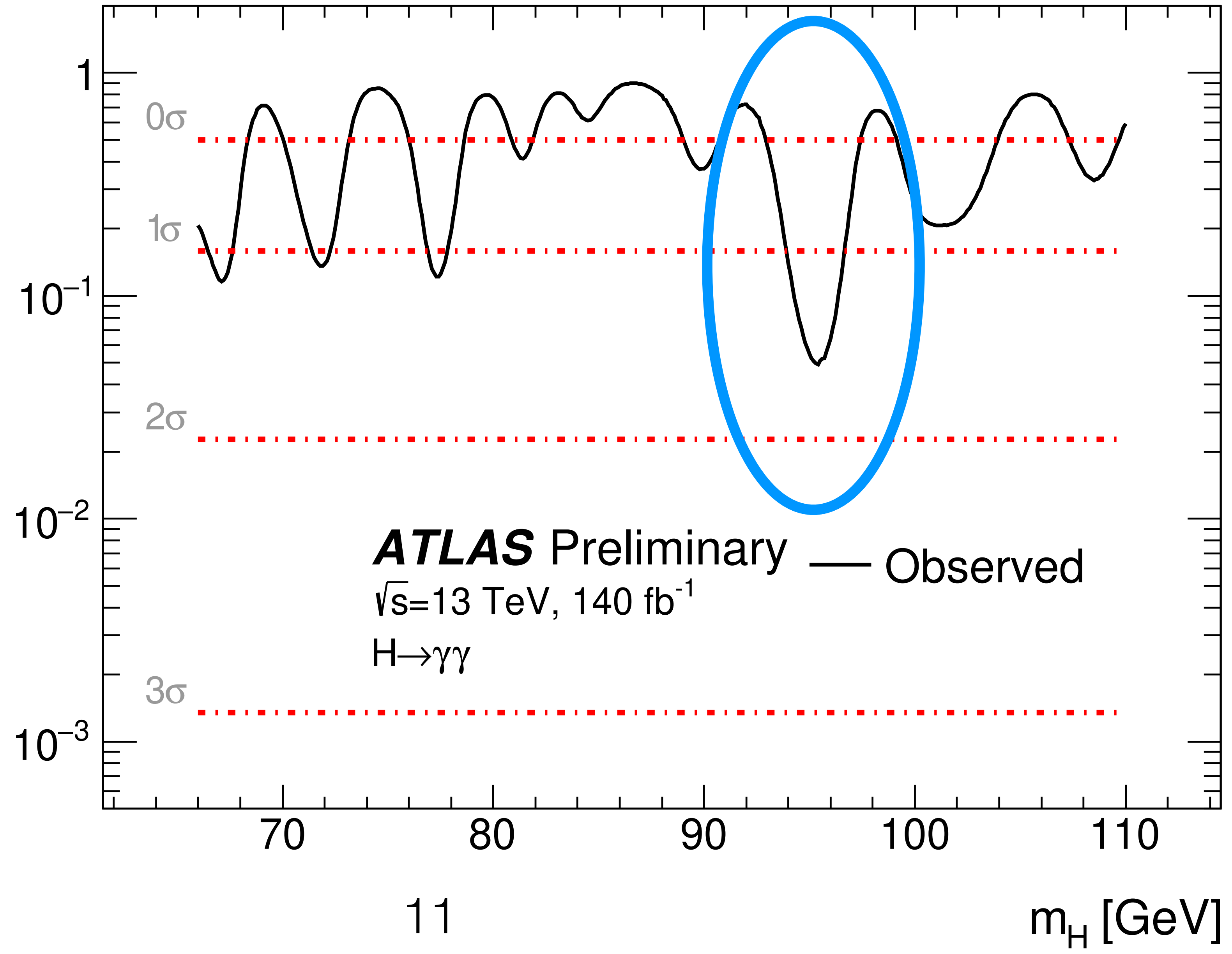
ATLAS also carried out a search in 66 < $m_{\gamma\gamma}$ < 110 GeV

- Categorization of events based on whether photon converts to electron pair or not
- Model-dependent search uses BDT for additional event categorization

ATLAS-CONF-2023-035







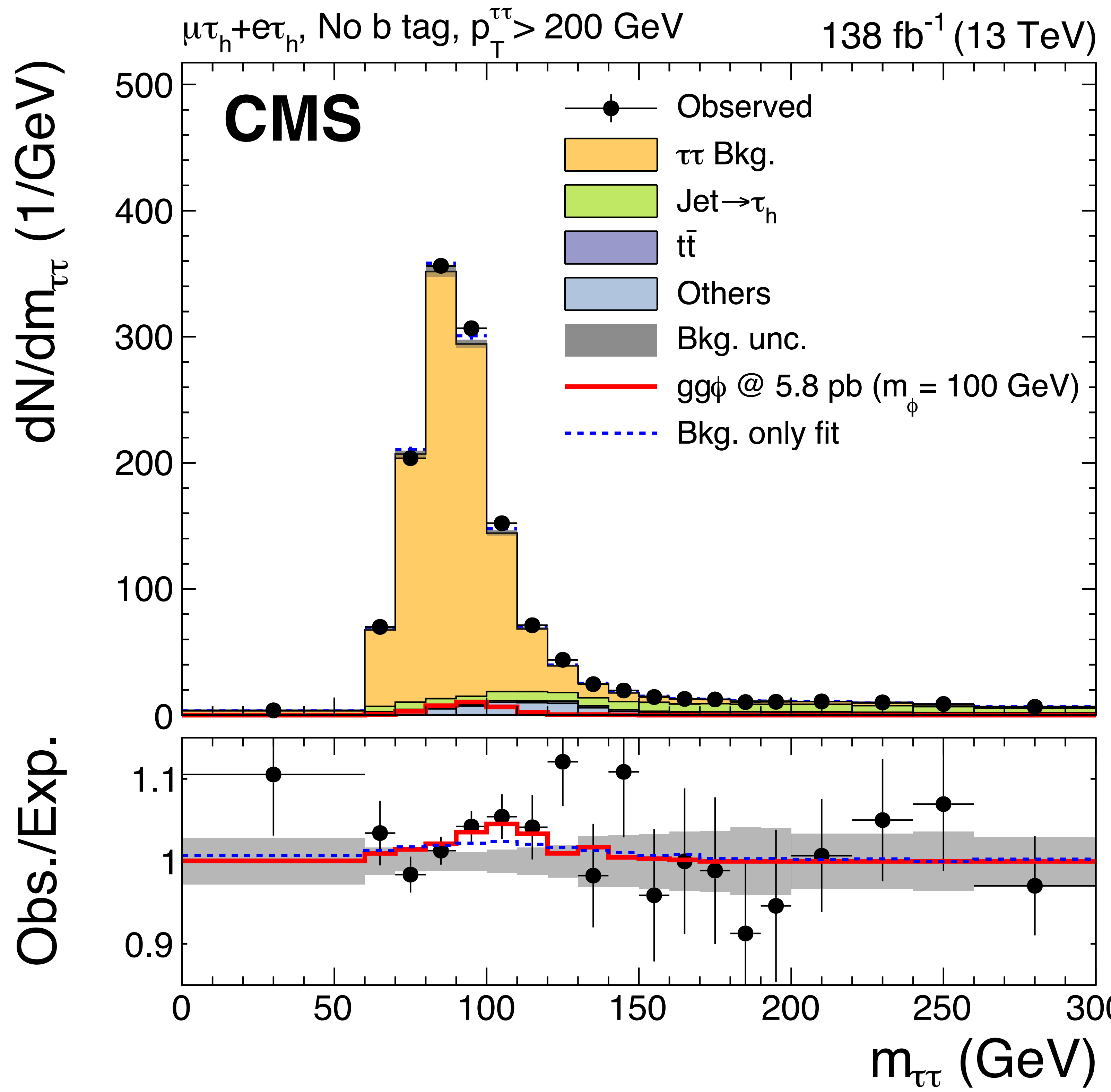
At 95.4 GeV, observe 1.7 σ (local) deviation for model-dependent search

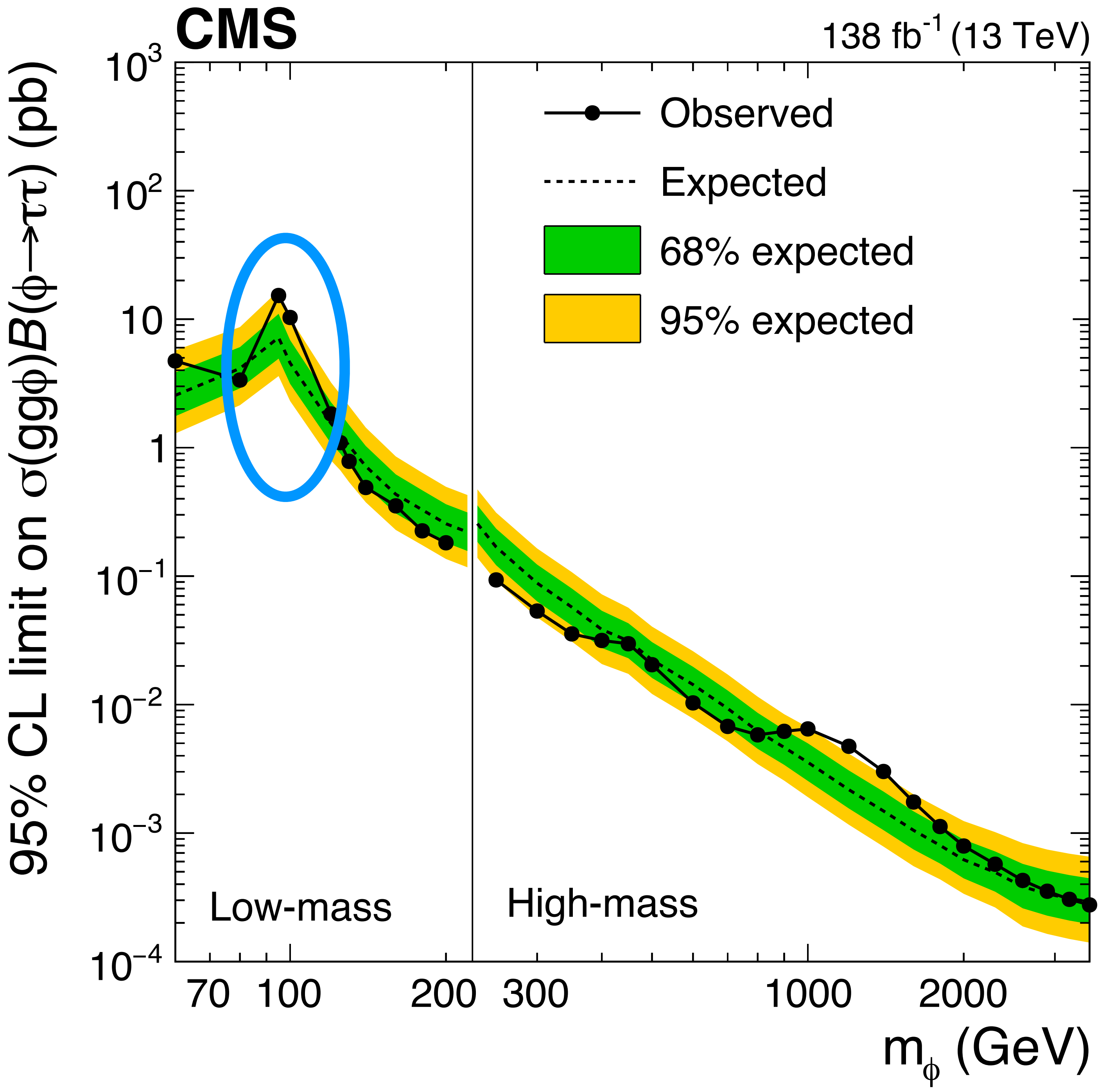
Low mass di-tau search

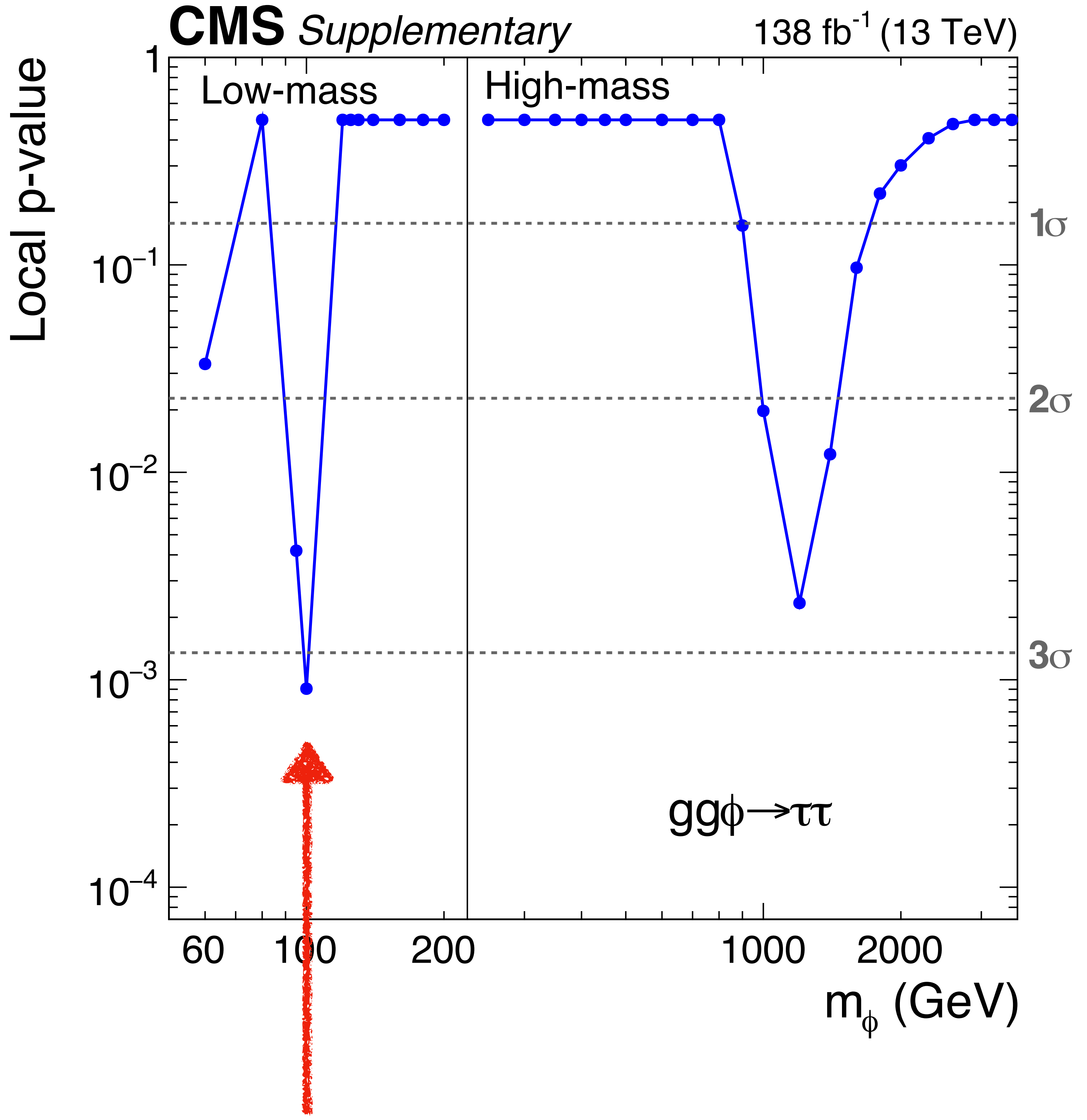
Search for additional Higgs bosons in $\tau\tau$ final state from CMS

- Event categorization based on b-tags, $p_T(\tau\tau)$

JHEP 07 (2023) 073







Largest deviation for $gg\phi$ production at $\mathbf{m_\phi = 100}$ **GeV** with local (global) significance of 3.1 (2.7) σ
2.6 (2.3) σ at 95 GeV

