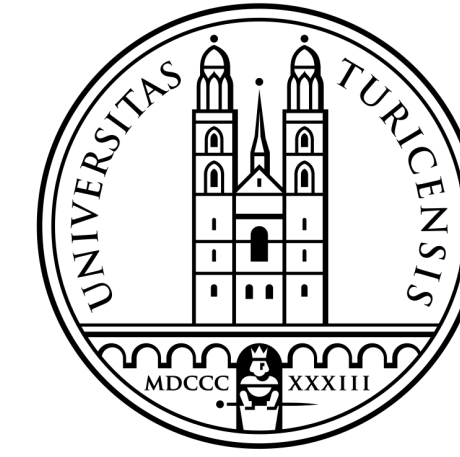




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**Swiss National
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Accumulating Evidence for New Higgs Bosons at the LHC

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BCVSPIN 2024

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Motivation

Hints for new Higgs Bosons

- **Minimality** of the scalar sector of the SM **not guaranteed** theoretically
- **ATLAS** recently performed **Model-Independent** analysis of $\gamma\gamma + X$ for **SM Higgs**
- Analysis involves **22 signal regions**

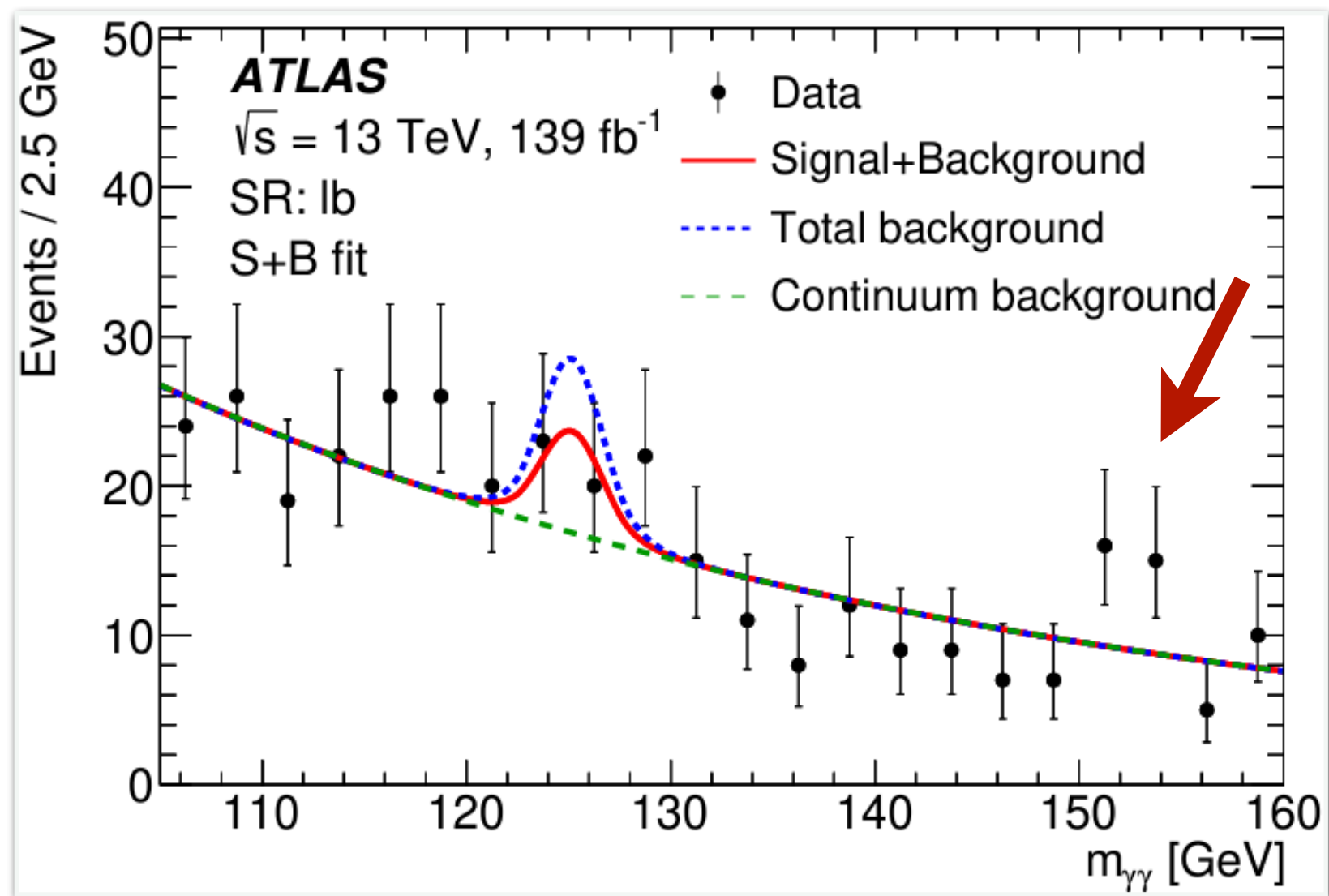
Full Run 2 Data

Heavy Flavor	Jets	Lepton	E_T^{miss}	Top	H_T	Photon
$\geq 3b, \geq 4b$	$\geq 4j, \geq 6j,$ etc.	$1\ell, 2\ell, \geq 3\ell,$ $1\tau, 2\tau$	$E_T^{\text{miss}} > 100 \text{ GeV},$ $E_T^{\text{miss}} > 200 \text{ GeV}$	$\ell b, t_{\text{lep}}, t_{\text{had}}$	$H_T > 500 \text{ GeV},$ $H_T > 1000 \text{ GeV}$	$m_{\gamma\gamma}^{12}, m_{\gamma\gamma}^{13}$

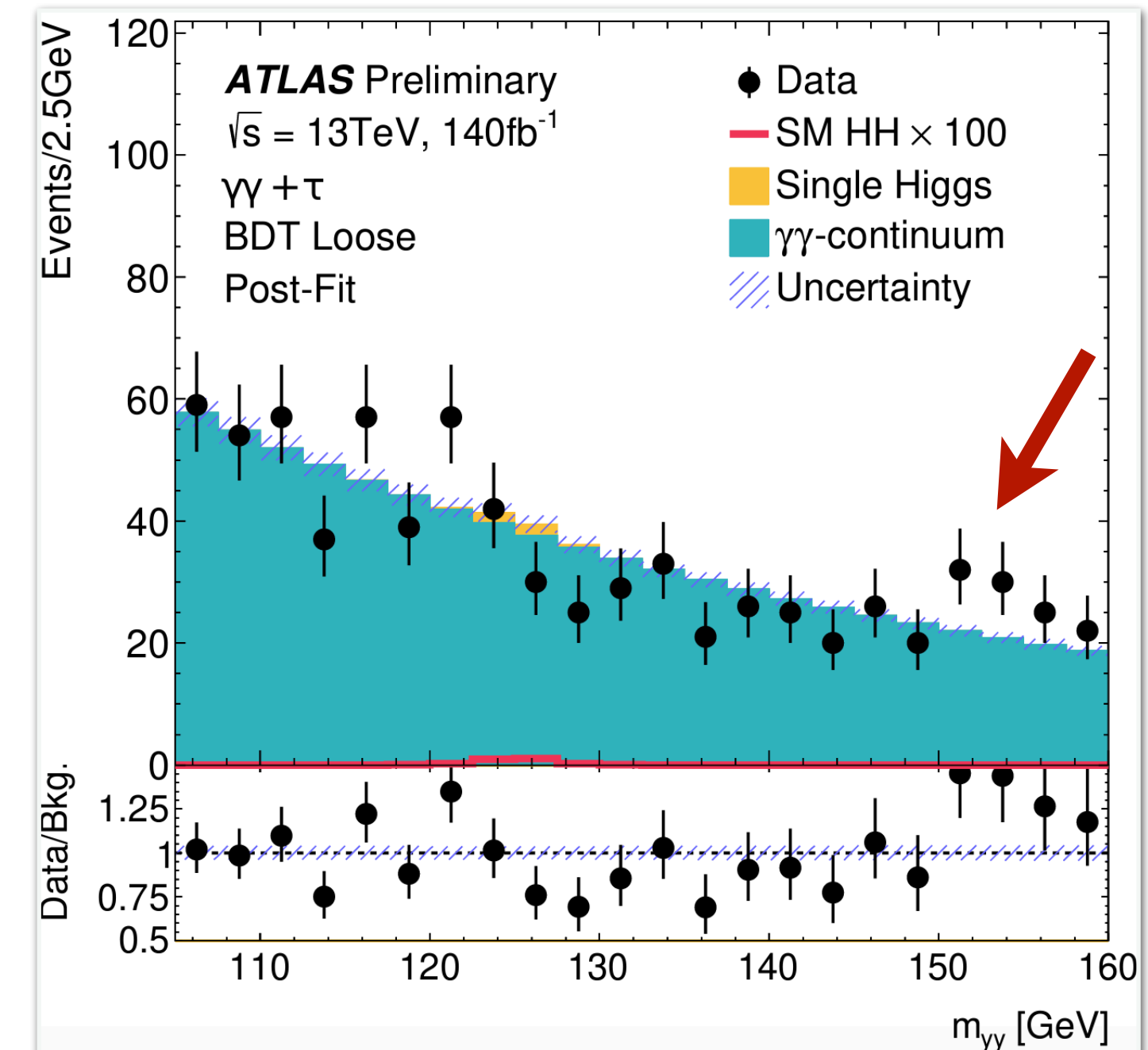
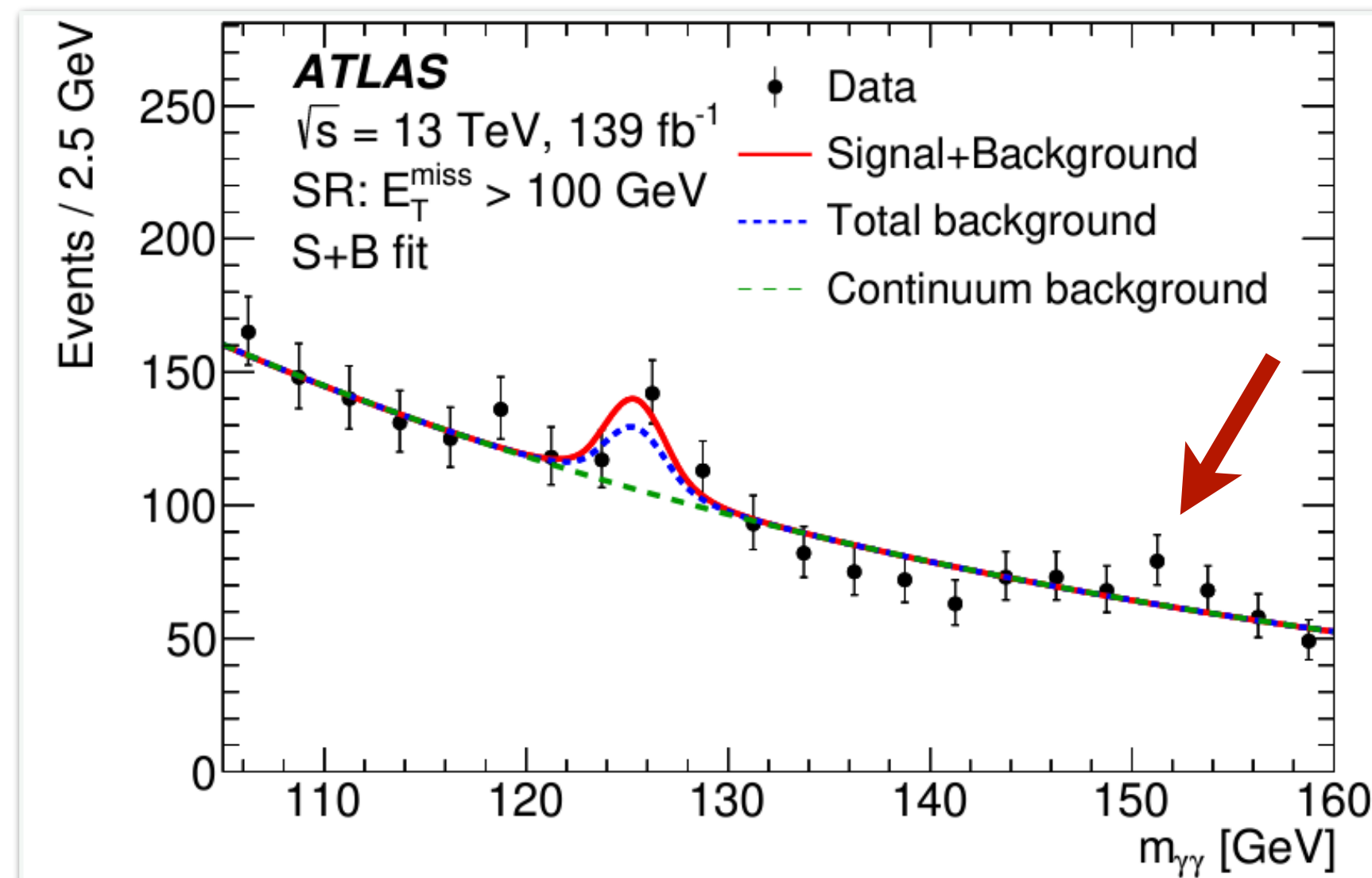
Motivation

