Searches for additional Higgs bosons in ATLAS

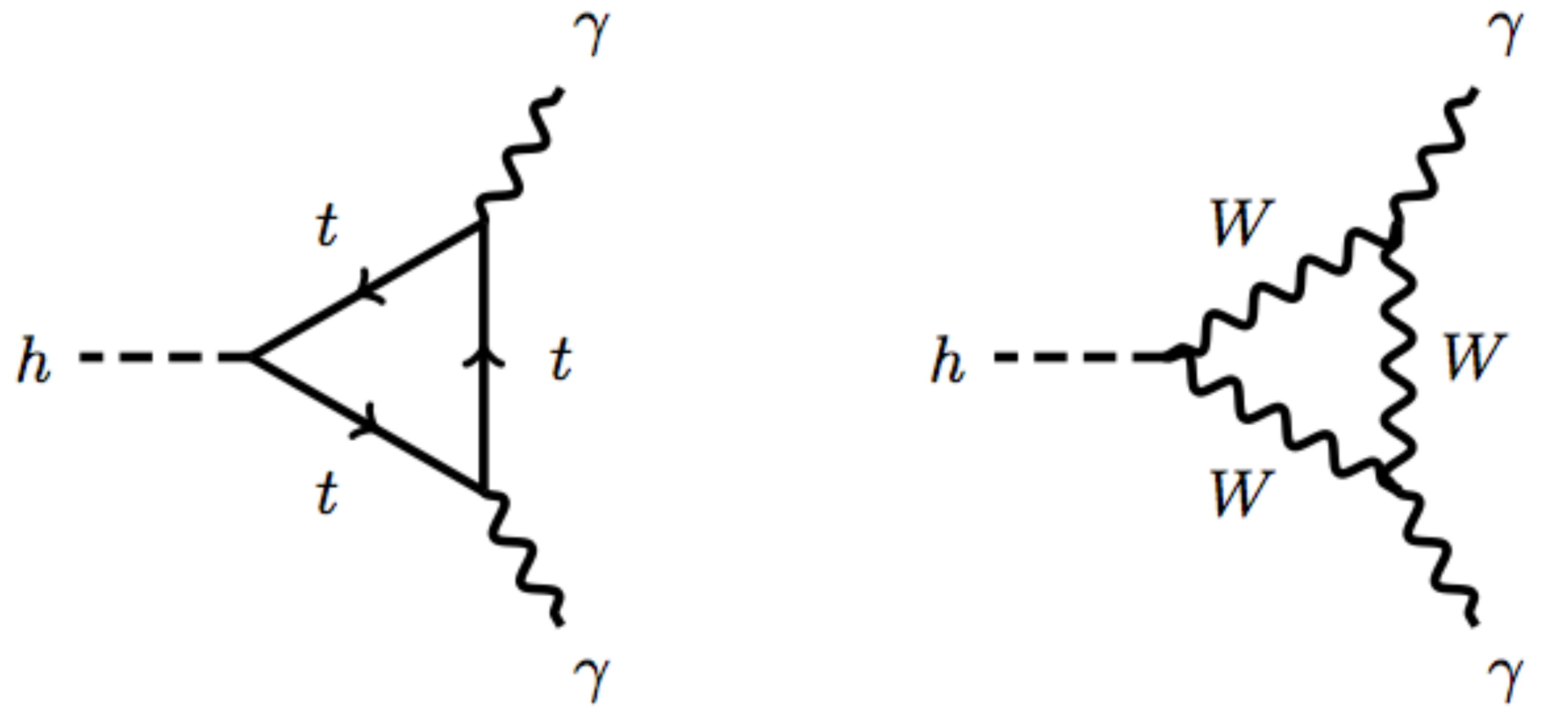
Kevin Nelson, on behalf of the ATLAS collaboration
October 23, 2024
PIC 2024
Athens, Greece

Outline

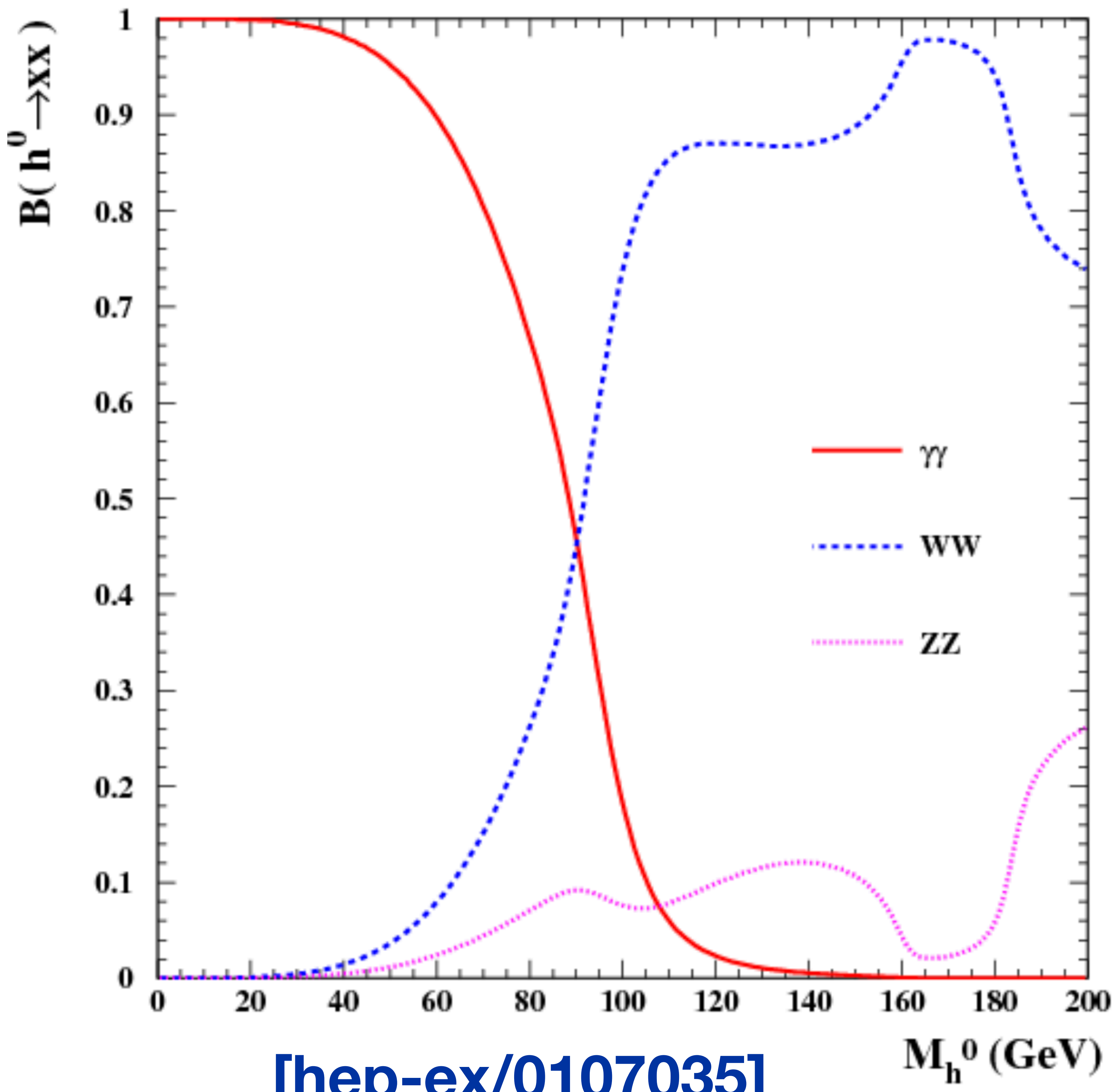
- **Diphoton resonance searches**
  - A clean, classic signature
- **Searches for light scalars in the $H_{125} \to aa$ decay mode**
  - Low p_T boosted objects necessitate new analysis ideas
- **Searches for charged Higgs bosons**
  - The latest ATLAS excess…
- **Results from as new as July 2024 in each of these three categories**

Searches for $\gamma\gamma$ resonances

- **Theoretical motivations:**
  - It is often difficult to turn off scalar $\rightarrow \gamma\gamma$ decays (and retain any SM interactions) due to loops of both fermions and vector bosons
  - Wide variety of models: ALP/R-axion, RS-graviton, 2HDM, NMSSM
  - Clean experimental signature
  - In fermiophobic models the branching ratio to photons can be enhanced by orders of magnitude compared to SM Higgs

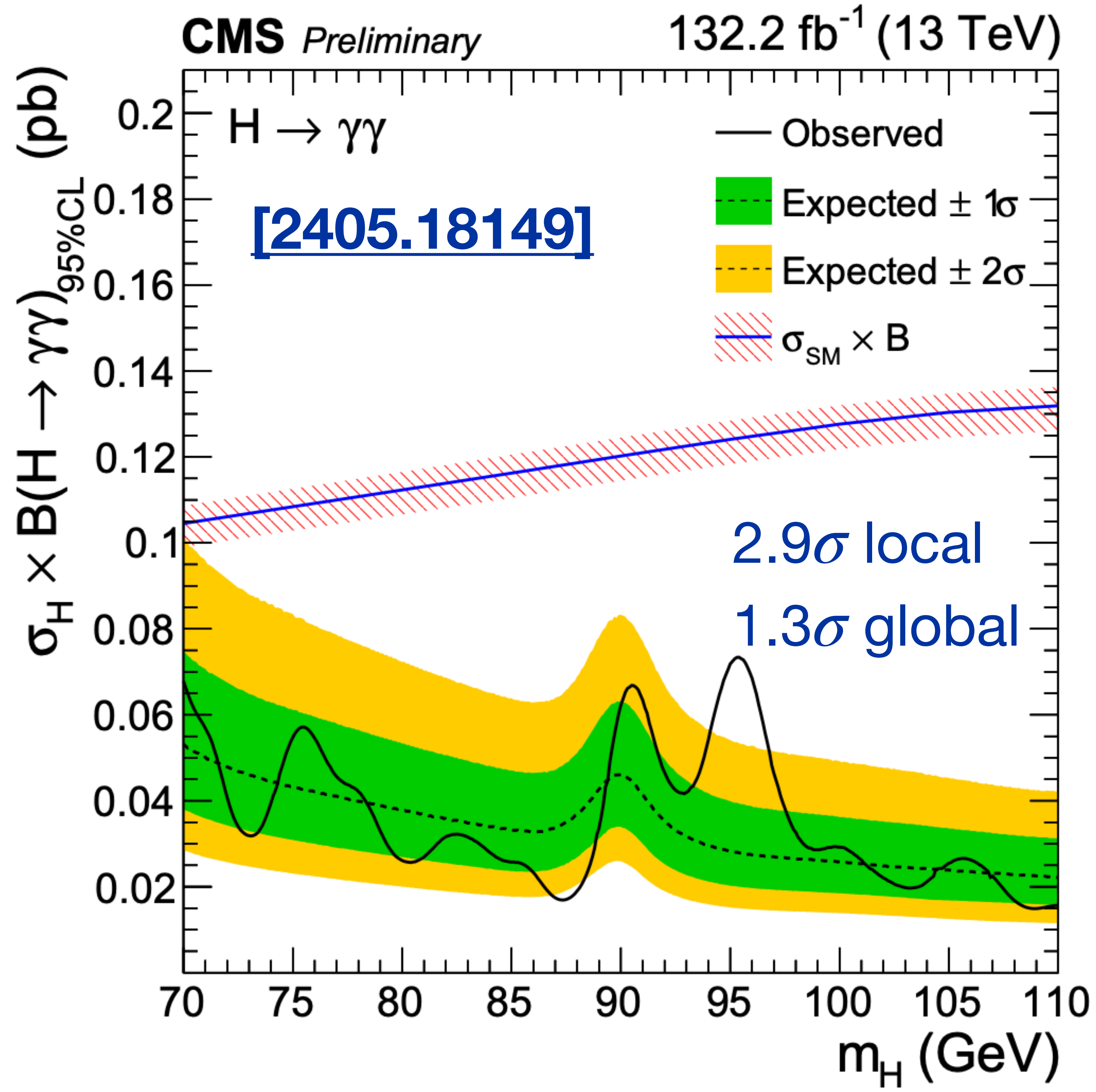


  - Pictured are branching fractions of a *fully fermiophobic* Higgs: All couplings to fermions=0



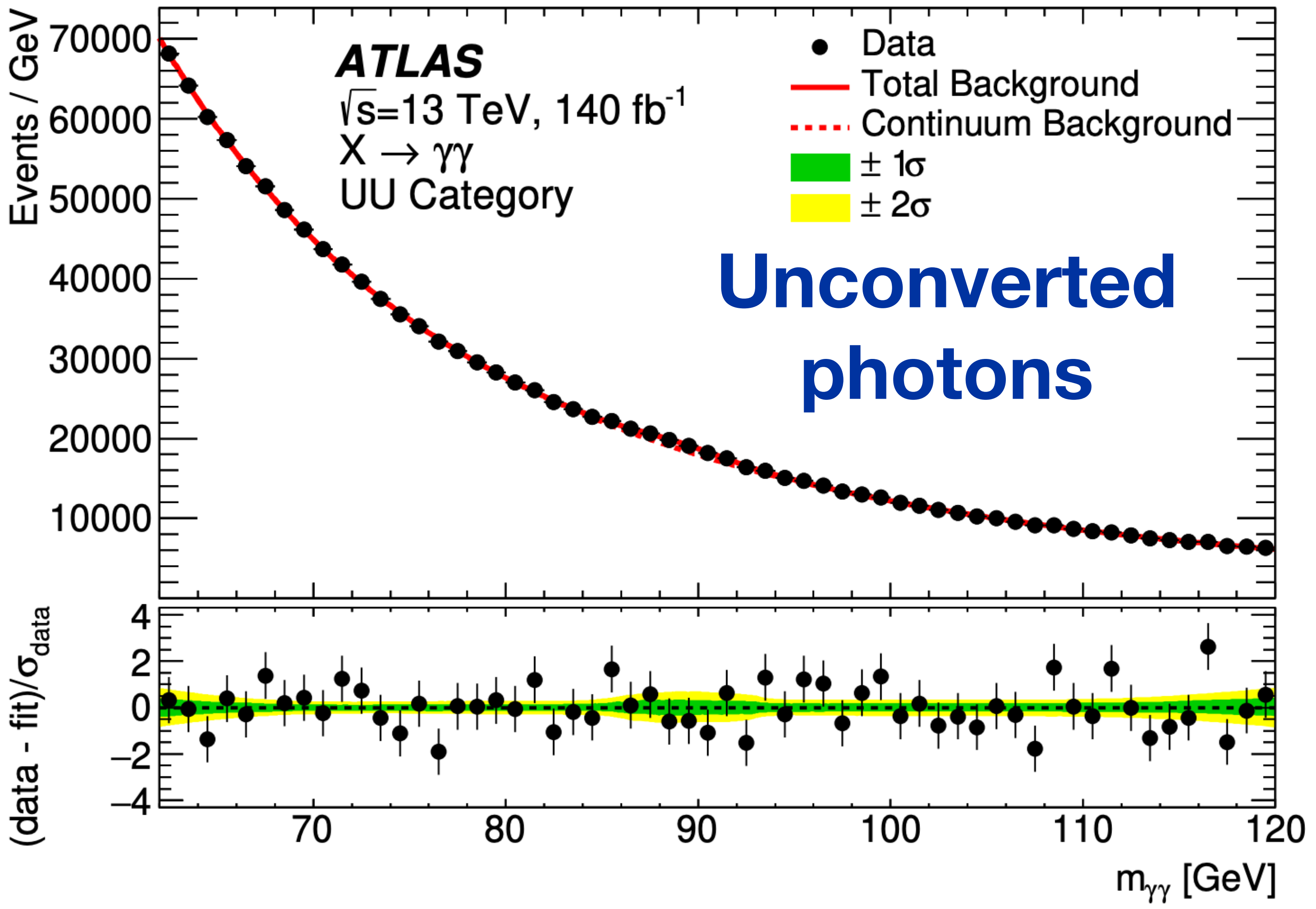
[hep-ex/0107035]

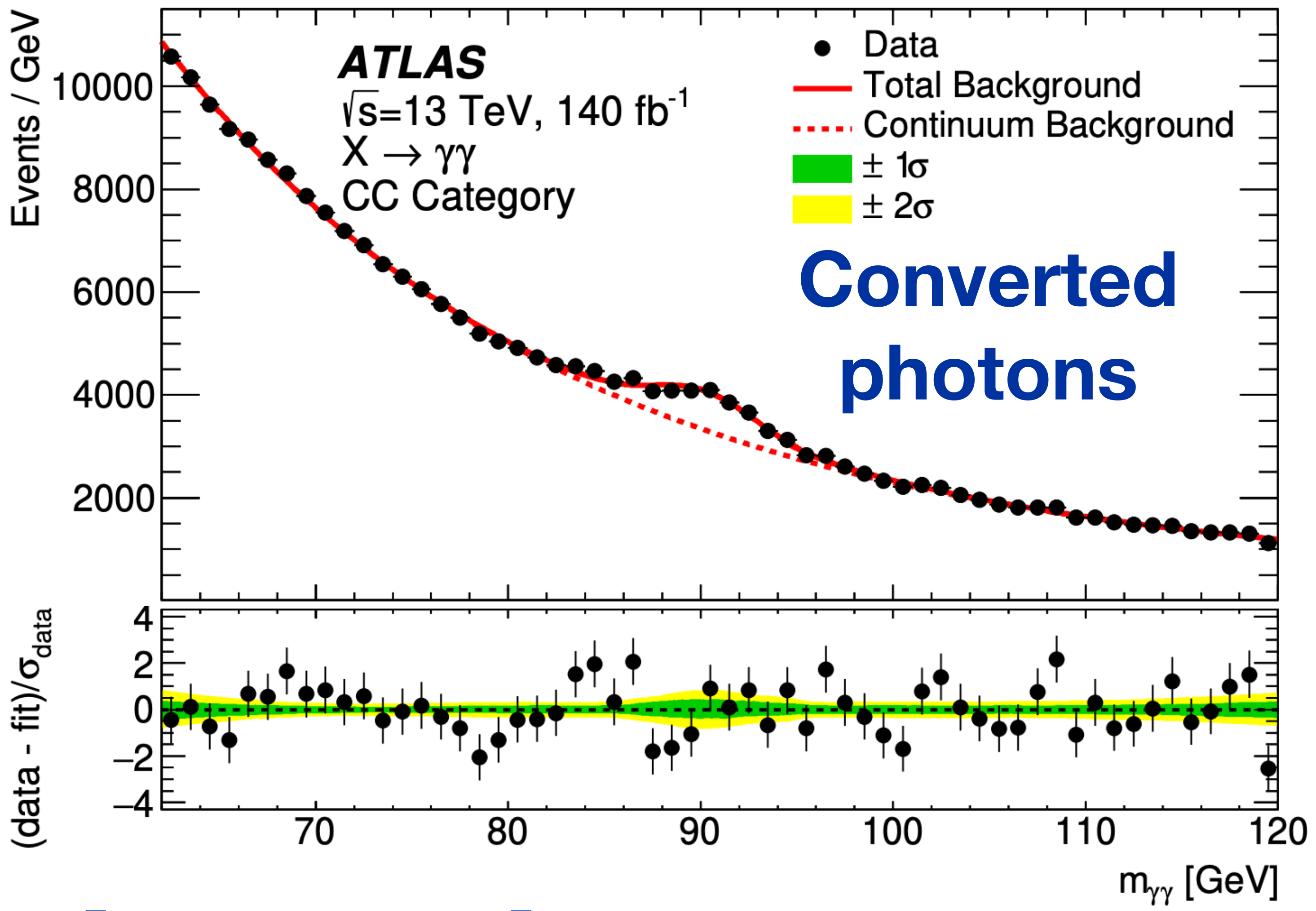
- **Recent experimental intrigue**
  - CMS 95 GeV



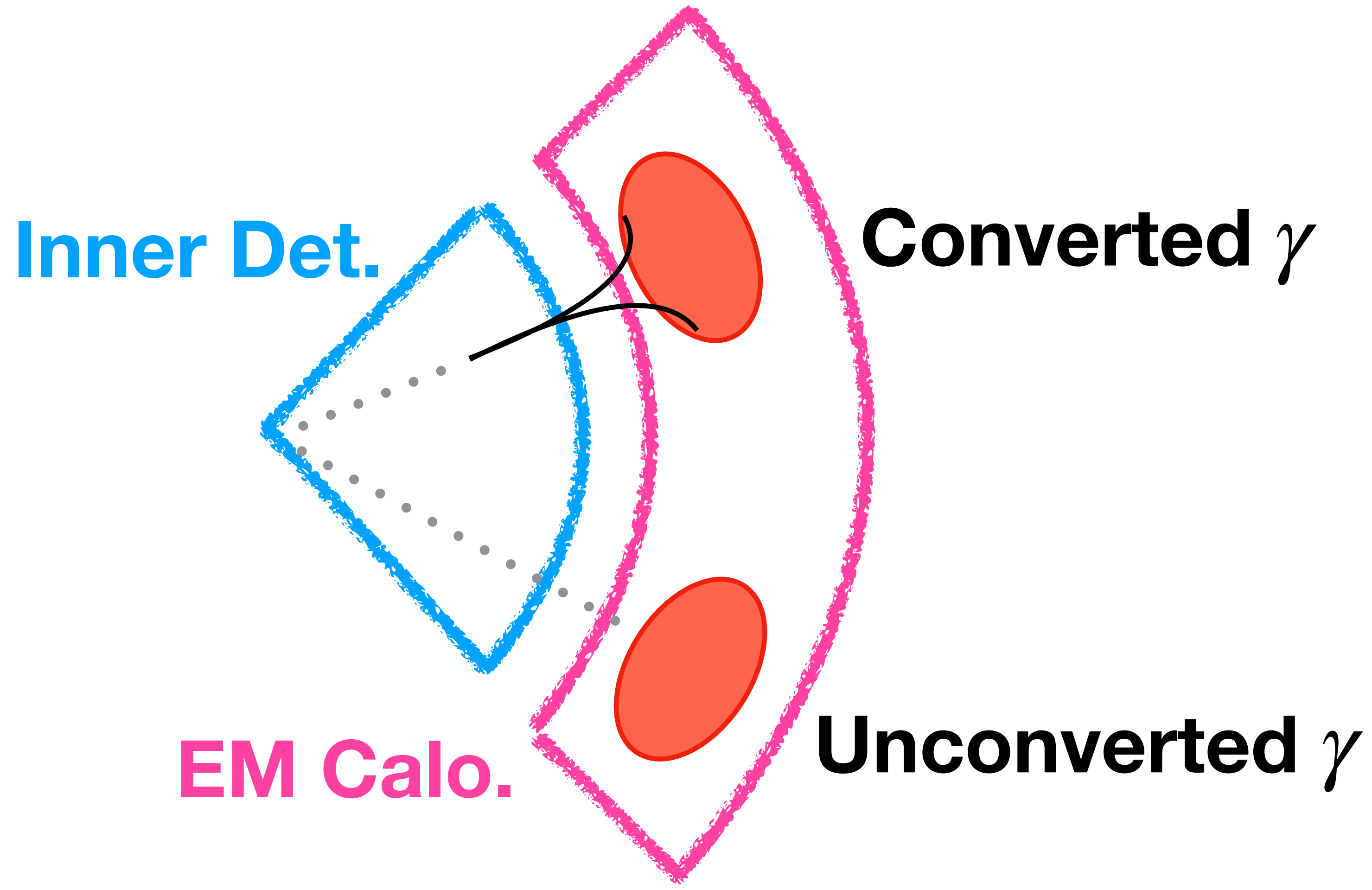
Searches for $\gamma\gamma$ resonances: 66-110 GeV

- **Photon conversion categories separate $Z \rightarrow ee$ fake background**



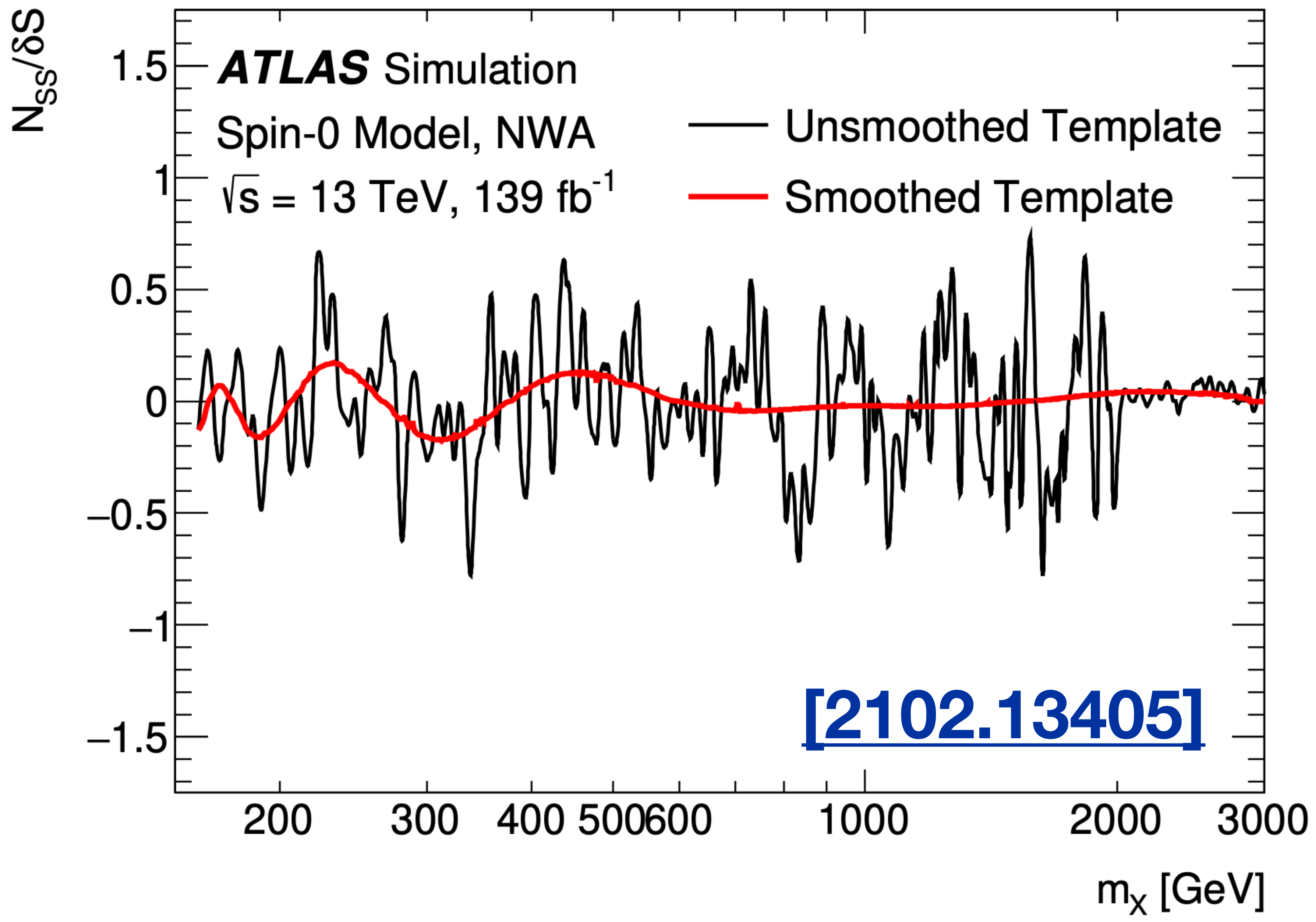


[2407.07546]