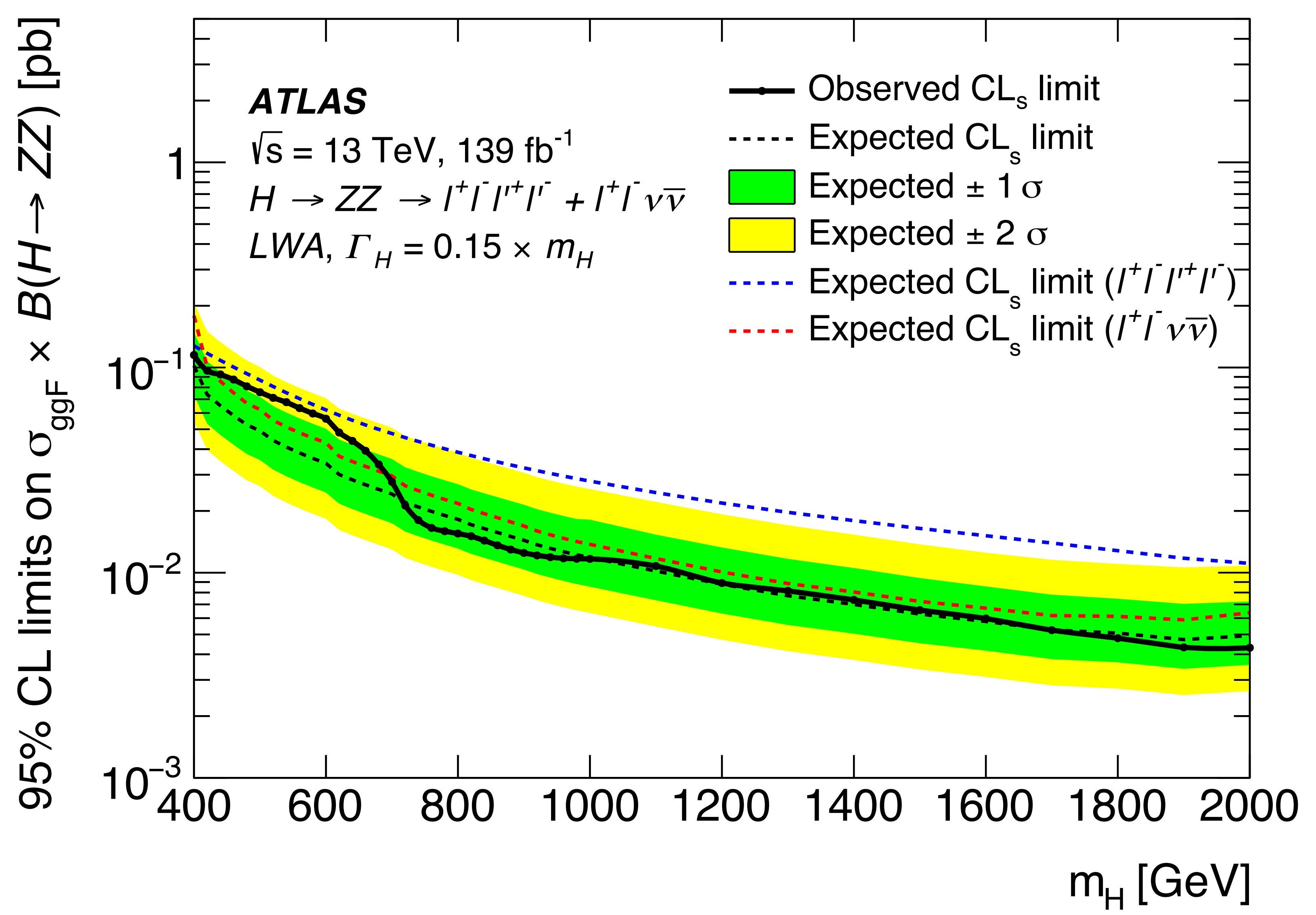
High mass ZZ search

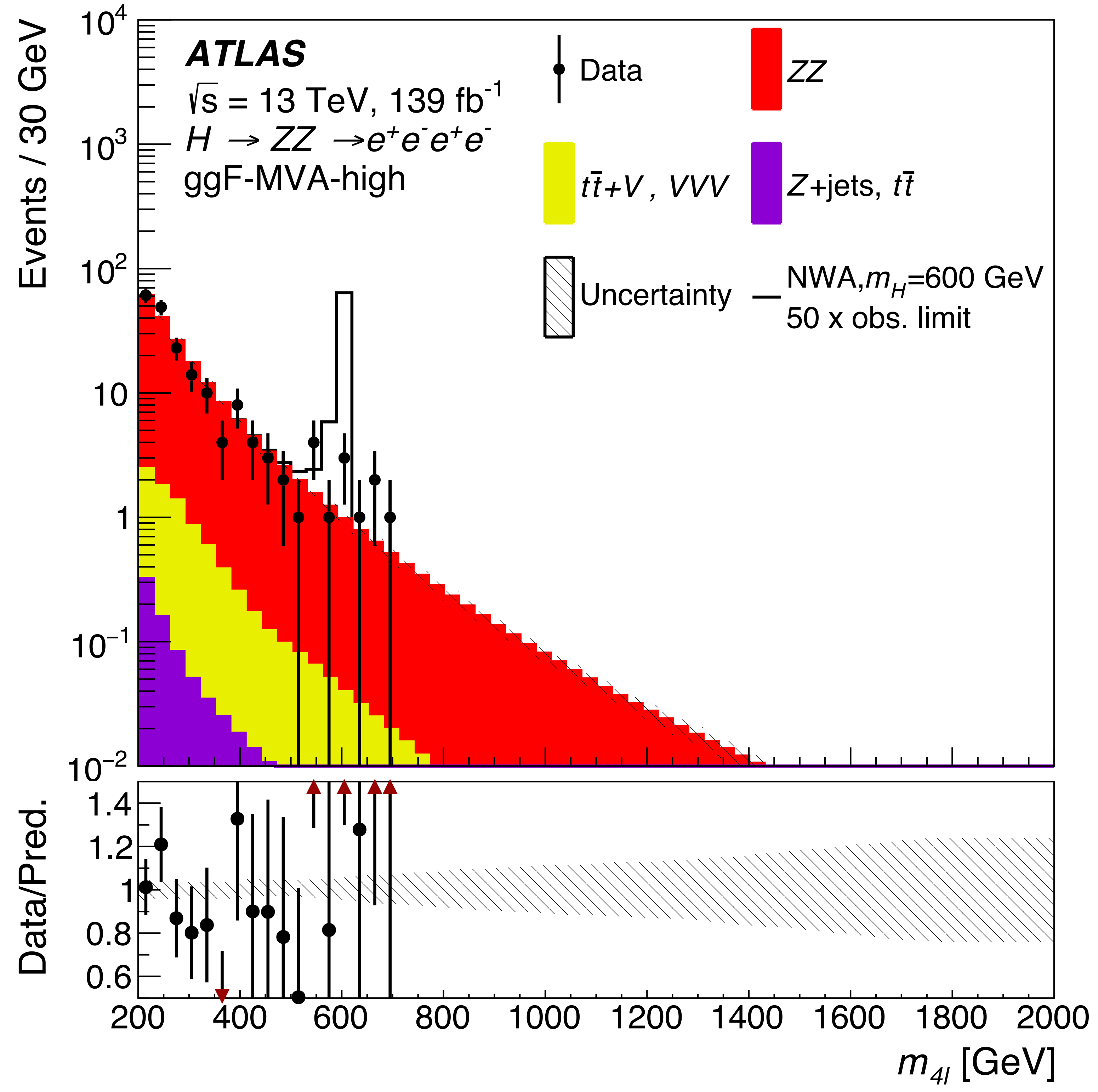
Search for heavy resonance decaying to ZZ in 200 < m_{ZZ} < 2000 GeV in 4l and 2l2ν final states from ATLAS

- Considers heavy Higgs in narrow width approximation (NWA), large width assumption (LWA) as well as spin-2 resonance (KK graviton)
- Both gluon fusion (ggF) and VBF production considered for NWA

EPJC 81 (2021) 332

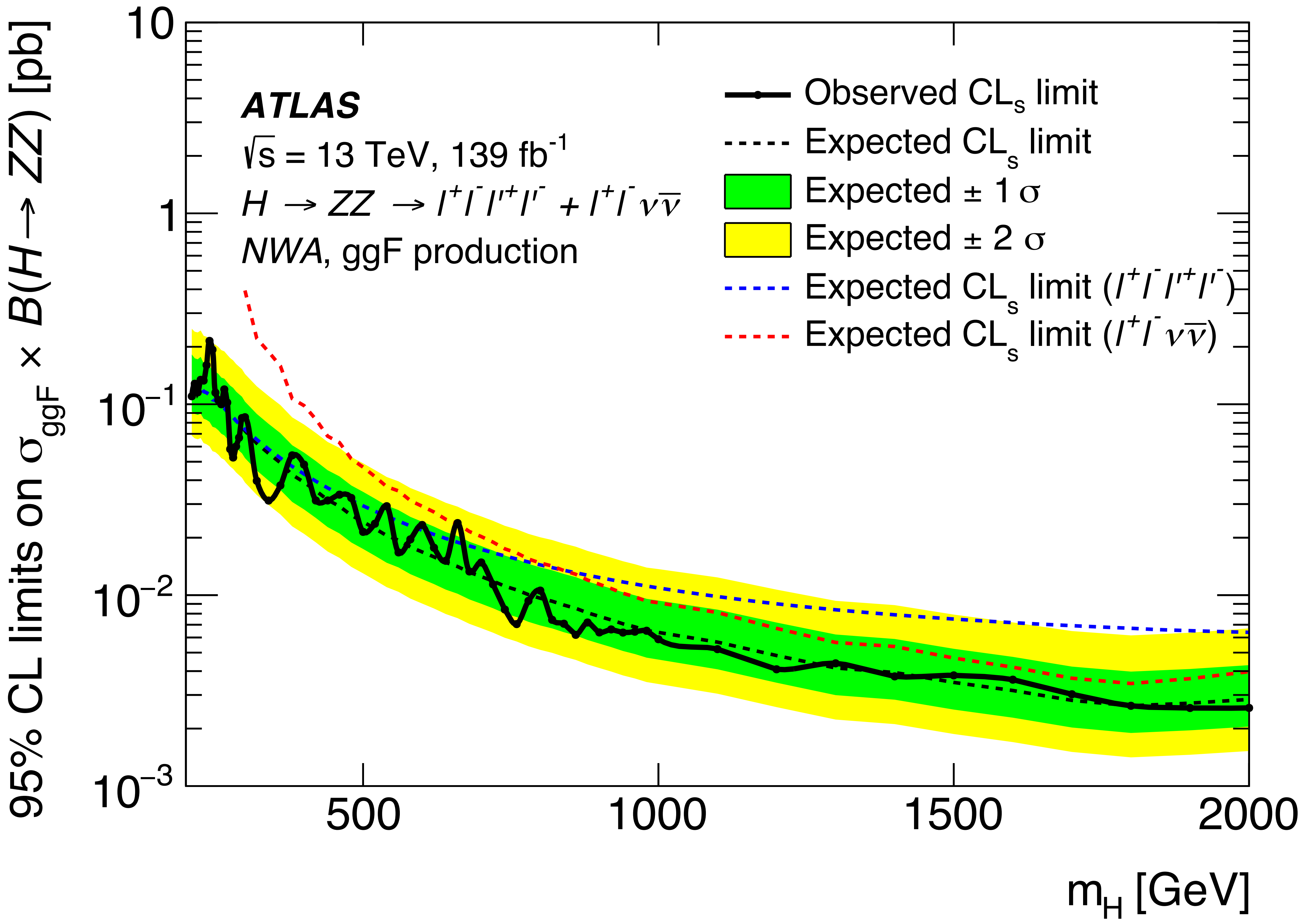
Results in LWA

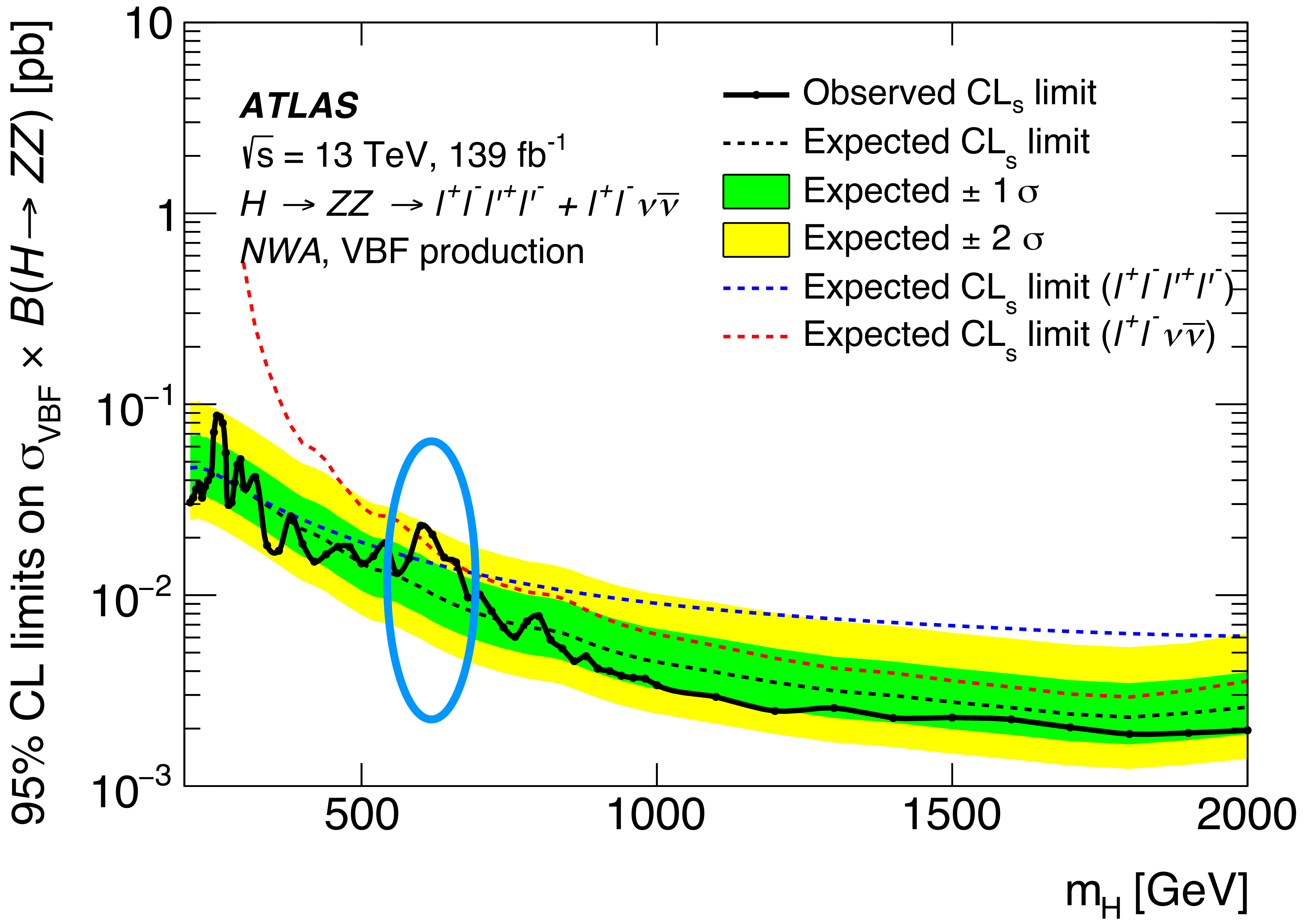




High mass ZZ search

Results in NWA





ggF: maximum deviation at **240 GeV**, with local (global) significance of 2.0 (0.5) σ

