Overview of BSM Higgs searches at the LHC

Extended scalar sectors from all angles

Halil Saka (University of Cyprus), on behalf of the CMS and ATLAS Collaborations

October 21, 2024

Higgs, as a gateway to BSM

In a decade, the SM Higgs boson has become:
- *signal*
- *background (e.g rare SM measurements, eg. VVV)*
- ***discovery tool***

*H serves as a “**standard candle**” in BSM analyses*

→ ***known mass, known decays***

ex/ $\mathrm{H} \rightarrow \mathrm{bb}$ *tagging*

*Motivates **searches for an extended scalar sector***

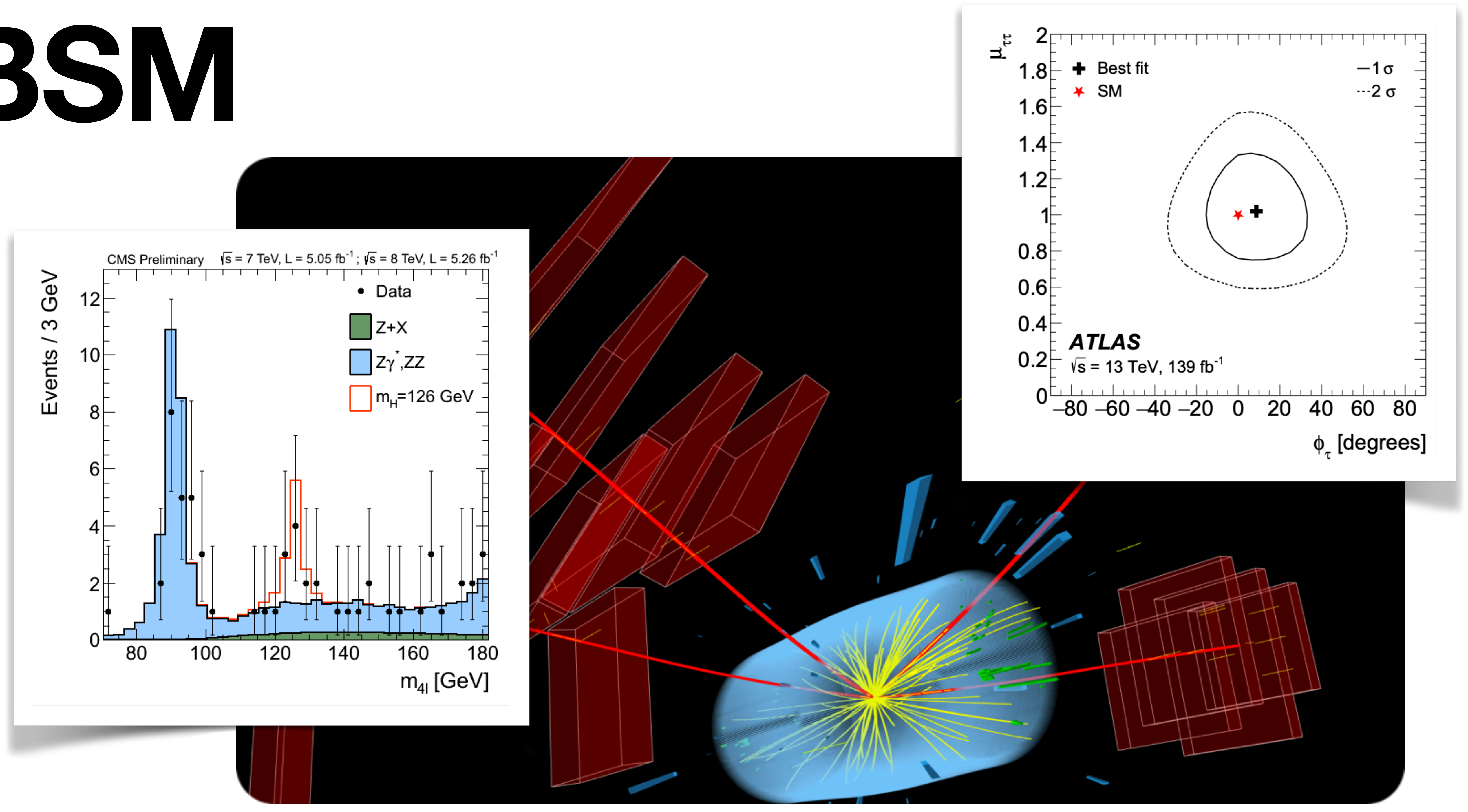
→ *new particles (with hidden dynamics) could **mix** with the SM H*

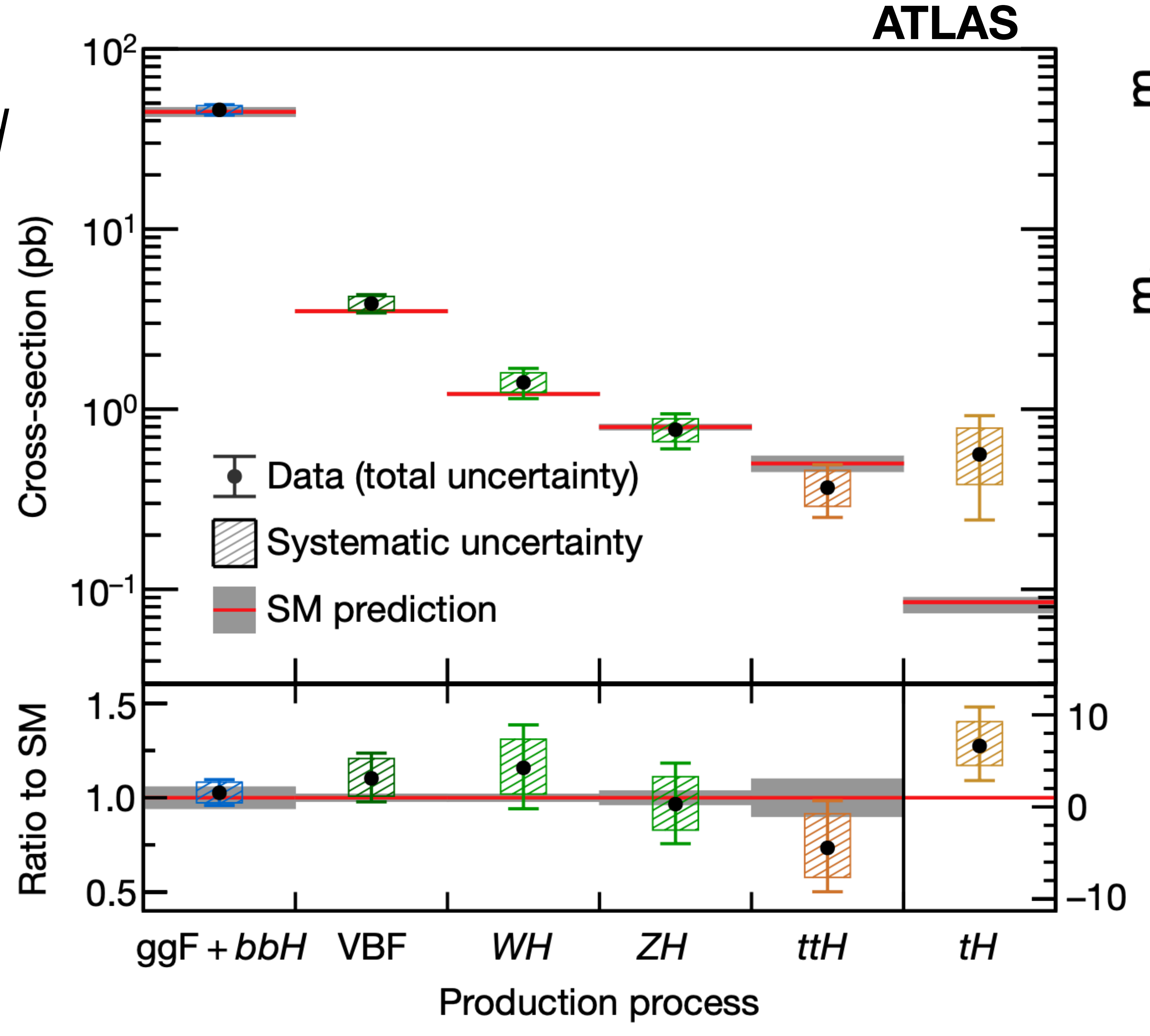
→ ***Higgs-like production/decays of the new particles***

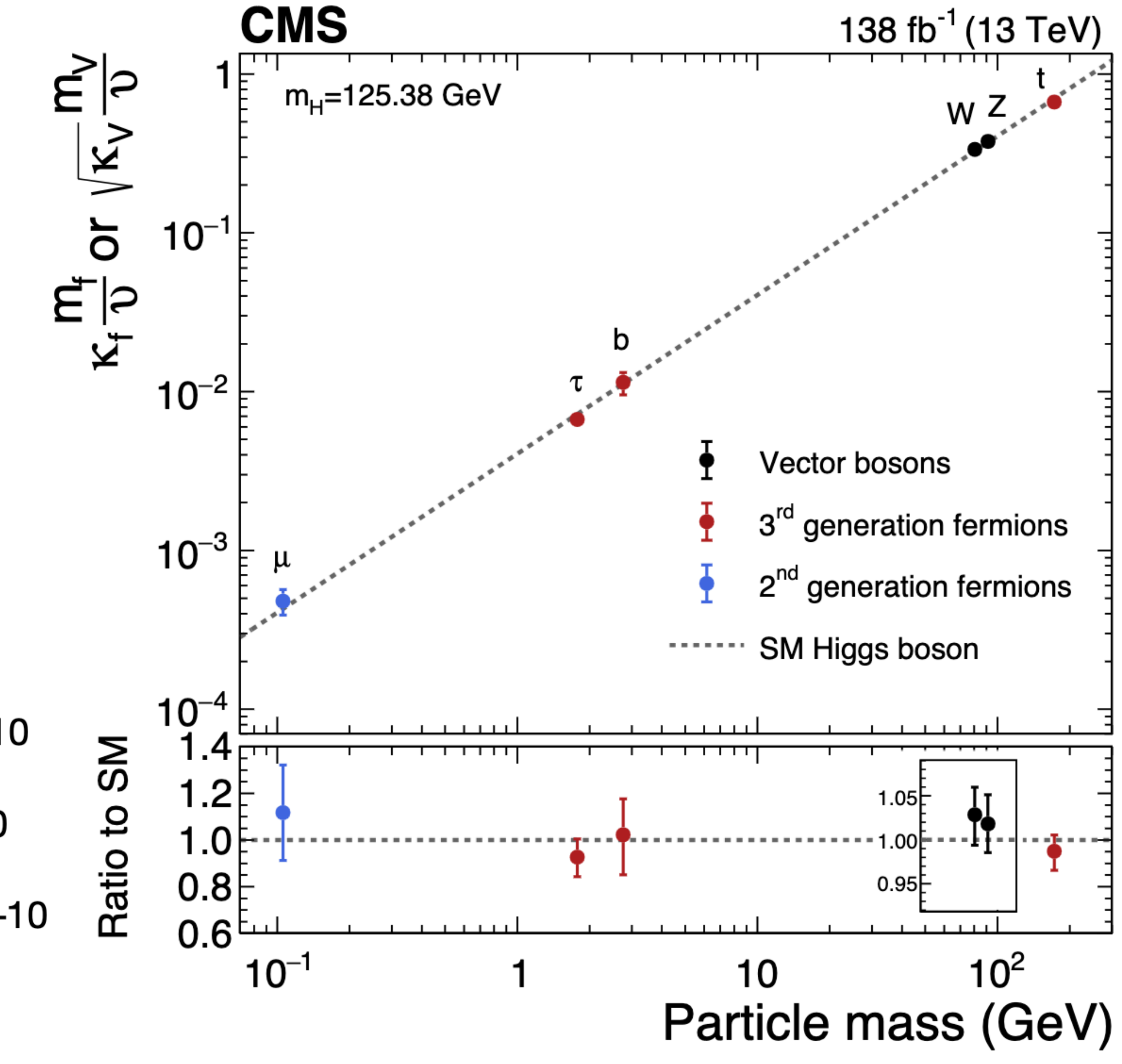
***Higgs still has** sufficient **freedom** for exotic couplings*

→*BR(H→non-SM) could be up to* $\mathcal{O}(10)\,\%$

→ *Can act as **portal to hidden sectors***







Many ways to add a scalar

+S	+TRSM	SM	2HDM (MSSM)	N2HDM	2HDM+S (NMSSM)	3HDM	GM	LRSM / Type-II seesaw
Real singlet	2 real singlets	Complex doublet	2 complex doublets	+ Real singlet	+ Complex singlet	3 complex doublets	2 triplets	
H_1	H_1, H_2	H	H, H_2 $A, H^{\pm}$	H, H_2, H_3 $A, H^{\pm}$	H, H_2, H_3 $A, a, H^{\pm}$	H, H_2 $H_1^{\pm}, H_2^{\pm}$	H, H_2, H_3, H_4 $H_1^{\pm}, H_2^{\pm}, H^{\pm\pm}$	H, H_2, A $H^{\pm}, H^{\pm\pm}$

ggF

VBF
tt
bb
V

Direct or associated production

$\oplus$

$X \to \gamma\gamma, f\bar{f}, VV$

$H^{\pm} \to HW^{\pm}, tb, ..$

$H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$

"simple" ~1D bump hunt

$H \to XX$

$X \to HH$

$X \to HY$

$X \to YY$

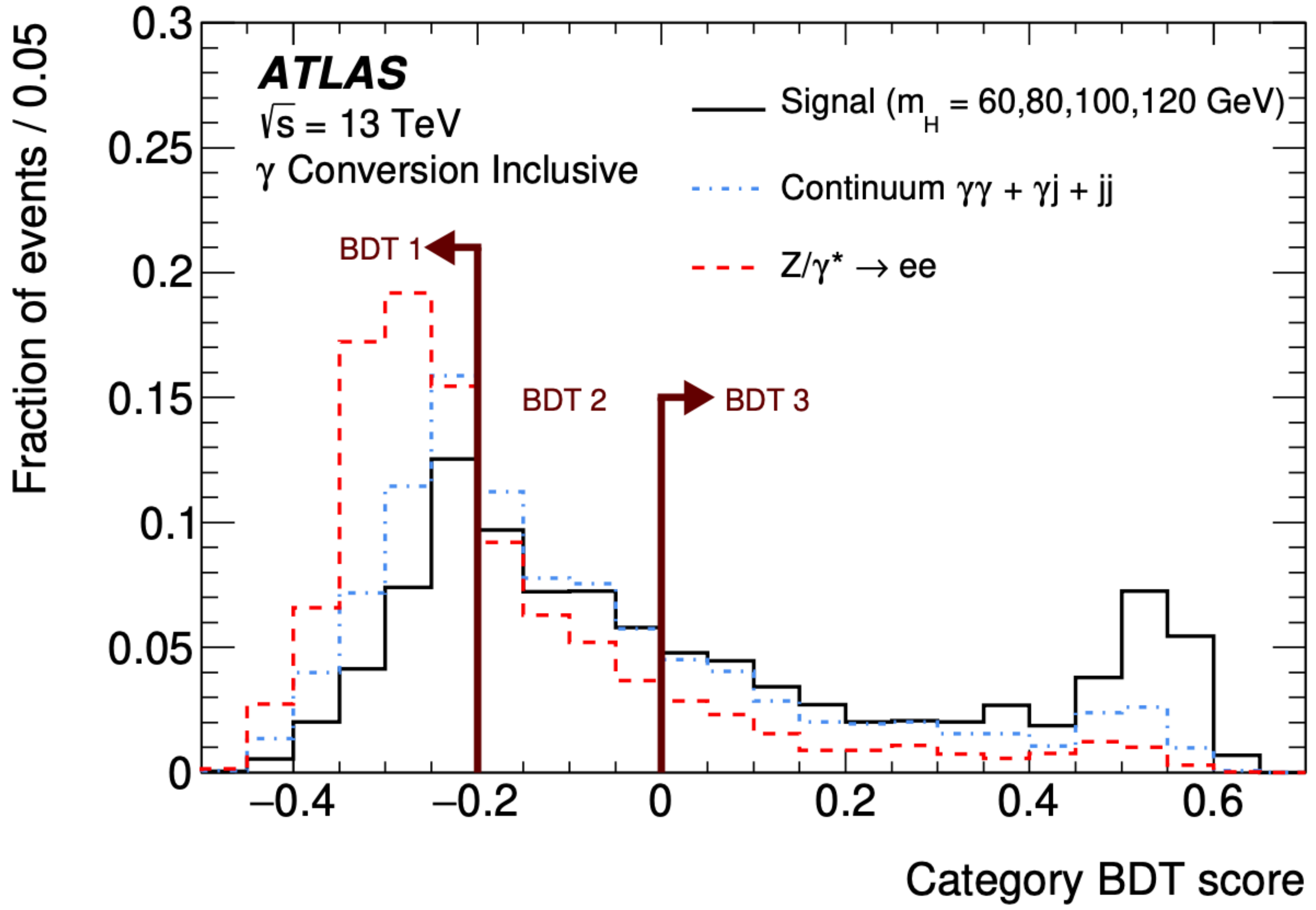
$X \to YZ$

Complex bump hunt

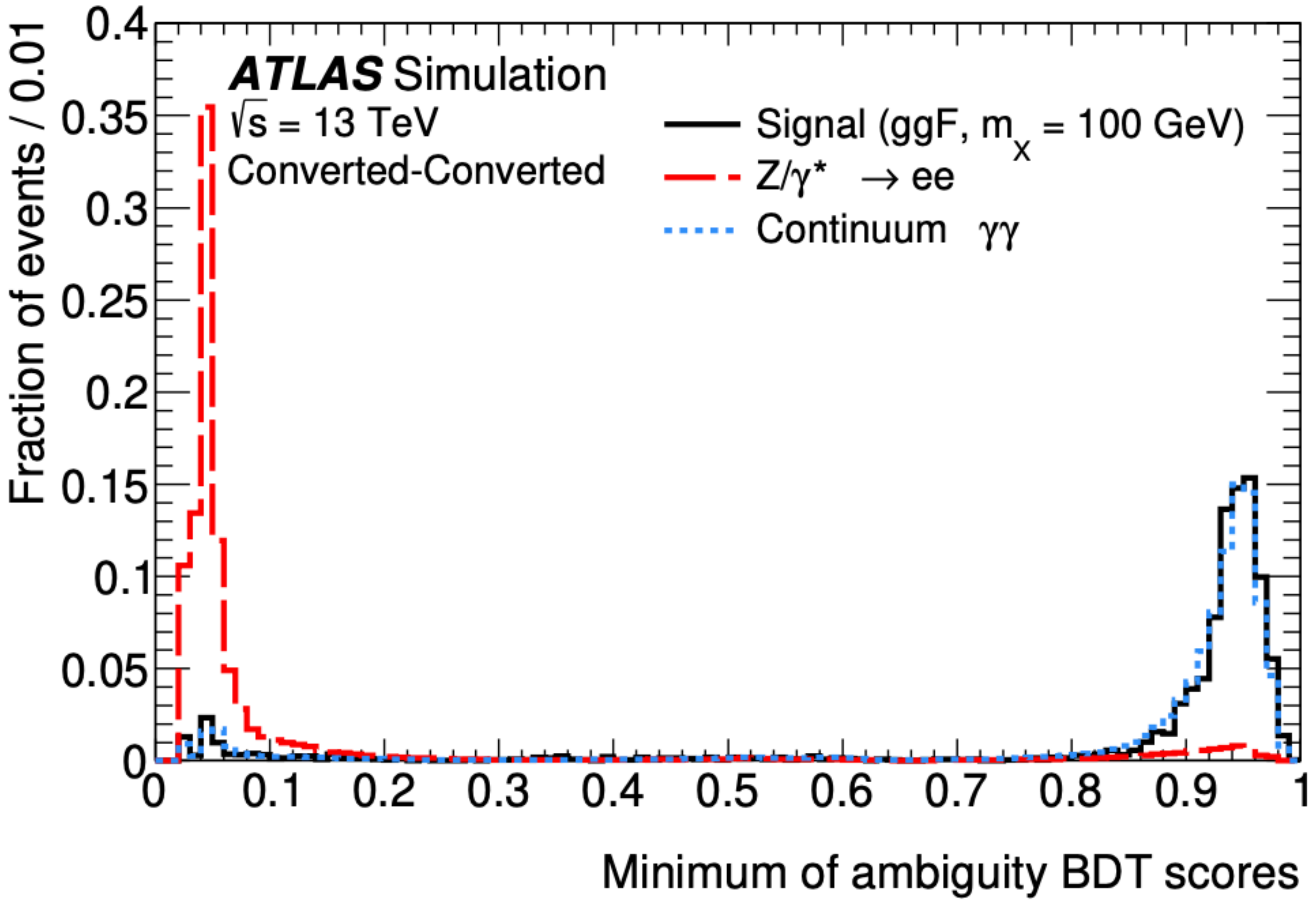
Direct production

H→γγ (low mass)

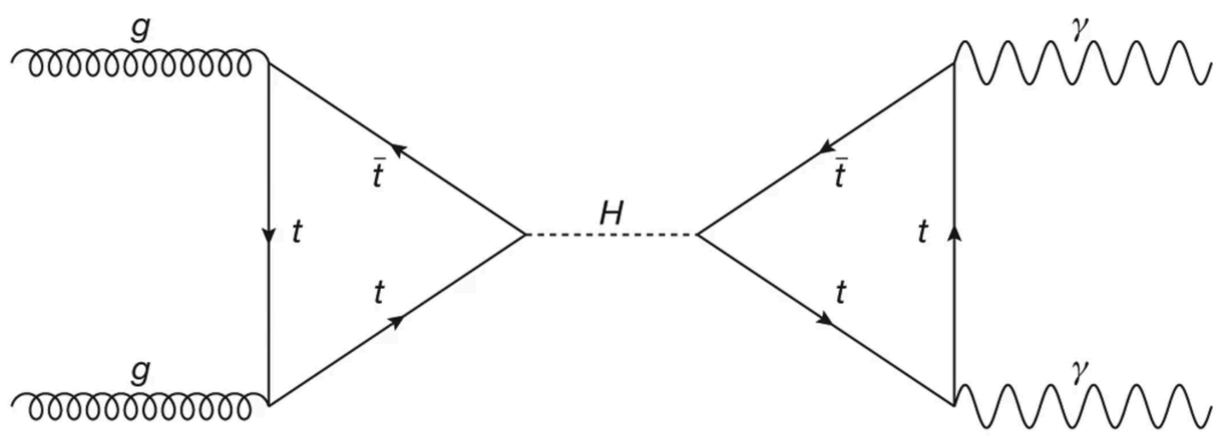
ATLAS HIGG-2023-12
arXiv:2407.07546

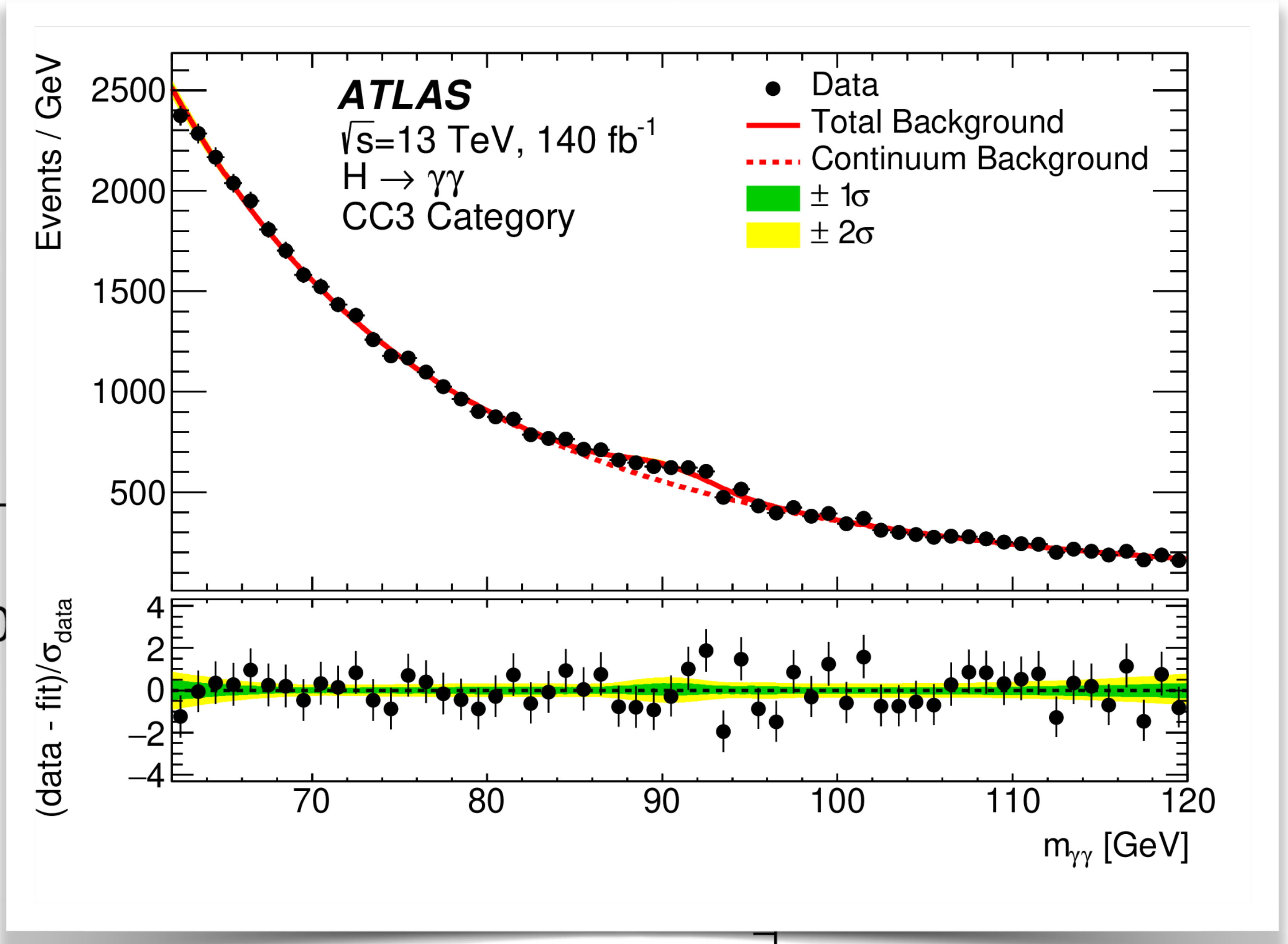


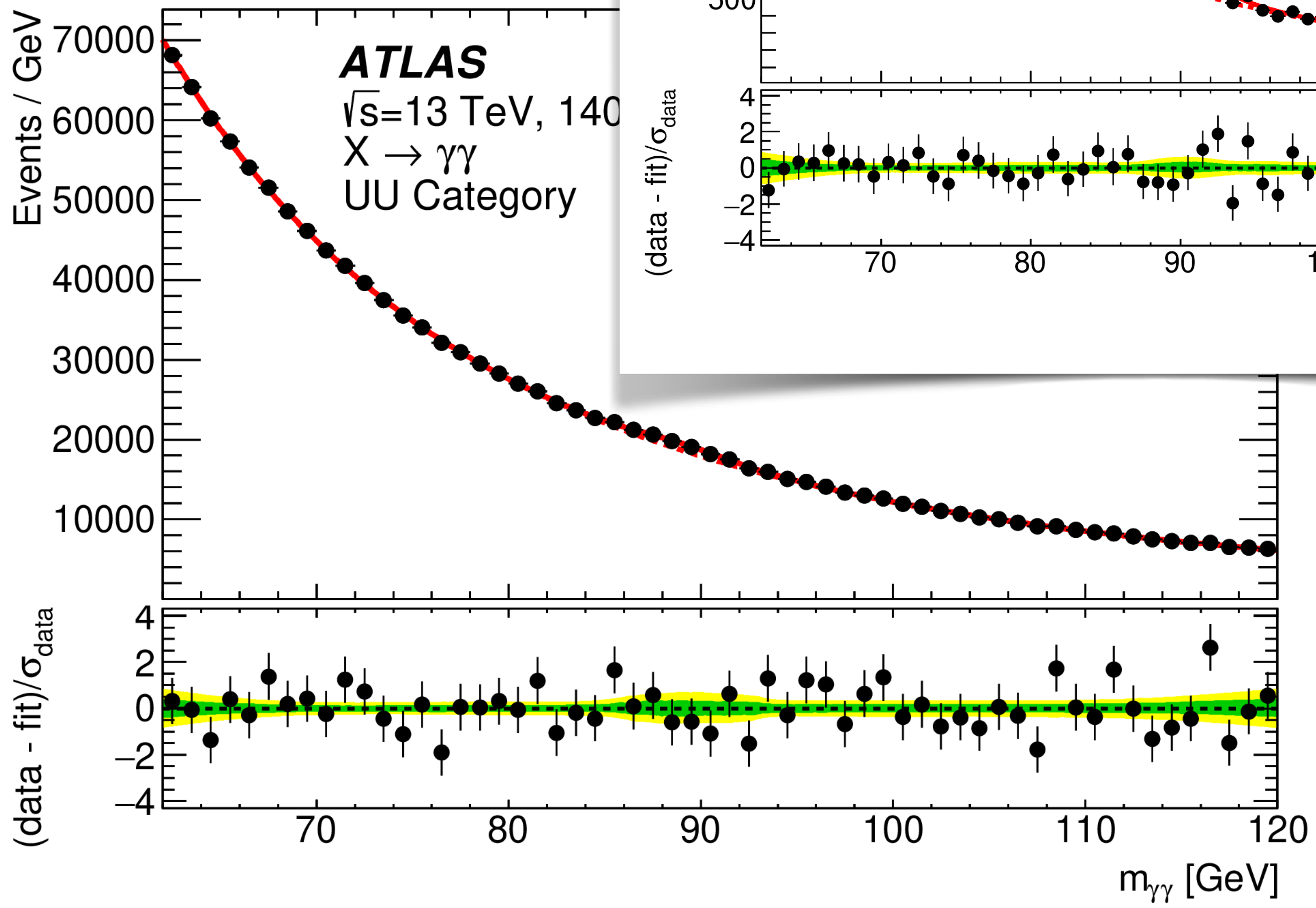
per photon pair



per photon







Bump hunt in the diphoton mass spectra with analytic functions (MC inspired)

Dominant DY background via ***electron conversions***

→usage of ***dedicated BDTs****:*

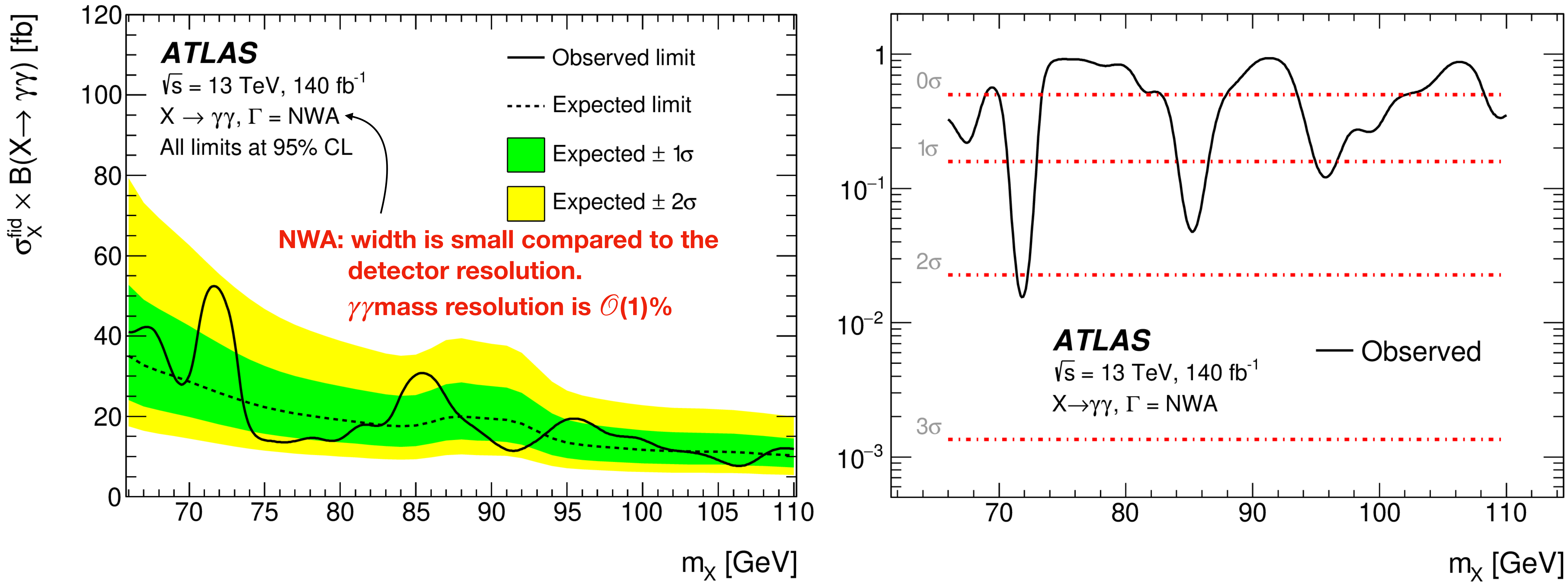
- *ambiguity BDT (model independent)*
- *category BDT (model dependent)*

Varying ***“degree of conversion” categories****: CC→UU*

$H \rightarrow \gamma\gamma$ (low mass)

ATLAS HIGG-2023-12

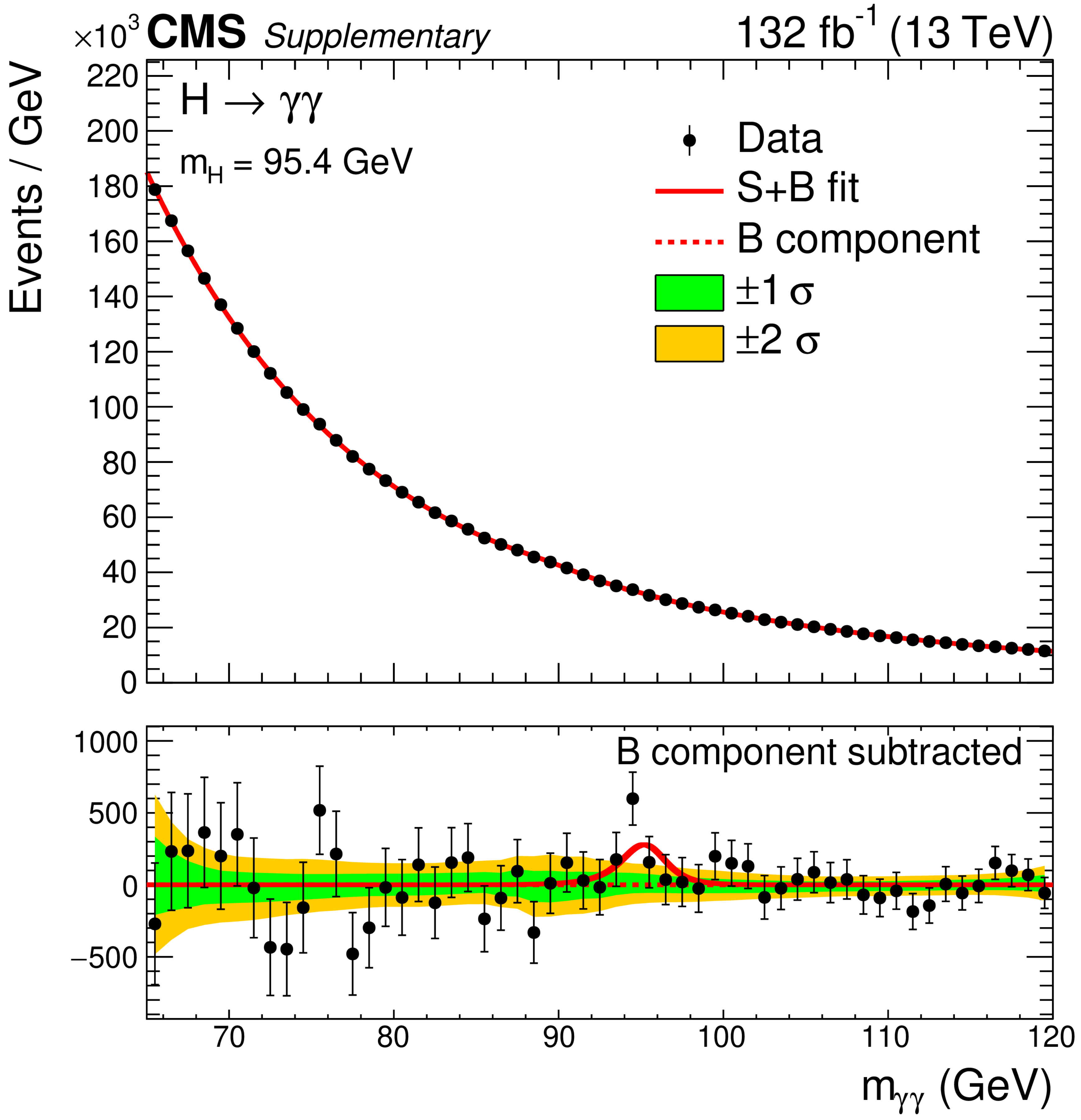
arXiv:2407.07546

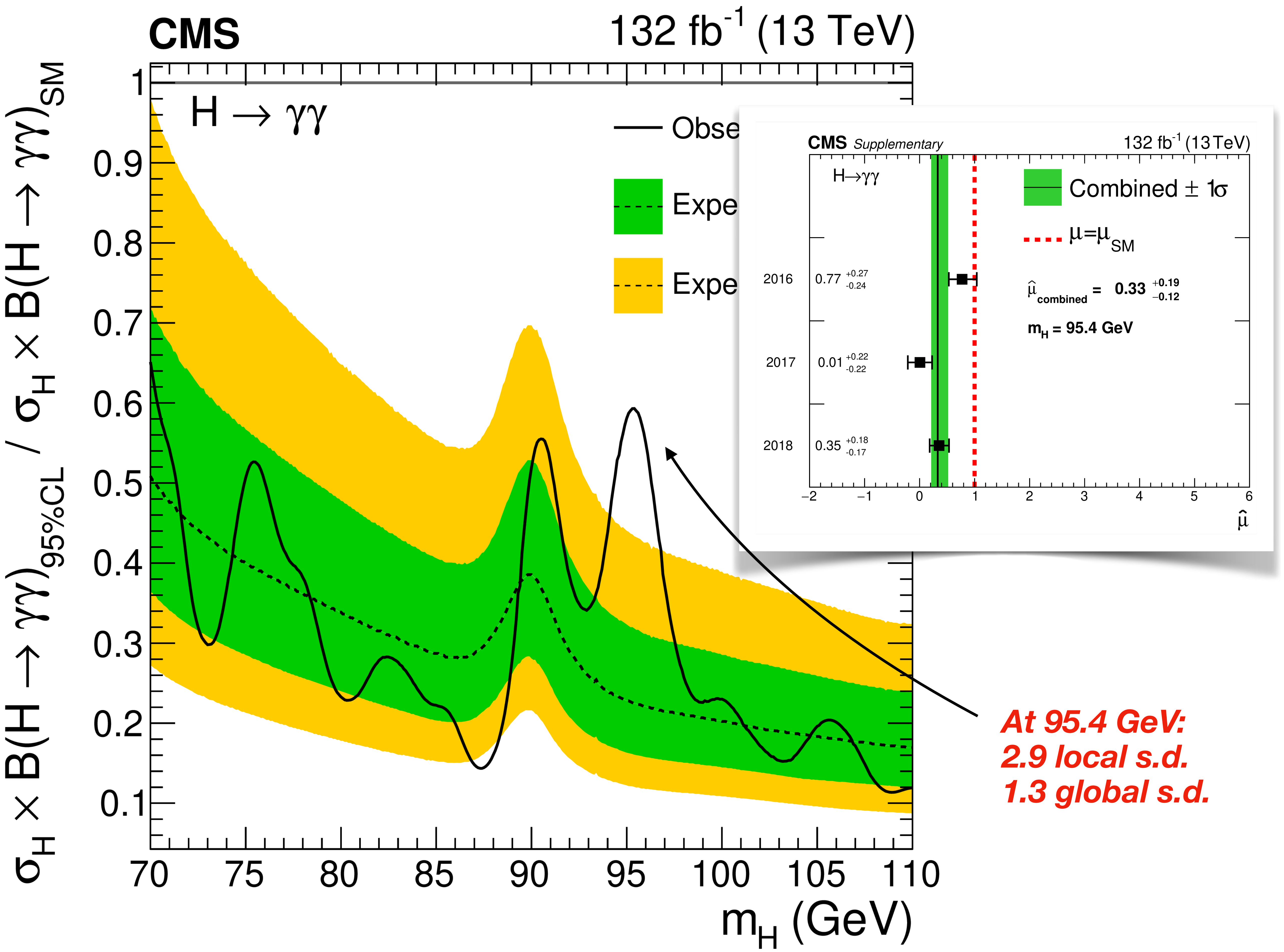


Model-dependent limits are also provided: assuming the production-mode $\sigma \times BR(\gamma\gamma)$ as predicted by SM at a given mass m

H→γγ (low mass)

CMS HIG-20-002
arXiv:2405.18149





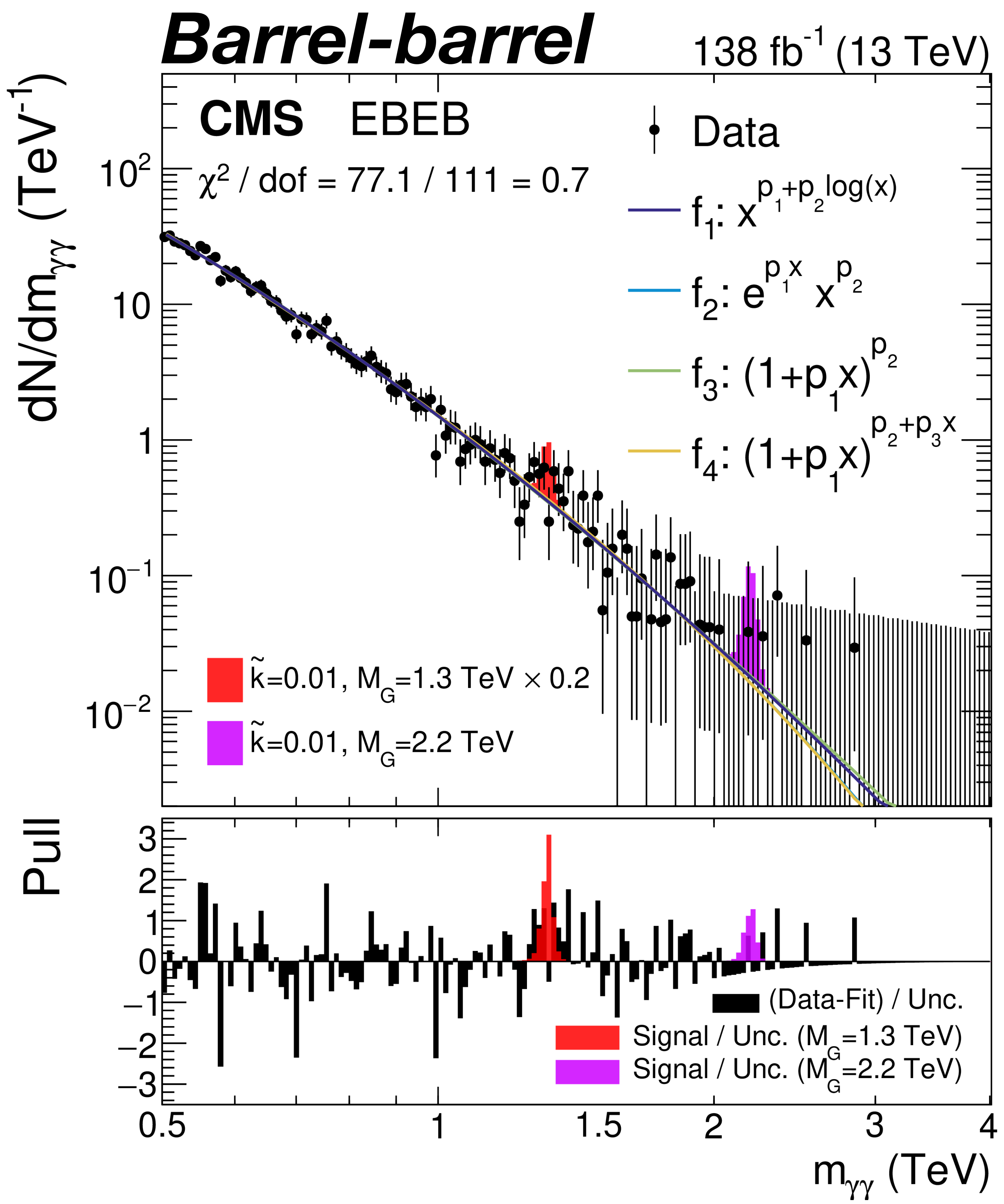
Multiple MVA discriminants *are used for* ***photon energy, ID, and event classification*** *(also uses vertex information)****.***

Search for narrow signal peak over ***smoothly-falling background (parametric fit).***

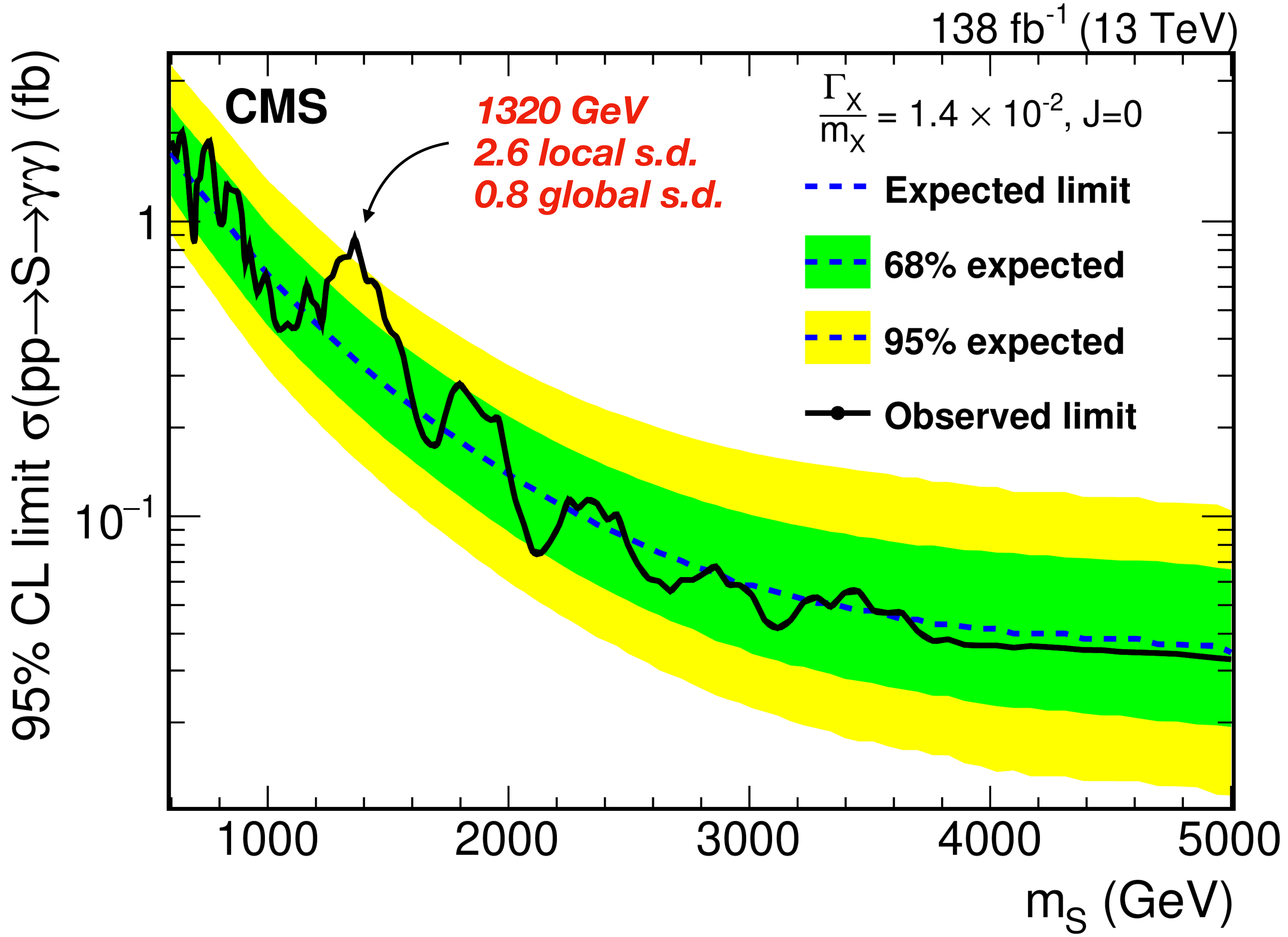
Targets ggF, VBF, ttH, VH modes*, via the Class MVA and jet multiplicity variables.*

$H\to\gamma\gamma$ (high mass)

CMS EXO-22-024
arXiv:2405.09320



Geometric event classification:
Barrel-Barrel, Barrel-Endcap (due to higher SM background contributions, poorer resolution)

