Accumulating Evidence for New Higgs Bosons at the LHC

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Based on: arXiv:2407.06267

Workshop on Multi-Higgs Models

3th September 2024

Outline

- Motivation
- Simplified Model Analysis
- Explaination in 2HDM-Type1
- General Aligned 2HDM
- Summary & Conclusion

Motivation

Hints for new Higgs Bosons

- Minimality of the scalar sector of the SM not guaranteed theoretically

Full Run 2 Data

- ATLAS recently performed Model-Independent analysis of $\gamma\gamma + X$ for SM Higgs

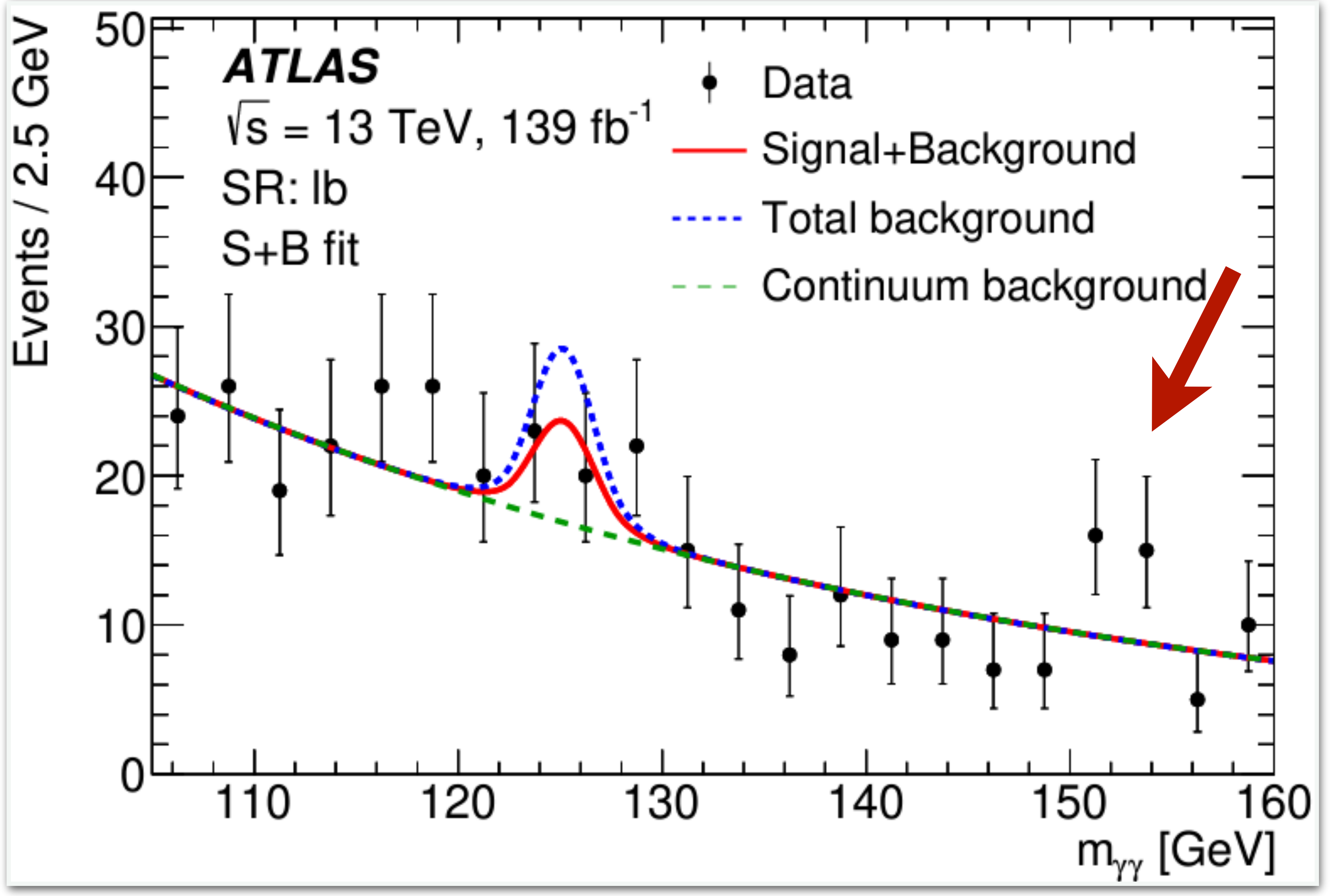
- Analysis involves 22 signal regions

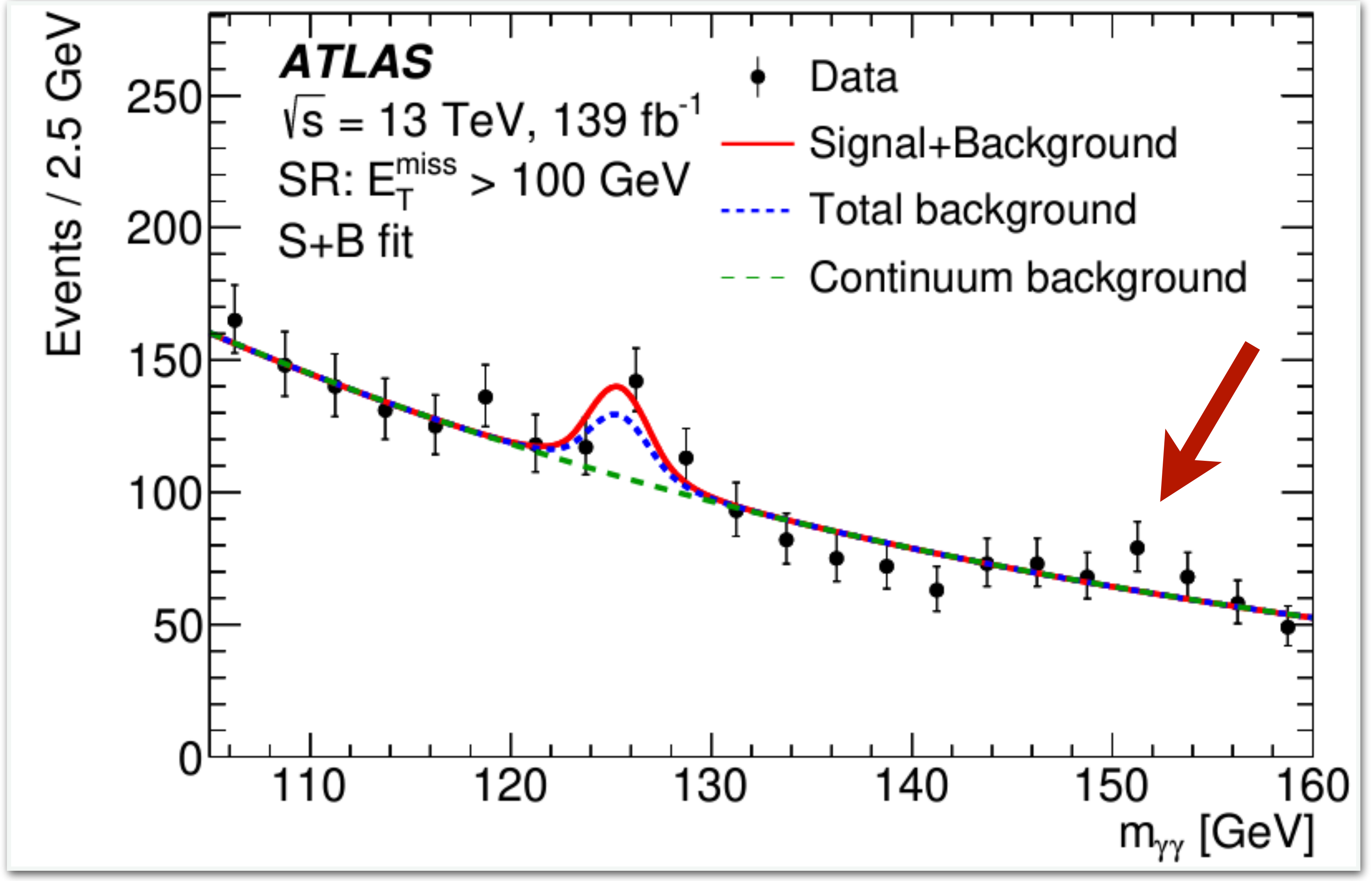
SRs	$\geq 3b$	$\geq 4b$	$\geq 4j$	$\geq 6j$	$\geq 8j$	$H_T > 500$	$H_T > 1000$	$H_T > 1500$	ℓb	$t_{\rm lep}$	$t_{\rm had}$
SRs	$\geq 1\ell$	2ℓ	$2\ell - Z$	SS-2ℓ	$\geq 3\ell$	$E^T_{\rm miss} > 100$	$E^T_{\rm miss} > 200$	$E^T_{\rm miss} > 300$	1τ or 2τ	$m^{12}_{\gamma\gamma}$	$m^{23}_{\gamma\gamma}$