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]



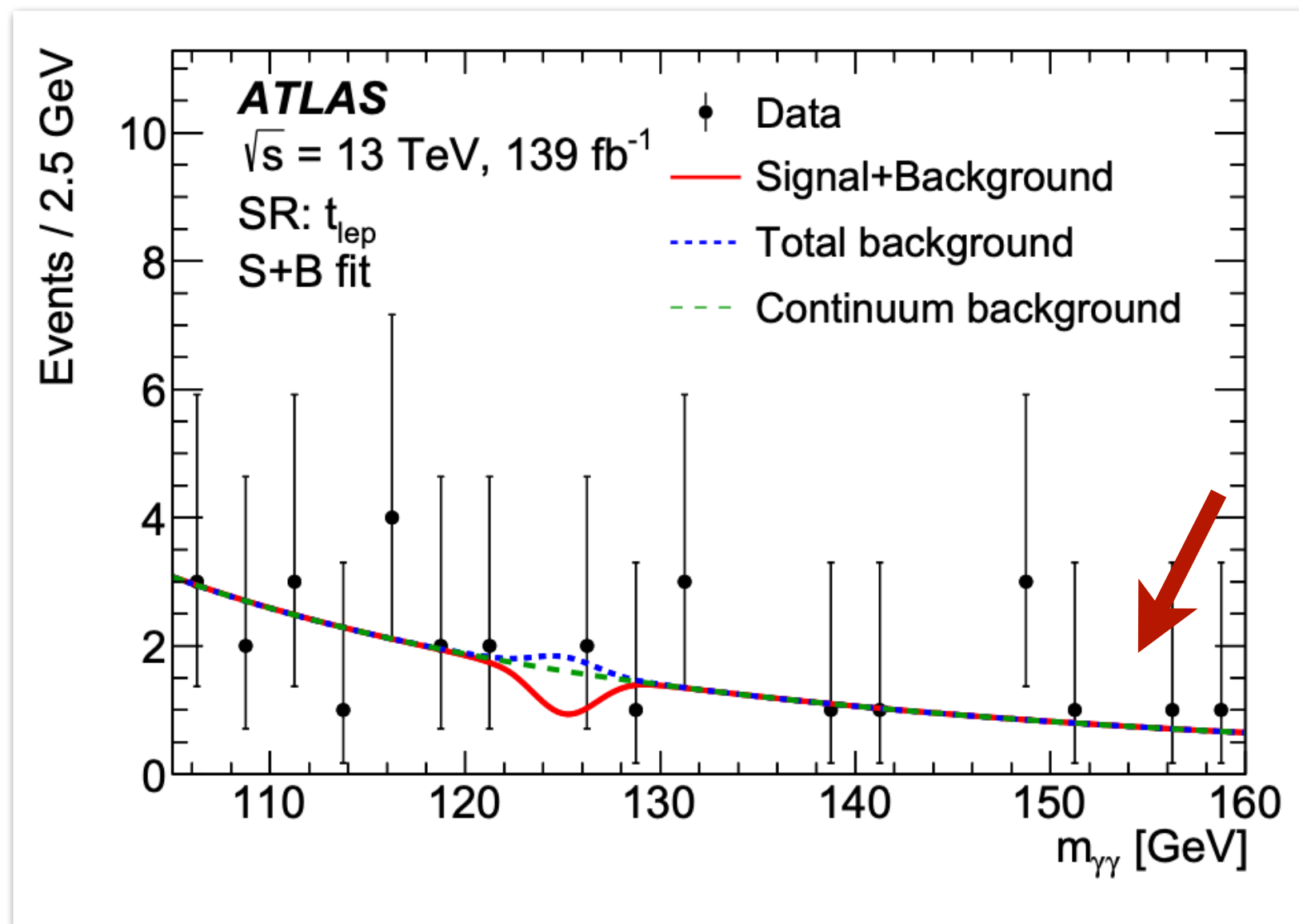
[ATLAS-CONF-2024-005]

- Possible new Higgs Boson?

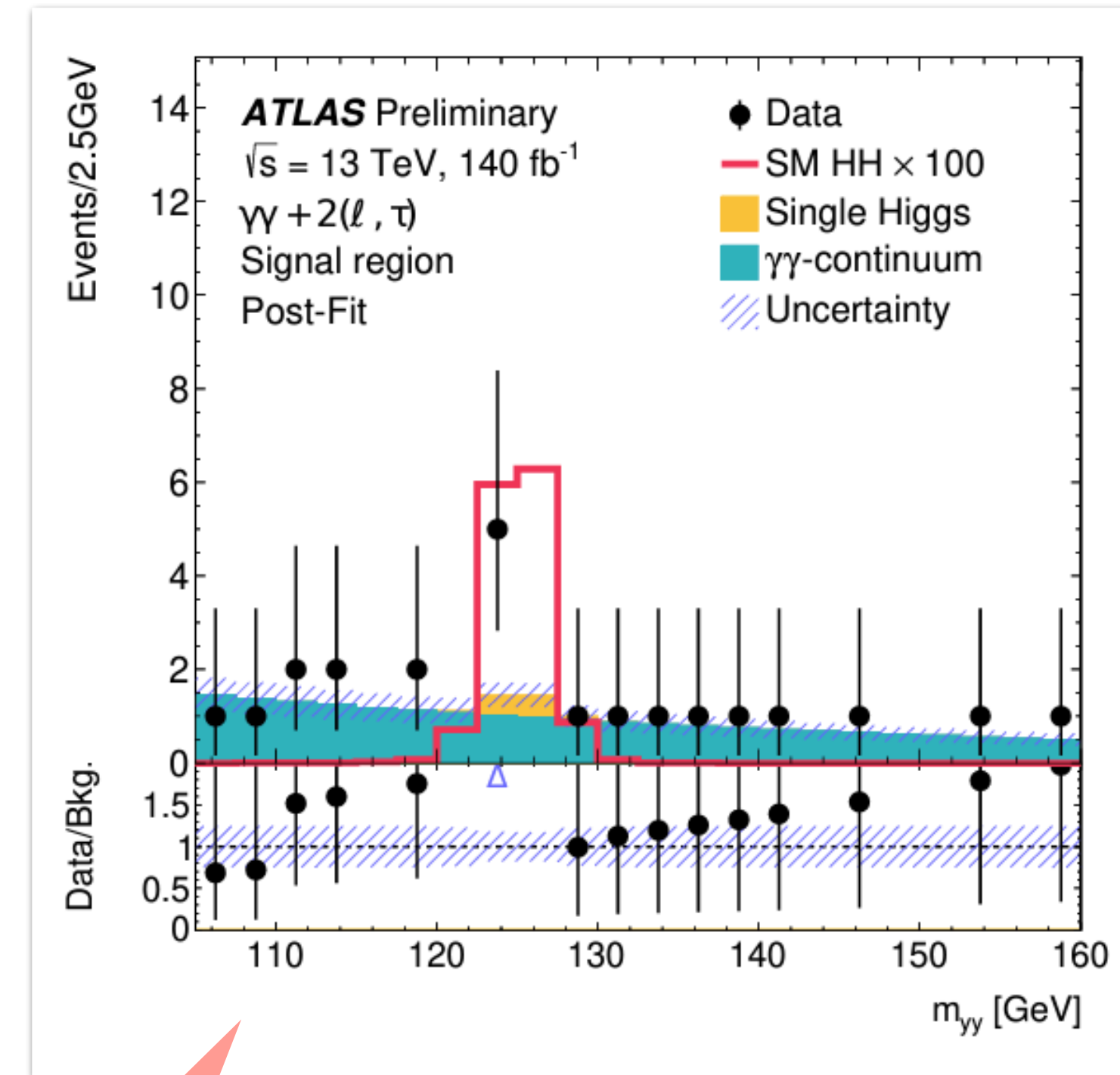
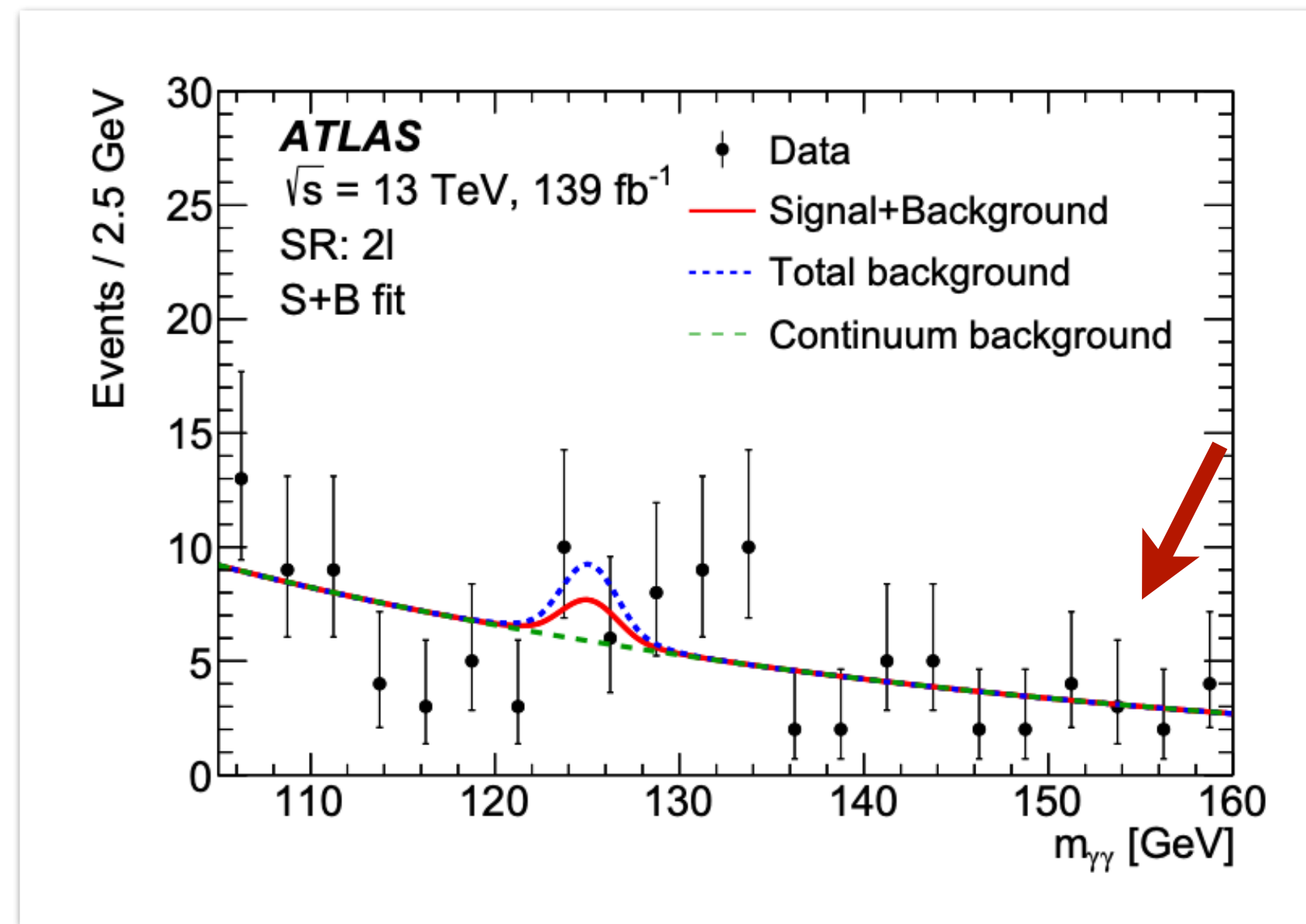
Motivation

Hints for new Higgs Bosons

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



[ATLAS: CERN-EP-2022-232]