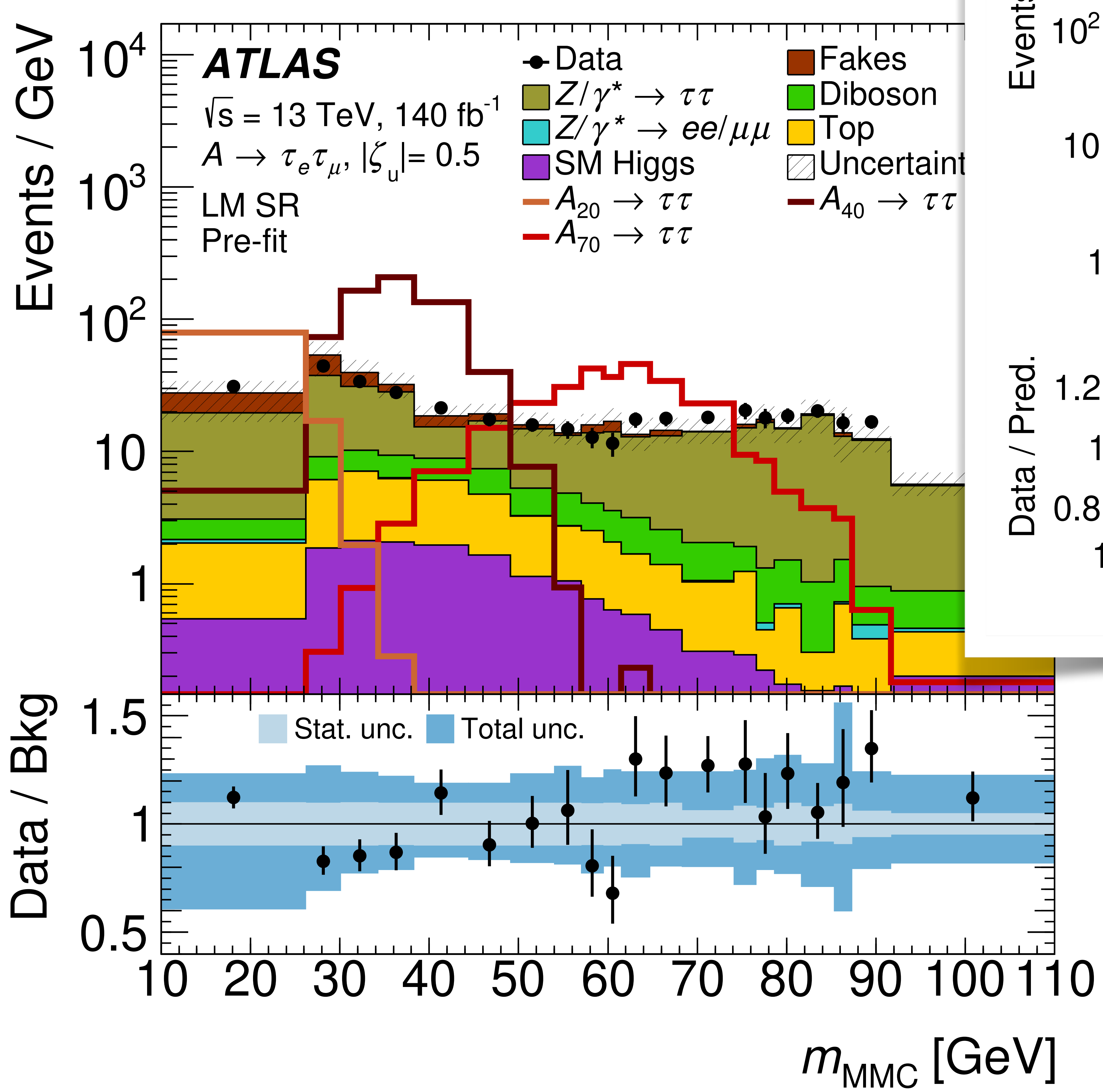


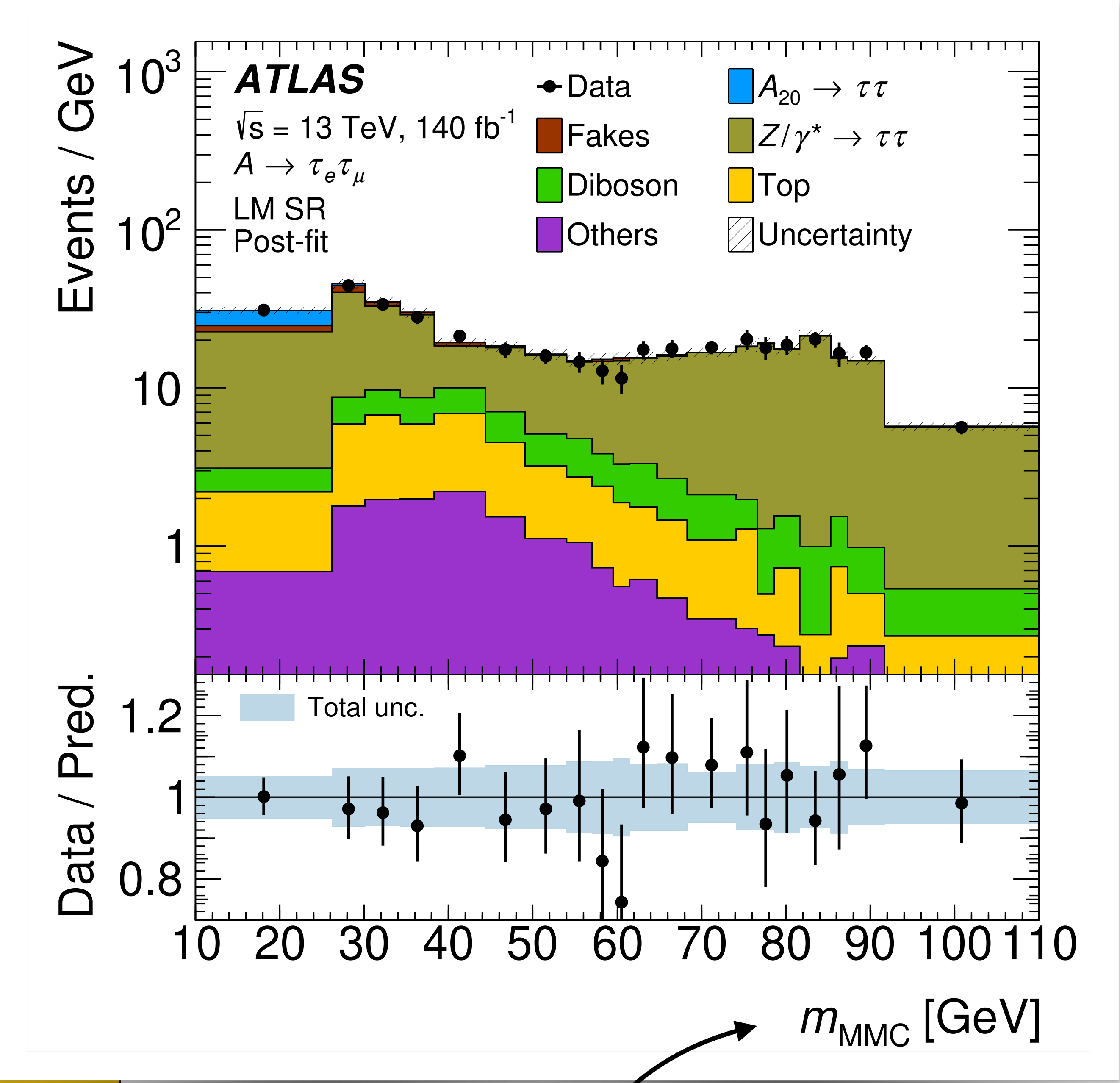
“Non-resonant” signatures are also probed with an alternative method (MC+data driven).

Also see ATLAS HIGG-2018-27 arXiv:2102.13405.

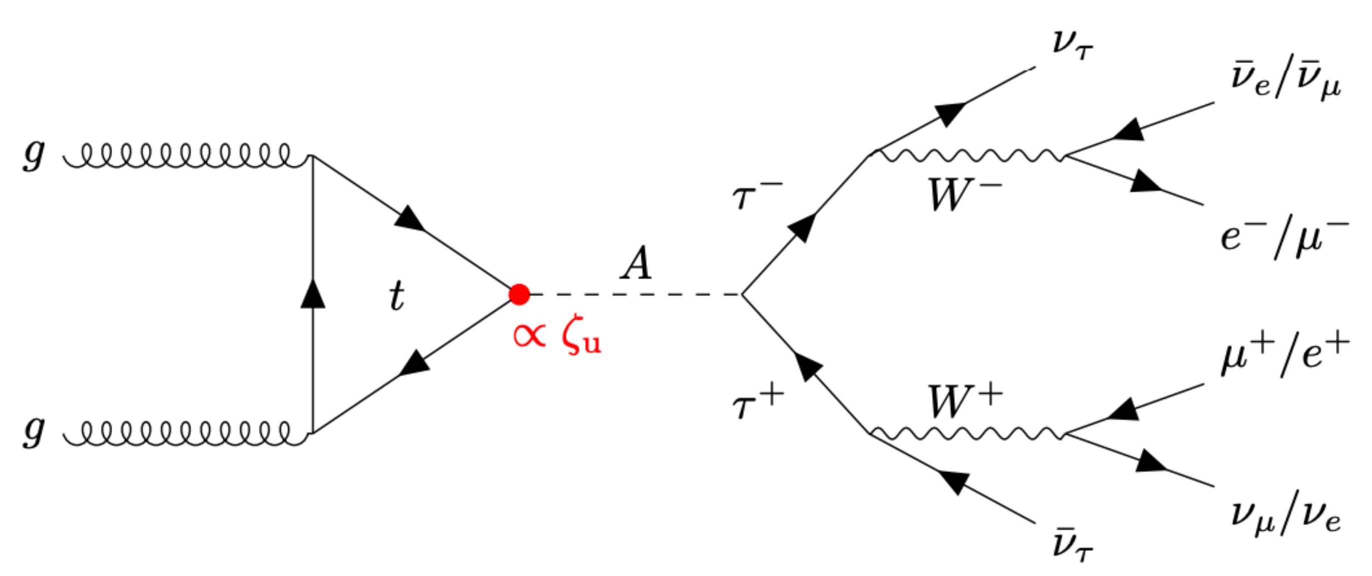
H→ττ (low mass)

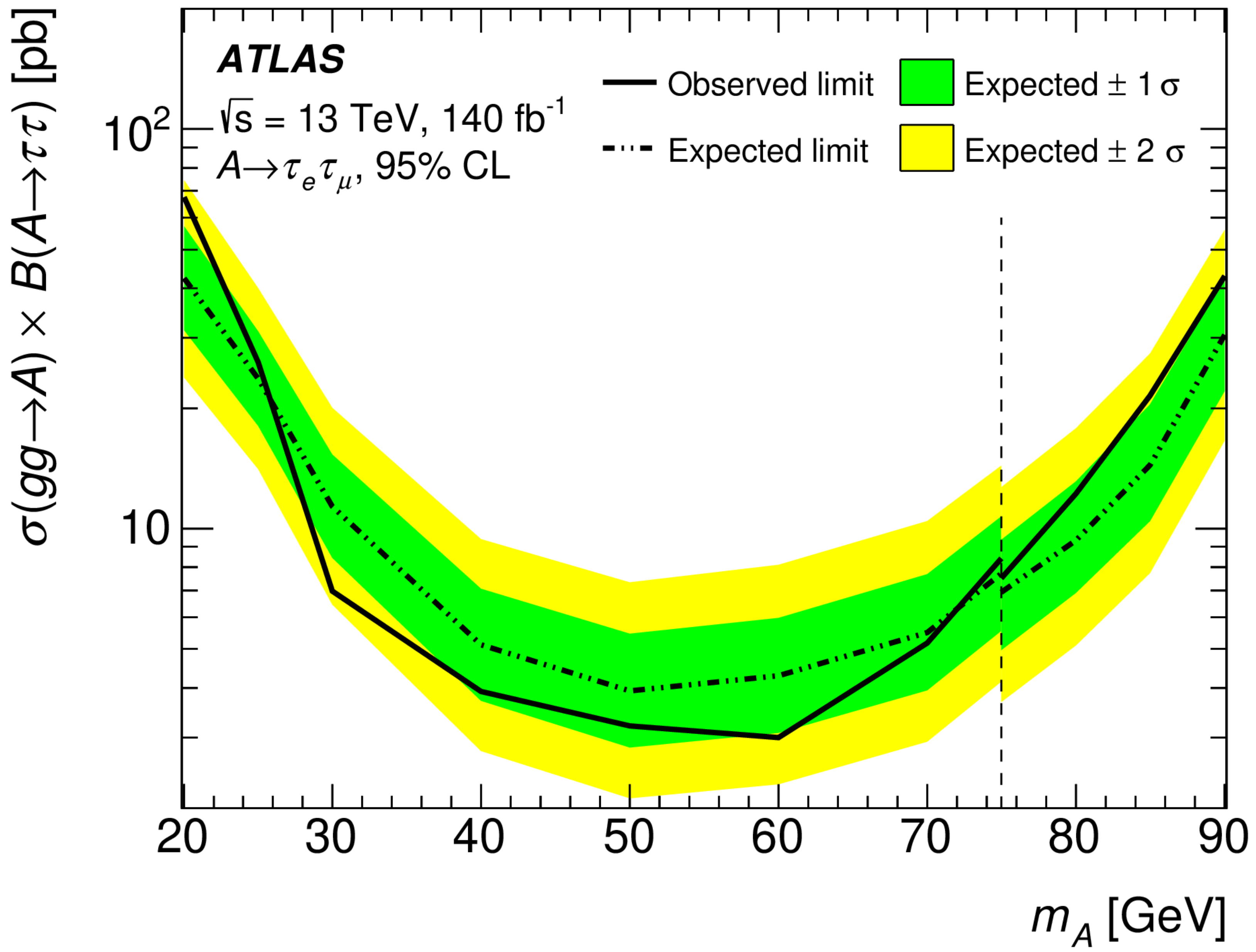
ATLAS HDBS-2021-08
arXiv:2409.20381





Missing Mass Calculator (MMC):
An advanced likelihood-based algorithm to estimate the ττ mass





$\tau\tau \to e\mu$ decays are considered

- *Overcomes **triggering** challenges and **DY/QCD** background*
- ***Data-driven** corrections to the **DY MC (N_{jets})***

First probe of the 20-60 GeV mass range
for this production and decay mode.

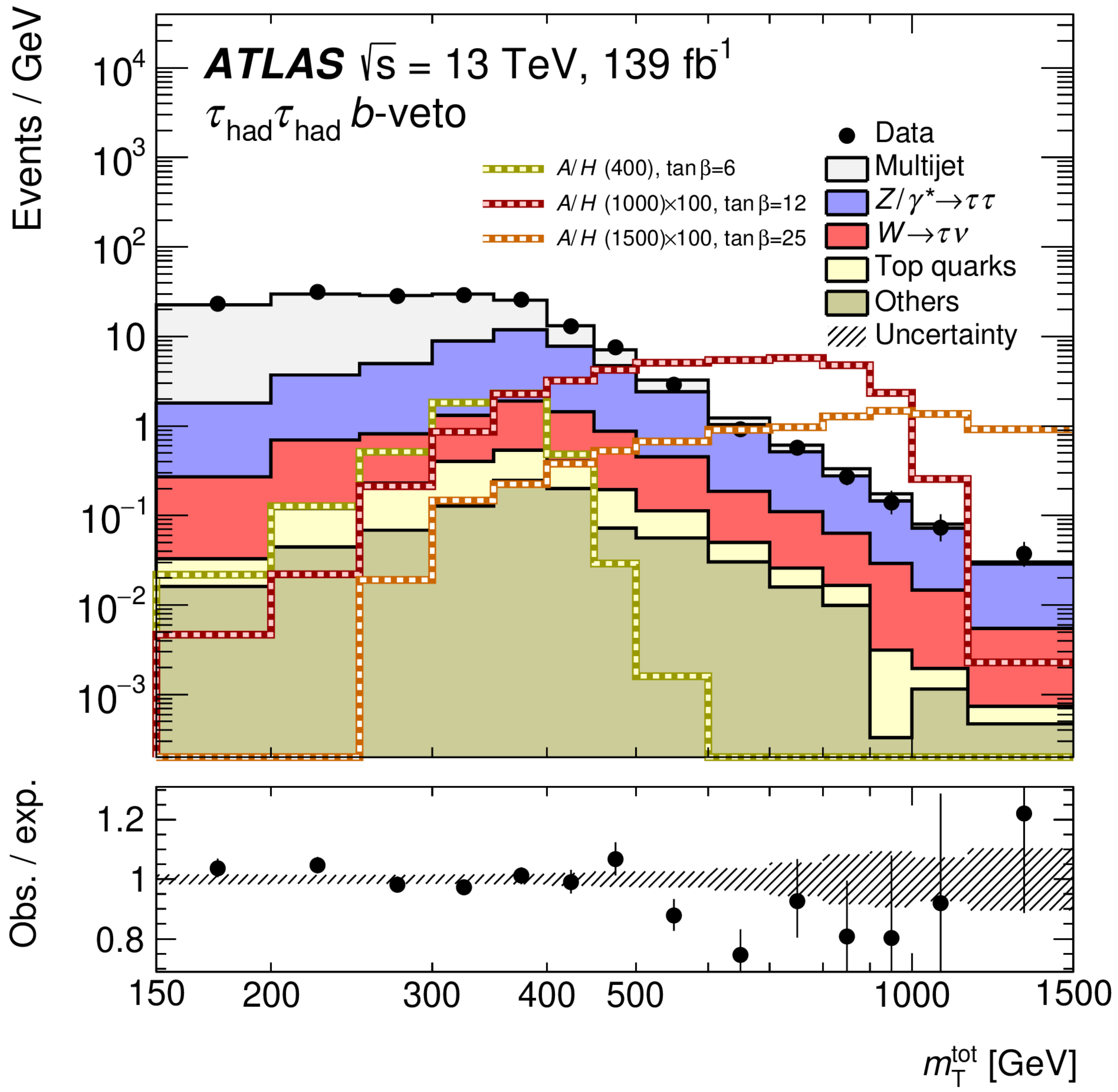
2HDM interpretation is also provided.

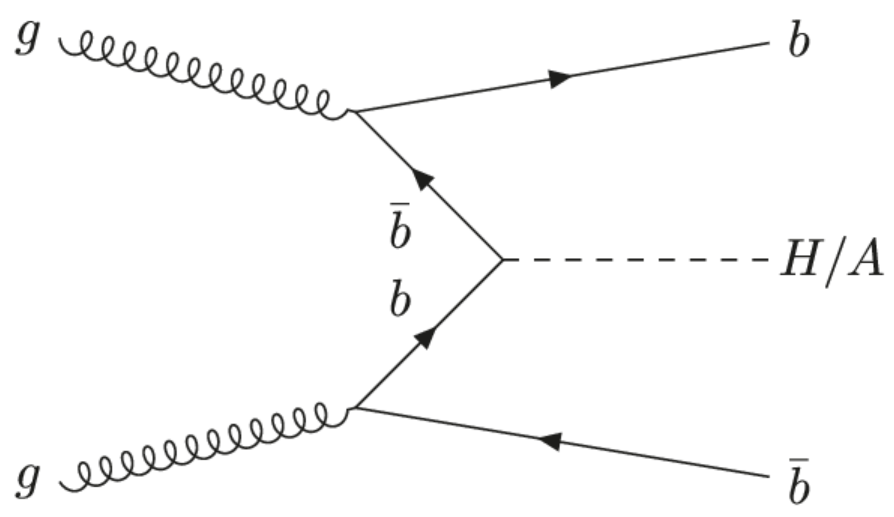
H→ττ (high mass)

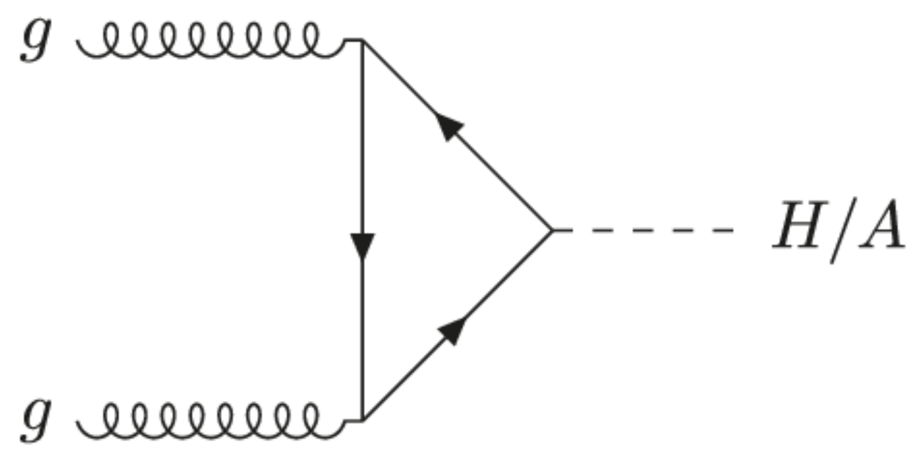
ATLAS HDBS-2018-46

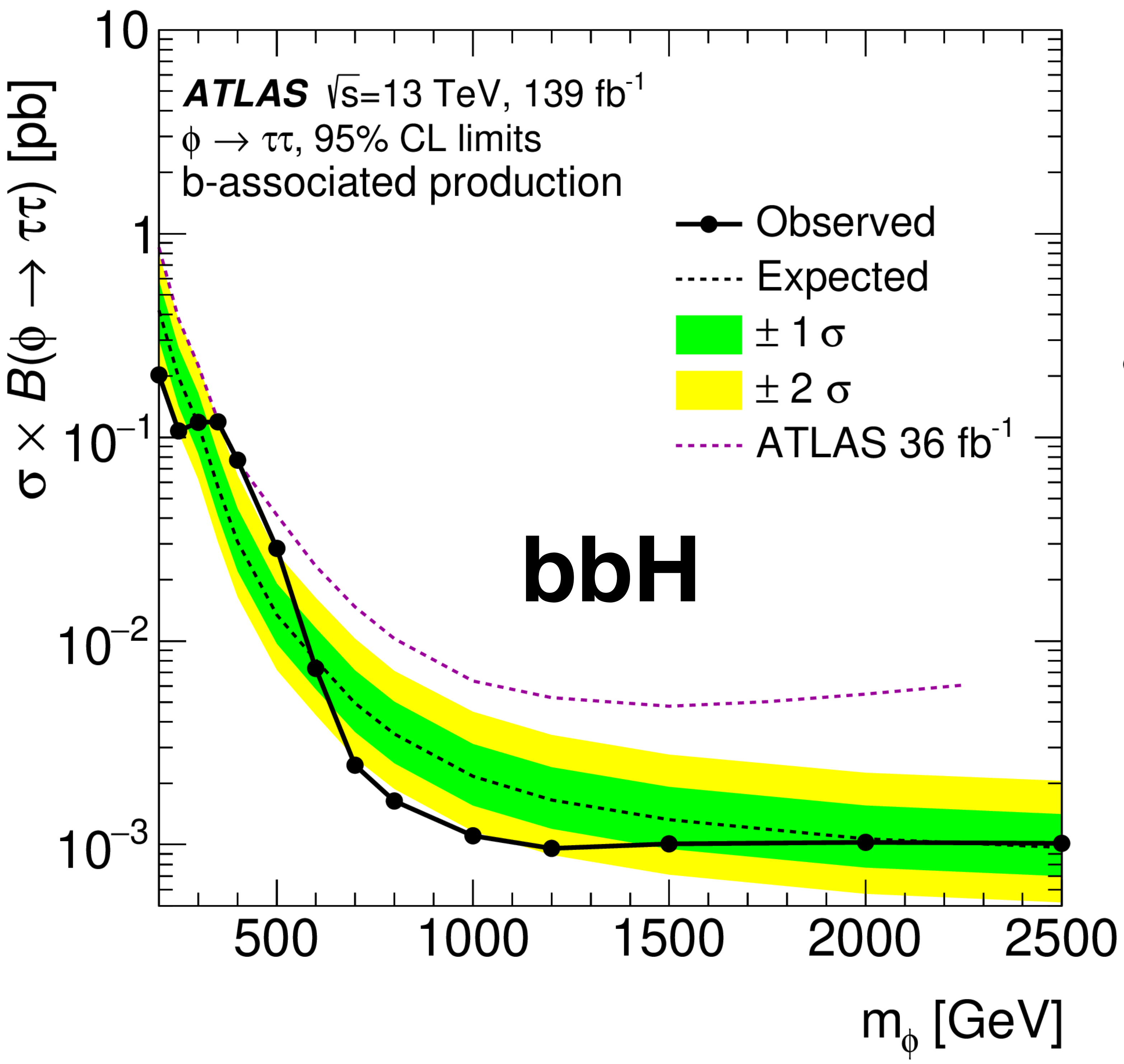
arXiv:2002.12223

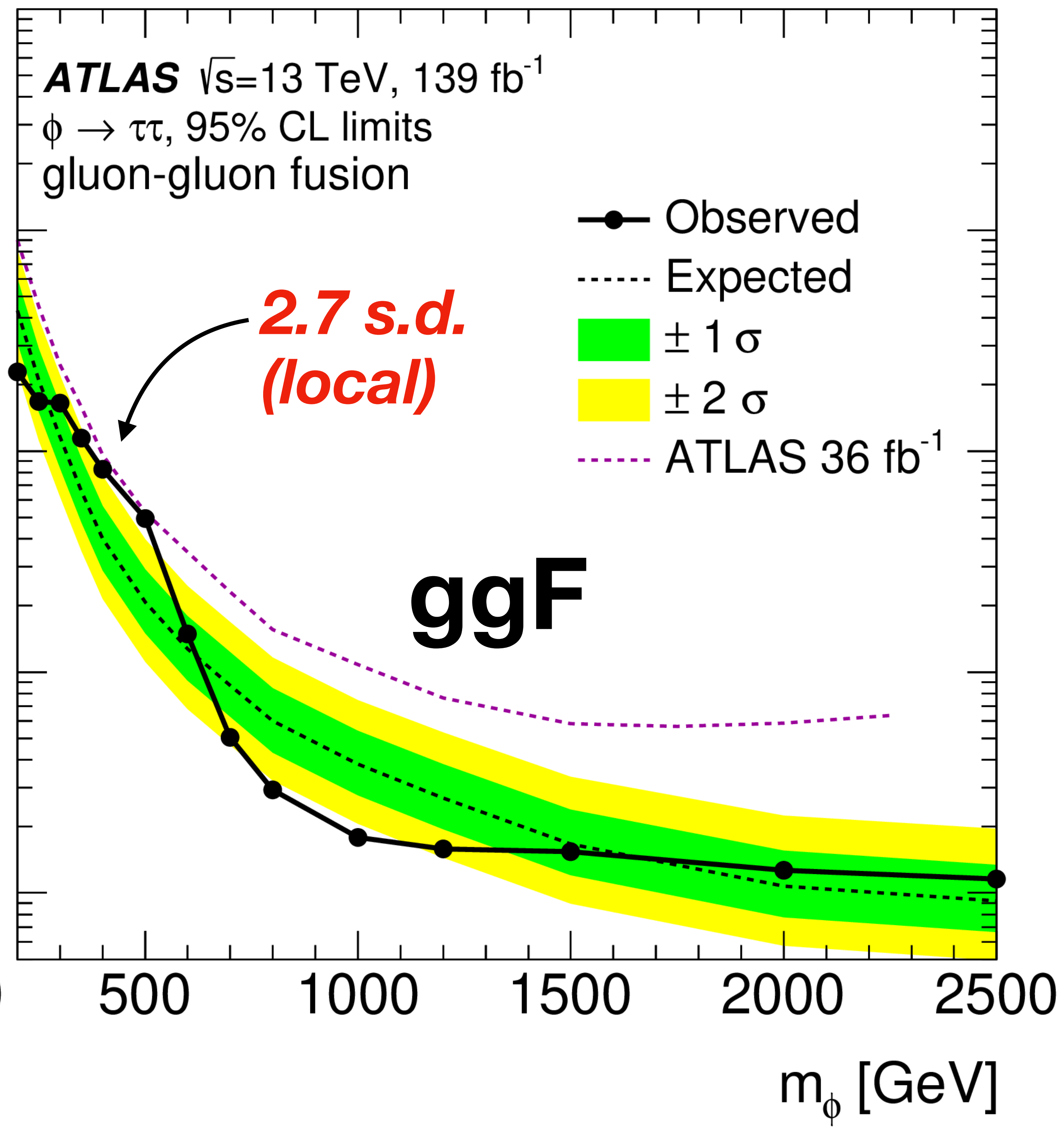
$$m_T^{tot} = \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{miss})^2}$$











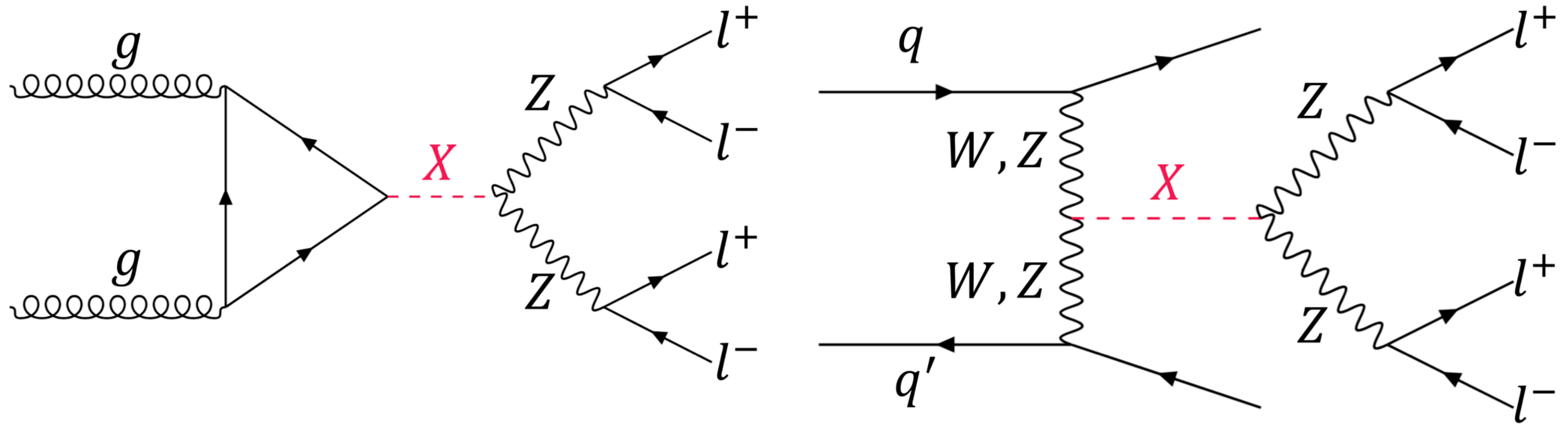
Targets $\tau_h\tau_h$, τ_he, $\tau_h\mu$ signatures with and without b-tags

→ two different production mechanisms: bbH/A vs ggF

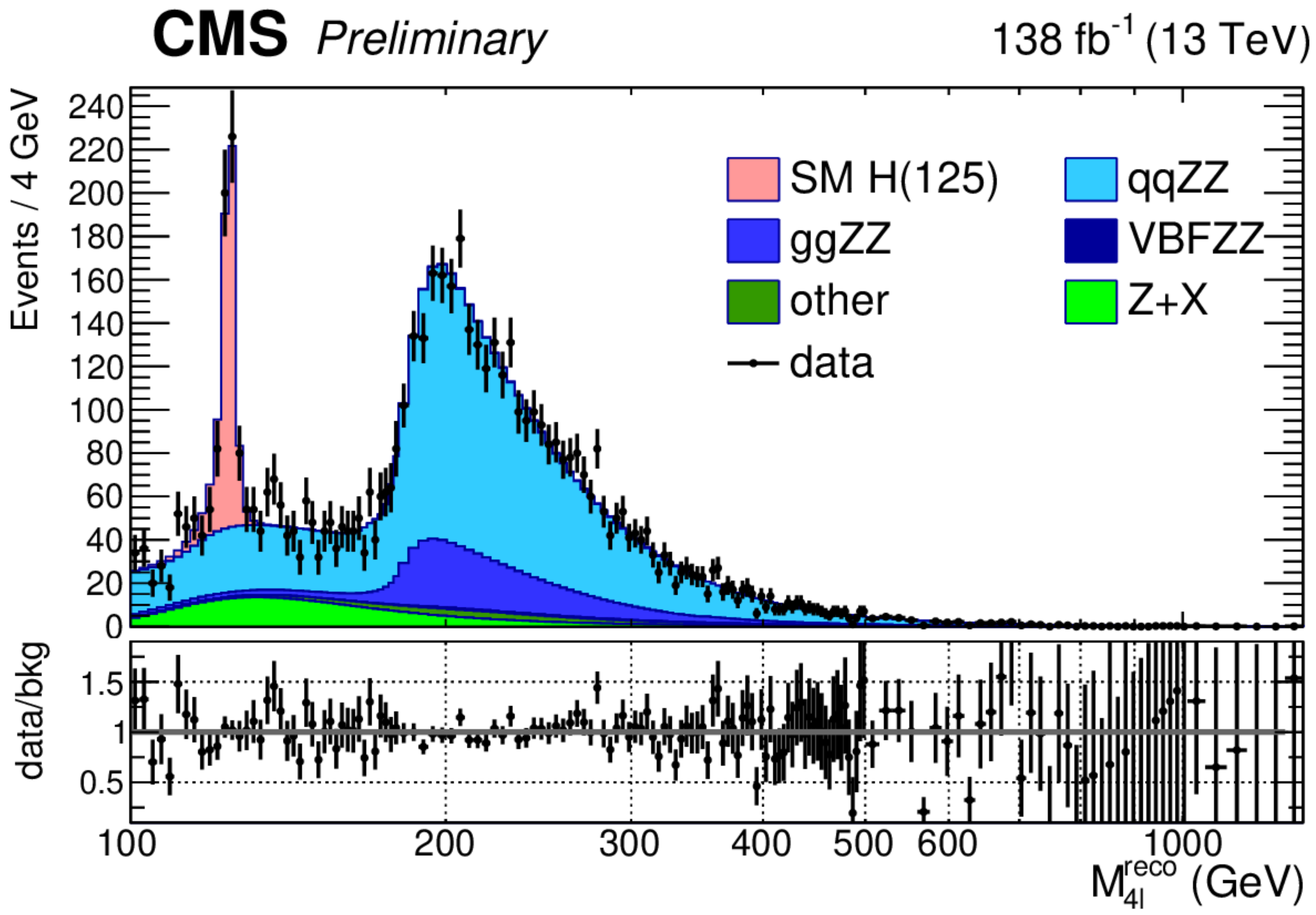
Probes the heavy mass range 0.2-2.5 TeV
2HDM interpretation also provided.

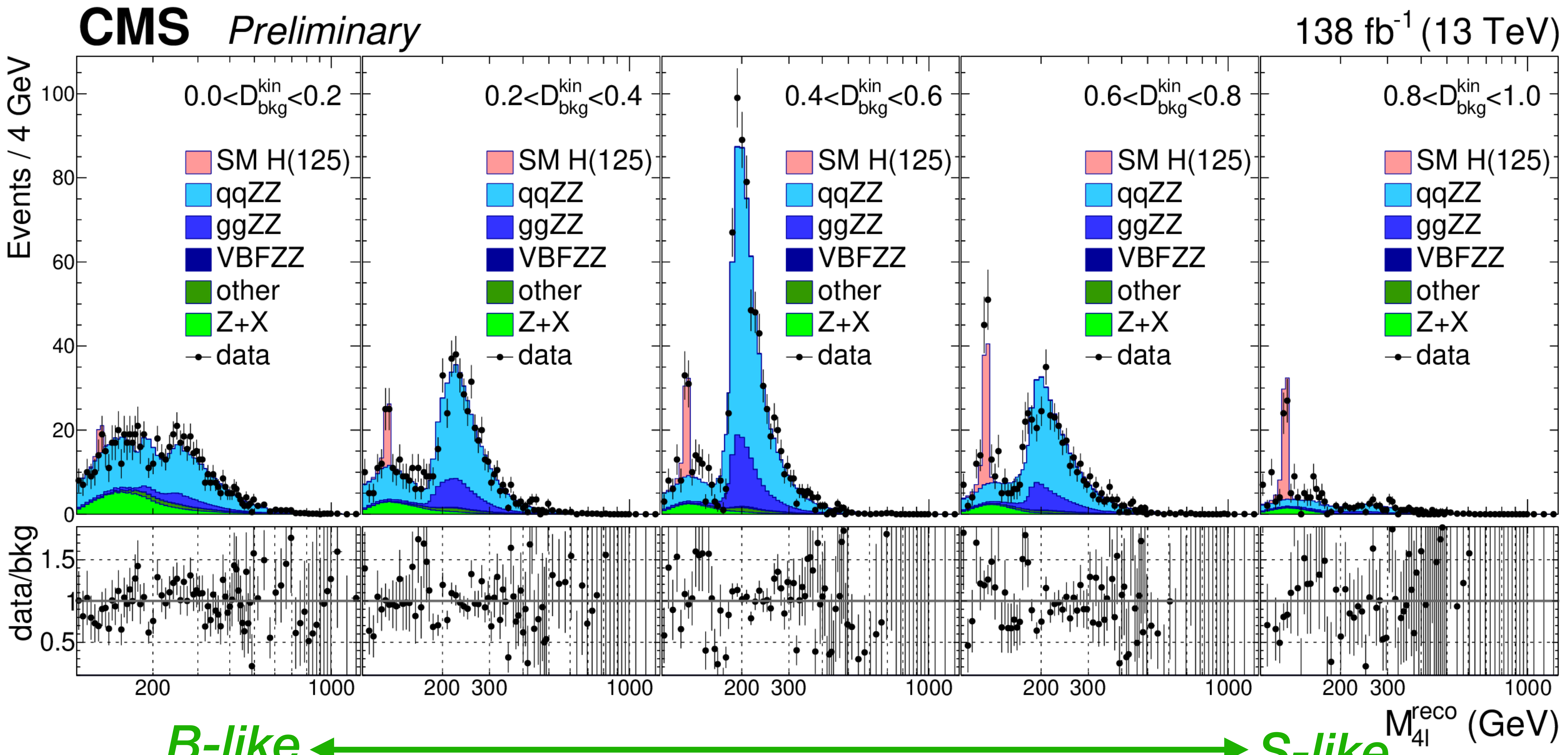
Also see CMS HIG-21-001, arXiv:2208.02717

X→ZZ→ℓℓℓℓ



CMS PAS-HIG-24-002





B-like ⟷ *S-like*

***Golden signature**, with 4 electrons and muons, **ZZ** could be the **dominant decay** at high masses.*

→ muons (electrons) down to 5 (7) GeV in p_T are considered.

*→ **FSR photon recovery** is applied to improve mass resolution of Zs.*

→SM is estimated from MC: Powheg (MCFM) for ggZZ (qqZZ), both reweighted to NNLO.

*A **likelihood ratio based kinematic discriminant** is used to define **categories**.* - - - - - - - - ▸

$$D^{kin}_{bkg} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{bkg}(\overrightarrow{\Omega}^{H\to 4\ell} \,|\, M^{reco}_{4\ell})}{\mathcal{P}^{gg}_{sig}(\overrightarrow{\Omega}^{H\to 4\ell} \,|\, M^{reco}_{4\ell})} \right]^{-1}$$

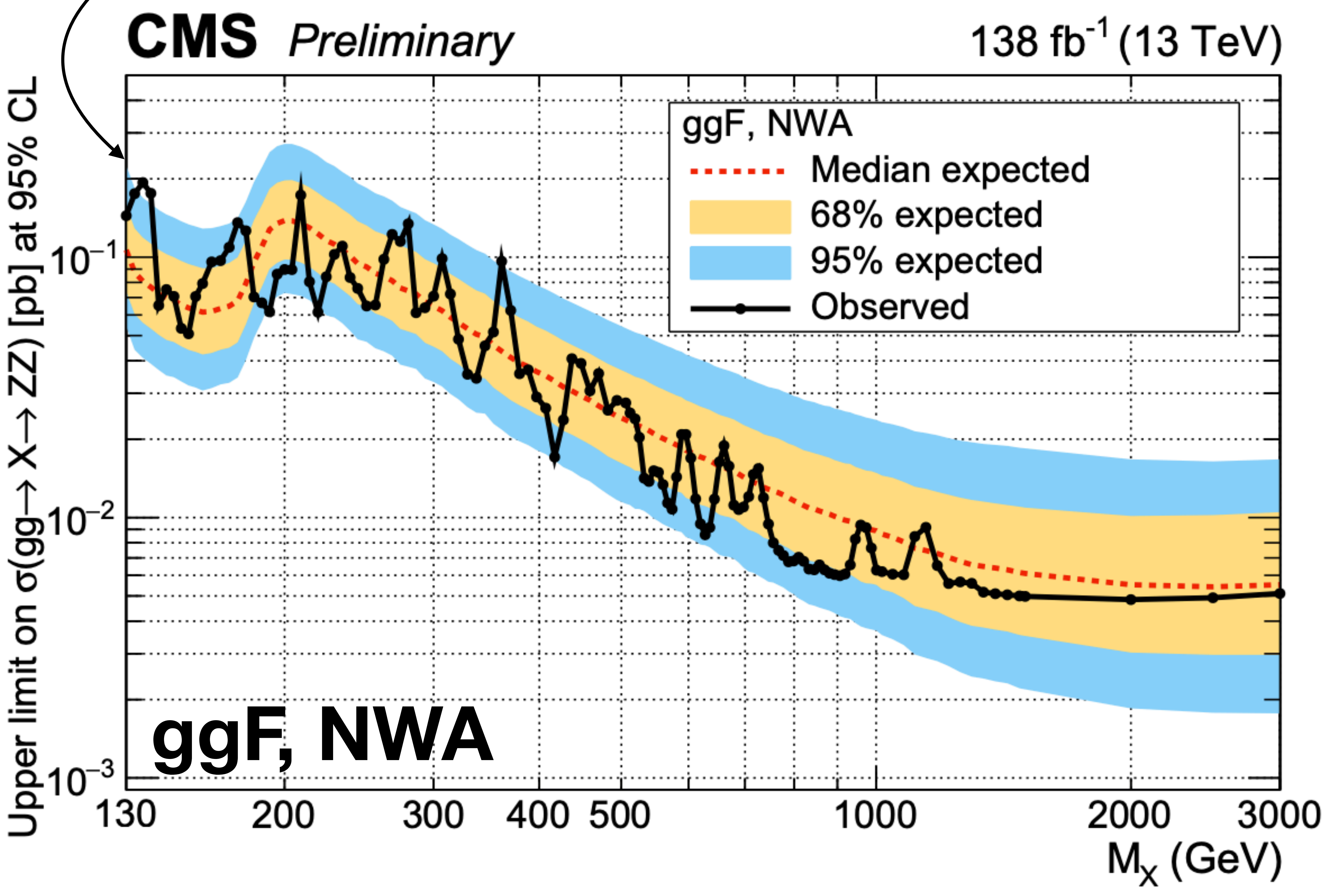
→ both against qqZZ contribution, and for VBF signal with additional jets.

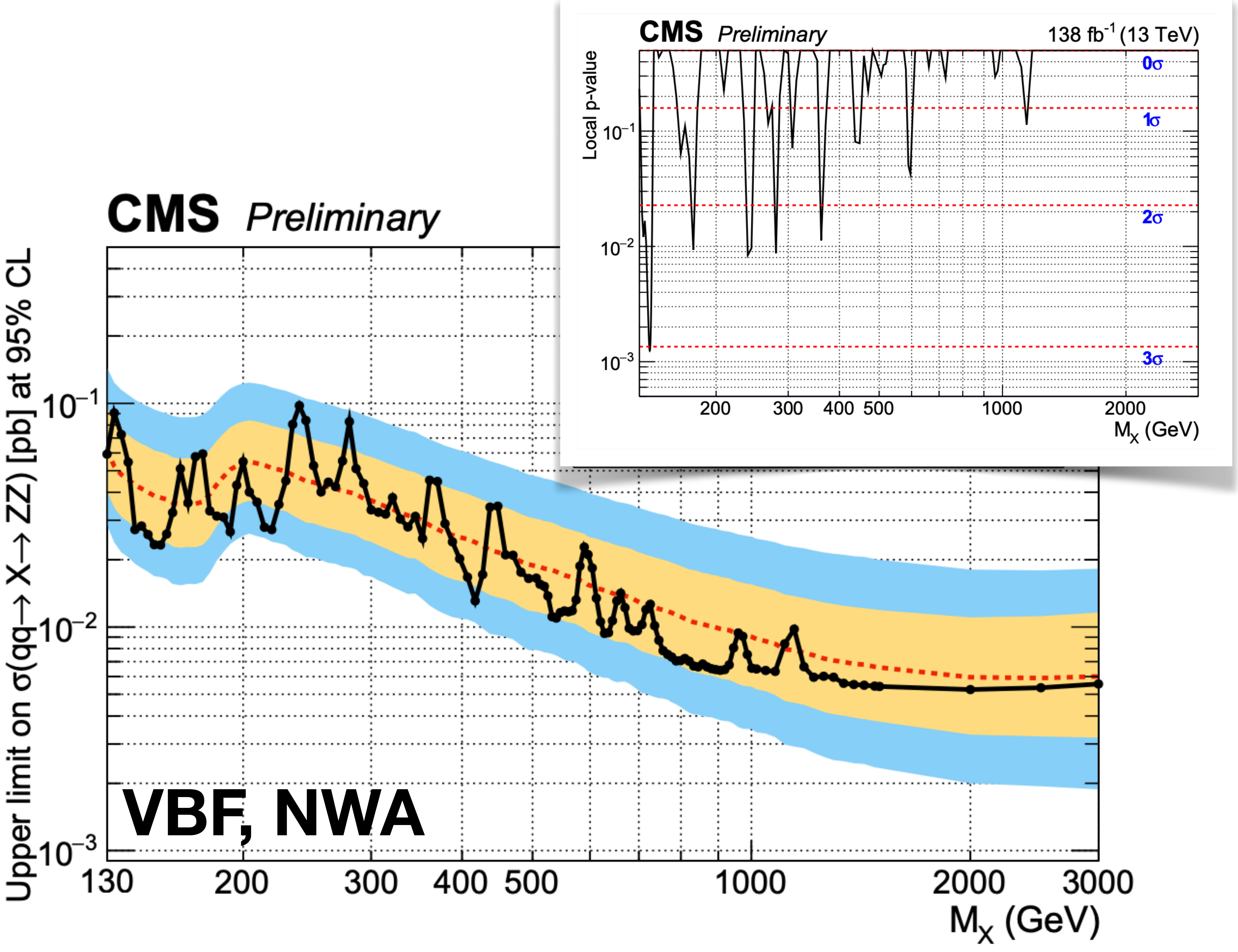
X→ZZ→ℓℓℓℓ

CMS PAS-HIG-24-002

~3 s.d. local, <2 s.d. global at ~138 GeV

No particular excess at ~680 GeV

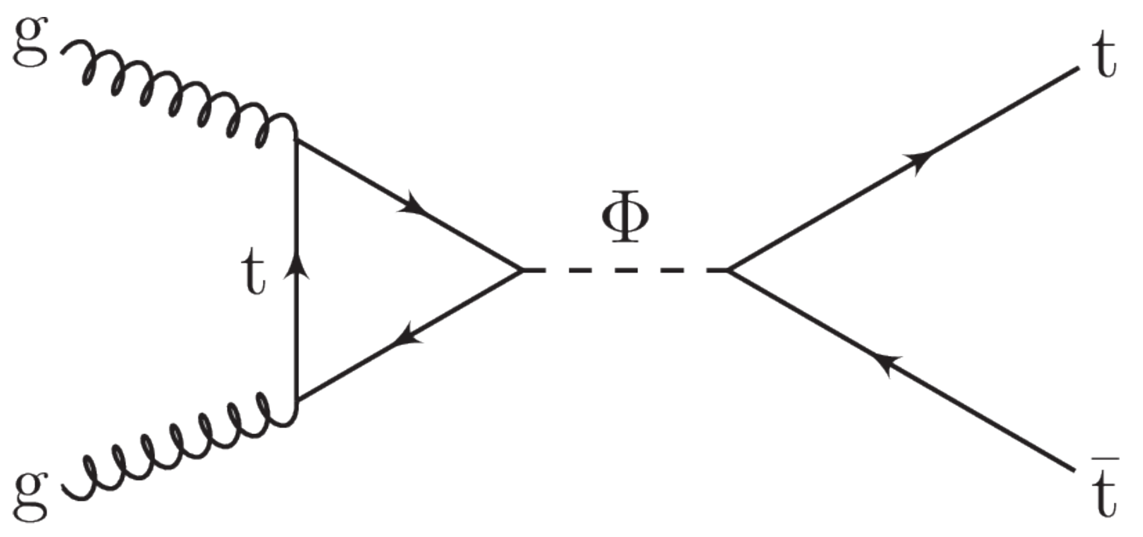




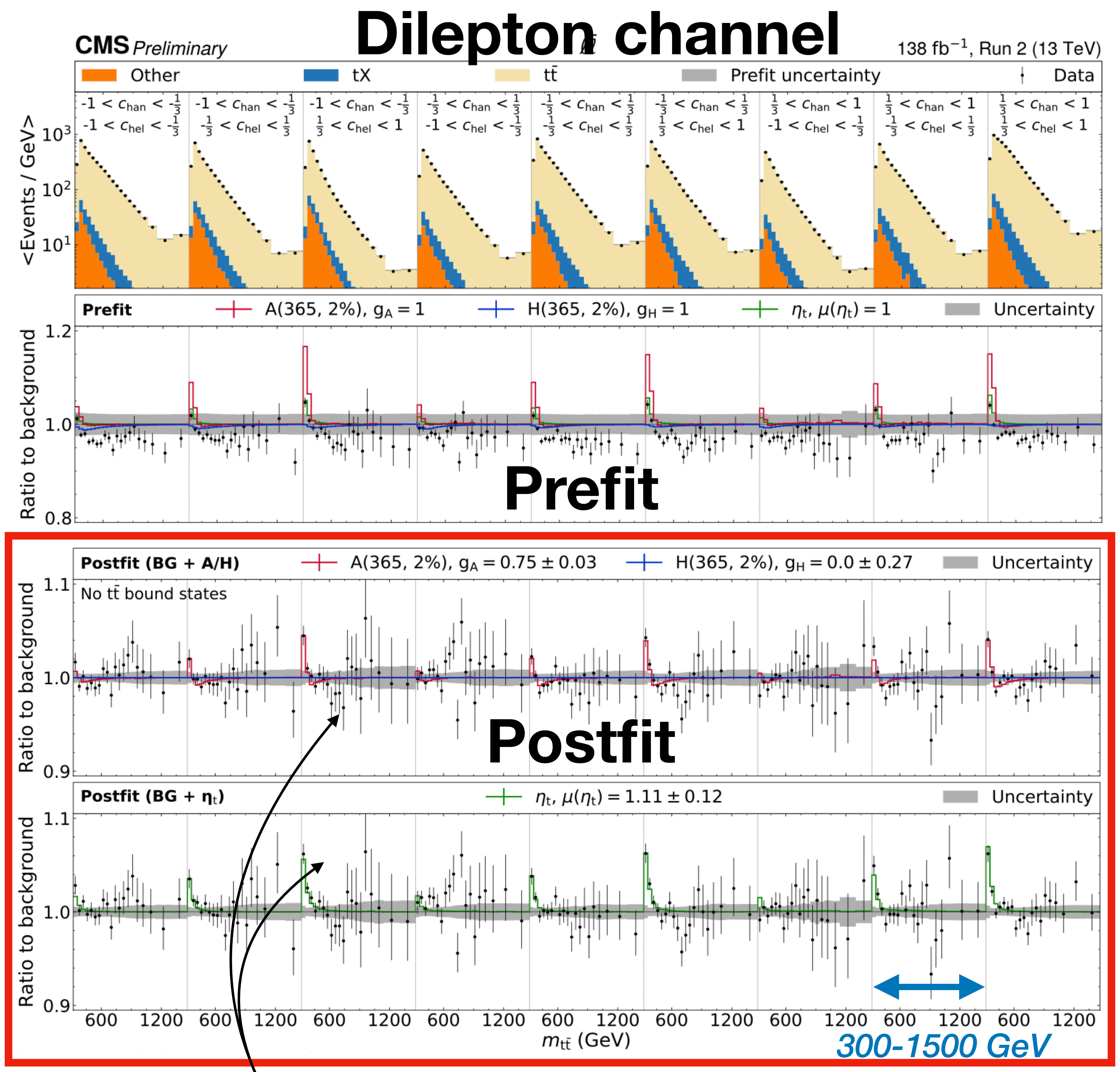
Finite widths including interference of signal with backgrounds are also considered.