Motivation

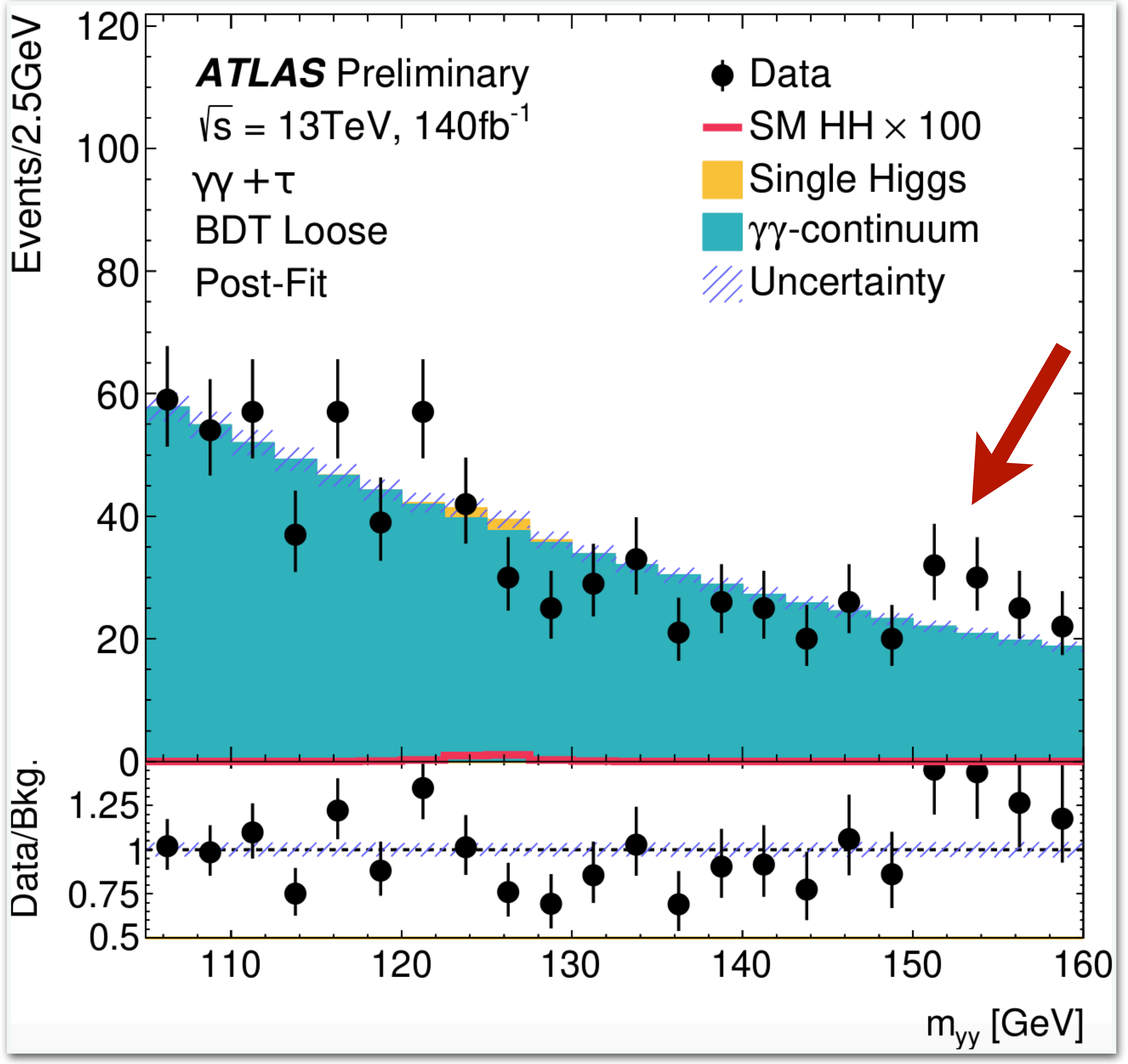
Hints for new Higgs Bosons

- Excesses Most Pronounced: $\gamma\gamma + \ell b$, $\gamma\gamma + \text{MET}$, $\gamma\gamma + 1\tau$, $\gamma\gamma + 4j$, $\gamma\gamma + 1\ell$





[ATLAS: CERN-EP-2022-232]



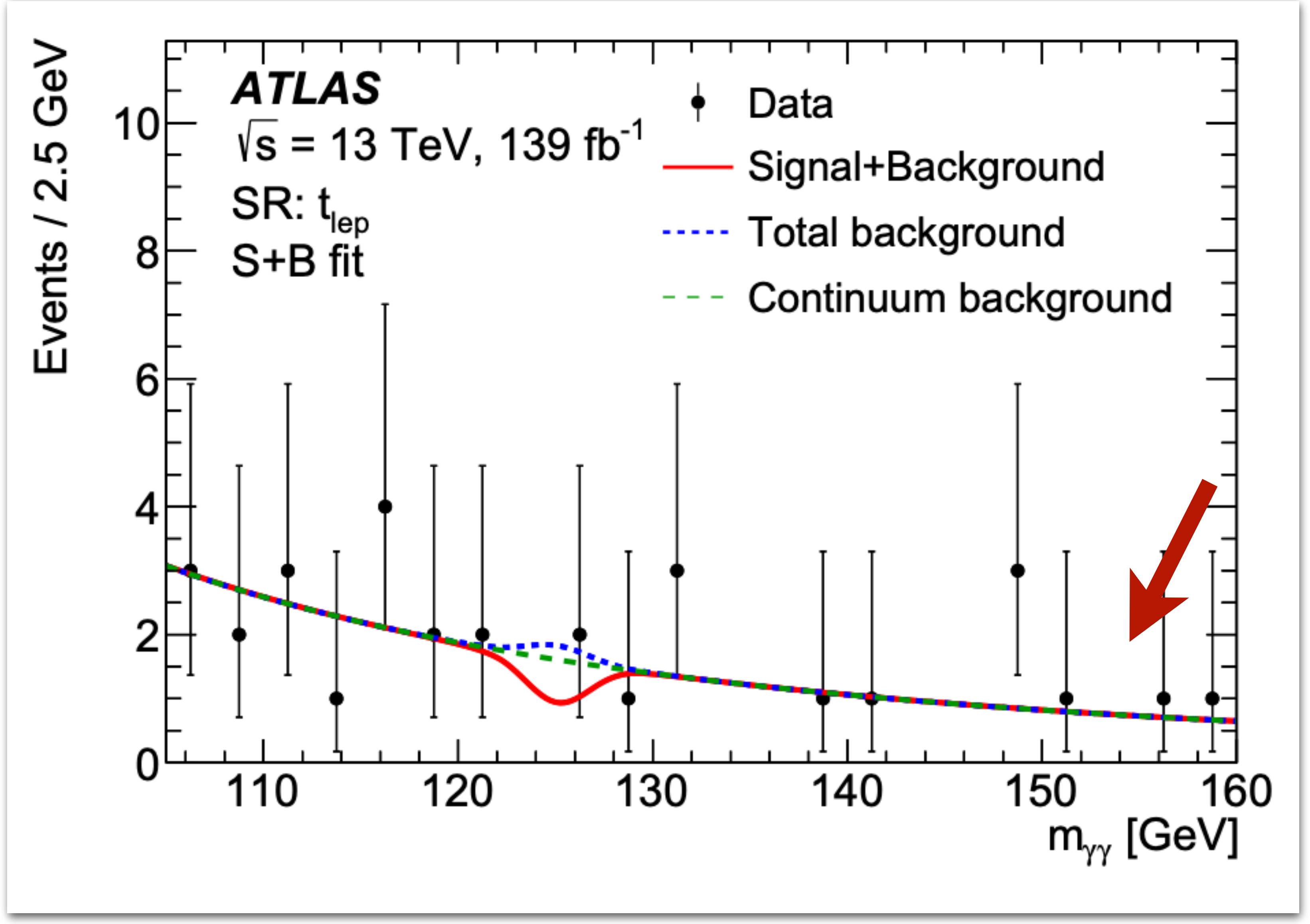
[ATLAS-CONF-2024-005]