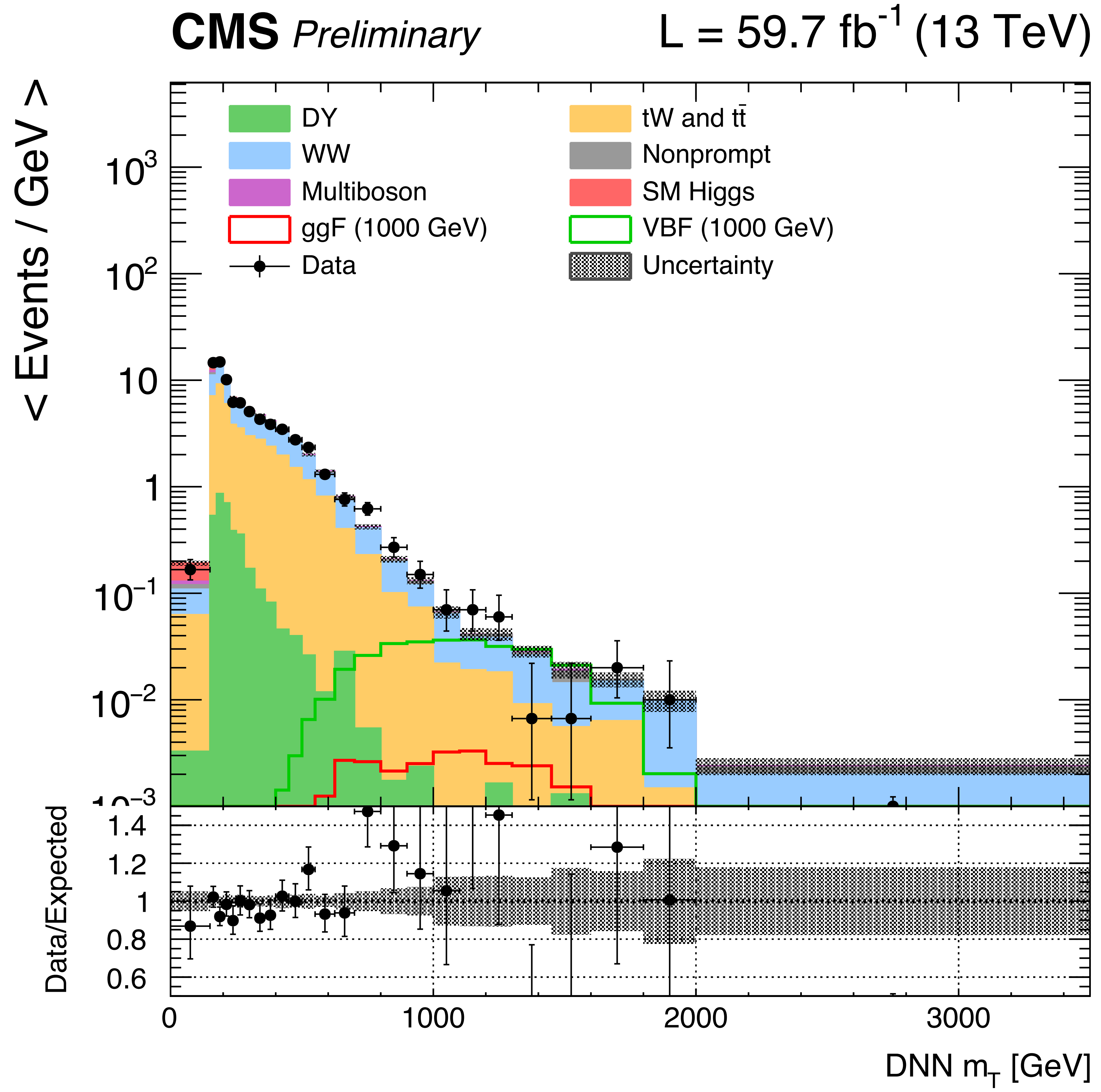
VBF: maximum deviation at **620 GeV**, with local (global) significance of 2.4 (0.9) σ

High mass W^+W^- search

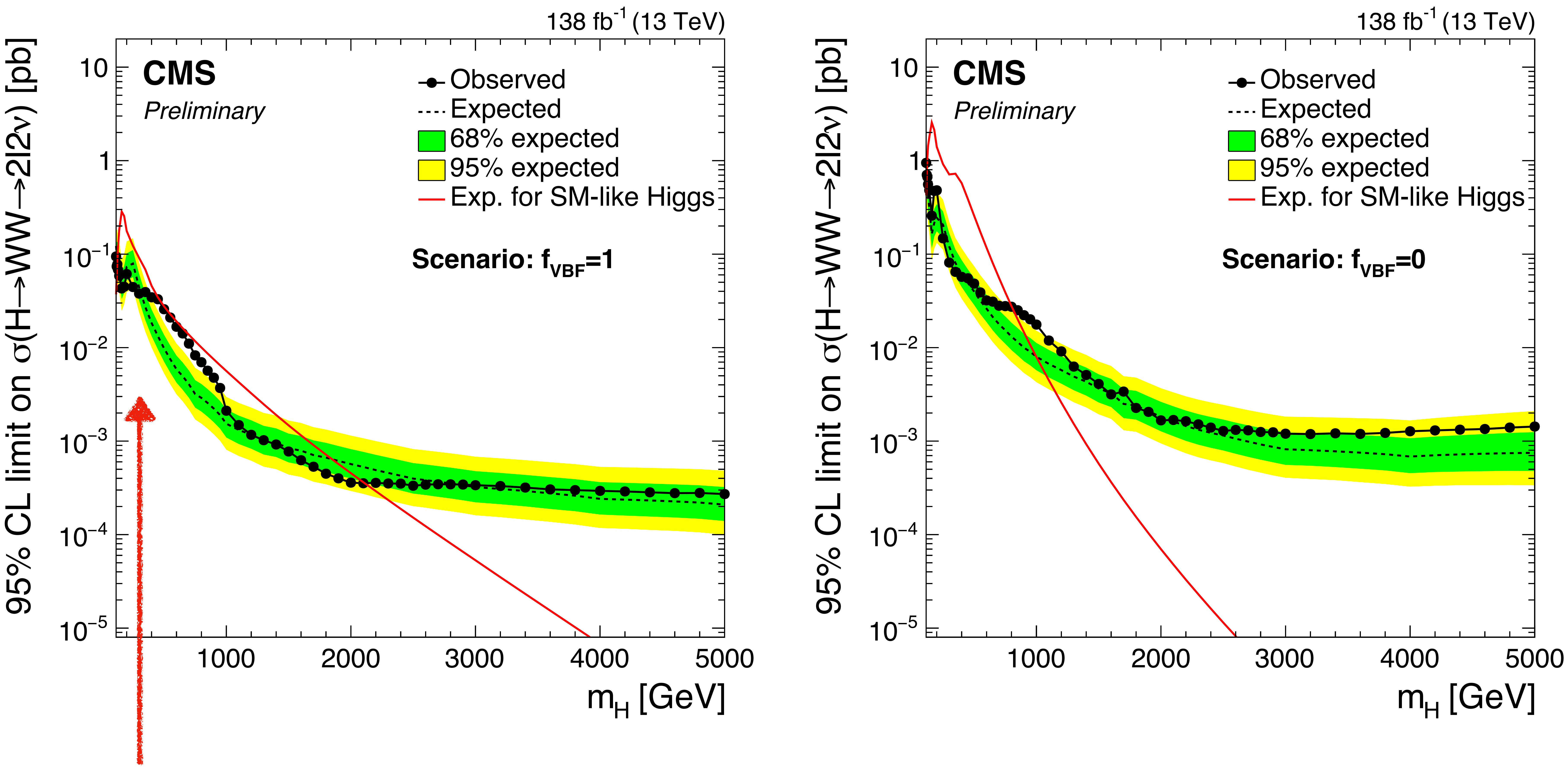
Search for heavy resonance decaying to W^+W^- in 115 < m_{WW} < 5000 GeV in $2l2\nu$ final states from CMS

- Search in final states with ee/eμ/μμ
- Considers range of signal width hypotheses
- Both gluon fusion and VBF production considered with different relative contributions
- Interpretation also in MSSM scenarios, 2HDM
- DNNs used for event classification, mass reconstruction

CMS-PAS-HIG-20-016



High mass W^+W^- search



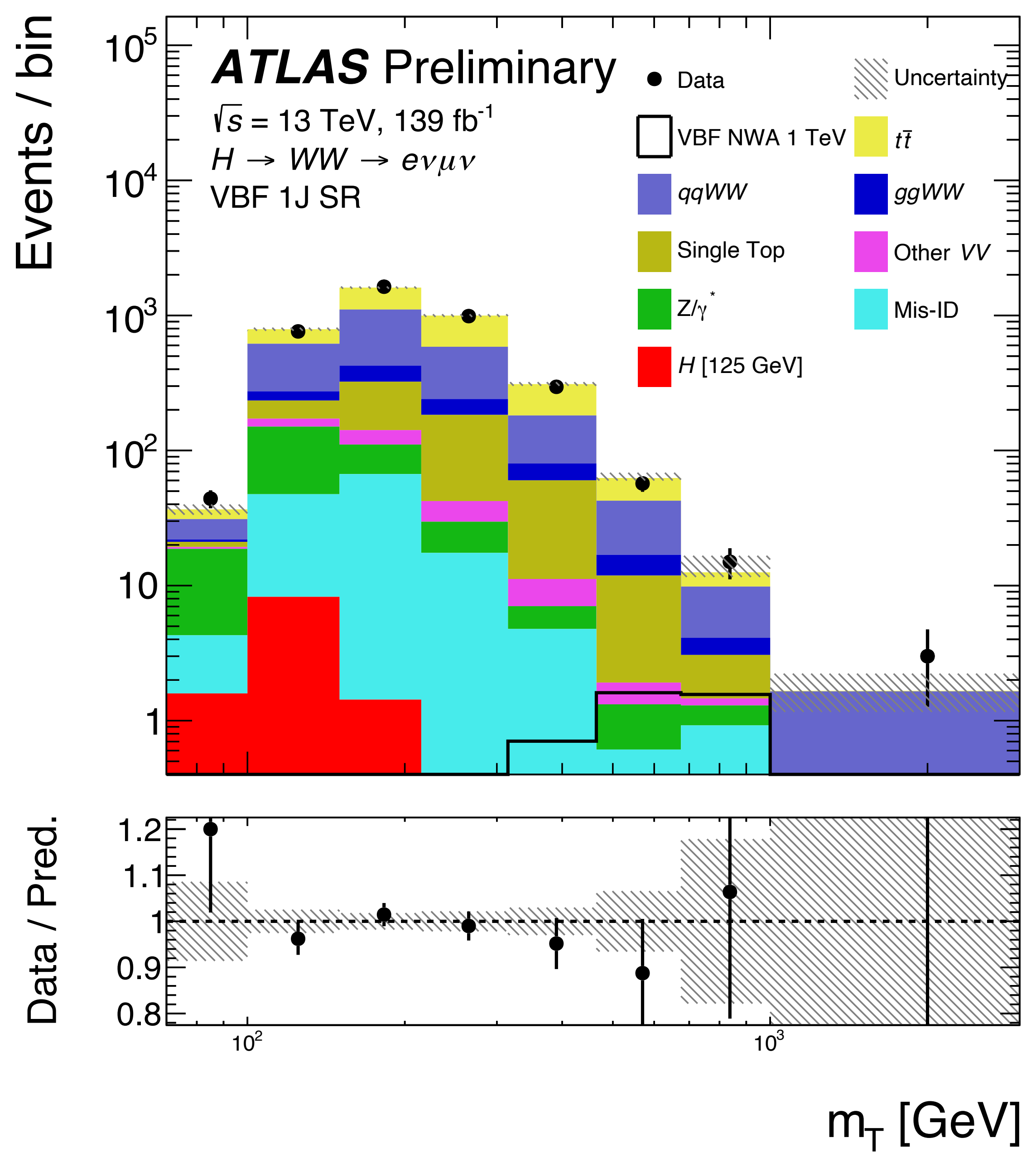
Largest local (global) significance of 3.8 (2.6) σ found for f_{VBF} = 1 scenario at **650 GeV**

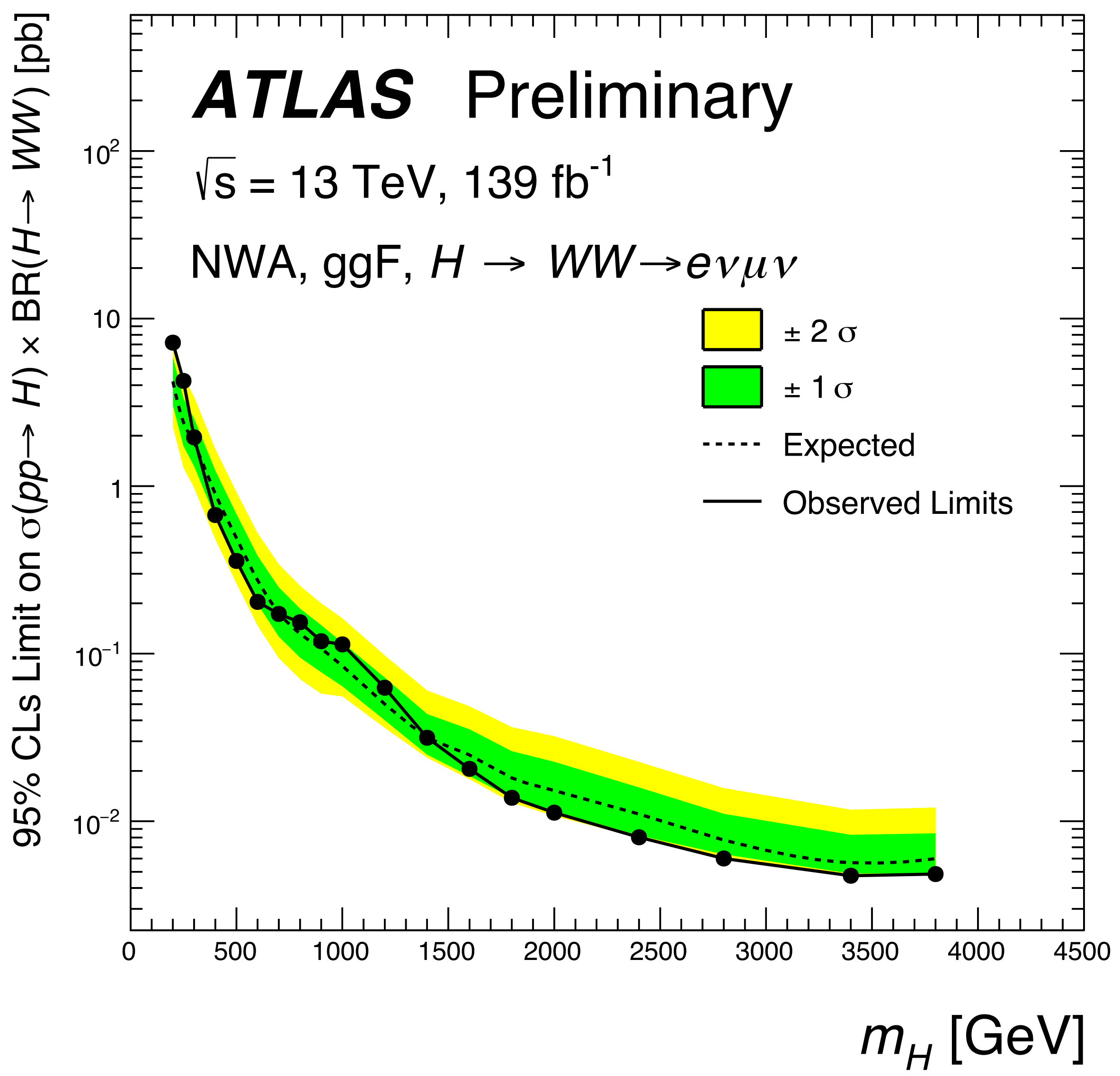
High mass W^+W^- search

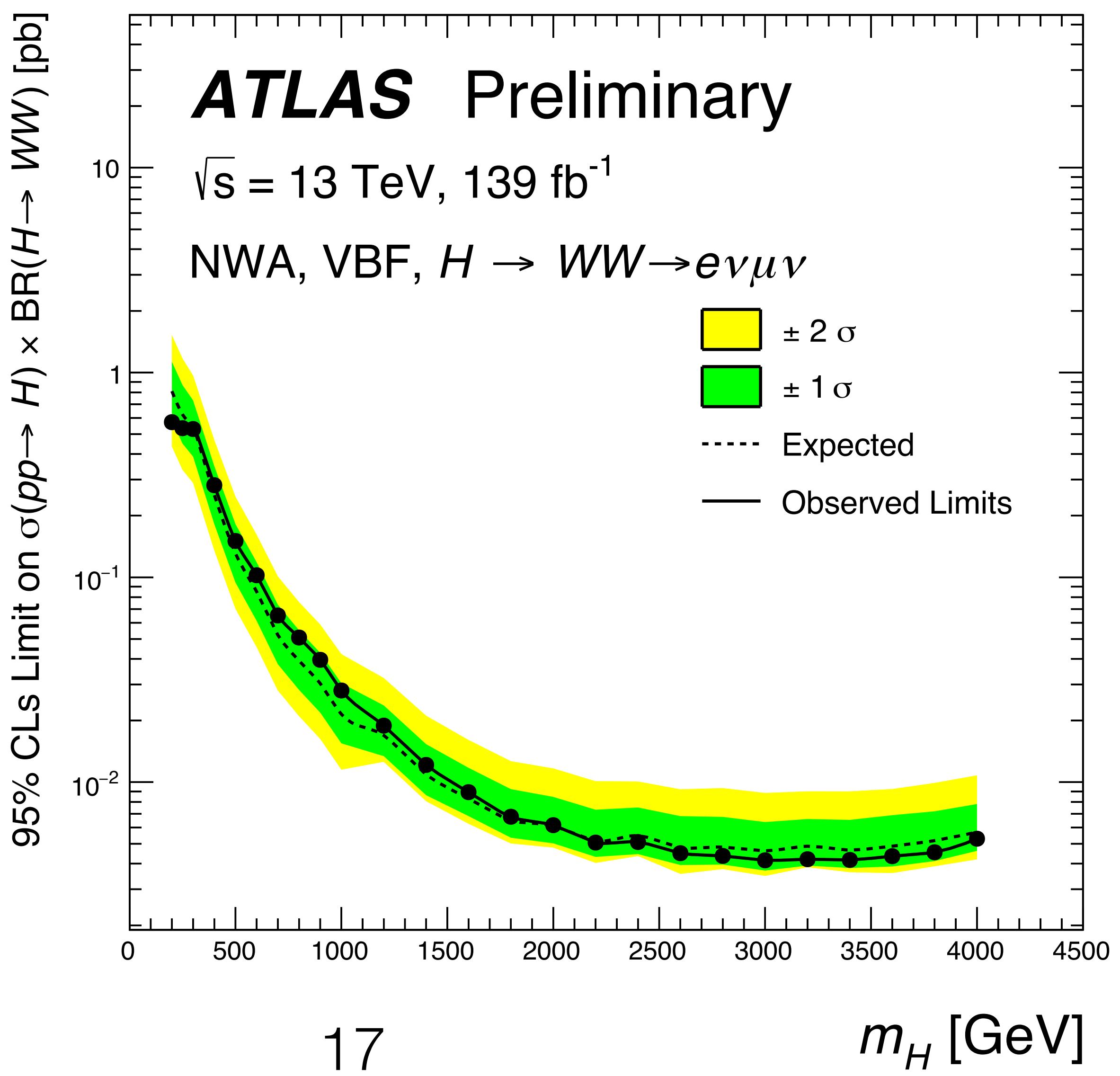
ATLAS-CONF-2022-066

ATLAS search in eμ$\nu\nu$ final states, 300 < m_{WW} < 4000 GeV

- Considers additional Higgs-like resonance in NWA, and other spin 0/1/2 models
- Gluon fusion and/or VBF production considered depending on model
- Transverse mass between dilepton system and E_T^{miss} used as signal discriminant