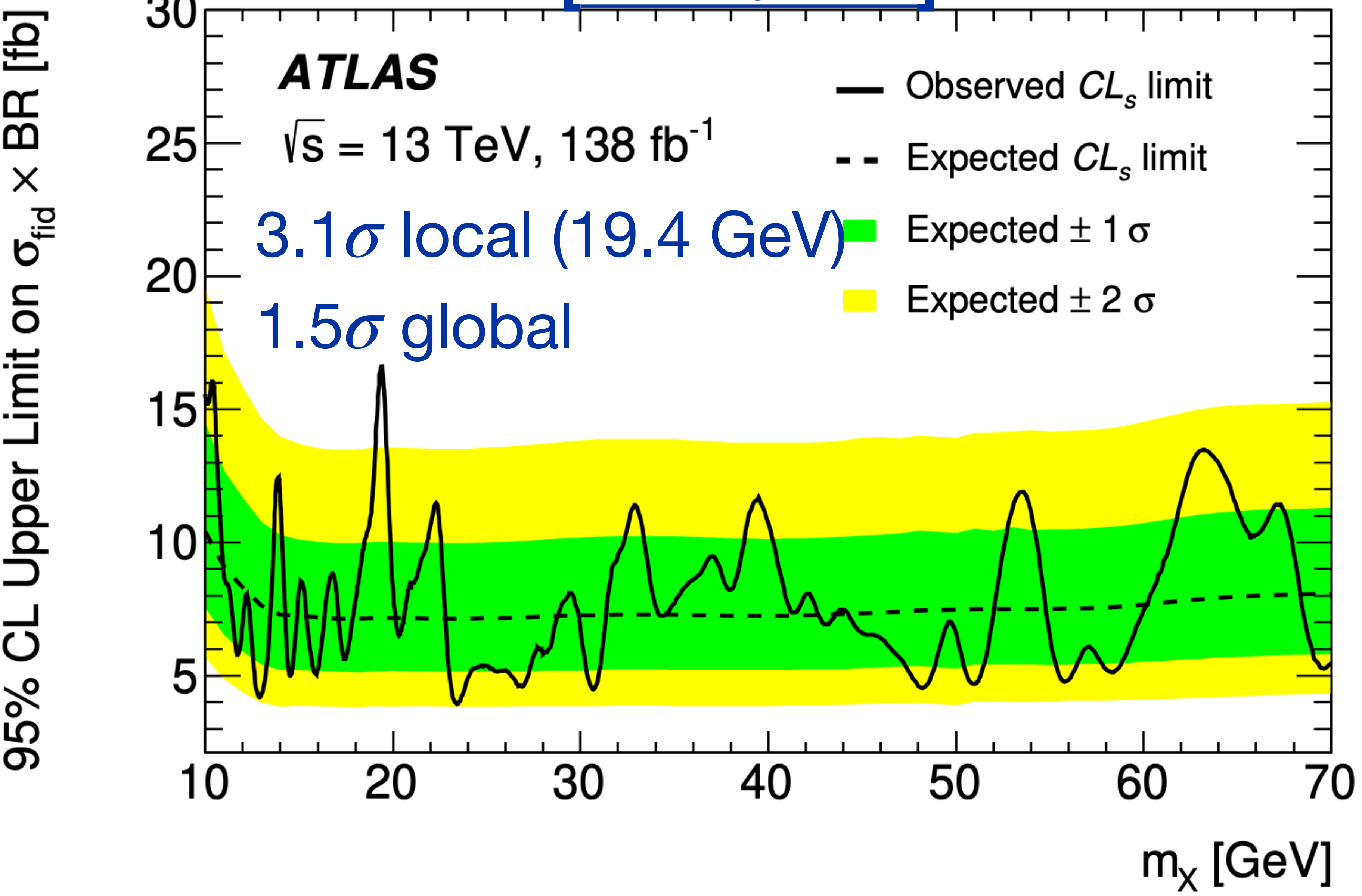
- **Require boosted $\gamma\gamma$ system: $E_T/m_{\gamma\gamma} > 22/58 \approx 0.38$**
  - Results in exponentially falling background which is easier to fit

- **Spurious signal systematic reduced by a factor of 3x (up to 30% improvement in limit) due to Gaussian process regression (low mass) and functional decomposition smoothing (high mass)**

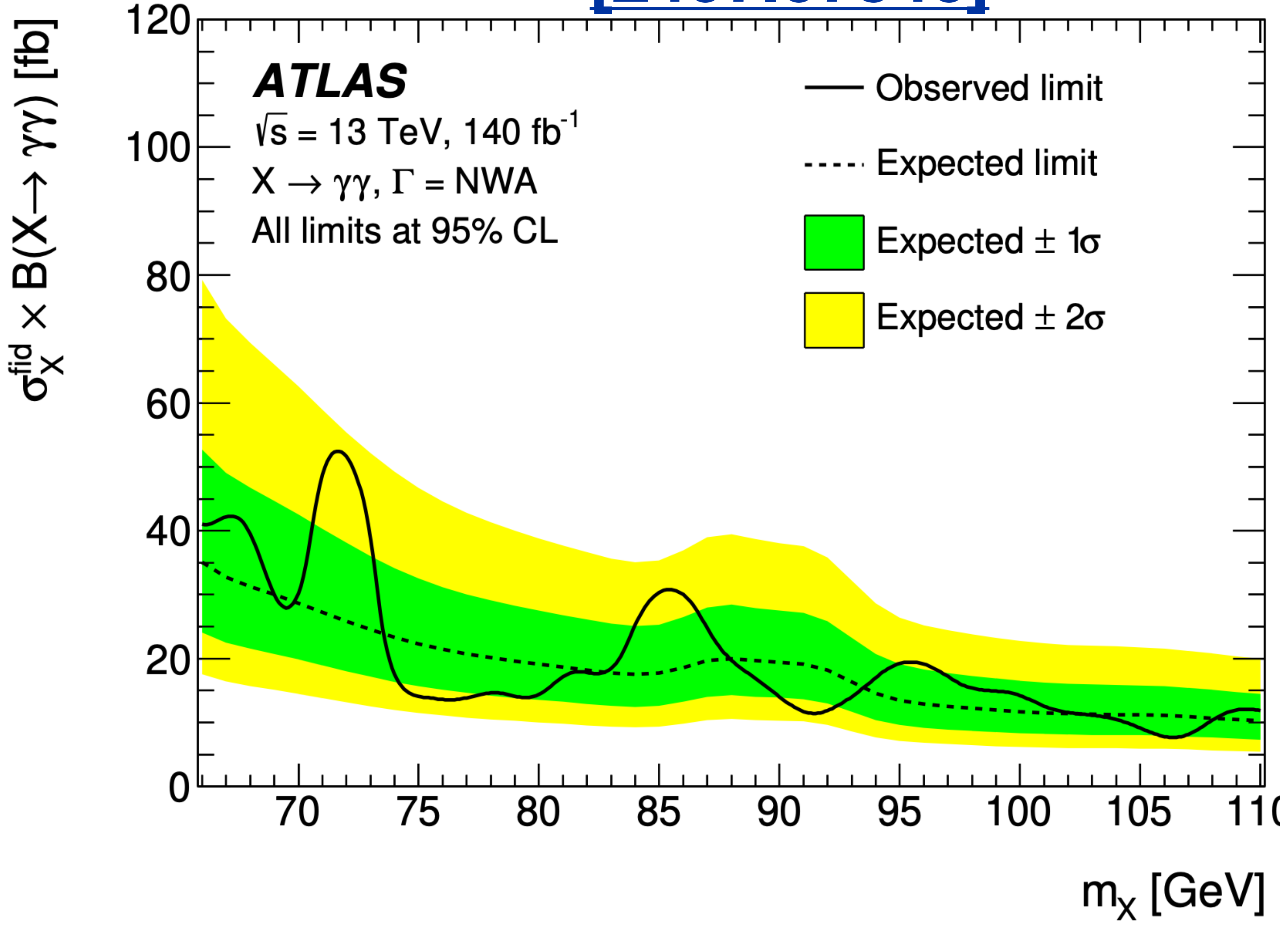


Searches for $\gamma\gamma$ resonances

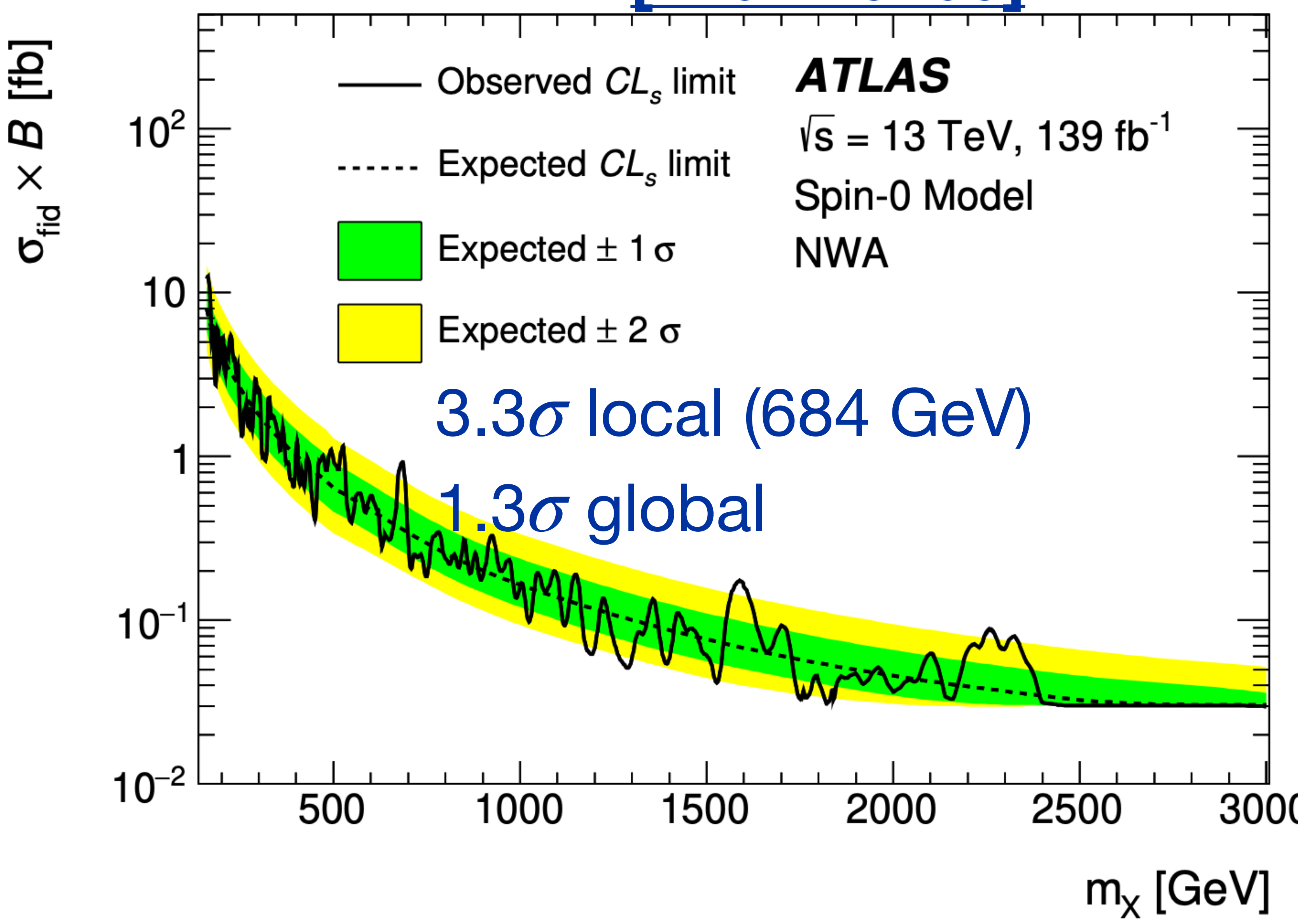
[2211.04172]



[2407.07546]



[2102.13405]

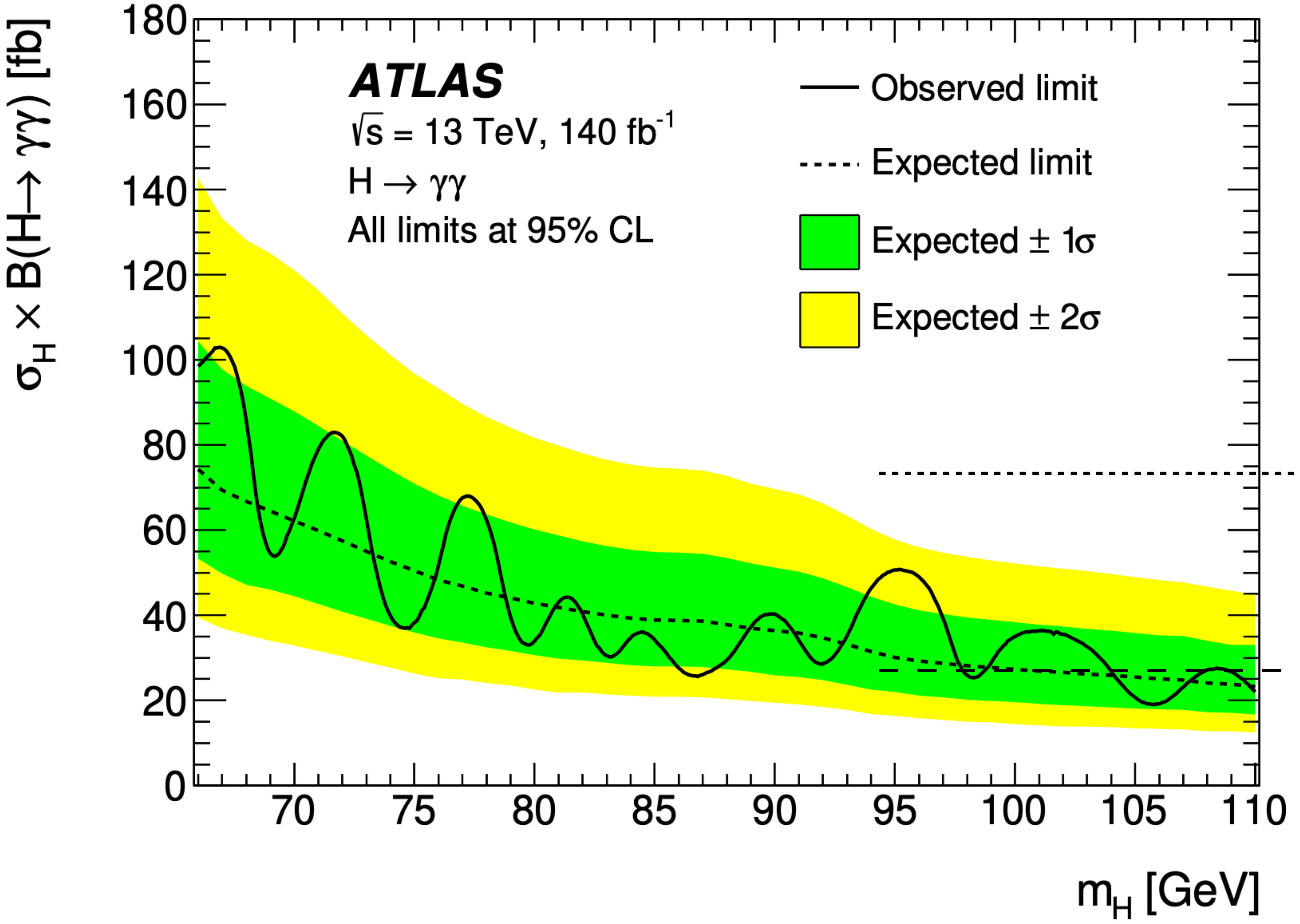


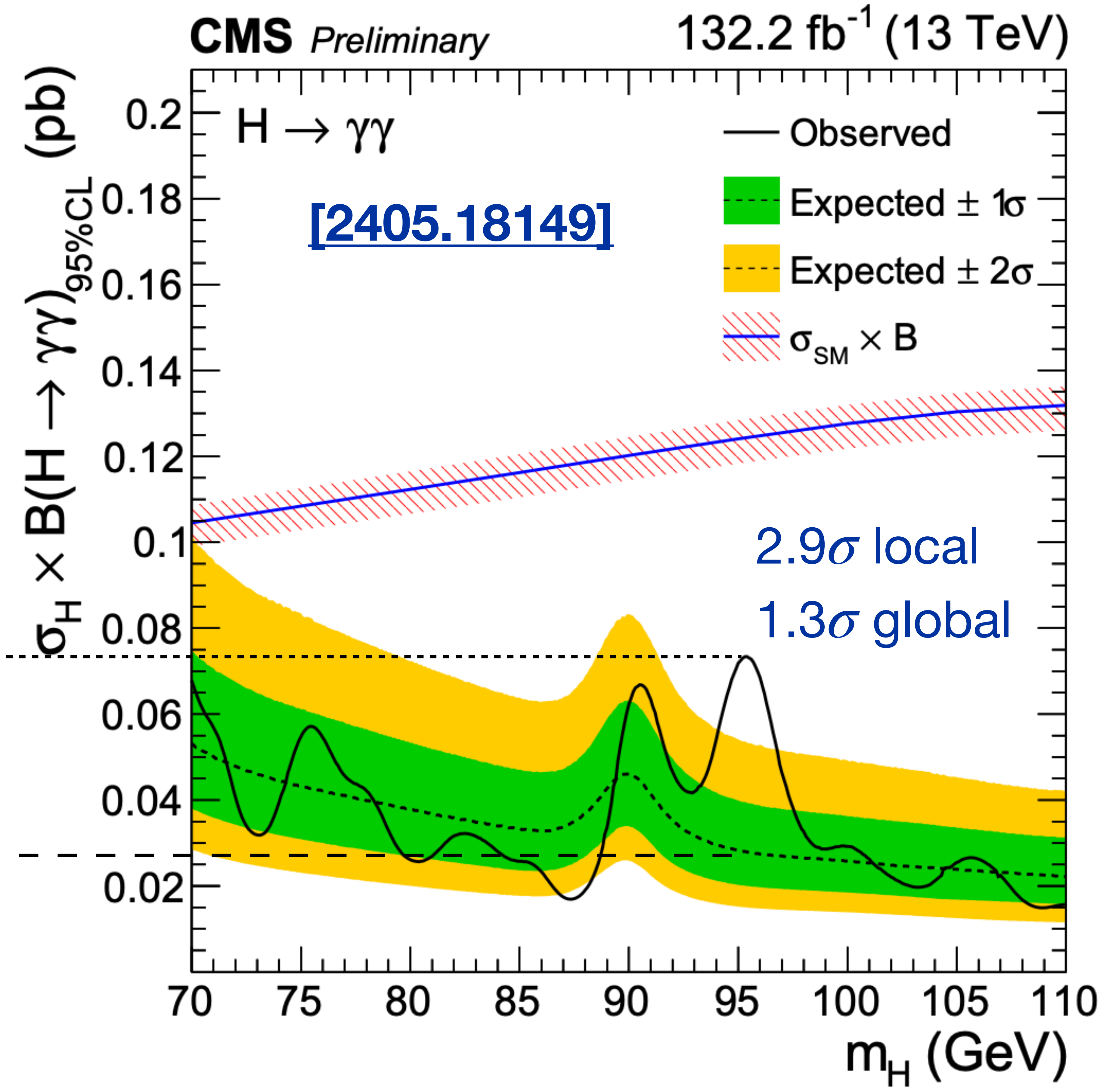
- **In the last 3 years, 3 searches have been performed to cover the mass ranges [10,110] and [160,3000] GeV**
  - Limits are fiducial cross section (× branching ratio). See 2407.07546 (or next slide) for direct comparison of 95 GeV excess to CMS with model dependent SM-Higgs like assumptions on production mode. BDT categories also used for model-dependent search.

- **No evidence for new Higgs bosons decaying to photons in ATLAS searches.**
  - Largest deviation: 3.3σ local at 684 GeV

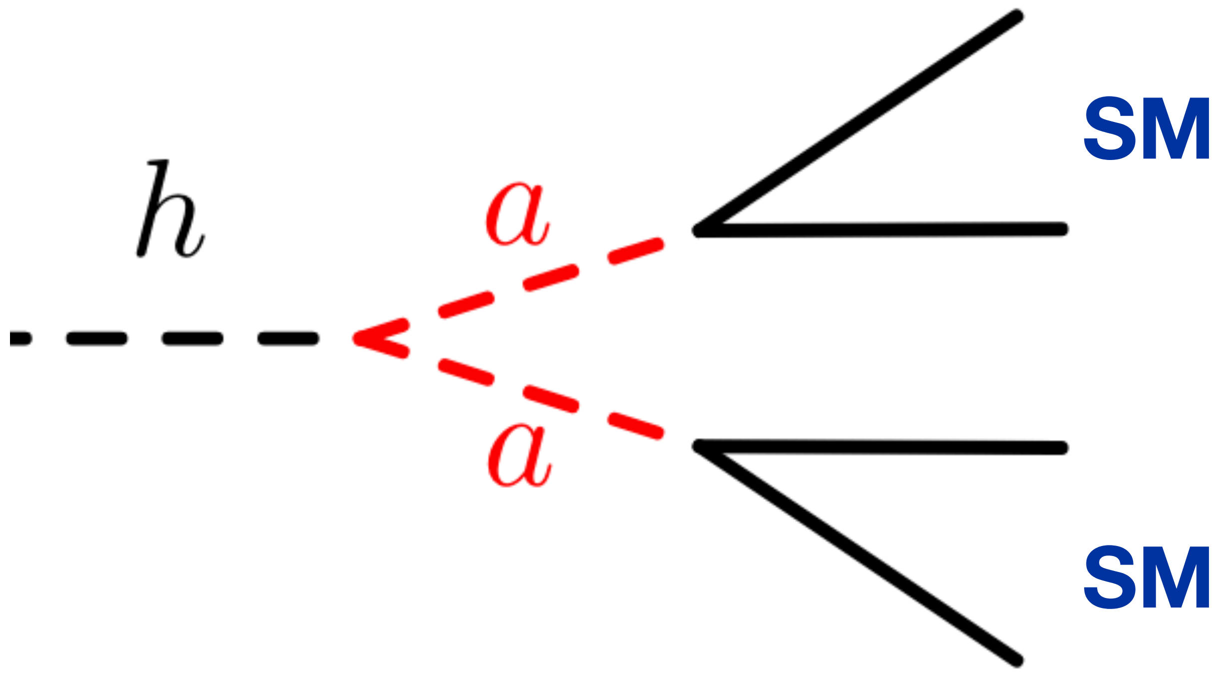
Searches for $\gamma\gamma$ resonances: 66 to 110 GeV