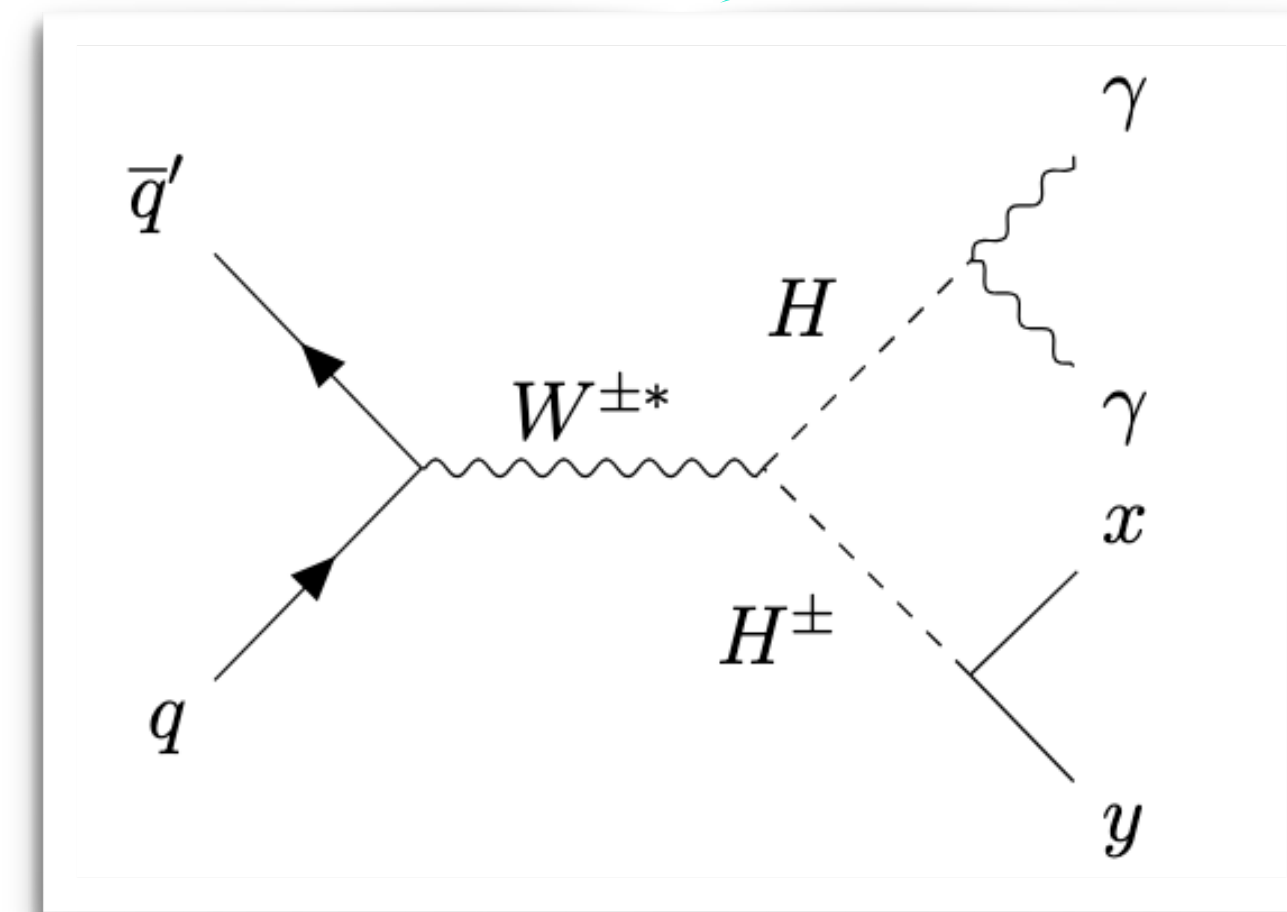
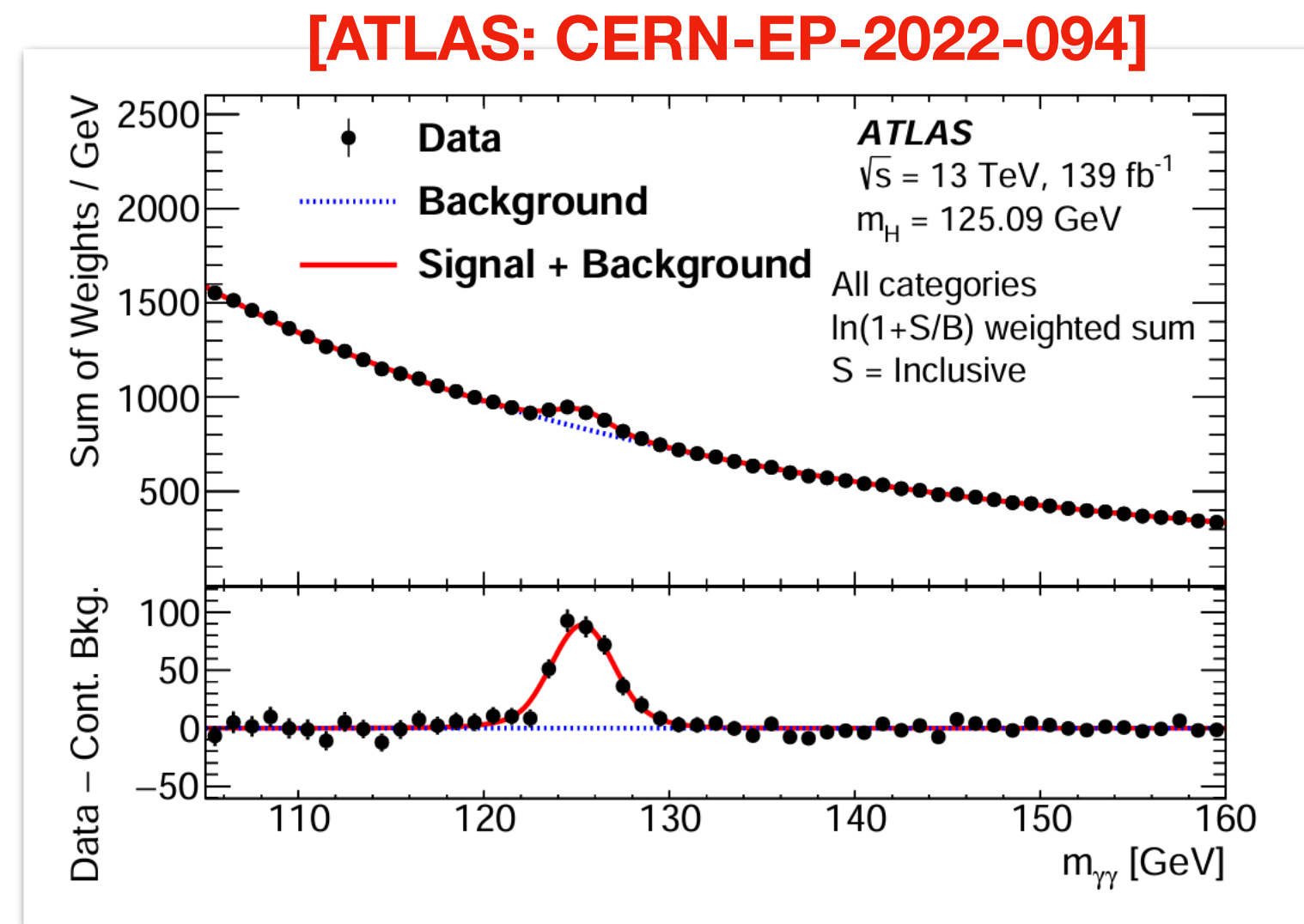
[ATLAS-CONF-2024-005]

Point towards
associated H^\pm

Motivation

Hints for new Higgs Bosons

- No excess in **Inclusive Searches**



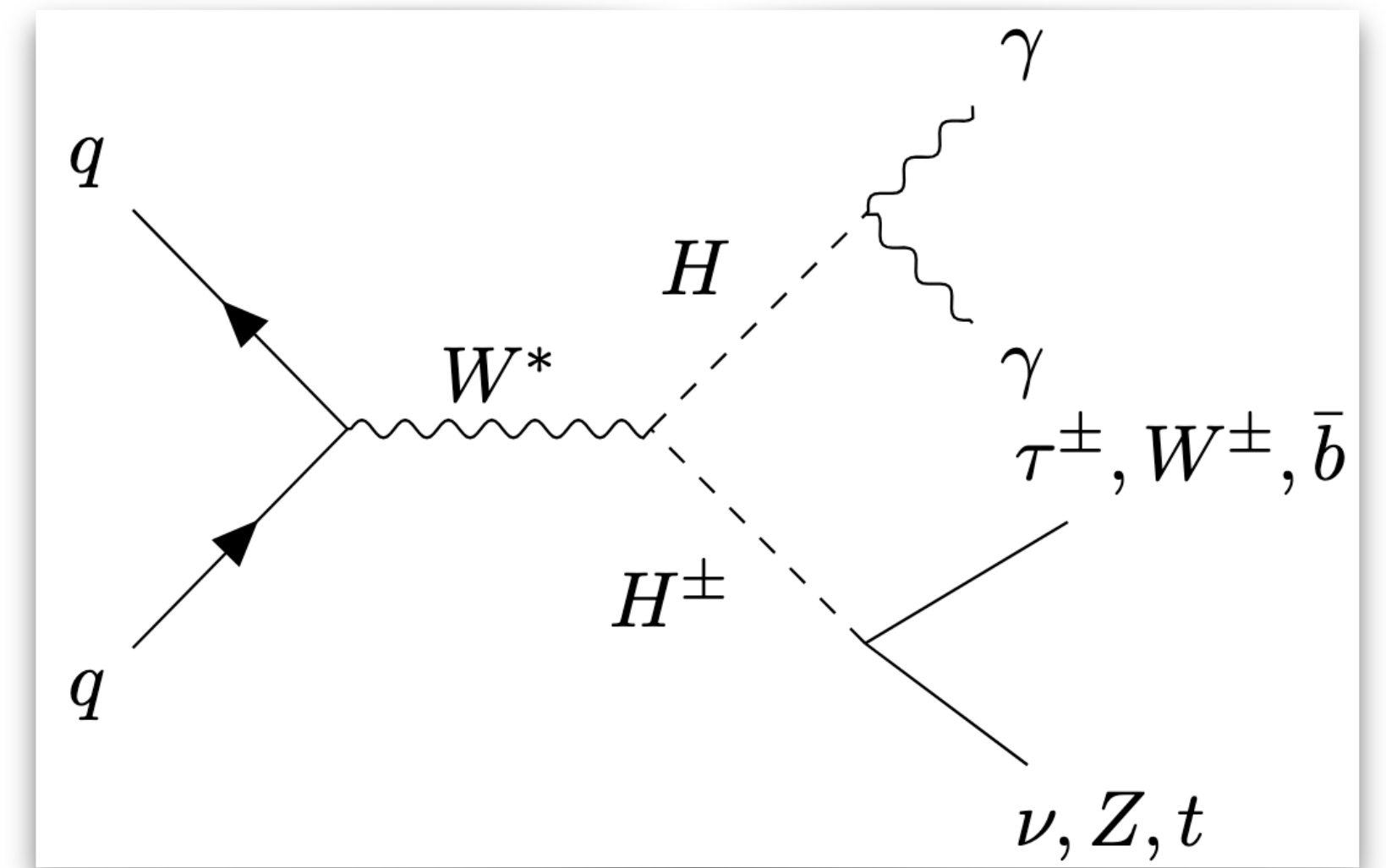
Dominant
Production Process

- Hints towards **DY production** of new Higgs at LHC
- Properties of H^{\pm} **unknown**