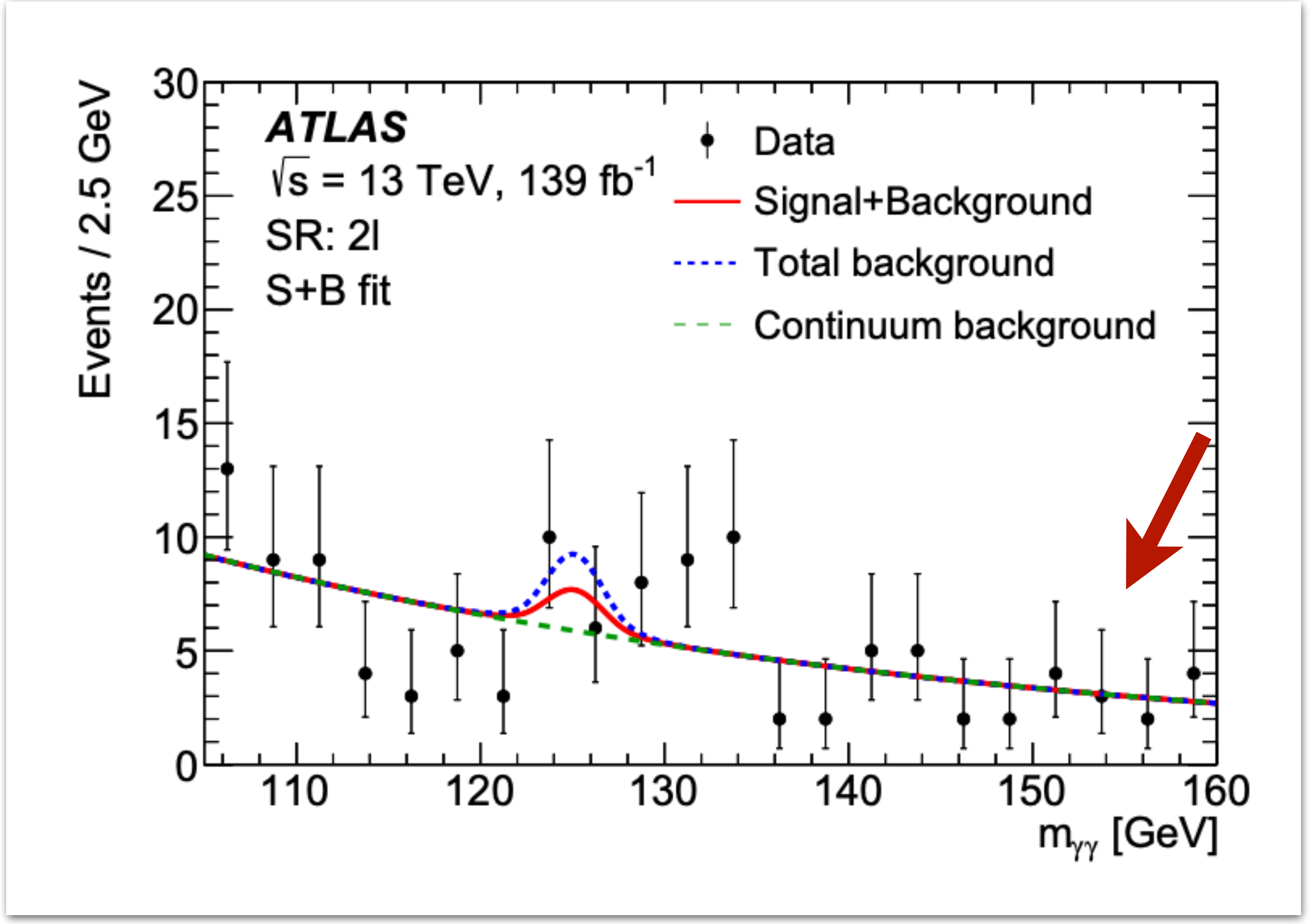
- Possible new Higgs Boson?

Motivation

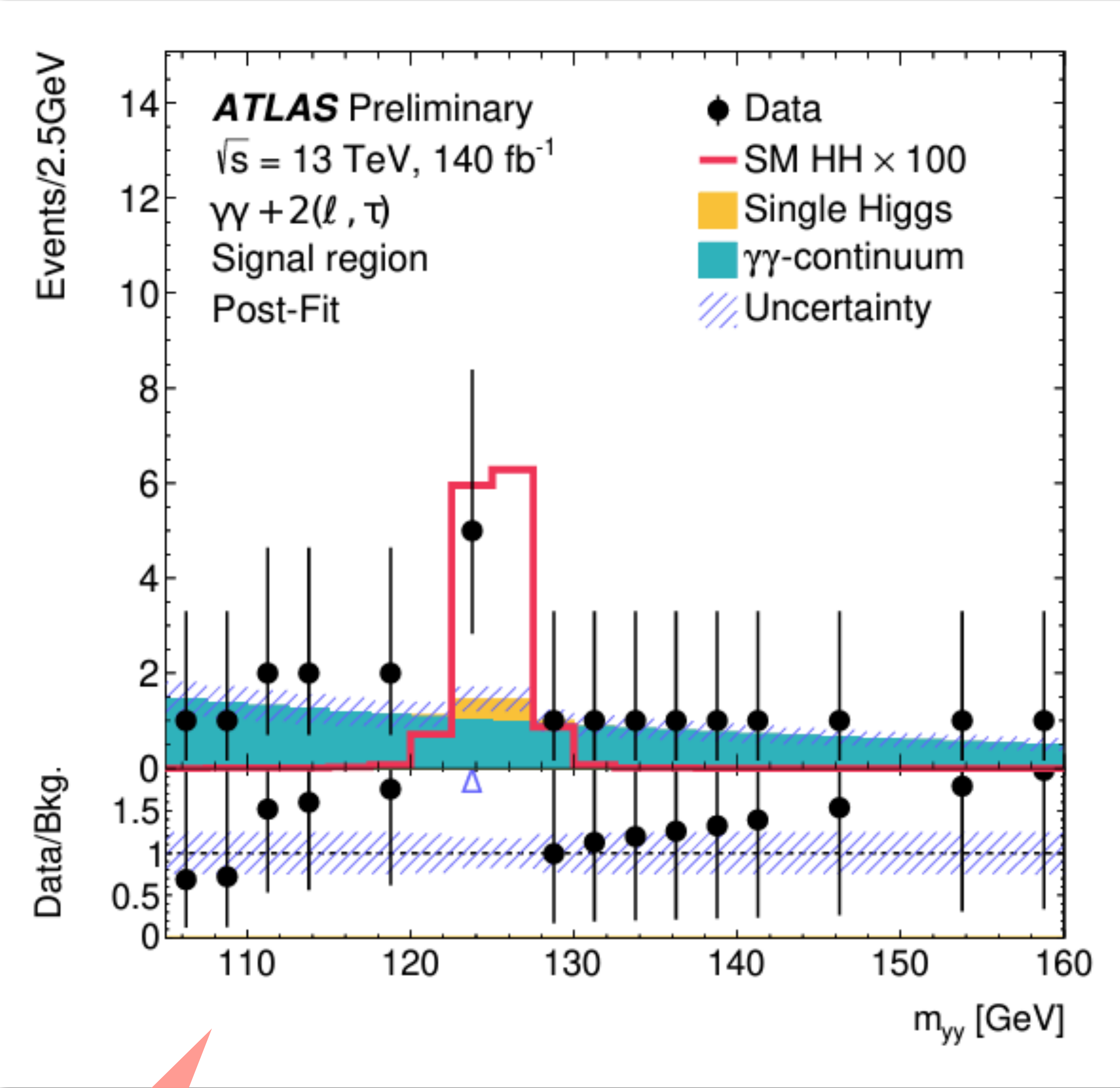
Hints for new Higgs Bosons

- No Excesses at 152 GeV in SRs: $\gamma\gamma + t_{\text{lep}}, \gamma\gamma + 2\ell,\ \gamma\gamma + 2\tau,$





[ATLAS: CERN-EP-2022-232]



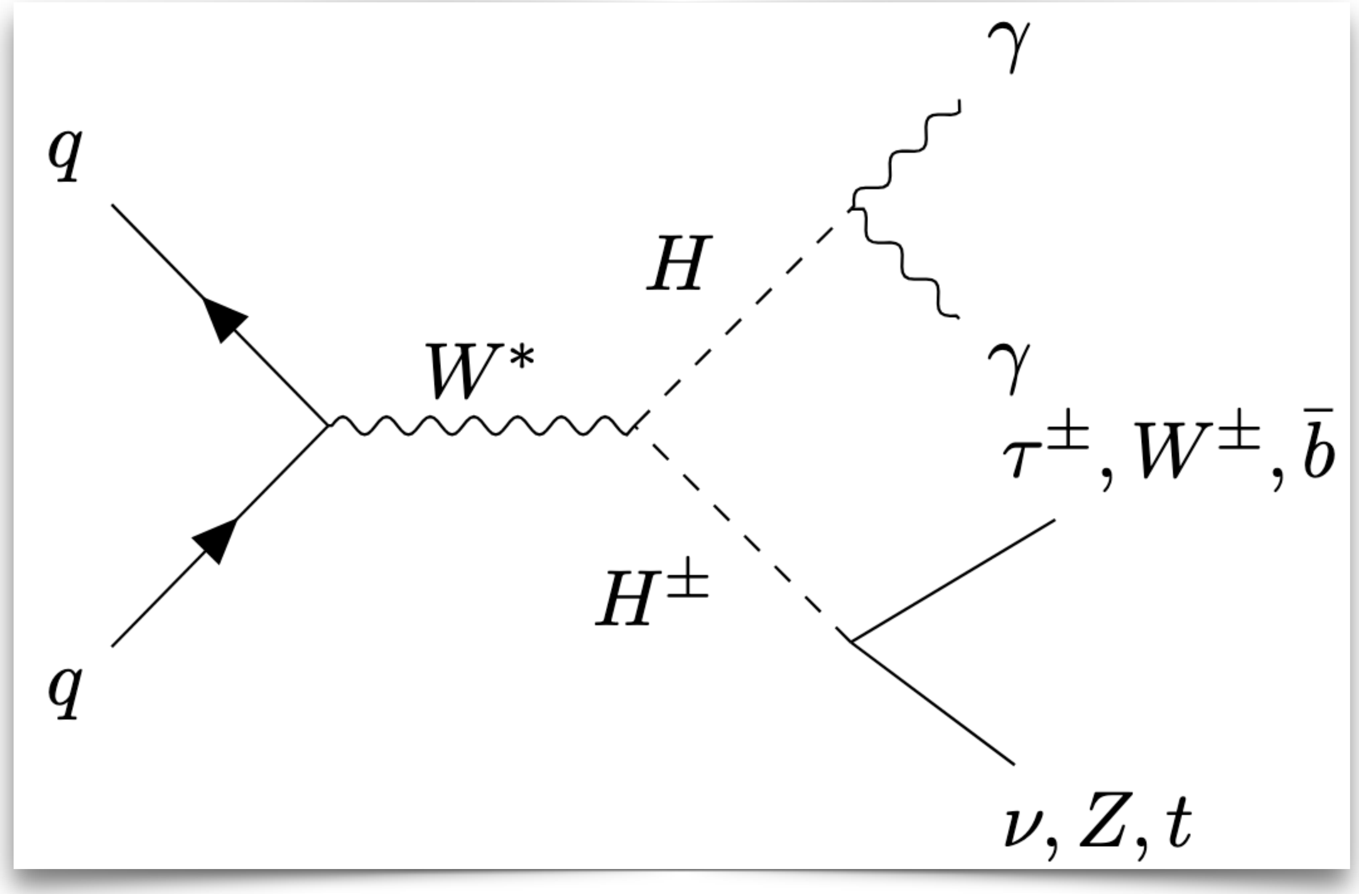
[ATLAS-CONF-2024-005]