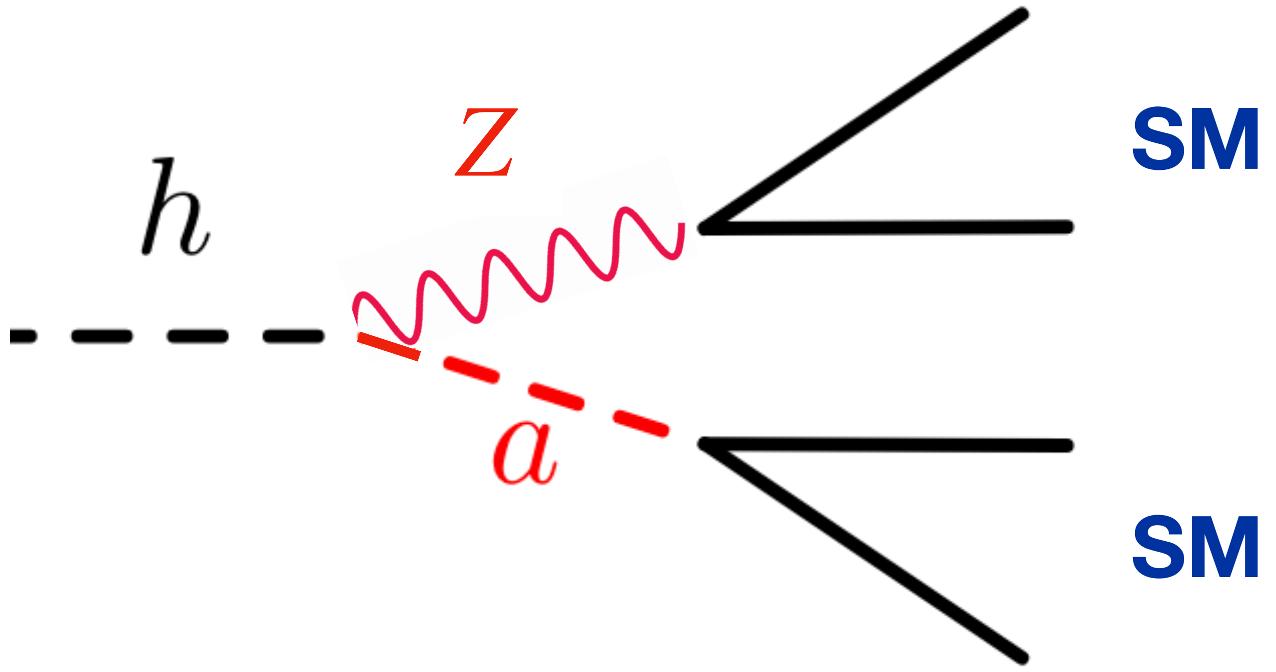
- **Model-dependent limit assumes production in ggF, VBF, VH, tH modes matches proportions of SM Higgs**
  - (This is not necessarily a good assumption, but we can run with it. Motivated by this direct comparison.)
- **ATLAS excludes the size of the CMS excess at the 95% CL**
  - ATLAS is about equally sensitive, but sees a far smaller bump
  - Remember, the CMS 95 GeV is not even the largest di-photon excess anymore, ATLAS sees 3.3σ local at 684 GeV…





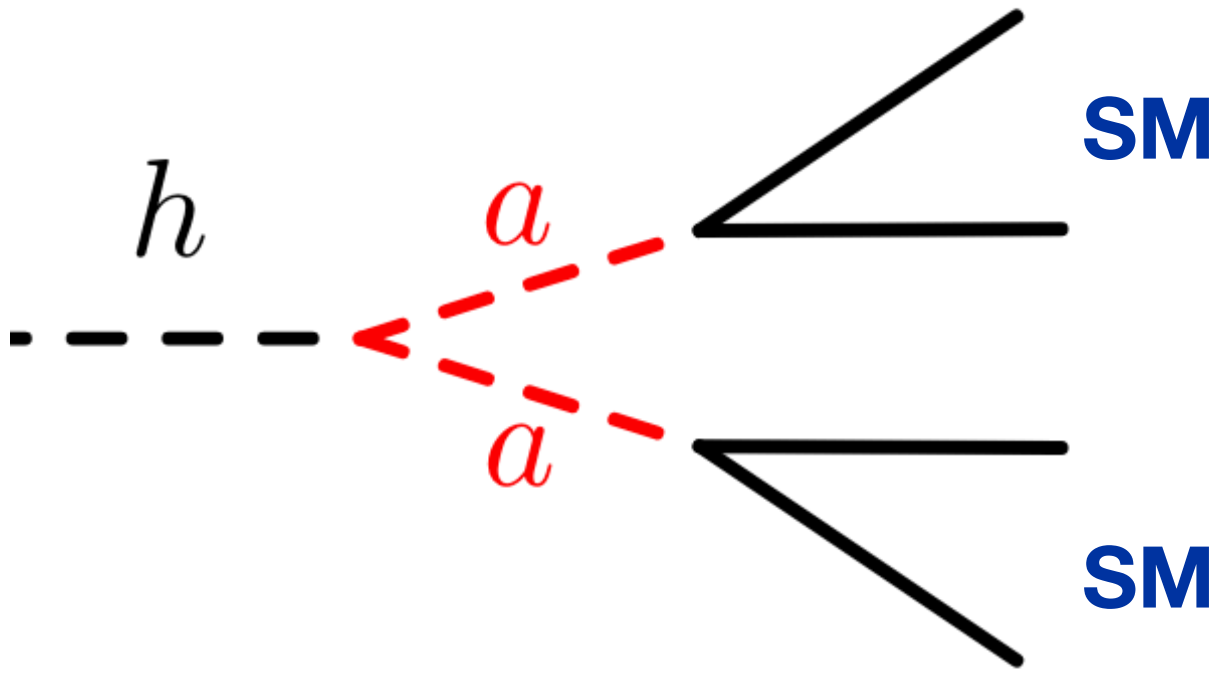
2HDM+S searches

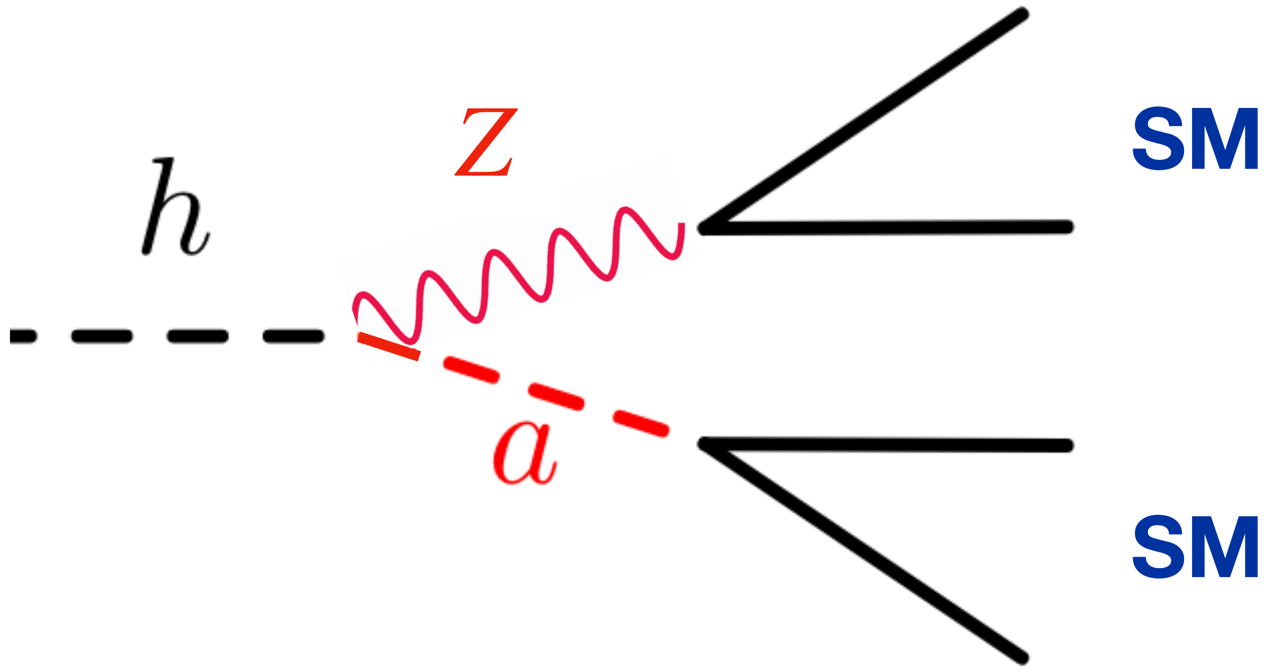




- **2HDM+S model: 2nd doublet+light psuedoscalar (a) are added to the SM.**
- **2HDM type, $\tan\beta$, m_a are free parameters.**
  - Depending on type, leptons, up-, down-type quark couplings to *a* scale like either $\tan\beta$ or $\cot\beta$
  - Almost any final state can become dominant
- **$a \to$ SM possible via $a \leftrightarrow \Phi_1, \Phi_2$ mixing.**
- **When m_a is small, SM 2-body decays merged. Also low p_T.**

2HDM+S searches





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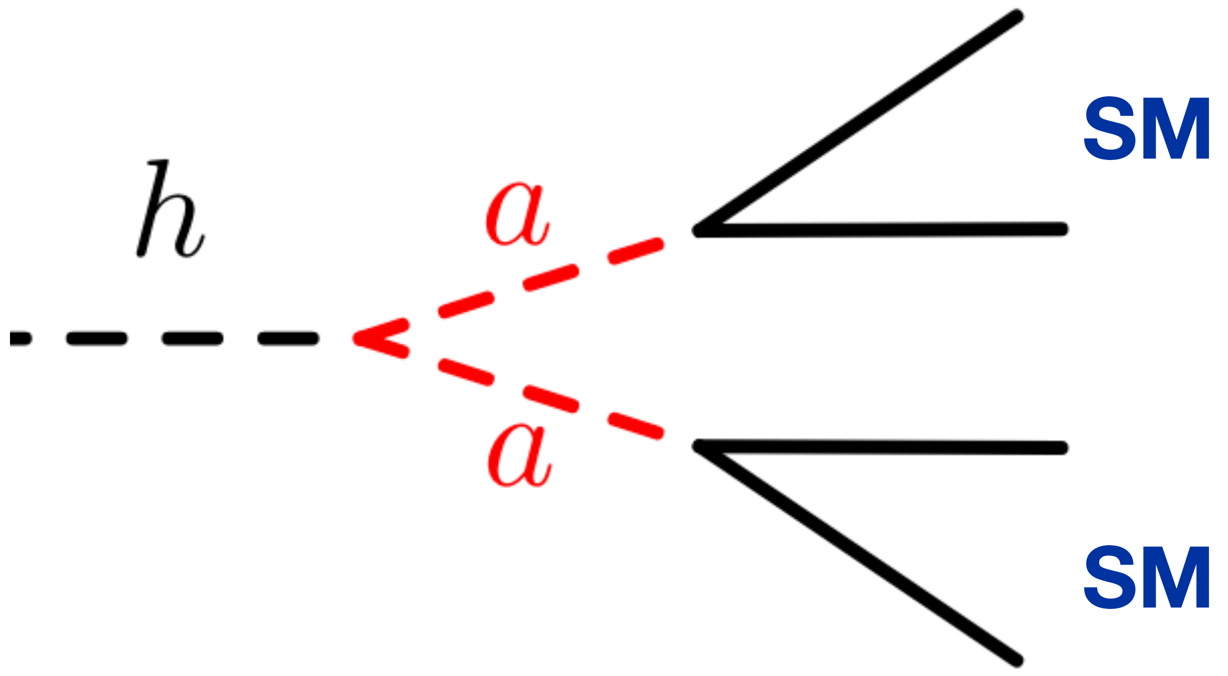
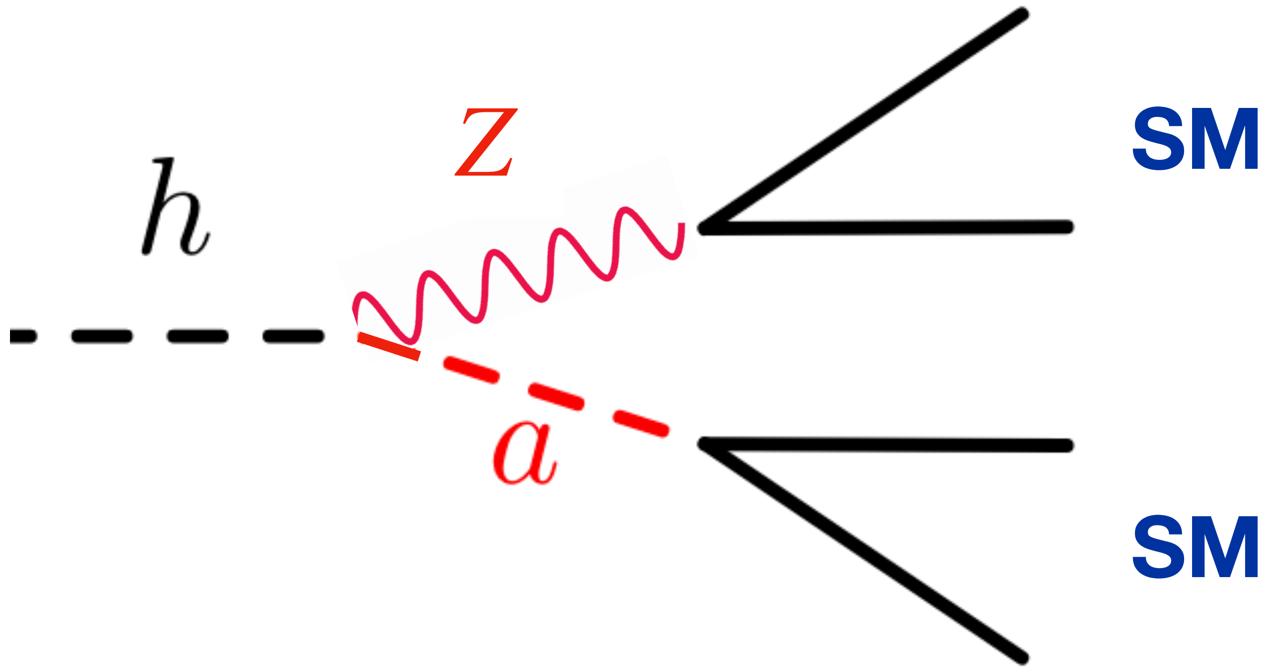
[1312.4992]

2HDM+S searches





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- **$a \to$ SM possible via $a \leftrightarrow \Phi_1, \Phi_2$ mixing.**
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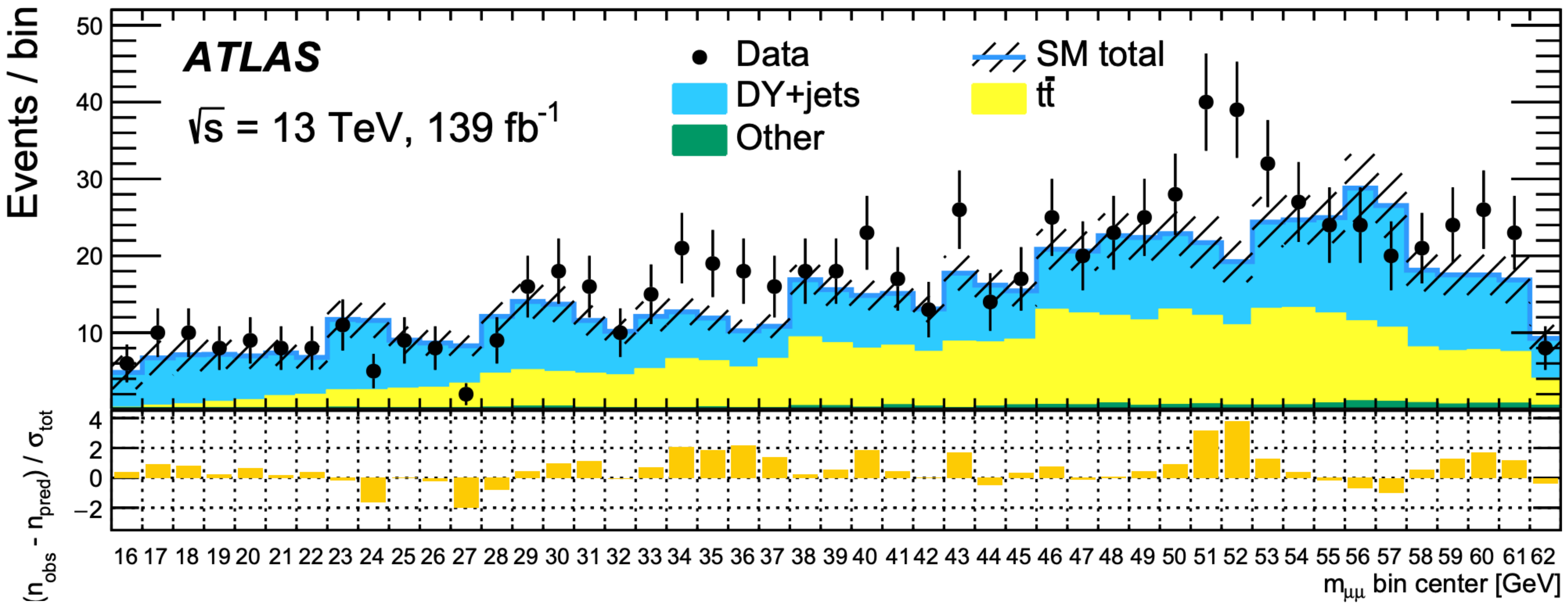
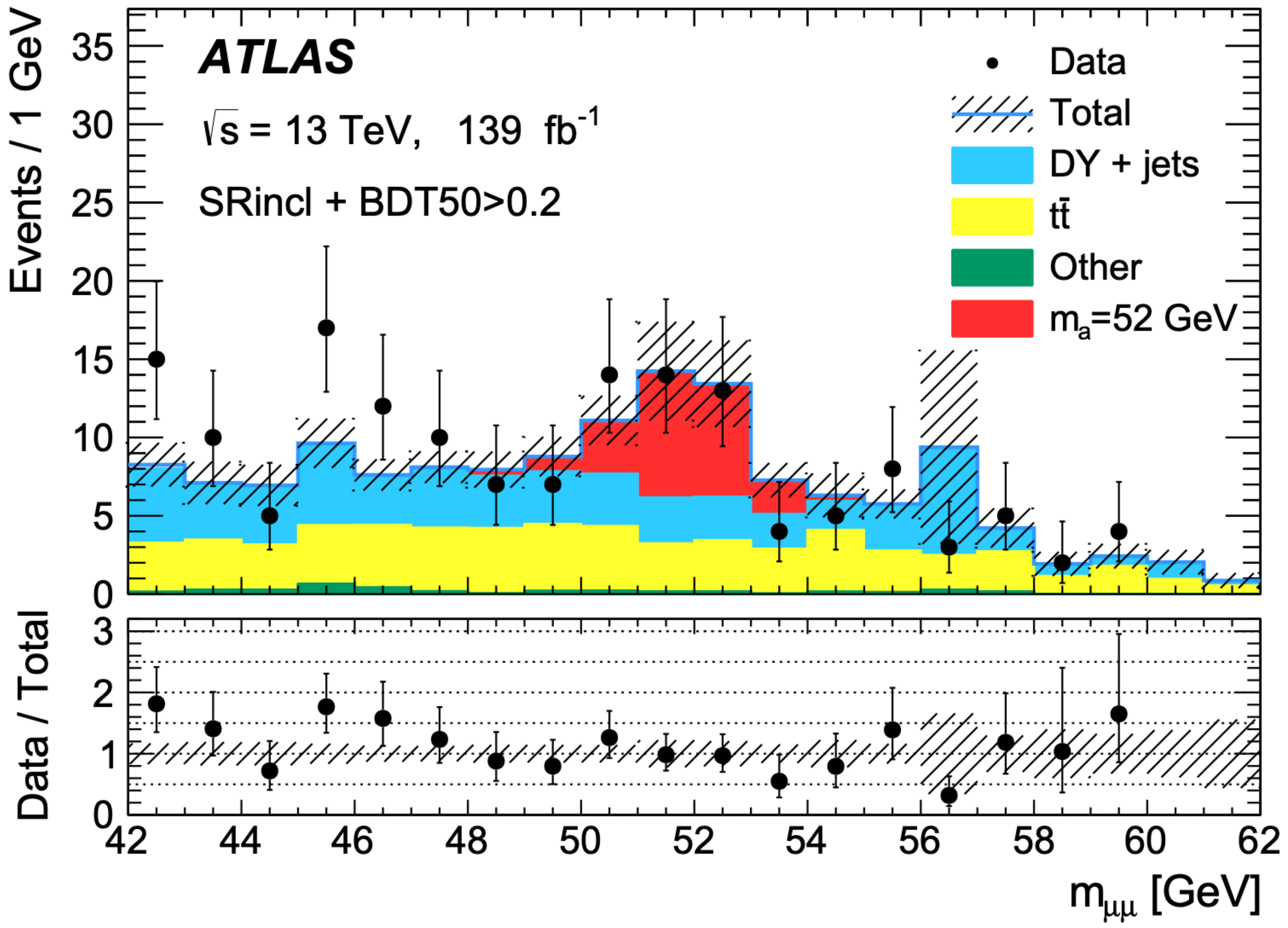
- ***a* can be DM mediator**
- **Enhanced coupling to leptons could solve muon g-2**

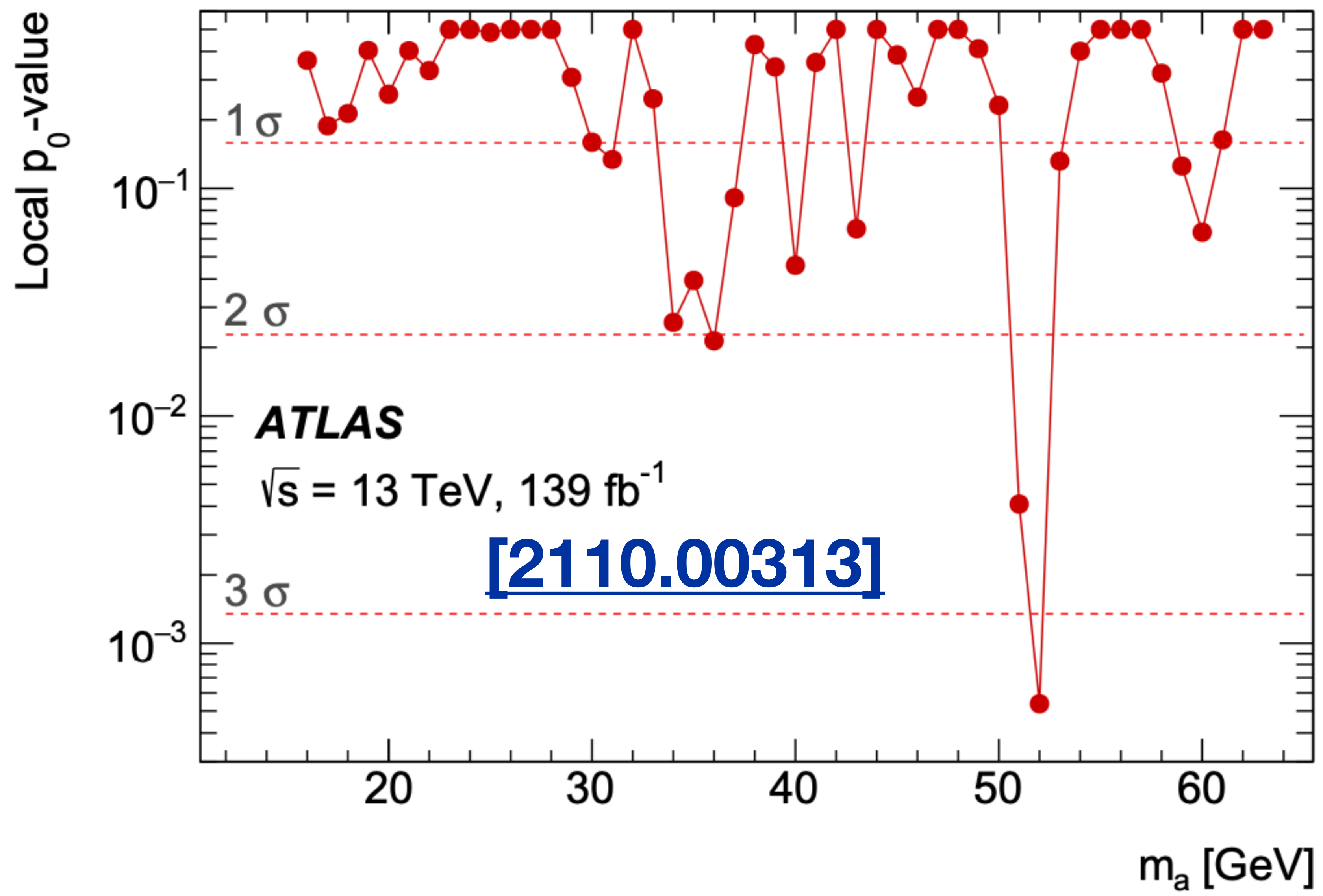
[1312.4992]

2HDM+S: $bb\mu\mu$

- **A bump was seen in the ATLAS search for $H \to aa \to bb\mu\mu$**
  - 3.3 (1.7) σ local (global)
- **Relatively "clean" signature due to di-muon resonance**
- **Need other final states to weigh in**
- **In particular, this excess could imply enhanced coupling between *a* and leptons**
- **Logical next step: $bb\tau\tau$**







[2110.00313]