Also see ATLAS HIGG-2018-09, arXiv:2009.14791

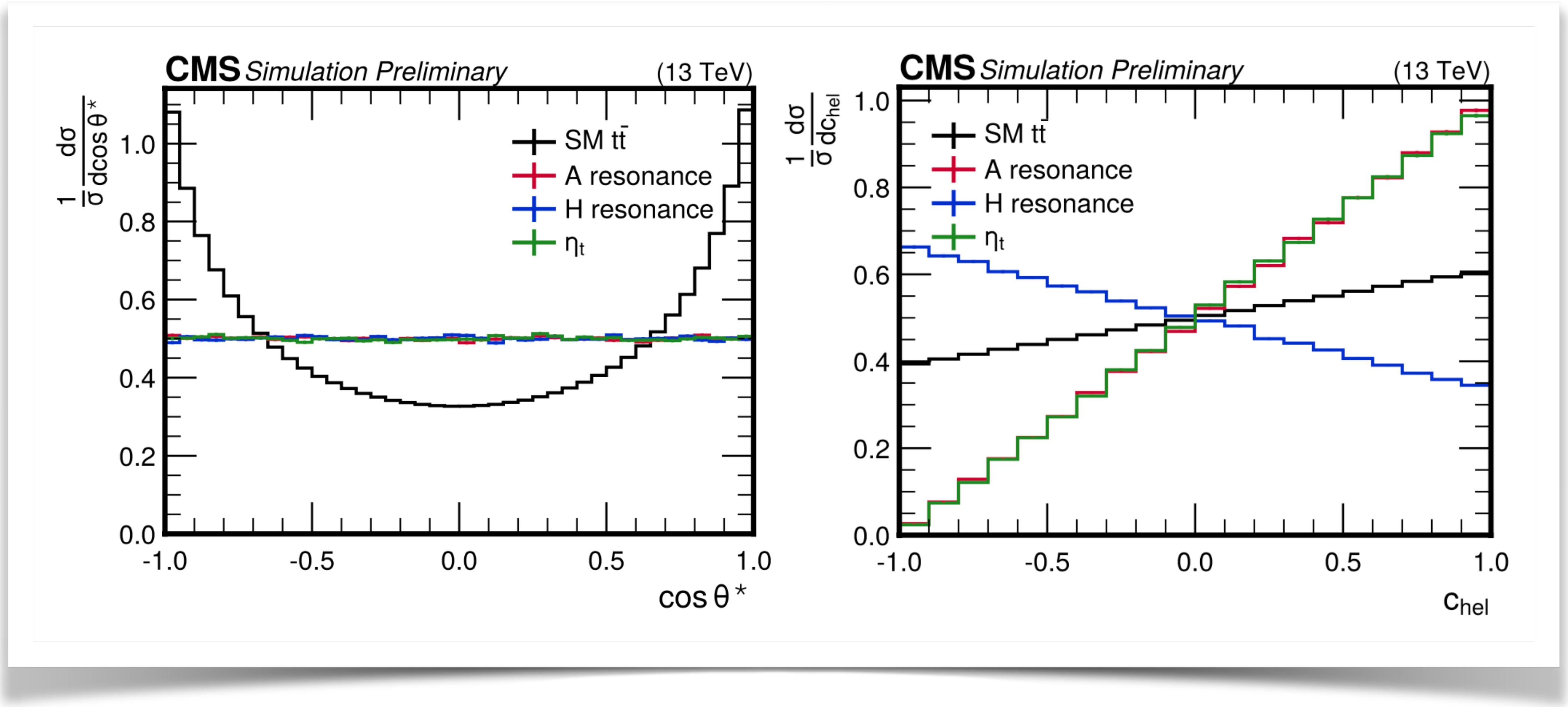
Di-top resonance: H/A→tt



CMS PAS-HIG-22-013



The combined "excess" is over 5 s.d.



*Considers **1(2)L channels**, via a 3D (2D) fit (**mass vs angular variables**).*

***Model-agnostic approach**:*

→ mass, CP parity, width are free parameters.

tt MC is corrected to NNLO QCD and NLO EWK precision.

*→ signal **interference** with SM $t\bar{t}$ production is considered, i.e. peak/dip.*

*At threshold, **non-perturbative QCD effects** become relevant:*

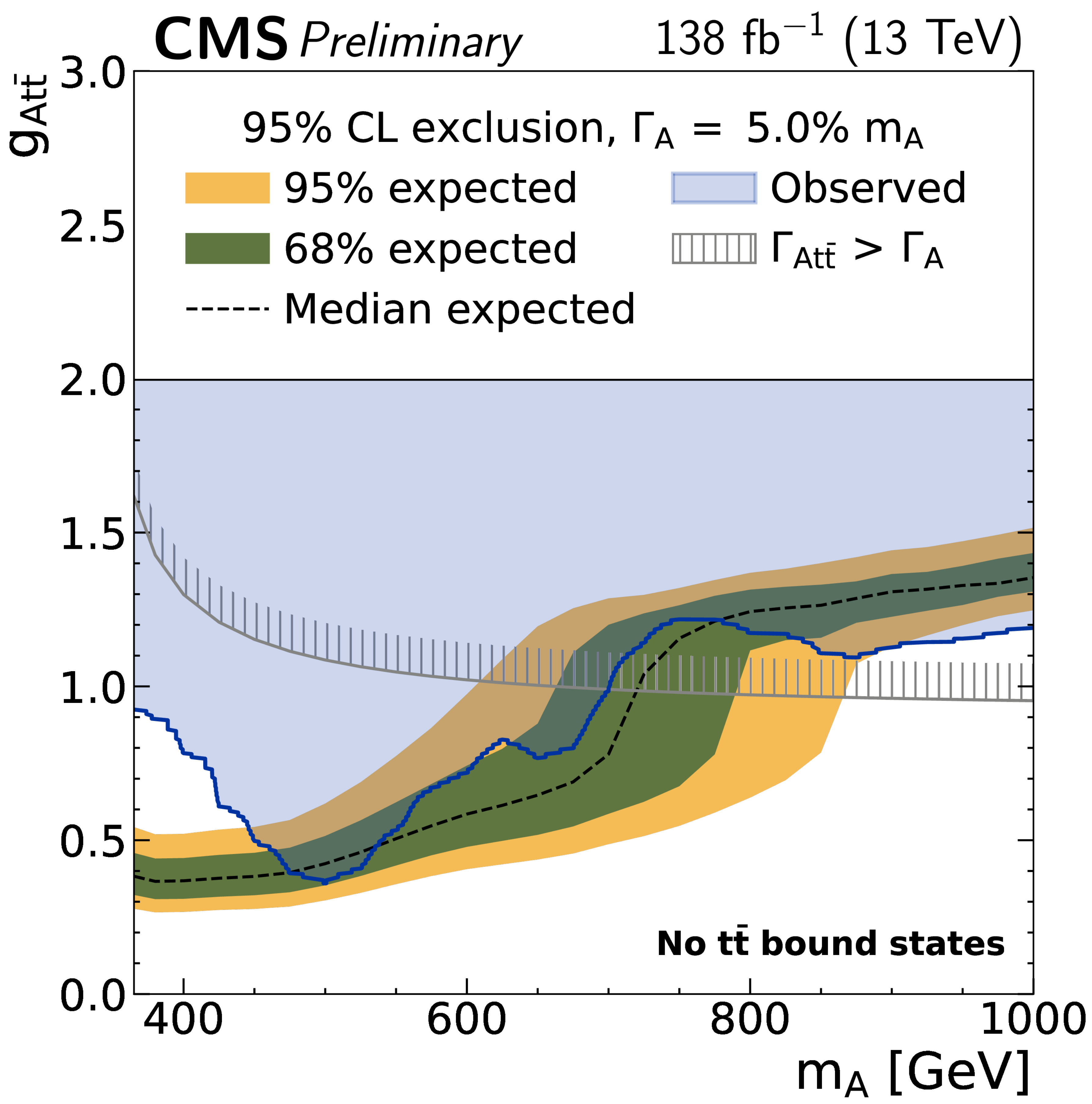
*→ **$t\bar{t}$ bound state η_t as a PS resonance:** $m = 343$ GeV, $\sigma = 6.43$ pb*

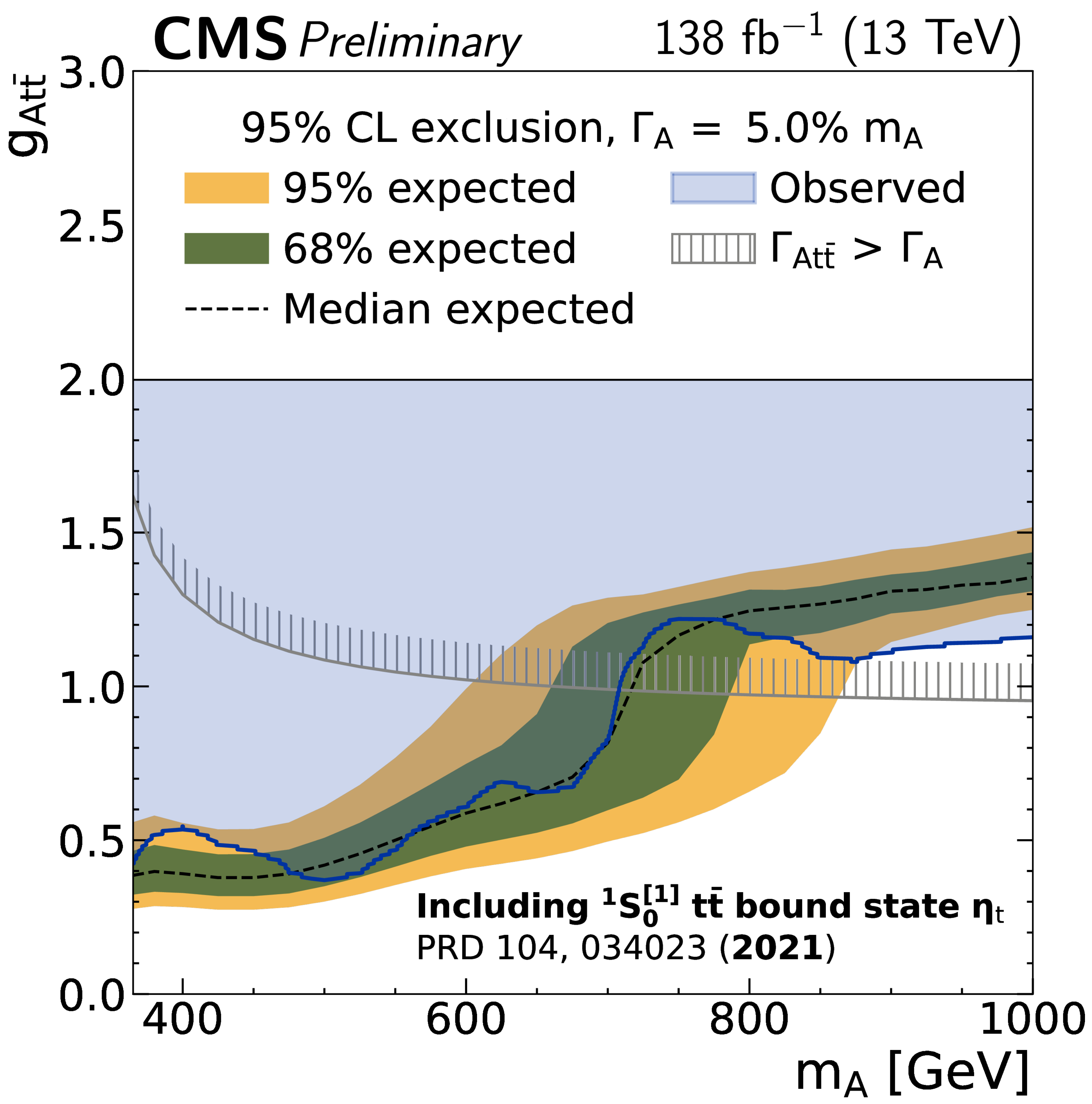
(Fuks, Hagiwara, Ma, Zheng arXiv: 2102.11281)

*Difficult to disentangle **a bound state from a fundamental pseudoscalar**!*

Di-top resonance: H/A→tt

CMS PAS-HIG-22-013





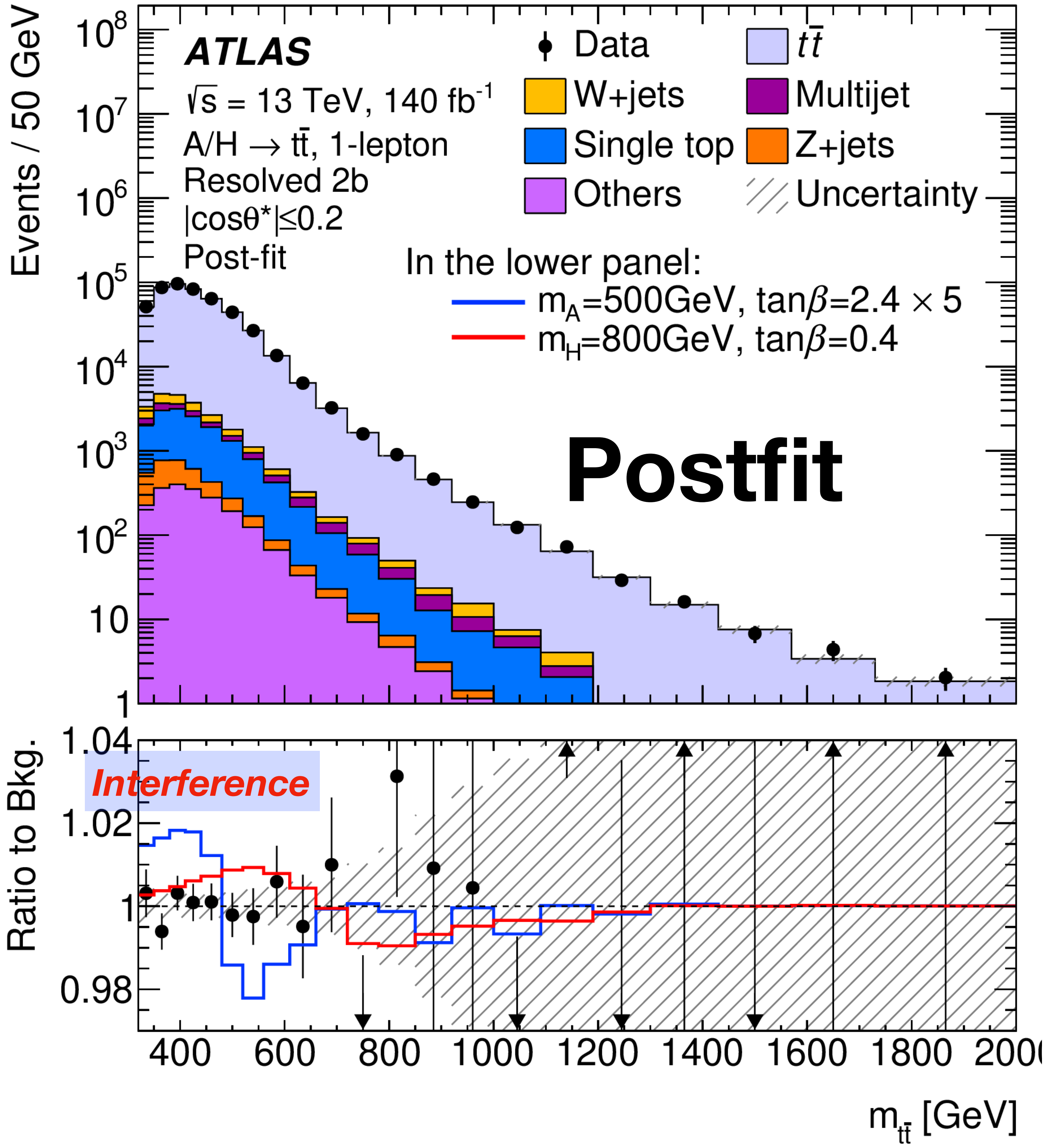
Data is consistent with SM expectations once/if the potential bound state is taken into account
(with unconstrained normalization).

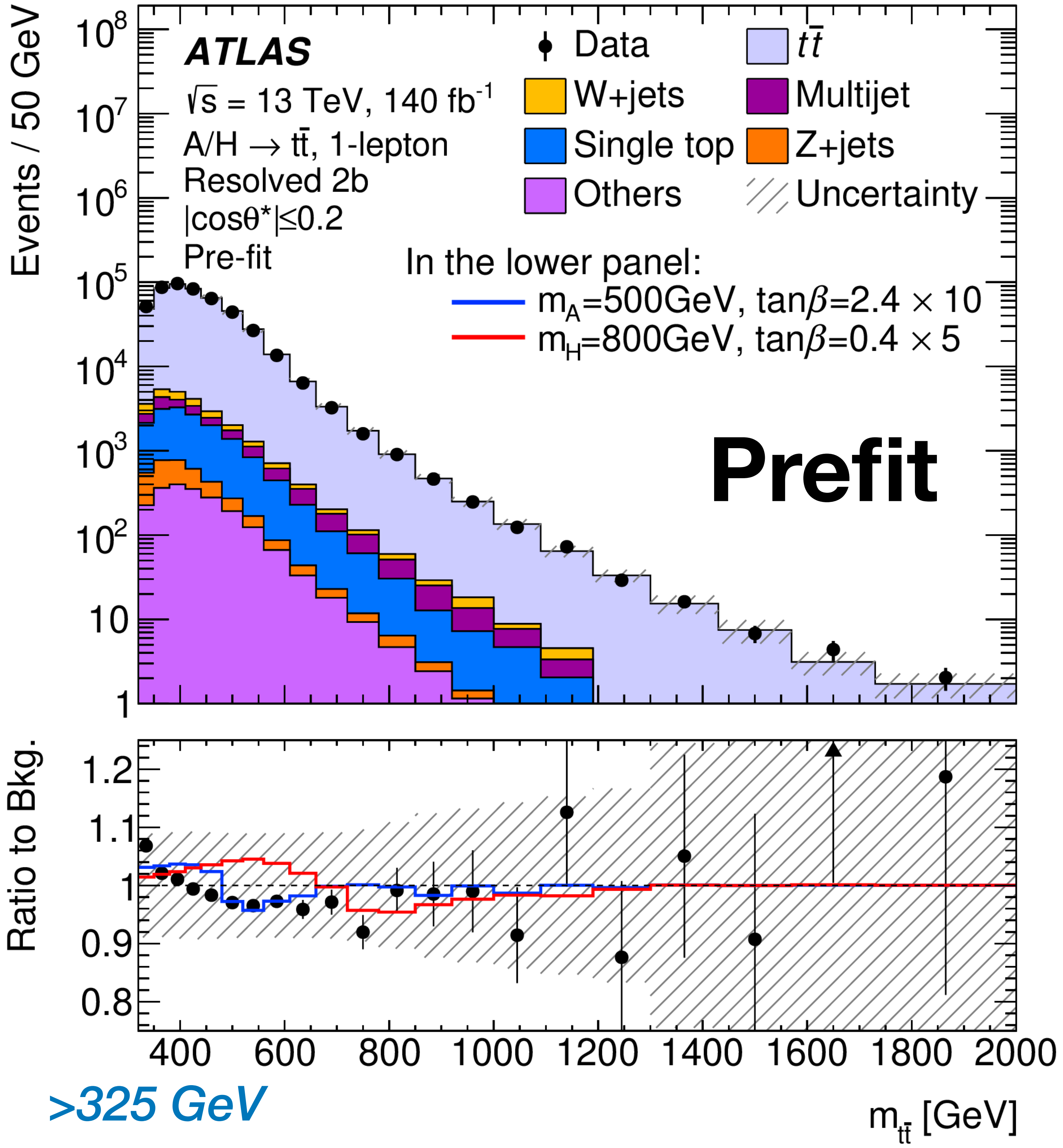
PS and S scenarios are probed: separately as well as simultaneously (a la 2HDM).

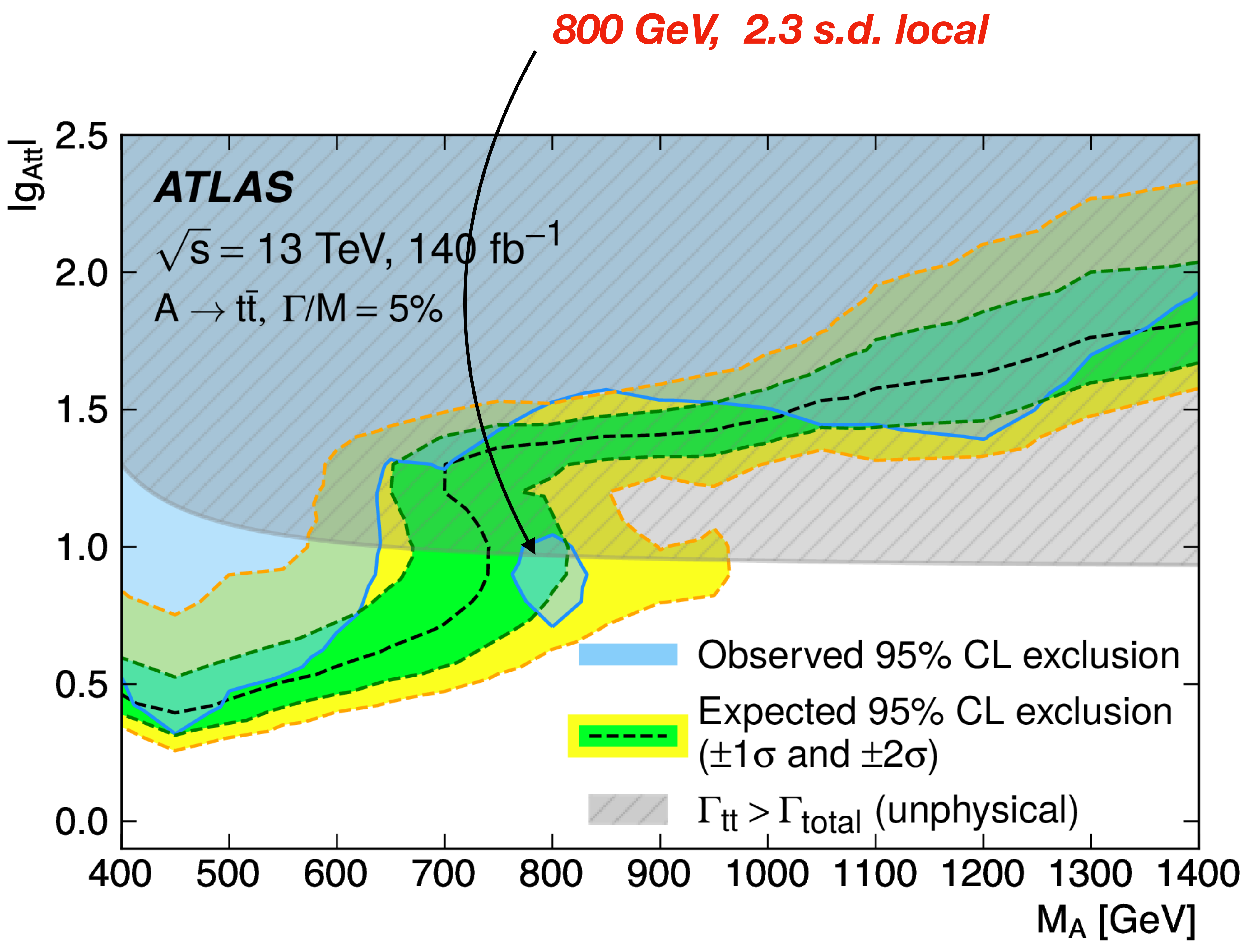
Di-top resonance: H/A→tt

ATLAS EXOT-2020-25

arXiv:2404.18986







The uncertainty due to the presence of a hypothetical $t\bar{t}$ bound state ("toponium"), which is not included in the MC simulation of the SM $t\bar{t}$ background, is expected to be negligible in this analysis as its effect is limited to the narrow kinematic region with $m_{t\bar{t}} < 350$ GeV [145]. This region does not contribute significantly to the sensitivity of the search, even for the smallest tested value of $m_{A/H} = 400$ GeV.

A previous, recent result ***by ATLAS does not see an excess.***

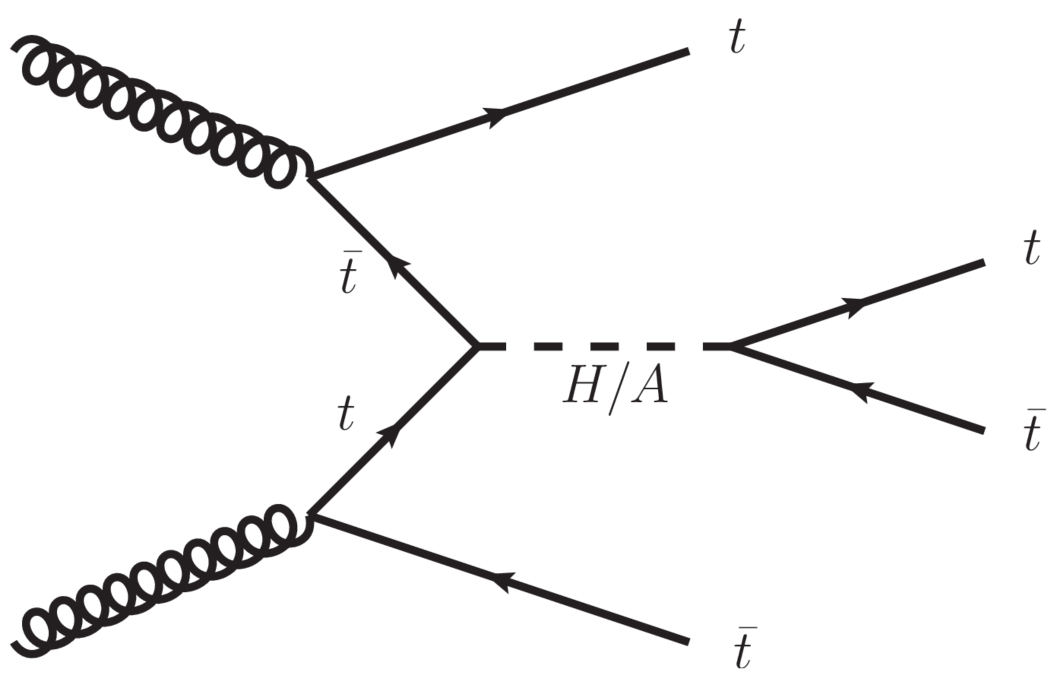
→analysis is not directly targeting the "η_t" region

This analysis also targets 1/2L channels, angular variables.

→ Also has a dedicated merged, 1 lepton category

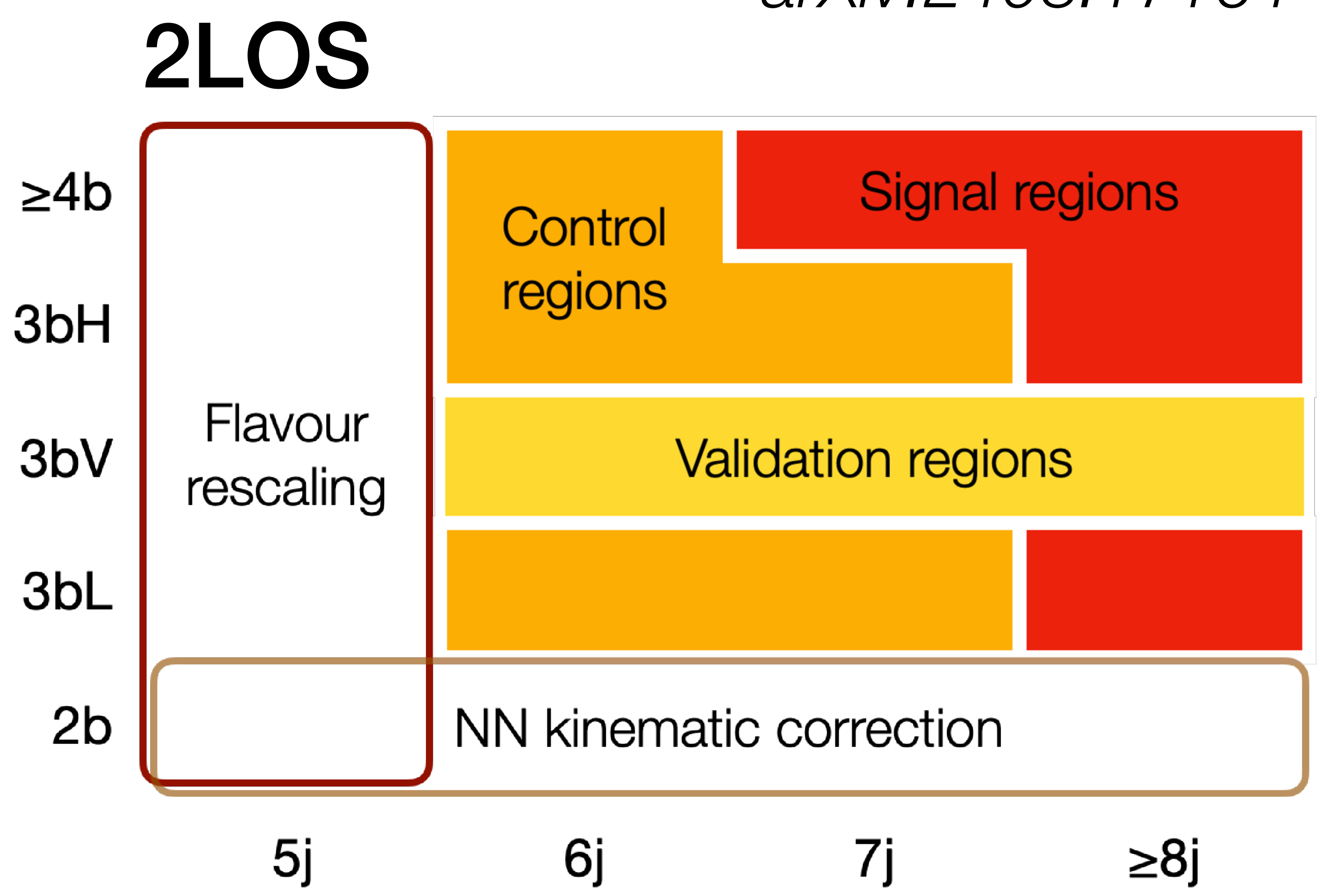
Associated production

ttH/A→tttt



ATLAS EXOT-2022-13
arXiv:2408.17164

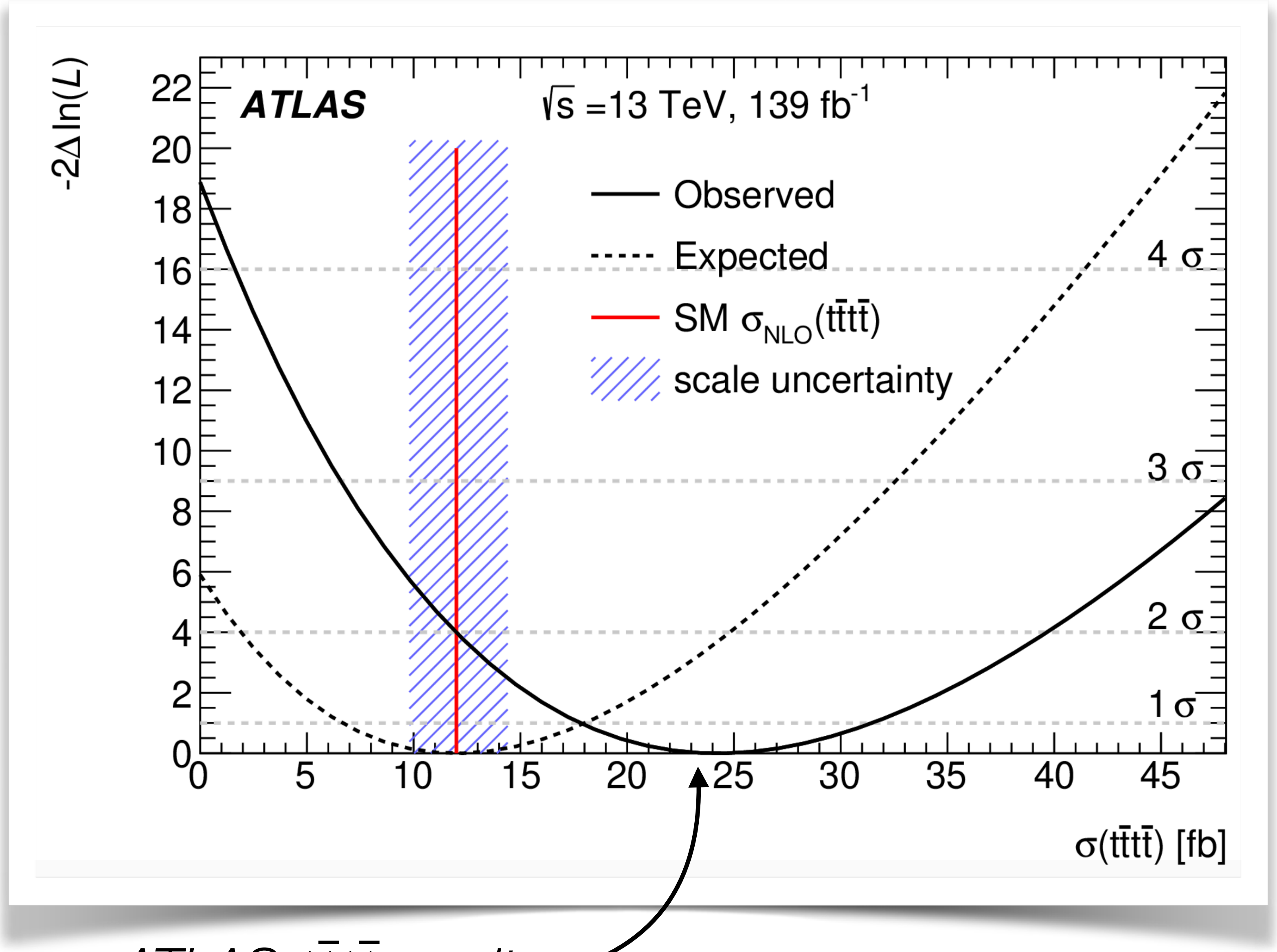
Against the recently observed $t\bar{t}t\bar{t}$ ***SM background****.*
→Both CMS and ATLAS observed a *mild excess.*



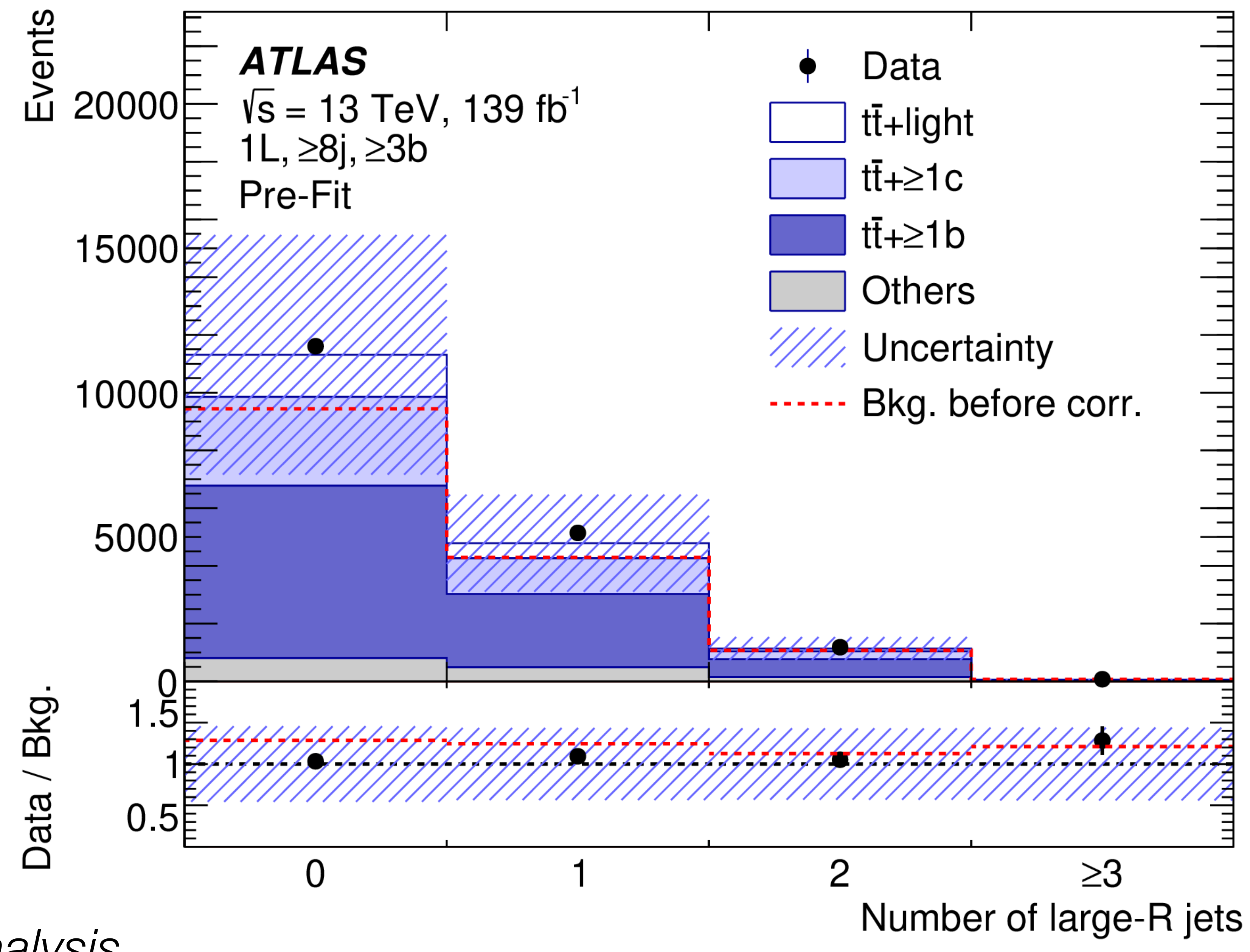
1L, 2LOS final states *are considered here, and they are combined with 2LSS, 3L, 4L results (arXiv:2211.01136).*

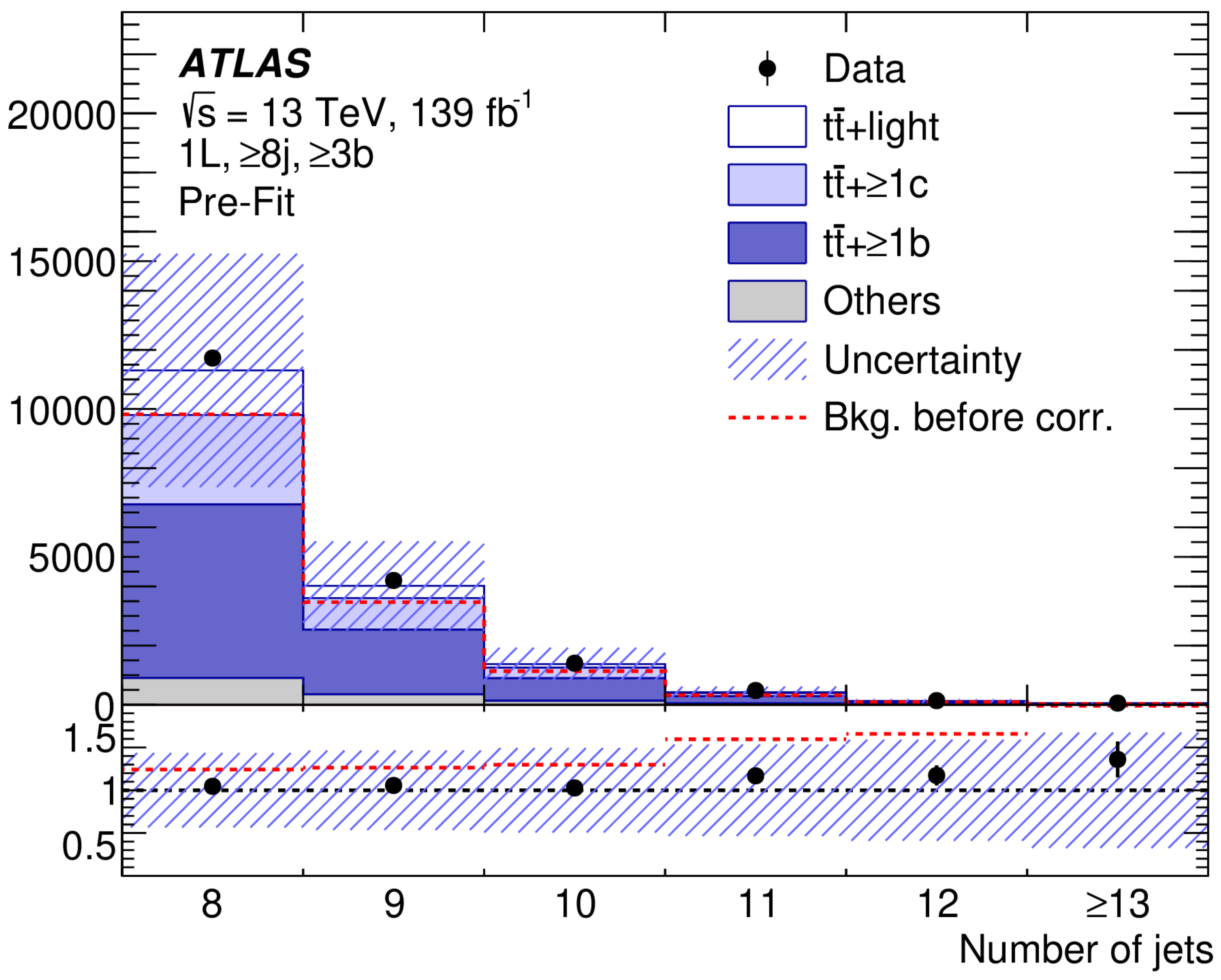
Interference effects with SM are smaller *w.r.t. direct production.*
→ $\mathcal{O}(1)$% in the phase space of interest.

Data-driven *corrections to $t\bar{t}$ MC at high* $\boldsymbol{N_{jet}}$ ***and/or high*** $\boldsymbol{p_T}$***, and for*** $\boldsymbol{t\bar{t}}$***+HF***



ATLAS $t\bar{t}t\bar{t}$ result
The cross-section is set to the SM value in the BSM analysis.