Simplified Model

Model Description

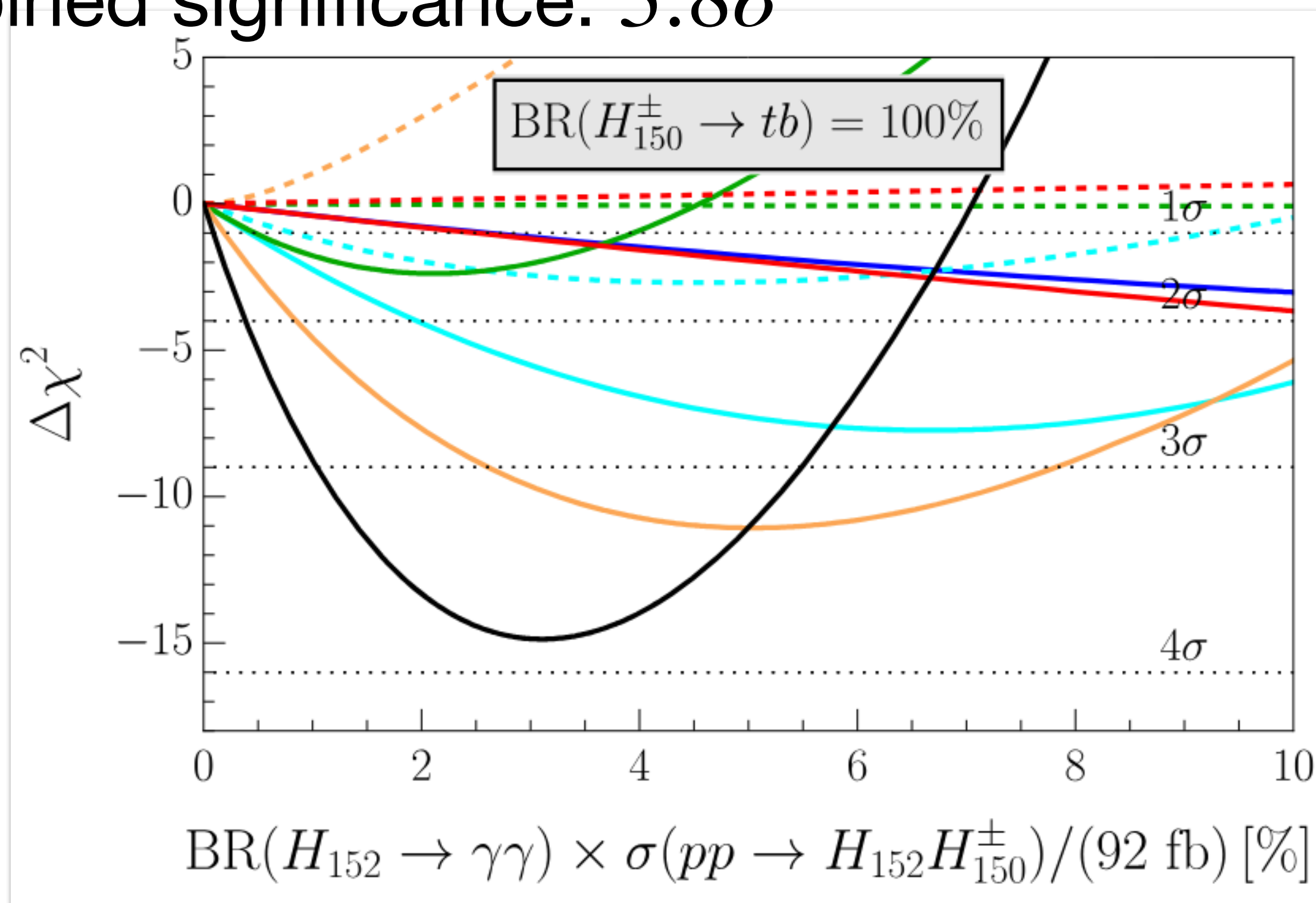
- Two New Particles: H , H^\pm
- H produced only via DY process
- Dominant decays of H^\pm : tb , $\tau\nu$, WZ
- Simulation Setup: MadGraph + Pythia + Delphes
- Log-Likelihood Fit performed using Poisson Statistics



Simplified Model

Charged Higgs Decay

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



Relevant SRs

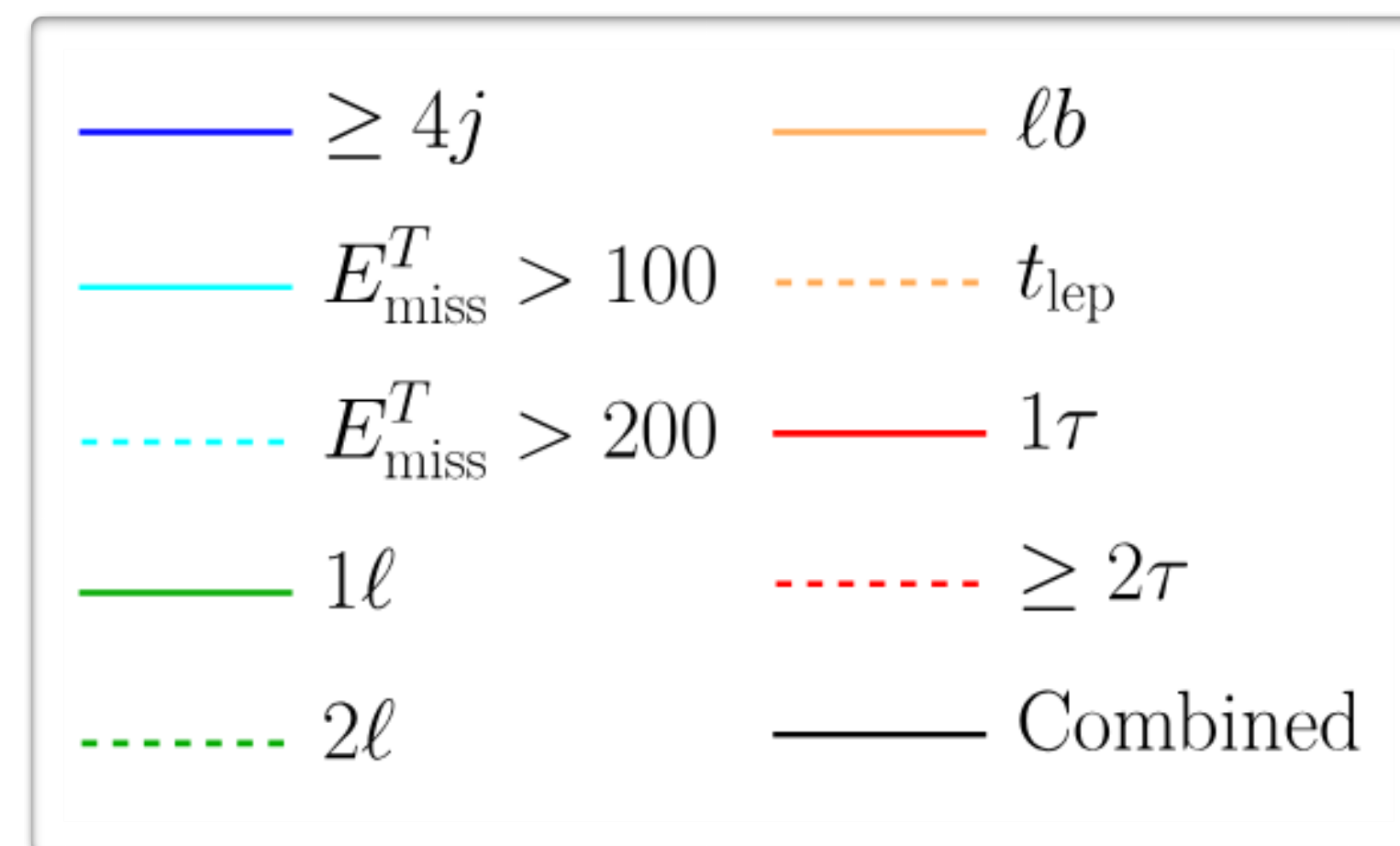
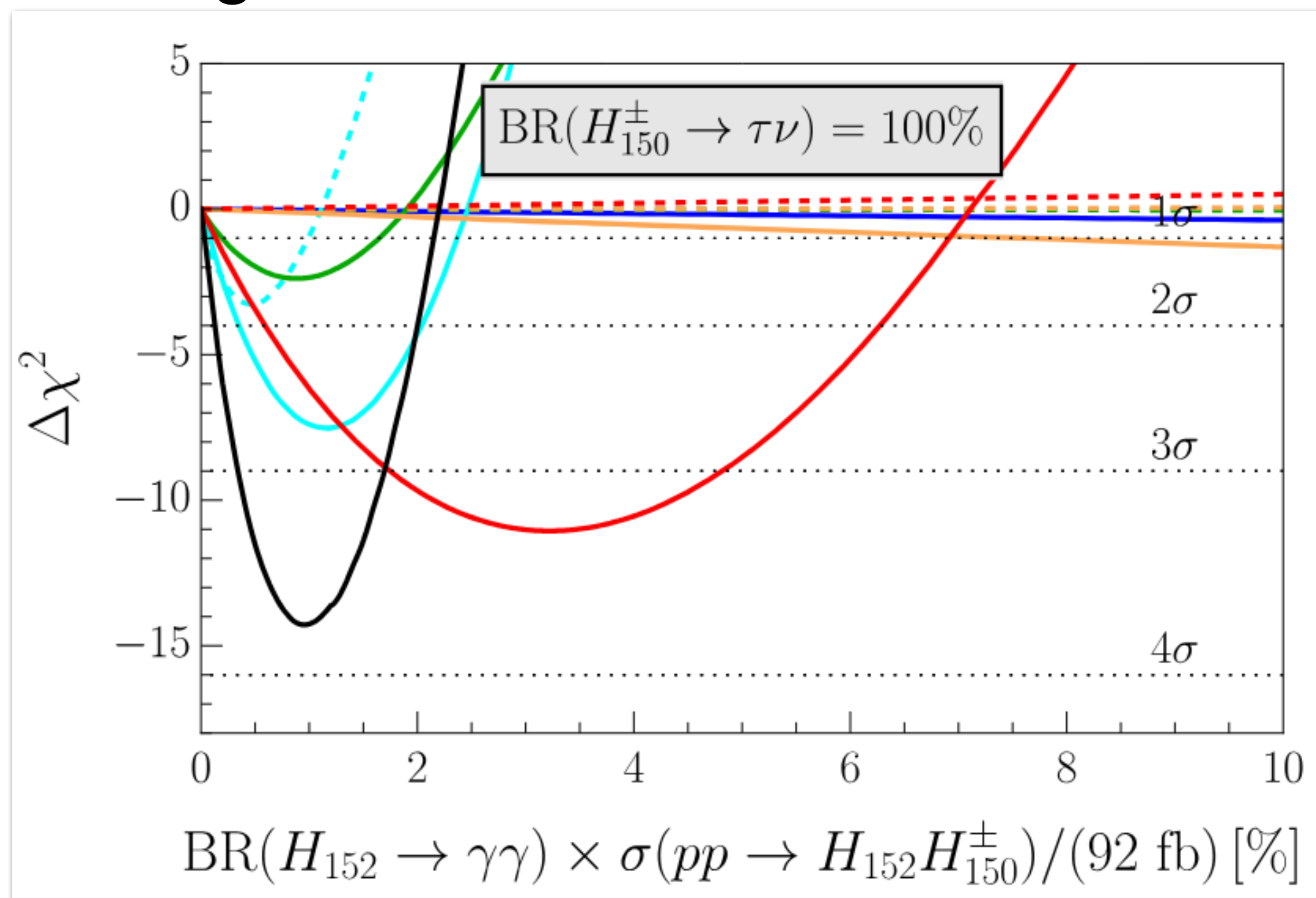
$\geq 4j$	lb
$E_{\text{miss}}^T > 100$	t_{lep}
$E_{\text{miss}}^T > 200$	1τ
1ℓ	$\geq 2\tau$
2ℓ	Combined