Point towards asssociated $H^{\pm}$

Motivation

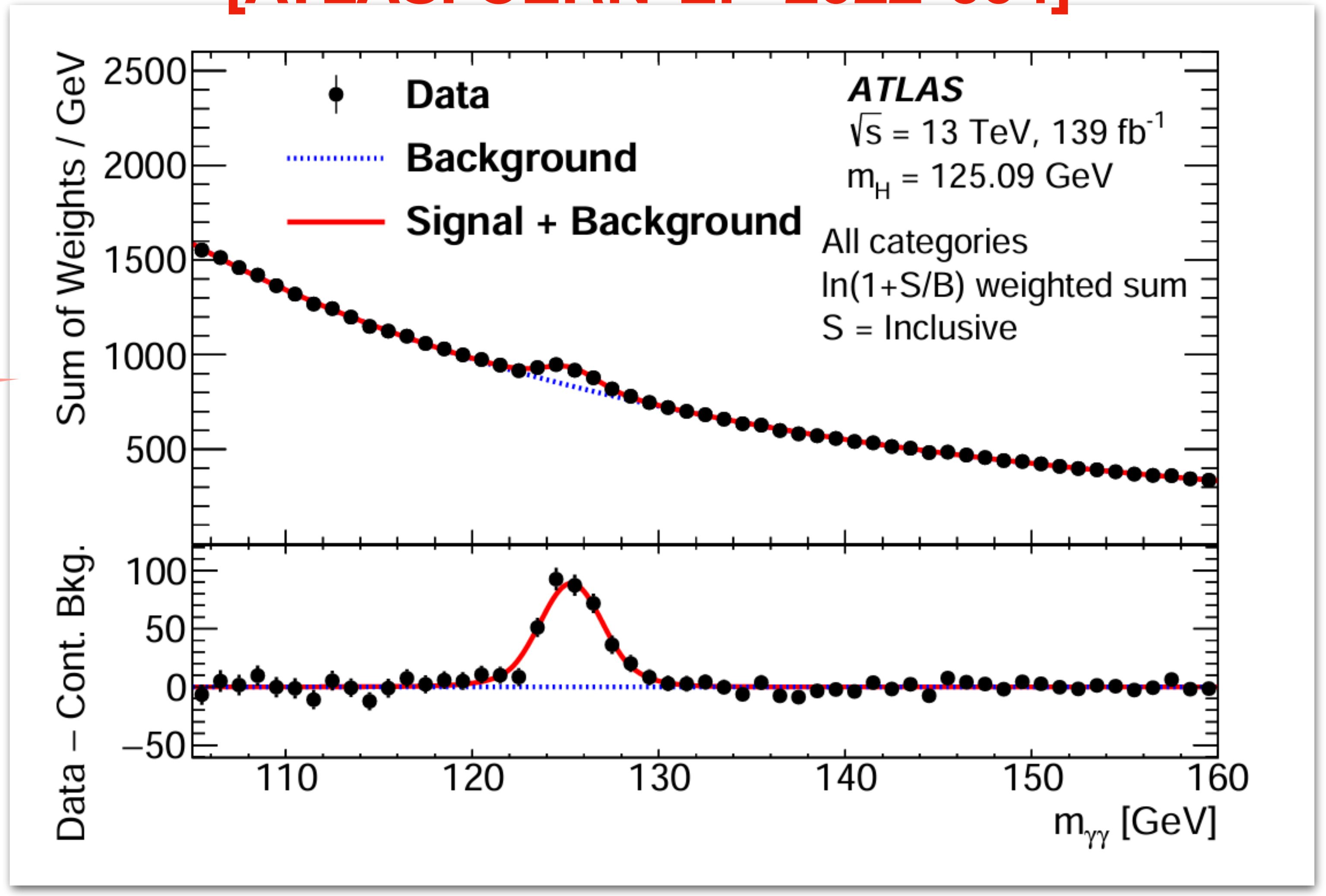
Hints for new Higgs Bosons

- Hints towards DY production of new Higgs at LHC



- No excess in Inclusive Searches

[ATLAS: CERN-EP-2022-094]