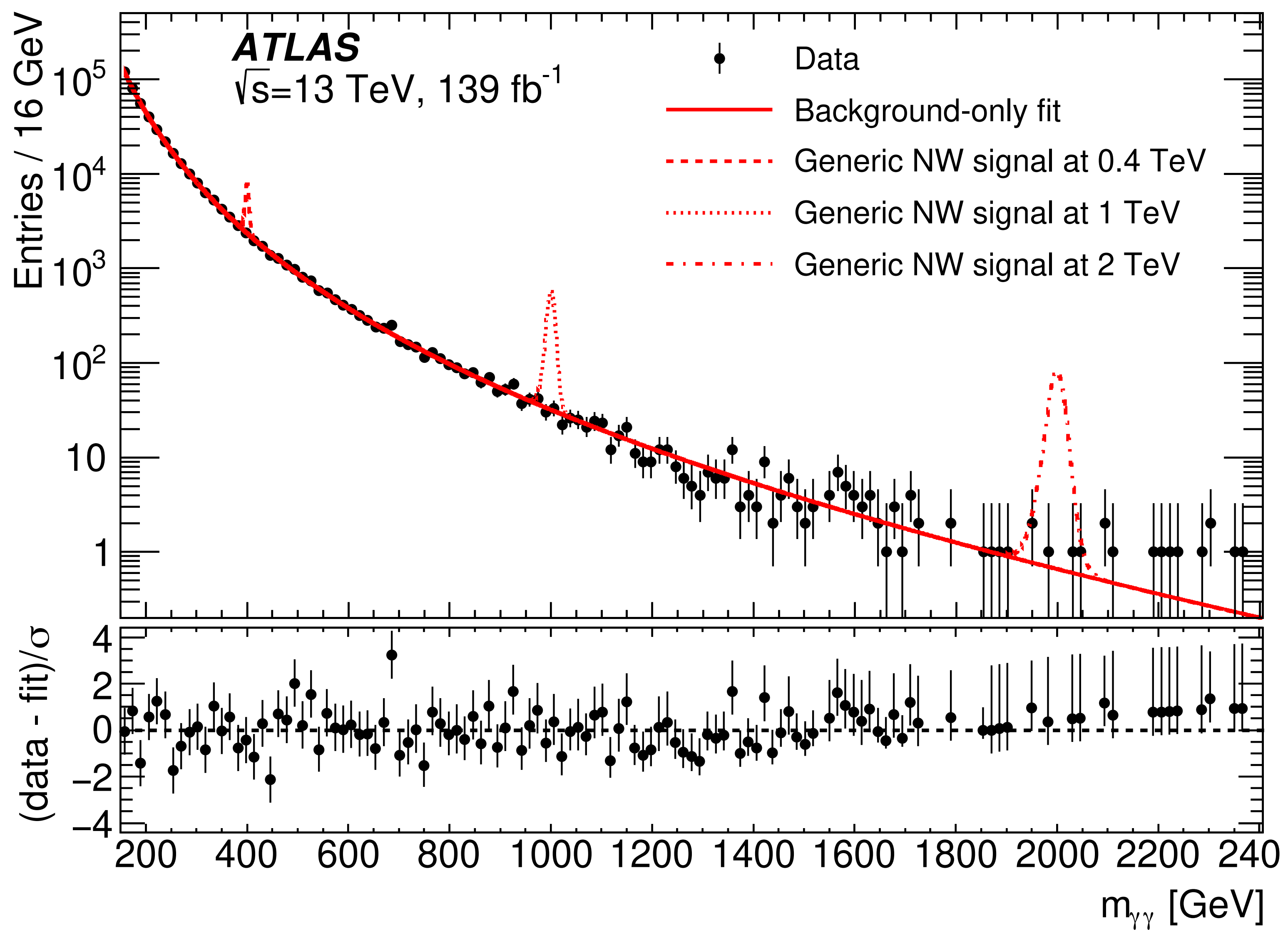
No significant excess observed!

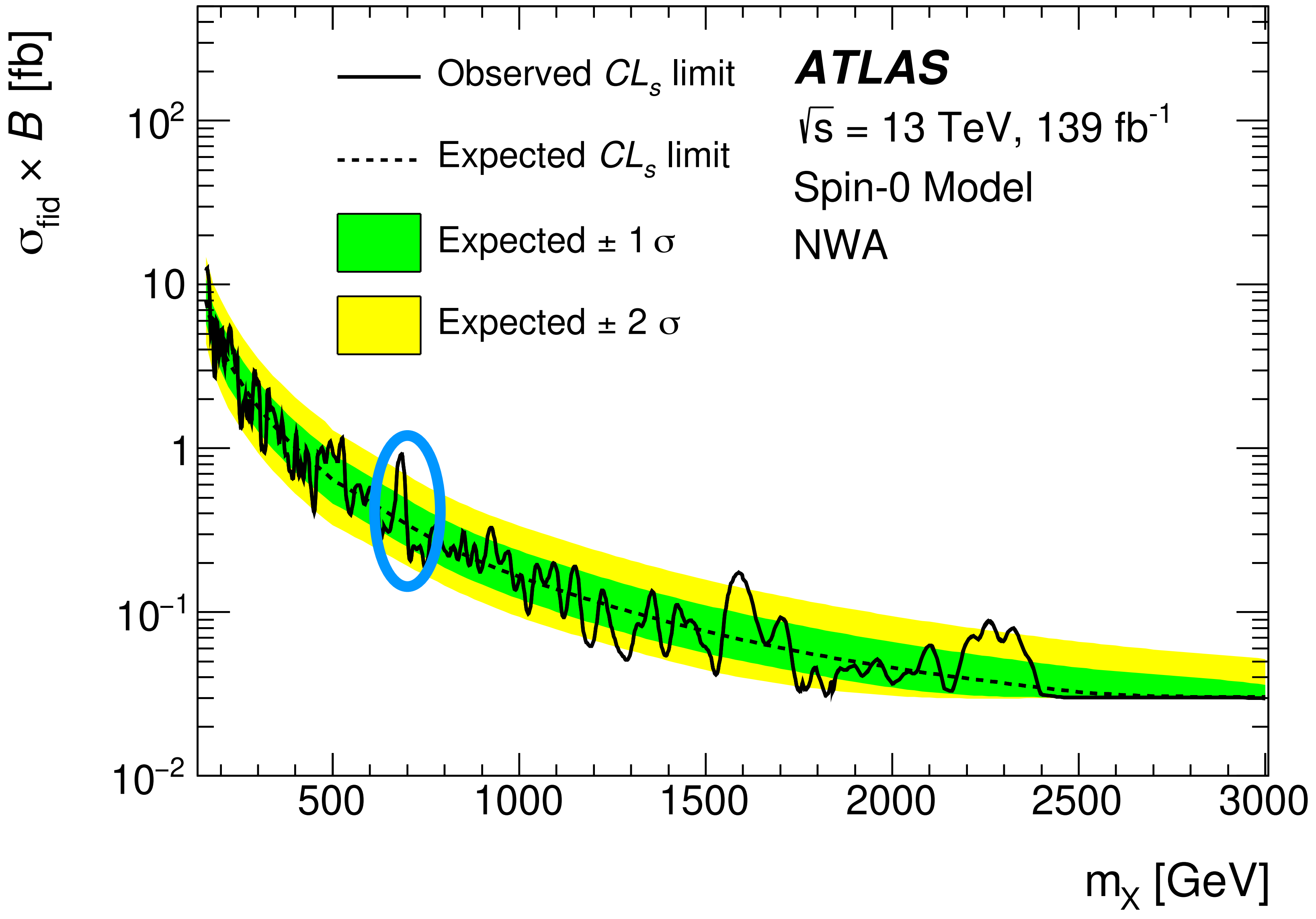
High mass di-photon search

Search for resonance decaying to γγ

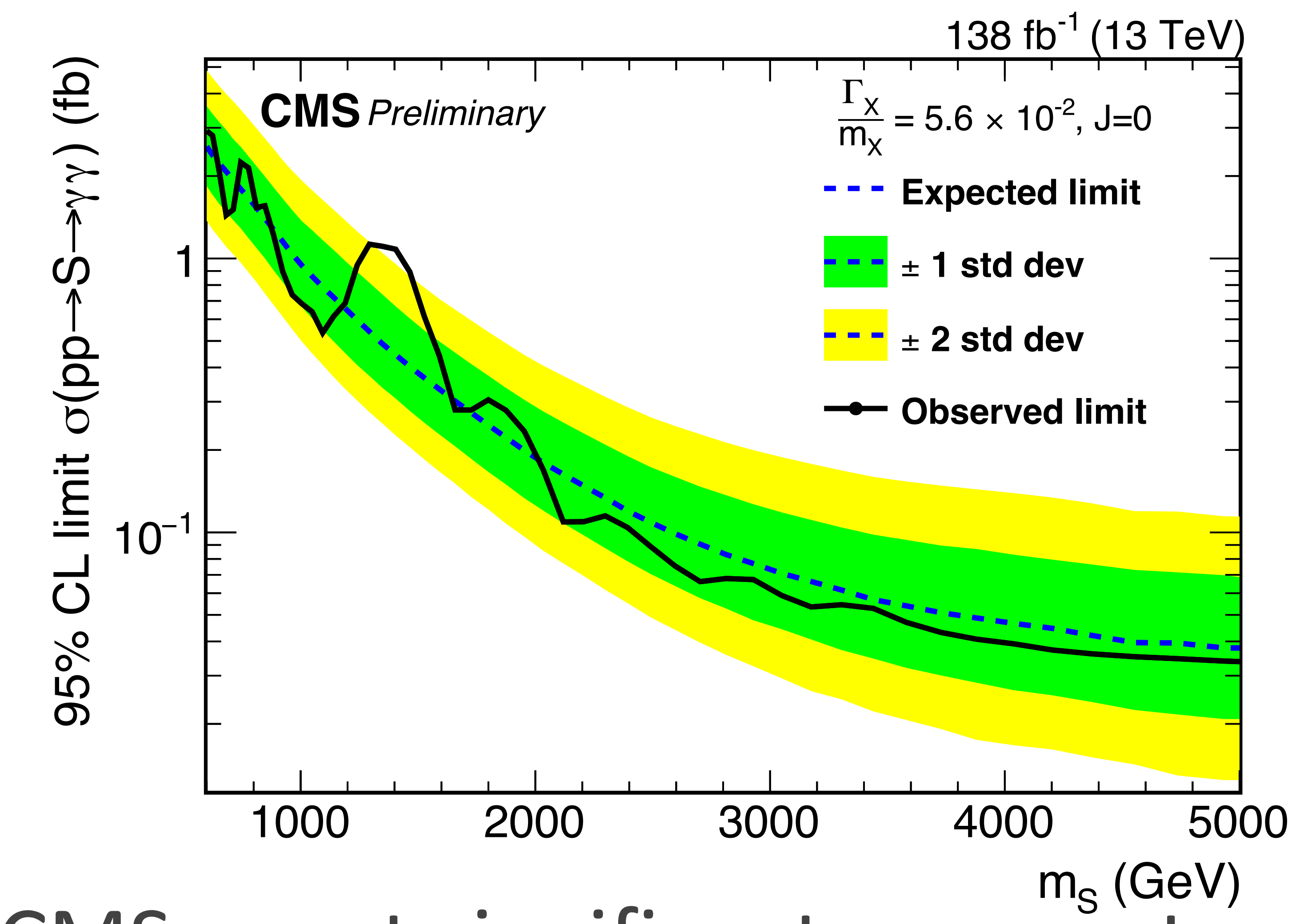
- Searches from ATLAS and CMS consider spin-0 and spin-2 resonances
- Fit to di-photon mass spectrum

PLB 822 (2021) 136651





CMS-PAS-EXO-22-004



CMS: most significant excess at **1.3 TeV** for broad resonance model: 2.6 (0.8) σ local (global) significance

ATLAS: most significant excess at **684 GeV**: 3.3 (1.3) σ local (global) significance

Searches for heavy particles decaying to scalars

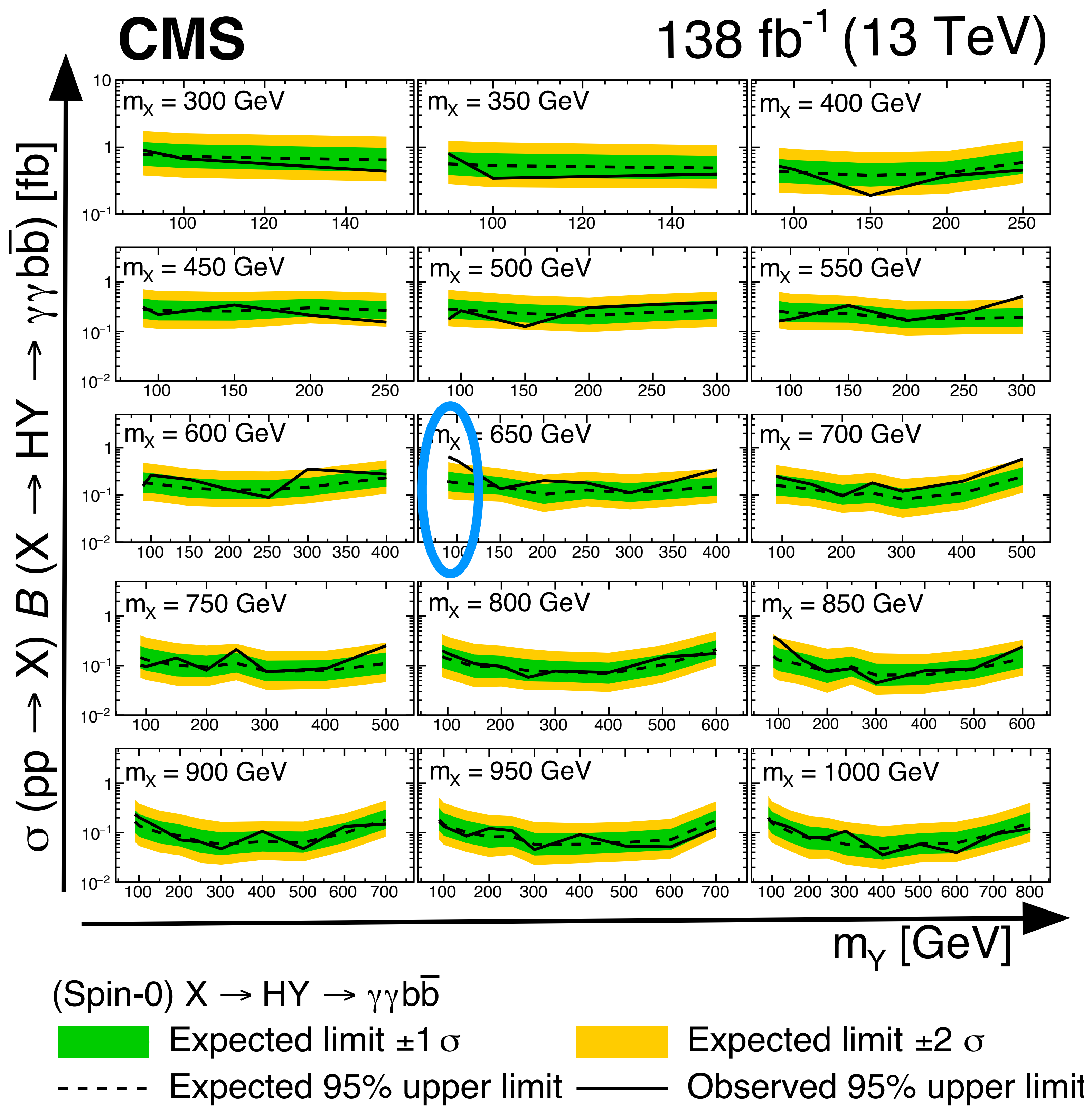
Search for heavy resonance X→YH

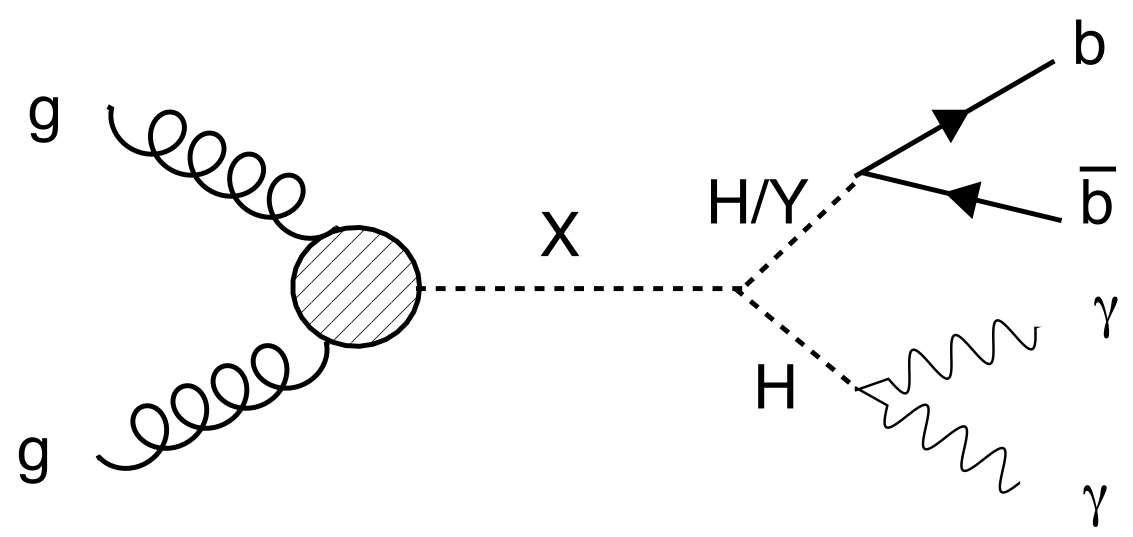
Searches targeting resonance decaying to H and additional scalar Y