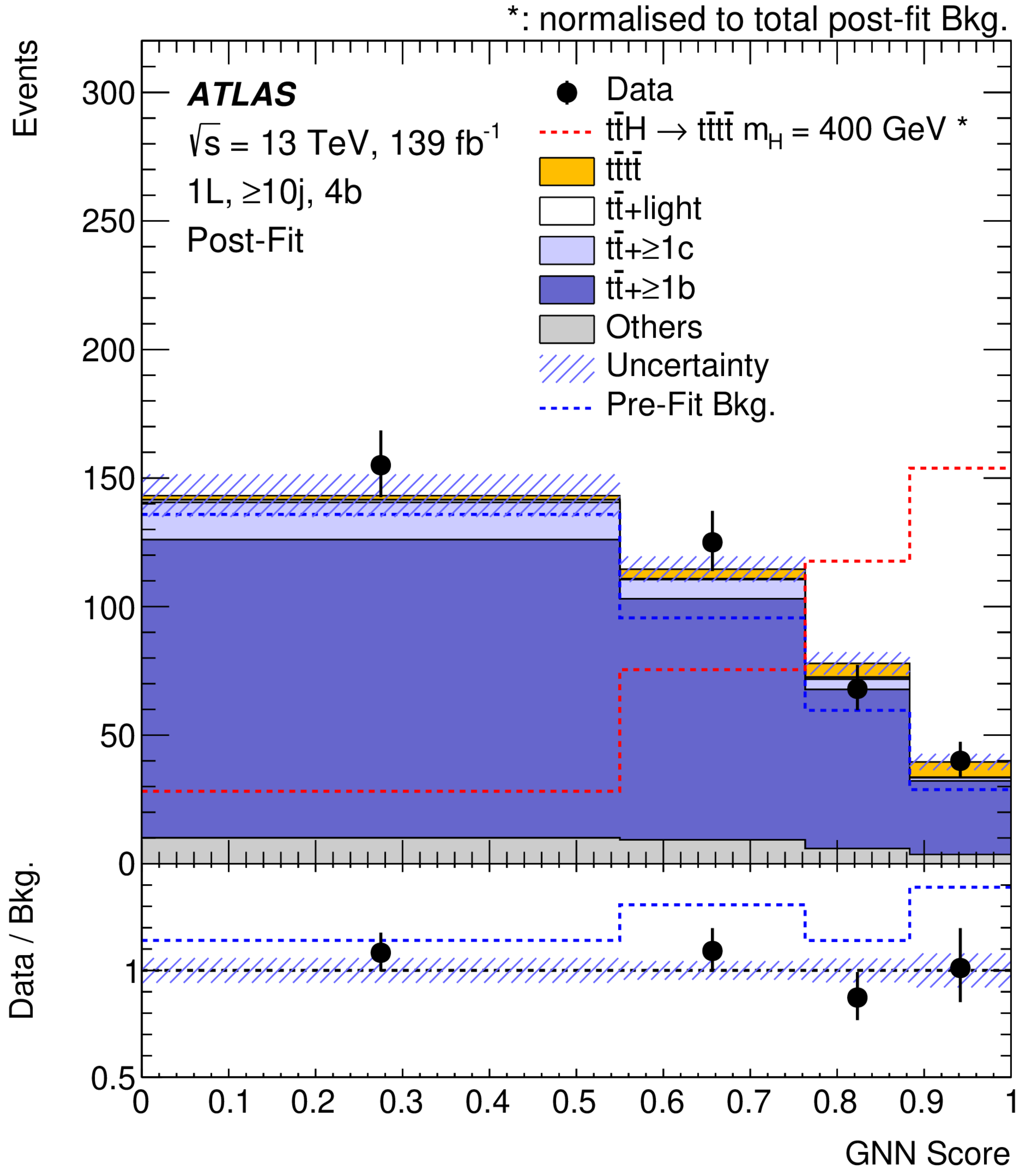


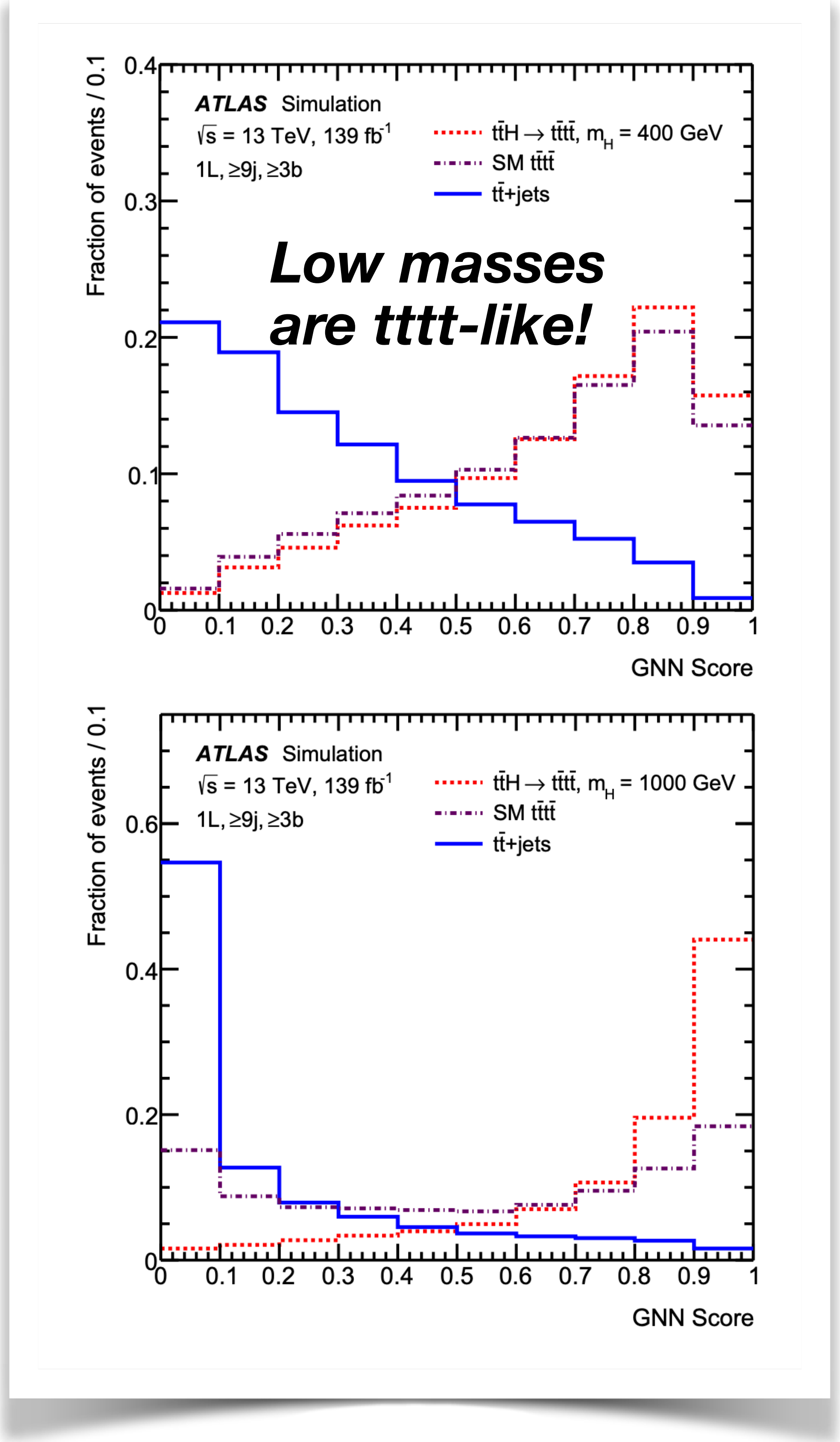


ttH/A→tttt

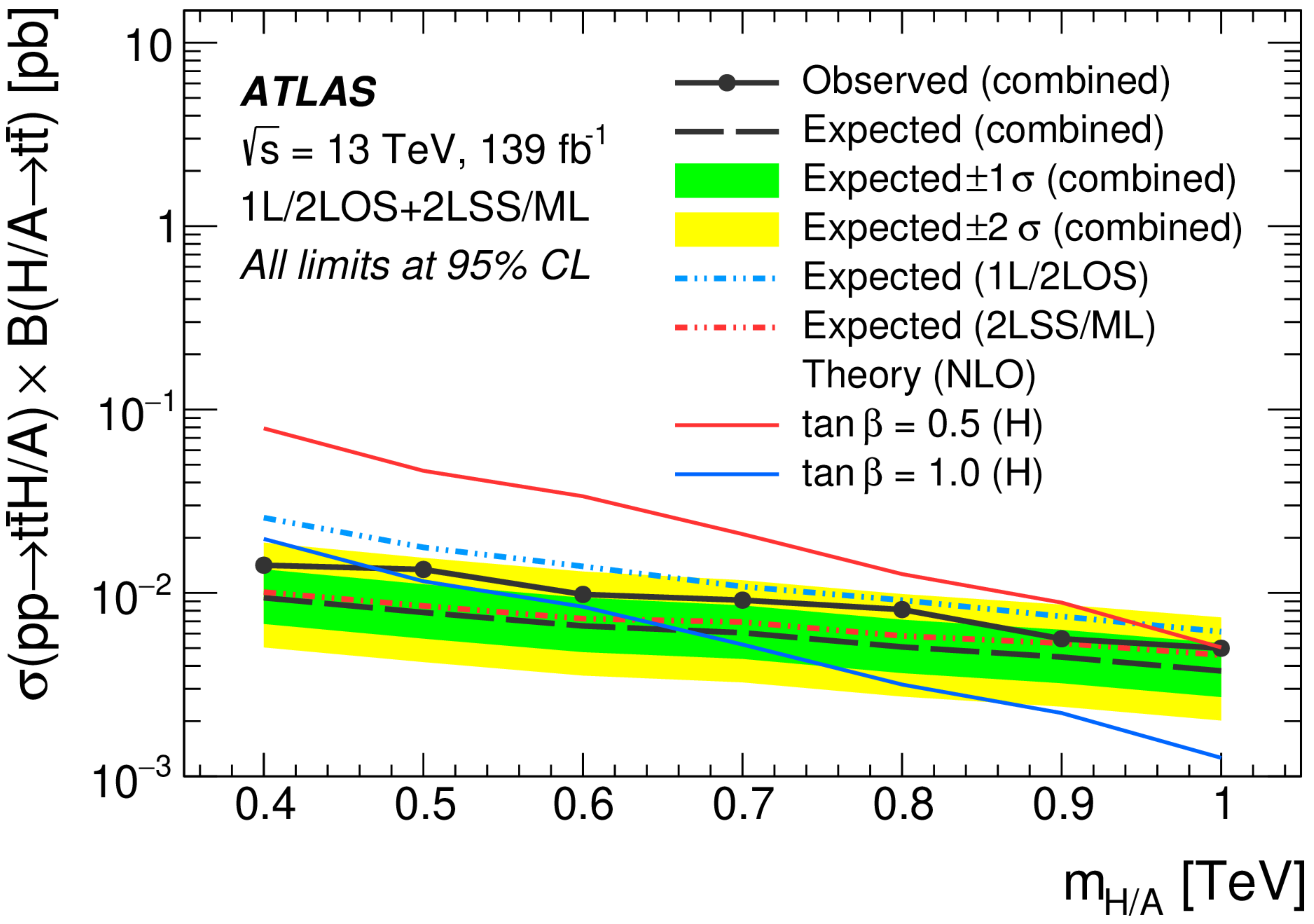
ATLAS EXOT-2022-13

arXiv:2408.17164





A parametrized GNN is used to separate S from B for a given mass hypothesis.



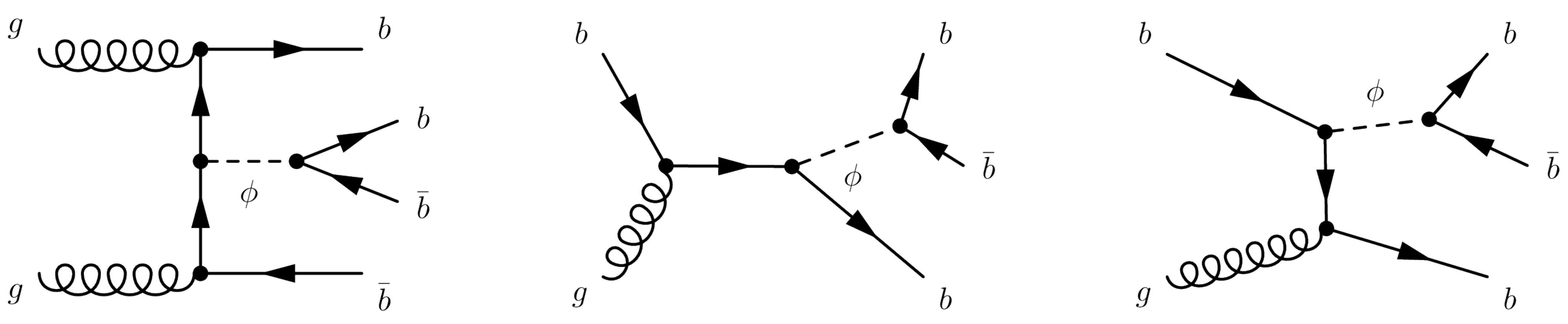
Results ***combined with the earlier 2LSS and ML*** *analysis.*

→ significant improvement at lower masses.

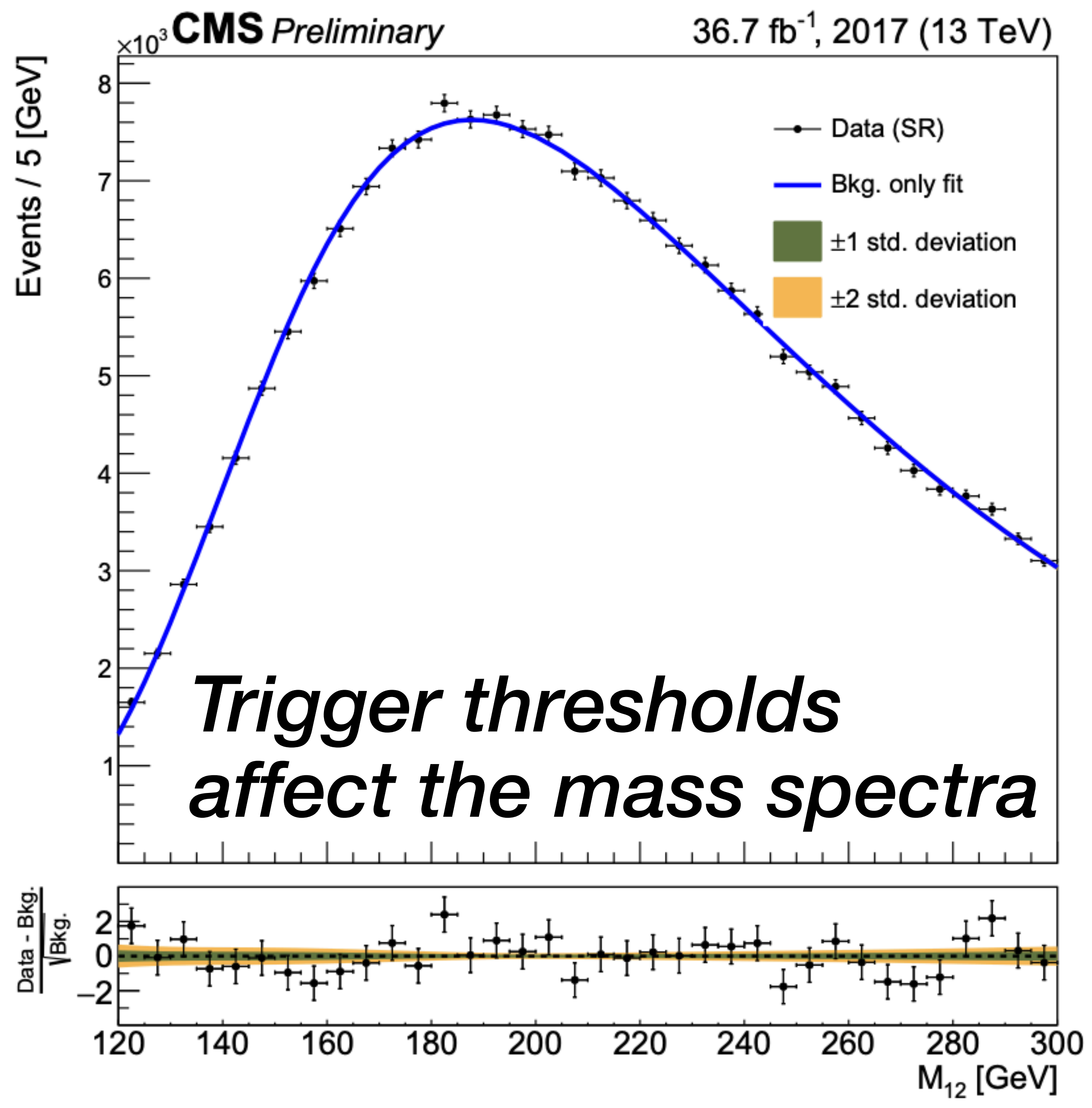
Near identical kinematics and acceptance between A and H.

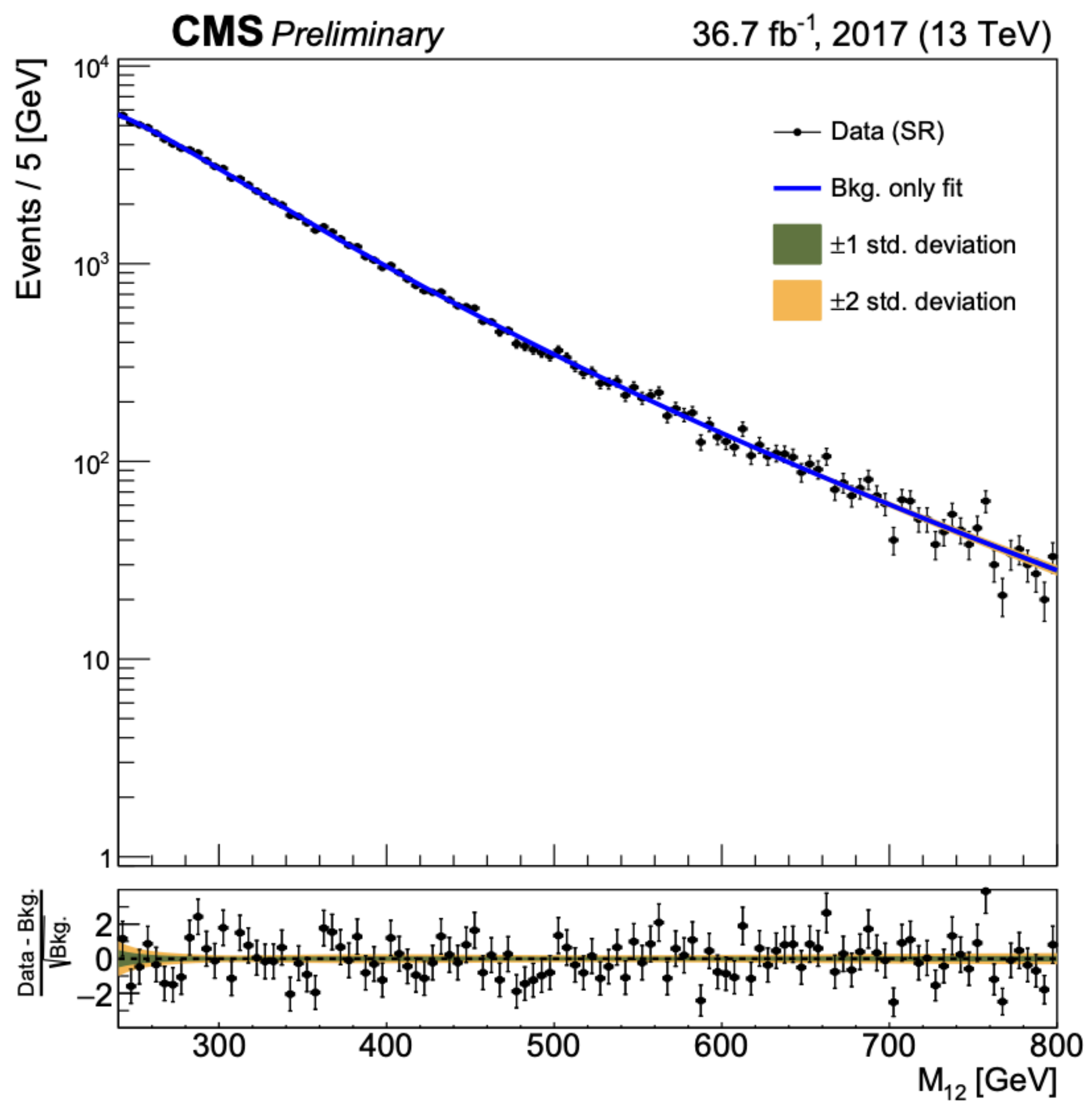
Also see CMS TOP-18-003 (2LSS+ML) ,arXiv:1908.06463

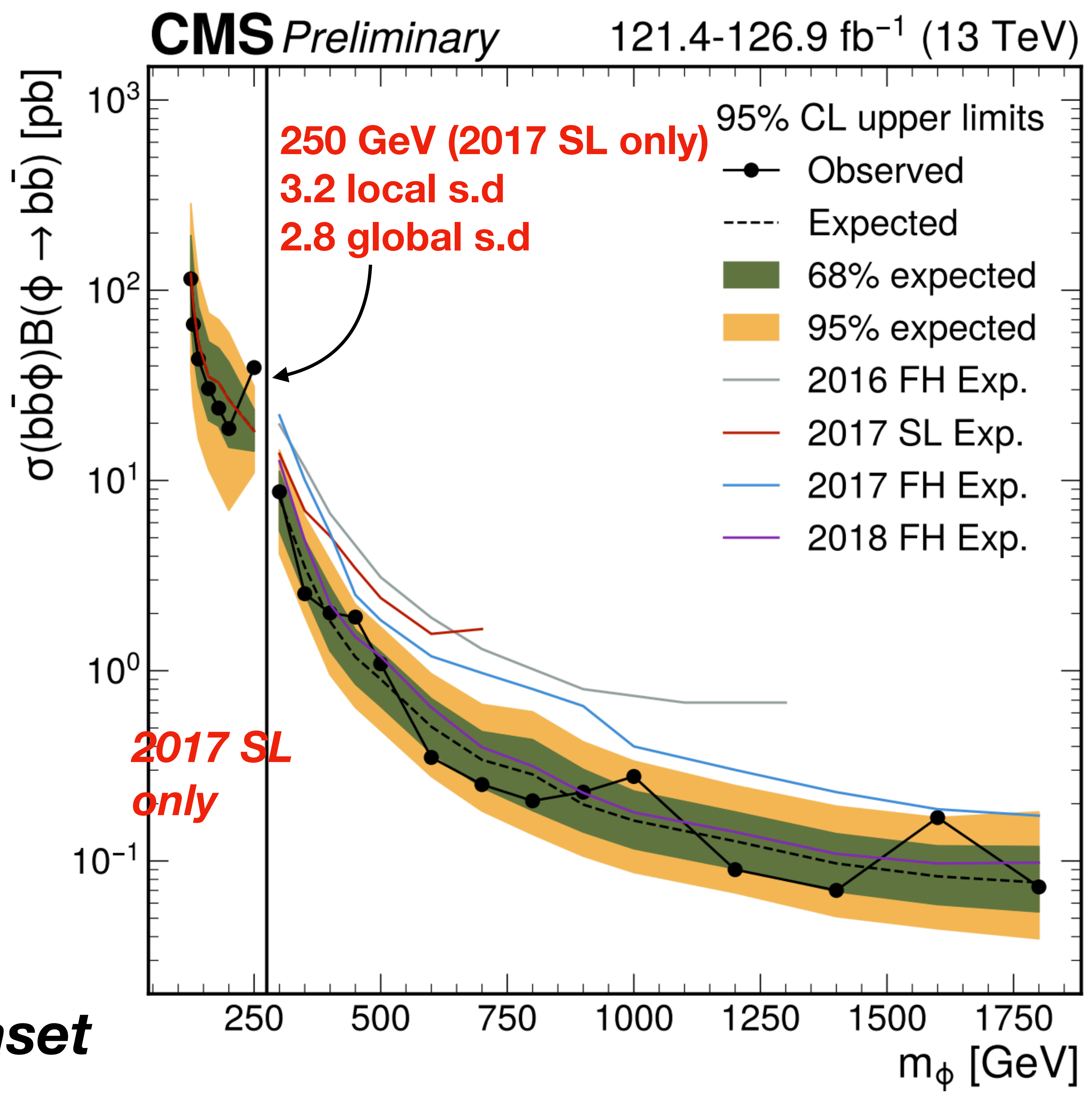
bbϕ (ϕ→bb)



CMS PAS-SUS-24-001







Fully hadronic *and* ***semileptonic categories*** *(to help with trigger thresholds)*

→ FH: 3 b jets at the trigger level

→ SL: ***3 b jets+muon*** *(access to 125-300 GeV mass range) -* ***2017 dataset***

Invariant mass of the two leading jets *is the primary discriminant.*

The data-driven background model is based on an ***analytic fit in CR*** *(3rd b-tag veto)*

→ a transfer factor is used to go to SR from CR

Results are combined with previously published 2016 dataset

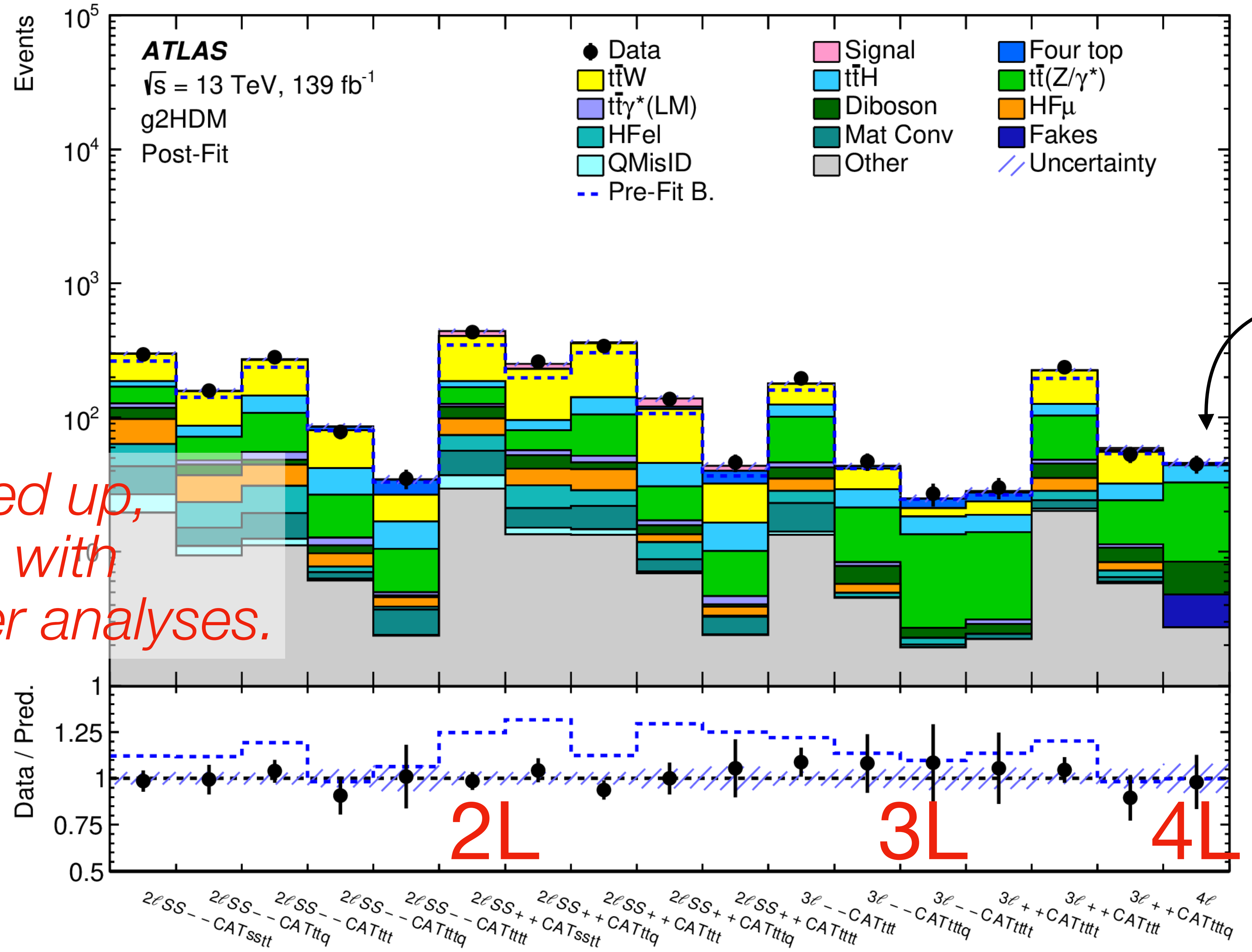
tqH: nondiagonal couplings

ATLAS HDBS-2020-03
arXiv:2307.14759

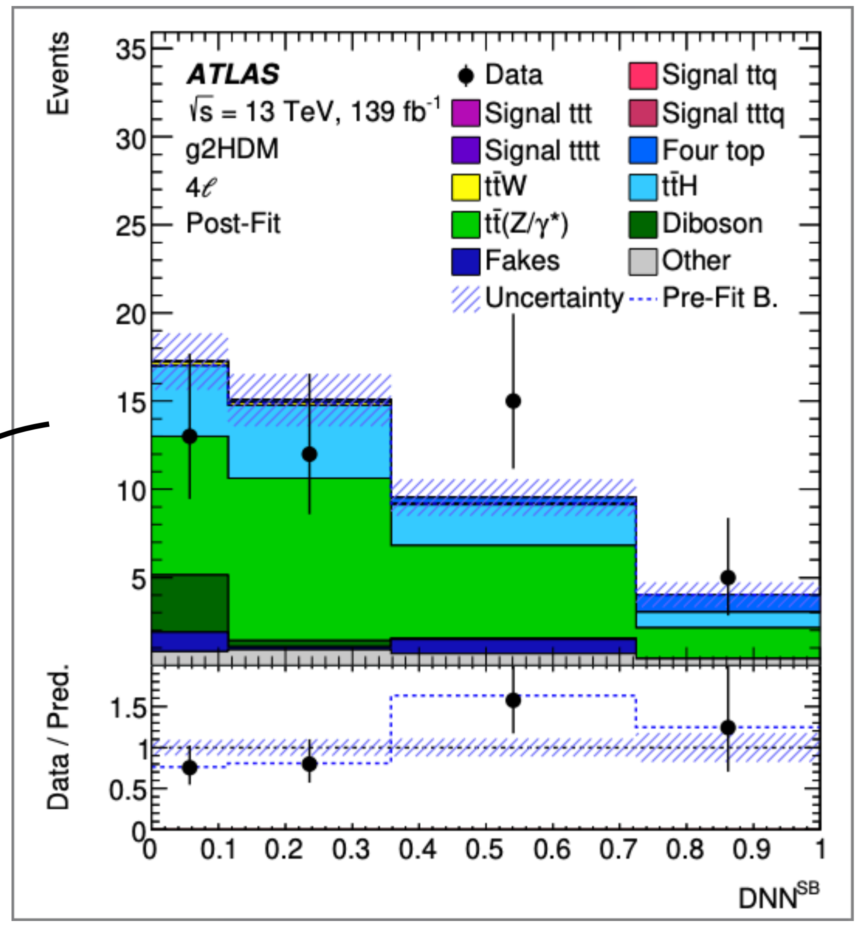
*First analysis targeting the **g2HDM model**:*

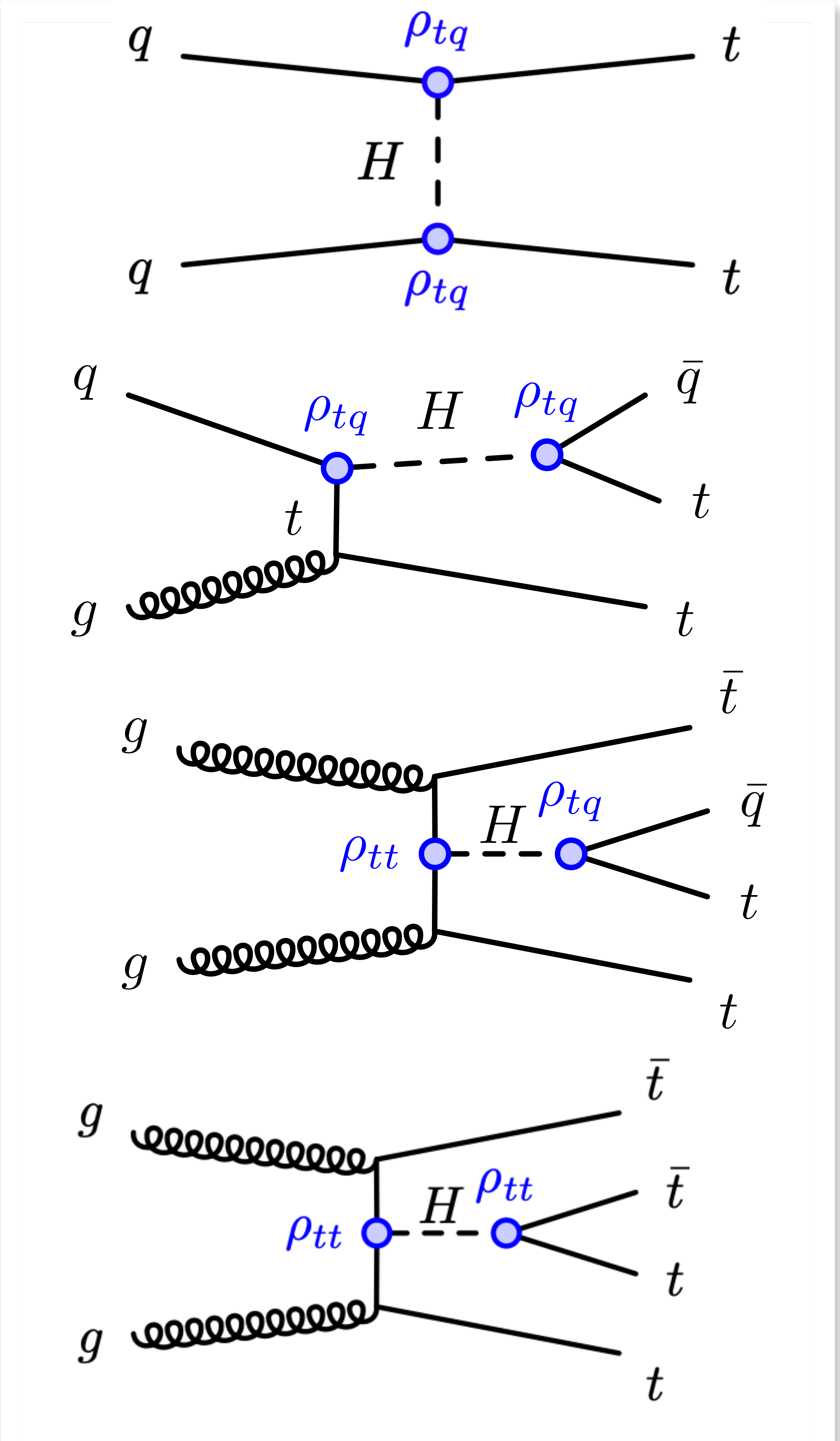
- *New heavy states are set to have sizable **non-diagonal Yukawa couplings to quarks.***
- ***Simultaneous** such couplings are probed.*

→ *First to target **BSM tri-top production.***



ttW is pulled up, consistent with many other analyses.





2-3-4 top signatures are considered!

*Multilepton **(2LSS, 3L, 4L) + b-jet final states**.*

→ *Two **DNNs are used** (N_{jet}, b-tag scores, MET, angular variables, H_T, etc..)*

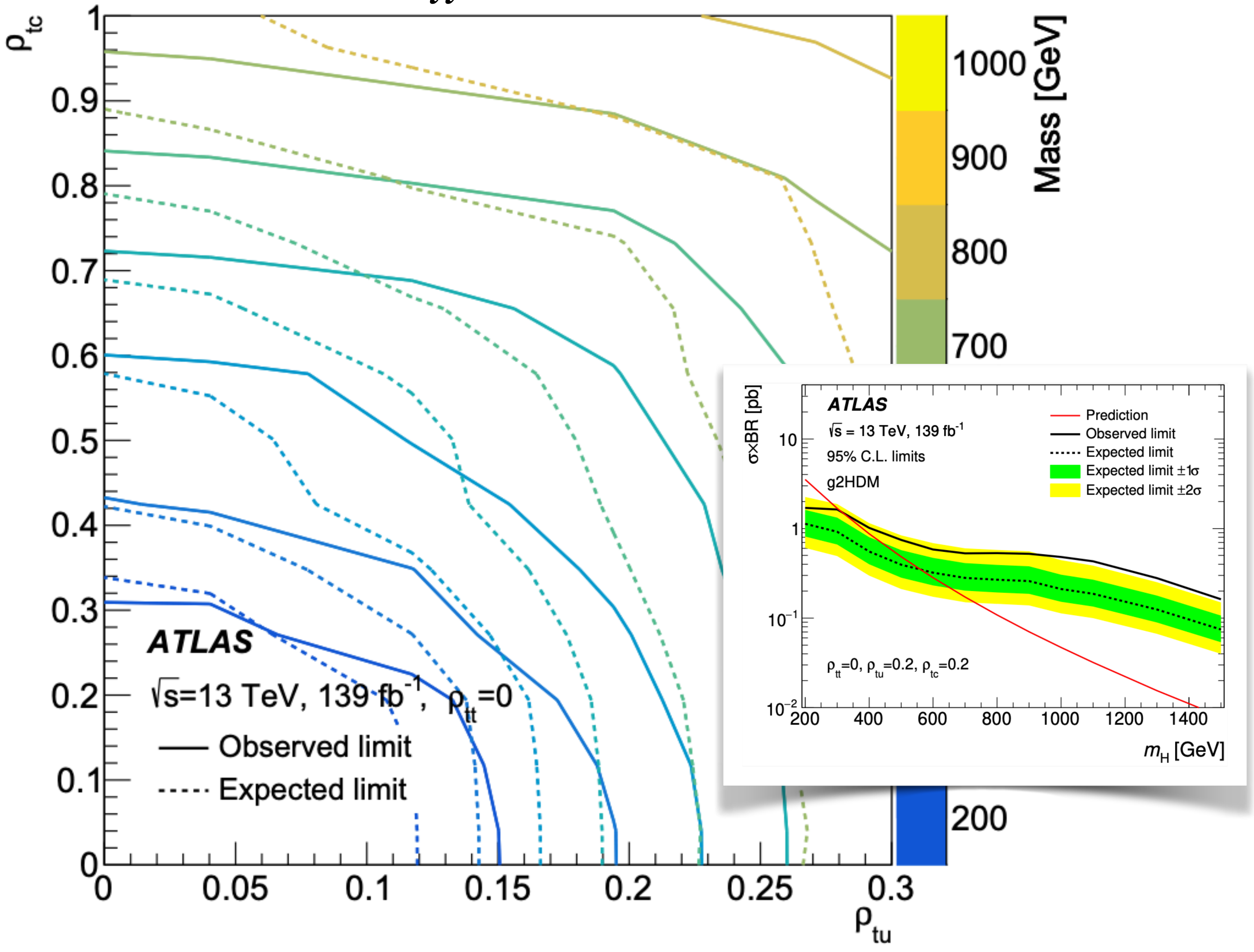
*(i) **categorize** events targeting all signal prod./decay **modes** (together with N_{lep} and Q_{lep}).*

*(ii) to **discriminate** S vs B in each category.*

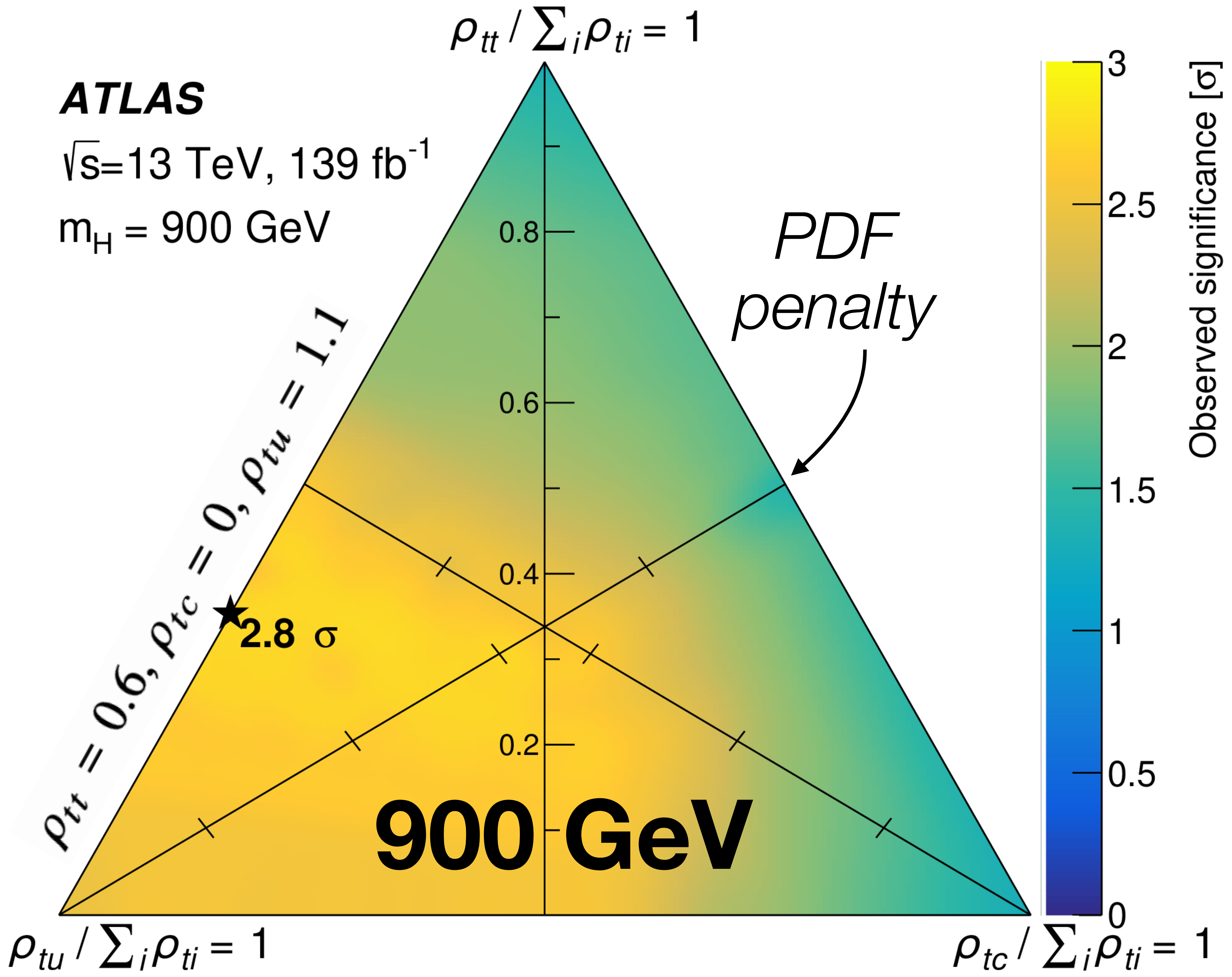
tqH: nondiagonal couplings

ATLAS HDBS-2020-03
arXiv:2307.14759

$\rho_{tt} = 0$



Other 3D "ρ-ρ-mass" planes are also probed.



"Triangle"** representation of **observed significances
→ less model-dependent (ρs are normalized to their sum)

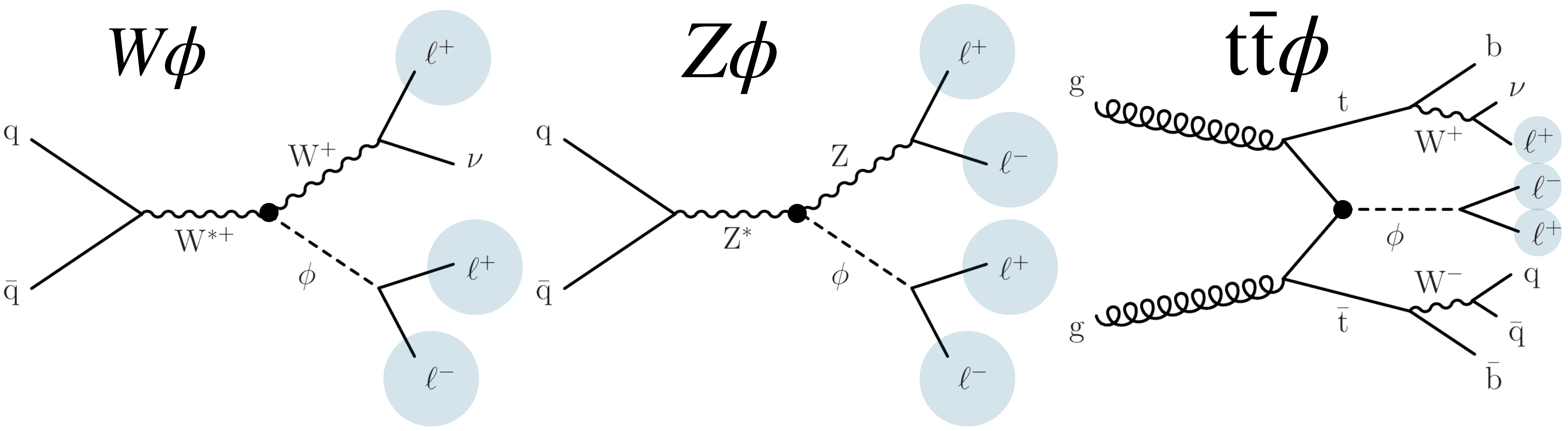
(This excess at 900 GeV is not compatible with the signal model, requires large undetected decay modes)

Also see CMS TOP-22-010 arXiv:2311.03261

Inclusive search: Xϕ→ℓℓ

CMS EXO-21-018

arXiv:2402.11098



Search for a new spin-0 particle in ***associated production with a W/Z boson or a $t\bar{t}$ pair***

- ***target mass range: 15-350 GeV*** → *dilepton resonance (NWA) in multilepton events*

Model independent *analysis:*

- *all lepton* ***flavor*** *pairs* ($ee, \mu\mu, \tau\tau$) *and* ***coupling*** *types (S, PS, Higgs-like production/decay)* → ***24 different scenarios***

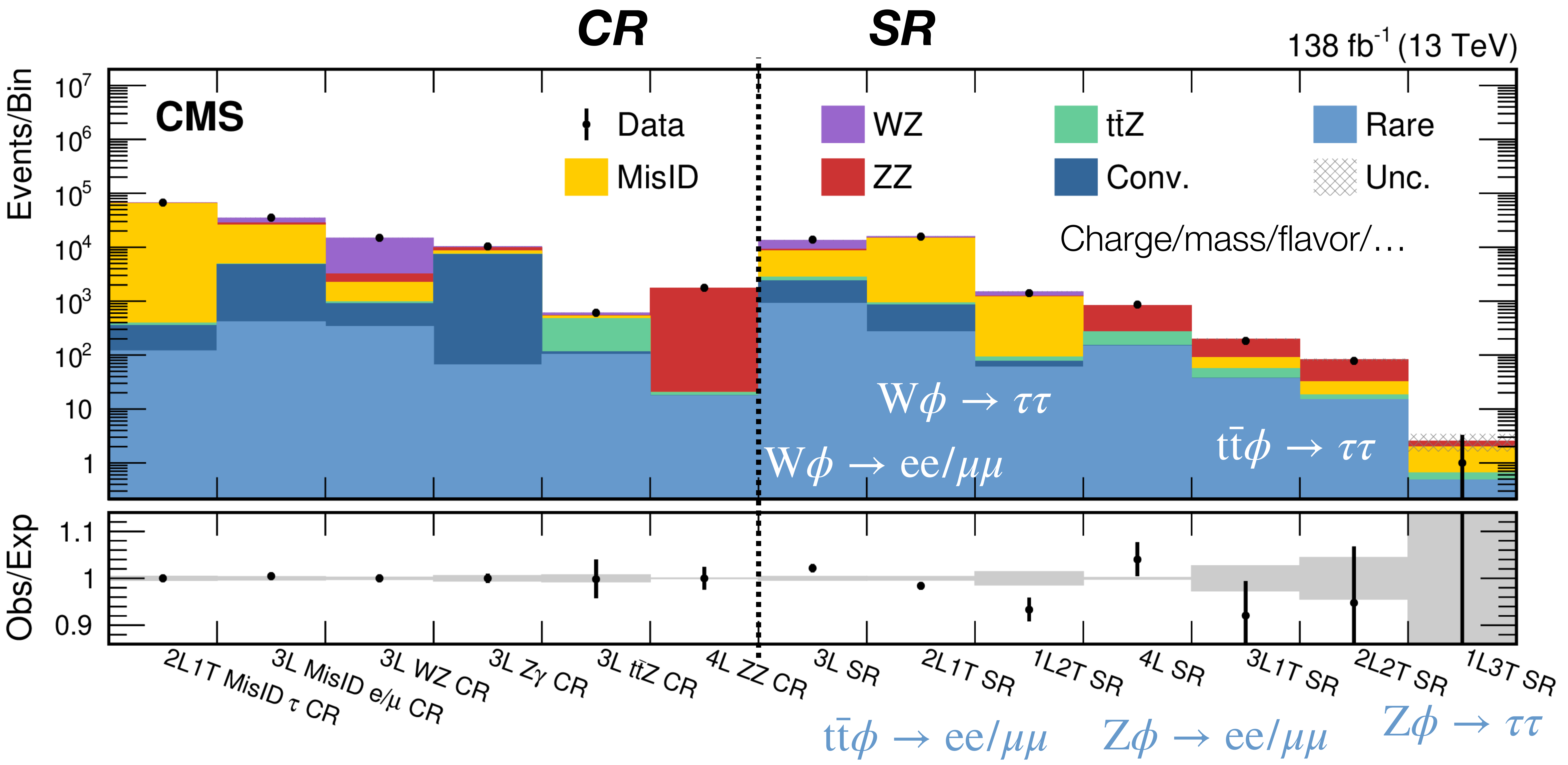
$$\frac{1}{\Lambda_S}\phi_S F^{a\mu\nu}F^a_{\mu\nu} + \frac{1}{\Lambda_{PS}}\phi_{PS} F^{a\mu\nu}\tilde{F}^a_{\mu\nu} \qquad -\frac{g_{\psi S}}{\sqrt{2}}\phi_S\bar{\psi}\psi - \frac{g_{\psi PS}}{\sqrt{2}}\phi_{PS}\bar{\psi}i\gamma_5\psi \qquad -2\sin\theta\,\frac{\phi_H}{v}\left(m_W^2 W^{+\mu}W^-_\mu + \frac{1}{2}m_Z^2 Z^\mu Z_\mu\right)$$

Inclusive search: Xϕ→ℓℓ

CMS EXO-21-018
arXiv:2402.11098

Builds on an ***inclusive multilepton analysis*** *(CMS EXO-21-002, arXiv:2202.08676) with many categories*

- first of its type "bump-hunt" at the LHC!