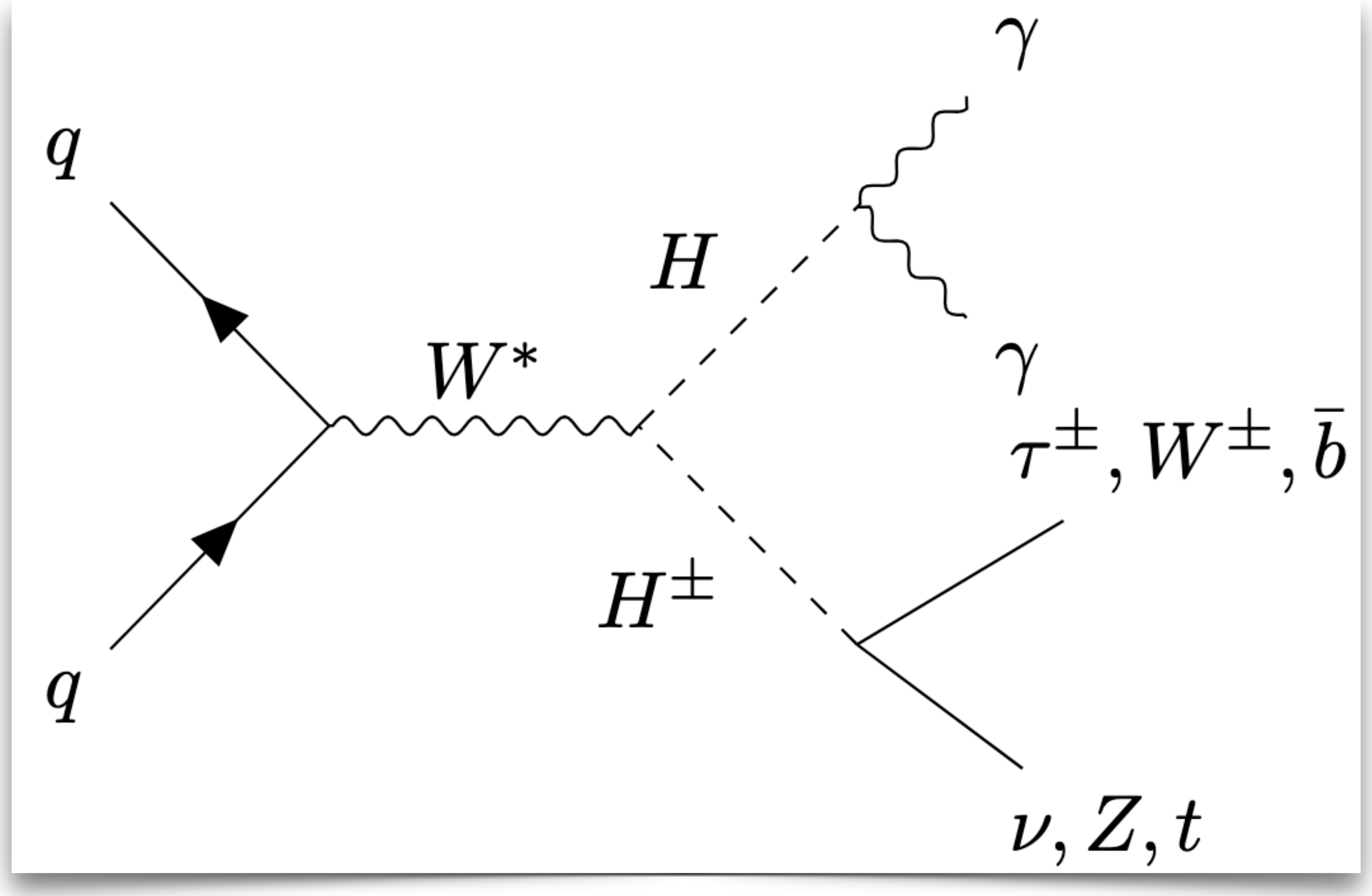


Full Run 2 Data

Simplified Model

Model Description

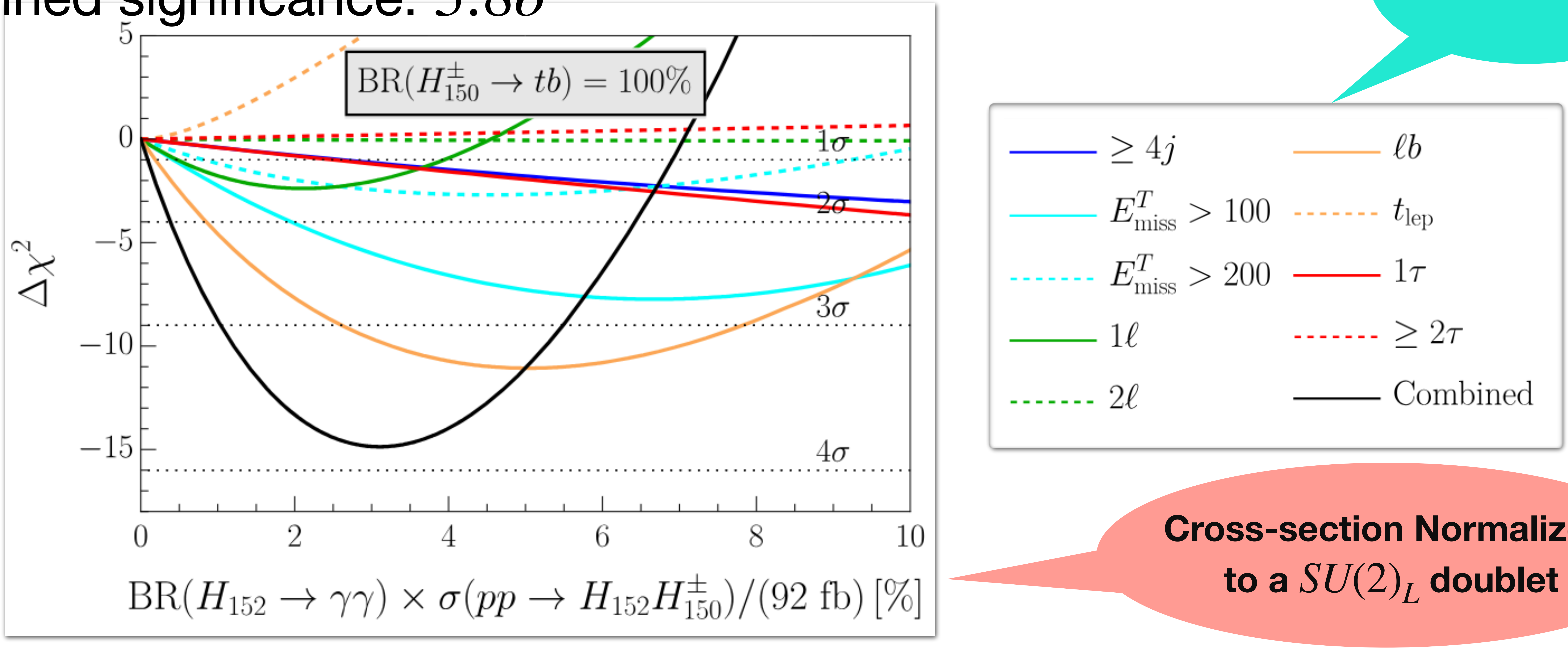
- Two New Particles: H, $H^{\pm}$
- H produced only via DY process
- Dominant decays of $H^{\pm}$: $tb, \tau\nu, WZ$
- UFO Model generated using FeynRules
- Simulation Setup: MadGraph + Pythia + Delphes
- Log-Likelihood Fit performed using Poisson Statistics



Simplified Model

Charged Higgs Decay

- $\mathrm{BR}(H^{\pm} \to tb \to bbW) = 100\,\%$
- Dominant Effect: $\gamma\gamma + \ell b, \gamma\gamma + MET, \gamma\gamma + 1\ell, \gamma\gamma + t_{\text{lep}}$
- Combined significance: 3.8σ



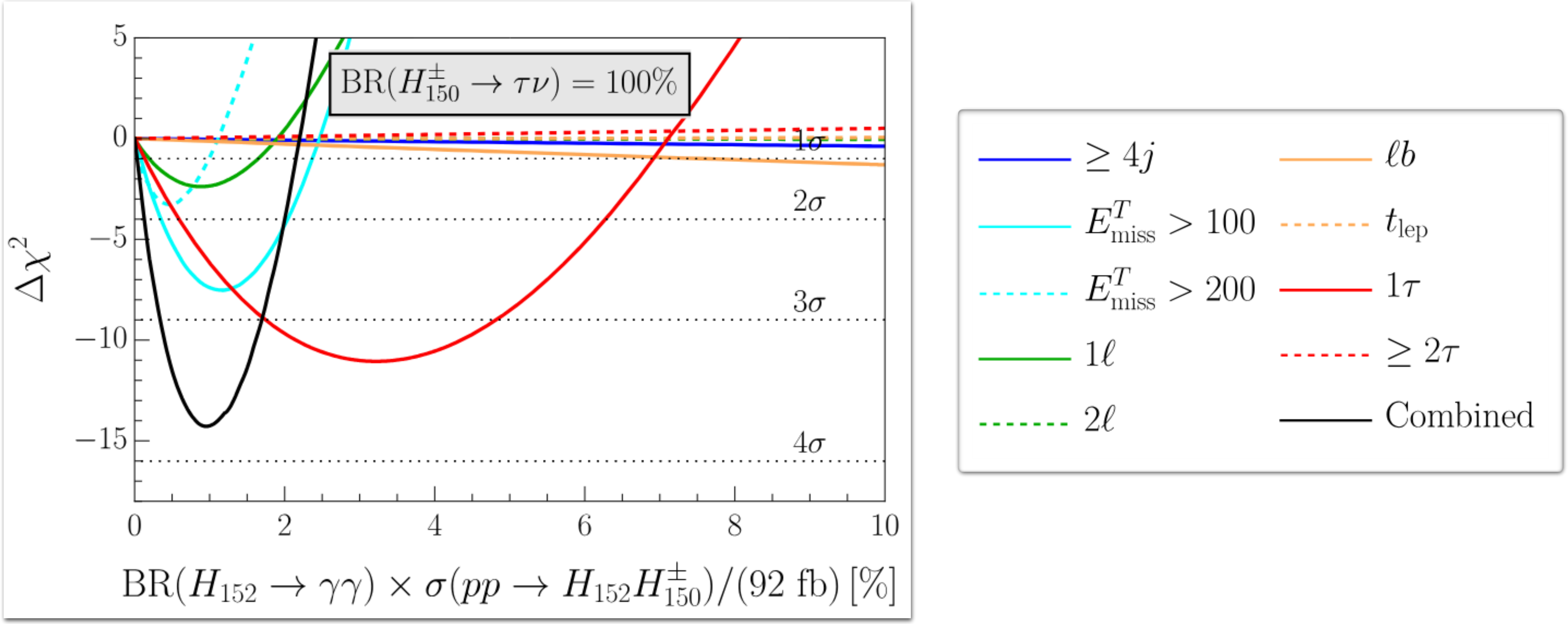
Relevant SRs

Cross-section Normalized to a $SU(2)_L$ doublet

Simplified Model

Charged Higgs Decay

- $\mathrm{BR}(H^{\pm} \to \tau\nu) = 100\,\%$
- Dominant Effect: $\gamma\gamma + MET, \gamma\gamma + 1\tau, \gamma\gamma + 1\ell$
- Combined significance: 3.8σ

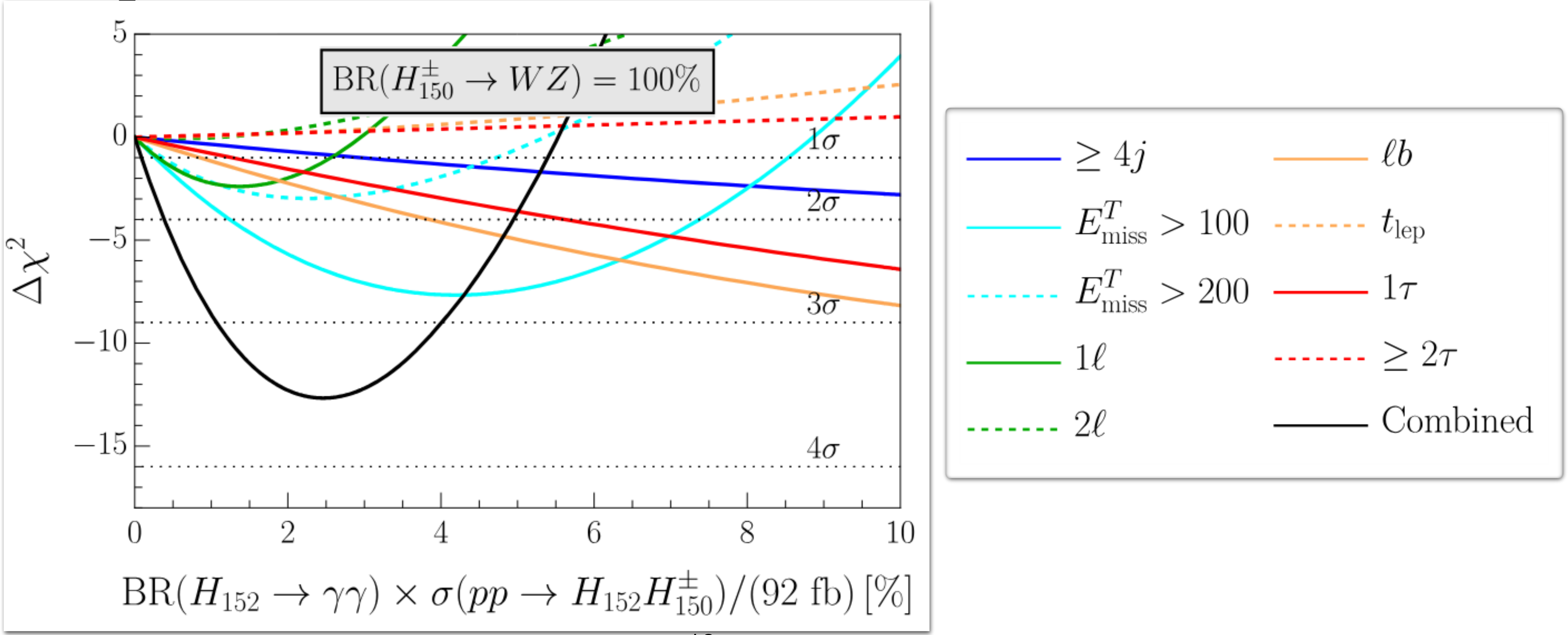


Simplified Model

Charged Higgs Decays

- BR($H^{\pm} \to WZ$) $= 100\,\%$
- Dominant Effect: $\gamma\gamma + MET, \gamma\gamma + 1\ell, \gamma\gamma + 2\ell, \gamma\gamma + 2\tau$
- Combined significance: 3.5σ