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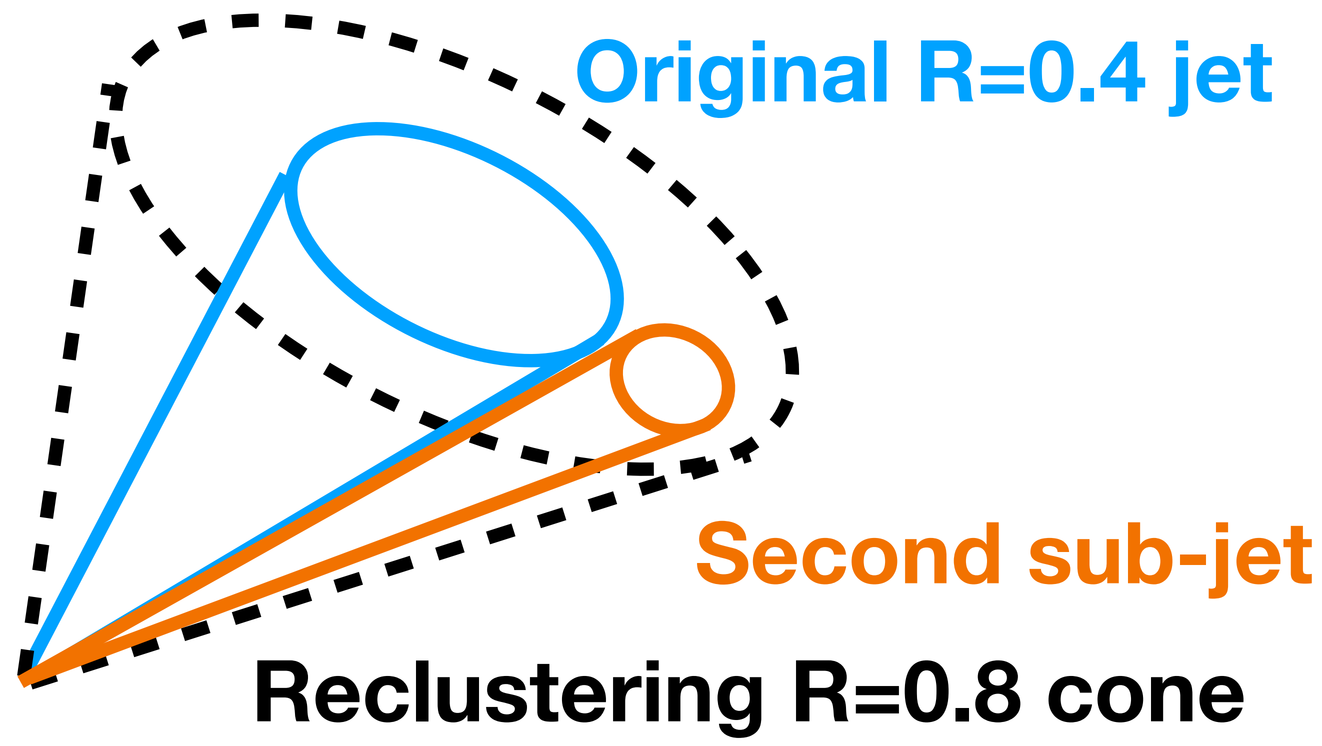
2HDM+S: $bb\tau\tau$

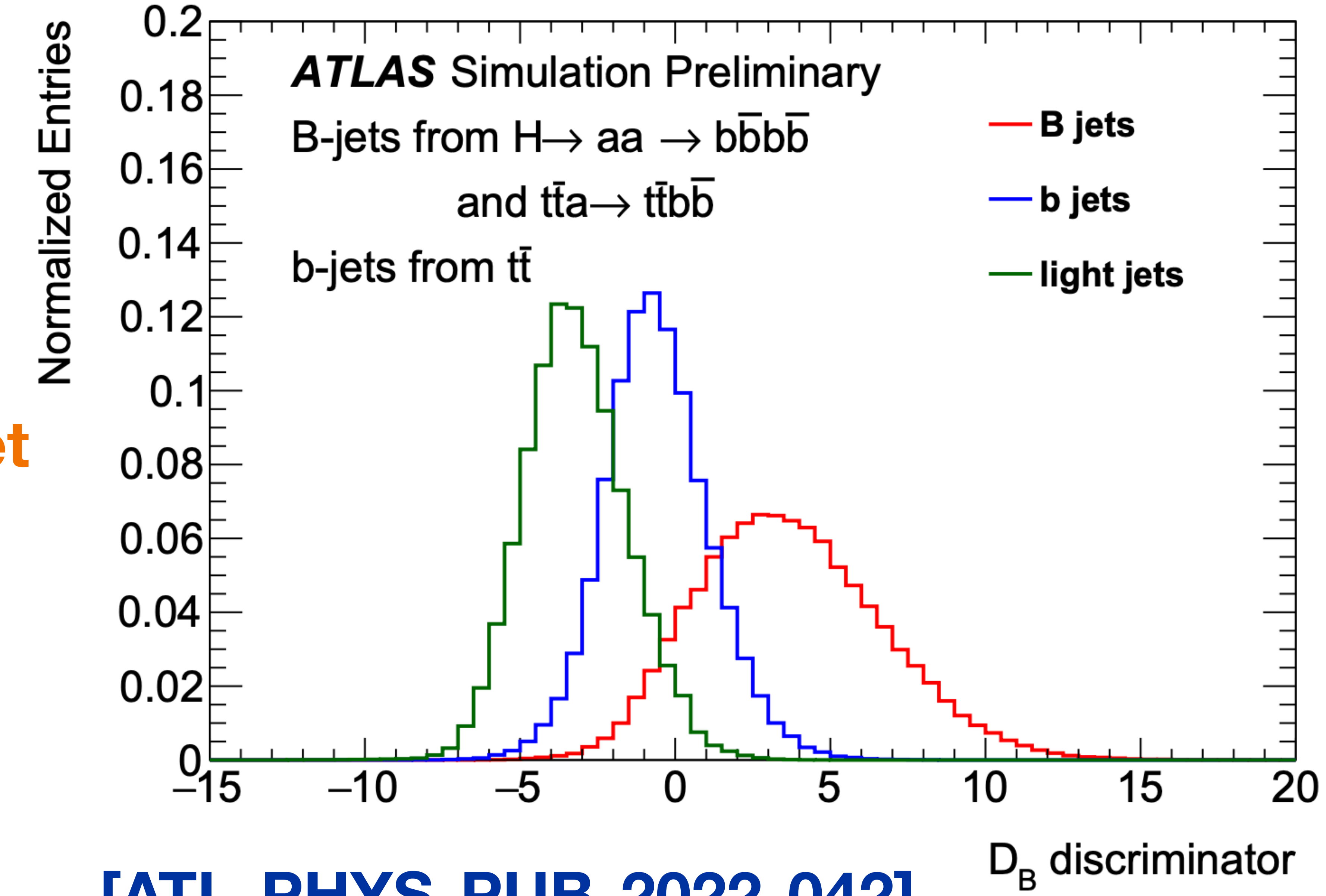
- **Quite difficult signature: low p_T, poor mass resolution**
- **Categorize based on experimental signature of tau and heavy flavor**
- **Use DeXTer deep sets based algorithm for Low-p_T merged "double" B-jet**
  - Recluster tracks around an ordinary jet in a R=0.8 cone
  - Cluster into precisely 2 sub-jets
  - Each sub-jet has minimum 5 GeV p_T, R=0.8 jet minimum 20 GeV

τ-lepton decays \ Heavy-flavor jets	$1B,0b$	$0B,1b$	$0B,2b$
$e\mu$	$(e\mu,1B)$	$(e\mu,1b)$	$(e\mu,2b)$
$\mu\tau_{had}$	$(\mu\tau_{had},1B)$	$(\mu\tau_{had},1b)$	$(\mu\tau_{had},2b)$
$e\tau_{had}$	$(e\tau_{had},1B)$	$(e\tau_{had},1b)$	$(e\tau_{had},2b)$

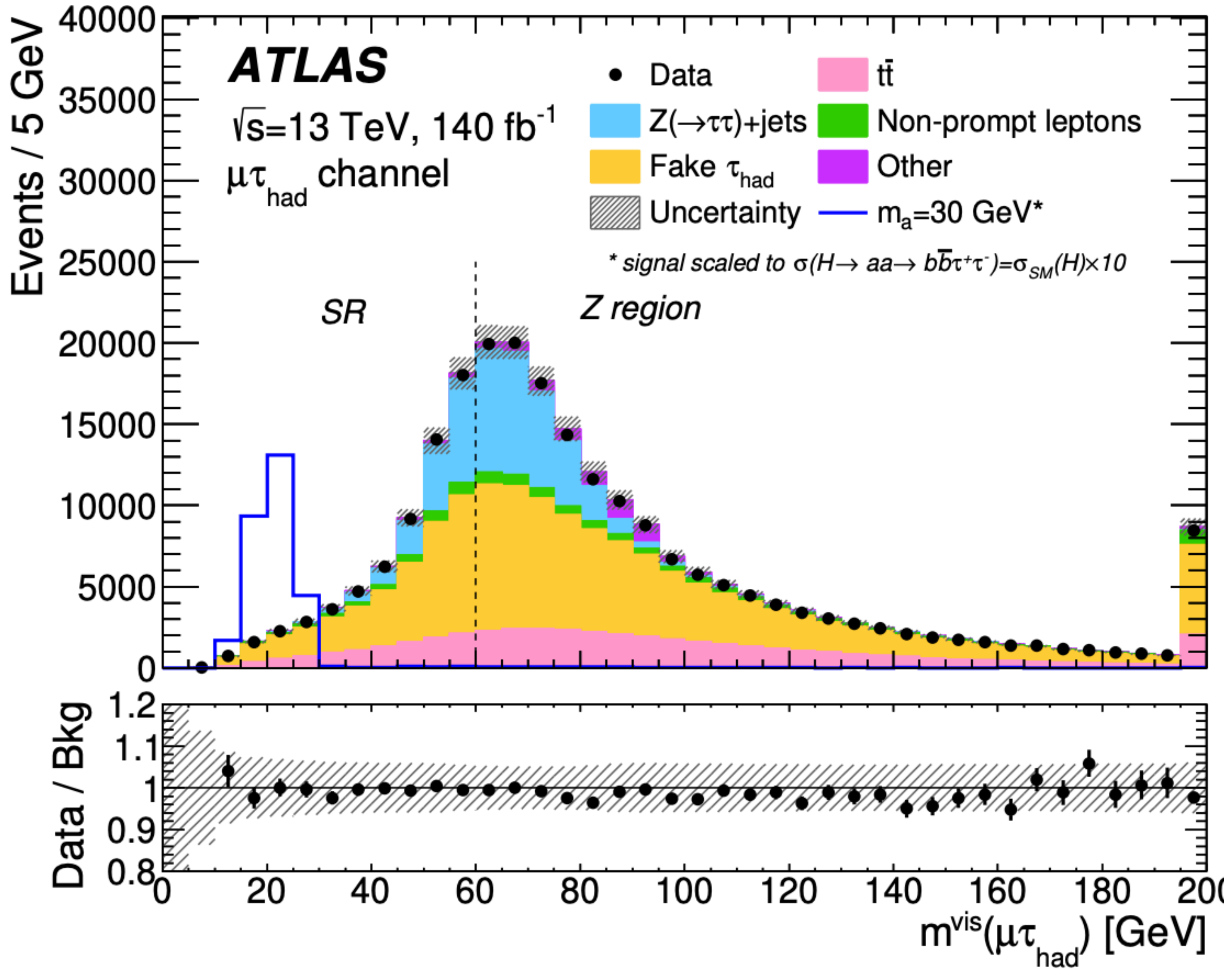
[2407.01335]



Note: after reclustering original jet may lose/gain constituents.

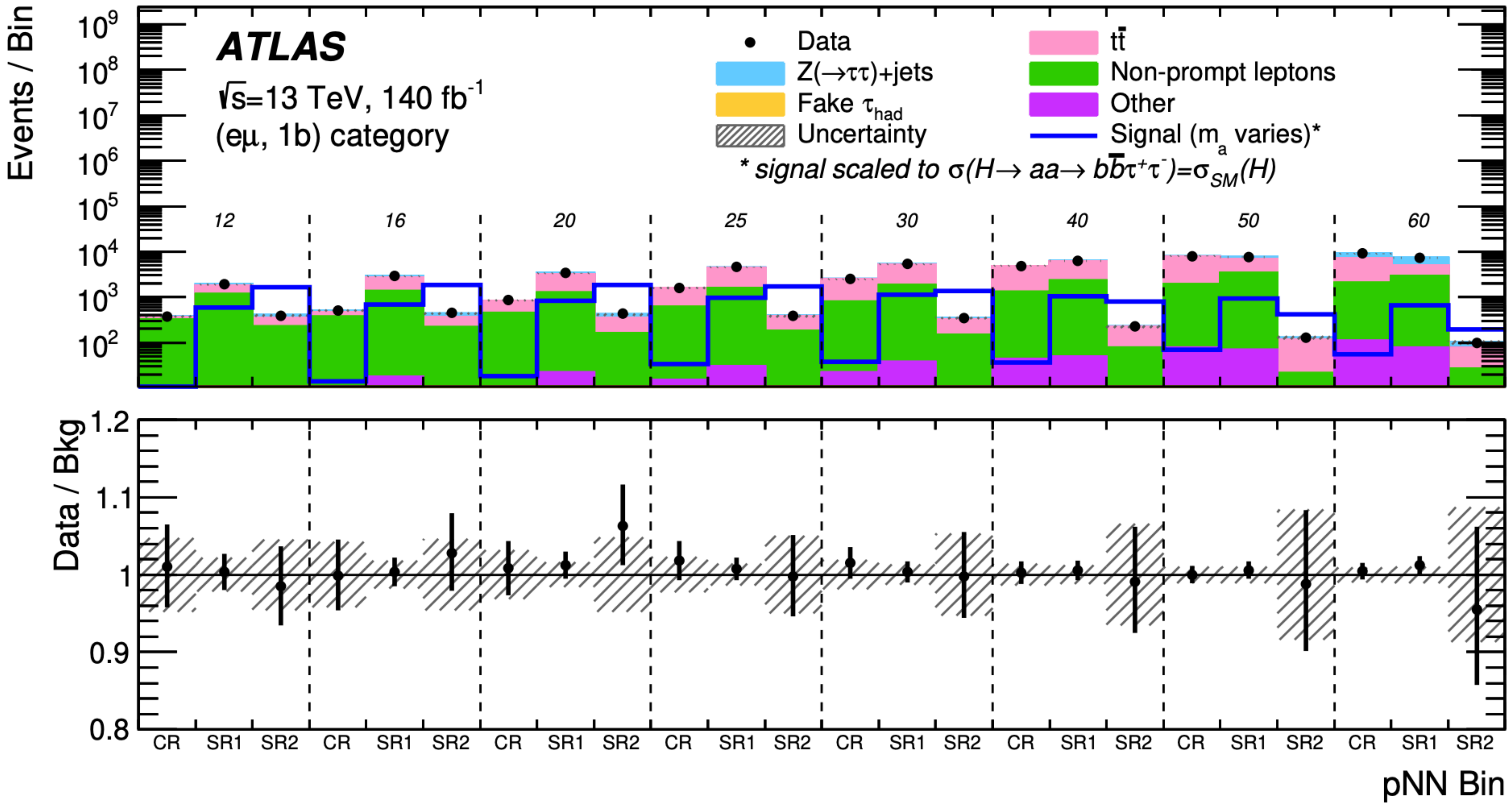


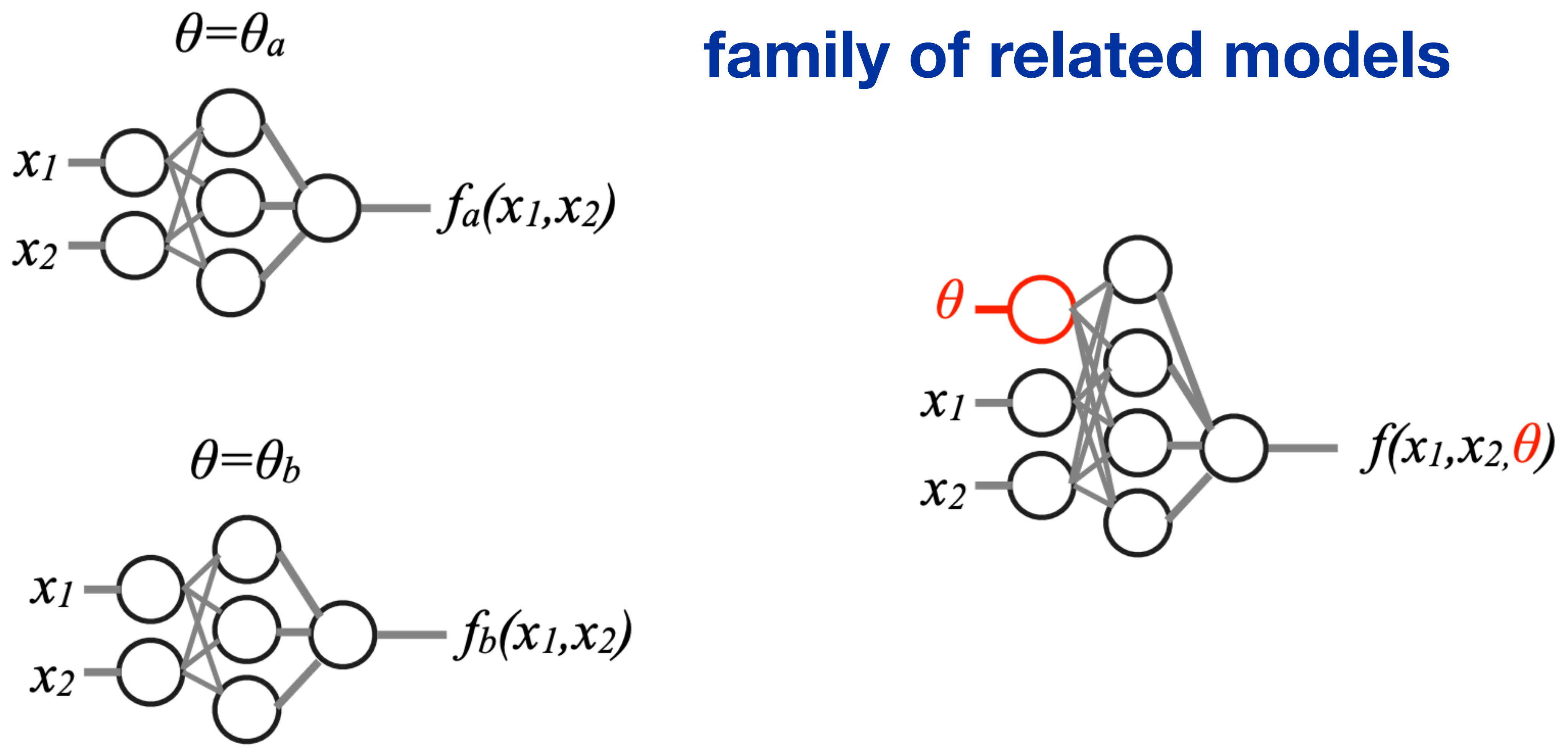
[ATL-PHYS-PUB-2022-042]



2HDM+S: $bb\tau\tau$

- **Use a parameterized NN [1601.07913] to search for low mass resonances**
- **For example, show pNN spectra for 8 mass points in the $(e\mu, 1b)$ category (1 of 9 categories)**



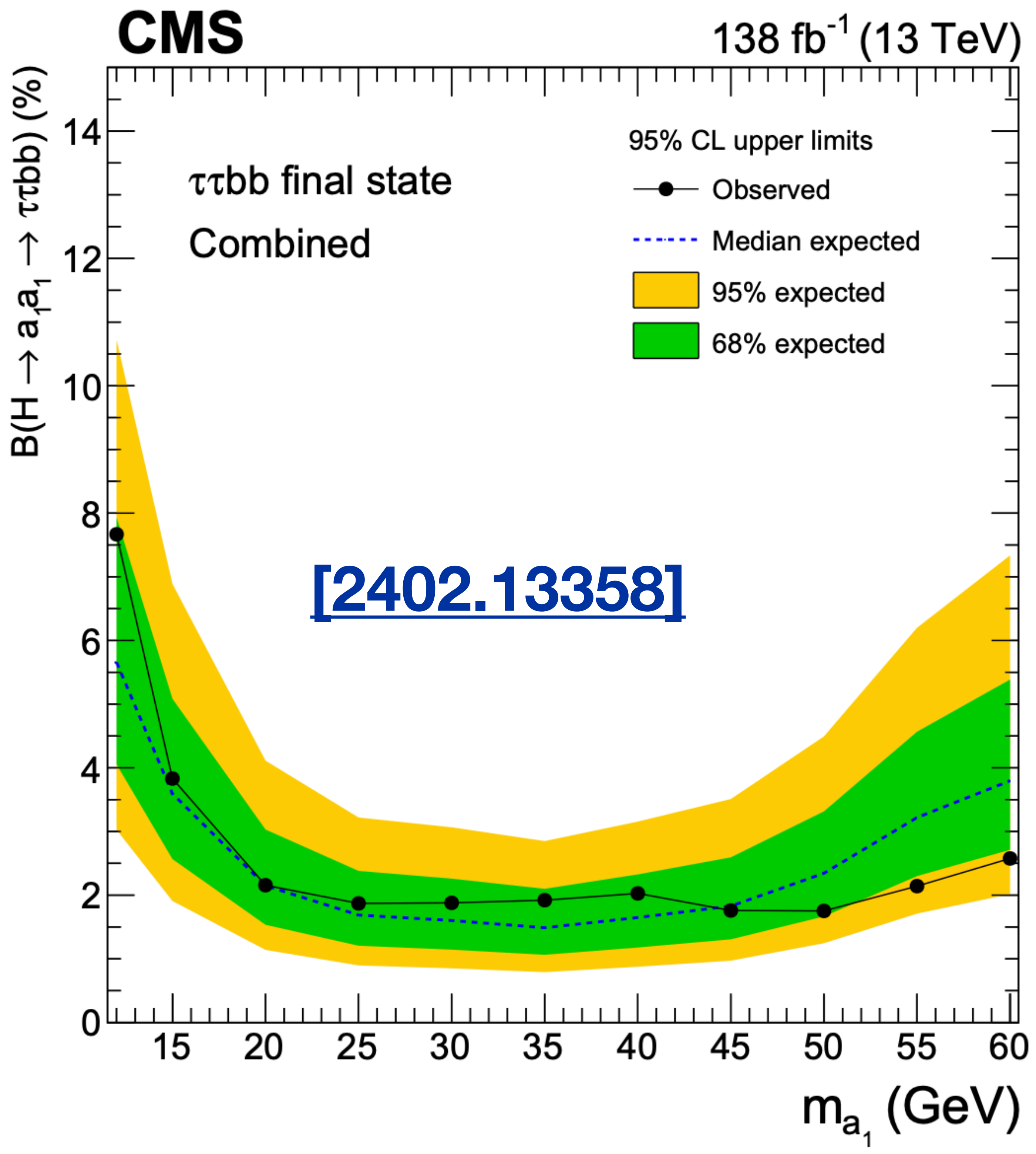


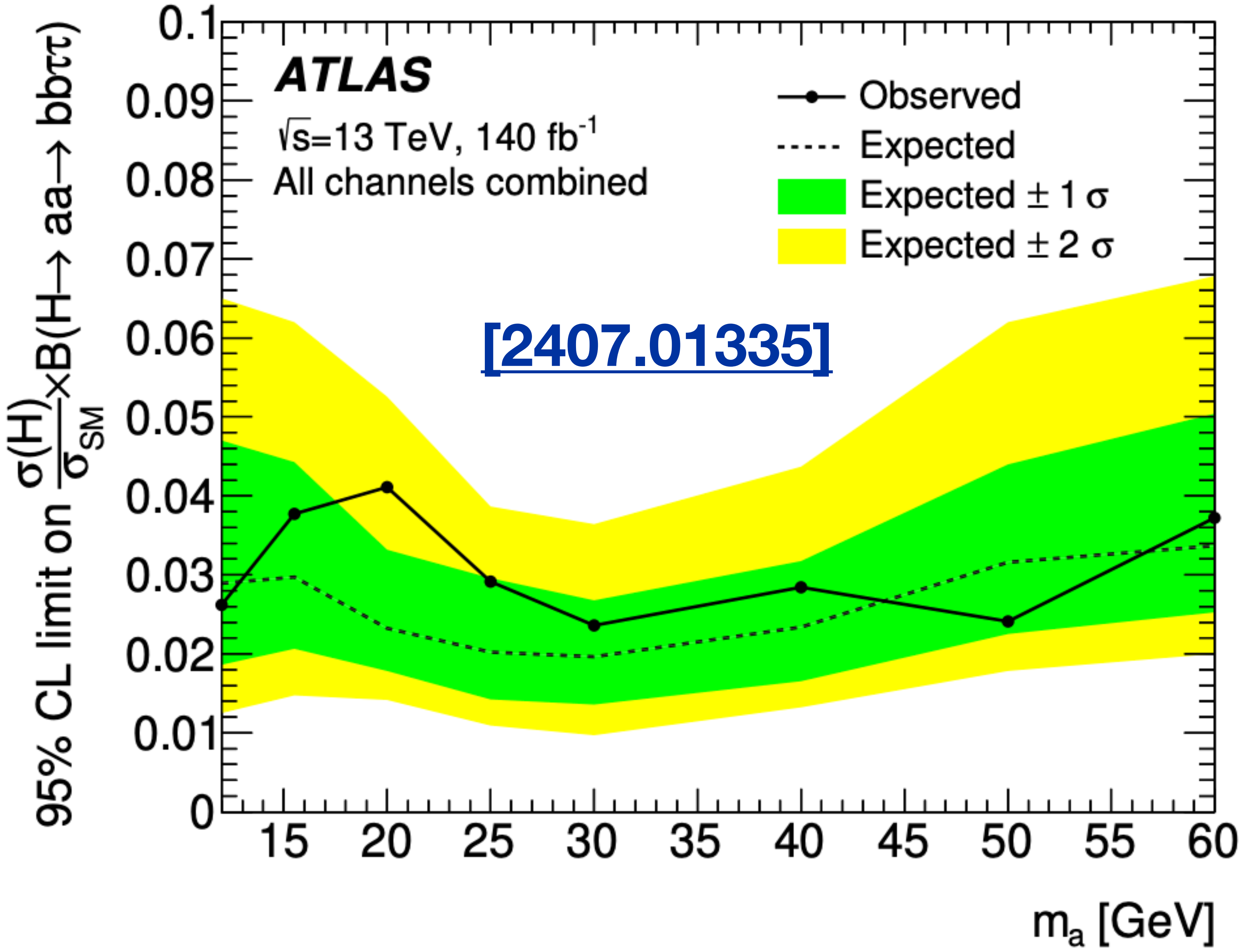
Mass hypothesis under consideration is a network input. Parameterizes response and allows for a search for a family of related models