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

Simplified Model

Charged Higgs Decay

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



Simplified Model

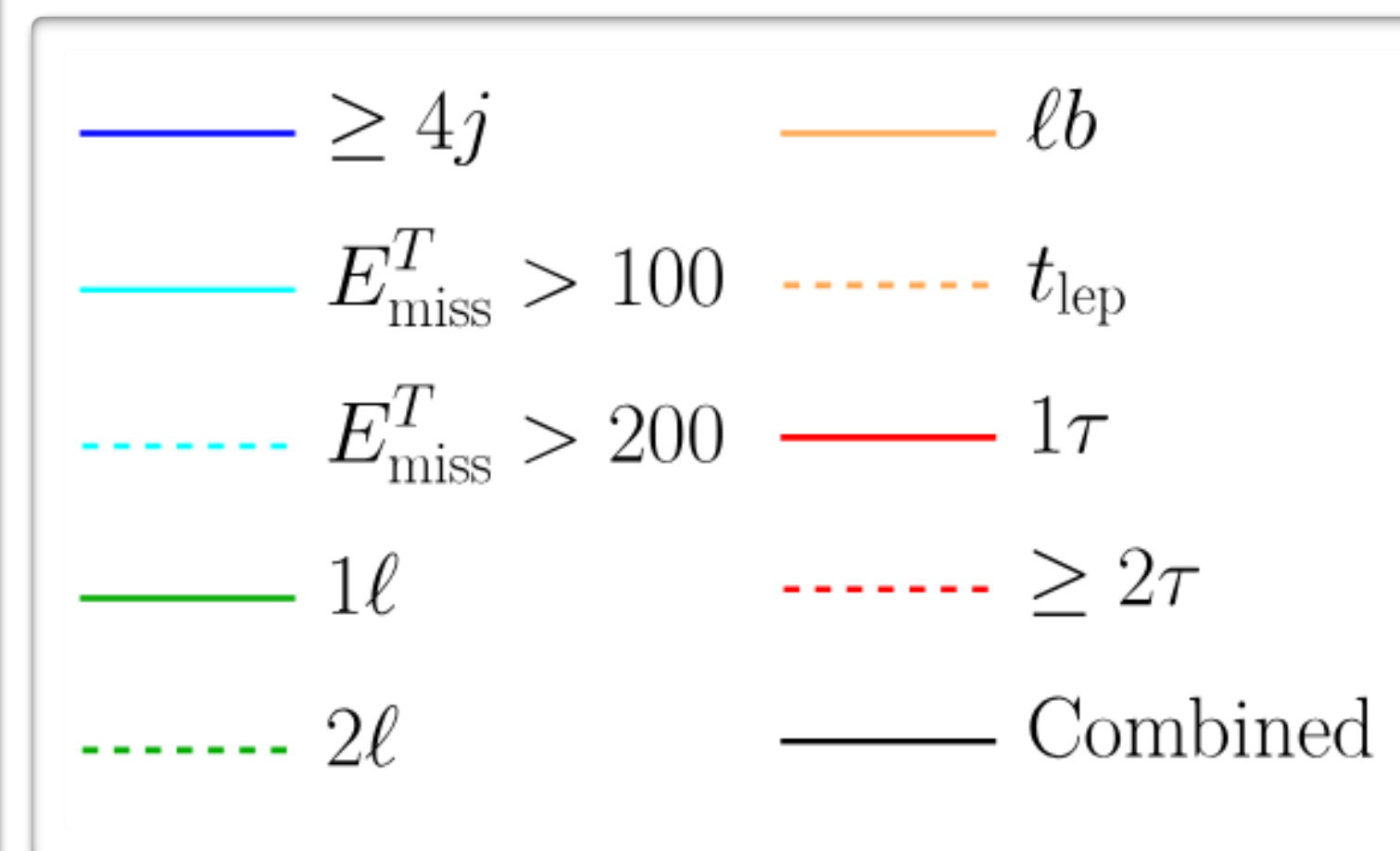
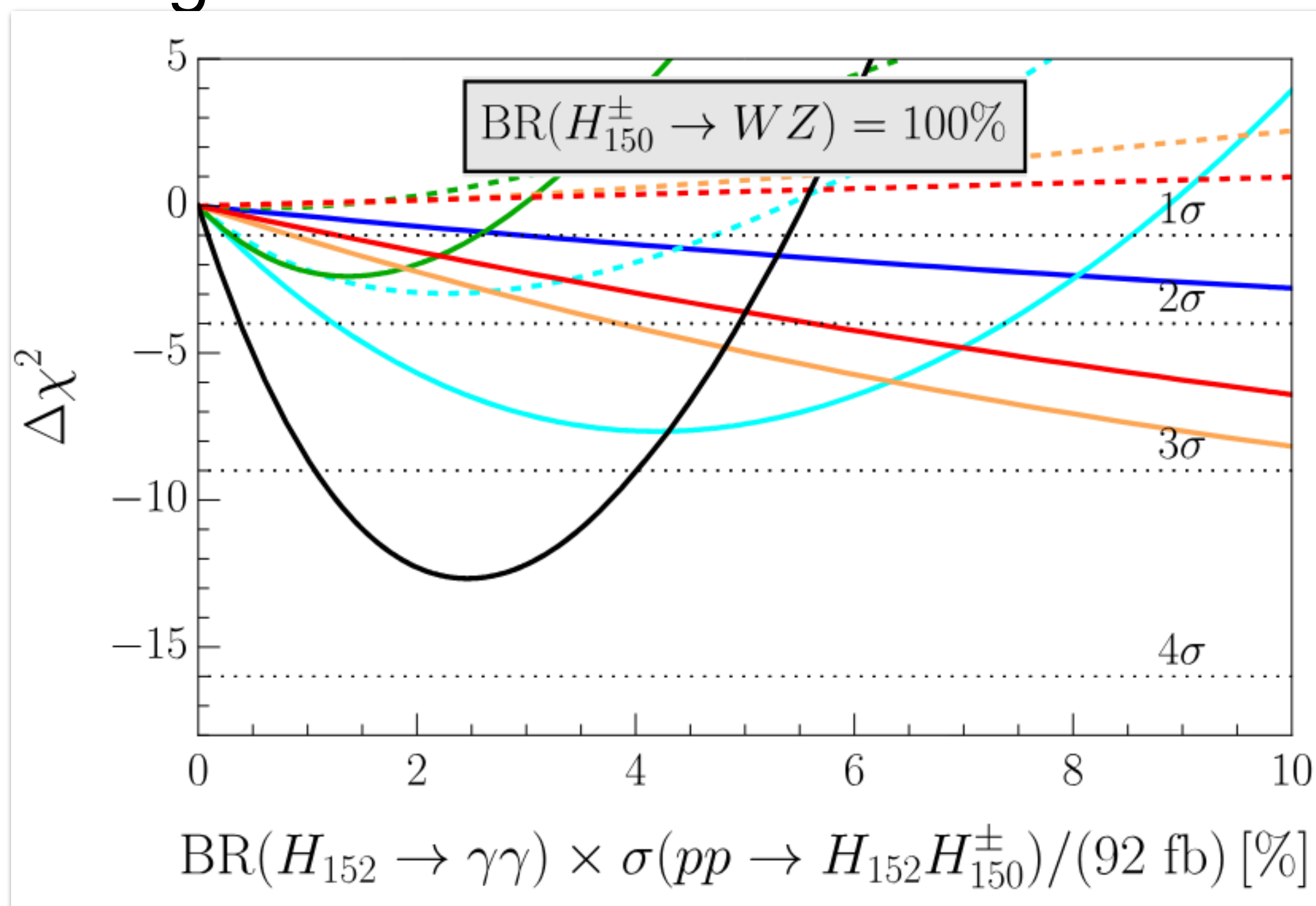
Charged Higgs Decay

○ $BR(H^\pm \rightarrow WZ) = 100\%$

Dominant in Triplet Model

○ Dominant Effect: $\gamma\gamma + MET$, $\gamma\gamma + 1\ell$, $\gamma\gamma + 2\ell$, $\gamma\gamma + 2\tau$

○ Combined significance: 3.5σ



Model Building

Key Points

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

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: $m_h, m_H, m_A, m_{H^\pm}, m_{12}^2, \tan \beta = v_2/v_1, \alpha$

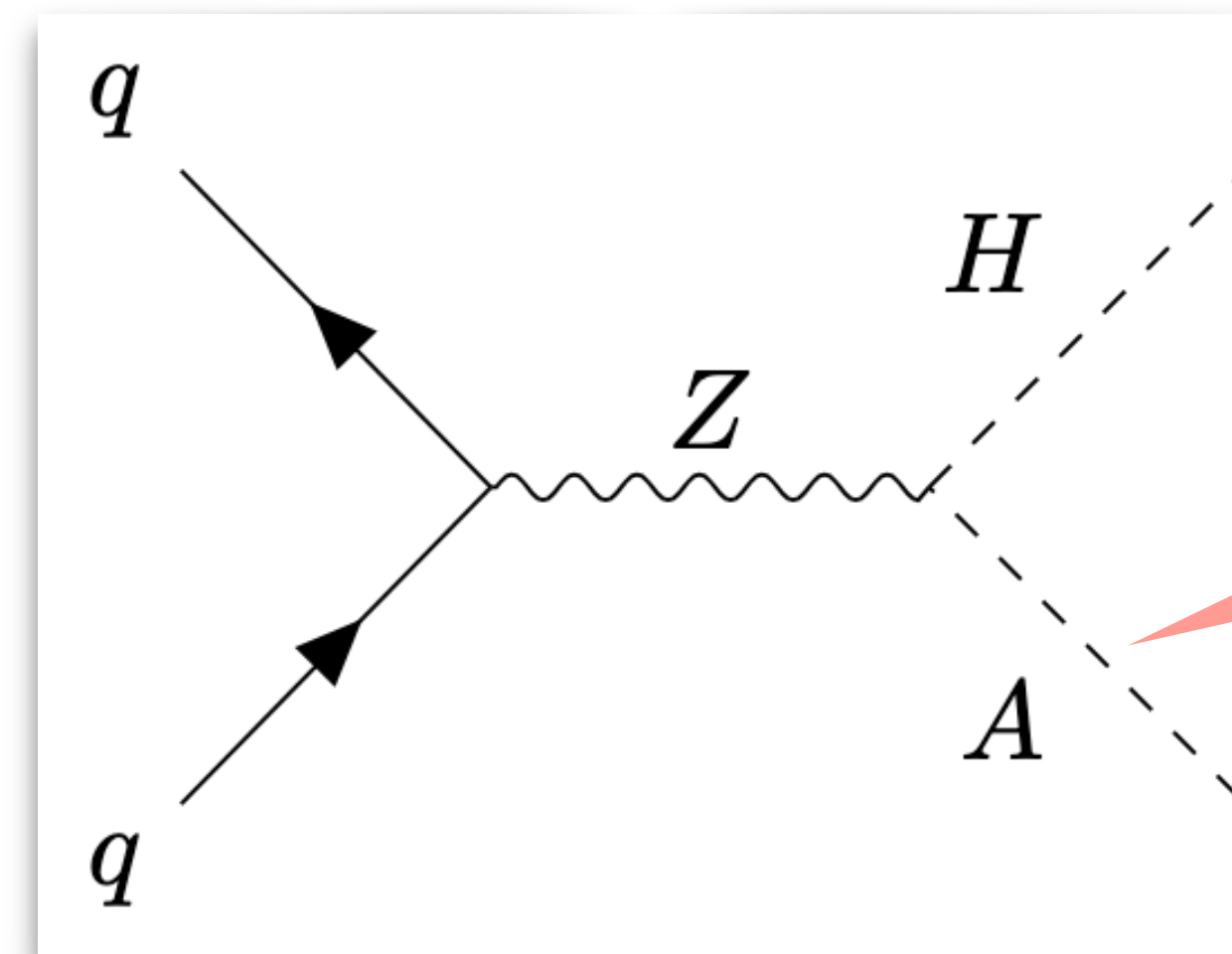
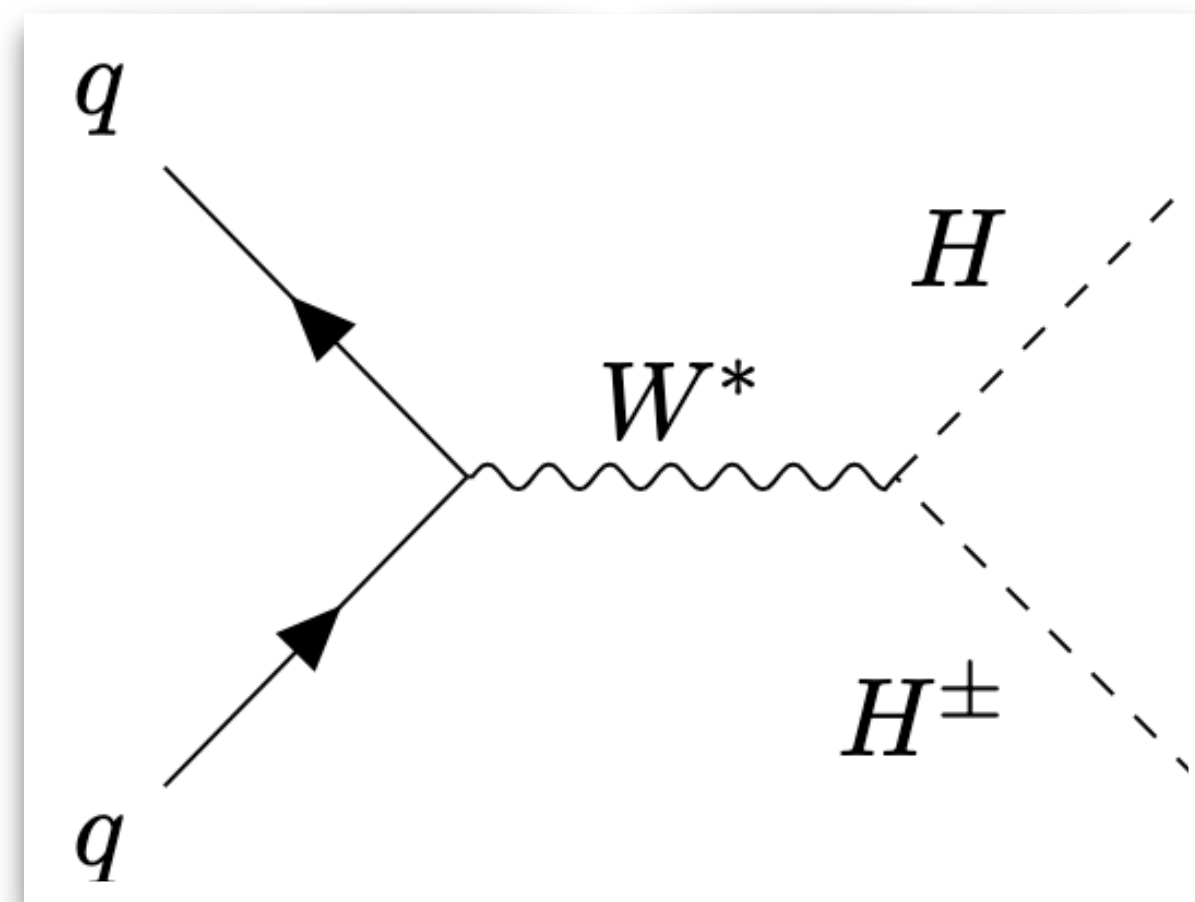
Explanation in 2HDM