Dominant in Triplet Model
(See Talk of G. Coloretti)



Simplified Model

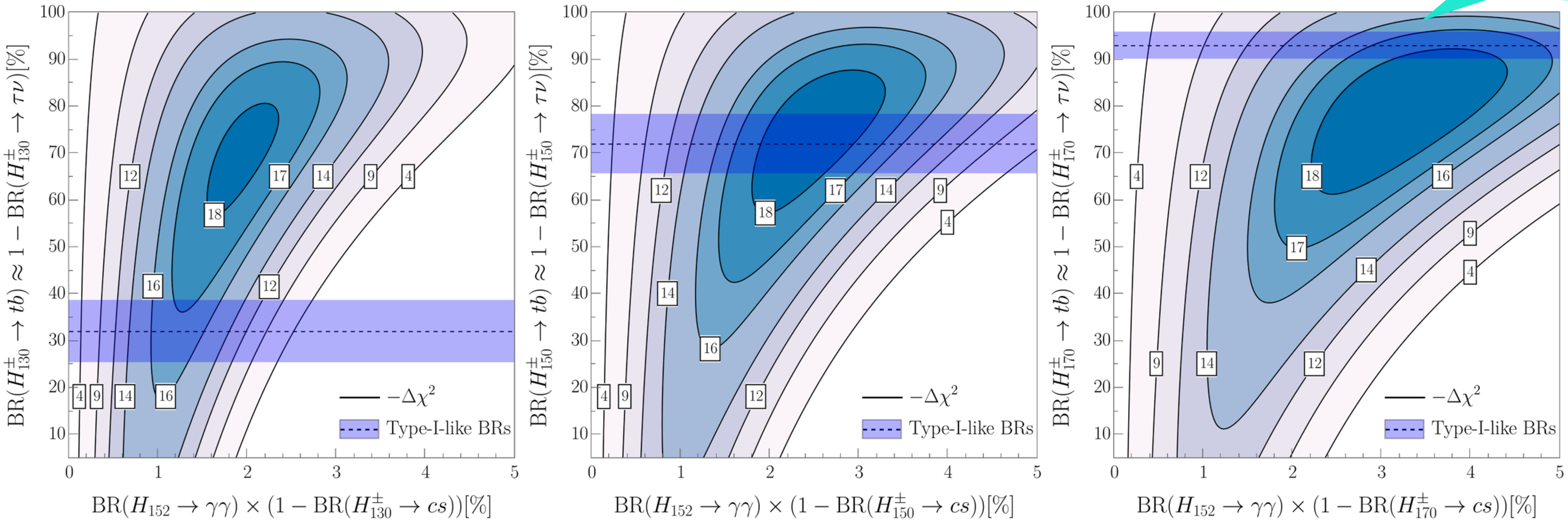
Charged Higgs Decays

- Combined decay modes: $H^\pm \to tb$, $H^\pm \to \tau\nu$

$H^\pm \to W^\pm Z$ **suppressed in 2HDM**

- $-\Delta\chi^2$ increases with $m_{H^\pm}$ due to enhanced $\gamma\gamma + lb$ vs $\gamma\gamma + t_{\rm lep}$

$H^\pm \to cs$ **has small impact**



- $\mathrm{BR}(H \to \gamma\gamma)$ increases with $m_{H^\pm}$

Model Building

Key Points

- Small total production cross-section
- Dominant DY production cross-section
- Large BR$(H^{\pm} \to tb)$ and BR$(H^{\pm} \to \tau\nu)$
- Small BR$(H^{\pm} \to WZ)$ to avoid multiple leptons
- Sizable BR$(H \to \gamma\gamma)$

Explanation in 2HDM

Description

- Two $SU(2)_L$ doublets: ϕ_1 and ϕ_2
- Scalar potential

$$V(\phi_1, \phi_2) = m_{11}\phi_1^\dagger\phi_1 + m_{22}\phi_2^\dagger\phi_2 - m_{12}^2(\phi_1^\dagger\phi_2 + \text{h.c.}) + \lambda_1(\phi_1^\dagger\phi_1)^2$$

$$+\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \lambda_5((\phi_1^\dagger\phi_2)^2 + \text{h.c})$$

- Scalar Particles: $h, H, A, H^\pm$
- Free Parameters: $m_h, m_H, m_A, m_{H^\pm}, m_{12}^2, \tan\beta = v_2/v_1, \alpha$