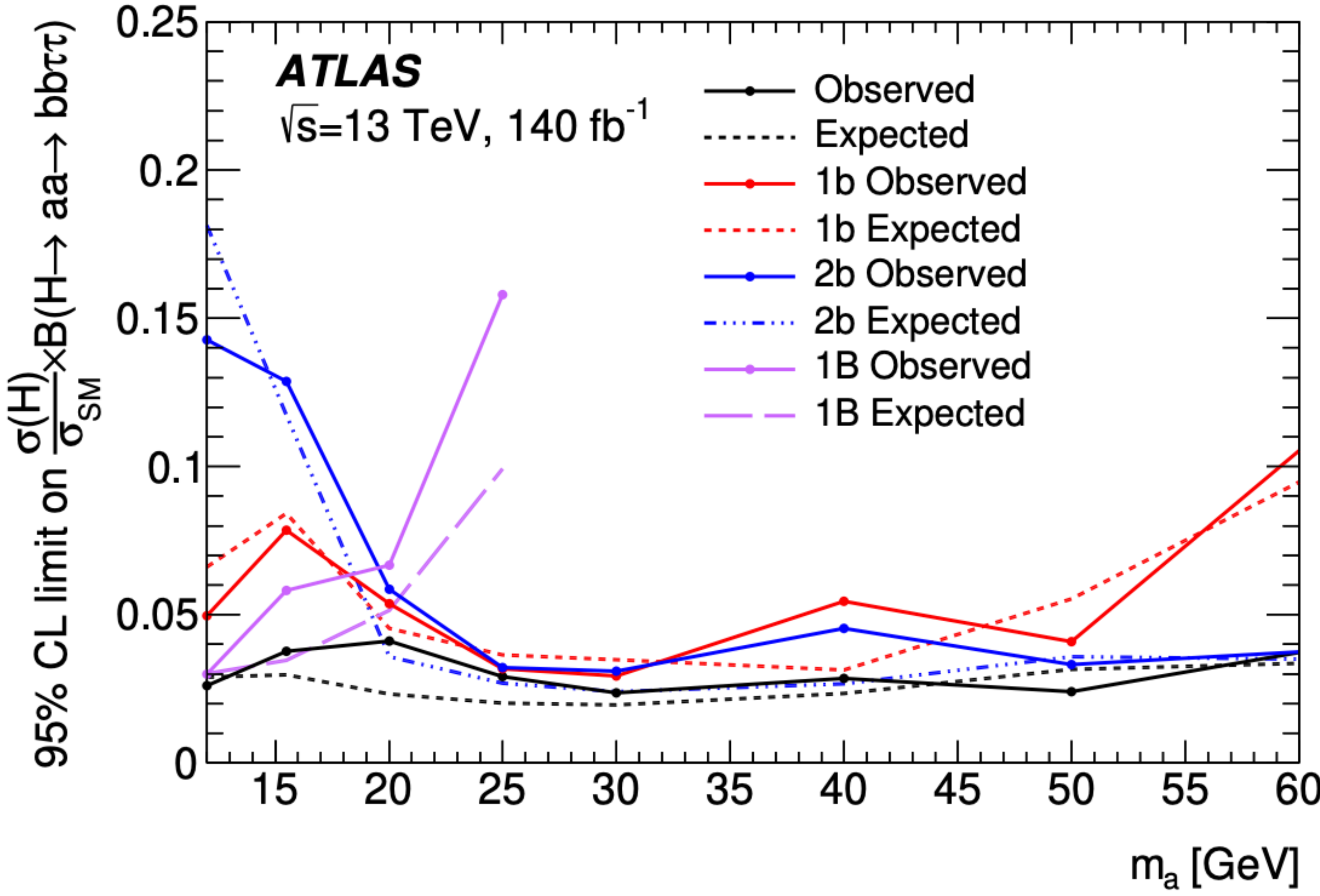
Non-paramerized NN: must train amodel for each mass hypothesis

2HDM+S: $bb\tau\tau$

- **No excess observed**
- **Boosted "B" tagger (2 sub-jets consistent with b) improves limit by a factor of 2 at low mass compared to CMS**
- **Bottom right shows limit using B vs 1b vs 2b heavy flavor category**
- **ATLAS and CMS have comparable limits above 20 GeV (resolved regime)**
  - Main source for any discrepancy is the barrel muon trigger efficiency is lower in ATLAS than CMS
- **This is not the end of $bb\mu\mu$ excess!**
  - Just means that if the excess is real, it likely does not couple proportional to lepton mass. Could be Z'.







Charged Higgs searches

- **Singly- and doubly- charged Higgs bosons present in Georgi-Machacek model**

- **Introduce a new Higgs triplet field with 9 degrees of freedom:**
  - A doubly charged particle, a two singly charged particles, and three real neutral particles

$$\chi = \begin{vmatrix} \chi^0 & \zeta^+ & \chi^{++} \\ \chi^- & \zeta^0 & \chi^+ \\ \chi^{--} & \zeta^- & \chi^0 \end{vmatrix}$$

- **Similarly to 2HDM, an angle parameterizes how much the new degrees of freedom participate in EWSB:**

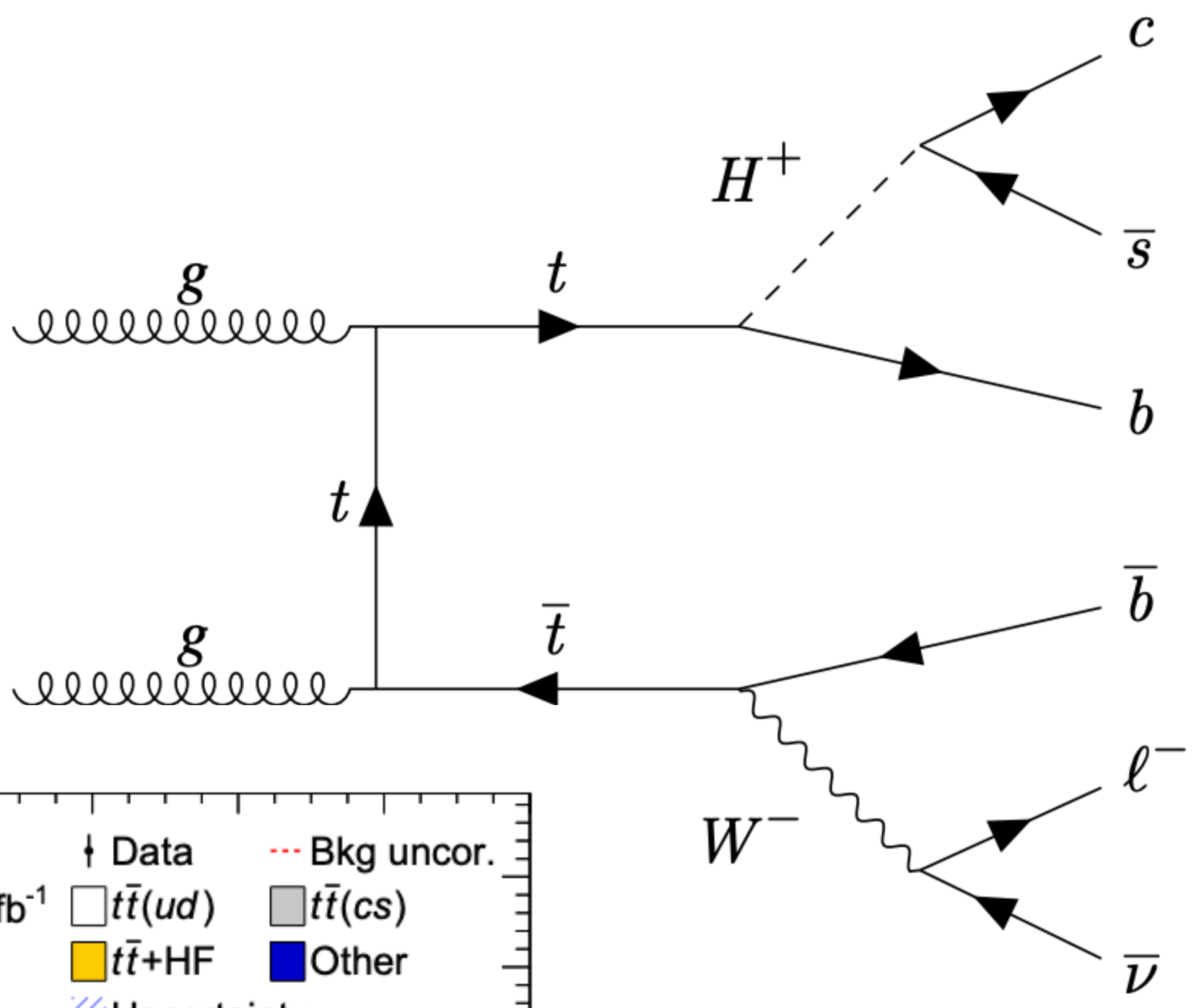
$$\sin^2\theta_H = 8b^2/v^2$$

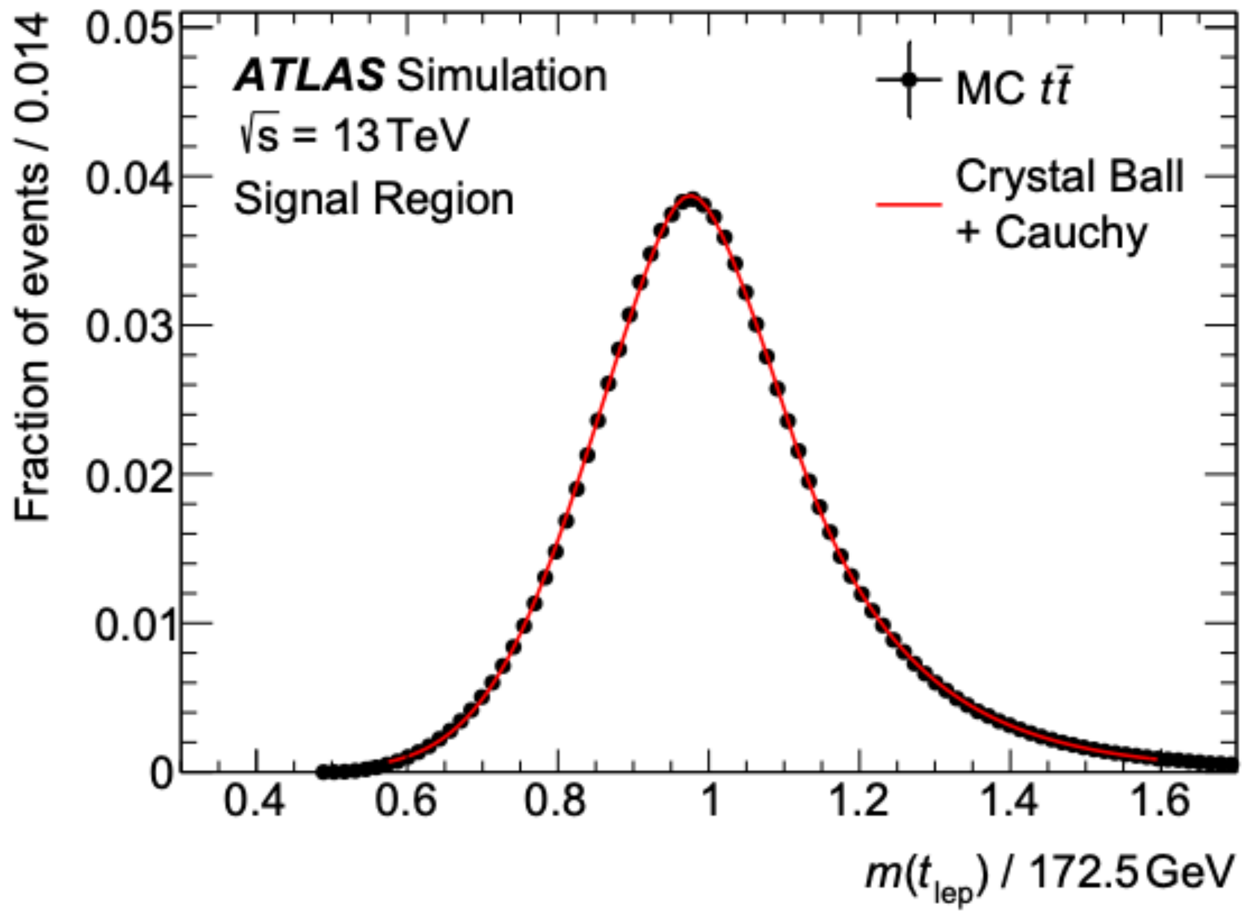
  - Where "b" is the VeV acquired by the scalars in χ and $v = 246$ GeV is determined by G_F, $\sin\theta_W$
  - If there is no VeV in the new triplet, it doesn't participate in EWSB

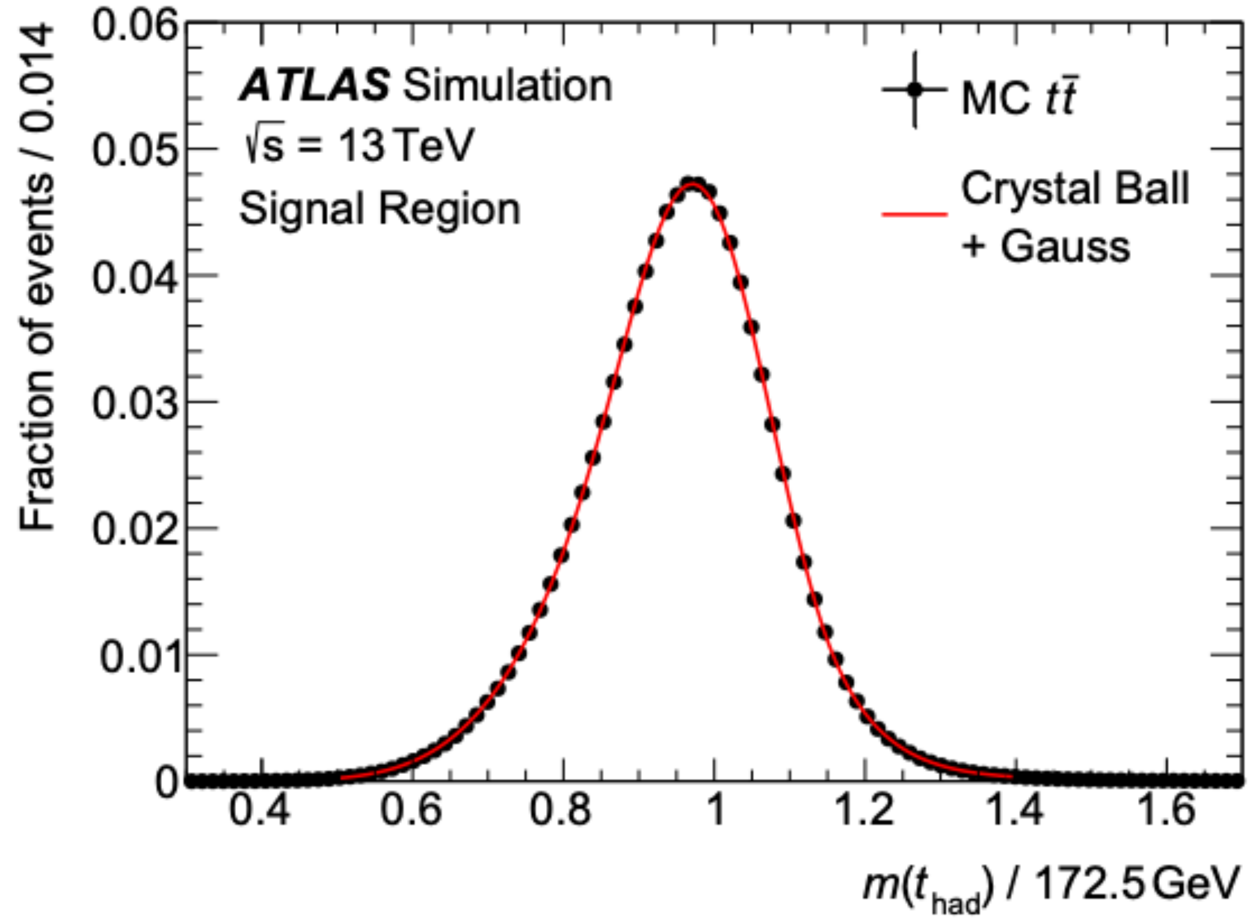
- **Charged Higgses also present in 2HDM/MSSM**

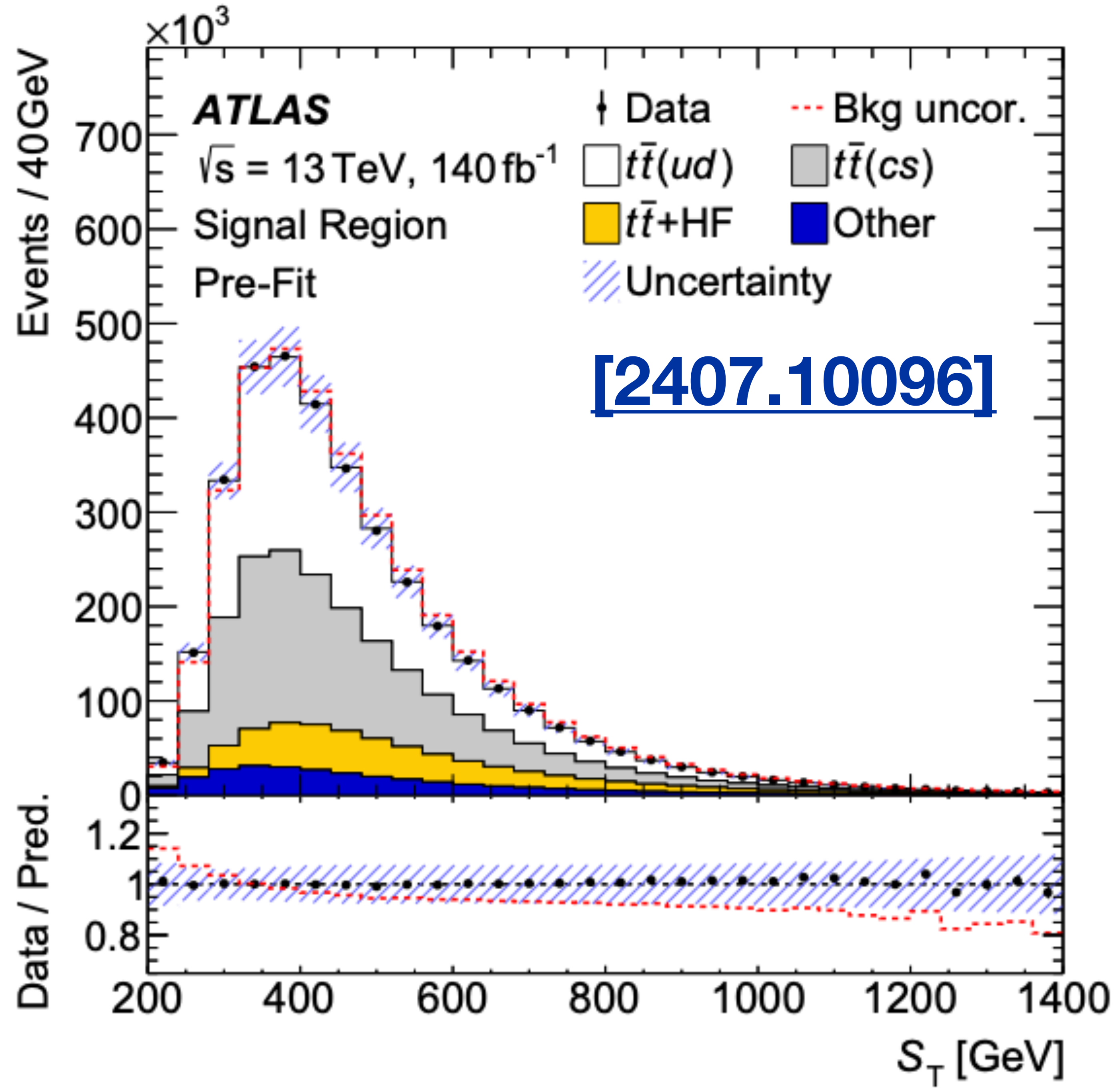
Search for $t \rightarrow H^{\pm}(\rightarrow cs)b$

- **$t\bar{t}$ event topology with lepton trigger**
  - Large background from semi-leptonic $t\bar{t}$ where $W \rightarrow cs$ or $W \rightarrow ud$ occurs
- **Exploit *b*- and *c*- tagging simultaneously**
  - *c*- tagging at the 24% and 45% efficient WPs (rejection of *b* ~15x and ~6x)
- **Address combinatoric jet assignment with likelihood method**
  - Leptonic and hadronic top decay observed mass distributions are different
  - Take all possible combinatorics and maximize $PDF_{\ell} \times PDF_{had}$









[2407.10096]

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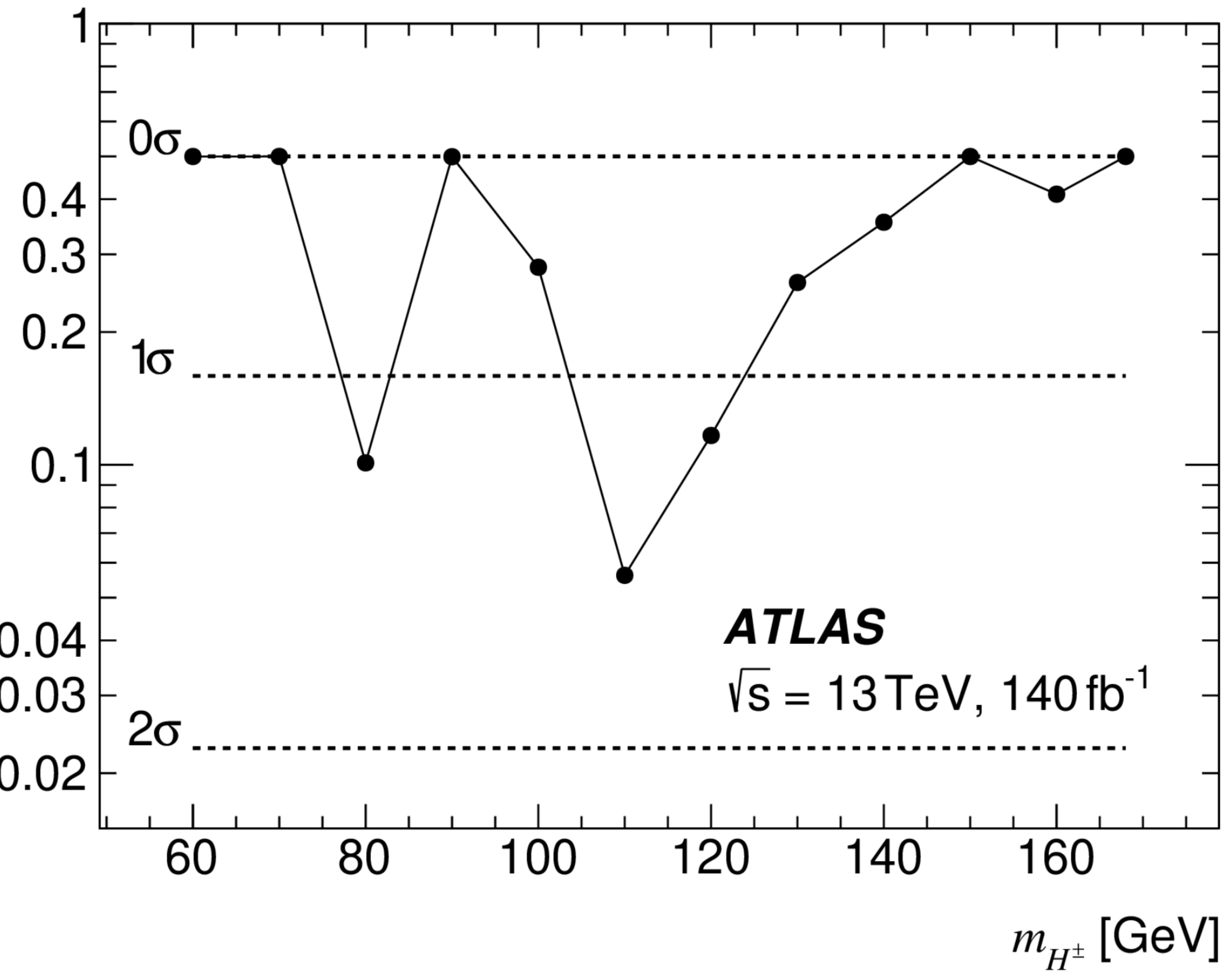
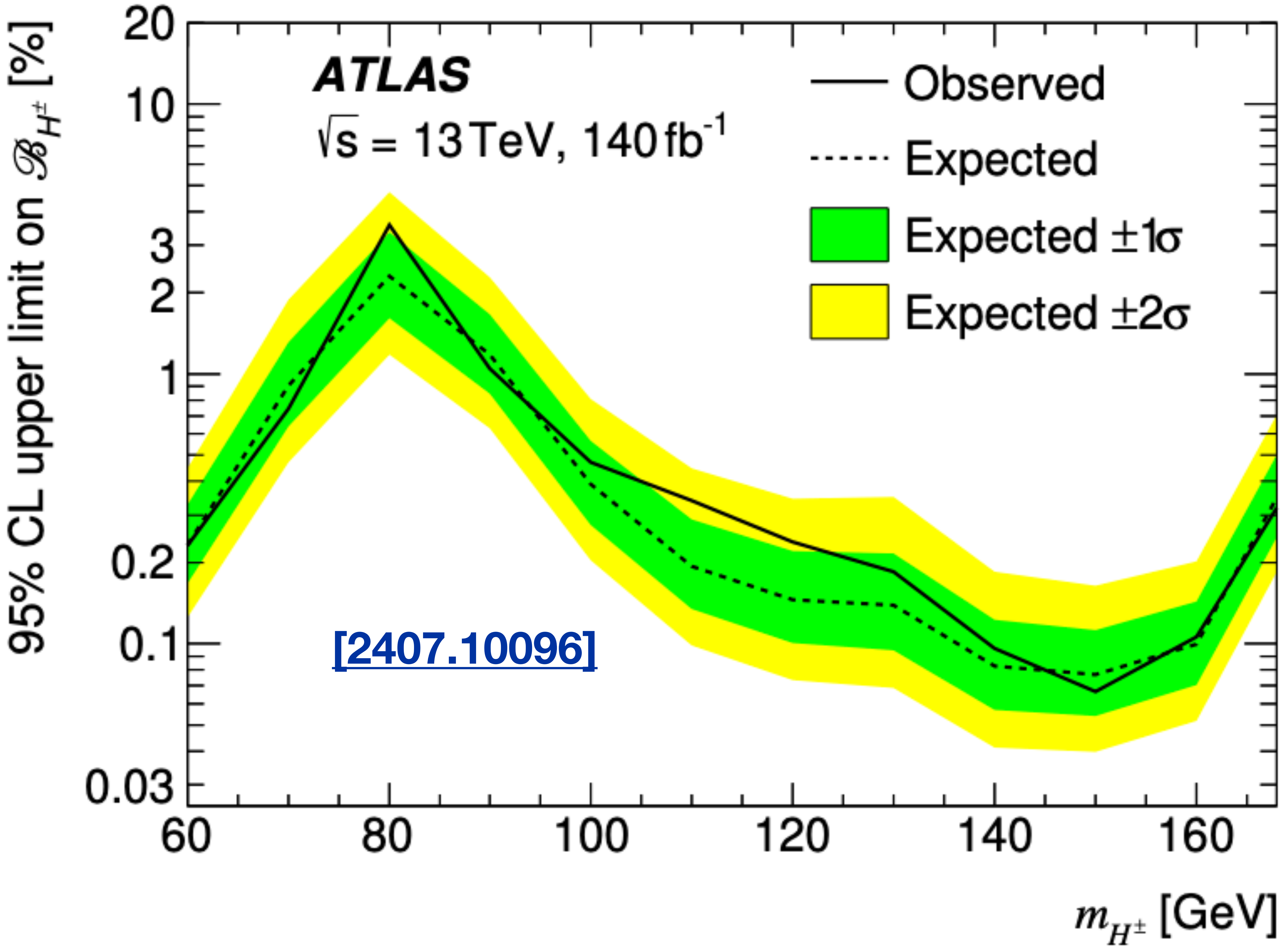
Search for $t \to H^{\pm}(\to cs)b$