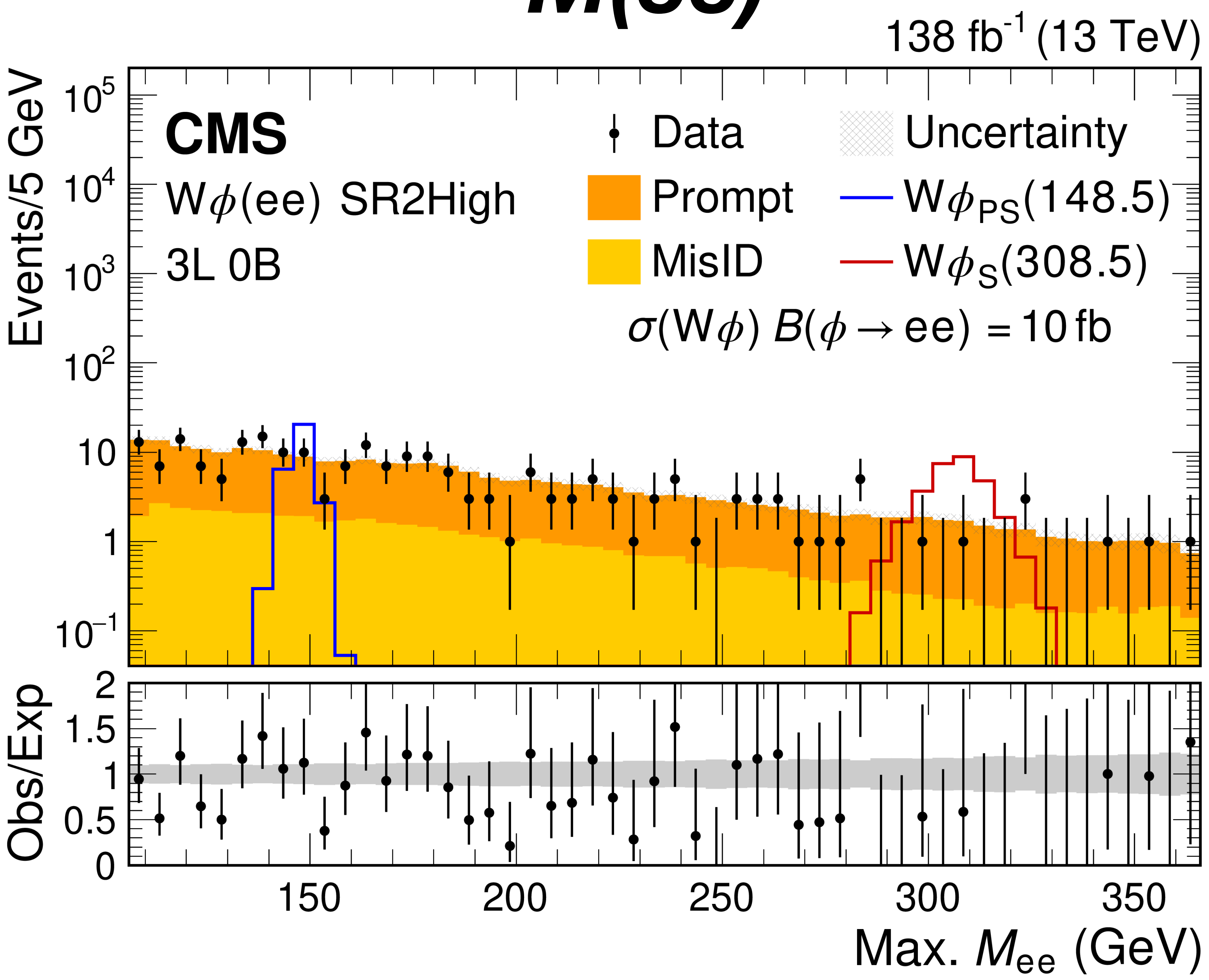
Inclusive search: $X\phi \rightarrow \ell\ell$

CMS EXO-21-018
arXiv:2402.11098

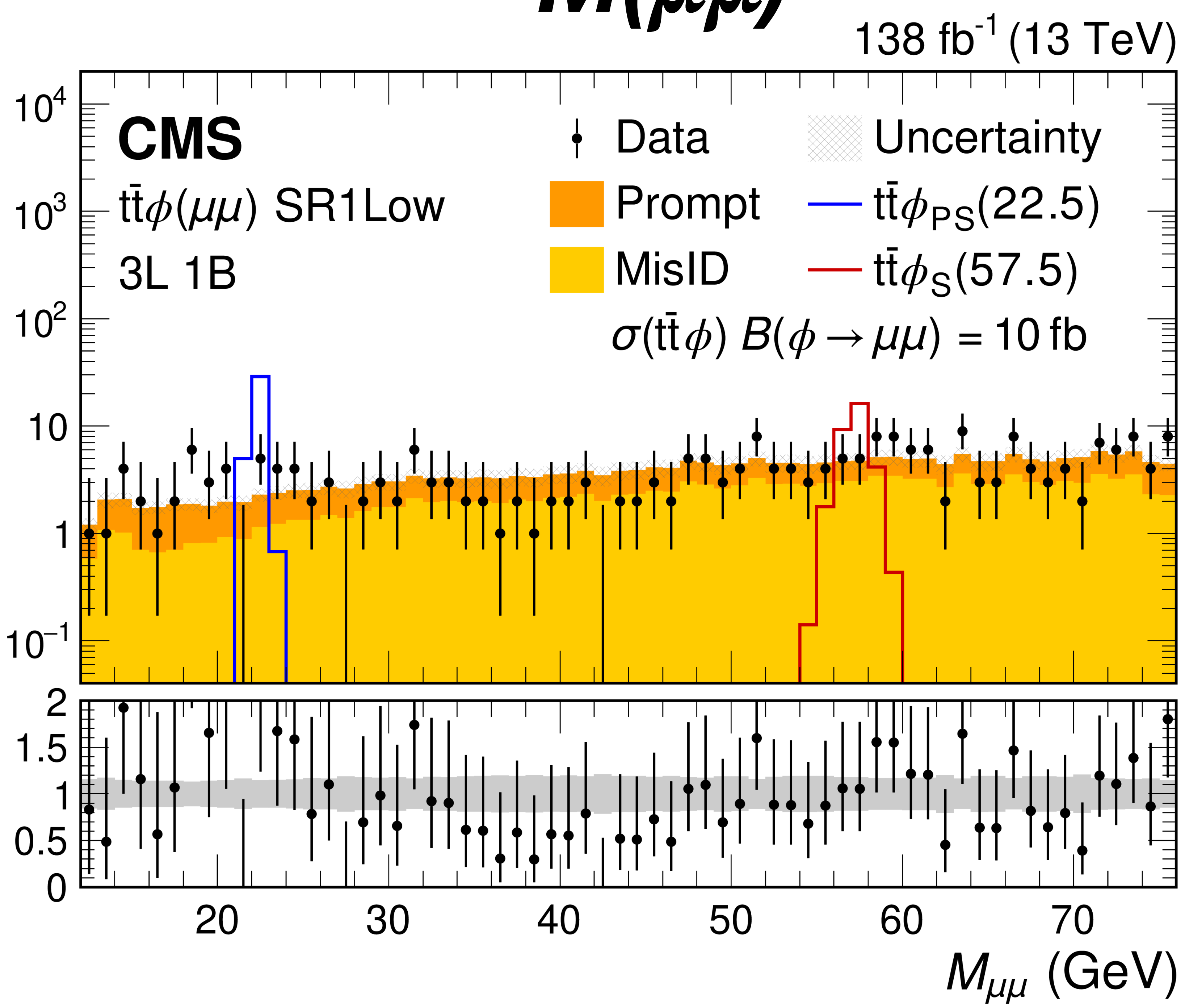
*Builds on an **inclusive multilepton analysis** (CMS EXO-21-002, arXiv:2202.08676) with many categories*

- first of its type "bump-hunt" at the LHC!

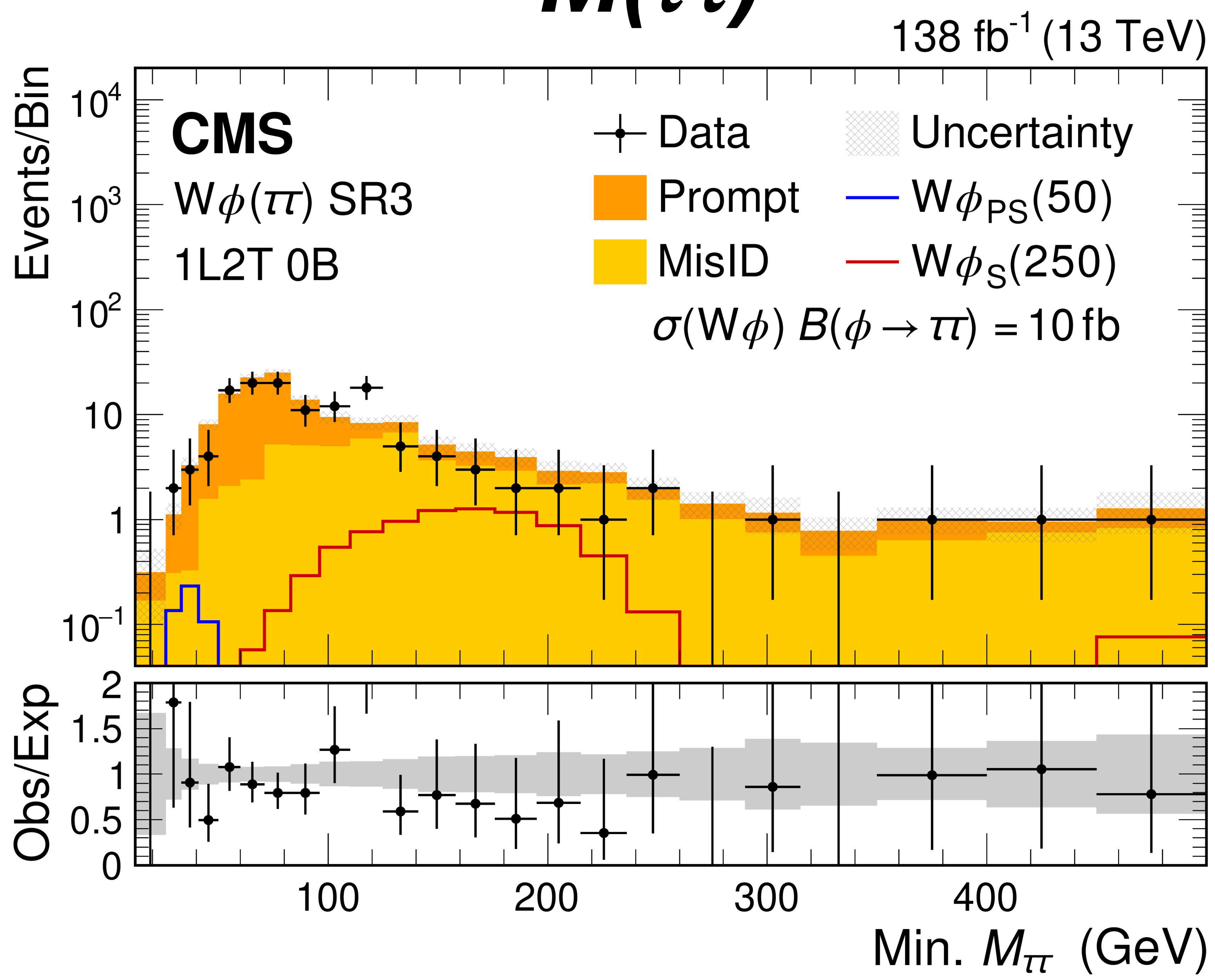
M(ee)



M(μμ)



M(ττ)

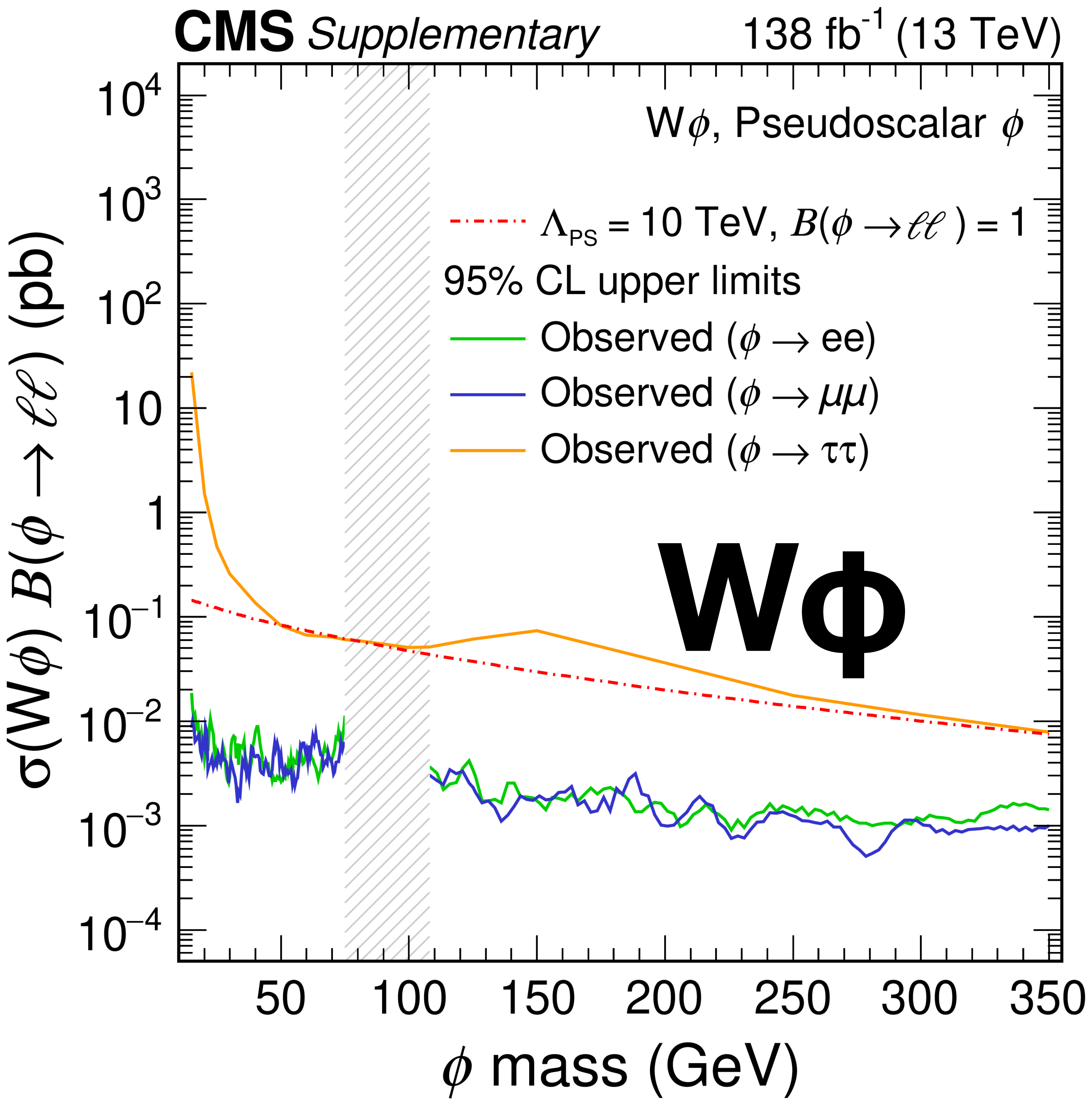


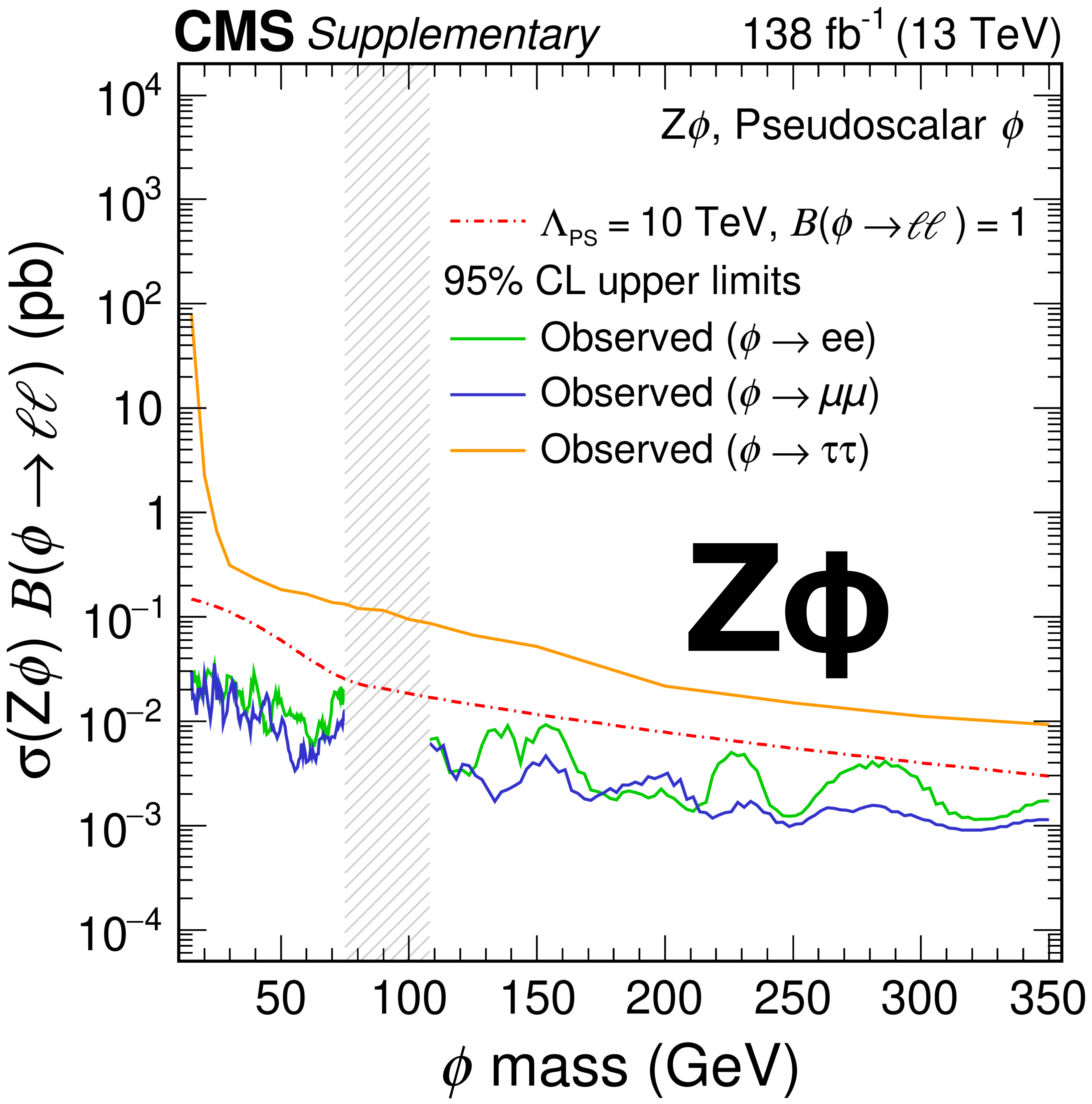
*Dilepton resonance of any flavor in **V(V)- and tt(V)-like multilepton** events:*

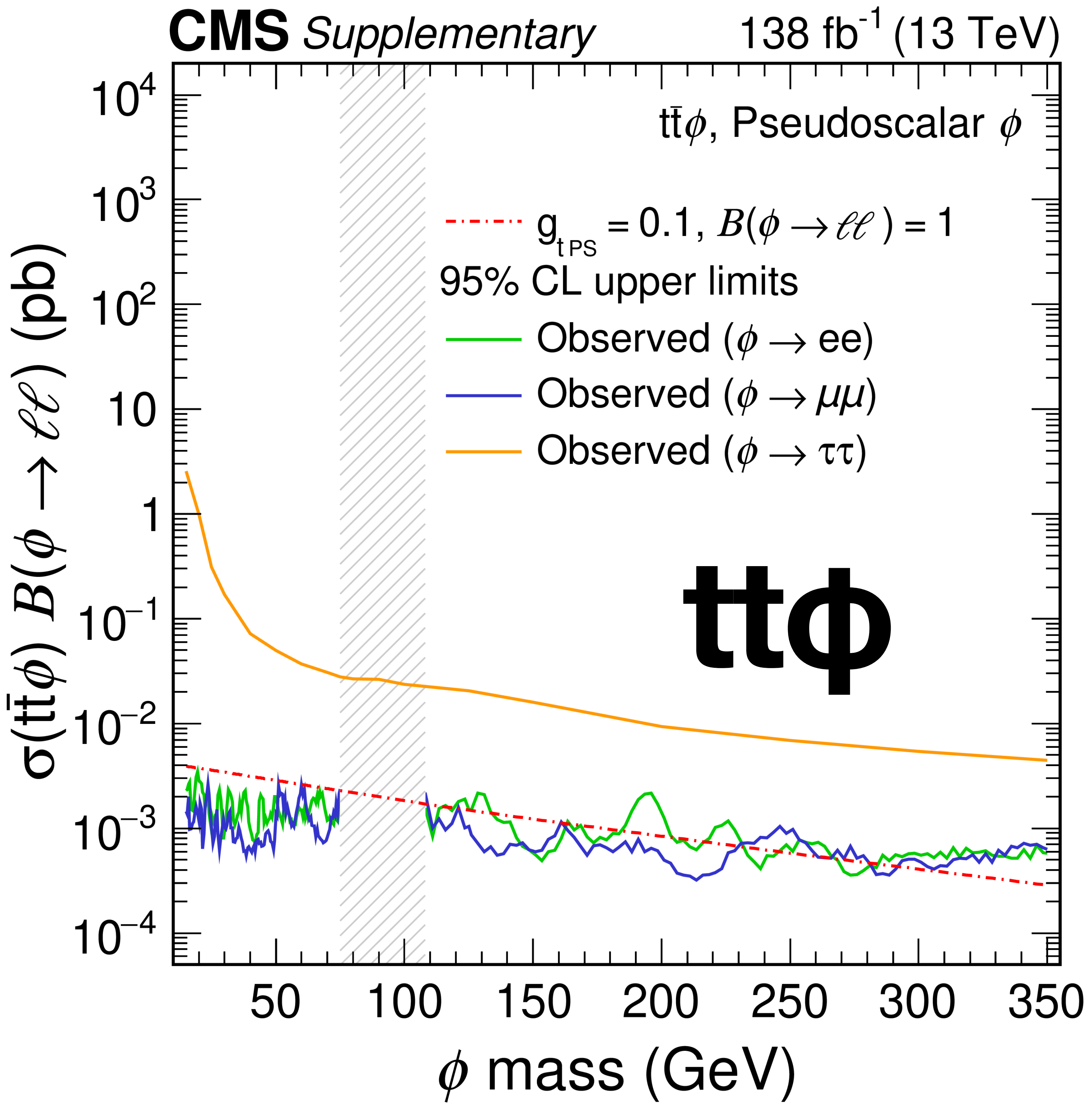
- → *MisID contributions are significant.*
- → ***Narrow** resonant signal shape for $ee/\mu\mu$ decays.*
- → ***Wide**, semi-resonant signal shape for $\tau\tau$ decays.*

Inclusive search: Xϕ→ℓℓ

CMS EXO-21-018
arXiv:2402.11098







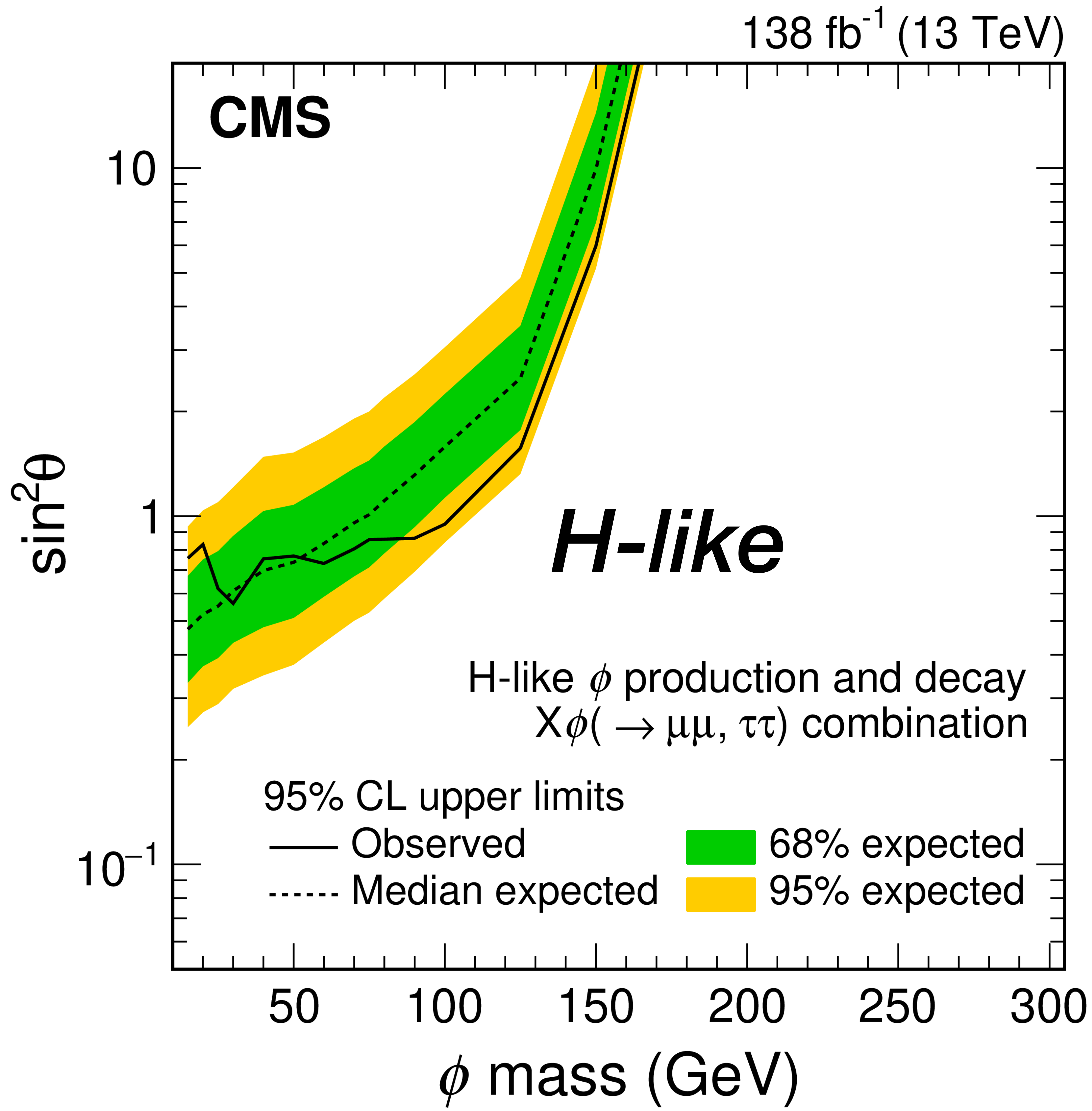
Model-independent pseudo-scalar limits

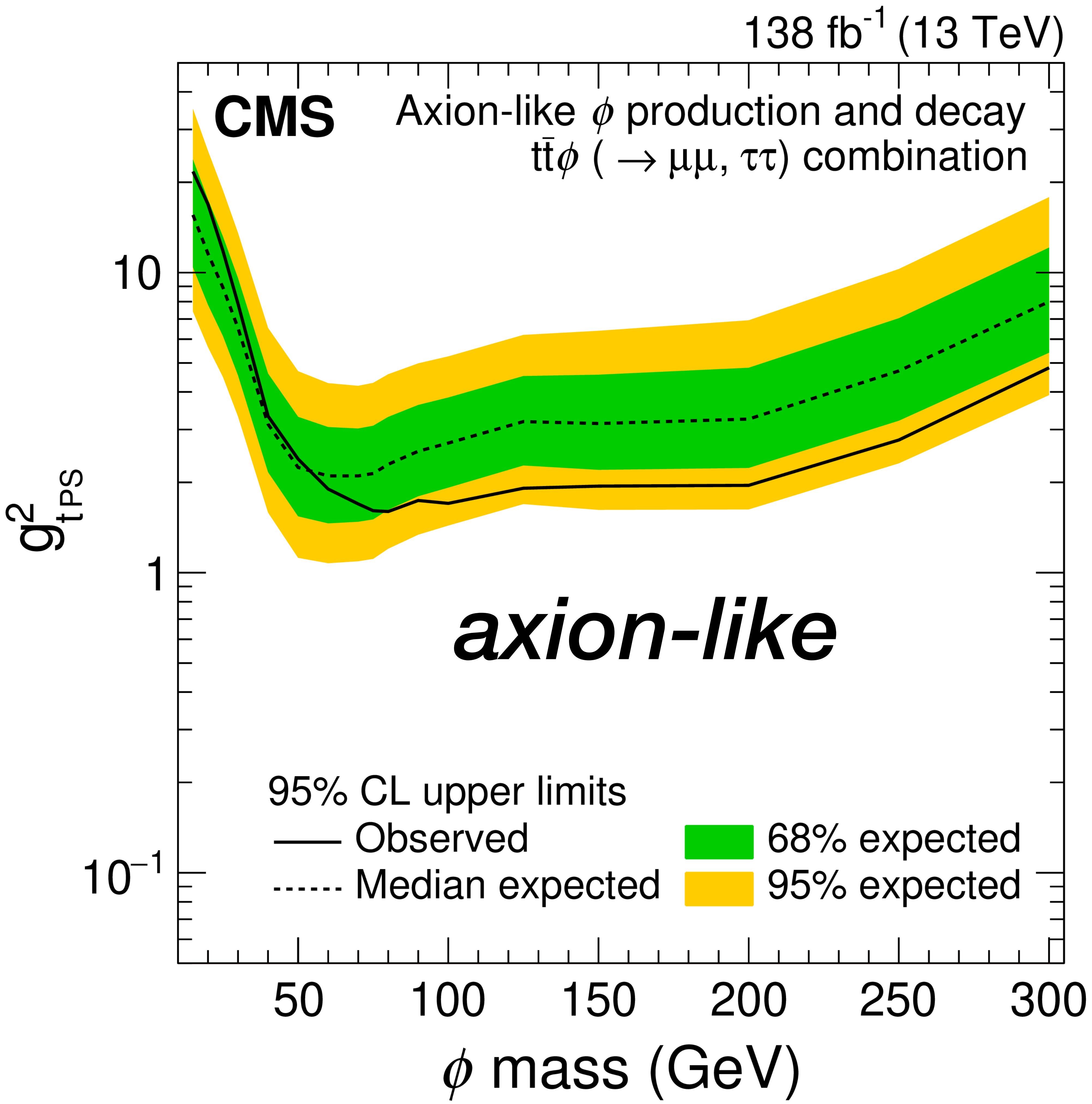
(similarly also for scalar/H-like scenarios)

Inclusive search: Xϕ→ℓℓ

CMS EXO-21-018

arXiv:2402.11098



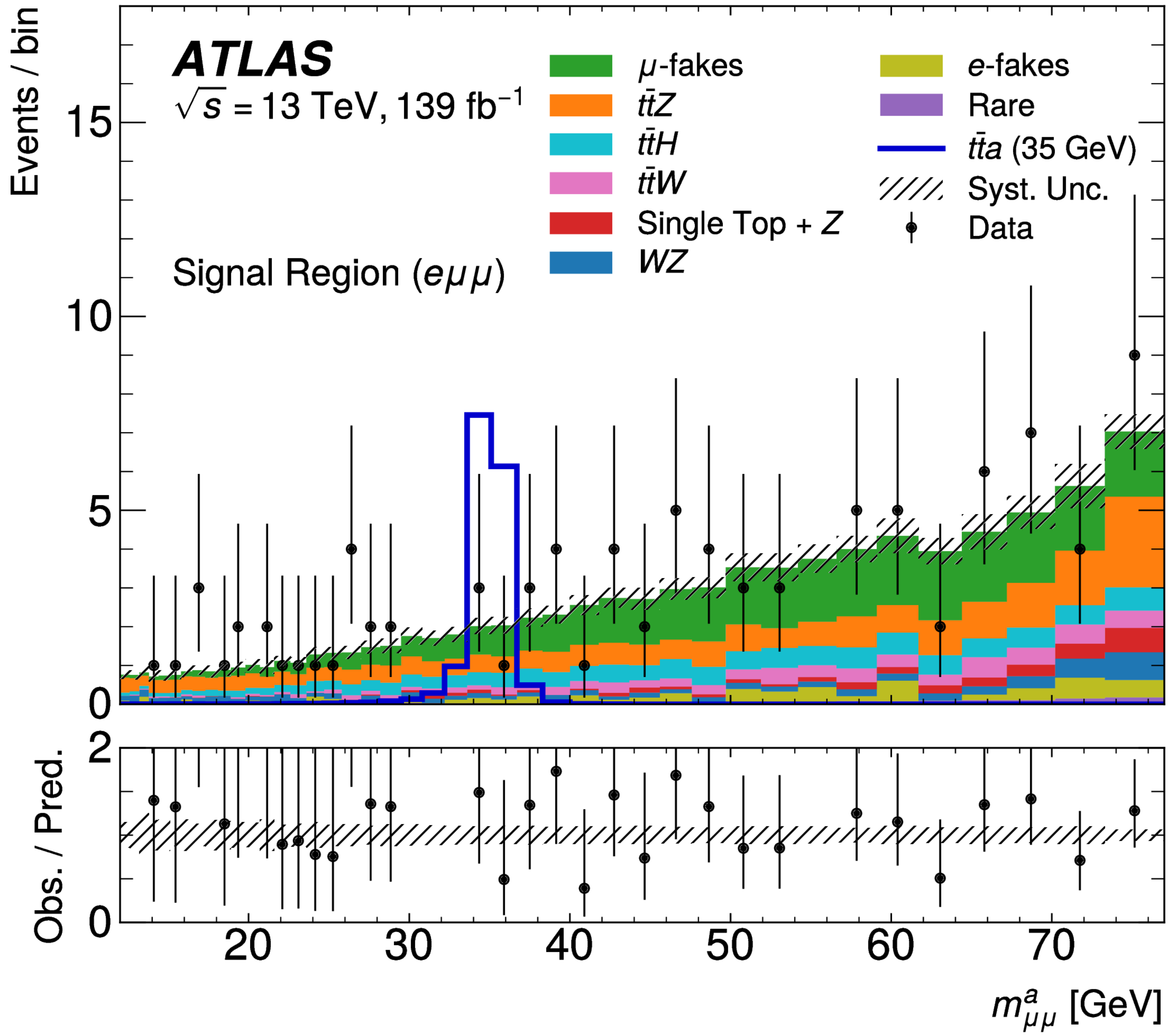


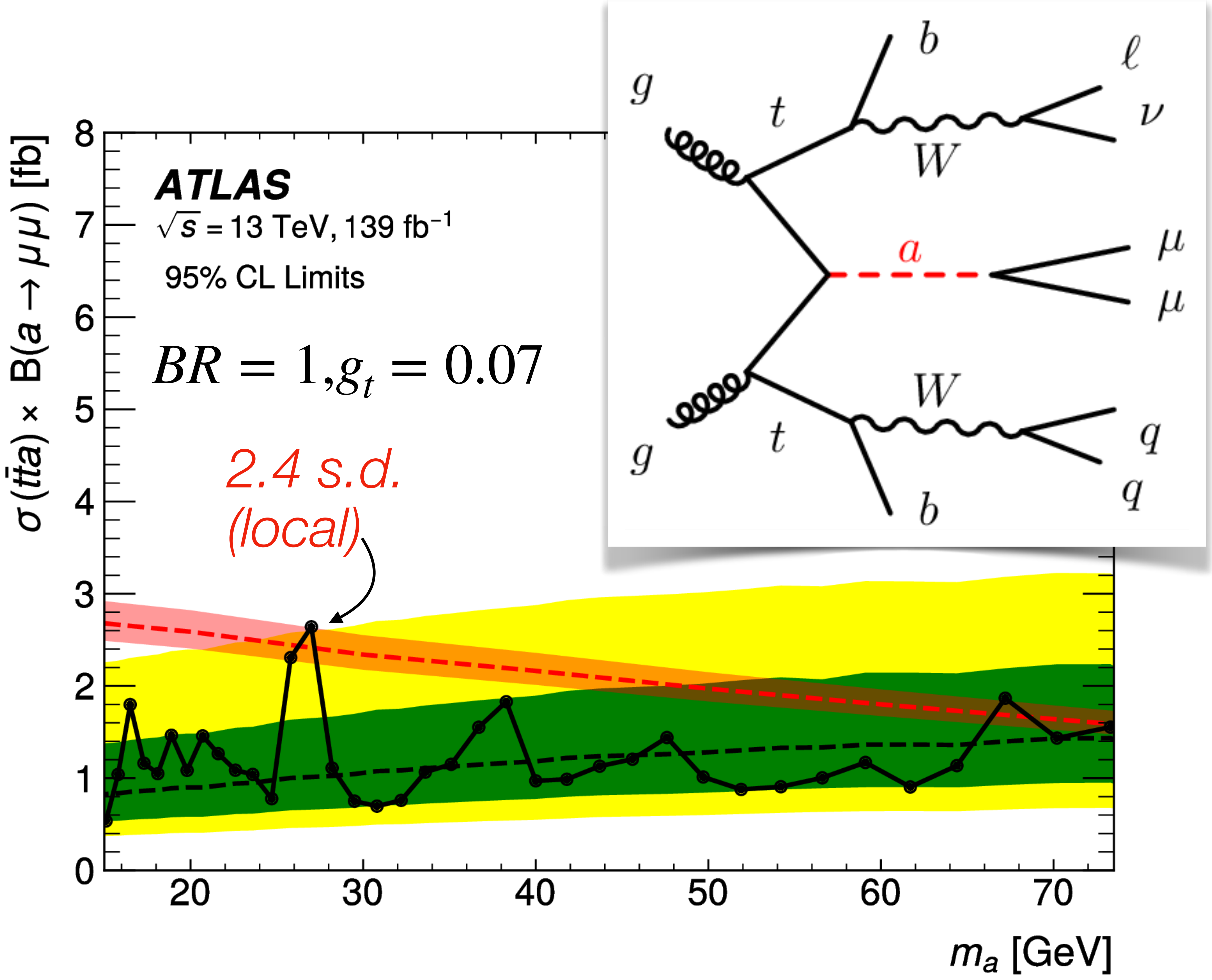
***Model-dependent limits**: H-like, axion-like, dilaton-like, …*

Light pseudoscalar: tta→$\mu\mu$

ATLAS HDBS-2020-12

arXiv:2304.14247





Targets $e\mu\mu$ and $\mu\mu\mu$ channels separately.

In 2HDM+a: $g_t = \sin\theta / \tan\beta$

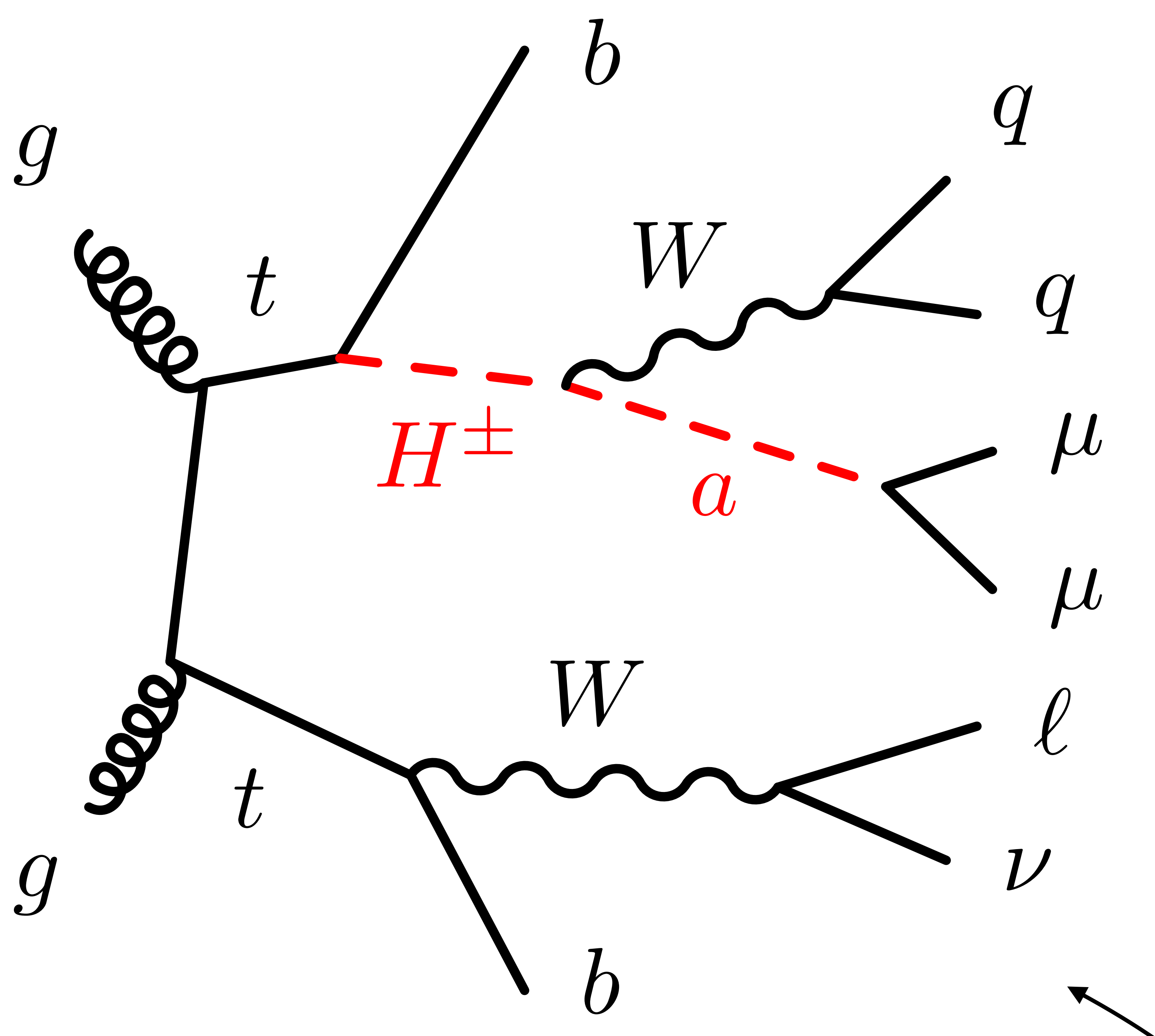
Similar approach as CMS EXO-21-018 $t\bar{t}\phi_{PS} \to \mu\mu$, but NLO signal model is used.

Charged states

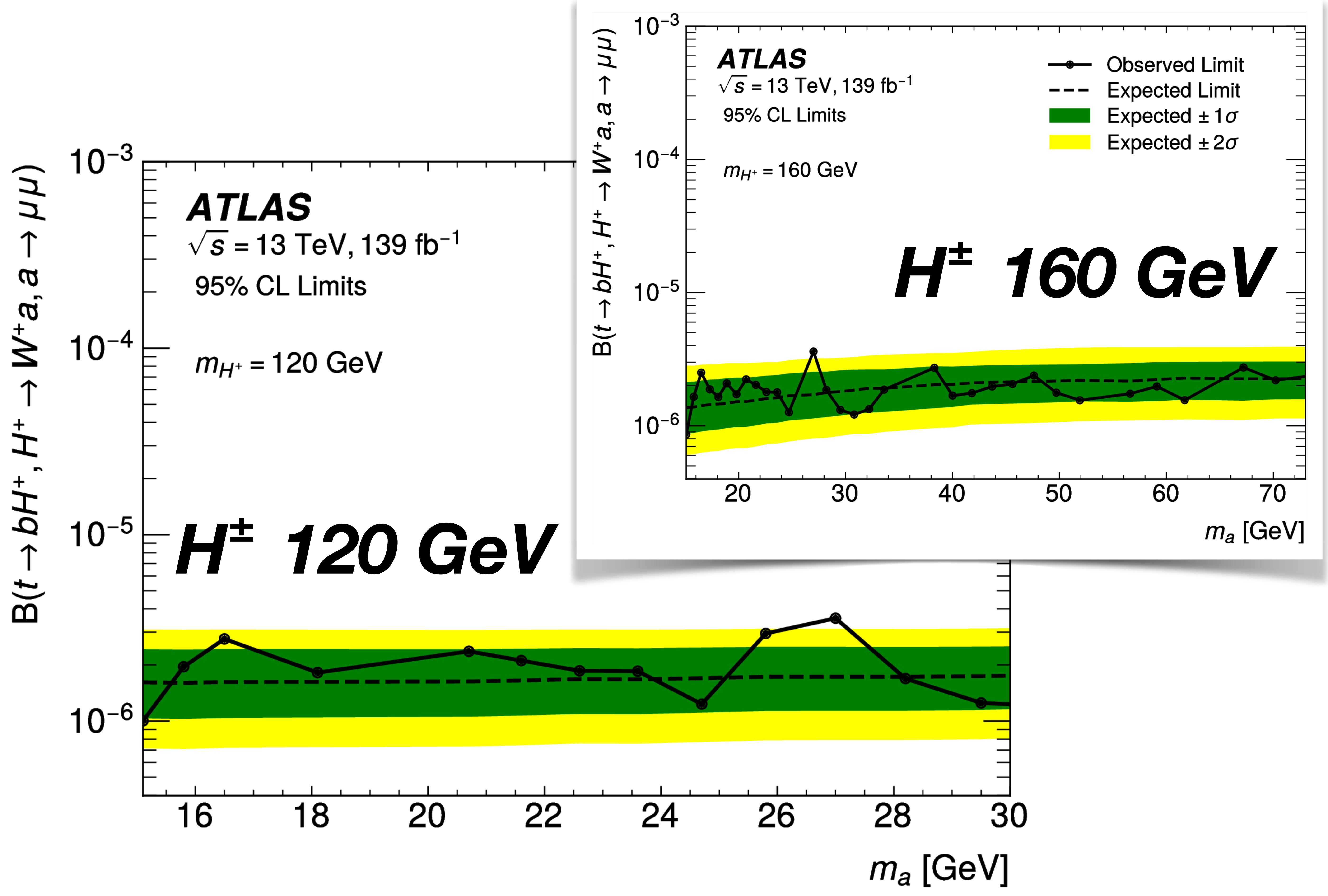
Light $H^{\pm}$ in top decays: $t \to H^{\pm}b \to W^{\pm}ab$

ATLAS HDBS-2020-12

arXiv:2304.14247



*The same search strategy is also used to probe for **light charged Higgs states in top decays**.*

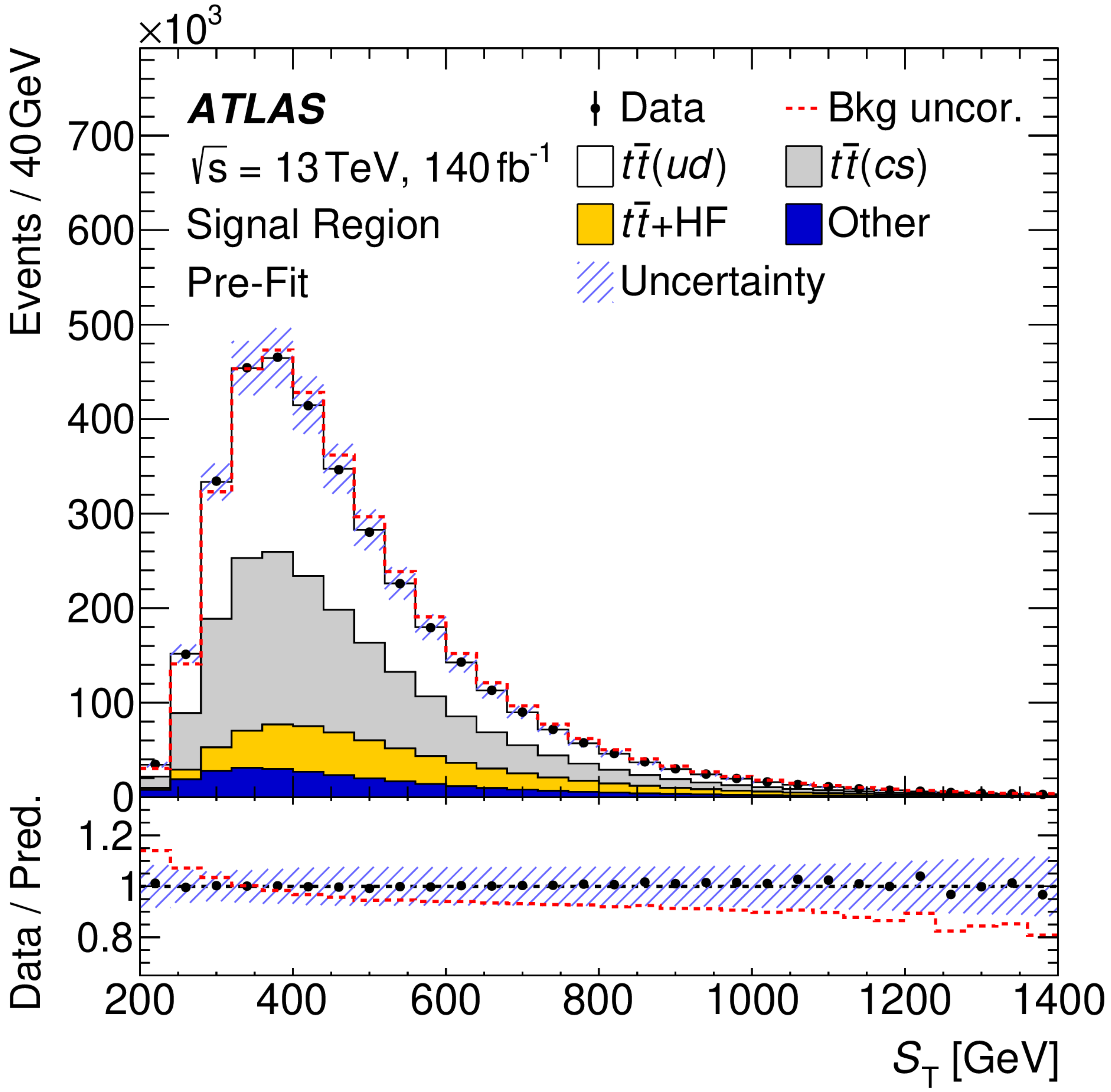


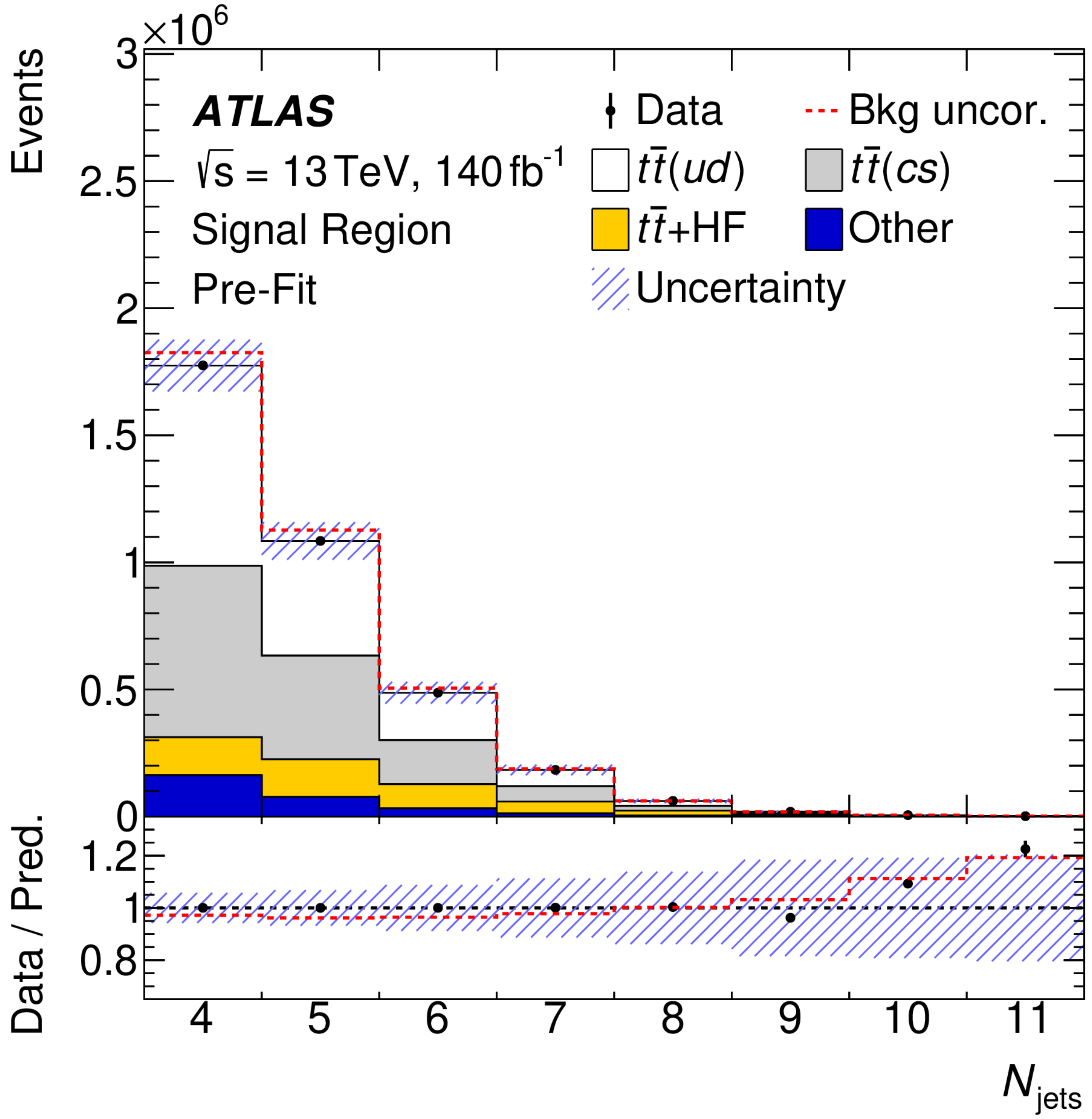
Kinematically allowed max. a / $H^{\pm}$ mass depends on $H^{\pm}$ / t mass