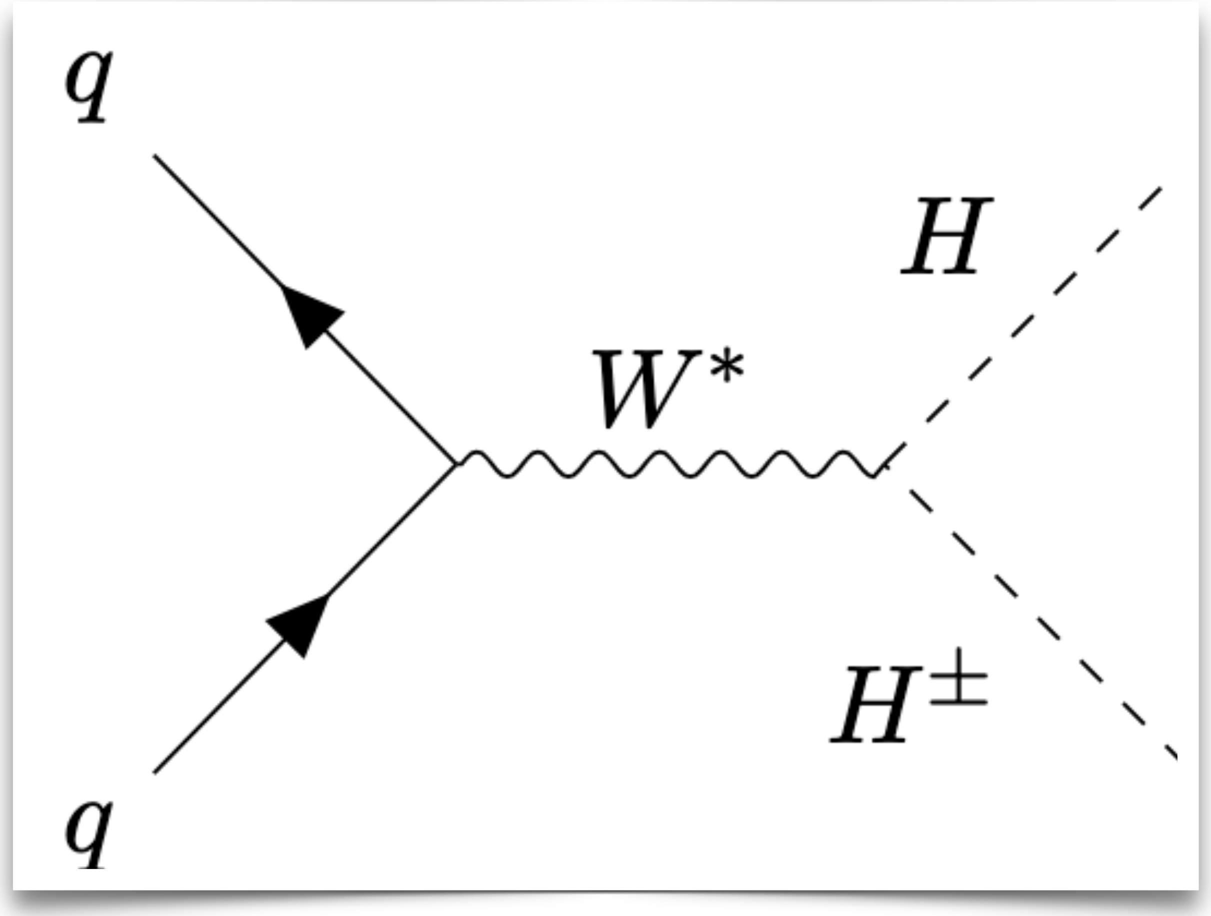
Explanation in 2HDM

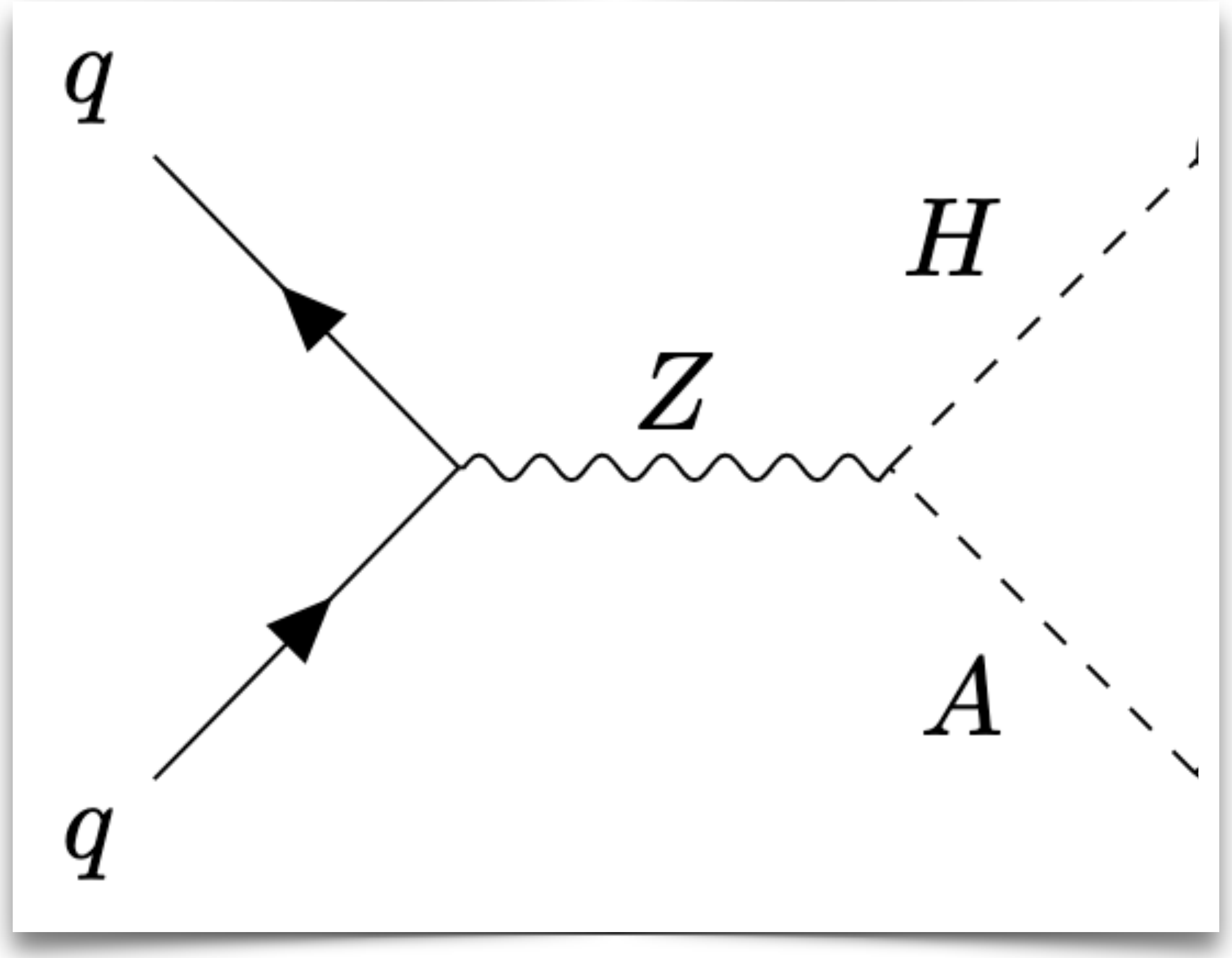
Type-I

- Yukawa Sector

$$Y = -\bar{Q}_L \phi_2 d_R - \bar{Q}_L \phi_2^c u_R - \bar{L}_L \phi_2 e_R$$

- Suppressed gluon-fusion, VBF, VH cross-section of H for large $\tan\beta$
- Dominant production channels for H





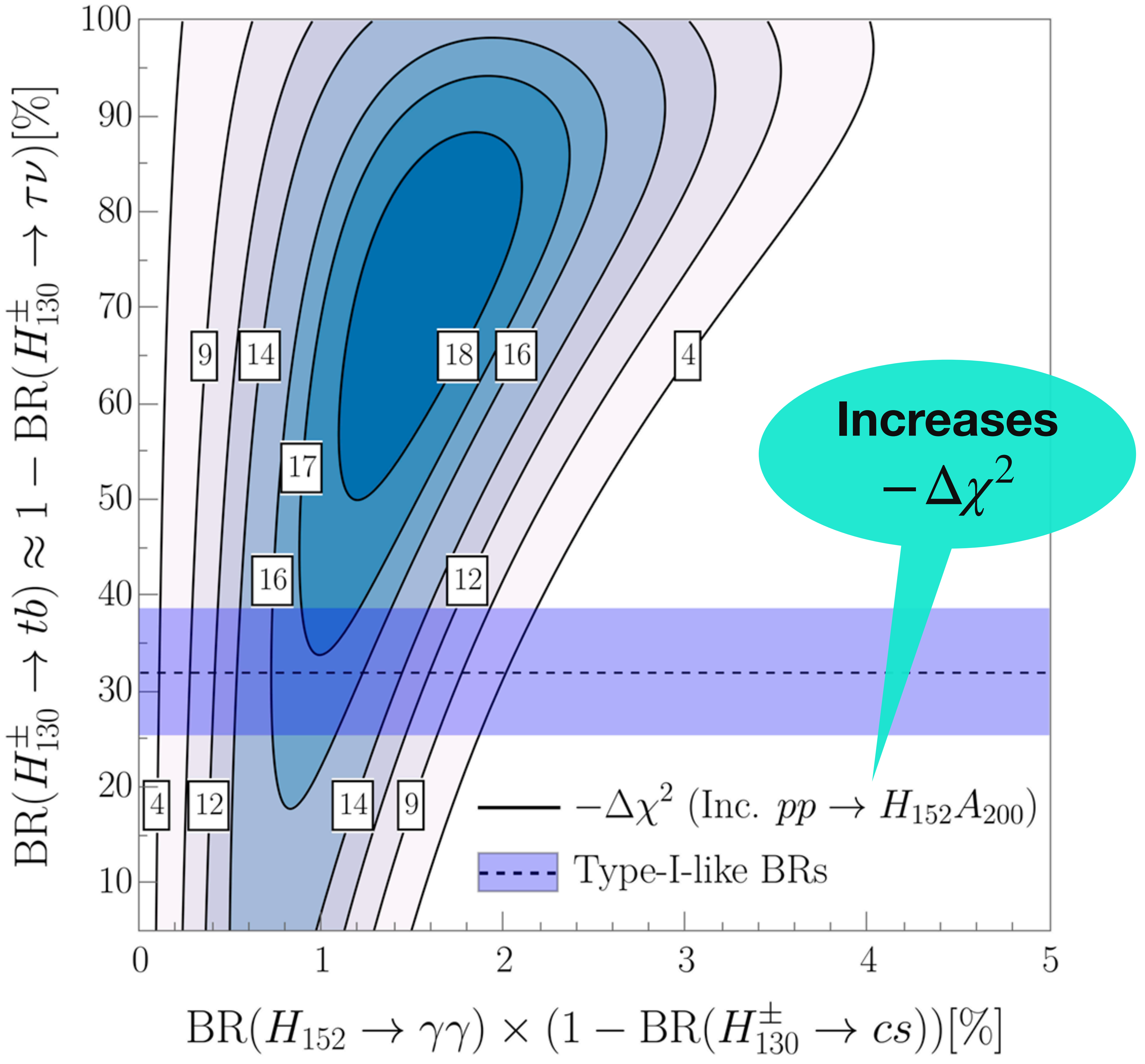
Small for large m_A

Explanation in 2HDM

Type-I

- Dominant decay modes of $H^{\pm}$: $\tau\nu\,, tb$
- Considered Benchmark Point:

$$m_H = 152 \text{ GeV}, m_{H\pm} = 130 \text{ GeV}, \alpha - \beta \approx \pi/2$$
$$m_A = 200 \text{ GeV}, \tan\beta = 20, m_{12}^2 = 1100 \text{ GeV}$$



- $\mathrm{Br}(H \to \gamma\gamma)$ required at the percent level
- Possible with Effective Operator: $F_{\mu\nu}F^{\mu\nu}\phi_1^{\dagger}\phi_2 + \text{h.c}$