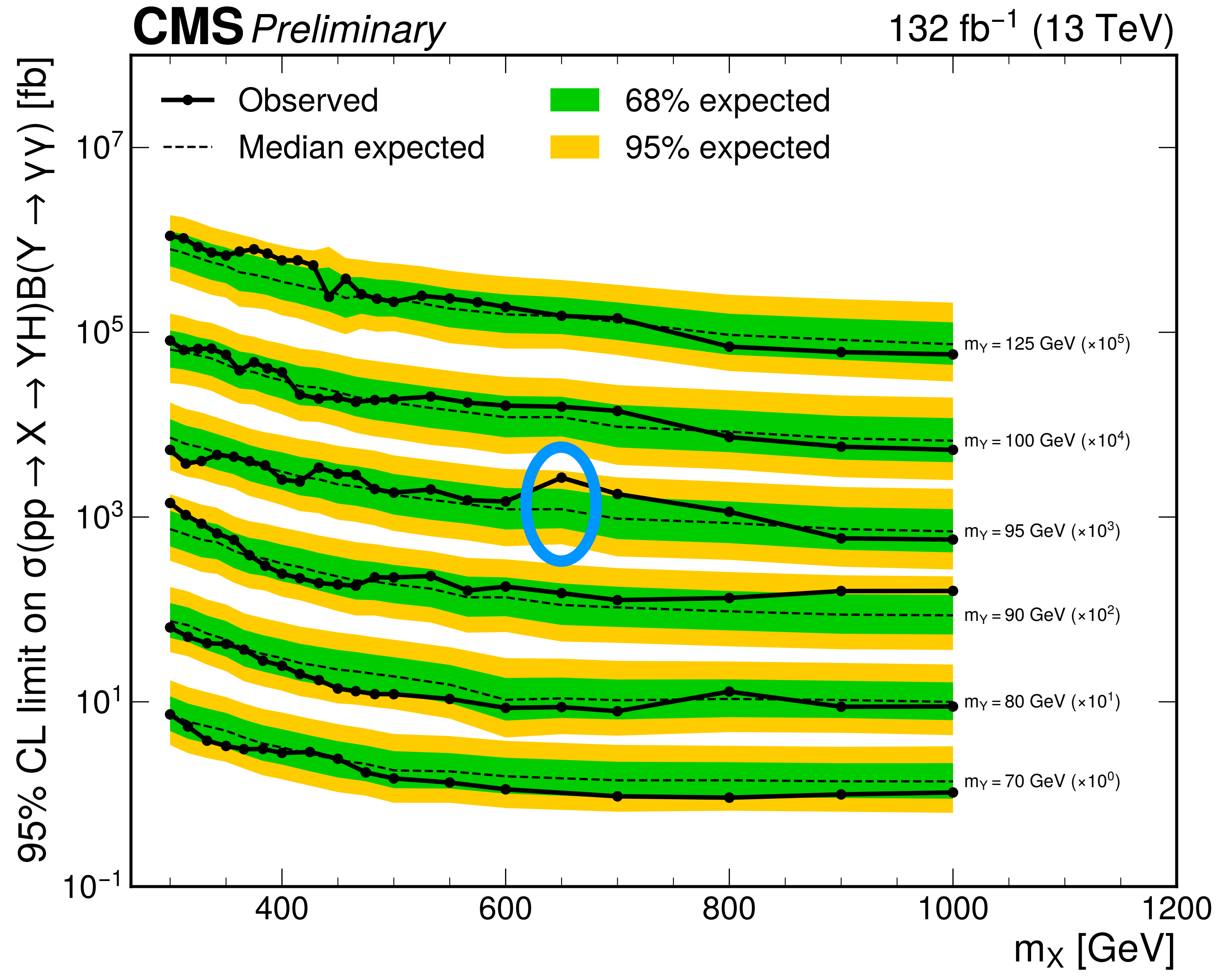
- Motivated by NMSSM, TRSM (SM extended by two real singlet fields)

CMS-PAS-HIG-22-012

arXiv:2310.01643







Most significant excess at **m_X = 650 GeV, m_Y = 90 GeV**: 3.8 (2.8) σ local (global) significance for Y(bb)H(γγ)

Mild excess seen in Y(γγ)H(ττ) at **m_X = 650 GeV, m_Y = 95 GeV** with 2.3 σ local significance (but large LEE)

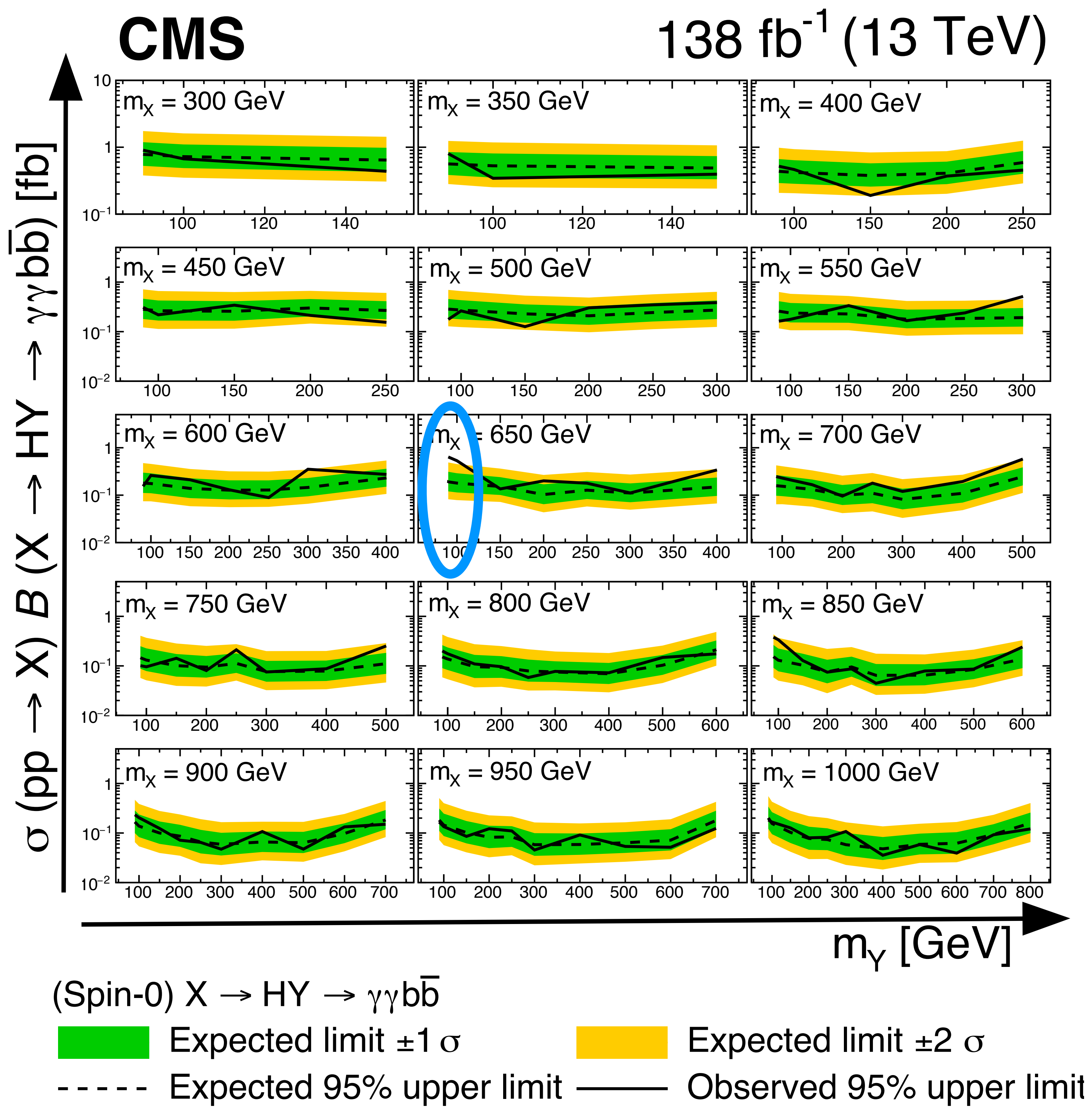
Search for heavy resonance X→YH

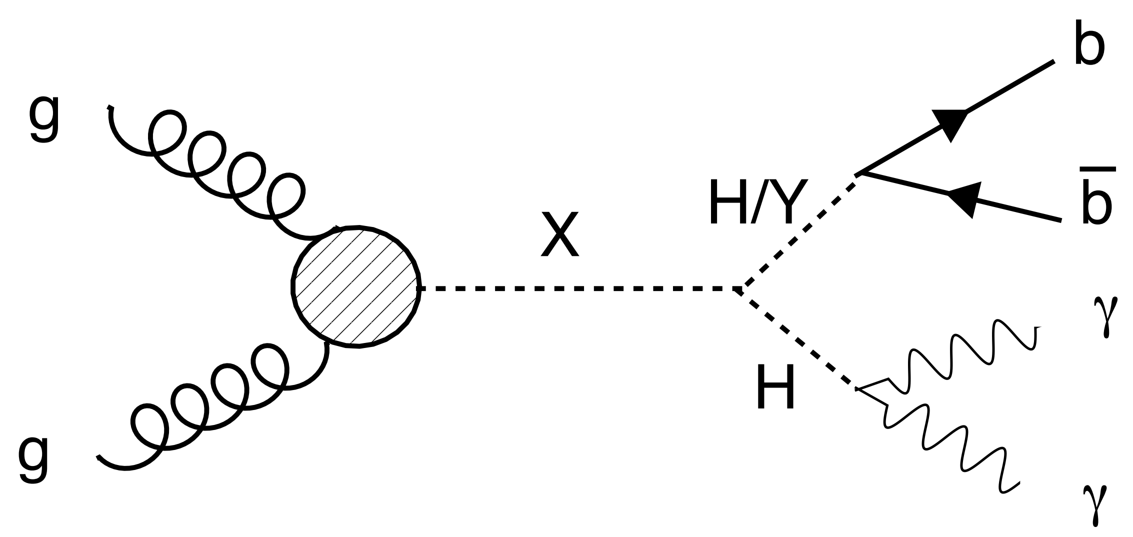
Searches targeting resonance decaying to H and additional scalar Y

- Motivated by NMSSM, TRSM (SM extended by two real singlet fields)

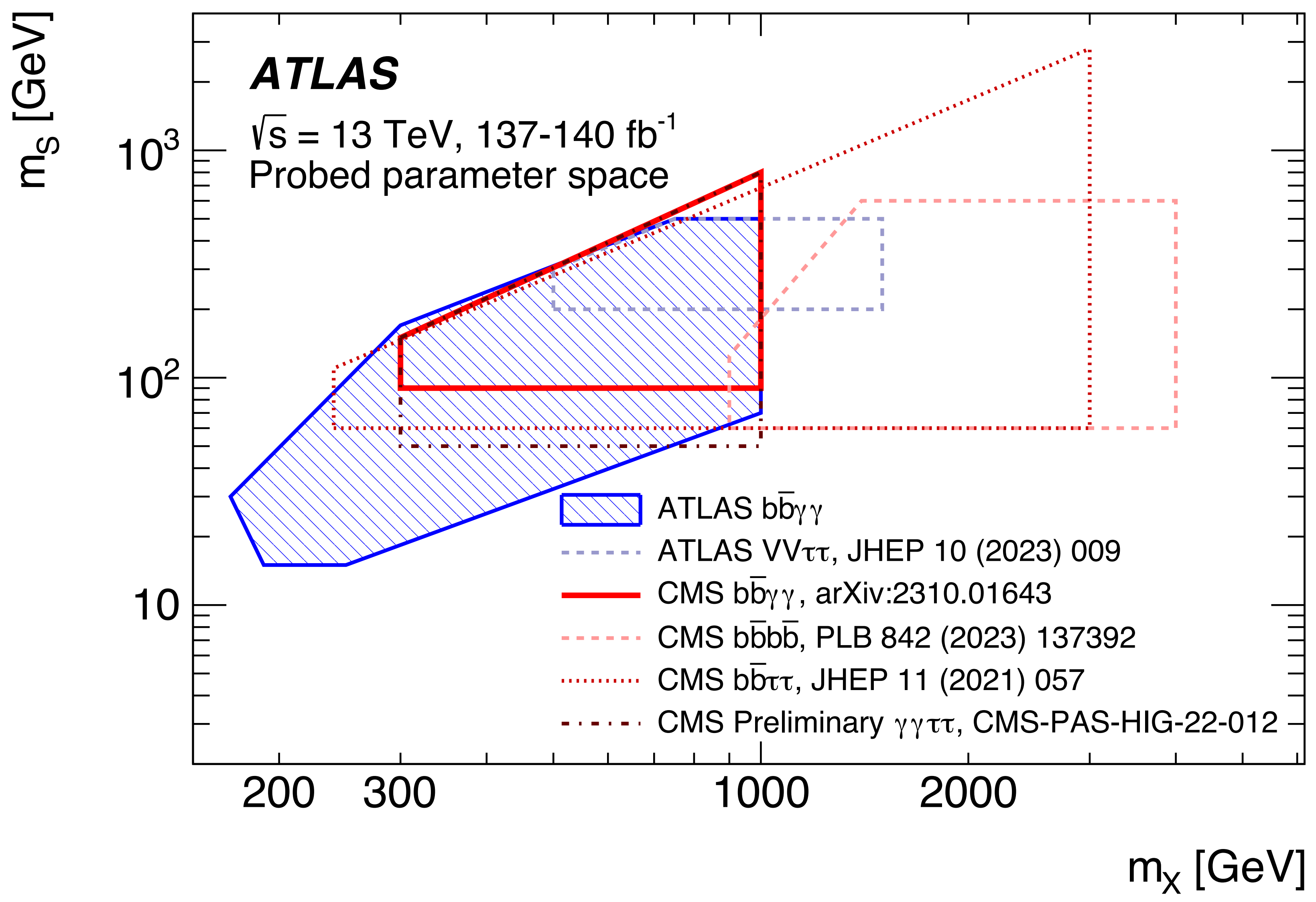
arXiv:2404.12915

arXiv:2310.01643





Most significant excess at **m_X = 650 GeV, m_Y = 90 GeV**: 3.8 (2.8) σ local (global) significance for Y(bb)H(γγ)