- **A BDT is used to build a discriminant for statistical interpretation**
- **Mass of the $H^{\pm}$ affects not only the c, s kinematics but also the *b* because a heavier $H^{\pm}$ can take more of the top mass-energy**

Search for $t \to H^{\pm}(\to cs)b$

- **No excess is observed**
- **CMS has [a search in 36 fb^{-1}], so ATLAS naturally is more sensitive. ATLAS also covers larger mass range.**





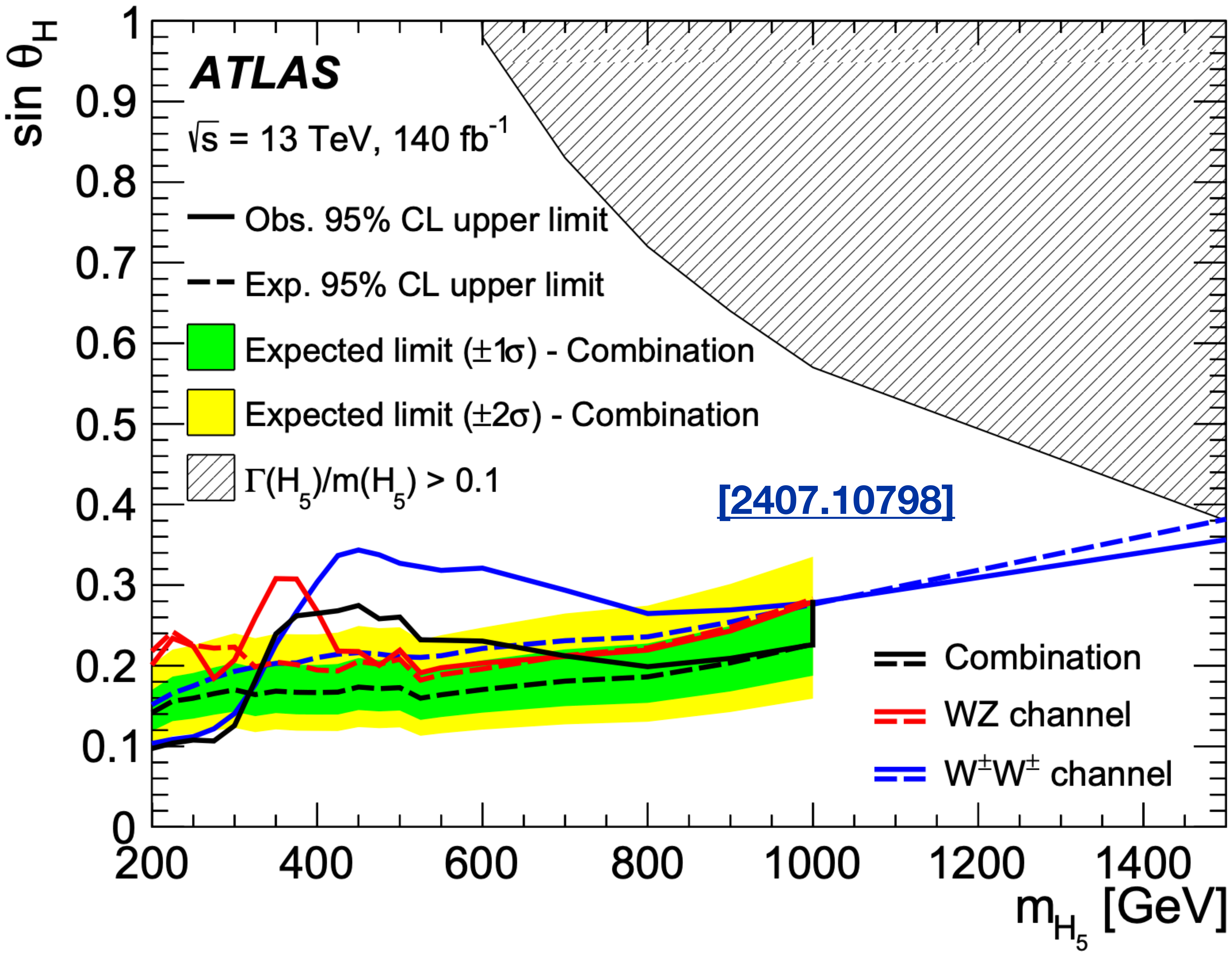
Charged Higgs searches: combination

- **Assuming the masses of new charged Higgses $H^{\pm}$ and $H^{\pm\pm}$ are identical (m_{H_5}), combine searches in the $W^{\pm}Z$ and $W^{\pm}W^{\pm}$ final states**

- **Near 400 GeV there is an excess 3.3 (2.5) σ local (global)**

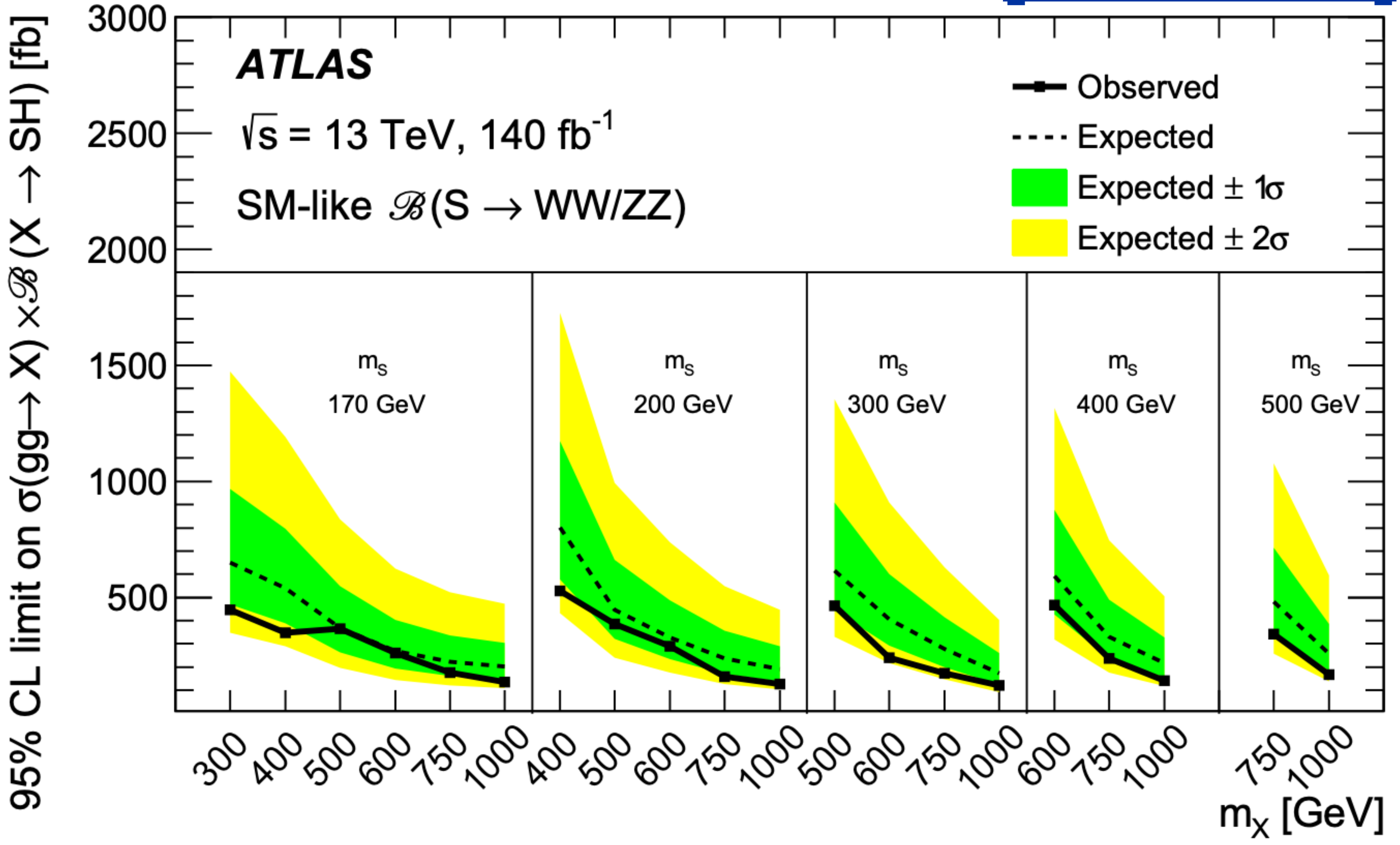
- **CMS is less sensitive (exp limit on $\sin\theta_H$ ~ 0.23 at 400 GeV) ATLAS exp limit on $\sin\theta_H$ ~ 0.16 at 400 GeV**

- **Combines searches: [2207.03925] [2312.00420]**

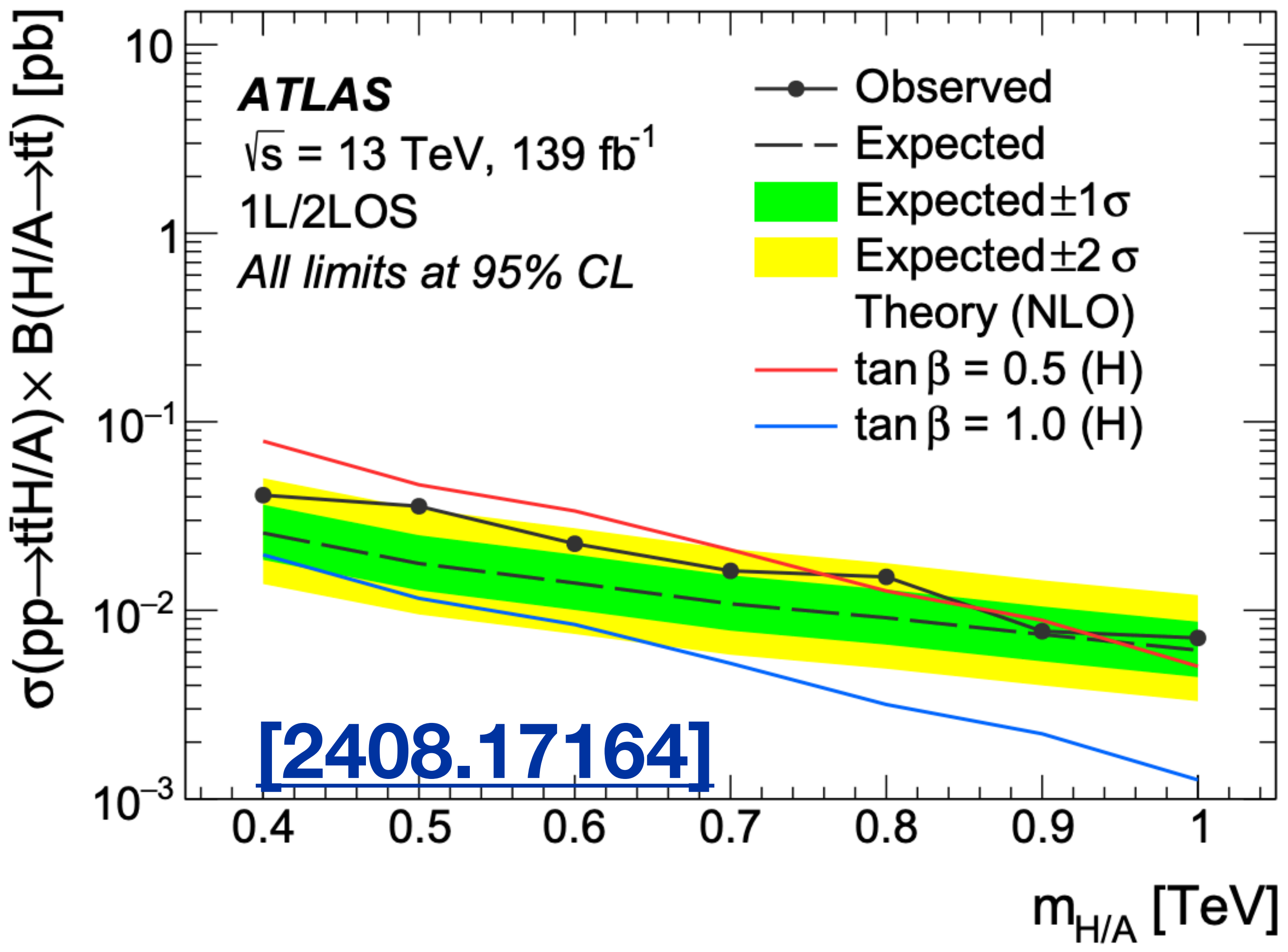


Cut for time (but no less interesting!)

$X \to SH \to VV\gamma\gamma$ [2405.20926]

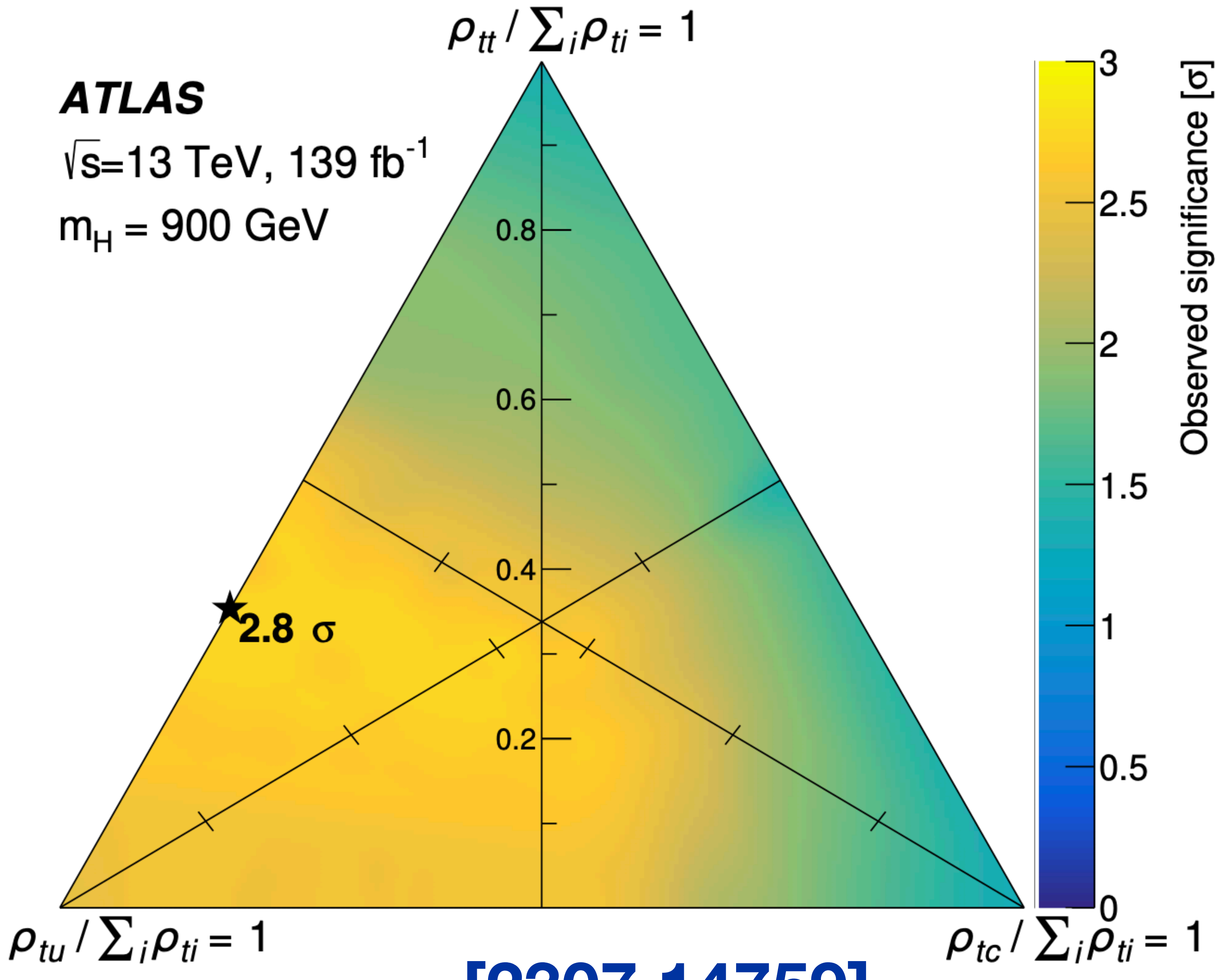


$t\bar{t}(A \to t\bar{t})$



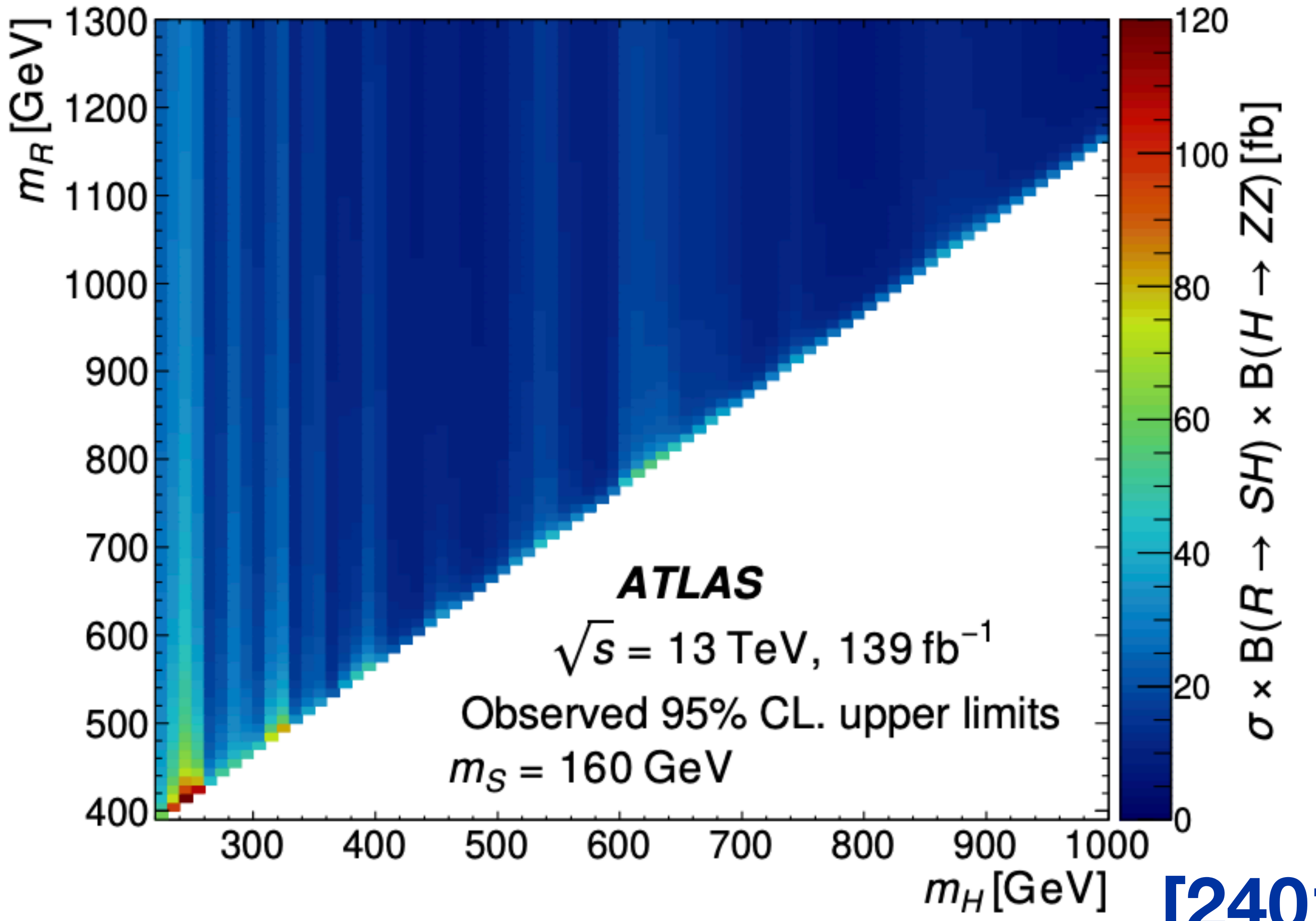
[2408.17164]

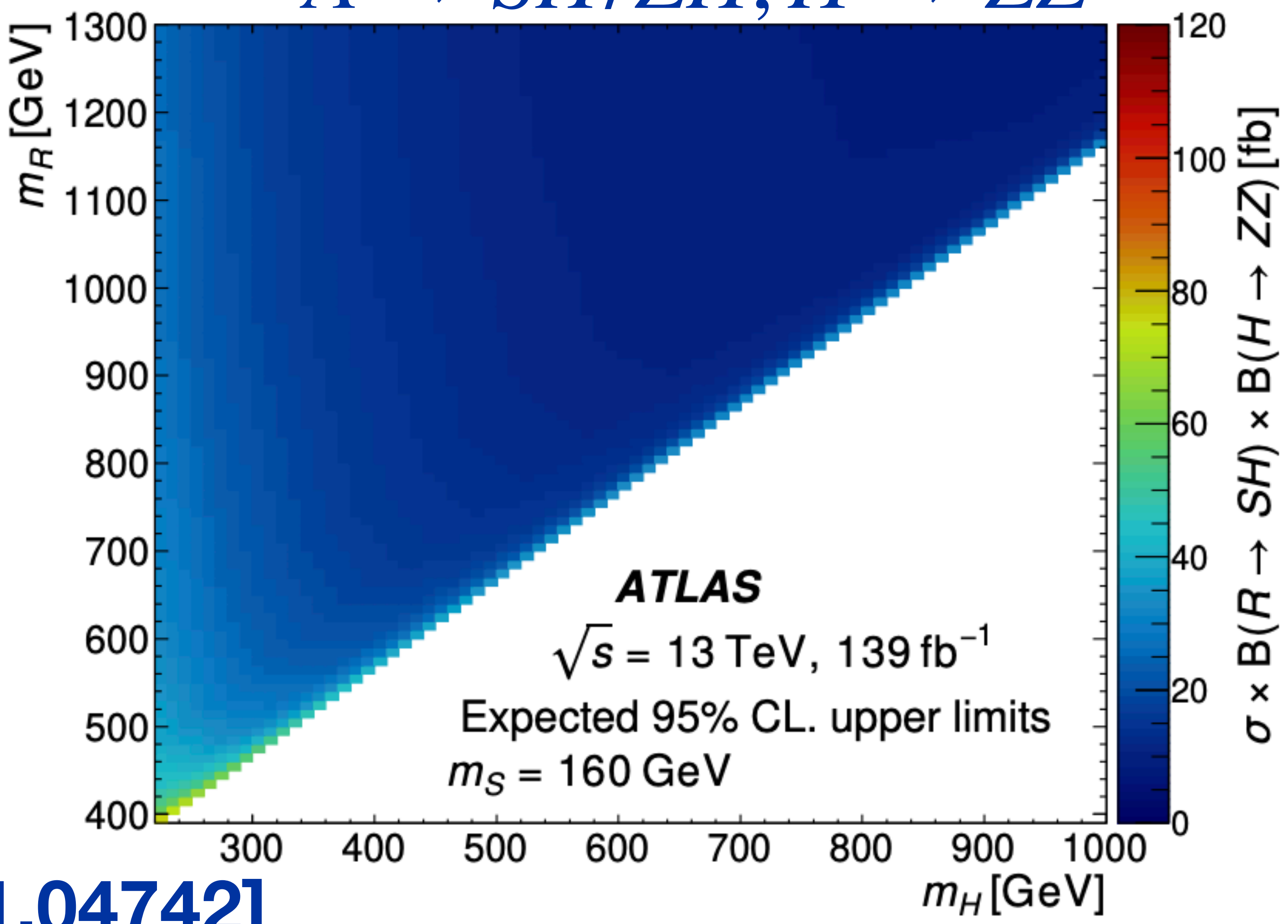
Lepton flavor violating heavy H



[2307.14759]