Type-I

- Yukawa Sector

$$Y = -\bar{Q}_L\phi_2d_R - \bar{Q}_L\phi_2^c u_R - \bar{L}_L\phi_2e_R$$

- 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

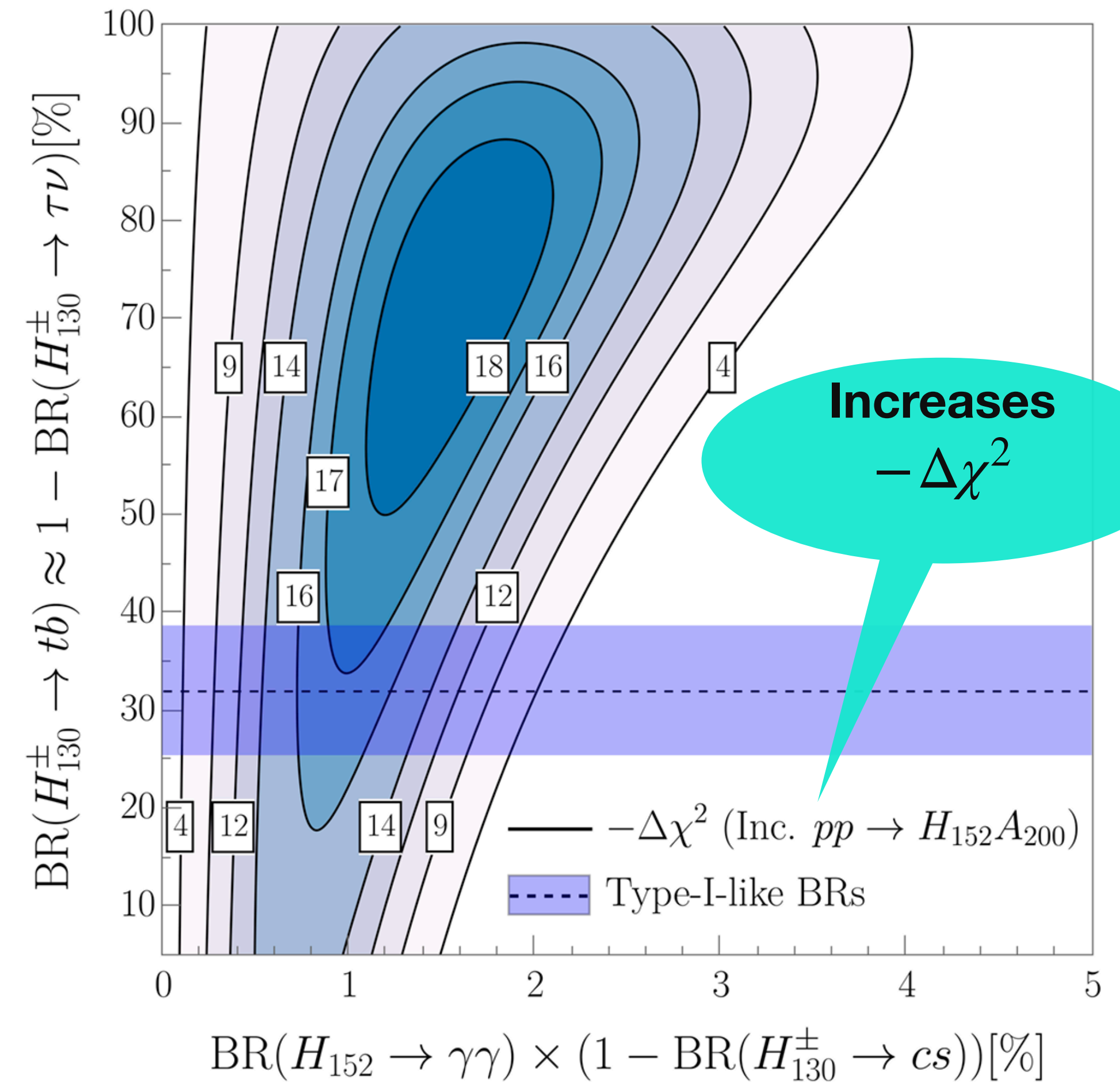
- Considered Benchmark Point:

$$m_H = 152 \text{ GeV}, m_{H^\pm} = 130 \text{ GeV}, \alpha - \beta \approx \pi/2$$

$$m_A = 200 \text{ GeV}, \tan \beta = 20, m_{12}^2 = 1100 \text{ GeV}^2$$

- $\text{Br}(H \rightarrow \gamma\gamma)$ required at the percent level

- Possible with Effective Operator: $F_{\mu\nu}F^{\mu\nu}\phi_1^\dagger\phi_2$ or in general 2HDM



General 2HDM

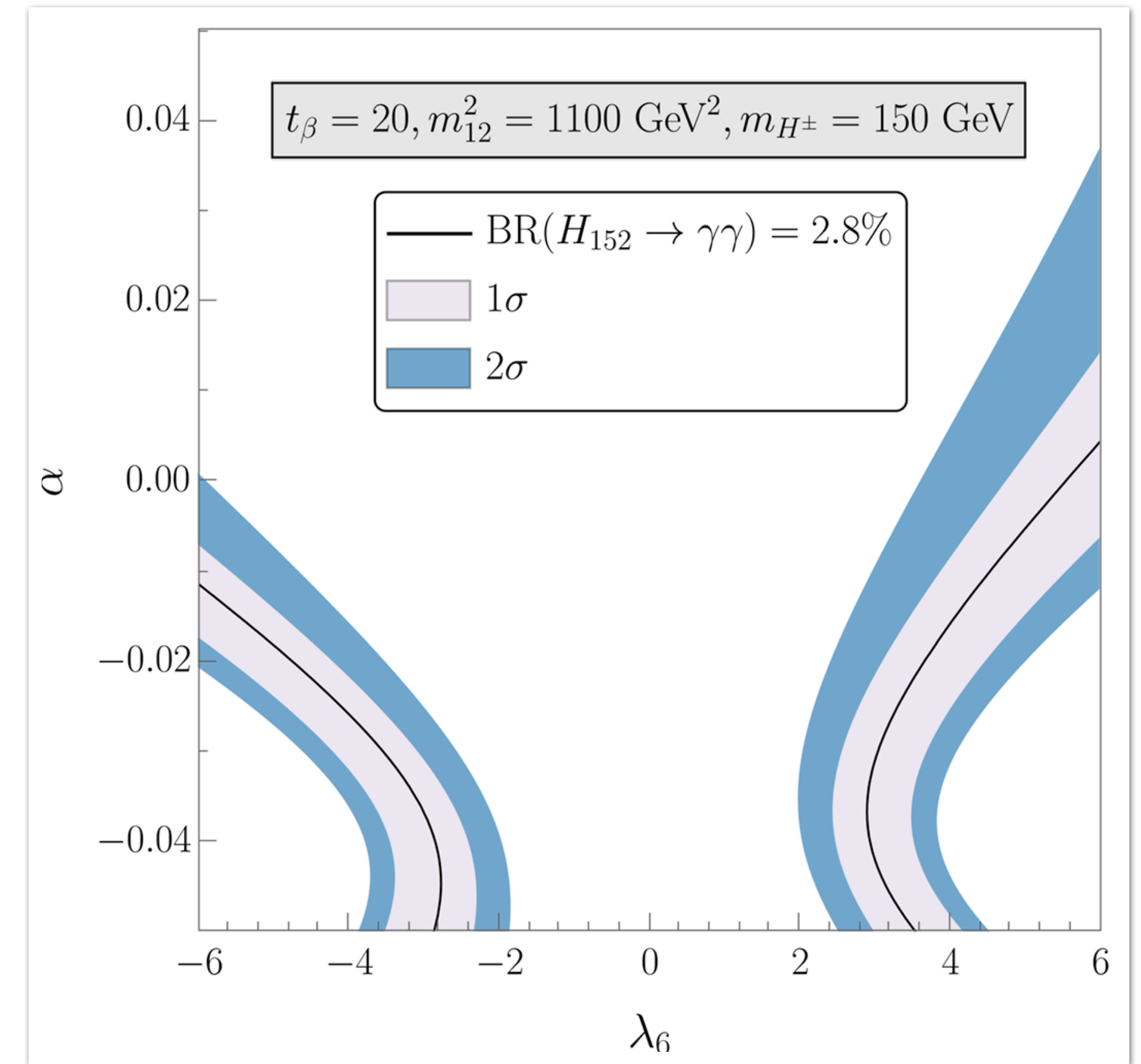
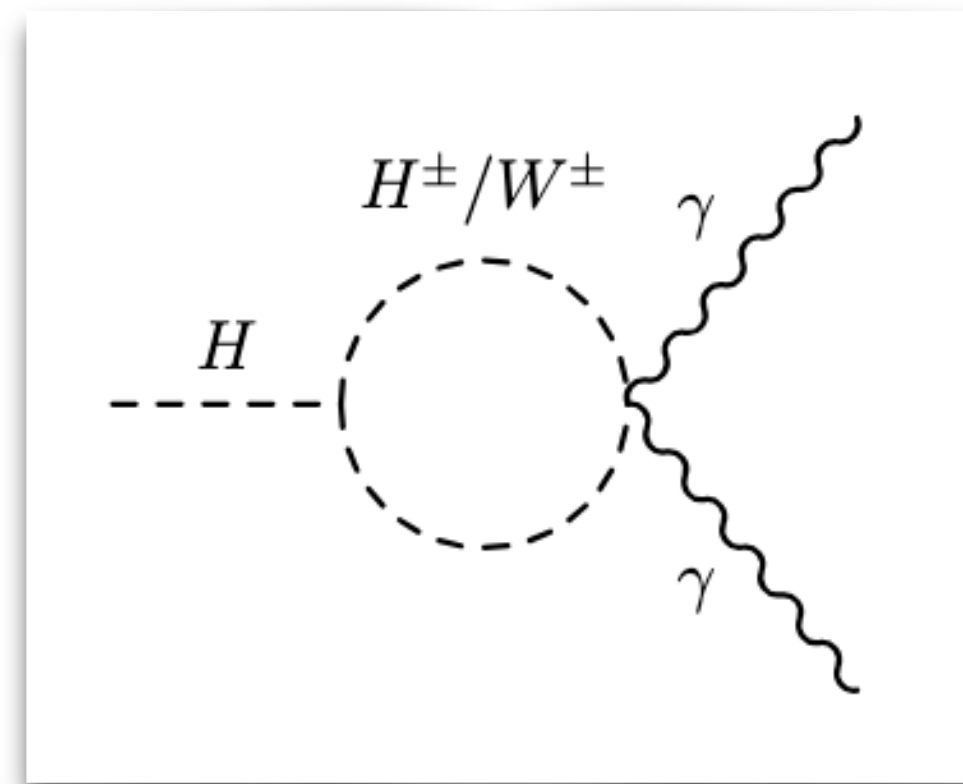
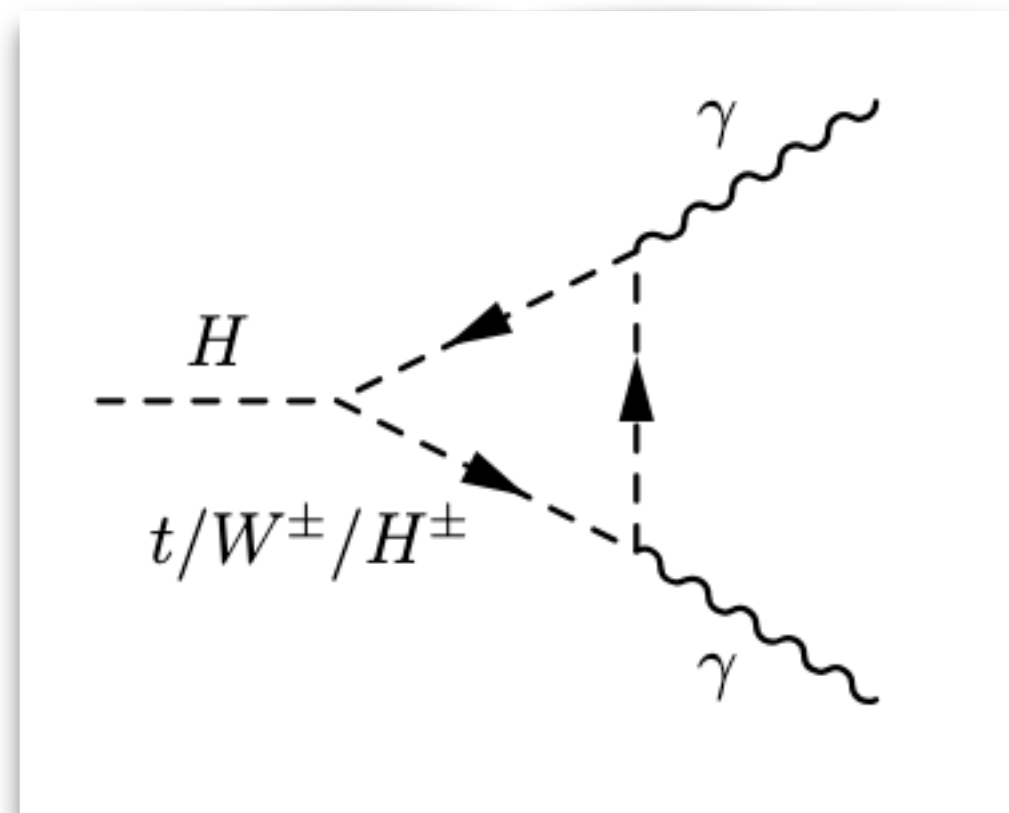
Large $H \rightarrow \gamma\gamma$

- Large $\text{Br}(H \rightarrow \gamma\gamma)$ possible in general 2HDM

Z_2 symmetry broken

$$\mathcal{L} \in -\lambda_6 H_1^\dagger H_1 H_2^\dagger H_2 + \text{h.c.}, \dots$$

- Modifies the $HH^\pm H^\mp$ vertex
- Enhanced $\text{Br}(H \rightarrow \gamma\gamma)$ via H^\pm loop



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 **Δ SM** and **2HDM**
- Large $\text{Br}(H \rightarrow \gamma\gamma)$ possible in **general 2HDM**

Thank you for your attention!