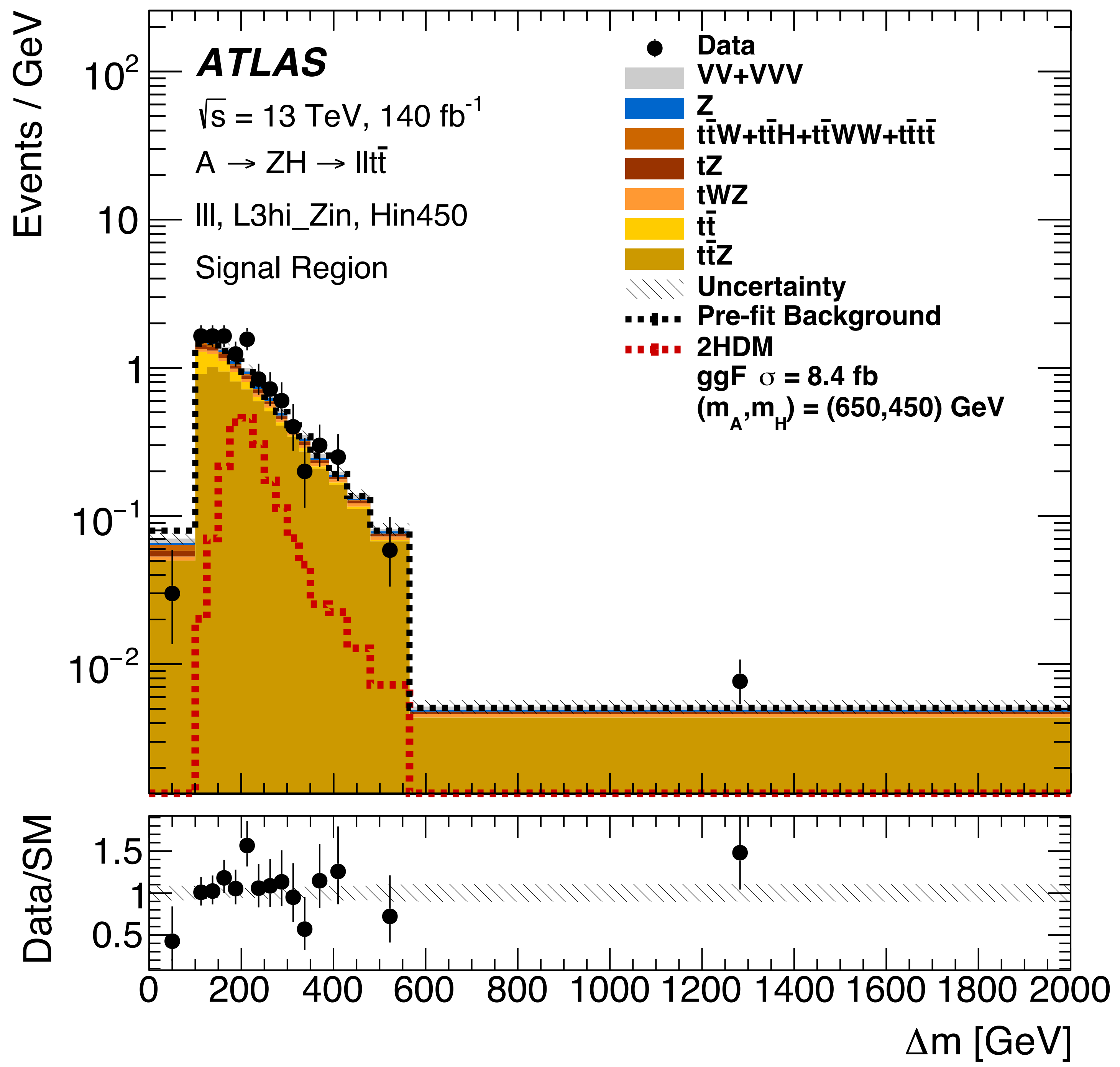
However, no excess seen by ATLAS X→Y(bb)H(γγ) search at same masses: largest deviation at **(m_X, m_Y) = (575, 200) GeV** with 3.5 (2.0) σ local (global) significance)

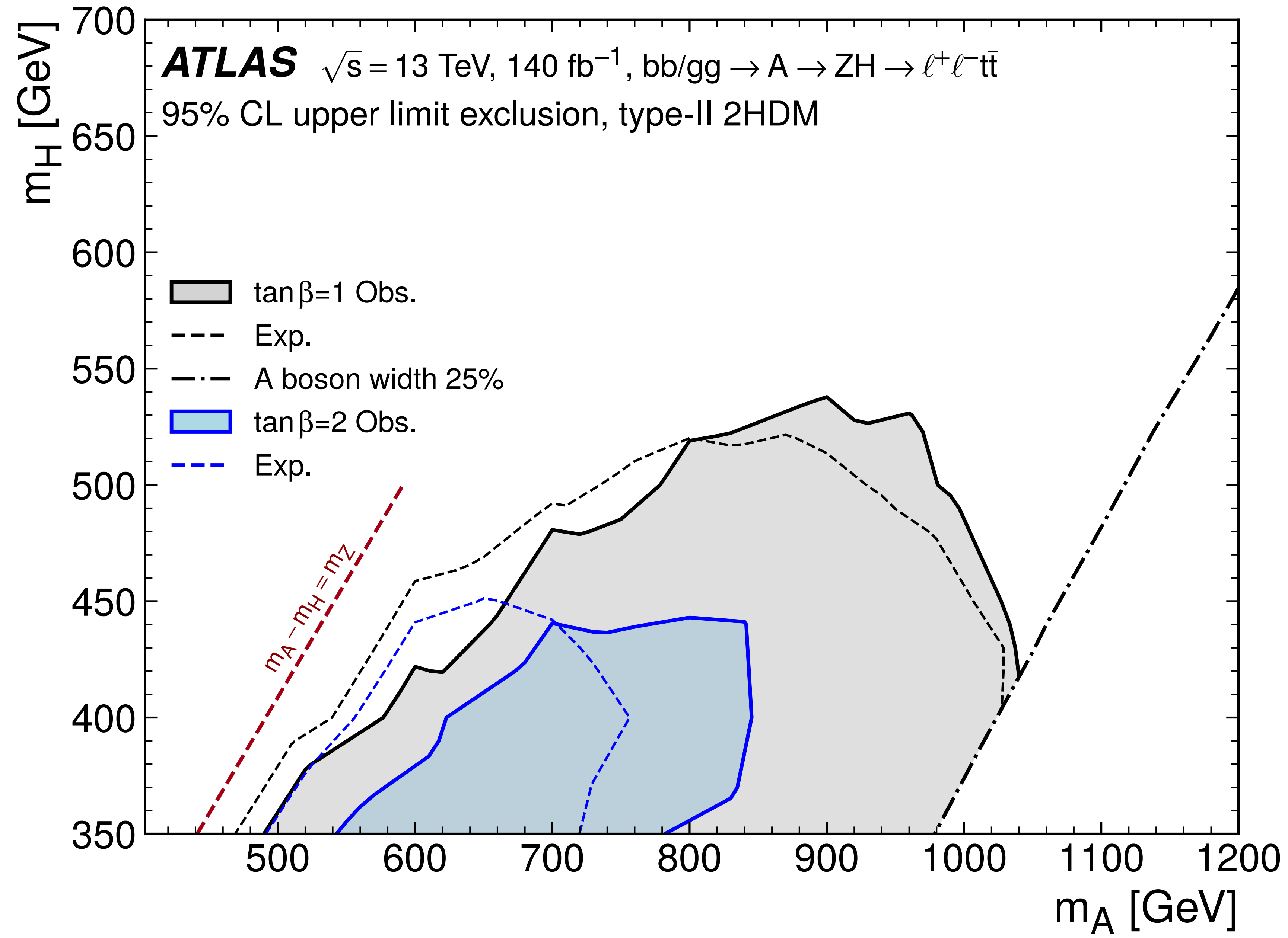
Search for A→Z(ll)H($t\bar{t}$)

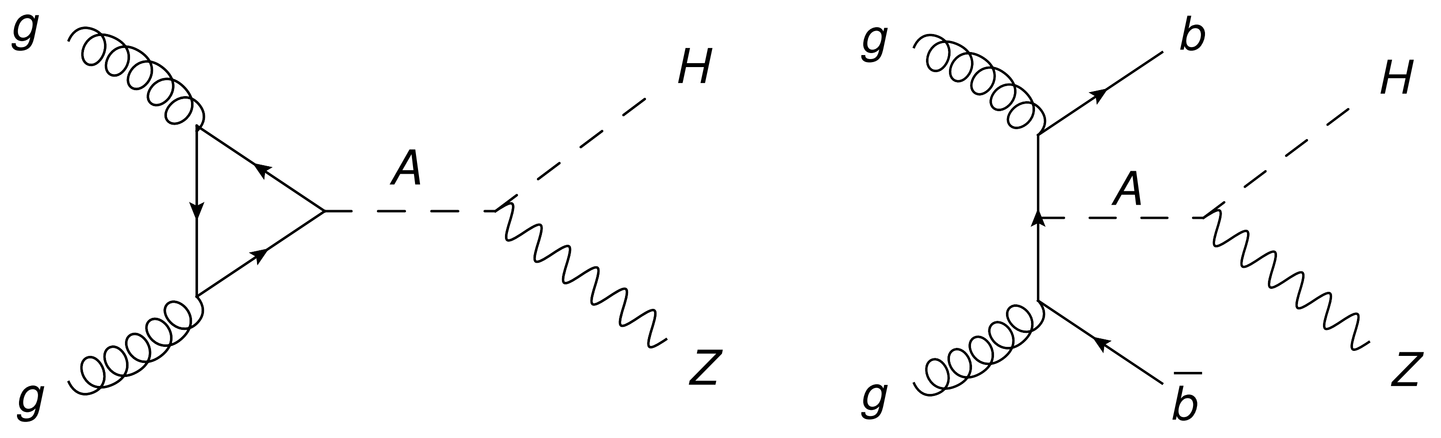
Search for CP-odd Higgs decaying to heavy CP-even Higgs and Z

JHEP 02 (2024) 197

- Motivated by 2HDM, $m_A > m_H$ favored by electroweak baryogenesis models featuring strongly first order EW phase transition: A→ZH dominates when $m_A - m_H > 250$ GeV
- H→$t\bar{t}$ becomes dominant when $m_H > 2\, m_t$. ATLAS search targets semi-leptonic $t\bar{t}$ decays
- Mass difference $\Delta m = m_A^{cand} - m_H^{cand}$ as signal discriminant







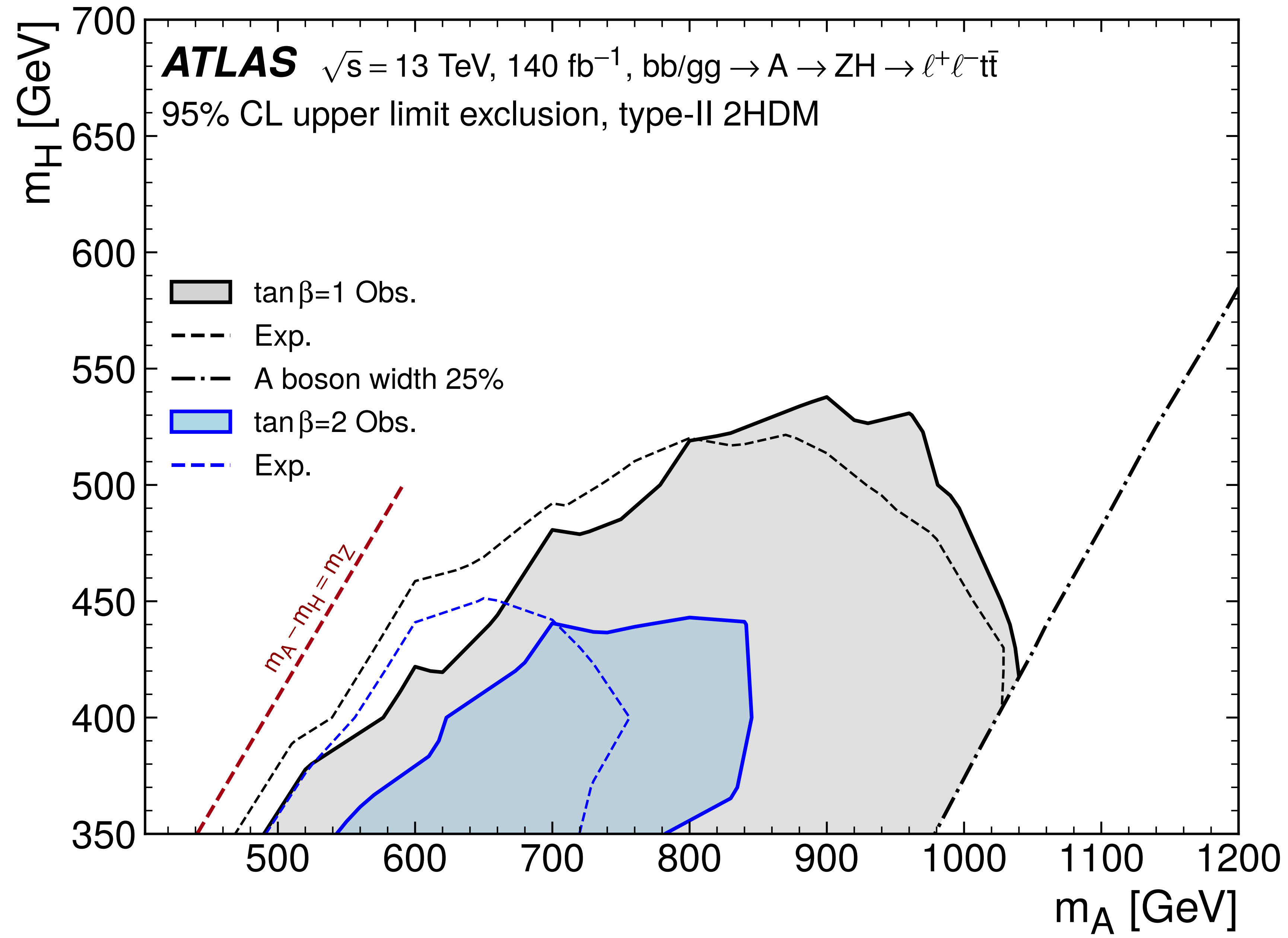
Most significant excess at **m_A = 650 GeV, m_H = 450 GeV**: 2.9 (2.4) σ local (global) significance

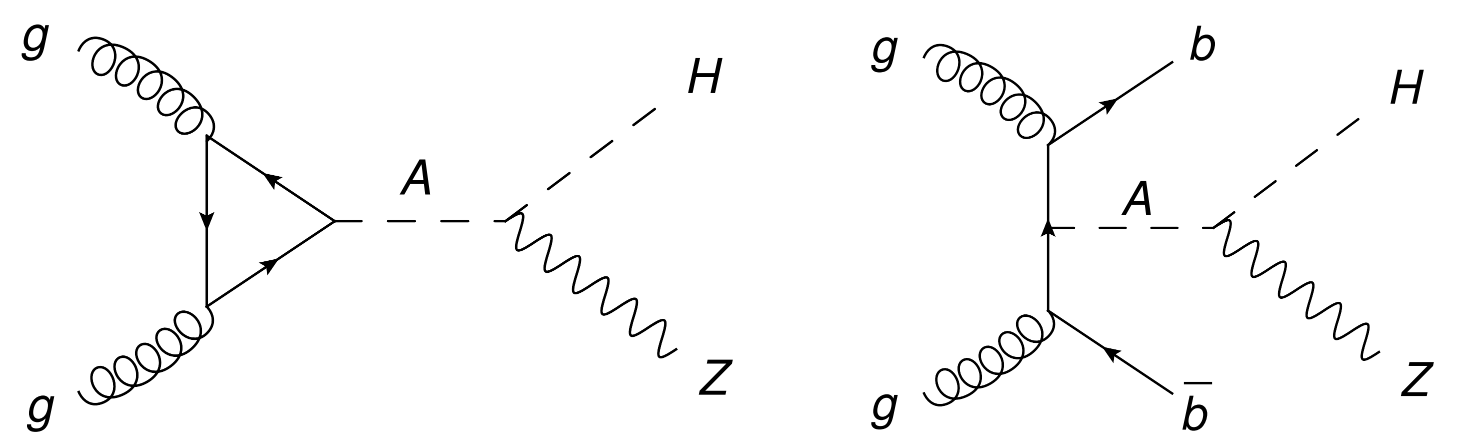
Search for A→Z(ll)H($t\bar{t}$)