$A \to SH/ZH, H \to ZZ$



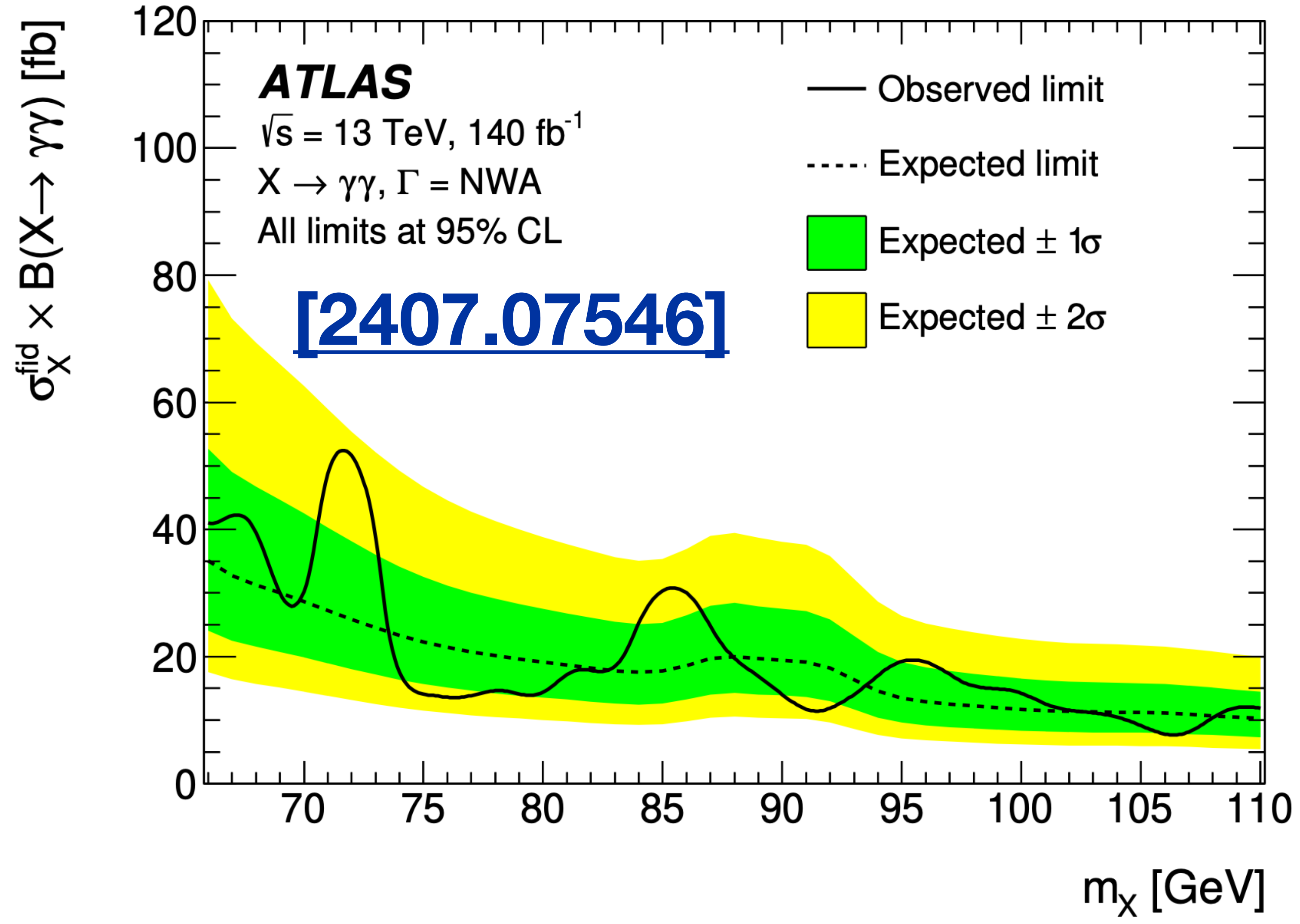


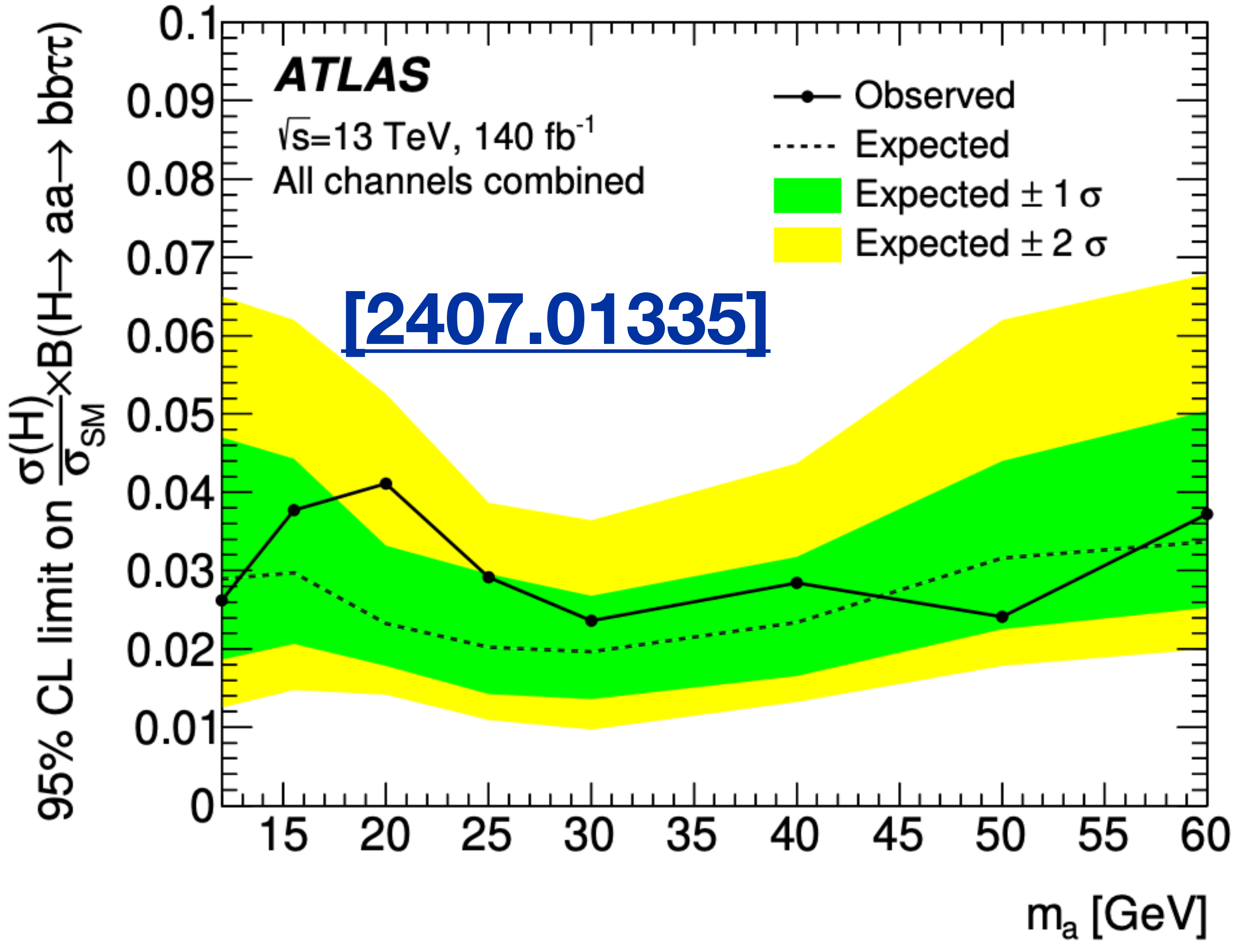
[2401.04742]

No significant excesses observed. Maximum 2.8σ local.

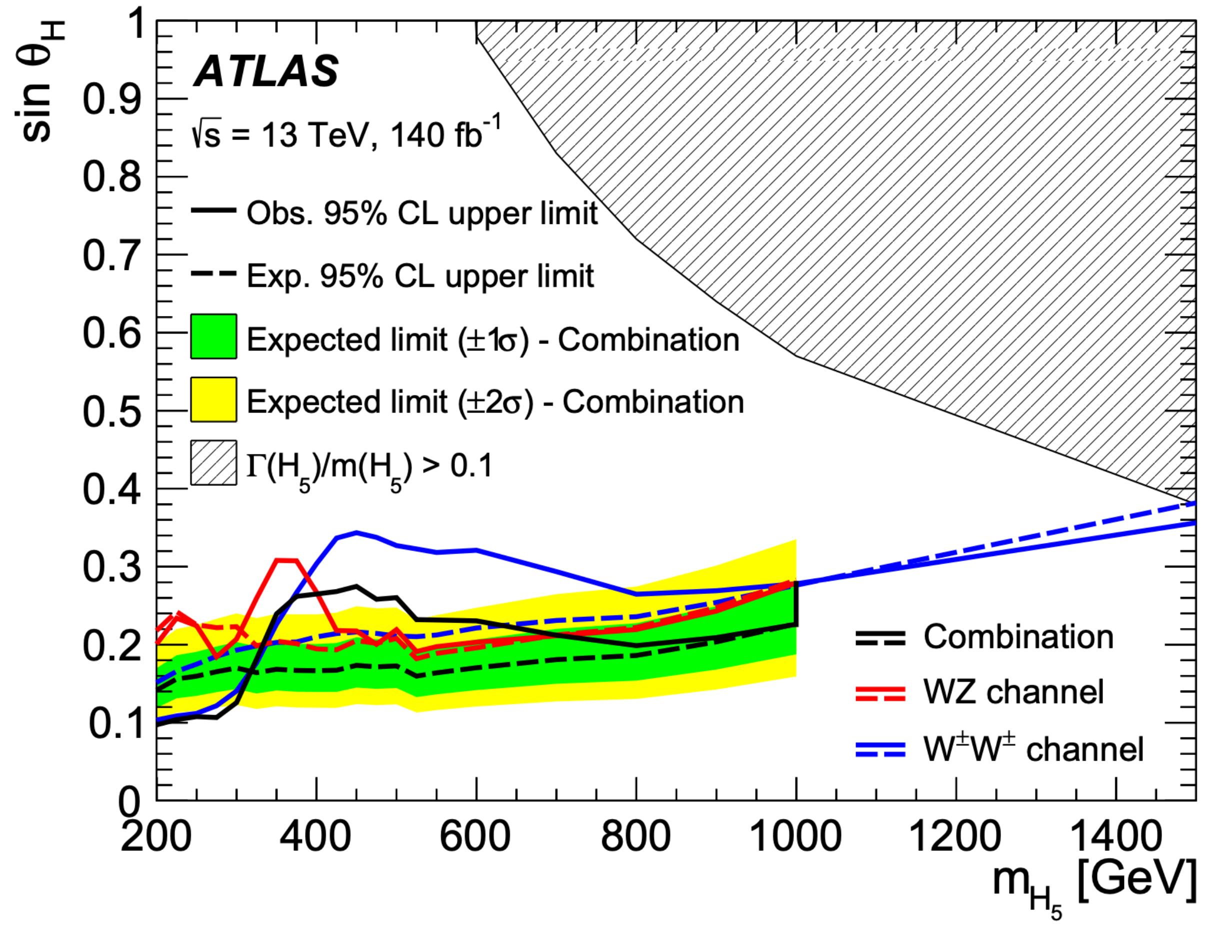
Conclusion

- **No evidence for new Higgs bosons in ATLAS**
  - Diphoton resonances
    - Largest excess: 3.3σ local at 684 GeV.
    - No evidence supporting the 95 GeV excess from CMS.
  - 2HDM+S low mass scalars
    - $bb\tau\tau$ was a cross-check on $bb\mu\mu$. No local excess above 2σ.
    - Means $bb\mu\mu$ excess likely not 2HDM+S particle, could be Z' boson (or nothing)
  - Charged Higgses
    - 3.3 (2.5) σ local (global) in combination of searches in $W^{\pm}Z$ and $W^{\pm}W^{\pm}$
    - A small hint of things to come? We should wait and see what CMS has to say





[2407.10798]



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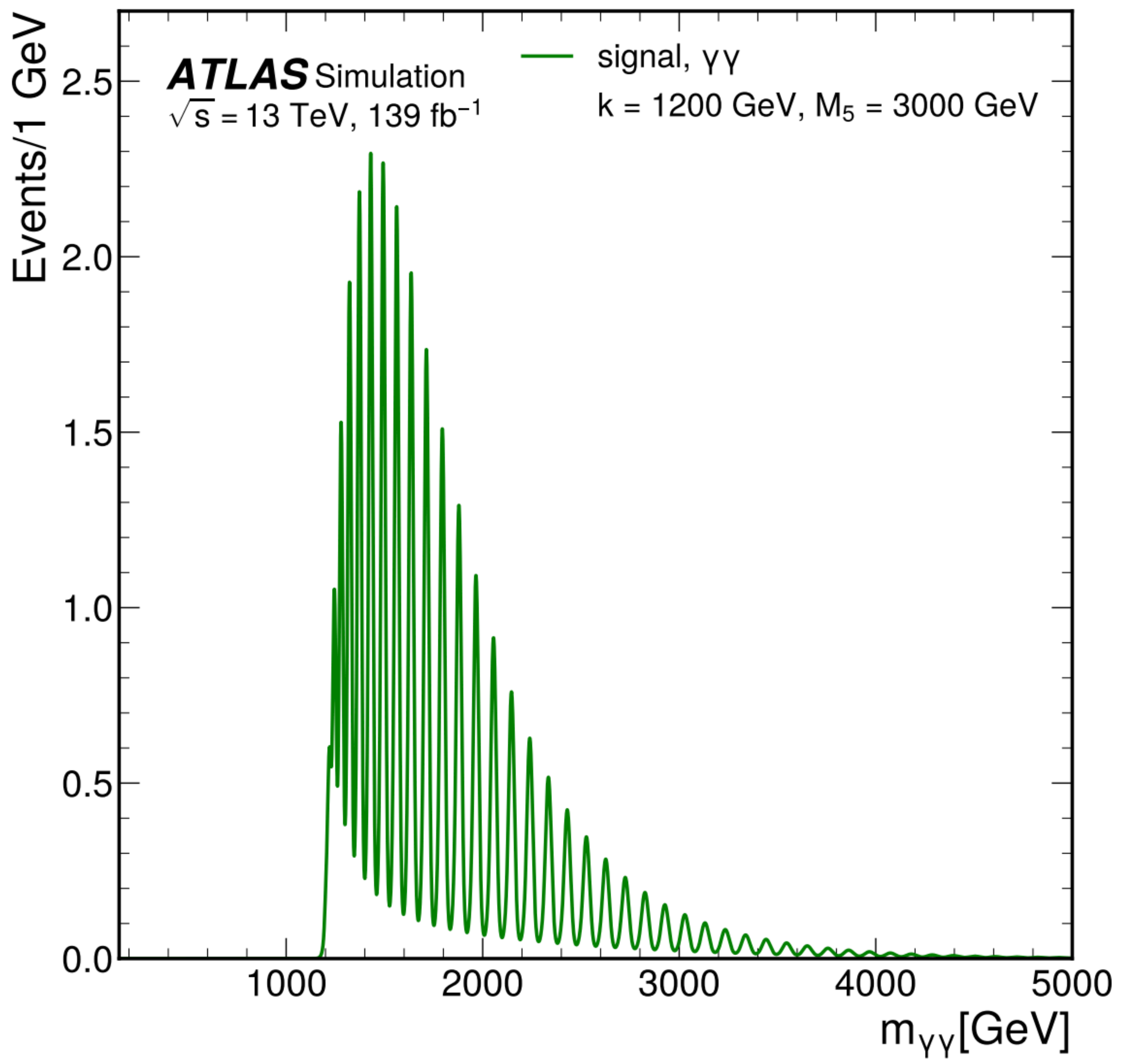
Backup

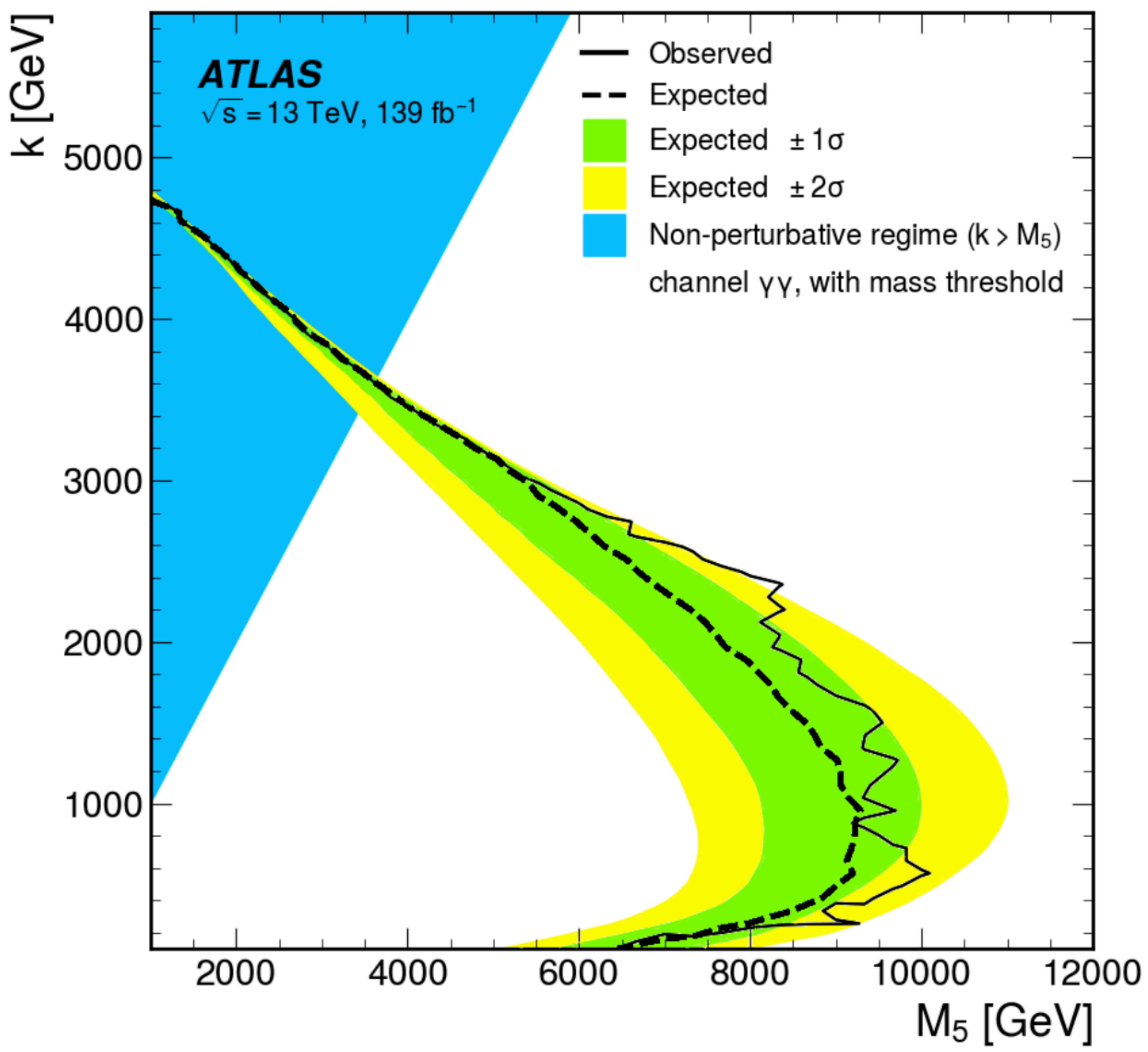
ATLAS diphoton: clockwork

- **Periodic signals**
- **k=mass parameter denoting start of periodic signals. M_5 is the reduced Planck mass (fundamental scale of the theory)**

Clockwork signal



Exclusion limits for graviton model

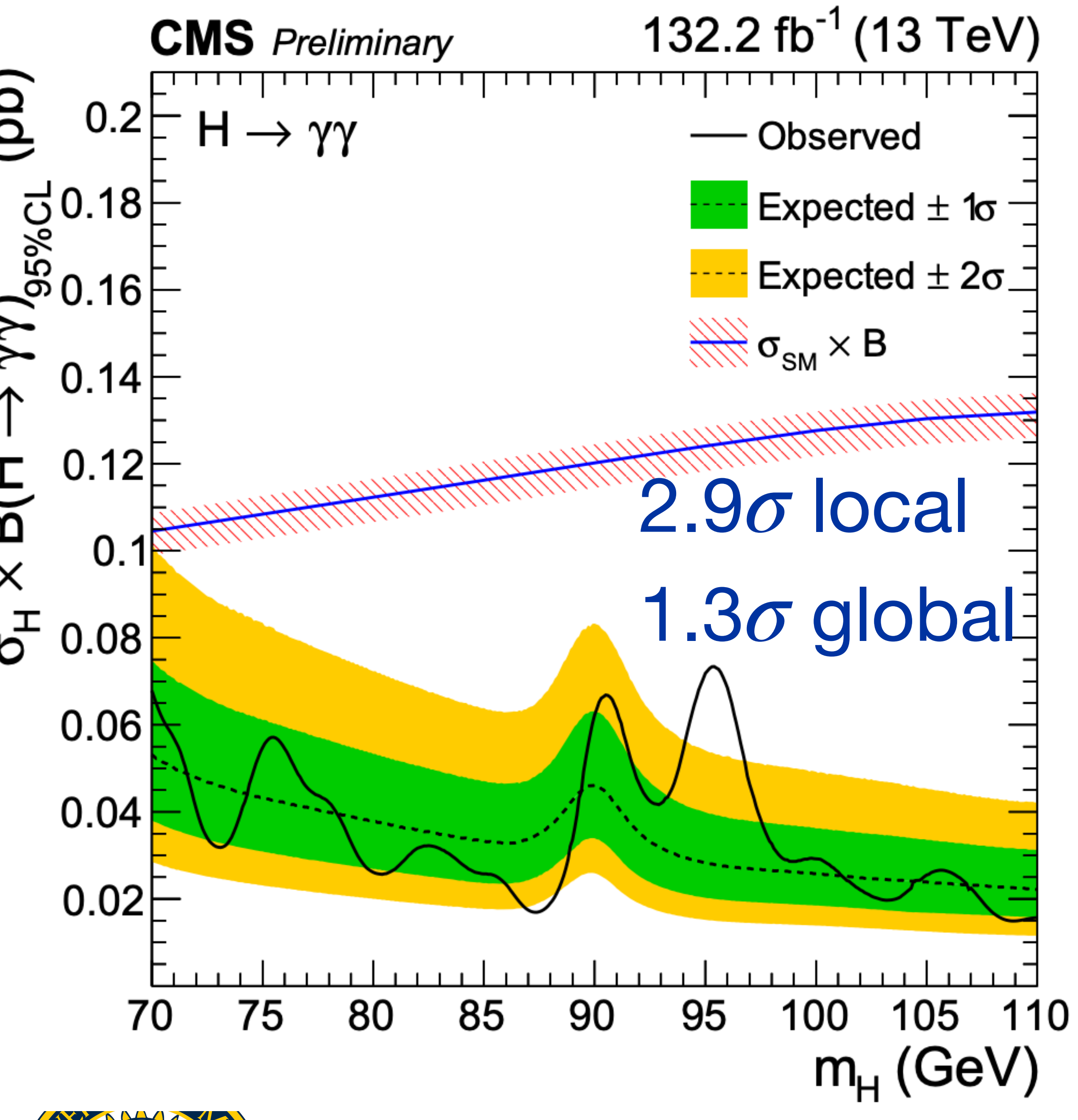


[2305.10894]