Backup

Explanation in Real Higgs Triplet

Model Description

- Extend SM with $Y = 0$, $SU(2)_L$ triplet: $\Delta = \frac{1}{2} \begin{pmatrix} v_\Delta + h_\Delta^0 & \sqrt{2}h_\Delta^+ \\ \sqrt{2}h_\Delta^- & -v_\Delta - h_\Delta^0 \end{pmatrix}$

- **No direct** coupling of Δ with fermions

Suppressed ggH

- Scalar **potential**

$$V = -\mu_\phi^2 \phi^\dagger \phi + \frac{\lambda_\phi}{4} (\phi^\dagger \phi)^2 - \mu_\Delta^2 \text{Tr}(\Delta^\dagger \Delta) + \frac{\lambda}{4} [\text{Tr}(\Delta^\dagger \Delta)]^2$$

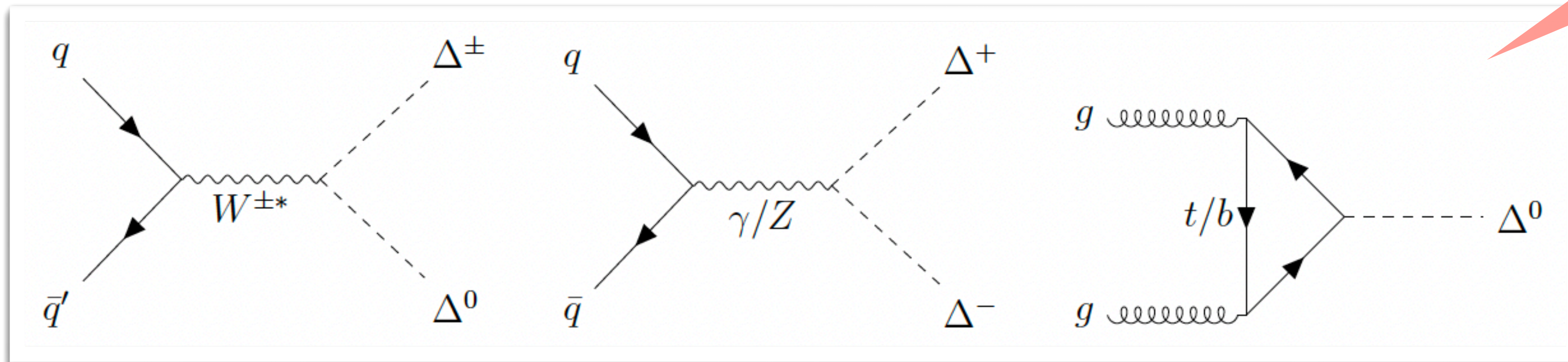
$$+ A \phi^\dagger \Delta \phi + \lambda_{\phi\Delta} \phi^\dagger \phi \text{Tr}(\Delta^\dagger \Delta)$$

where ϕ is the SM doublet.

Explanation in Real Higgs Triplet

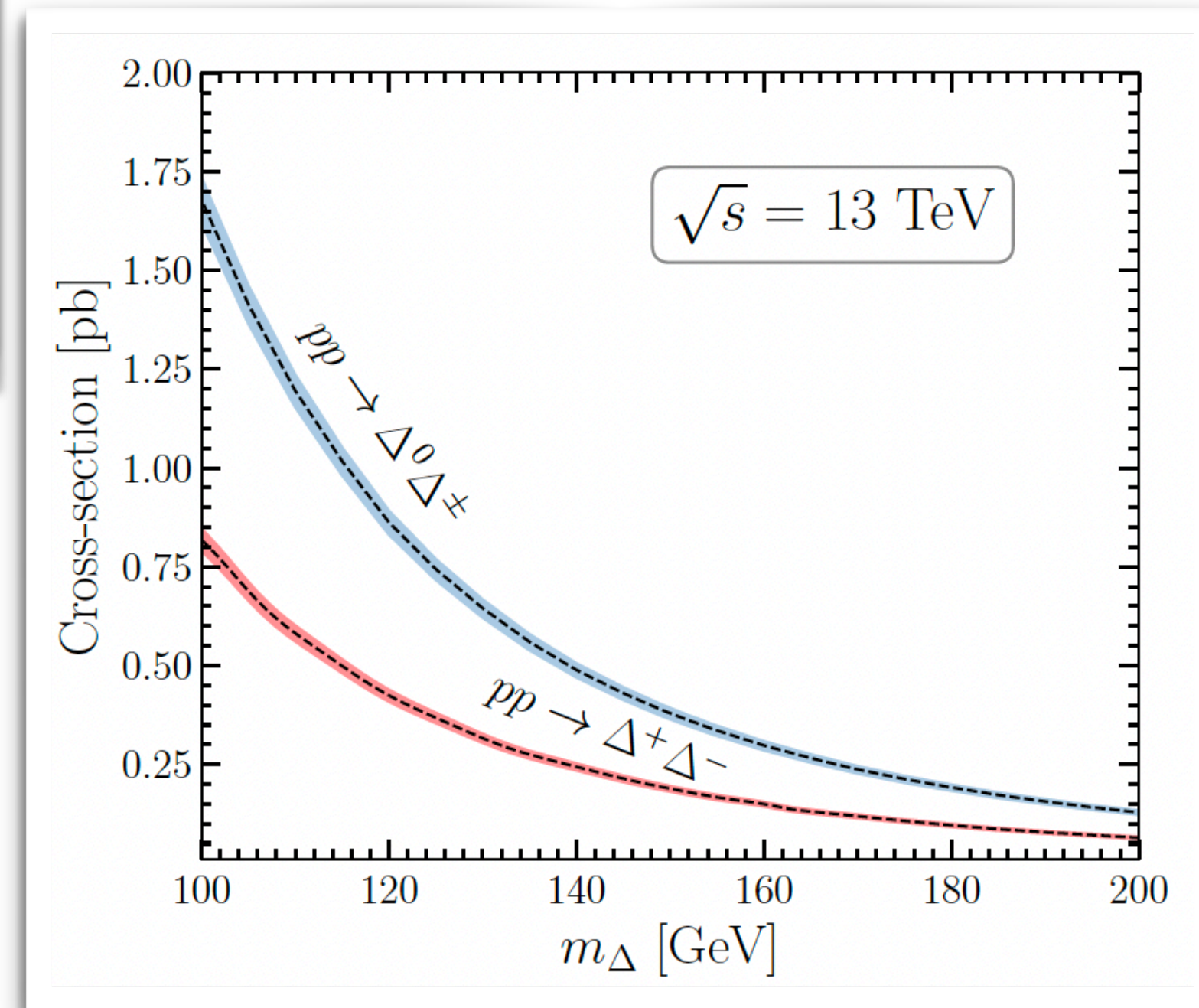
Model Description

- Triplet Higgs **production channels** at LHC



Suppressed by mixing

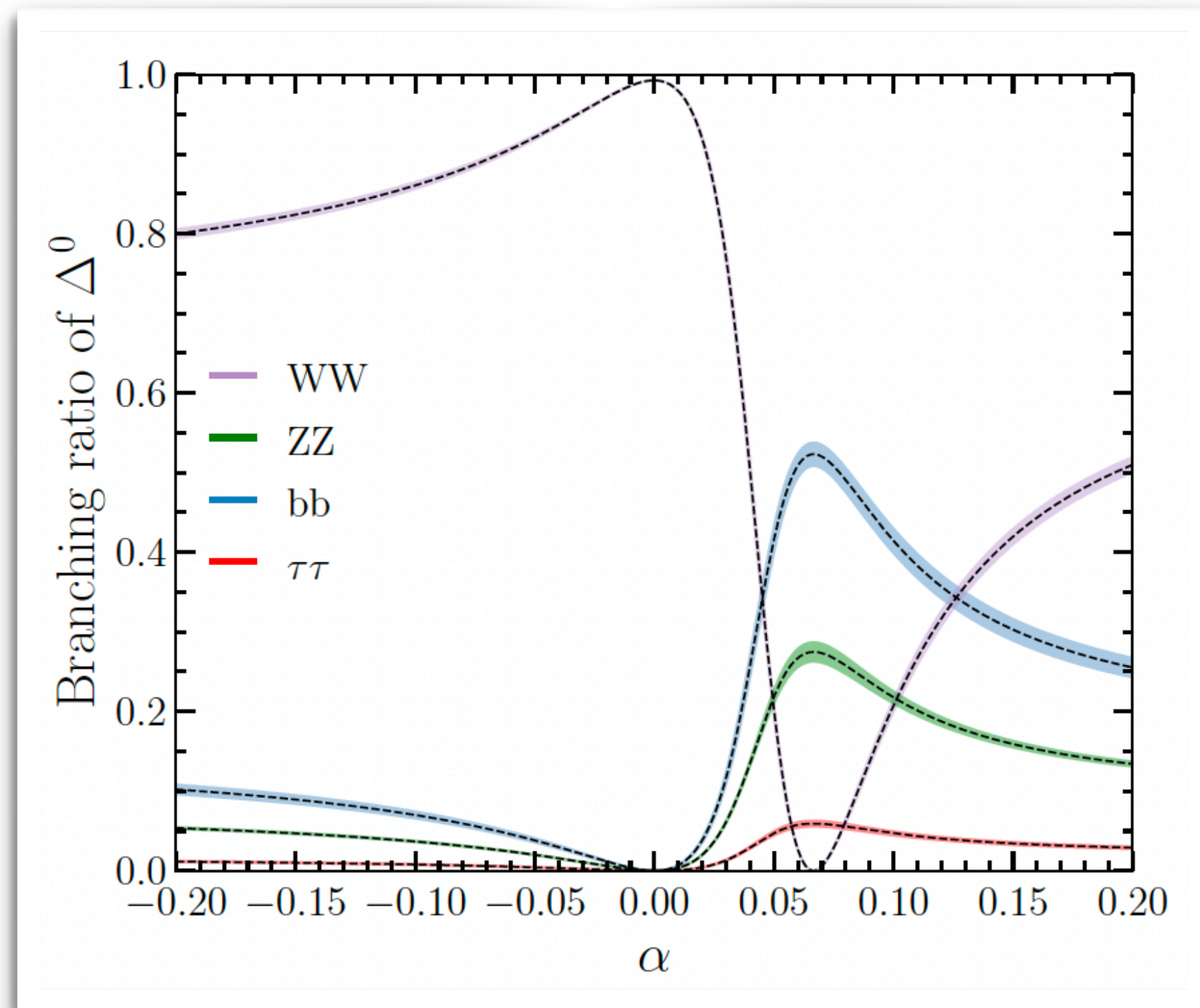
- Triplet Higgs **DY production cross-section**