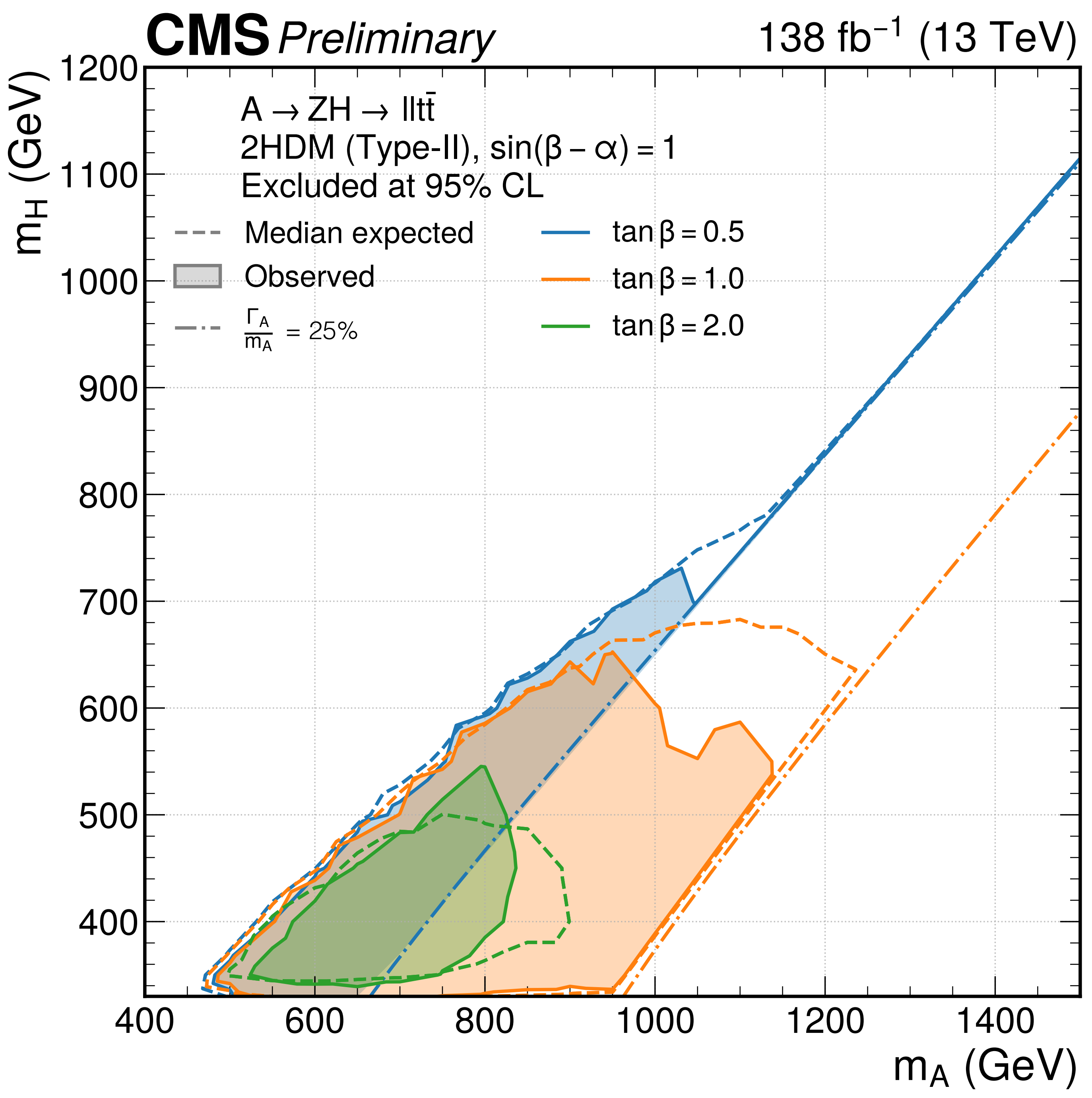
Search for CP-odd Higgs decaying to heavy CP-even Higgs and Z

CMS-PAS-B2G-23-006

- Motivated by 2HDM, $m_A > m_H$ favored by electroweak baryogenesis models featuring strongly first order EW phase transition: A→ZH dominates when $m_A - m_H > 250$ GeV
- H→$t\bar{t}$ becomes dominant when $m_H > 2\,m_t$. ATLAS search targets semi-leptonic $t\bar{t}$ decays
- Mass difference $\Delta m = m_A^{cand} - m_H^{cand}$ as signal discriminant







Most significant excess at **m_A = 650 GeV, m_H = 450 GeV**: 2.9 (2.4) σ local (global) significance

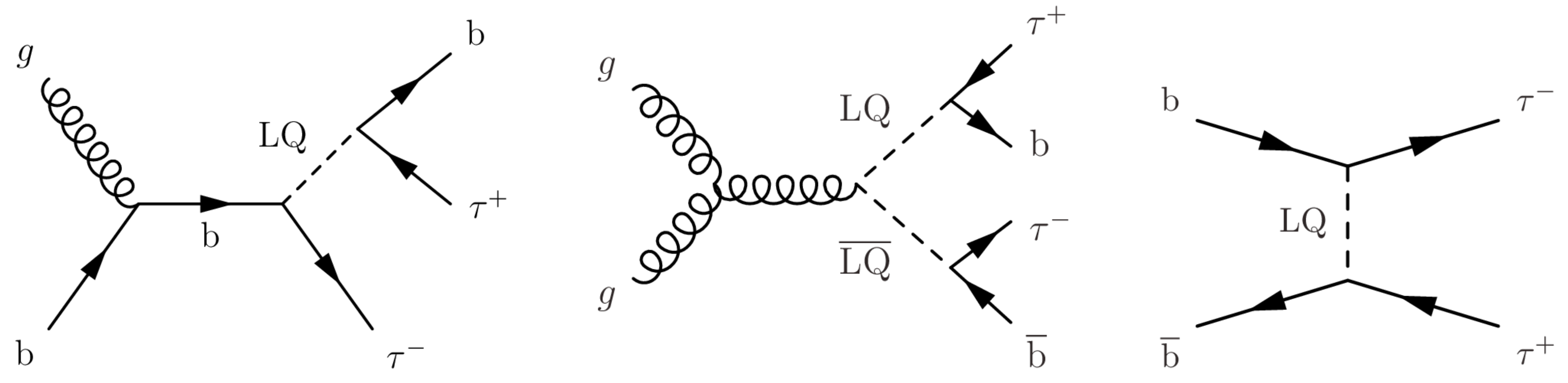
However, excess not confirmed by recent CMS search in final state with all-hadronic $t\bar{t}$ decays

Searches in b+τ final states for leptoquarks, vector-like leptons

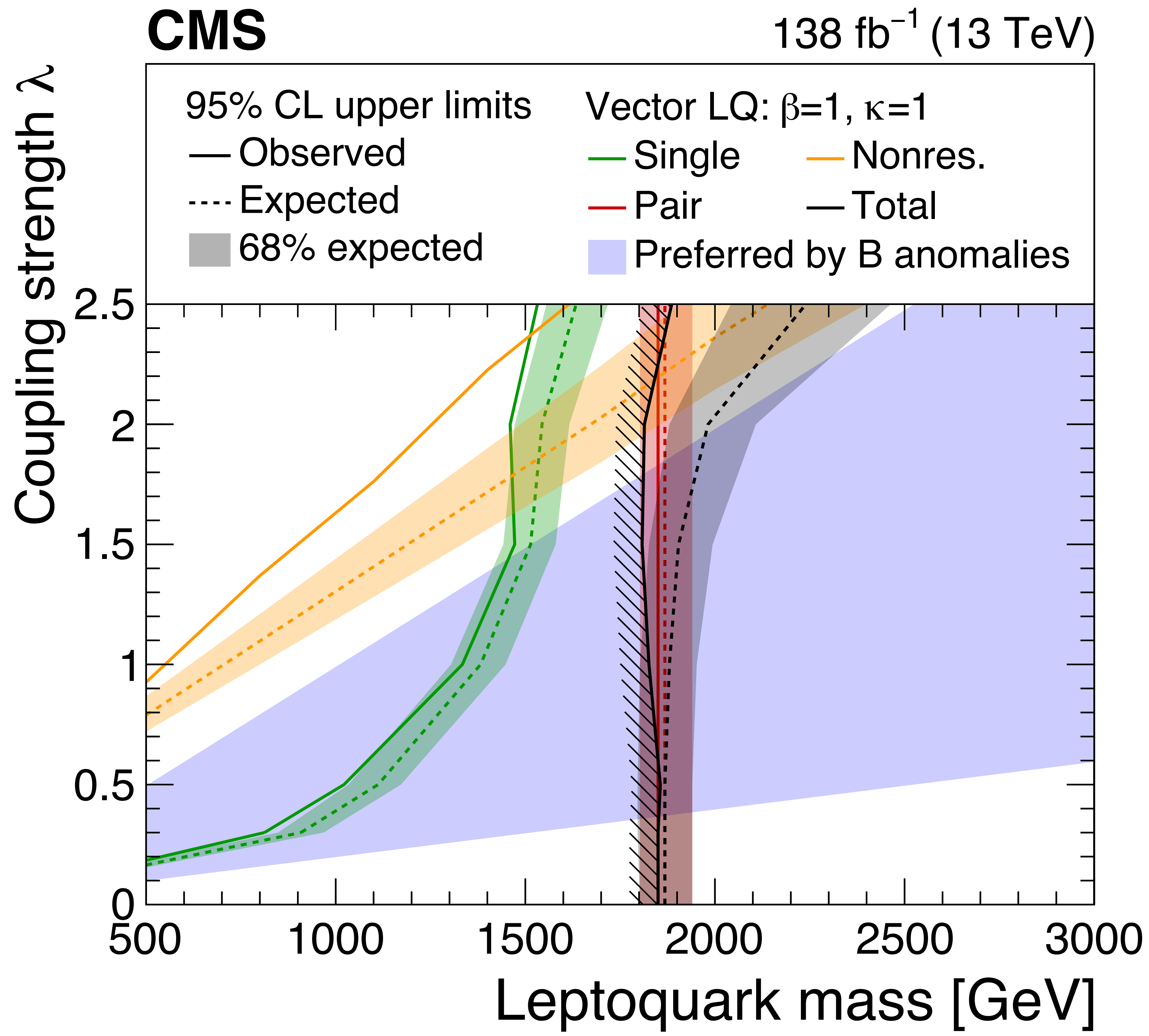
Leptoquarks coupled to 3rd generation

Search for LQ → bτ

- Motivated by B anomalies
- Consider single and pair production, non-resonant production

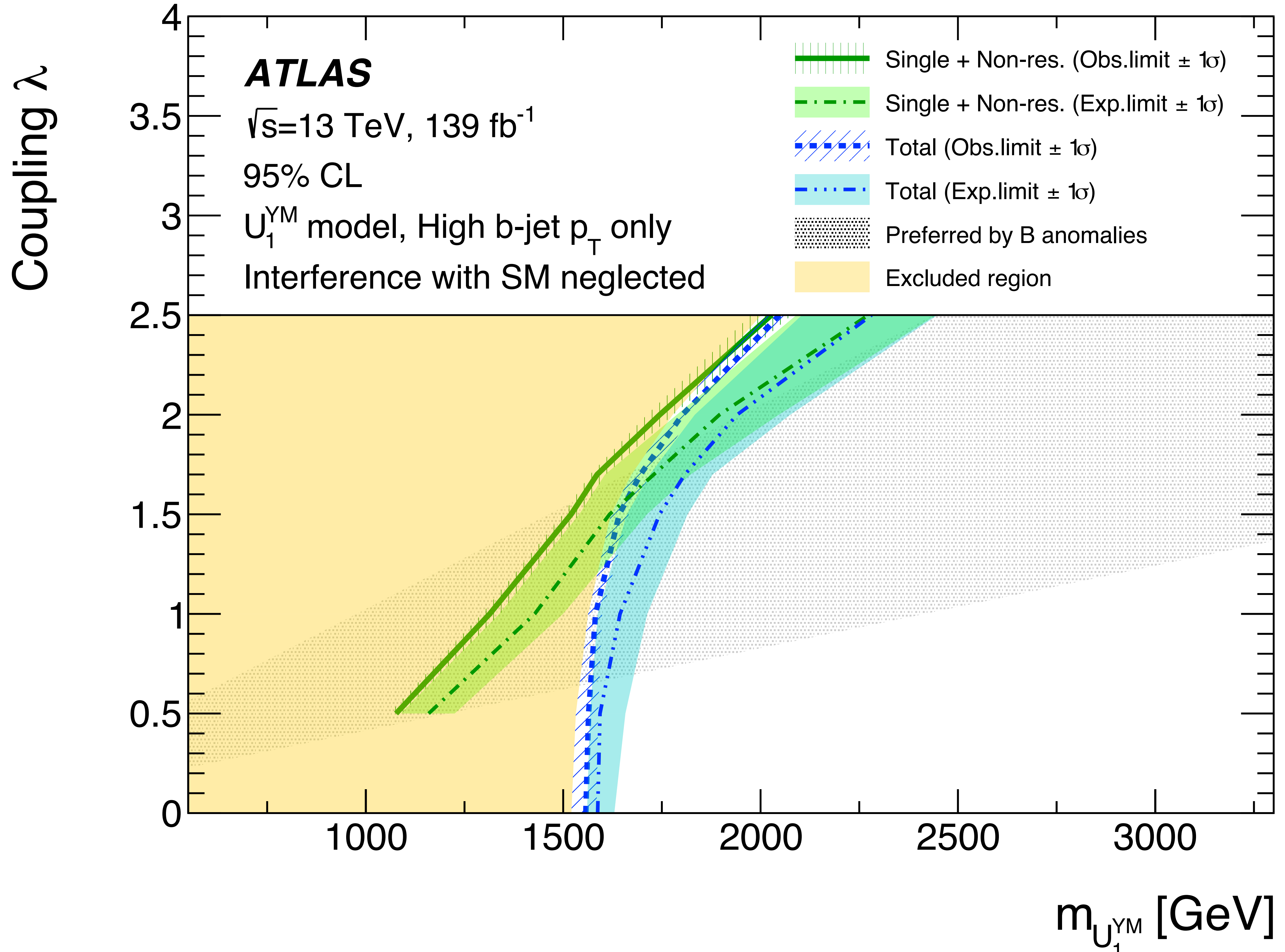


arXiv:2308.07826



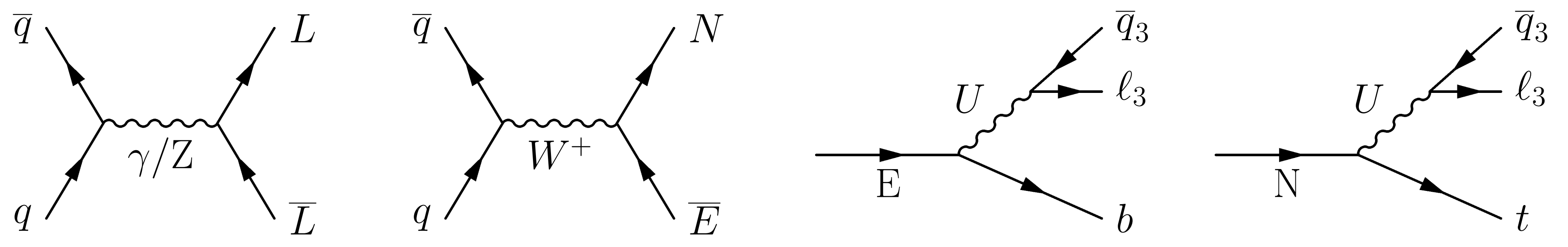
CMS observes excess with local significance 2.8 σ for LQ mass **2 TeV**, coupling strength λ=2.5: excluded by ATLAS