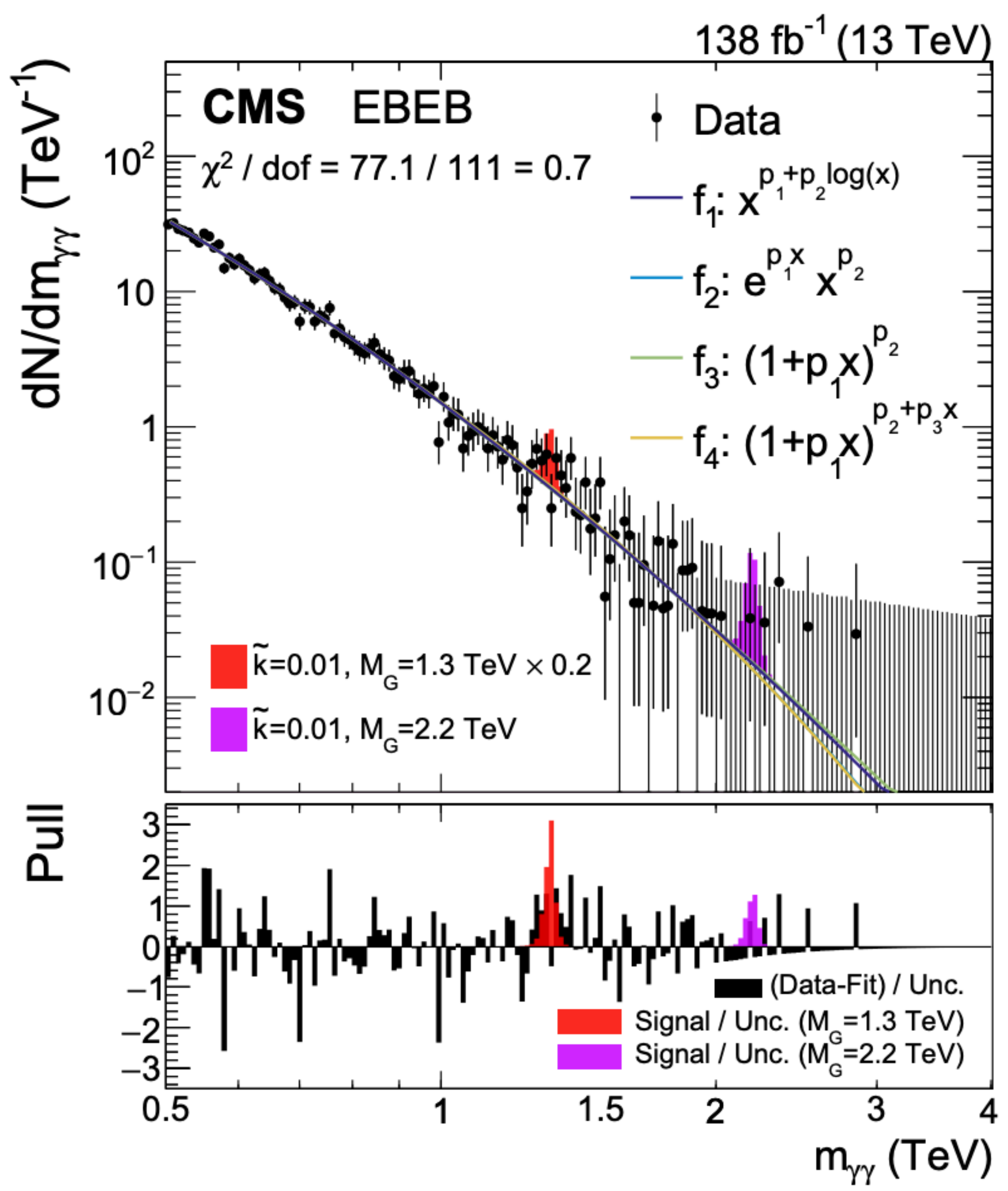
CMS diphoton

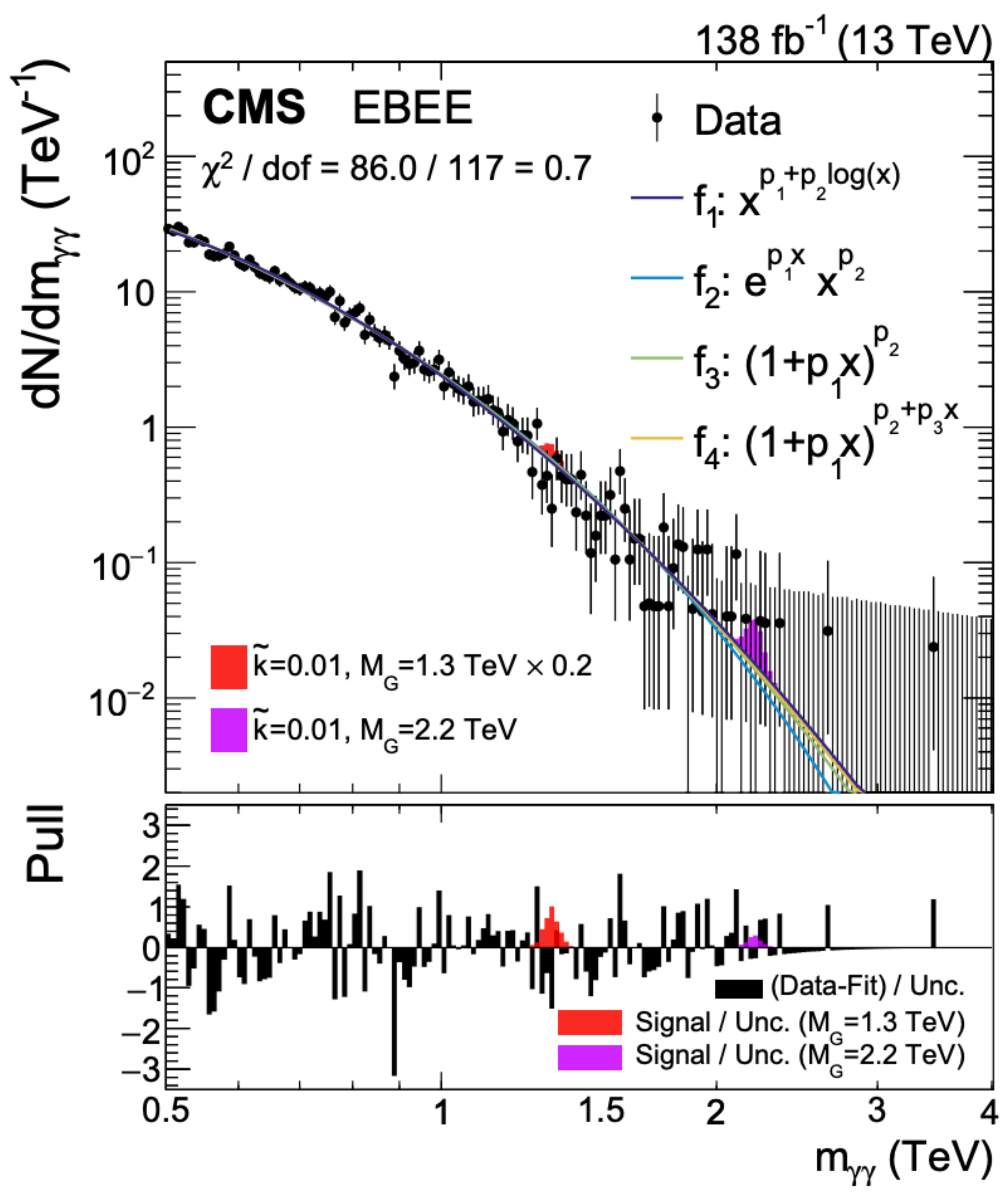
- **Could not find a full run 2 search below 70 GeV from CMS**
- **High mass searches up to $m_{\gamma\gamma}$~3 TeV are shown.**
  - Mass spectrum is categorized based on barrel vs endcap.

[2405.18149]



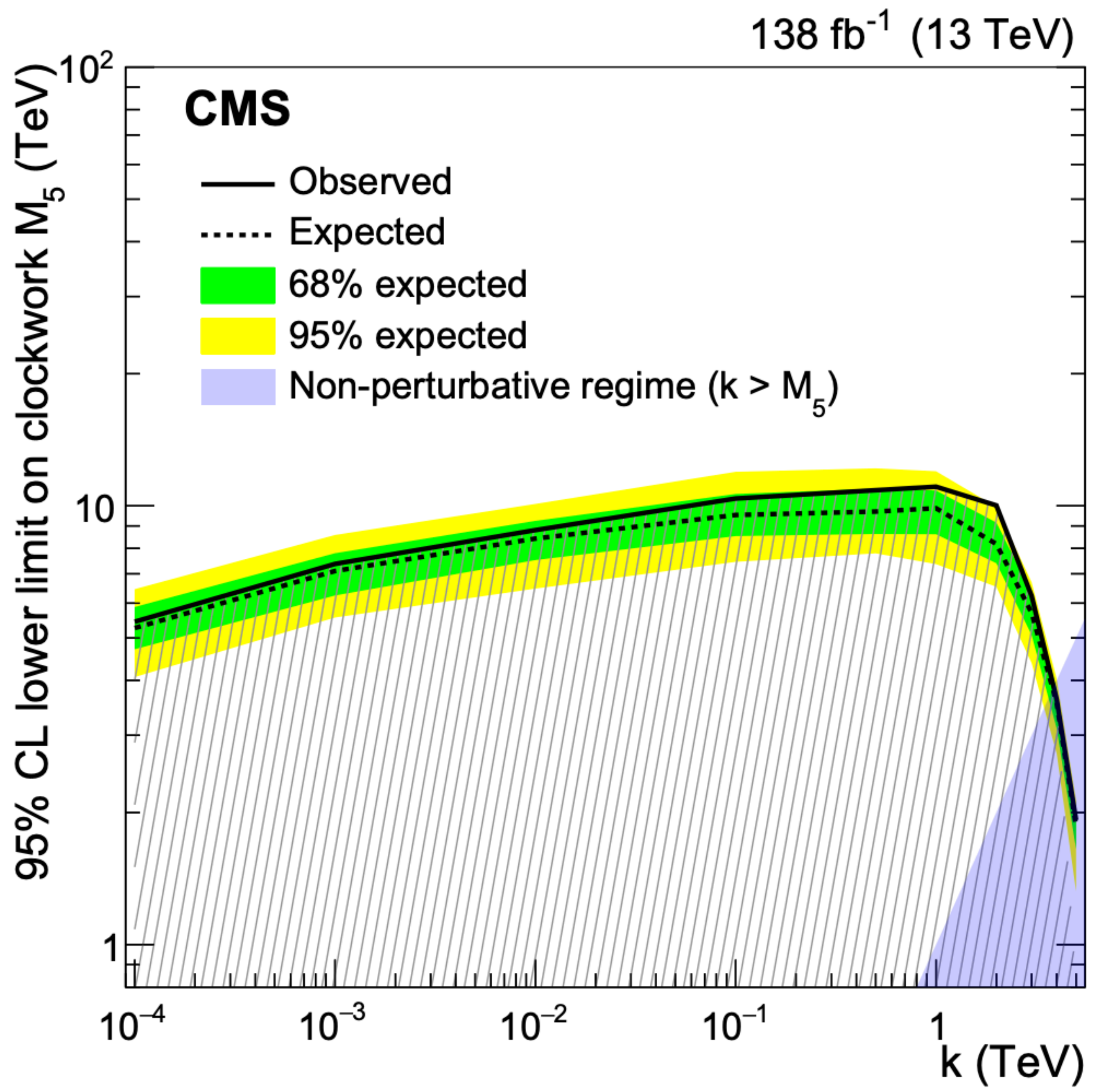
Observed $\gamma\gamma$ spectra





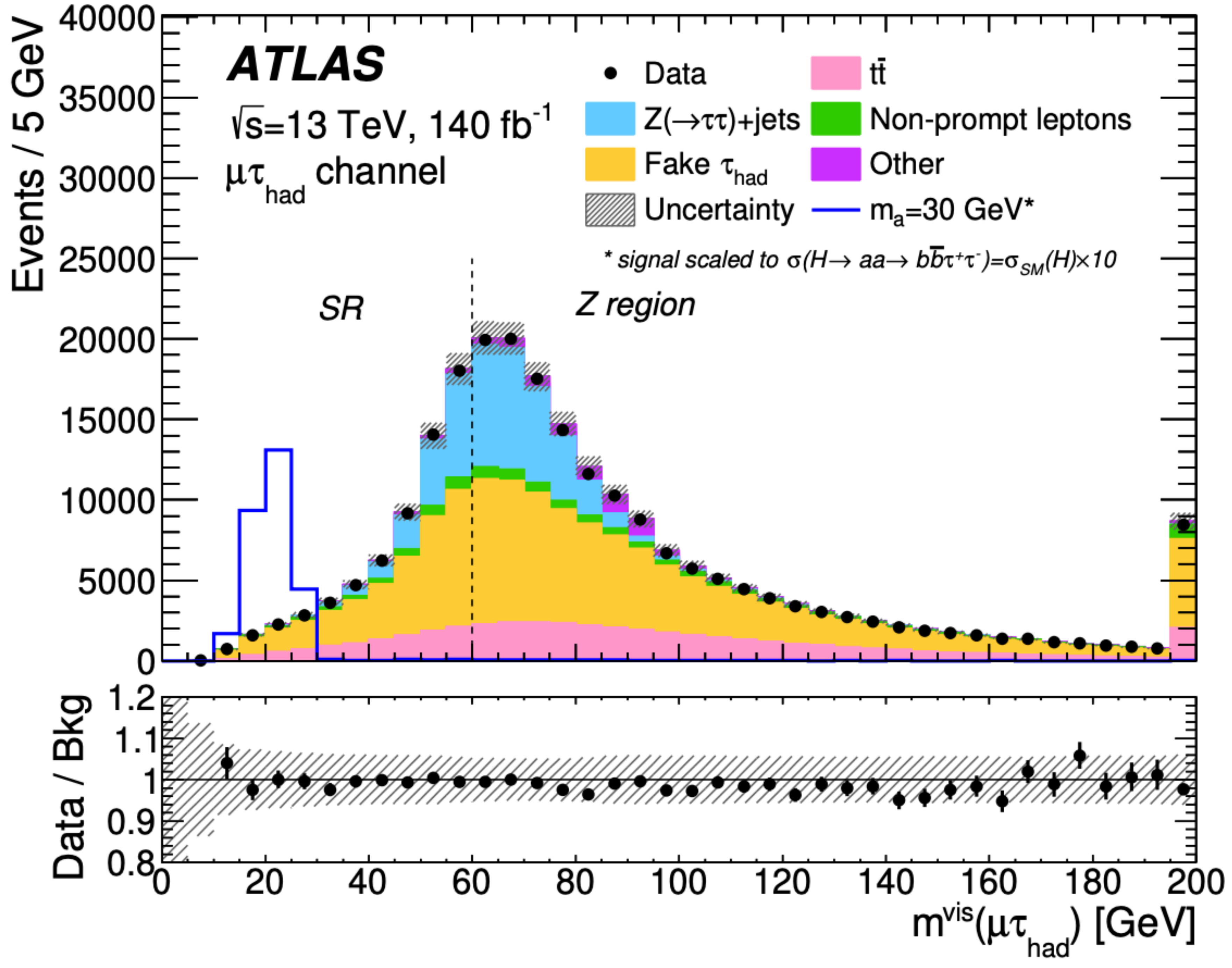
[2405.09320]

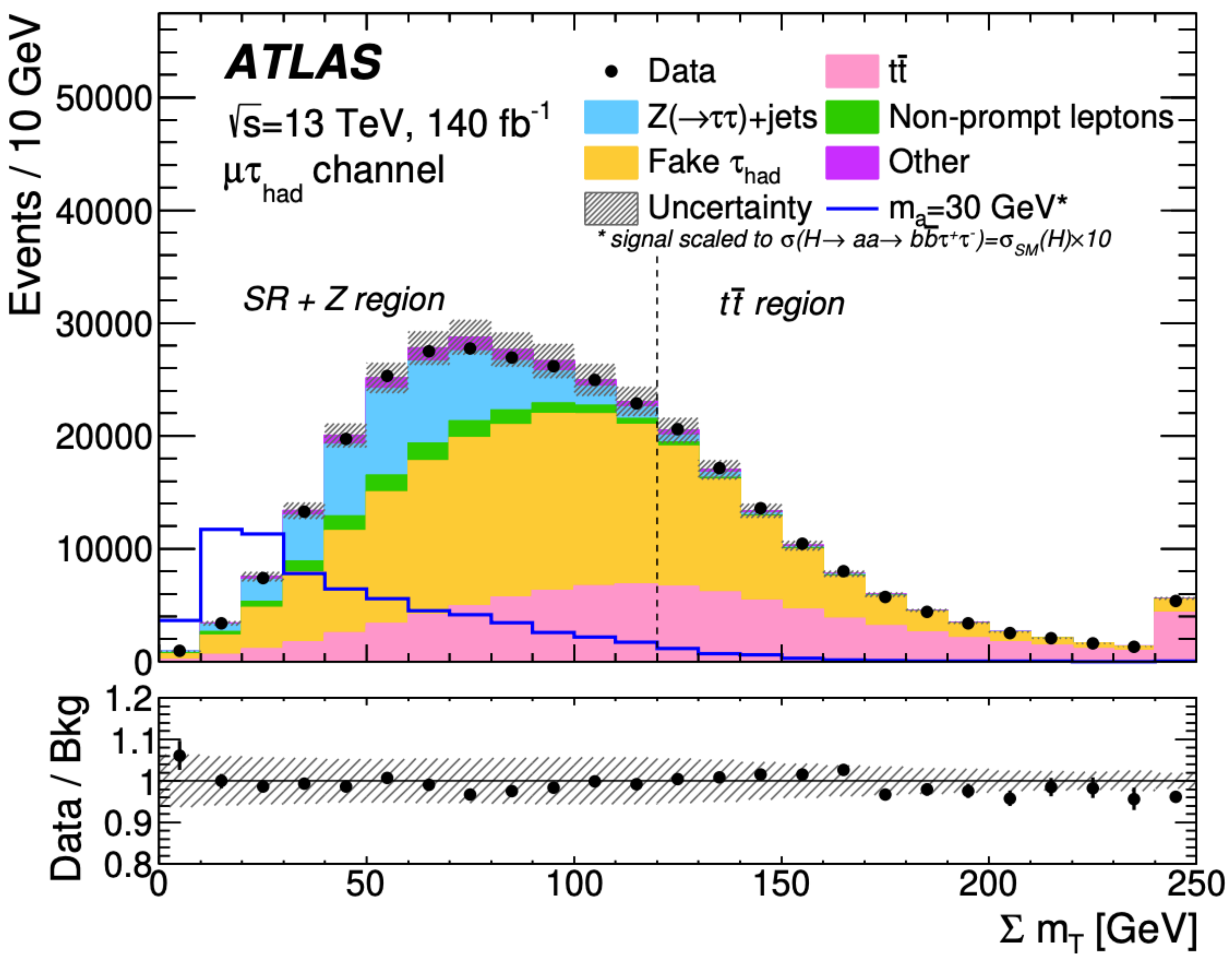
Clockwork limits



2HDM+S: $bb\tau\tau$

- **Control regions for Z, $t\bar{t}$**

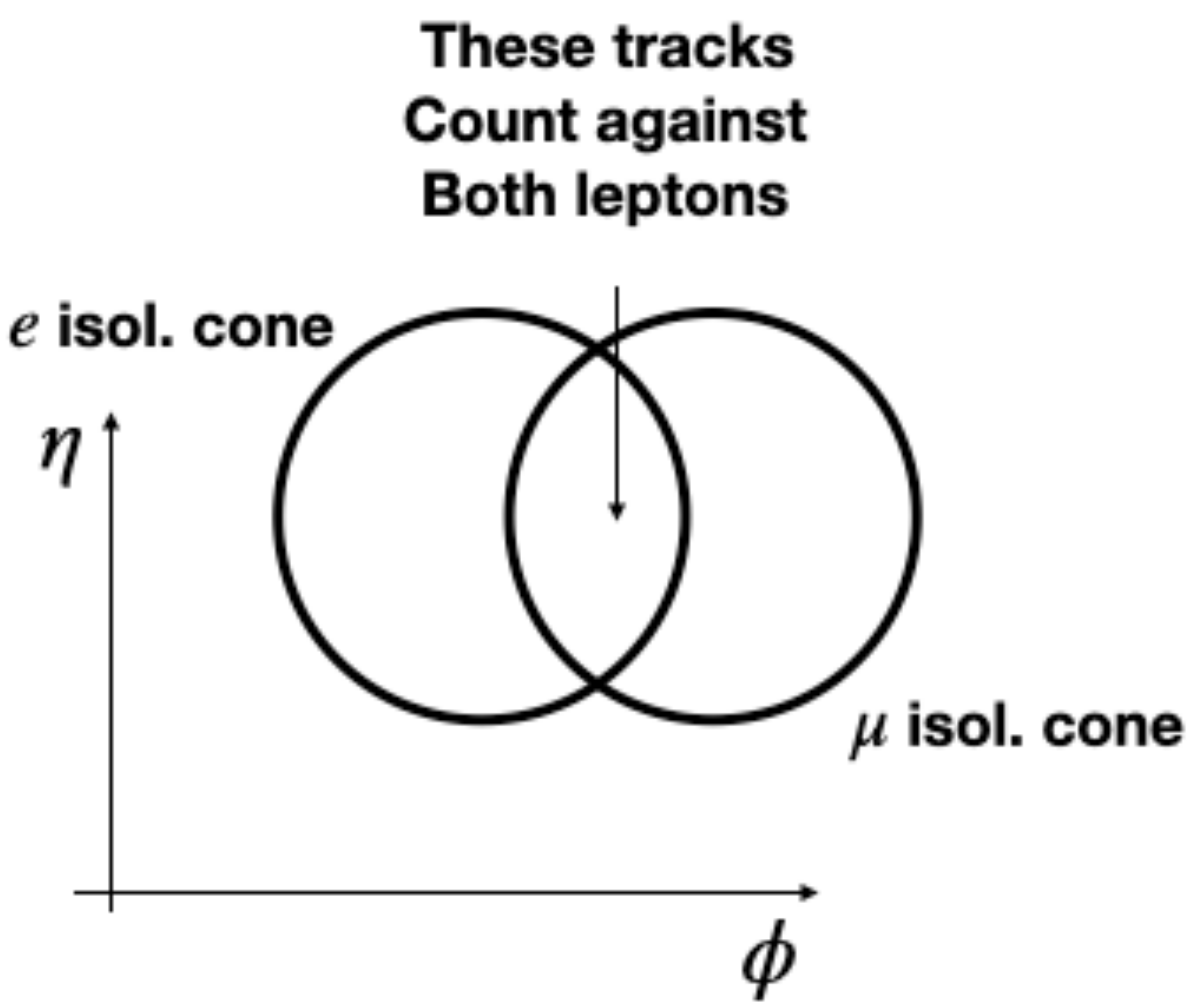




Kevin Nelson

2HDM+S: $bb\tau\tau$

- **Major backgrounds: $t\bar{t}$, Z+jets, fake leptons/taus**
  - $t\bar{t}$, Z+jets modeled with MC. Fake leptons use matrix method. Fake taus use fake factor method.
- **In $e\mu$ channel, lepton isolation cones can overlap in boosted regime**
  - Ignore lepton for each other's isolation, but still tracks/calorimeter deposits can fall into the middle of the Venn diagram
  - Causes *correlation* of isolation discriminant, breaks down matrix method Results become un-physical.
- **Developed a correction to 2-lepton matrix method:**
  - Re-weight the population of events when both leptons fail isolation
  - Remain agnostic to which lepton "should" have failed isolation
  - Correction is proportional to the fraction of overlap between isolation cones



$$(-w_L^e w_L^\mu)^{\text{corr}} = (1 - f(\Delta R))\left(-w_L^e w_L^\mu\right) + f(\Delta R) \times \frac{1}{2}\left(w_L^e w_T^\mu + w_T^e w_L^\mu\right),$$

$$f(\Delta R) = c \times \left(\frac{2}{\pi}\arccos\left(\frac{\Delta R}{2r}\right) - \frac{\Delta R}{\pi r^2}\sqrt{r^2 - \frac{(\Delta R)^2}{4}}\right),$$

[2407.01335]

Search for $t \to H^{\pm}(\to cs)b$

- **Full list of BDT input variables**

Table 2: Final list of BDT input variables used in the training.

Variable type	Variable name	Definition
Top-quark kinematic variables		
t_{had}	j_1 p_{T}	p_{T} of j_1-labelled jet
	j_2 p_{T}	p_{T} of j_2-labelled jet
	b_{had} p_{T}	p_{T} of b_{had}-jet
	$b_{\text{had}}^{t_{\text{had}}-\text{rest}}$ p	Momentum of b_{had}-jet in t_{had} rest frame
	dijet mass	Invariant mass of j_1+j_2 jets
	(j_1+b_{had}) mass	Invariant mass of j_1+b_{had} jets
	(j_2+b_{had}) mass	Invariant mass of j_2+b_{had} jets
	$\cos\theta$	Boson spin sensitive variable
t_{lep}	b_{lep} p_{T}	p_{T} of b_{lep}-jet
	Lepton p_{T}	p_{T} of reconstructed lepton
	W mass	Invariant mass of reconstructed W boson
	t_{lep} mass	Invariant mass of reconstructed t_{lep}
	t_{lep} p_{T}	p_{T} of reconstructed t_{lep}
$t\bar{t}$-system	$\Delta R(b_{\text{lep}},b_{\text{had}})$	ΔR between the b_{lep}-jet and b_{had}-jet
	$t\bar{t}$ mass	Invariant mass of t_{had}+t_{lep}
Event variables		
Event level	N_{jets}	Number of jets in the event
	S_{T}	Scalar p_{T} sum of all calibrated objects
	$\overline{P}_{t\bar{t}}$	Normalised probability of correct jet labelling
Flavour-tagging variables		
Flavour-tagging score	j_1 PCFT	PCFT score of j_1
	j_2 PCFT	PCFT score of j_2
	b_{had} PCFT	PCFT score of b_{had}-jet
	b_{lep} PCFT	PCFT score of b_{lep}-jet
Number of tags	$N_{c\text{-tagLo}}$	Number of jets passing loose c-tag WP (b-veto)
	$N_{c\text{-tagTi}}$	Number of jets passing tight c-tag WP (b-veto)
	$N_{b\text{-tag70}}$	Number of jets passing 70% b-tag WP
	$N_{b\text{-tag60}}$	Number of jets passing 60% b-tag WP

Charged Higgses

- **Comparison of ATLAS and CMS combinations for charged Higgses**