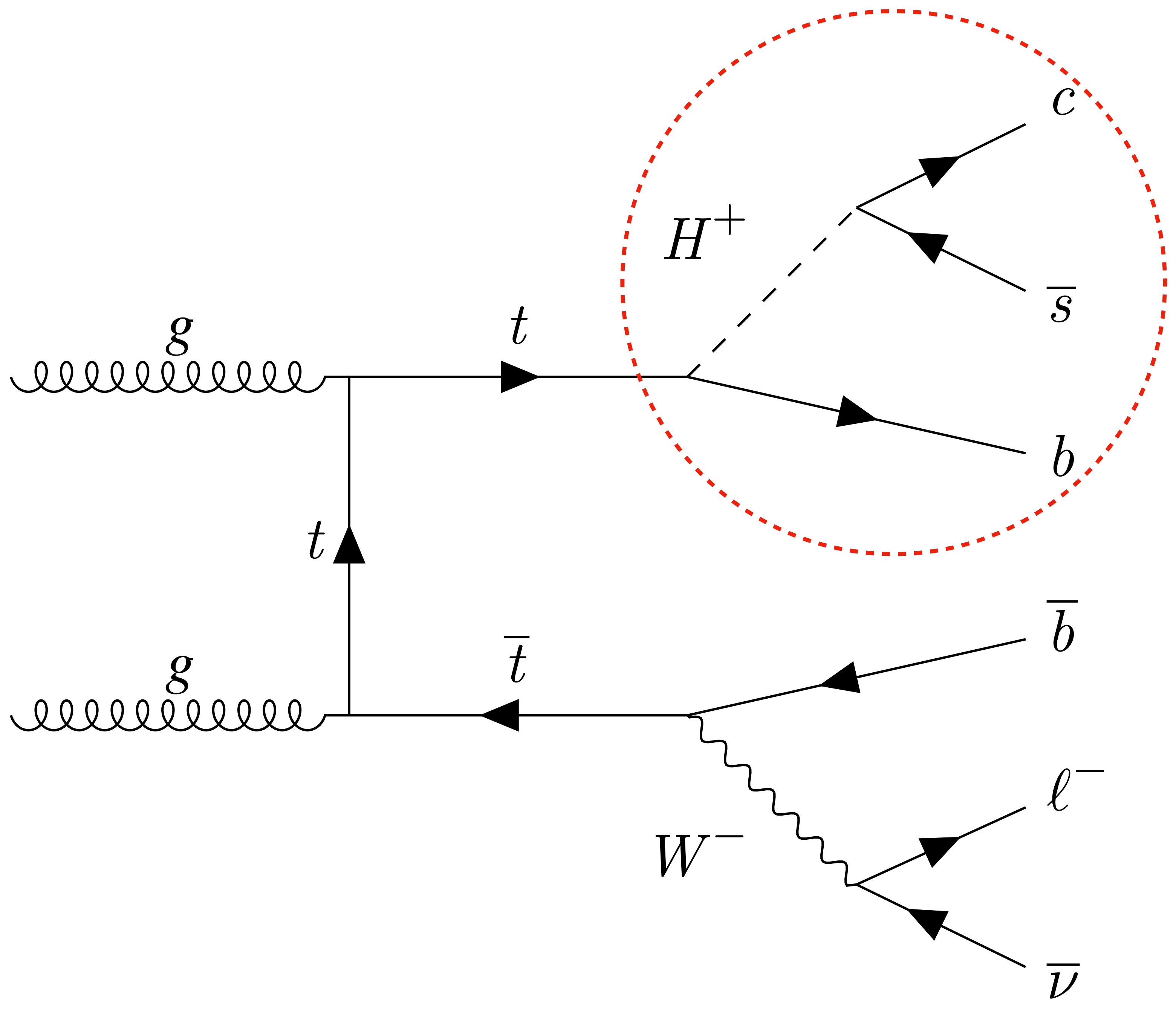
Light H± in top decays: H± →cs

ATLAS HDBS-2020-11

arXiv:2407.10096







Single electron/muon *channel is targeted.*

Top pair production *is the most significant background.*

Data-driven correction *to $t\bar{t}$ MC (Powheg) as a function of* ***S_T in bins of N_{jets}***

Top quark reconstruction *is performed to obtain* ***t_{lep} and t_{had} masses.***

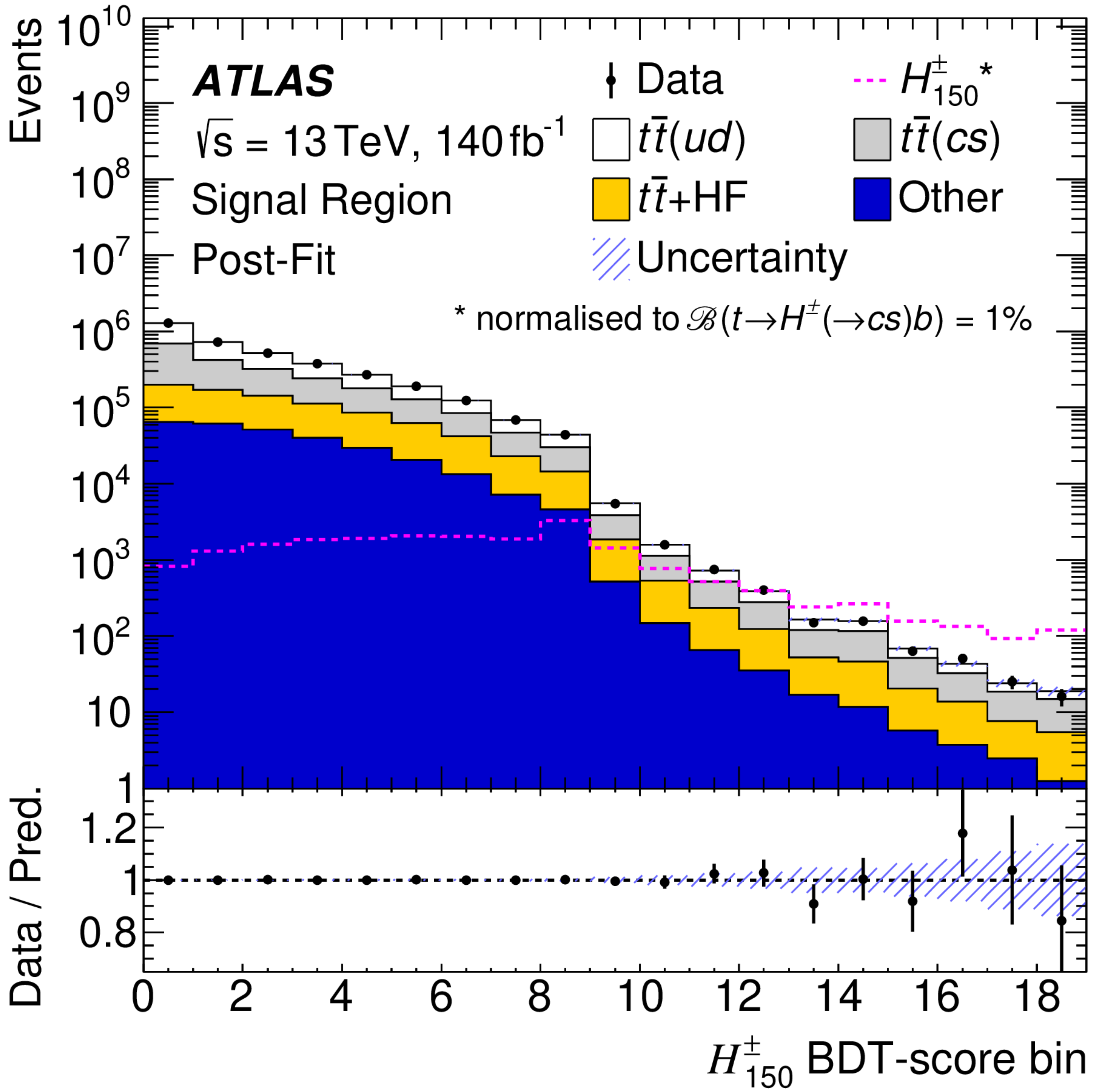
Other related light $H^{\pm}$ searches target $H^{\pm} \to cb$, $H^{\pm} \to \tau\nu$.

Also see CMS heavy $H^{\pm}$ analysis: HIG-21-010 arXiv:2207.01046 with $H^{\pm} \to HW^{\pm}$ decays

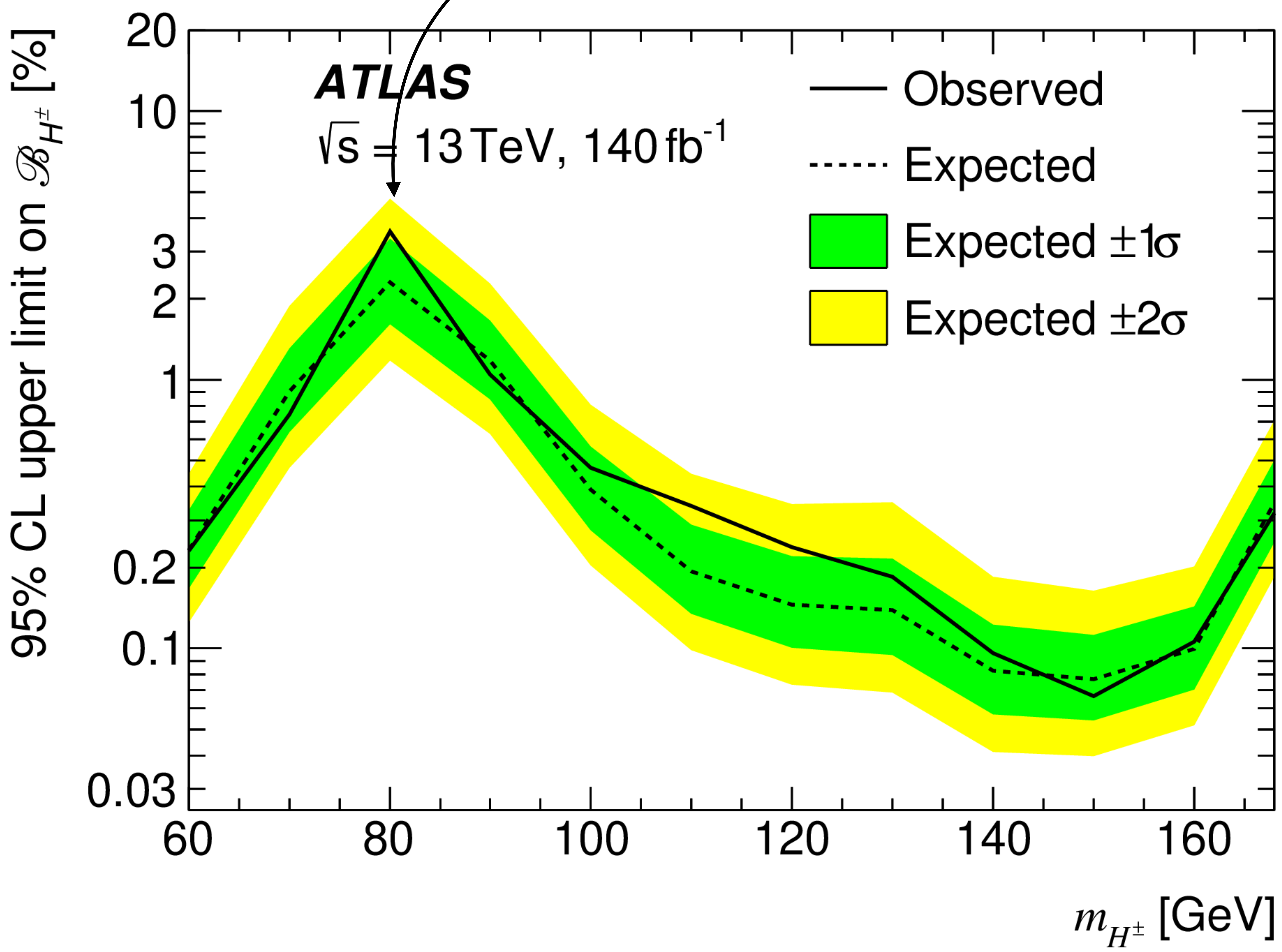
Light H± in top decays: H± → cs

ATLAS HDBS-2020-11

arXiv:2407.10096



Similar signal and $t\bar{t}$ background kinematics at 80 GeV (~ M_W)



*A **BDT**-score is used to fit for signal.*

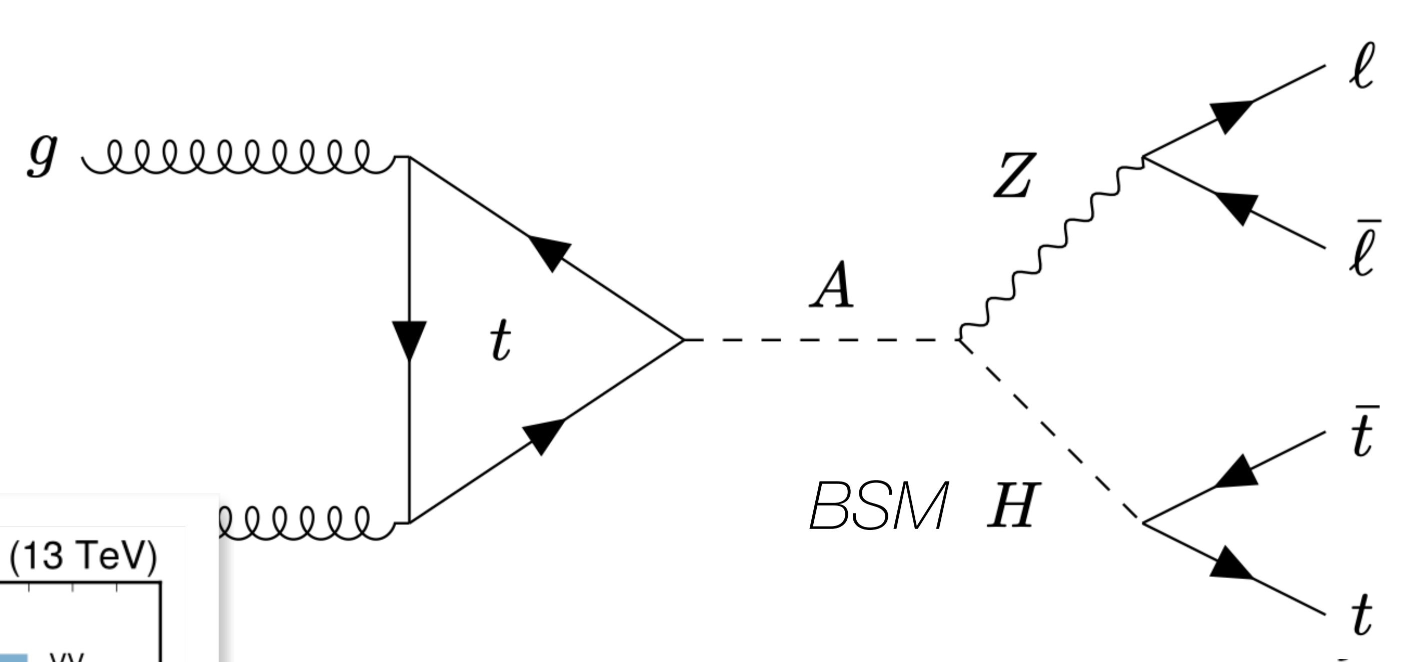
- *trained with **top-quark** kinematic variables, **event** variables (S_T, N_{jets},...), and **flavor-tagged** variables (b, c, light flavor jets).*
- *multiple versions are trained per-given-mass signal.*

The most stringent limits on this type of signal!

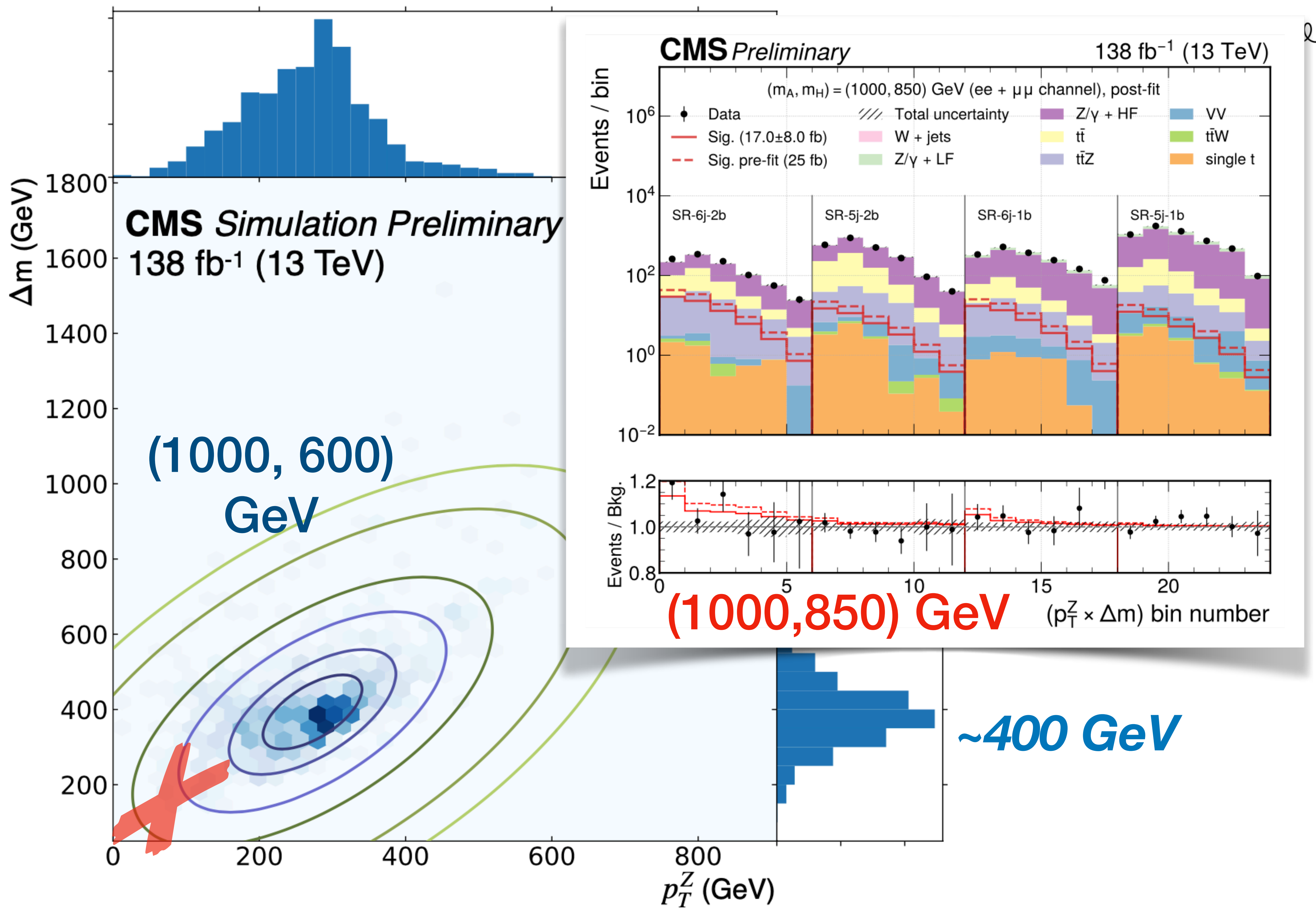
Multi-resonances

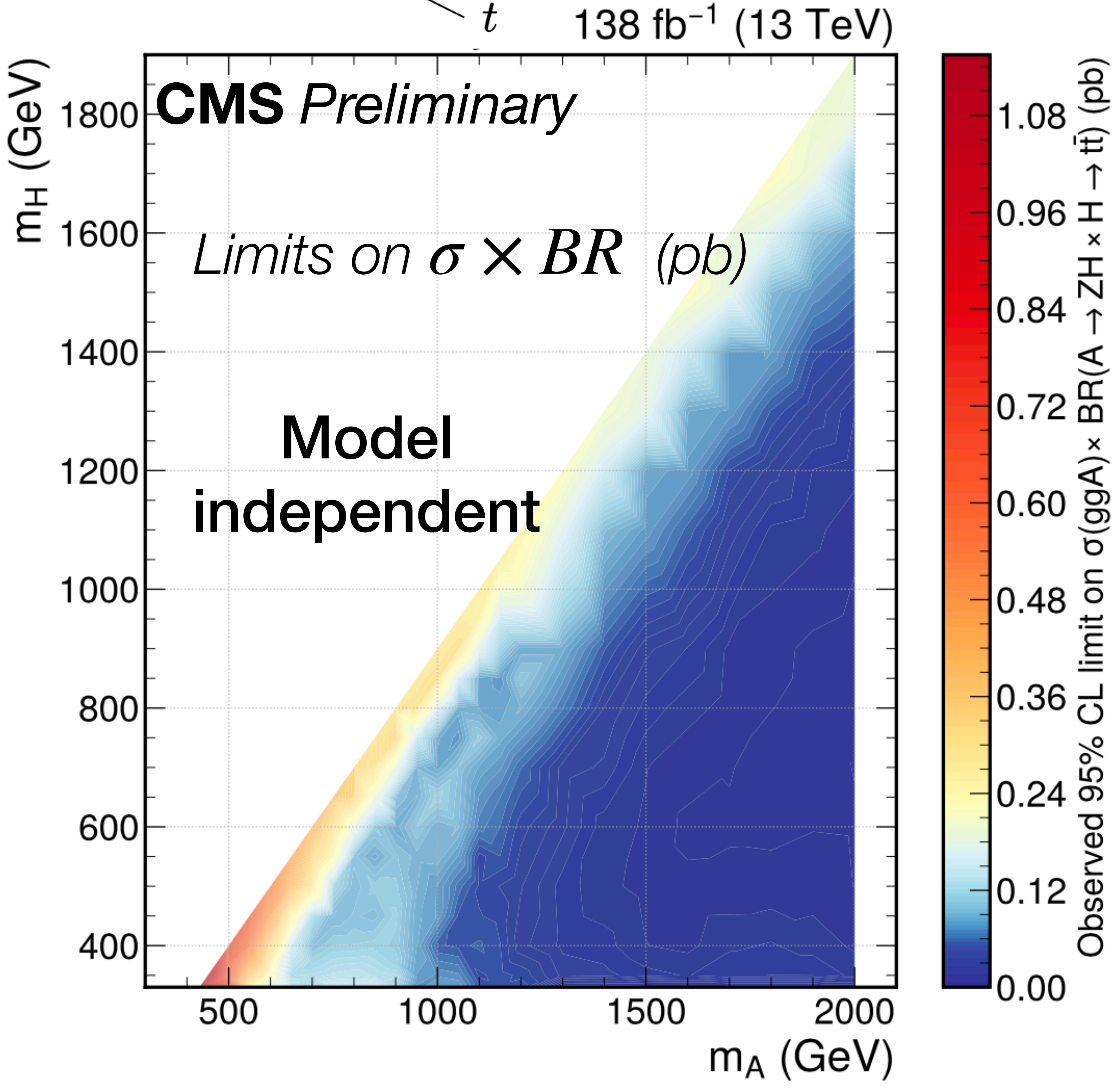
A→ZH (Z→ℓℓ, H_{BSM}→tt)

CMS PAS-B2G-23-006



Max Z p_T at ~300 GeV: ΔM - M(Z)





Triple-resonance structure: *Z (**dilepton**), $t\bar{t}$ (**6 or 5 jets**), and $t\bar{t}$+Z:*

→ *ΔM and Z p_T are used: Z p_T is a **clean, leptonic quantity,** cut-off defined by ΔM =m(ttZ)-m(tt).*

*ΔM **suppresses jet energy uncertainties.***

***Interference effects with SM ttZ are small** in these variables (w.r.t. experimental resolution).*

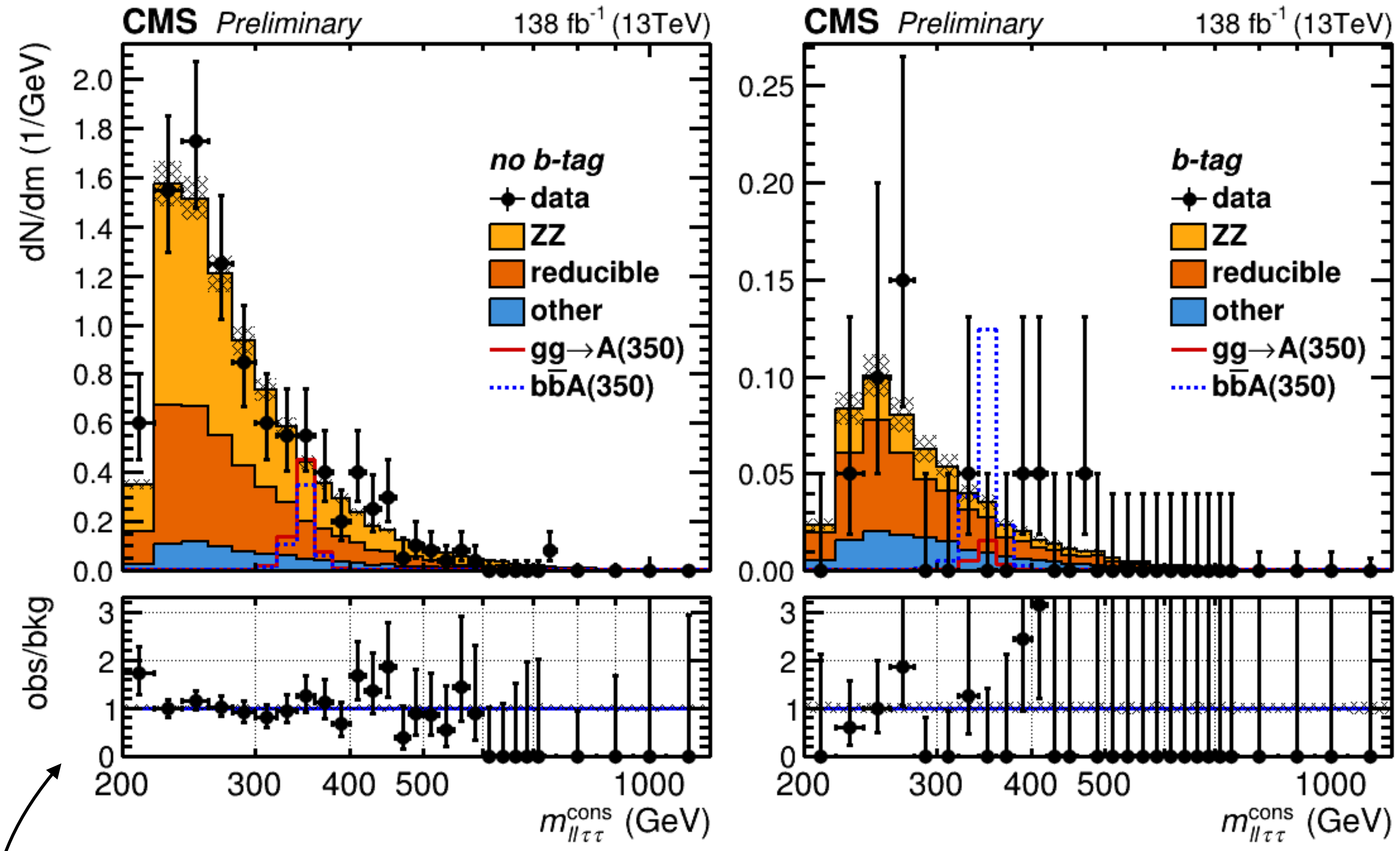
→ *Signal regions are carved out in **quantiles** around the peak on the ΔM and Z p_T plane*

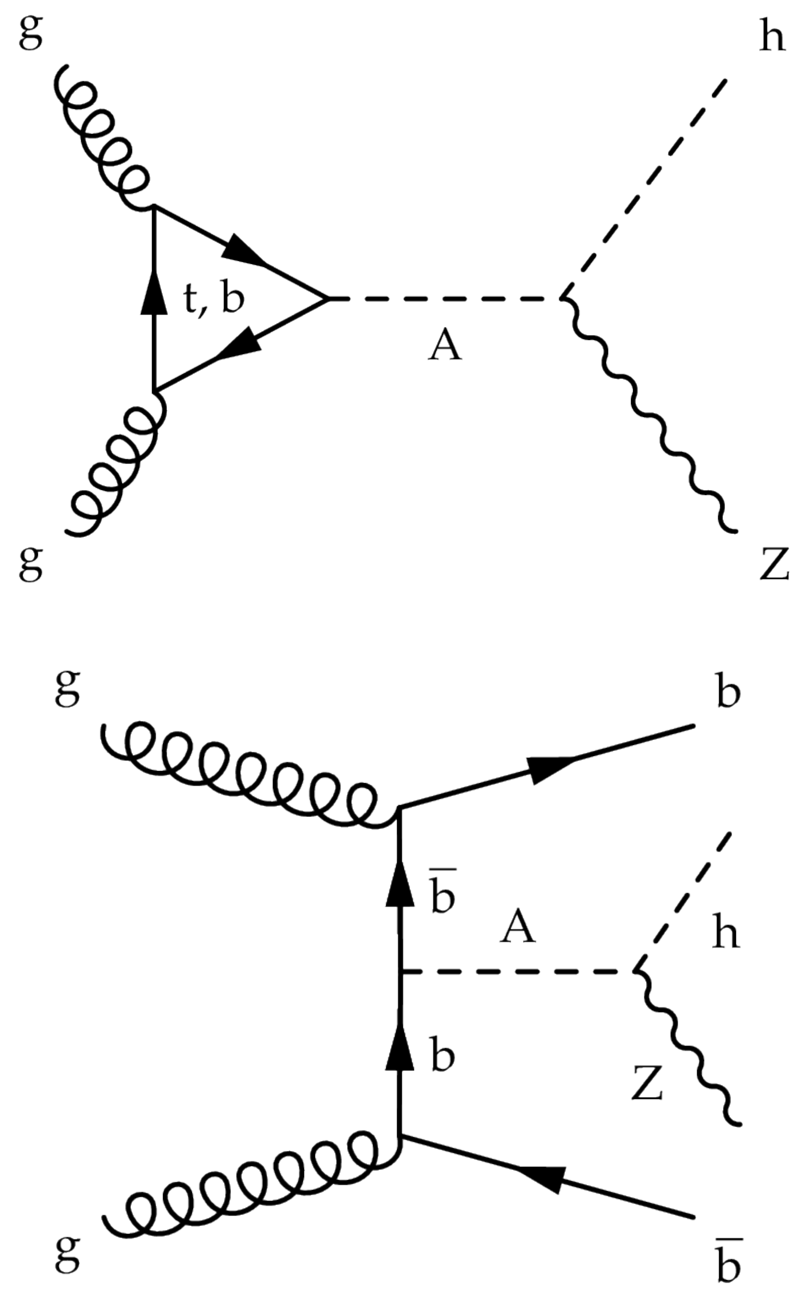
*Data driven 40% uncertainty on the **DY+heavy flavor component.***

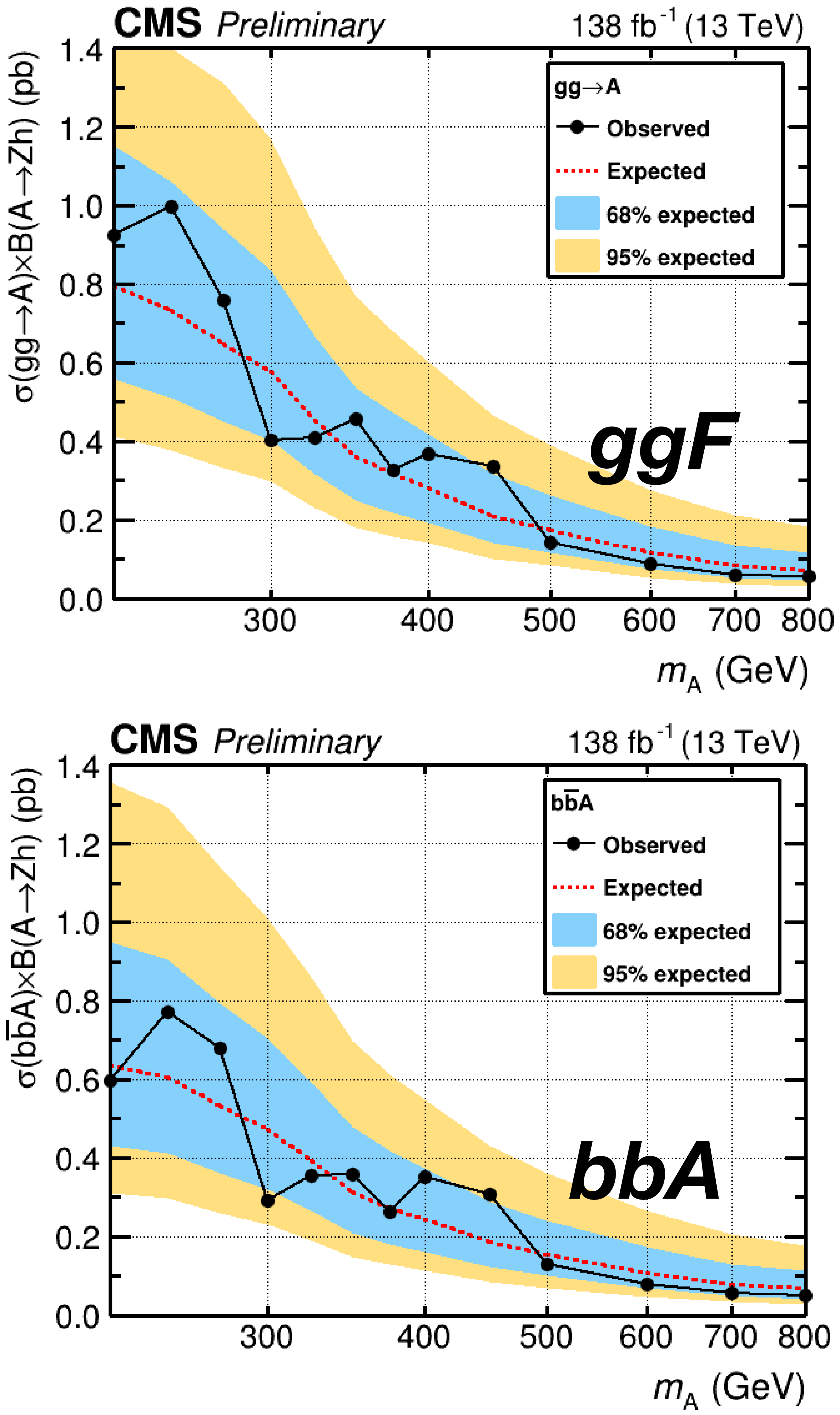
A→ZH (Z→ℓℓ, H_{125}→ττ)

$H \to bb$ decays are also targeted by ATLAS/CMS.

CMS PAS-HIG-22-004







***Six decay modes** are considered ($Z \to ee, \mu\mu$, $H \to \tau_h\tau_h/\tau_h e/\tau_h\mu$).*

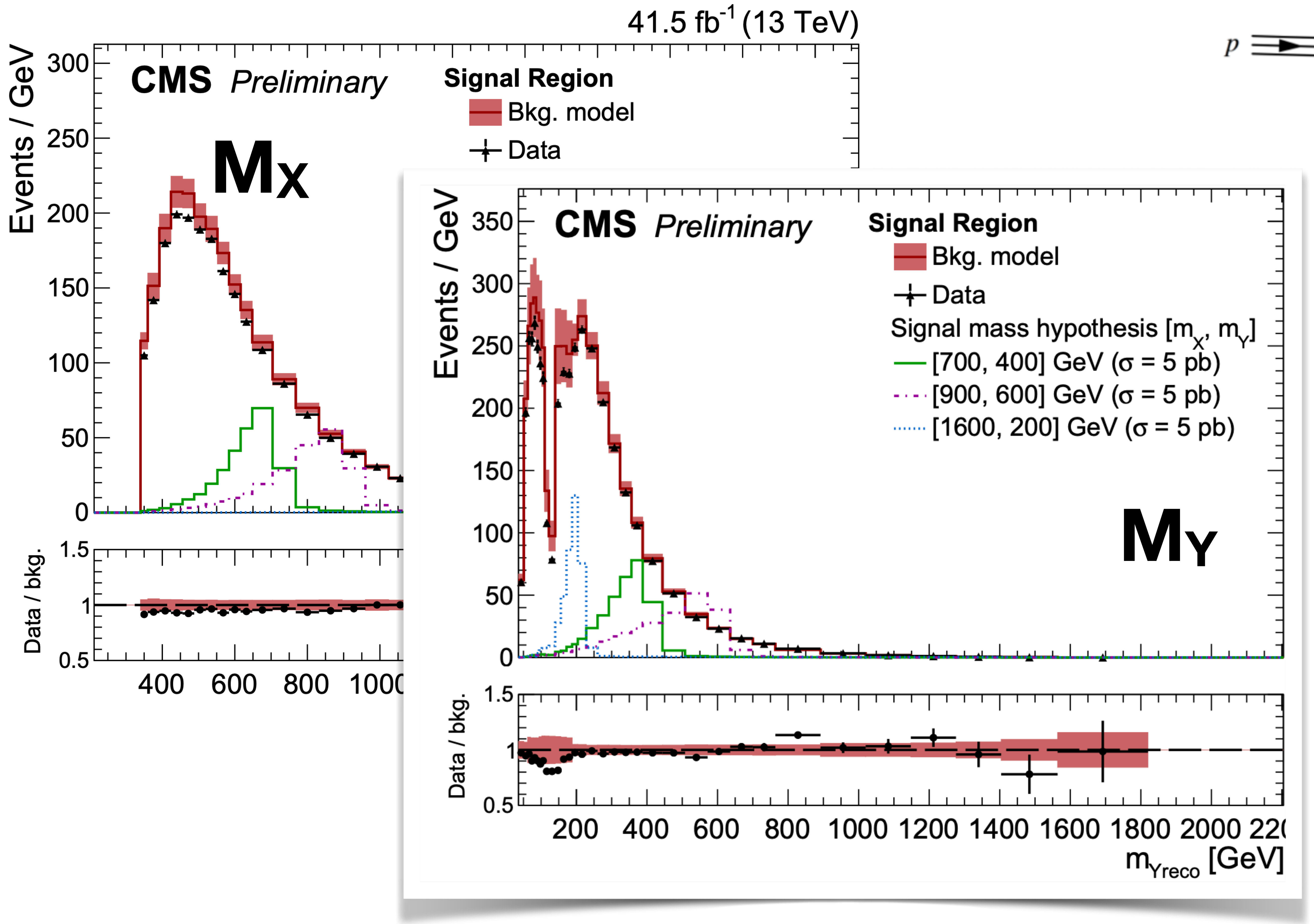
*"A" boson **mass reconstructed** via the **FastMTT algorithm to correct for MET***

→ *simplified likelihood function using MET (value and unc.) and visible tau decay products.*

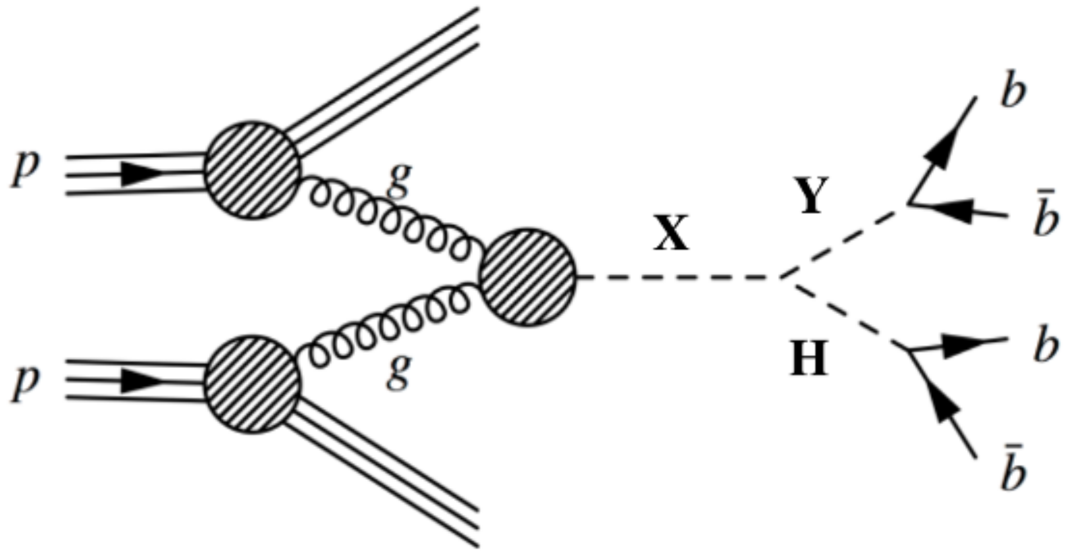
***ggF and bbA** production modes are fitted simultaneously with **2 signal strengths**.*

→ *Model dependent (MSSM) limits are also provided*

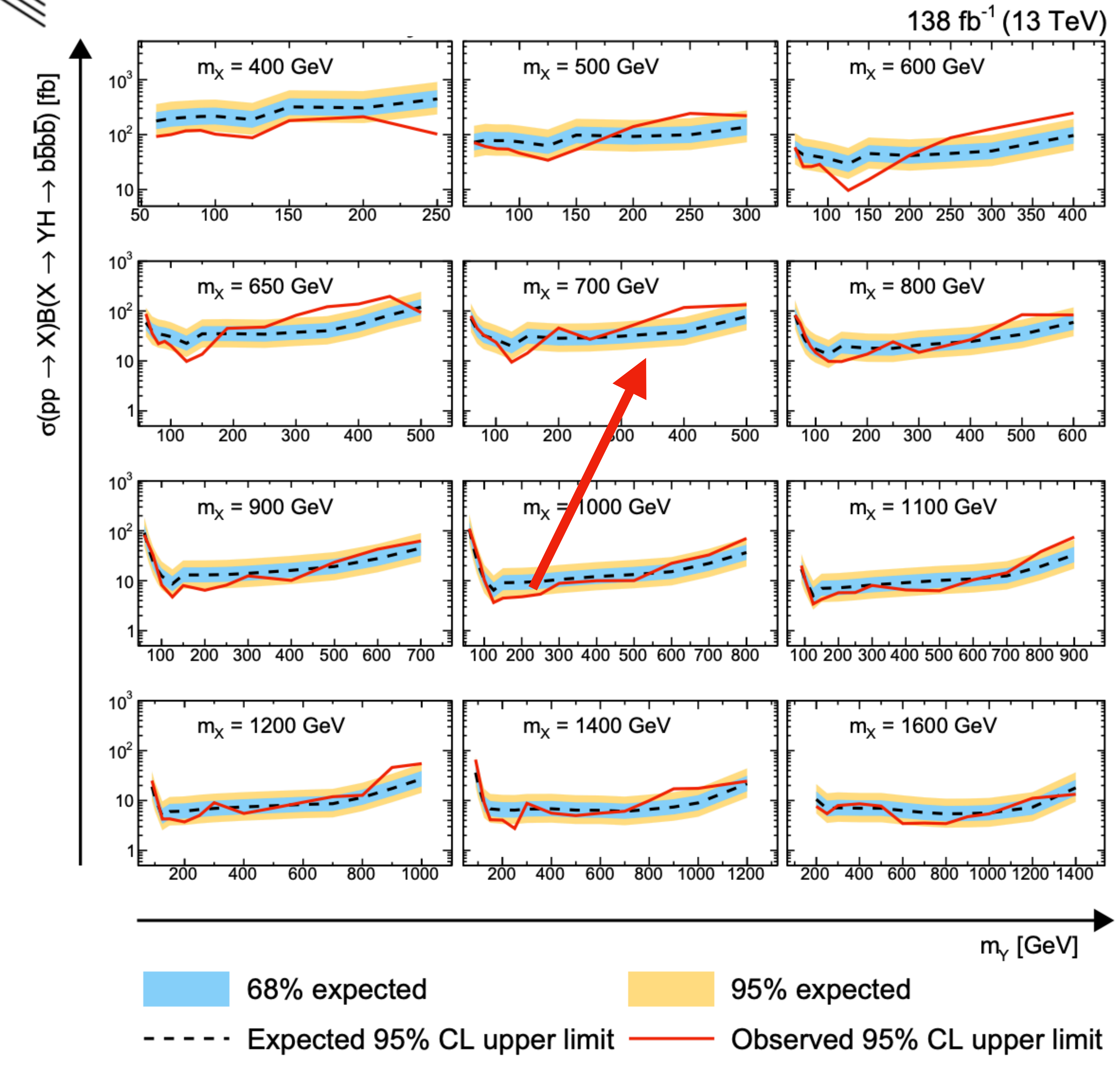
X→YH (Y→2b, H_{125}→2b)



CMS PAS-HIG-20-012



Model dependent (NMSSM) limits also provided



Resolved signature (4 jets, b-tagged)

*Signal is extracted via a **2D fit to the m_X-m_Y plane.***

*Events with **3 b-tagged jets are used for background estimation**, via a BDT-reweighter technique (arXiv:1608.05806)*

*Limits scan over the **X-Y mass plane**:*

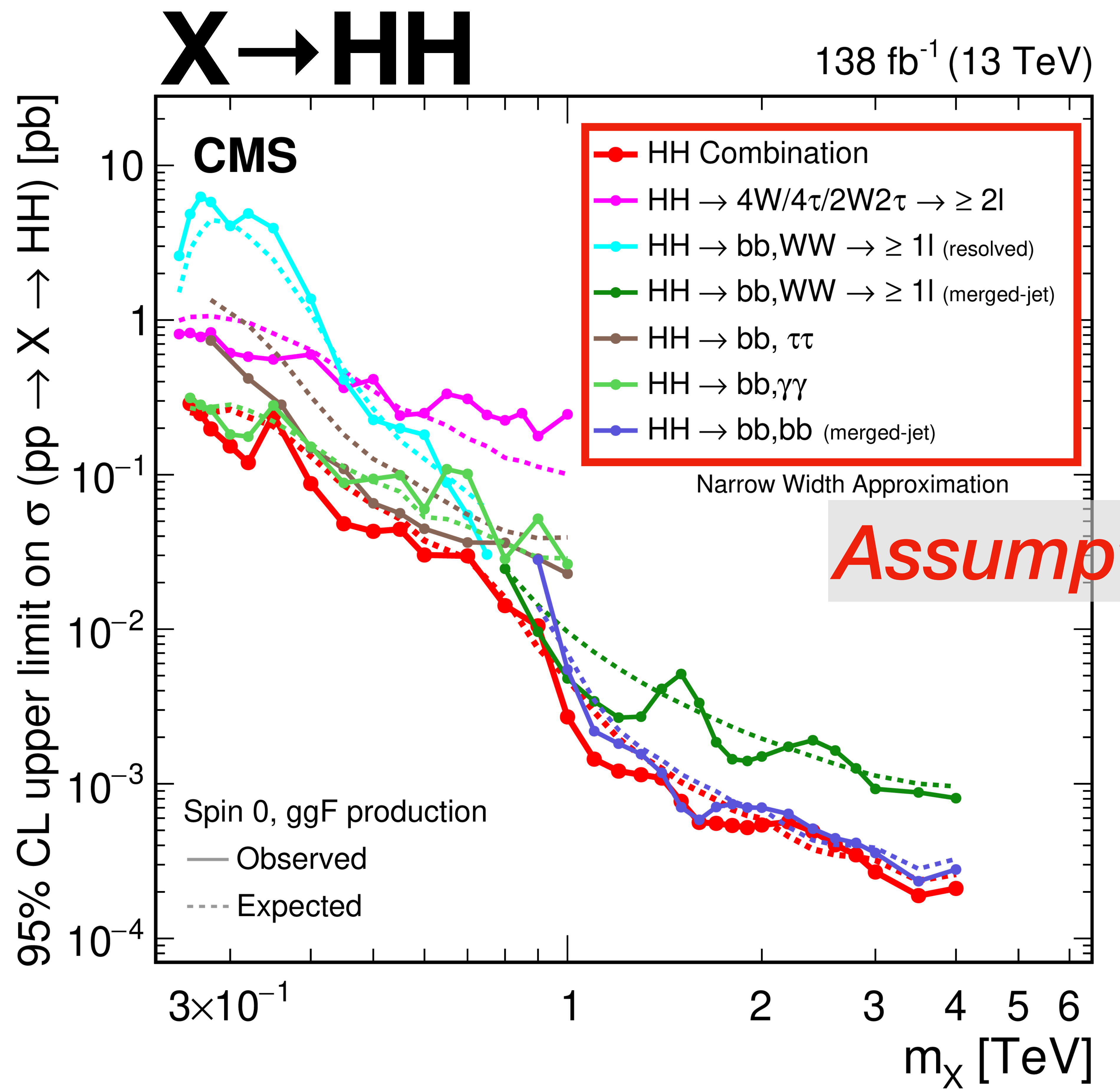
→ largest excess ~4.1 local (2.8 global) s.d. at (700,400) GeV

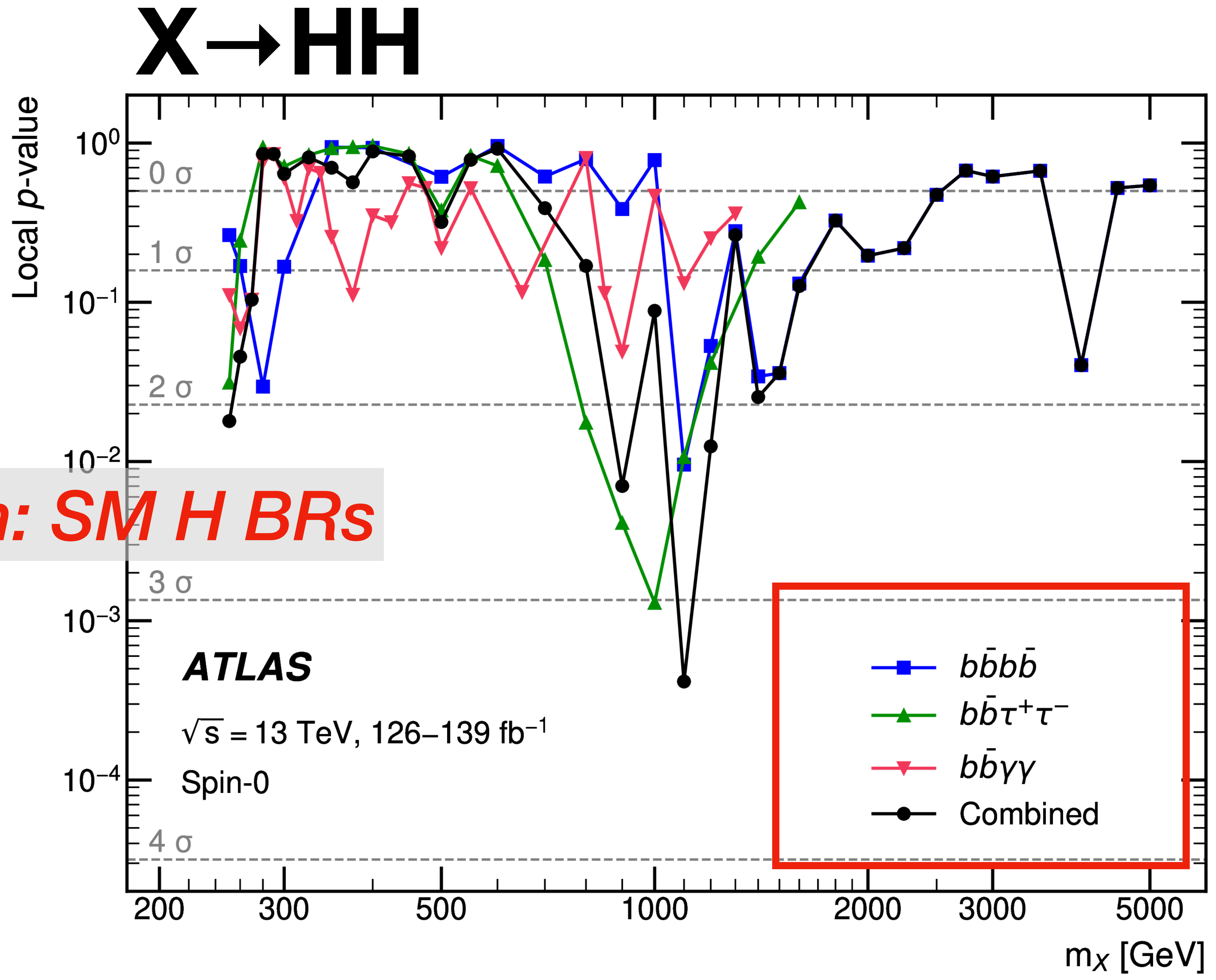
Also see ATLAS HDBS-2018-41 arXiv:2202.07288

Taking Run 2 stock: summary papers

CMS B2G-23-002 *arXiv:2403.16926*

ATLAS HDBS-2023-15 *arXiv:2405.04914*





Assumption: SM H BRs

The previous analyses belong to a much larger effort!