JHEP 10 (2023) 001



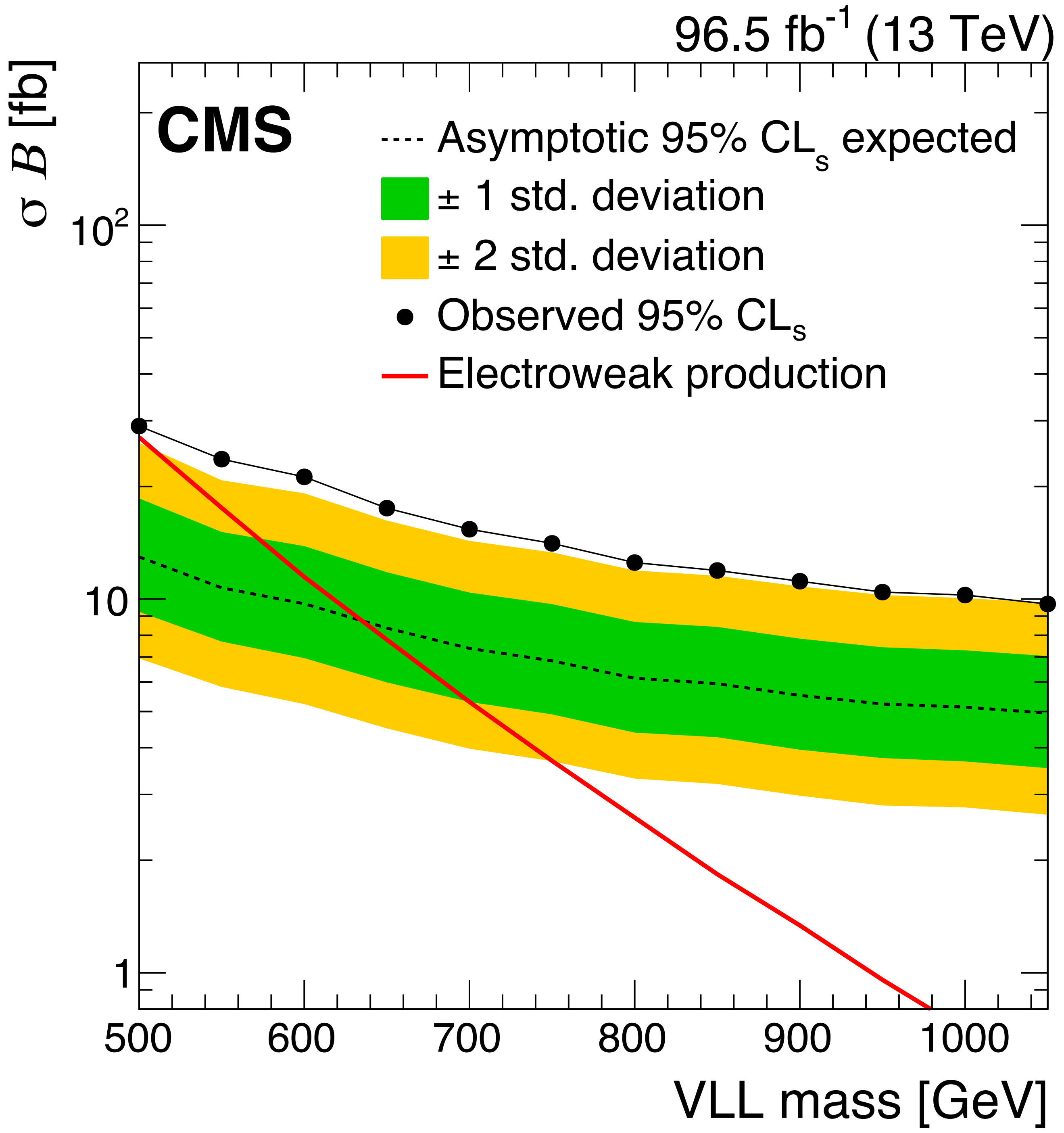
Vector-like leptons

Search for pair production of VLLs in final state with ≥3 b-tagged jets and upto 2 τs with CMS 2017+2018 data

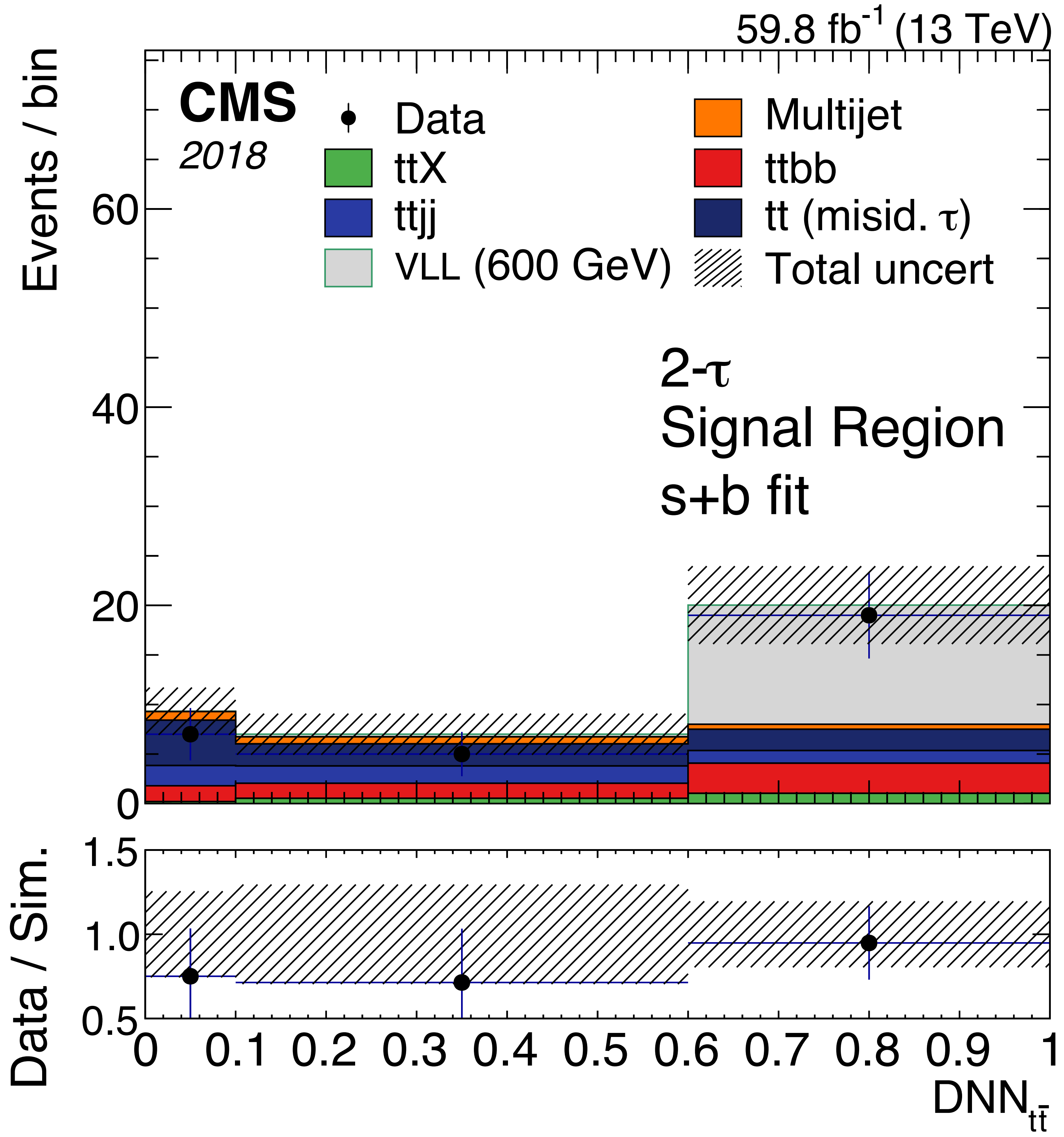


- "4321 model", motivated by B anomalies
- EW pair production of VLLs with decay via virtual vector LQ coupled to 3rd generation
- Fit to N_{jet} or DNN distribution in different event categories

PLB 846 (2023) 137713



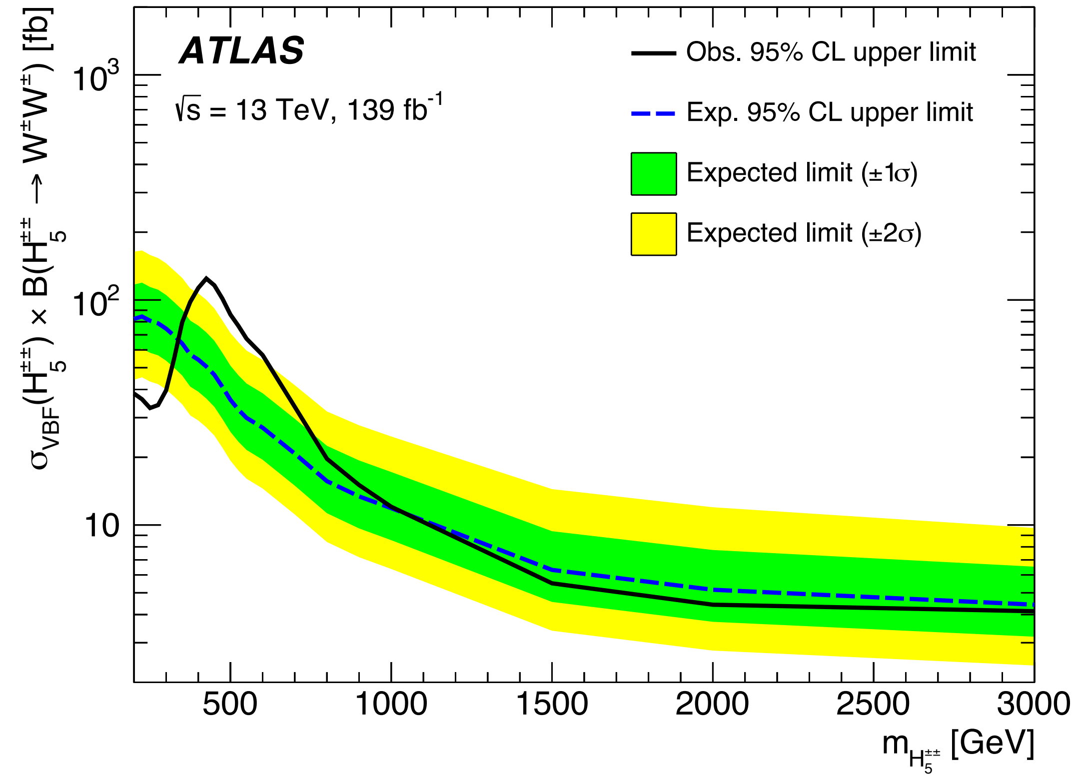
Excess with local significance 2.8 σ observed for VLL mass 600 GeV

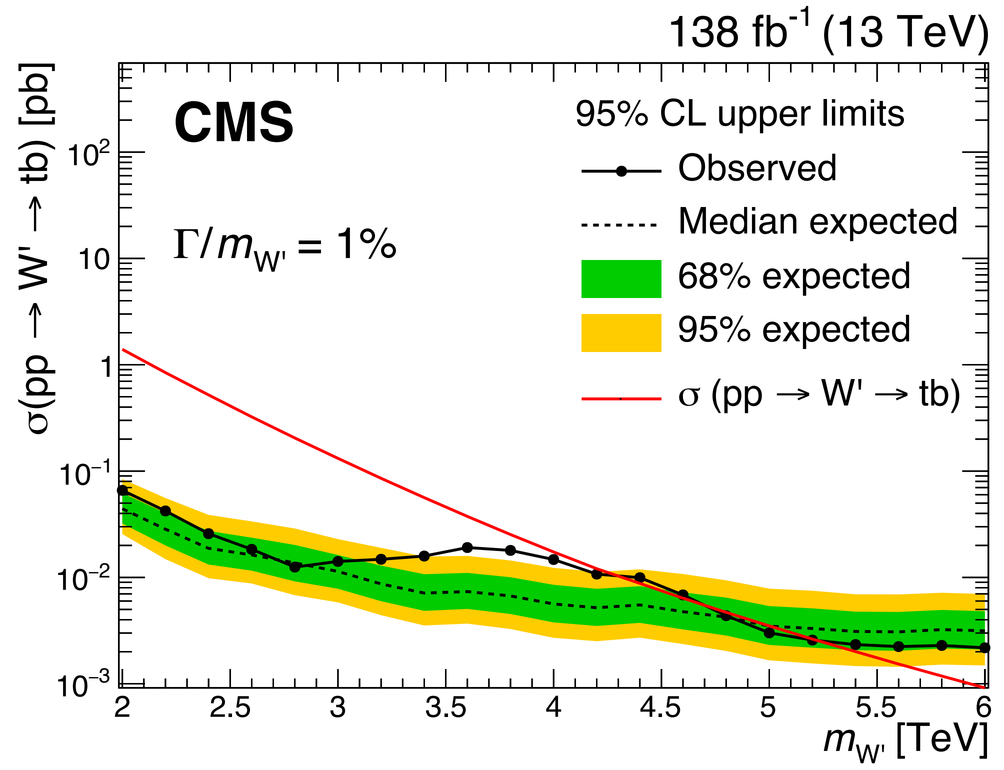


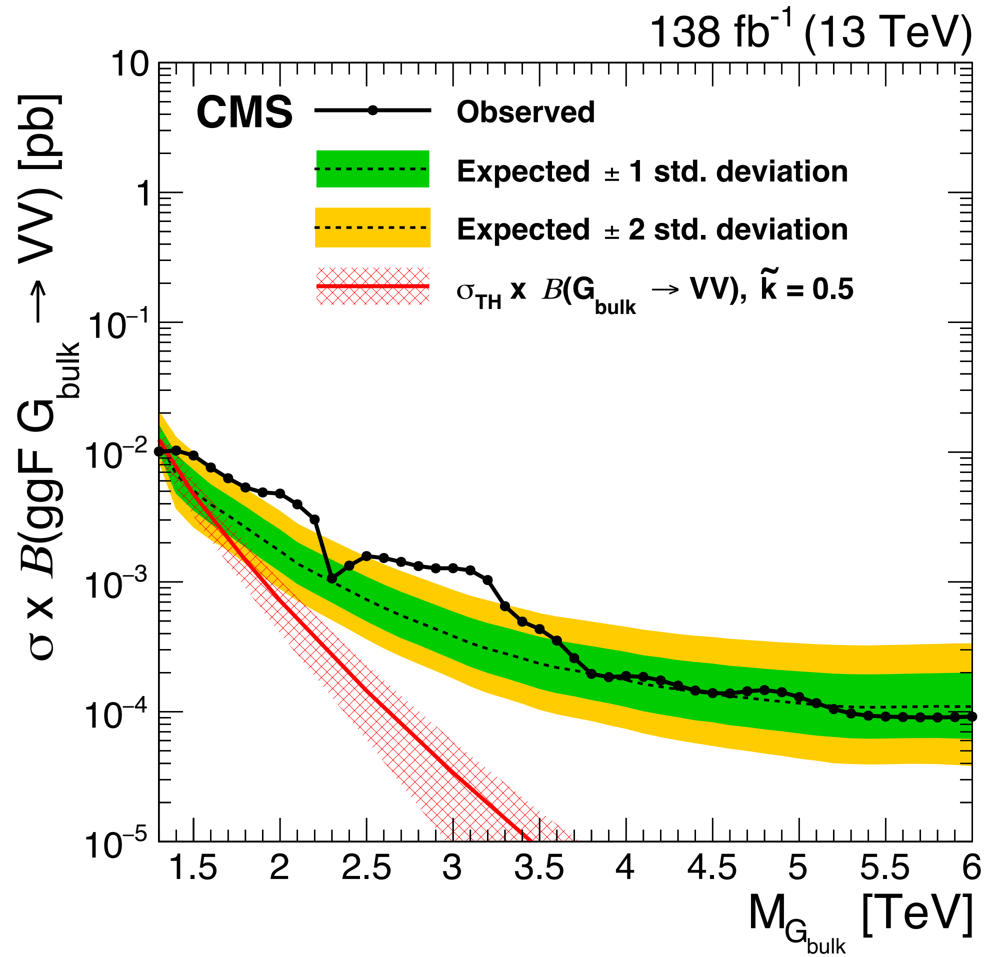
Many more interesting results …

Did not have time to cover several others, including …

- Doubly charged Higgs: excess of 3.3 (2.5) σ local (global) for $m_{H^{\pm\pm}}$ 450 GeV (Georgi-Machacek model) in same-sign WW scattering at ATLAS (JHEP 04 (2024) 026)
- Searches for Spin-1/Spin-2 resonances e.g.:
  - W'→tb, CMS: 2.6 (2.0) σ local (global) significance for W' mass 3.8 TeV (arXiv:2310.19893)
  - W'/Z' in heavy vector triplet model / spin-2 graviton in bulk model decaying to VV/VH, CMS: 3.6 (2.3) σ local (global) at 2.1, 2.9 TeV (PLB 844 (2023) 137813)
- And more …







Summary

Vast and rich program of experimental searches for new physics at ATLAS and CMS with LHC Run 2 data. Philosophy: leave no stone unturned!

No observation of BSM physics yet, but some intriguing excesses seen at the 2-3 **σ** level worth following up …

- Some excesses in extended Higgs sector searches across multiple final states …
  - **low-mass** γγ, ττ (**90-95 GeV**)
  - **high-mass** dibosons (**~650 GeV**)
- Some excesses seen in one experiment but apparently not the other …
  - X→Y(bb)H(γγ) at (m_X,m_Y) = (650, 95) GeV in CMS (not confirmed by ATLAS)
  - A→Z(ll)H($t\bar{t}$) at (m_A,m_H) = (650, 450) GeV in ATLAS (not confirmed by CMS)
  - LQ→bτ at high mass in CMS (appears excluded by ATLAS)
- More searches to come with Run 2 data, and looking forward to Run 3 and HL-LHC to follow up …

Searches using Run 3 data at √s=13.6 TeV ramping up

- Expanding sensitivity through variety of approaches: ML, new triggers and data-processing techniques, and more …

shutterstock.com · 62153212