Possible in composite models

General 2HDM

Large $H \to \gamma\gamma$

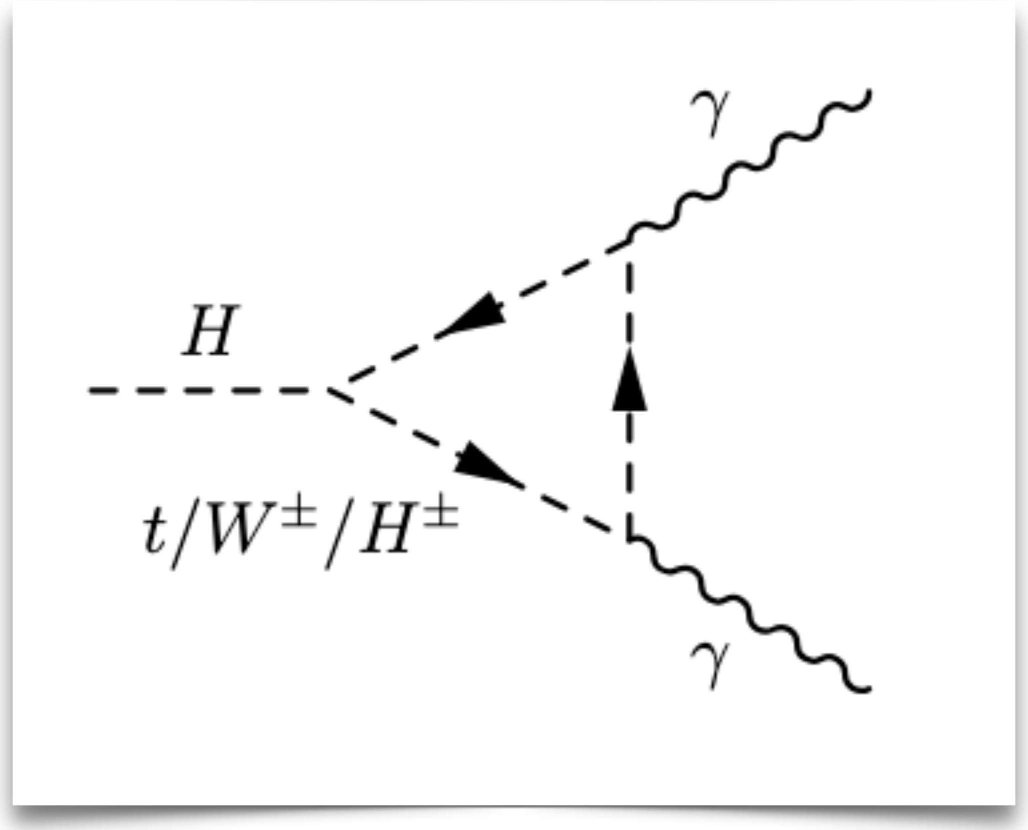
Z_2 symmetry broken

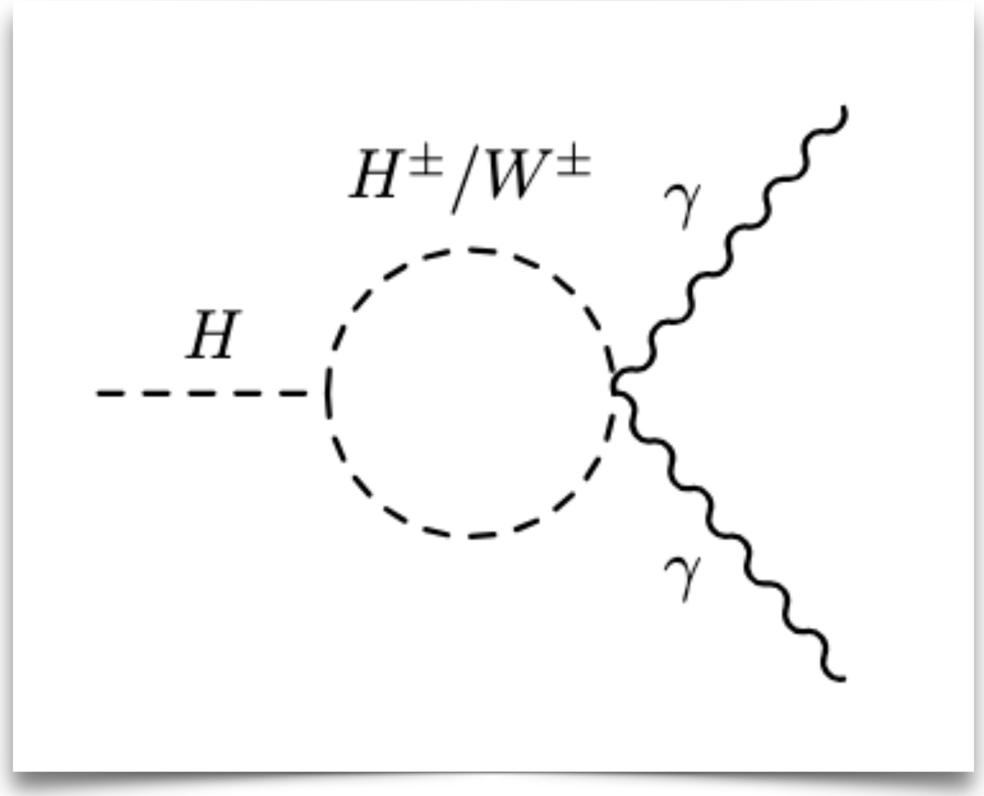
- Large Br$(H \to \gamma\gamma)$ possible in general 2HDM

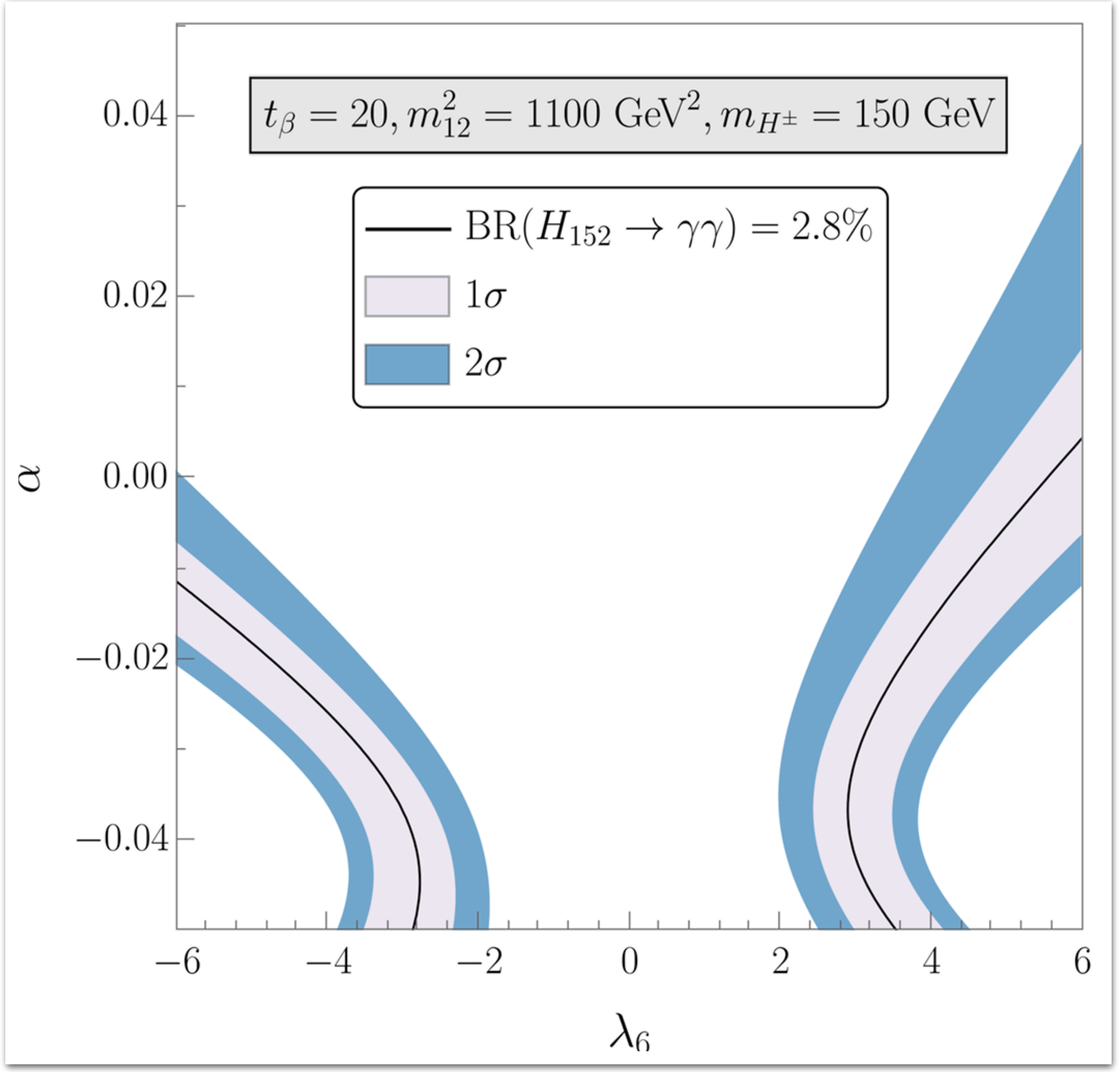
$$\mathscr{L} \in -\lambda_6 H_1^\dagger H_1 H_2^\dagger H_1 + \mathrm{h.c.},.$$

- Modifies the $HH^\pm H^\mp$ vertex

- Enhanced Br$(H \to \gamma\gamma)$ via $H^\pm$ loop







General 2HDM

FCNC & CP-Violation

- General 2HDM may lead to FCNC at tree-level
- Avoided in flavour aligned 2HDM
- If 152 GeV is *CP*-odd, large $\mathrm{Im}(\lambda_6)$ required for $\mathrm{BR}(A \to \gamma\gamma)$

$$\mathscr{L} \in -\lambda_6 H_1^\dagger H_1 H_2^\dagger H_1 + \mathrm{h.c.}, .$$

- Leads to additional *CP*-violation

Summary & Outlook

- Model-Independent analysis by ATLAS of $\gamma\gamma + X$ in 22 SRs
- Excesses observed in some SRs
- Hints for associated production of Neutral Higgs Boson
- Explanation possible in 2HDM + an effective operator
- Large Br$(H \to \gamma\gamma)$ in general aligned 2HDM

Thank you for your attention!