(HH, HV, HY, … with various interpretations including HVT, WED, etc)

Outlook

*Spin-0 BSM resonances provide an **extremely rich** signal space.*

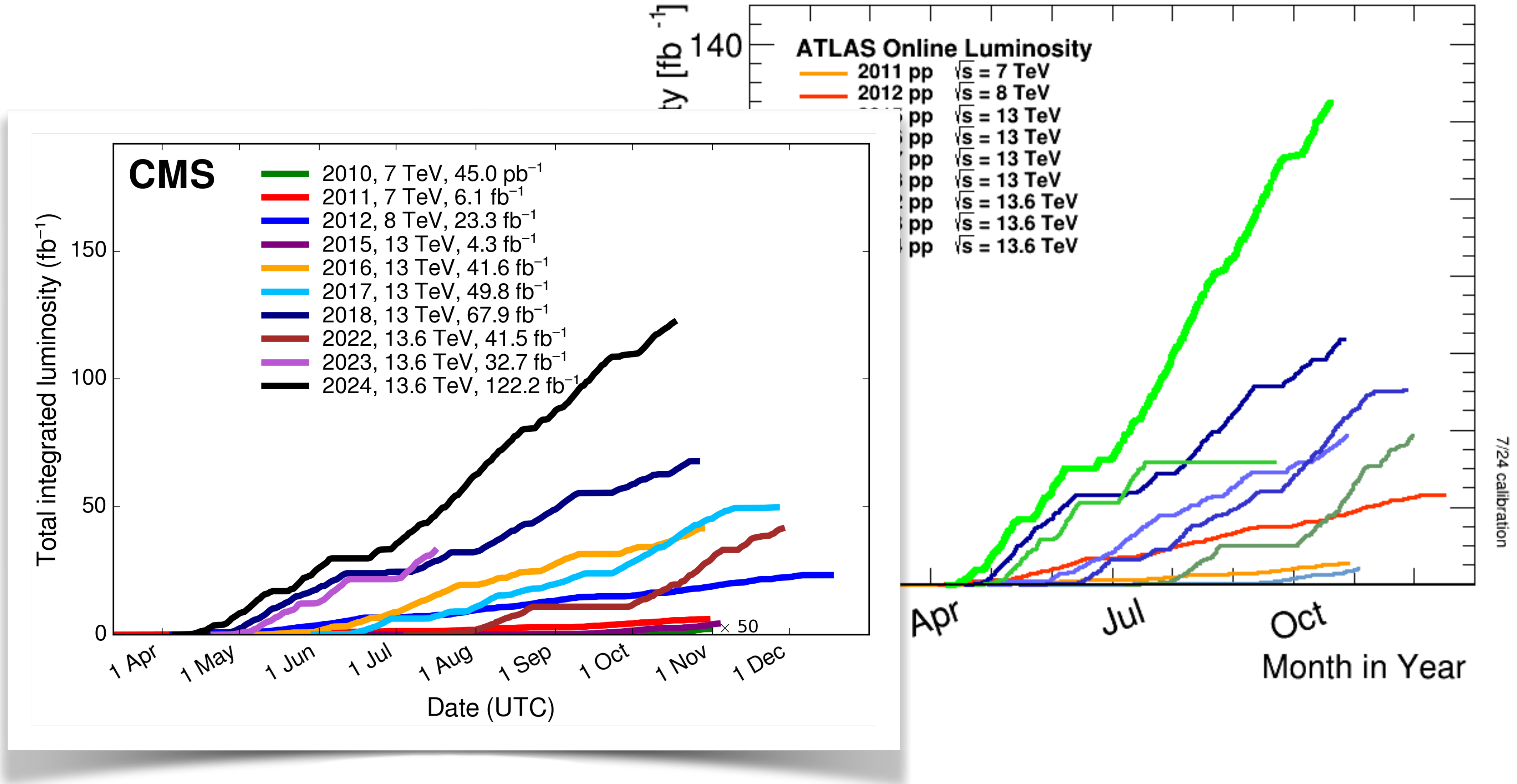
***Exotic possibilities** also exist (e.g. $\Phi \rightarrow \phi\phi$, $\mathrm{H} \rightarrow \phi\phi$, ..):*
- ***merged diphotons** CMS EXO-22-022 [arXiv:2405.00834]*
- ***displaced muons** ATLAS EXOT-2019-24 [arXiv:2203.00587]*
- ***displaced muons** CMS EXO-23-014 [arXiv:2402.14491] (Run3)*
- ***displaced jets** CMS EXO-23-013 [arXiv:2409.10806] (Run3)*
- ***soft taus** in scouting dataset CMS-NOTE-2024-006 (Run3)*

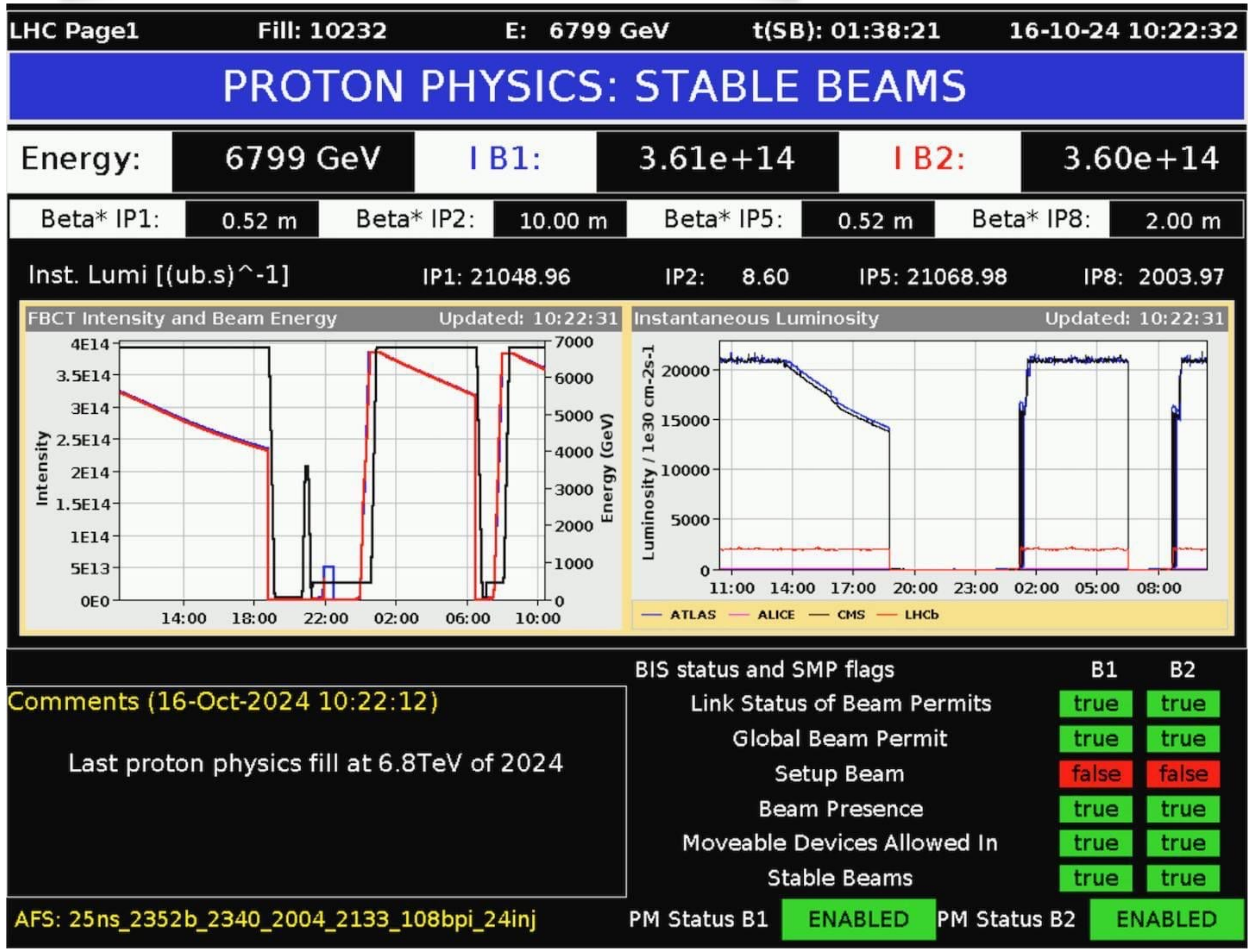
and many more!

Some excesses/deficits…, but:
- ***deficiencies**(?) in state-of-the-art SM simulations/calculations*
- *collective tensions(?) in **rare SM processes** vs BSM physics*
- *more data is a curse :) and the blessing!*

*Let us not forget the **“less common” decay modes***
- *decays into electrons ?*
- *flavor violation?*
- *…*

Data have the answer, waiting for the right question.





Backup

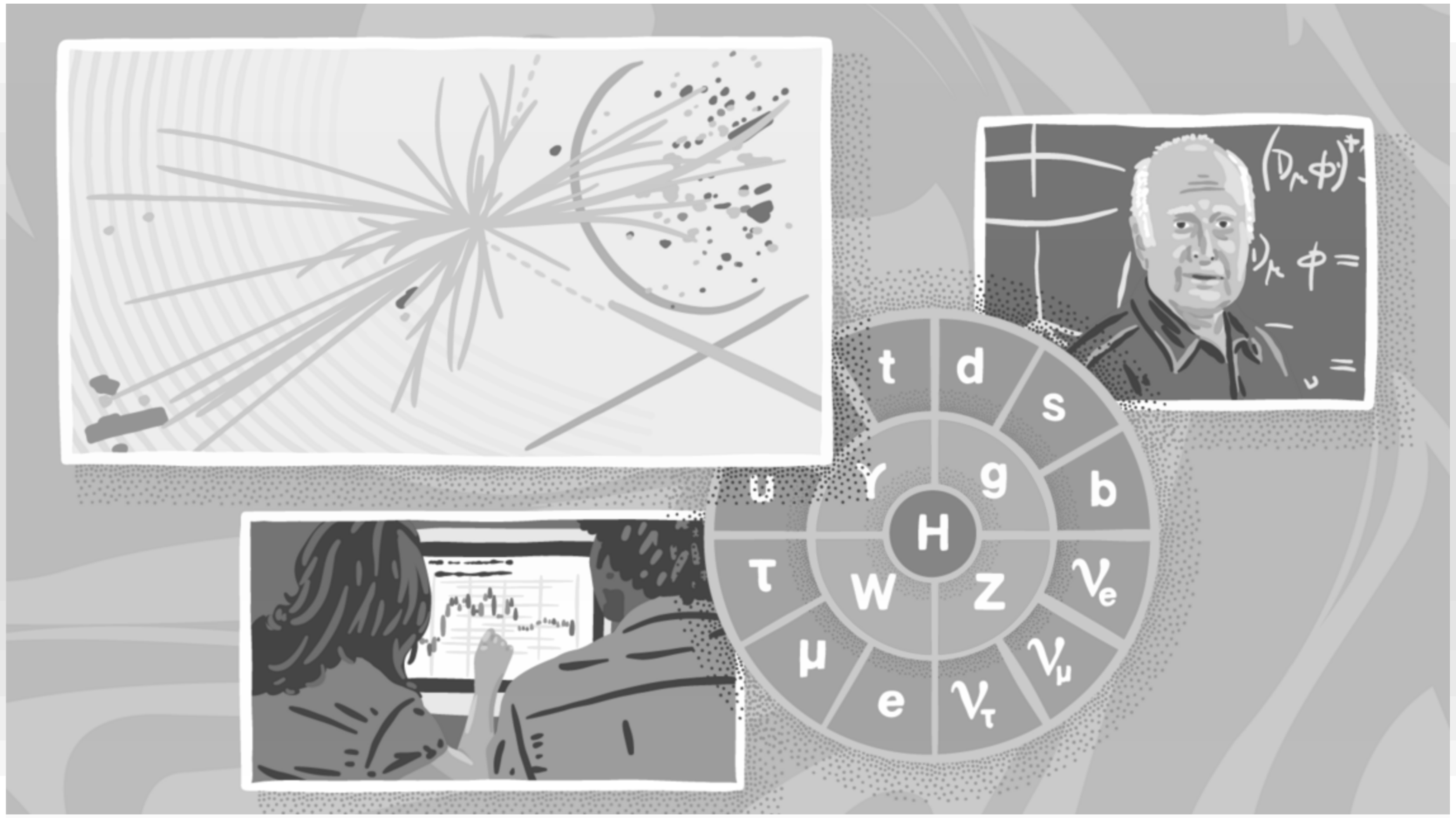
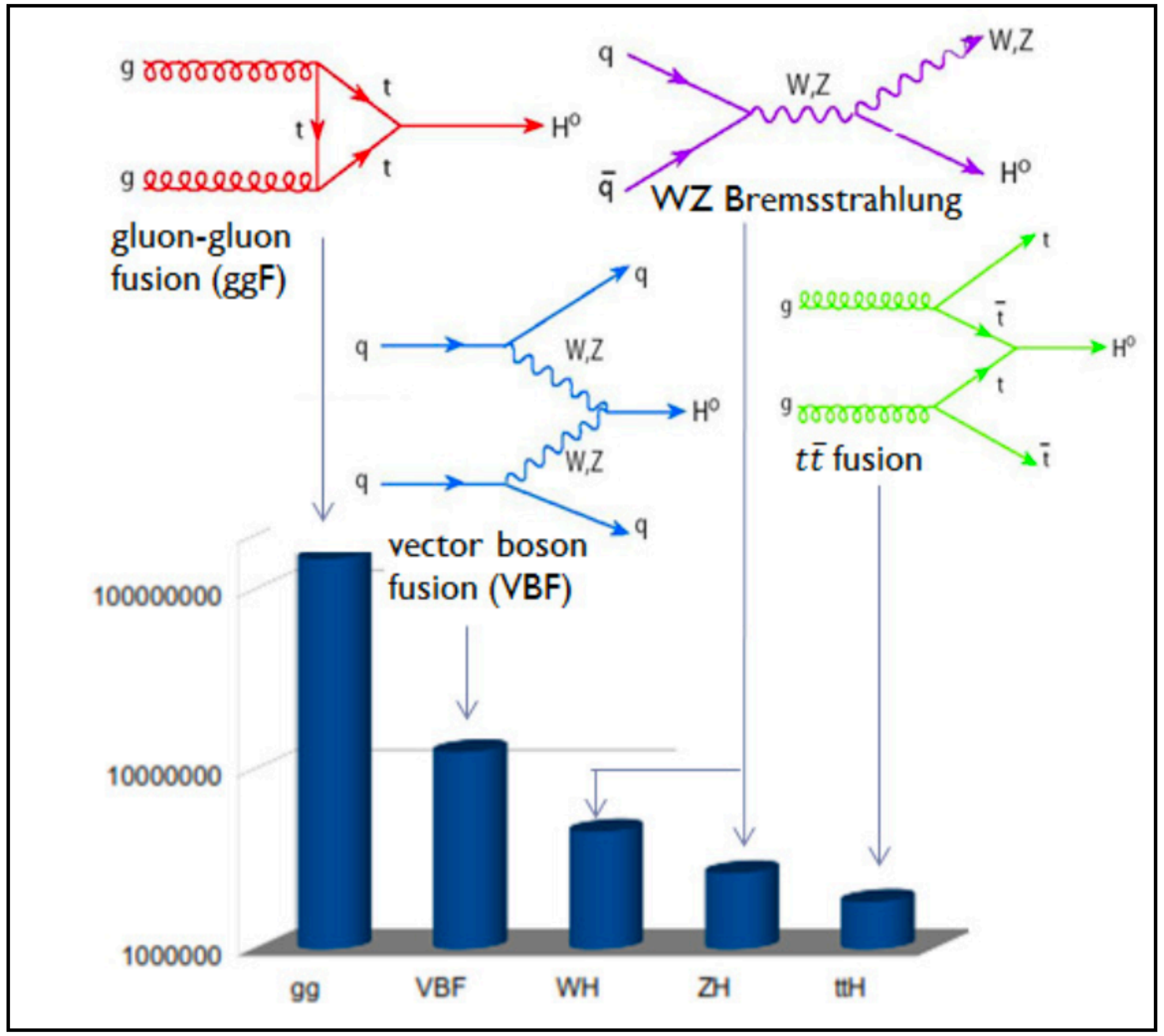


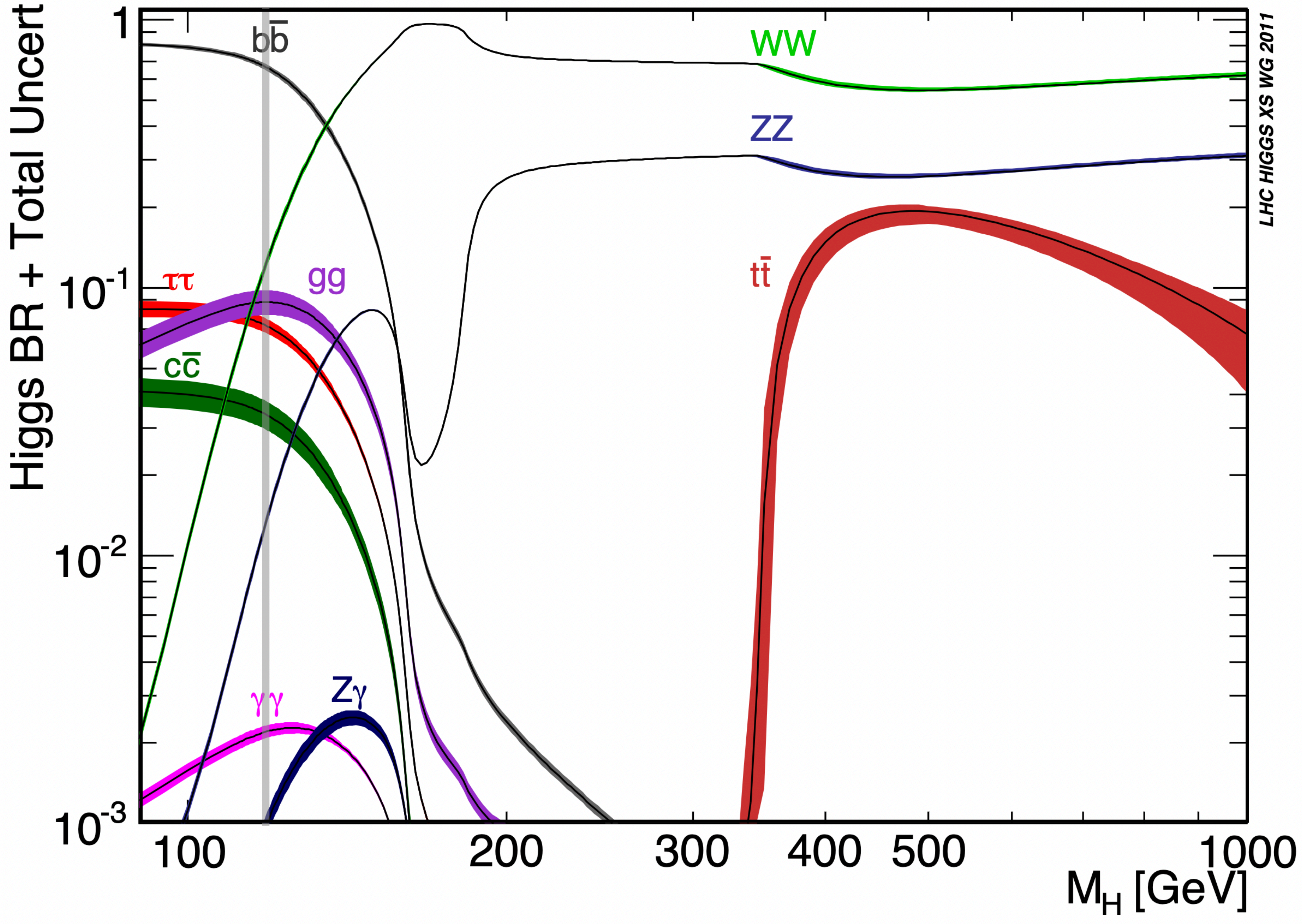
Illustration by Sandbox Studio, Chicago with Steve Shanabruch

https://www.symmetrymagazine.org/article/us-physicists-prioritize-closer-study-of-the-higgs

Higgs boson production and decay

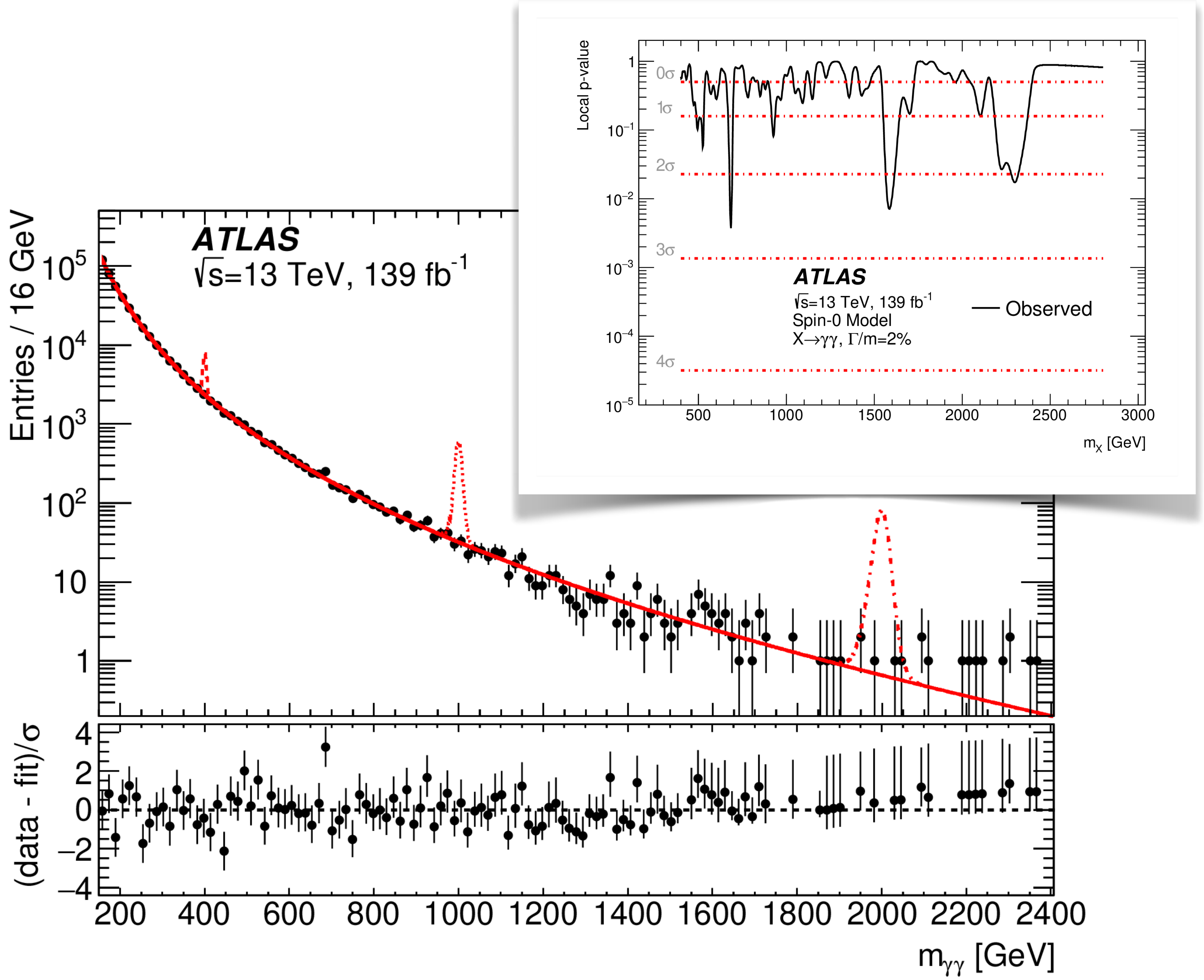


ggF and VBF are the dominant production modes at the LHC.

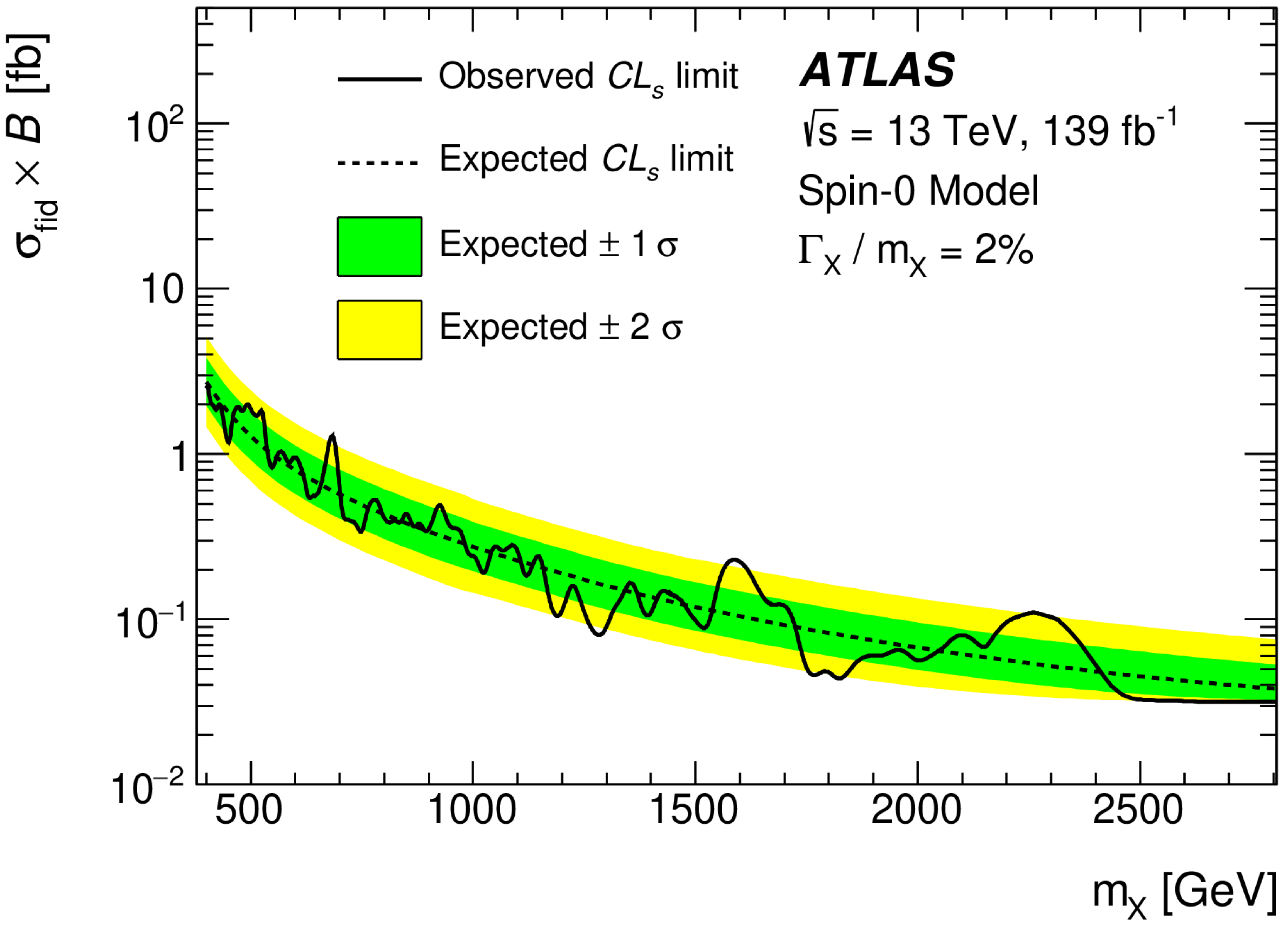


H→γγ (high mass)

ATLAS HIGG-2018-27
arXiv:2102.13405



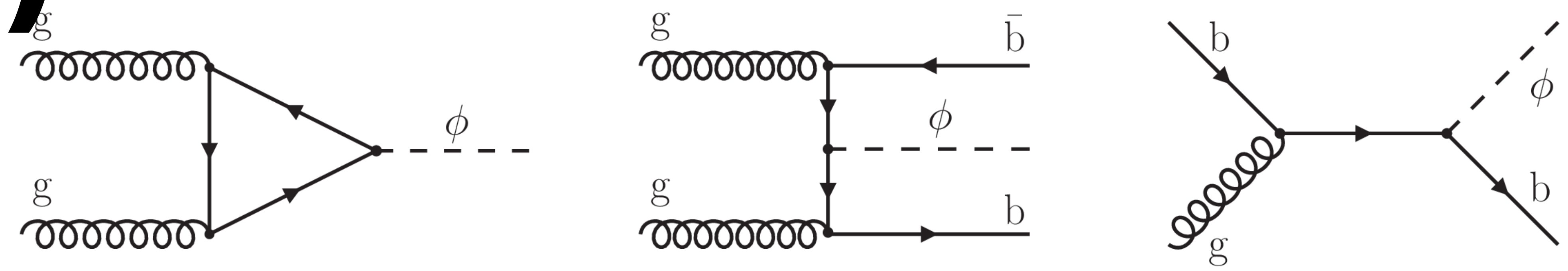
Heaviest mass observed is ~2.36 TeV

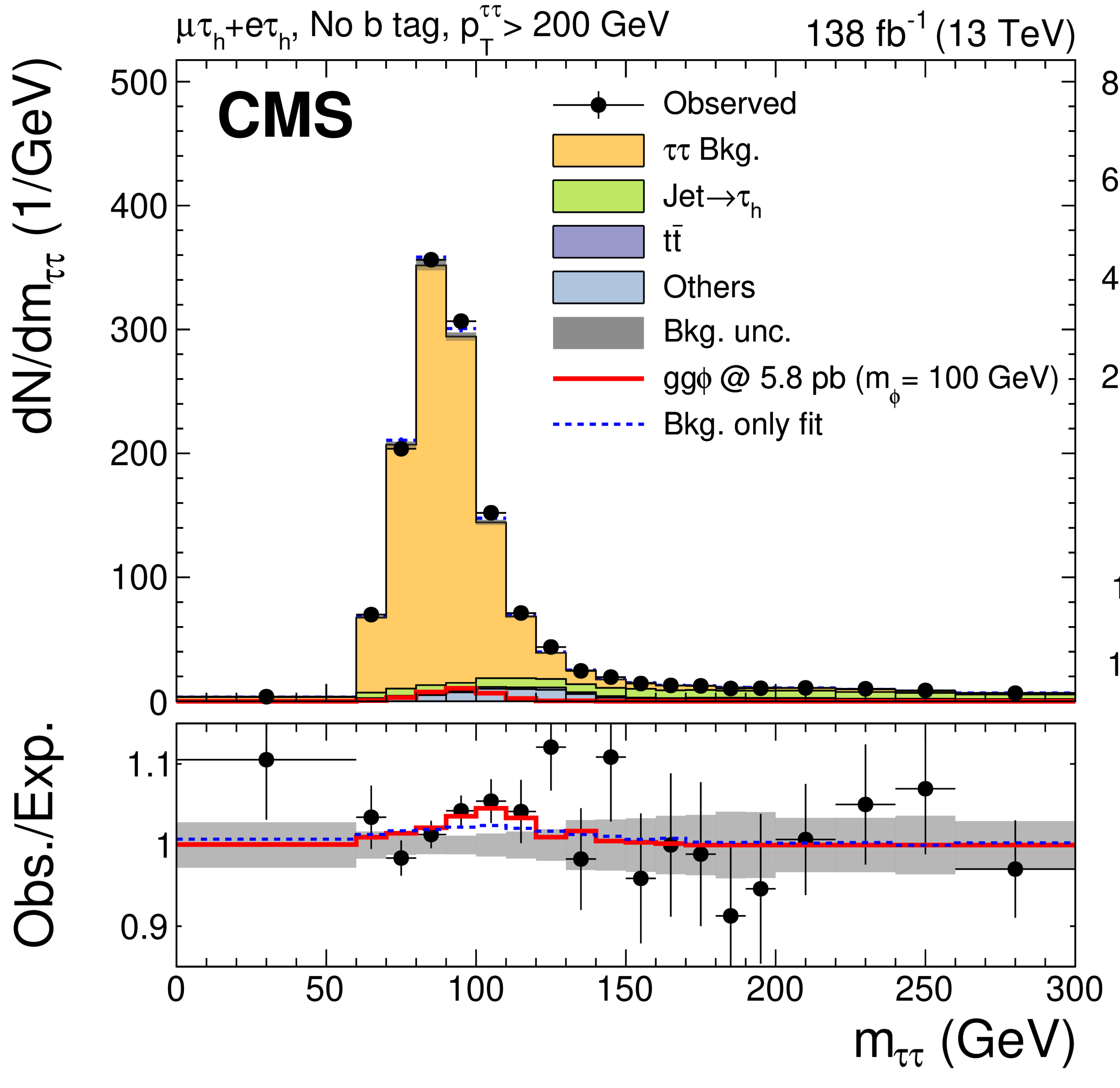


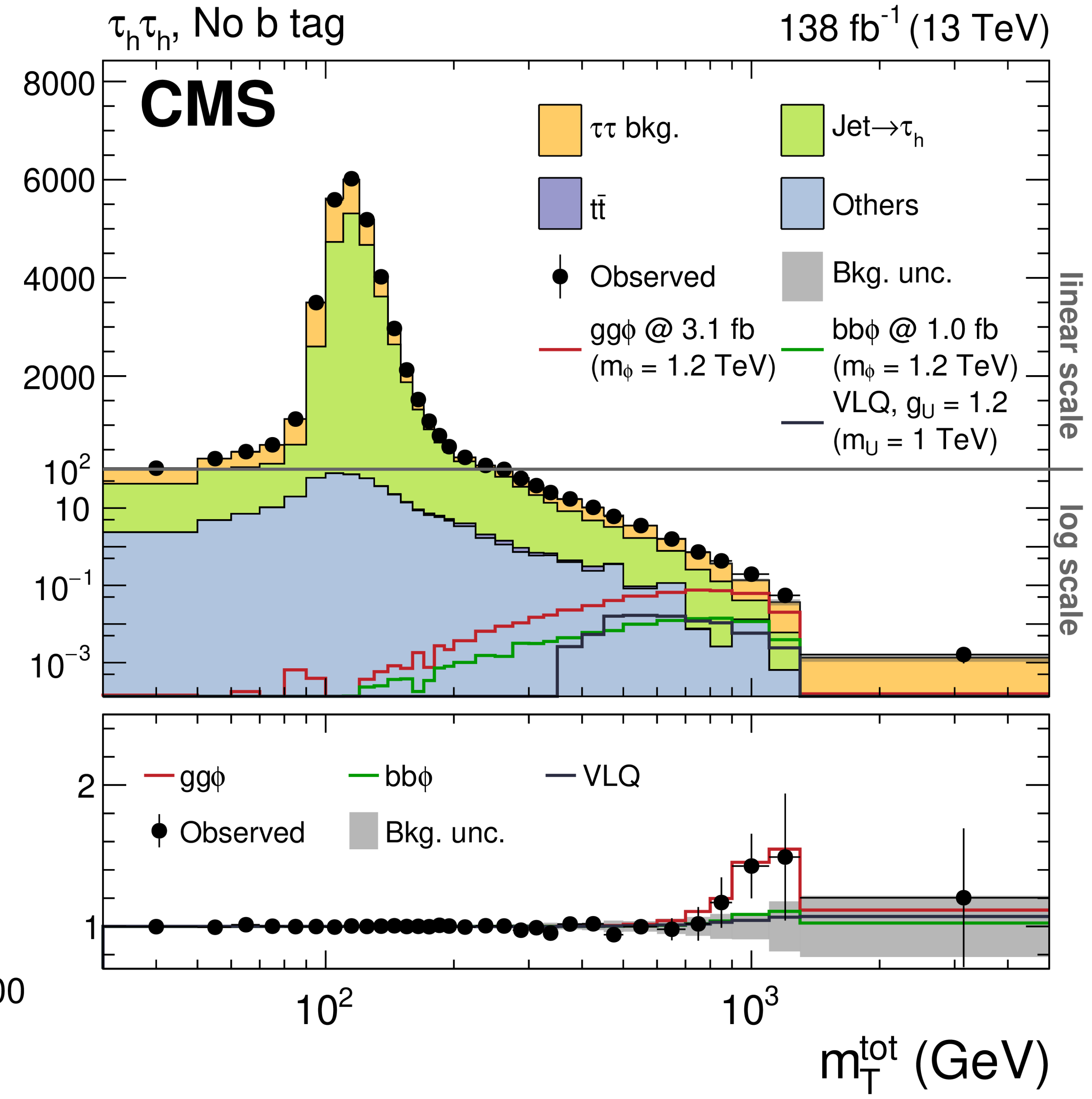
H→ττ (low/high mass)

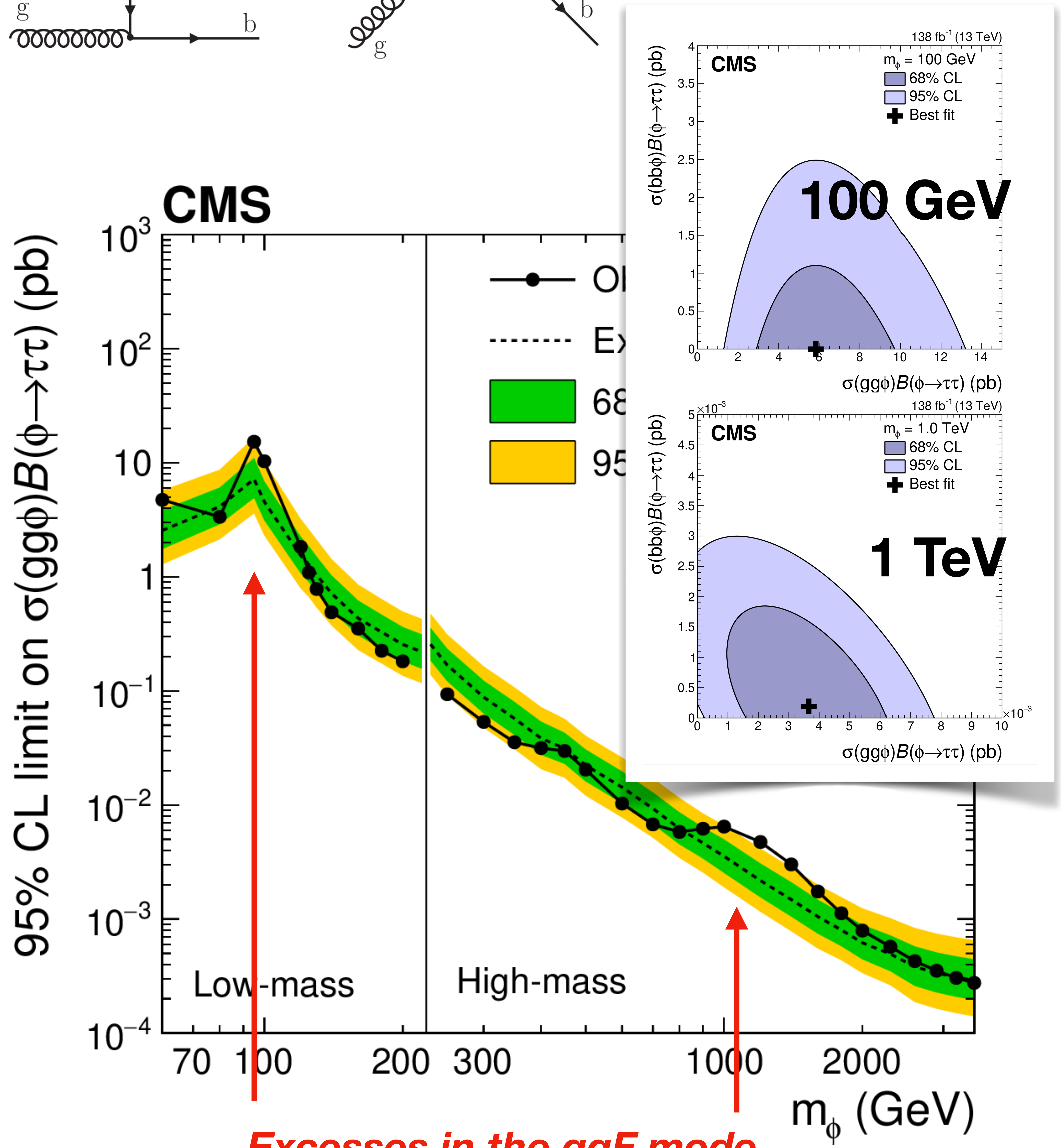
CMS HIG-21-001

arXiv:2208.02717









Excesses in the ggF mode

*Targets **direct and b-associated production modes**.*

*Irreducible ττ background is estimated via the **"tau-embedding"** method.*

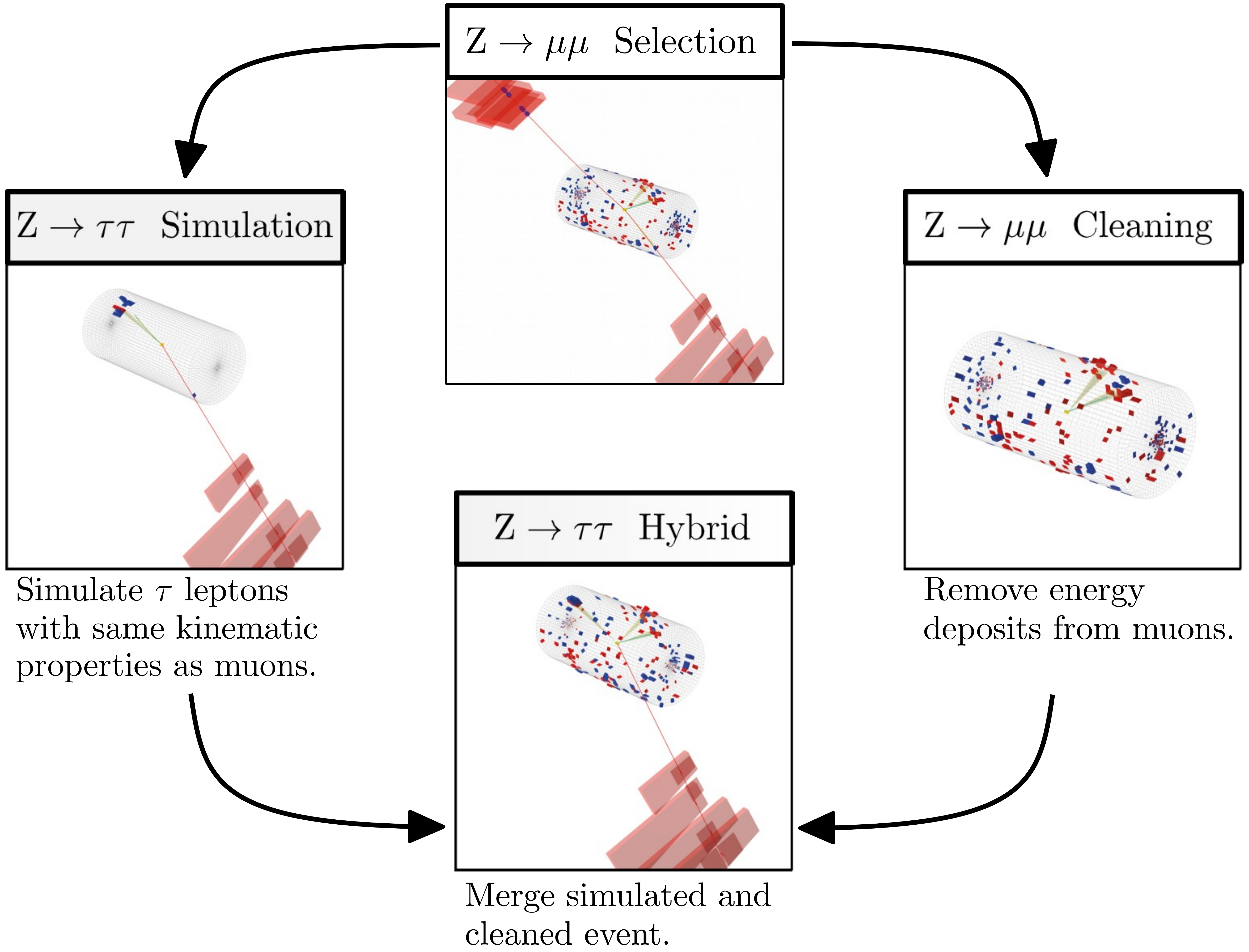
***Interference effects** among different production modes are taken into account → modifies the p_T spectrum of the new resonance.*

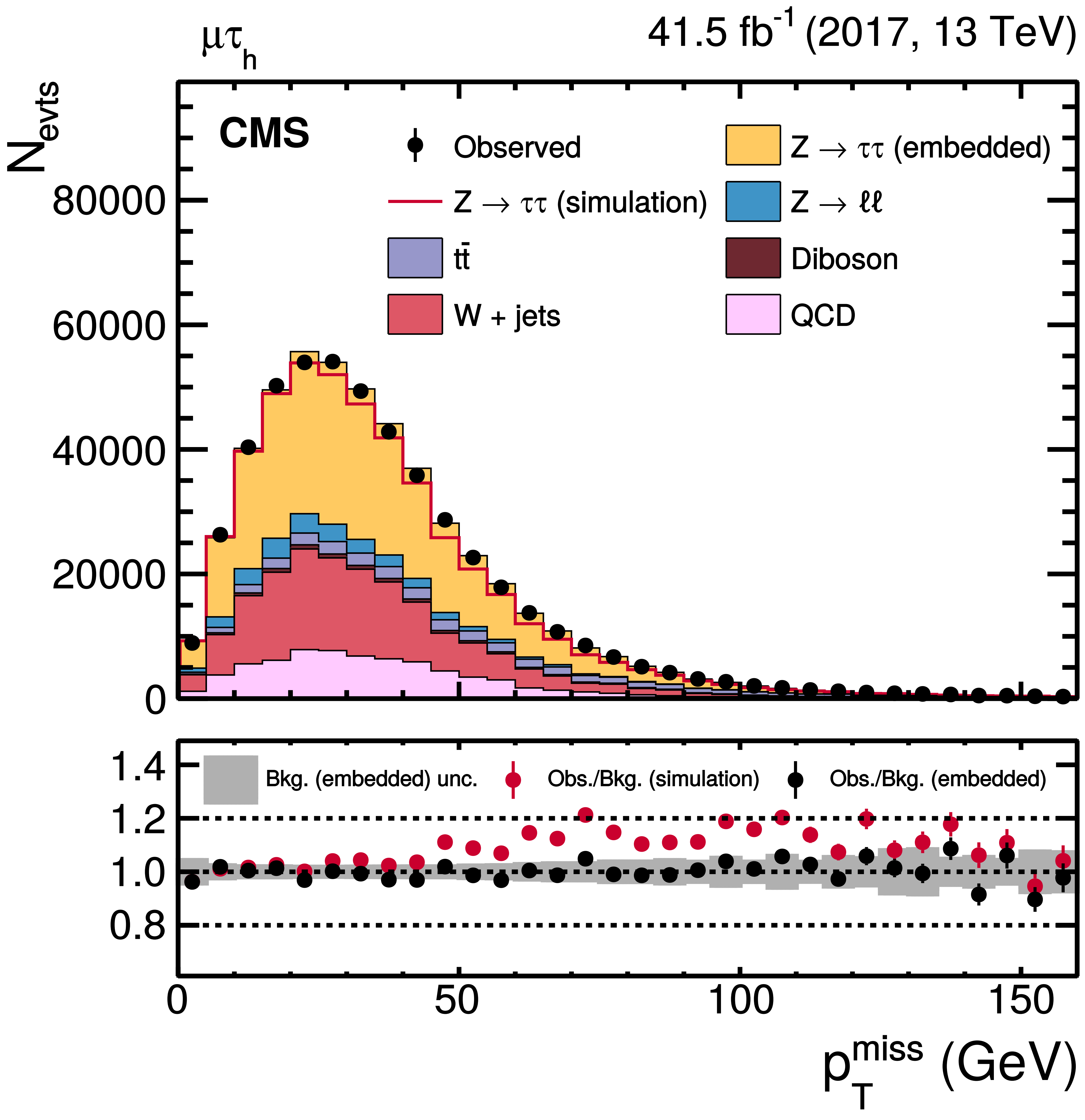
2HDM interpretations are also provided, with an NN-aided multi-categorization signal and background processes.

Tau embedding technique

CMS TAU-18-001

arXiv:1903.01216



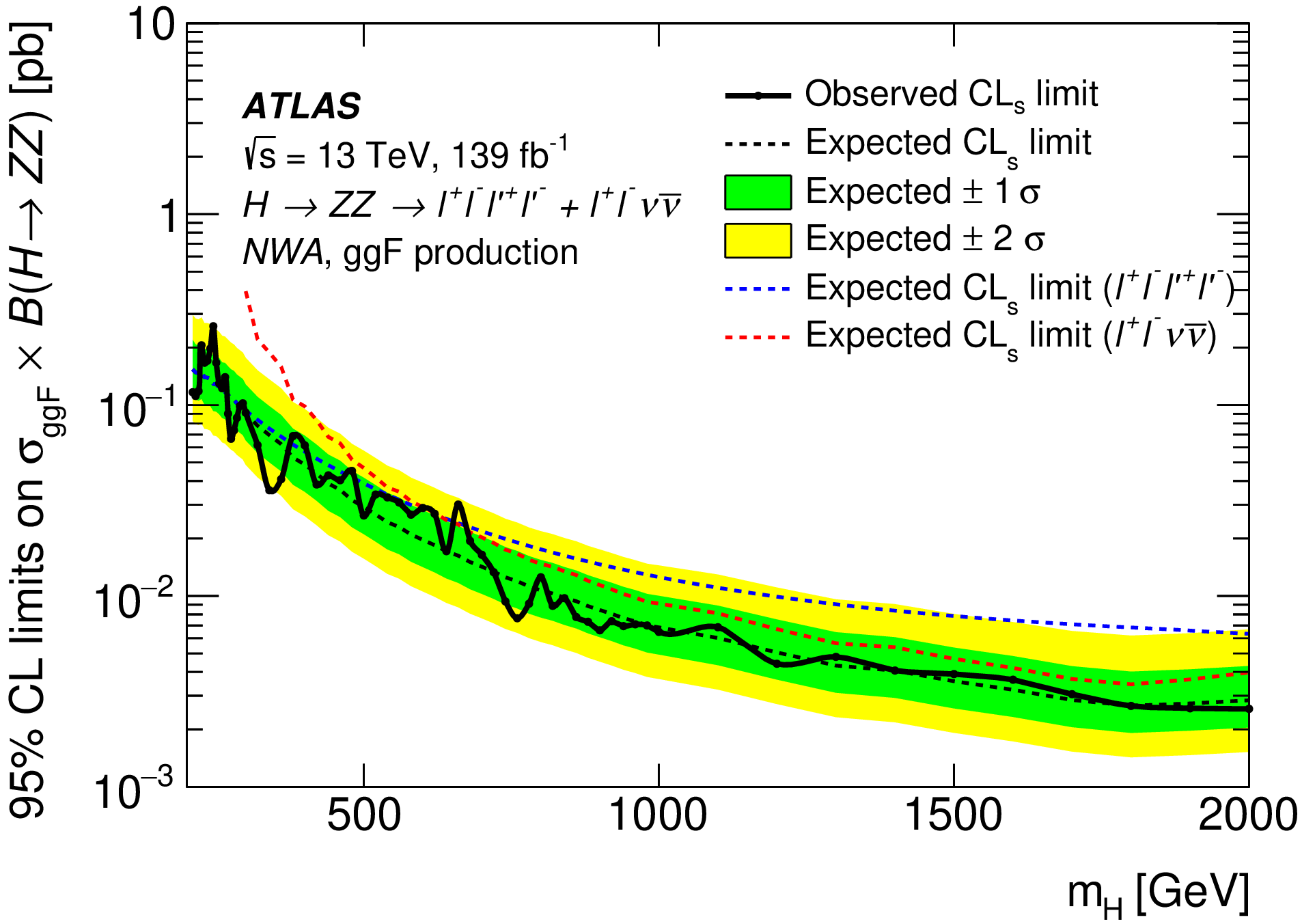


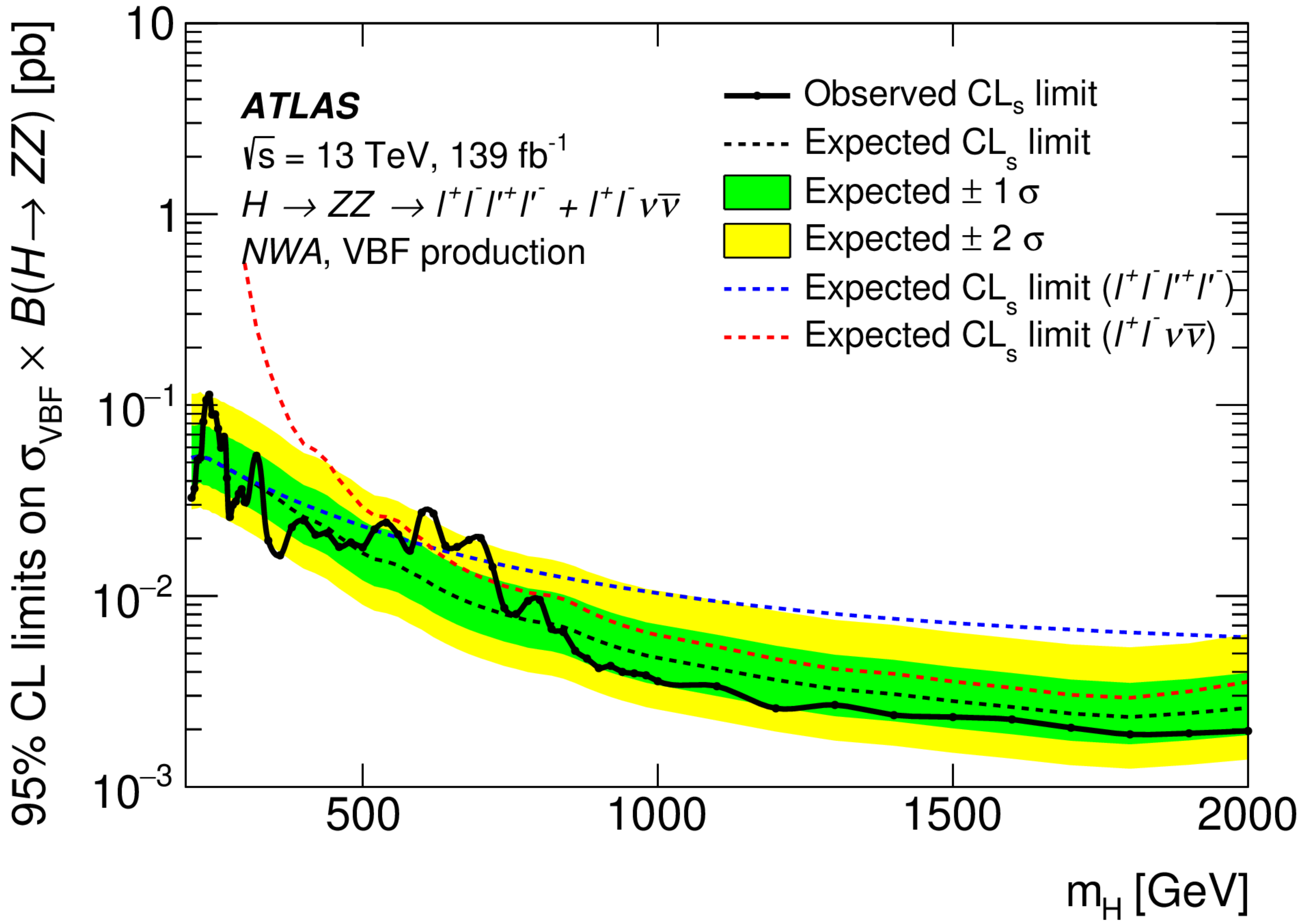
Embedding technique eliminates possible issues with underlying event description, pileup contributions, or production of associated jets.

X→ZZ→ℓℓℓℓ/ℓℓνν

ATLAS HIGG-2018-09

arXiv:2009.14791





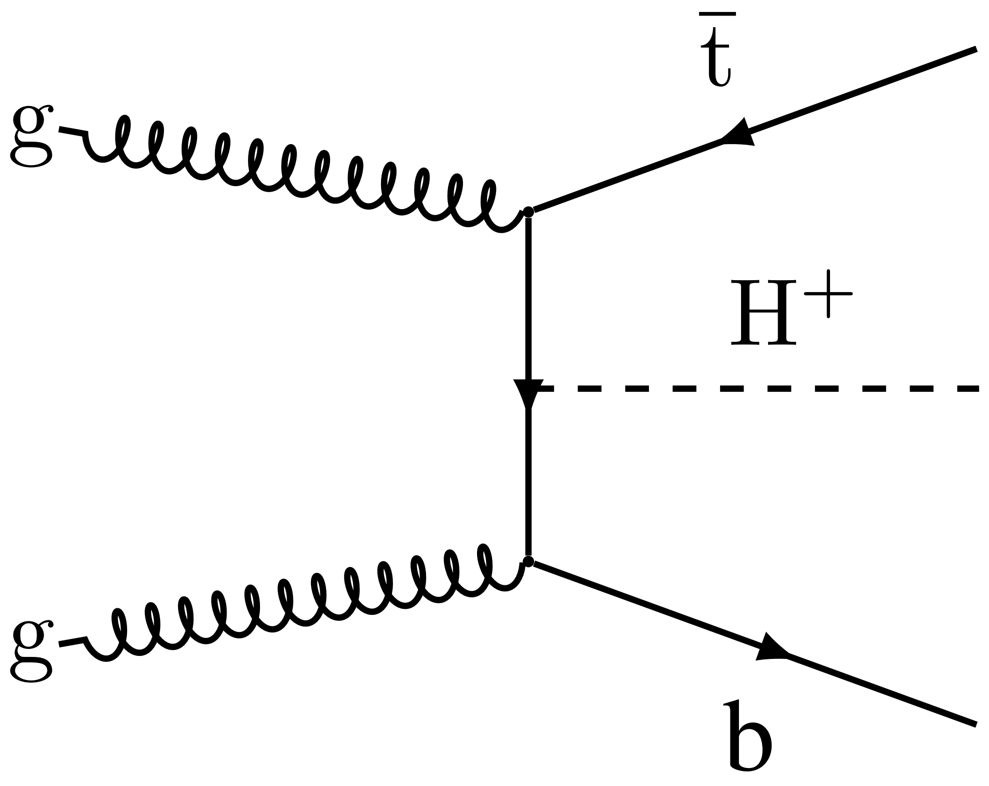
Limits, as obtained in the "cut-based" categorization.

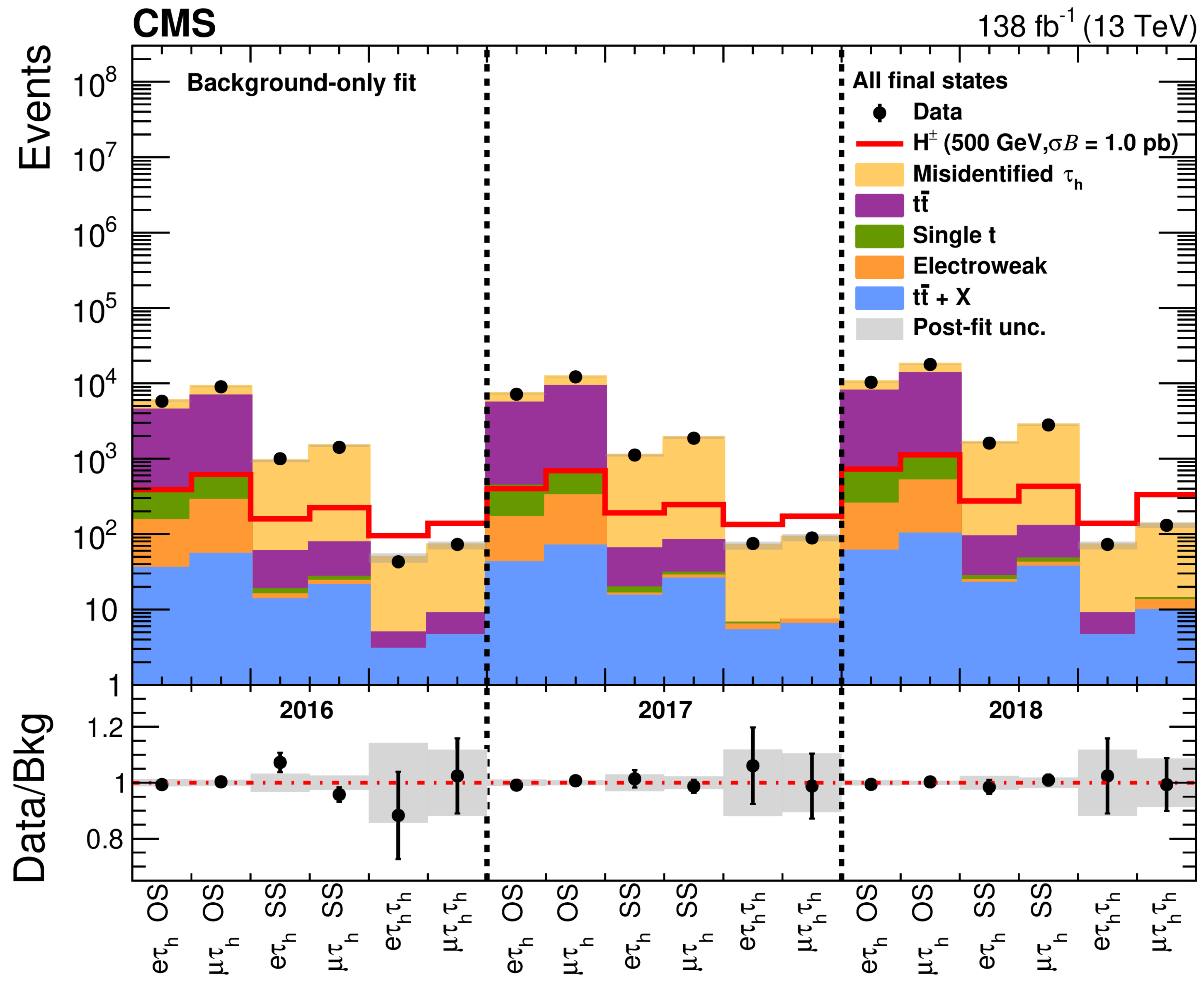
$H^{\pm} \rightarrow HW^{\pm}$ $(H \rightarrow \tau\tau)$

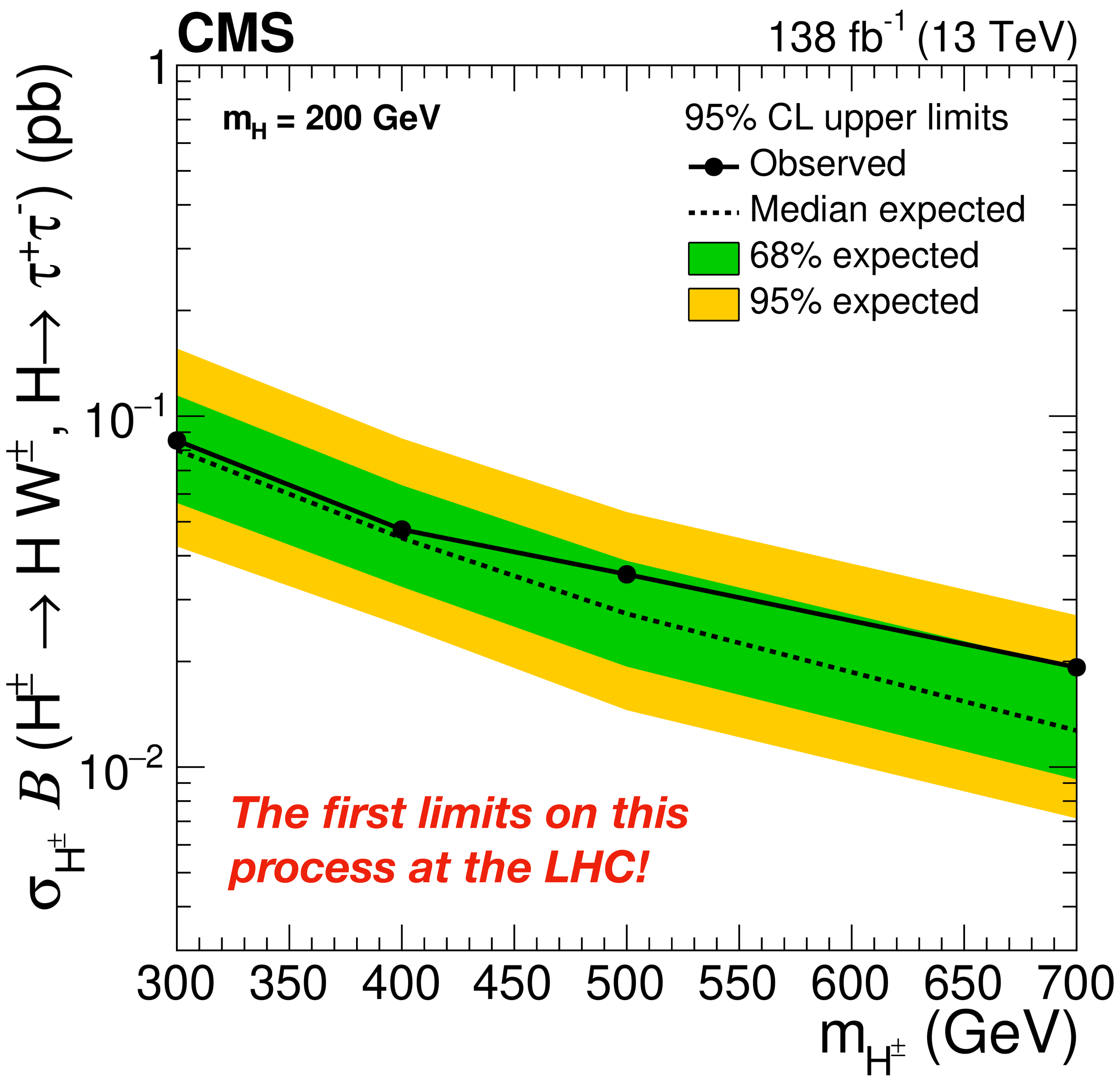
CMS HIG-21-010
arXiv:2207.01046

Charged scalar produced in assoc. with top and b quarks
- *complicated final state*, heavy resonance not readily reconstructible

Lepton-based categorization (flavor and charge, OS/SS):
- 2L: $e\tau, \mu\tau$, 3L: $e\tau\tau, \mu\tau\tau$
- **BDT-based approach in dilepton** final states
  — *also using tagging of* ***hadronic decays of top*** *quarks.*
- **Transverse mass in trilepton** final states

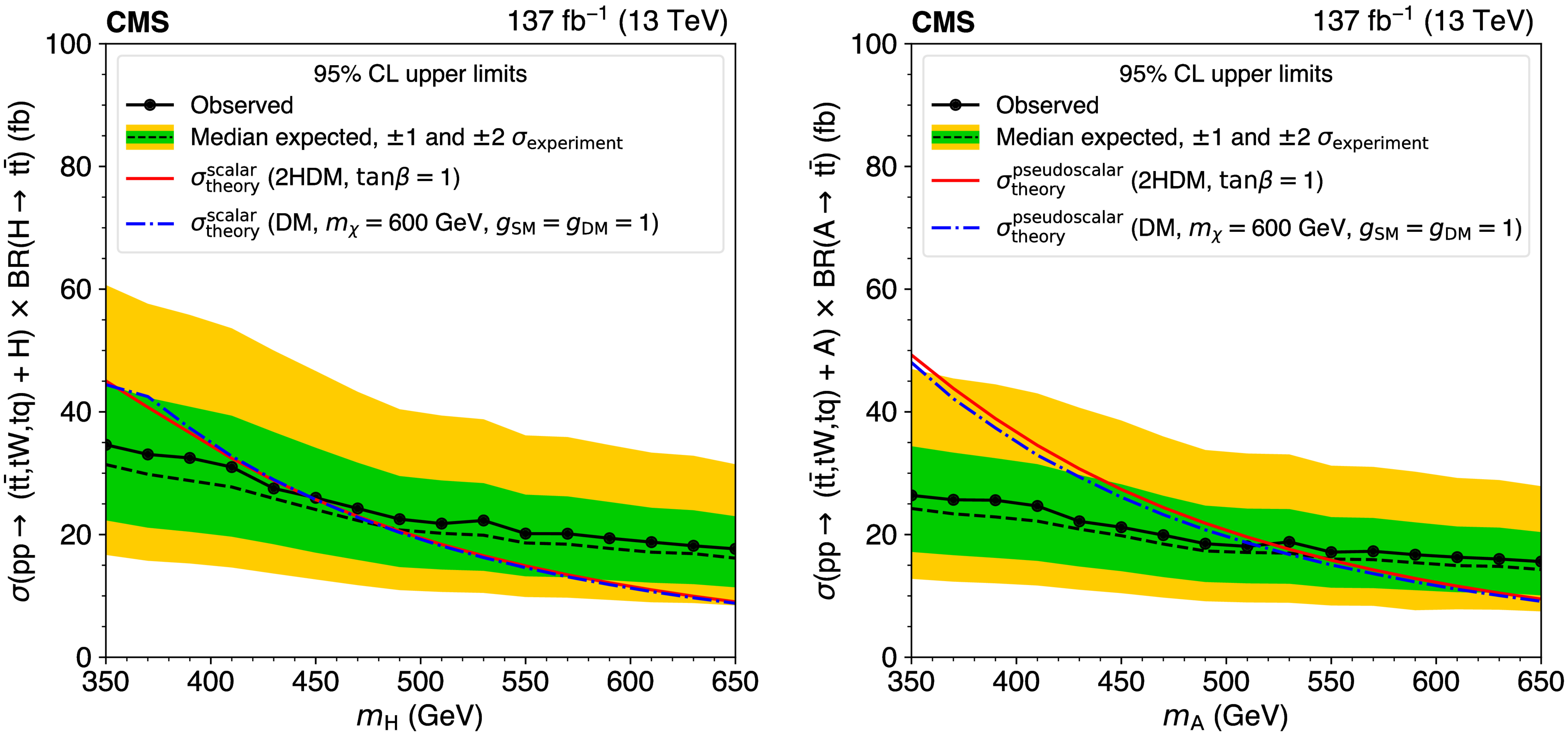






ttH/A→tttt

CMS TOP-18-003
arXiv:1908.06463



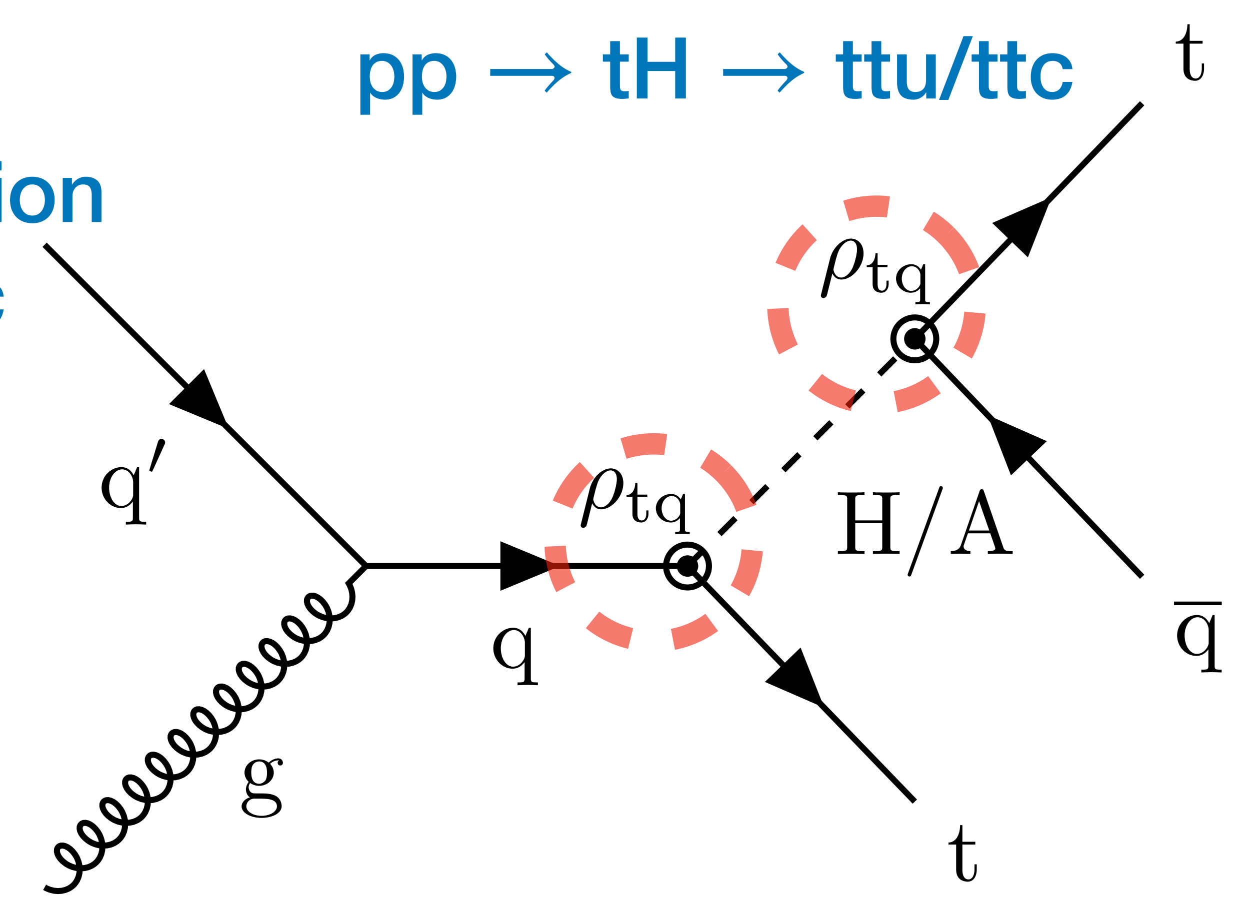
Analysis probes 2LSS and ML channels.

tH/A (H/A→tq)

CMS TOP-22-010

arXiv:2311.03261

PDF suppression for q=c

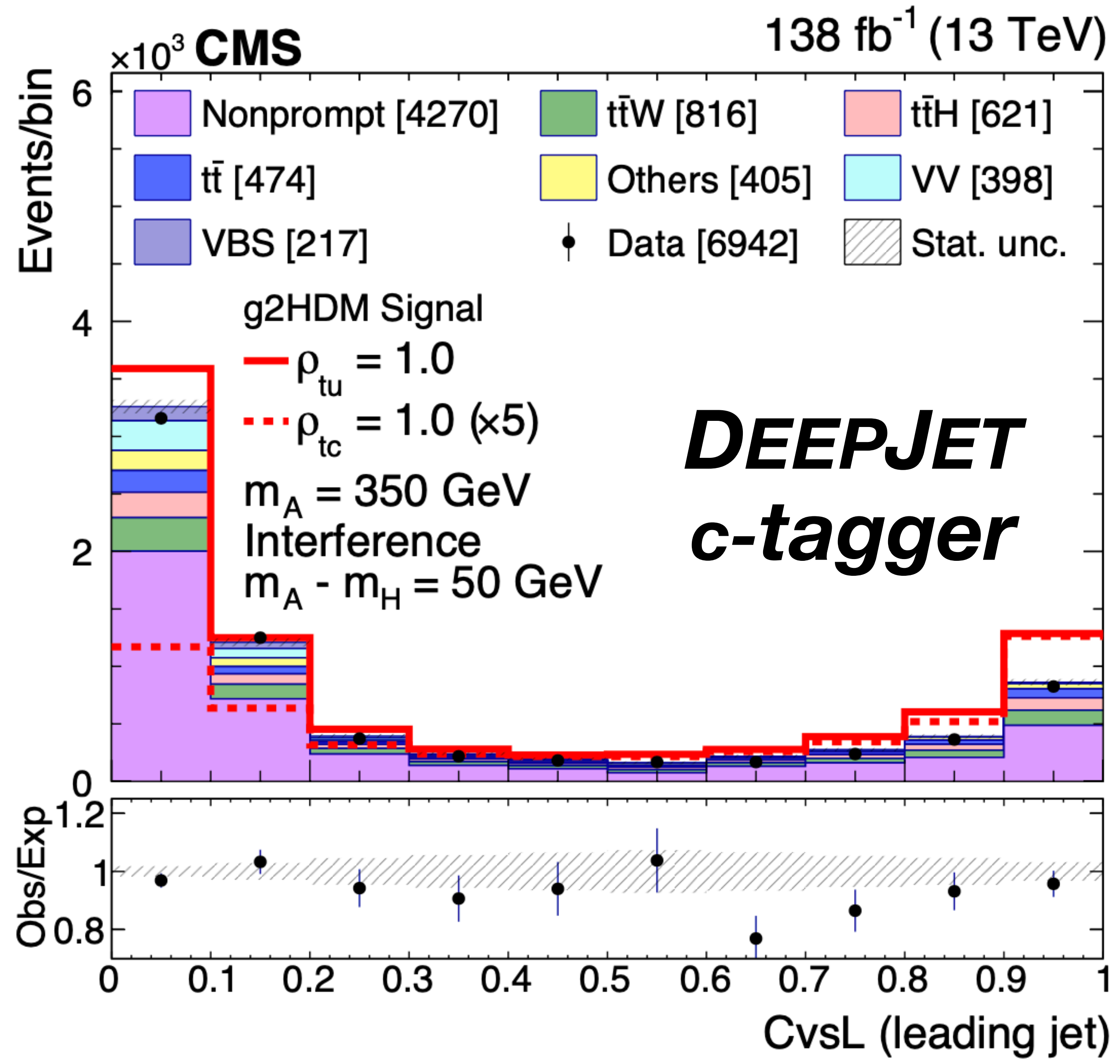


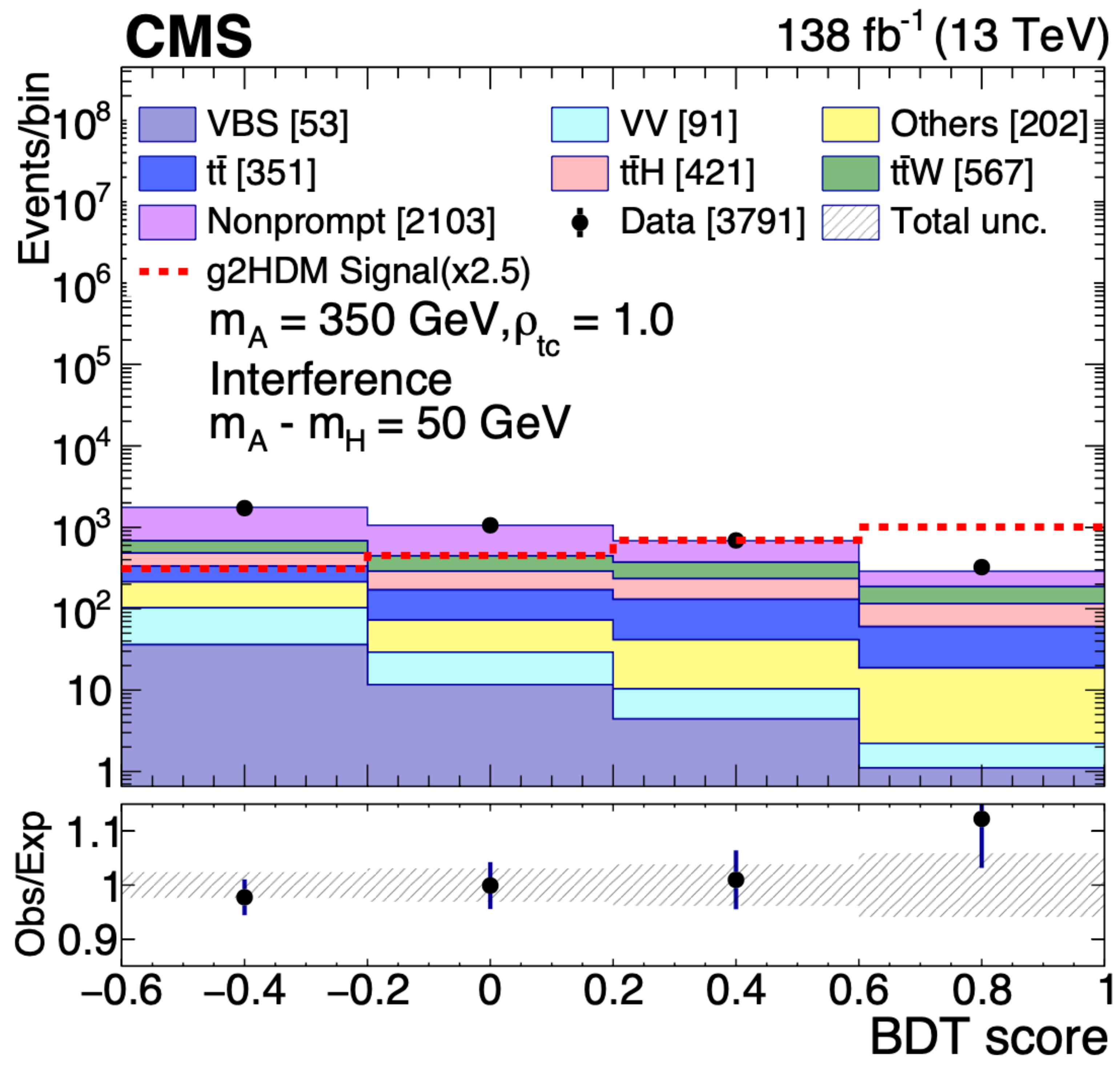
This analysis targets ρ_{tu} **or** ρ_{tc}**, one coupling at a time.**

- **2LSS is the target signature**.
- A dedicated **BDT training** is used to discriminate S from B.

Input variables

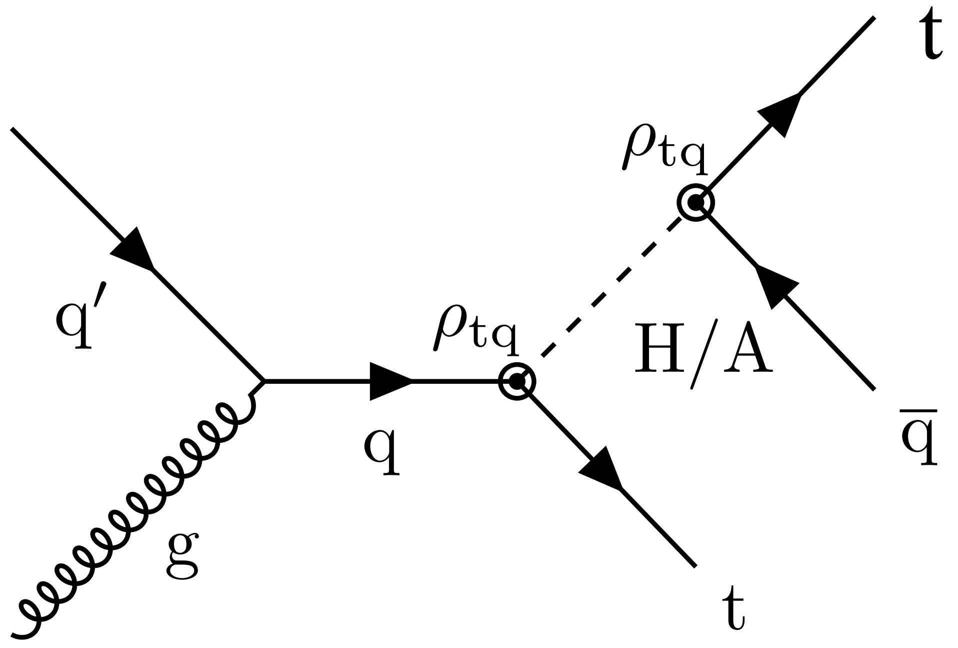
$\mathrm{CvsL}(j_a)$
$\mathrm{CvsB}(j_a)$
$\Delta R(j_a, j_b)$
$m(j_a, j_b)$
$\Delta R(j_a, l_b)$
$m(j_a, l_b)$
$p_\mathrm{T}(\ell_a)$
$m(\ell_1, \ell_2, j_a)$
$m(\ell_1, \ell_2)$
H_T
$p_\mathrm{T}^\mathrm{miss}$





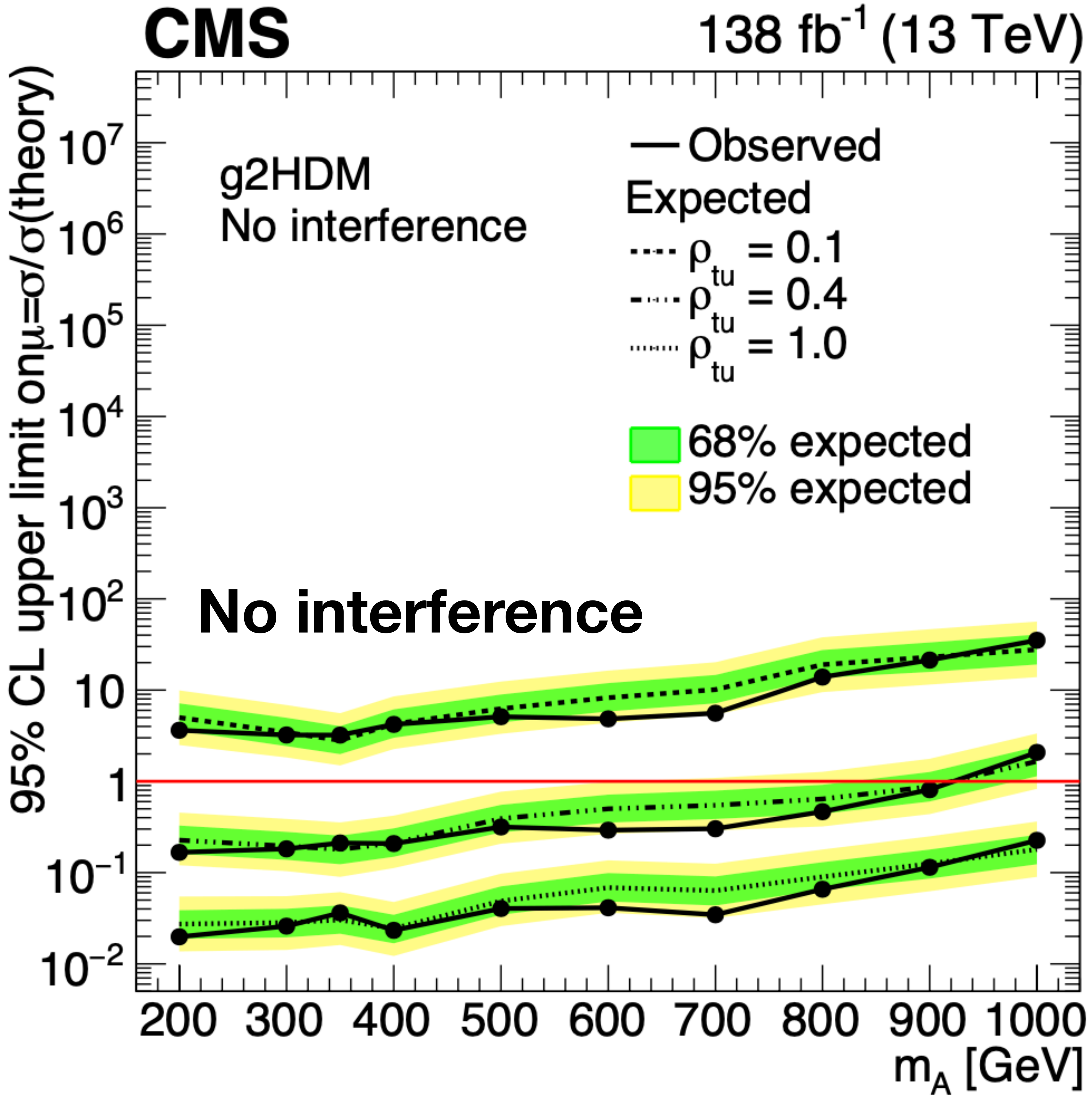
BDT distributions are ~independent of coupling values, only depend on mass.

tH/A (H/A→tq)



CMS TOP-22-010

arXiv:2311.03261

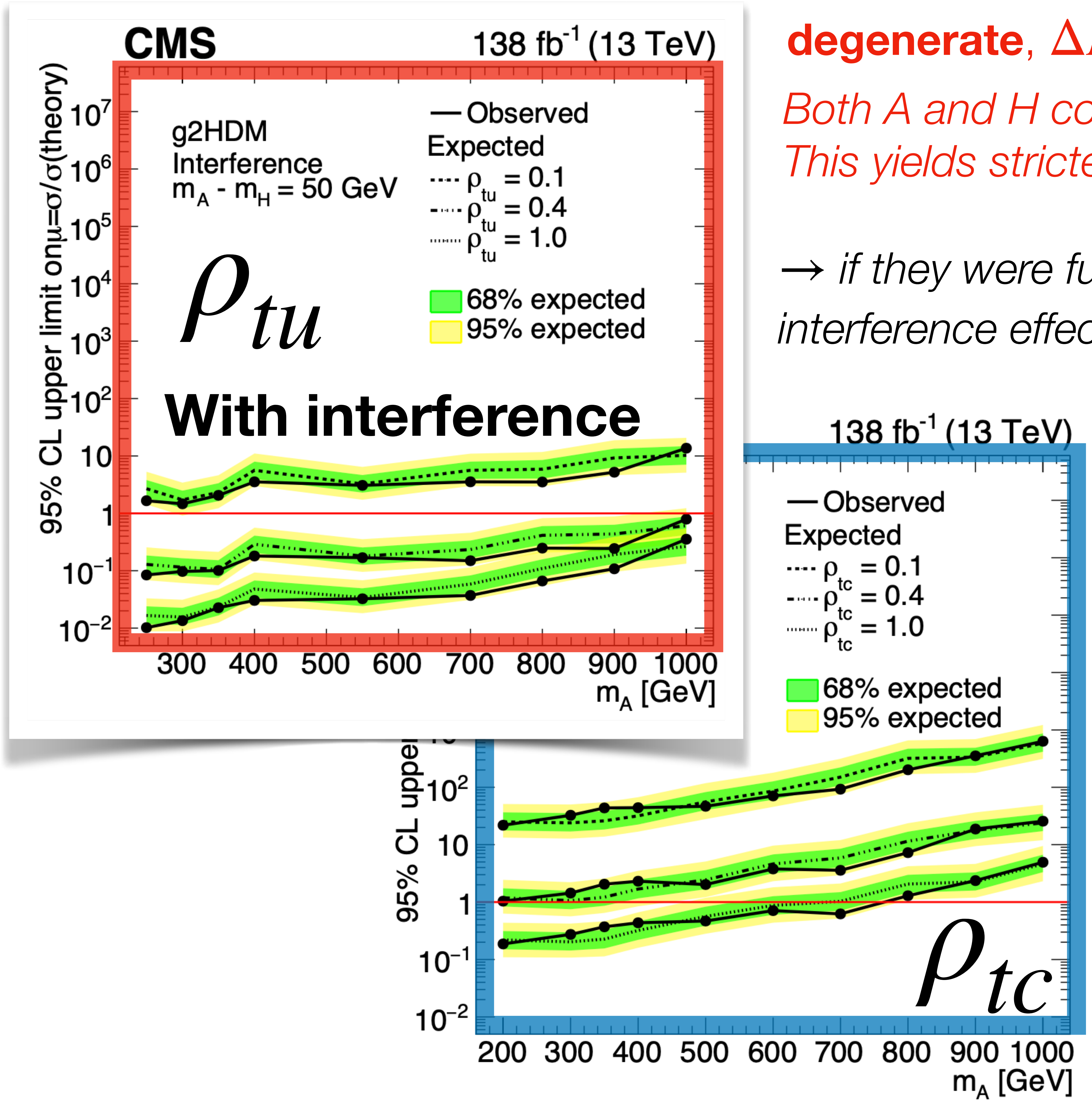


Alternate scenario:

A and H are near-mass-degenerate, ΔM=50 GeV.

Both A and H contributions are present. This yields stricter limits!

→ if they were fully mass degenerate, interference effects suppress x-section.



The PDF penalty!

A ↔ H can be used interchangeably in the derived constraints.