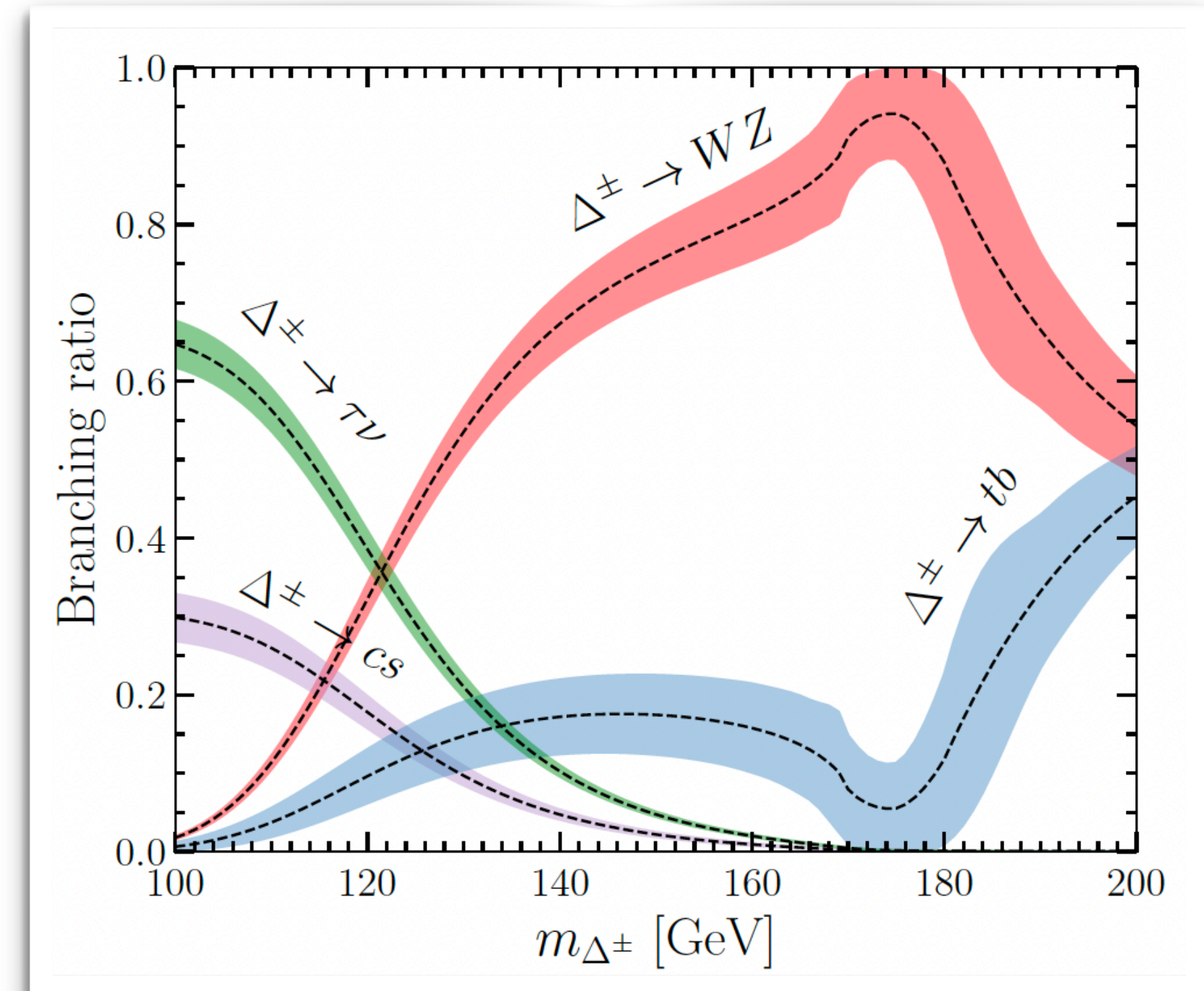
Explanation in Real Higgs Triplet

Model Description

- Dominant Triplet Higgses **decay channels**



Branching Ratio of Δ_0
($m_{\Delta_0} = 150$ GeV)



Branching Ratio of Δ^\pm
($\alpha = 0.1$)

Real Higgs Triplet

Basis Transformation

Physical to Lagrangian Basis

$$m_h^2 = \frac{\lambda_\Phi v_\Phi^2}{2} + \tan \alpha \left(\lambda_{\Phi\Delta} v_\Delta - \frac{A}{2} \right) v_\Phi,$$
$$m_{\Delta^0}^2 = \frac{\lambda_\Delta v_\Delta^2}{2} + \frac{A v_\Phi^2}{4v_\Delta} - \tan \alpha \left(\lambda_{\Phi\Delta} v_\Delta - \frac{A}{2} \right) v_\Phi,$$
$$m_{\Delta^\pm}^2 = A \frac{v_\Phi^2 + 4v_\Delta^2}{4v_\Delta},$$

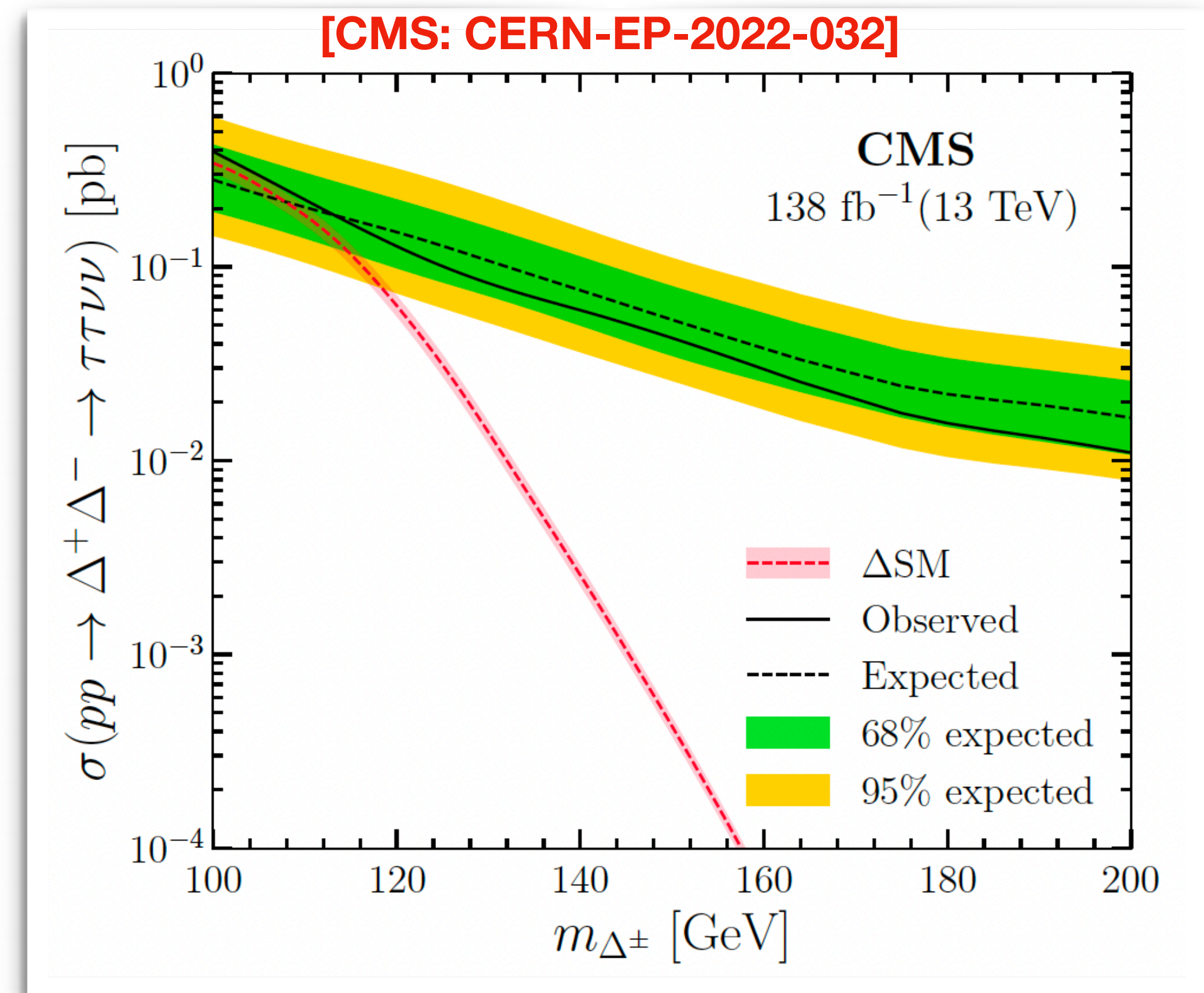
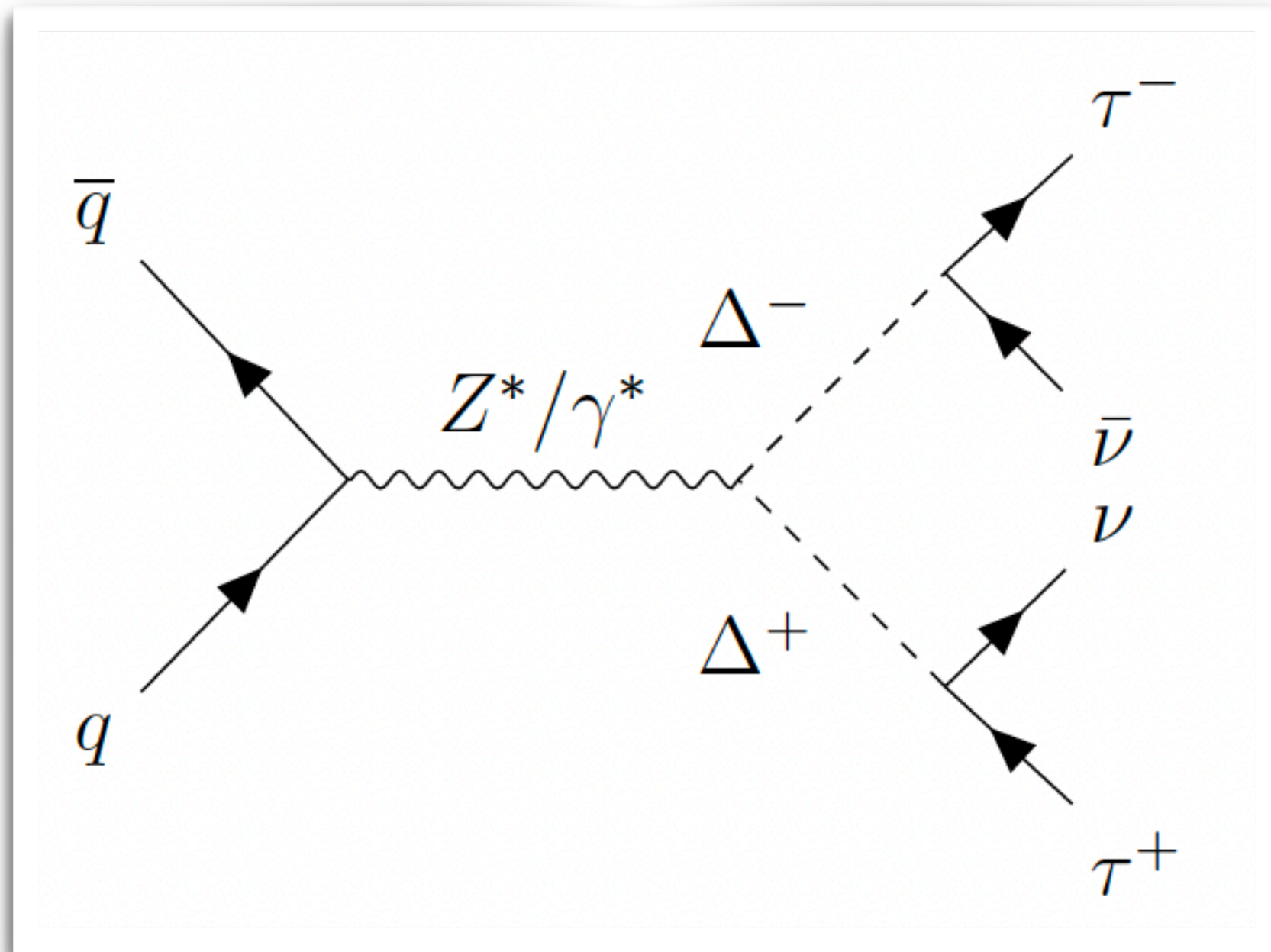
Lagrangian to Physical Basis

$$\lambda_\Phi = \frac{2m_h^2}{v^2},$$
$$\lambda_\Delta = \frac{2}{v_\Delta^2} [m_{\Delta^0}^2 - m_{\Delta^\pm}^2],$$
$$\lambda_{\Phi\Delta} = \frac{\alpha}{vv_\Delta} (m_{\Delta^0}^2 - m_{\Delta^\pm}^2) + \frac{2}{v^2} m_{\Delta^\pm}^2,$$
$$A = \frac{4v_\Delta}{v^2} m_{\Delta^\pm}^2.$$

Explanation in Real Higgs Triplet

Model Constraints

- Mass of Δ^\pm constrained from **stau-like searches**

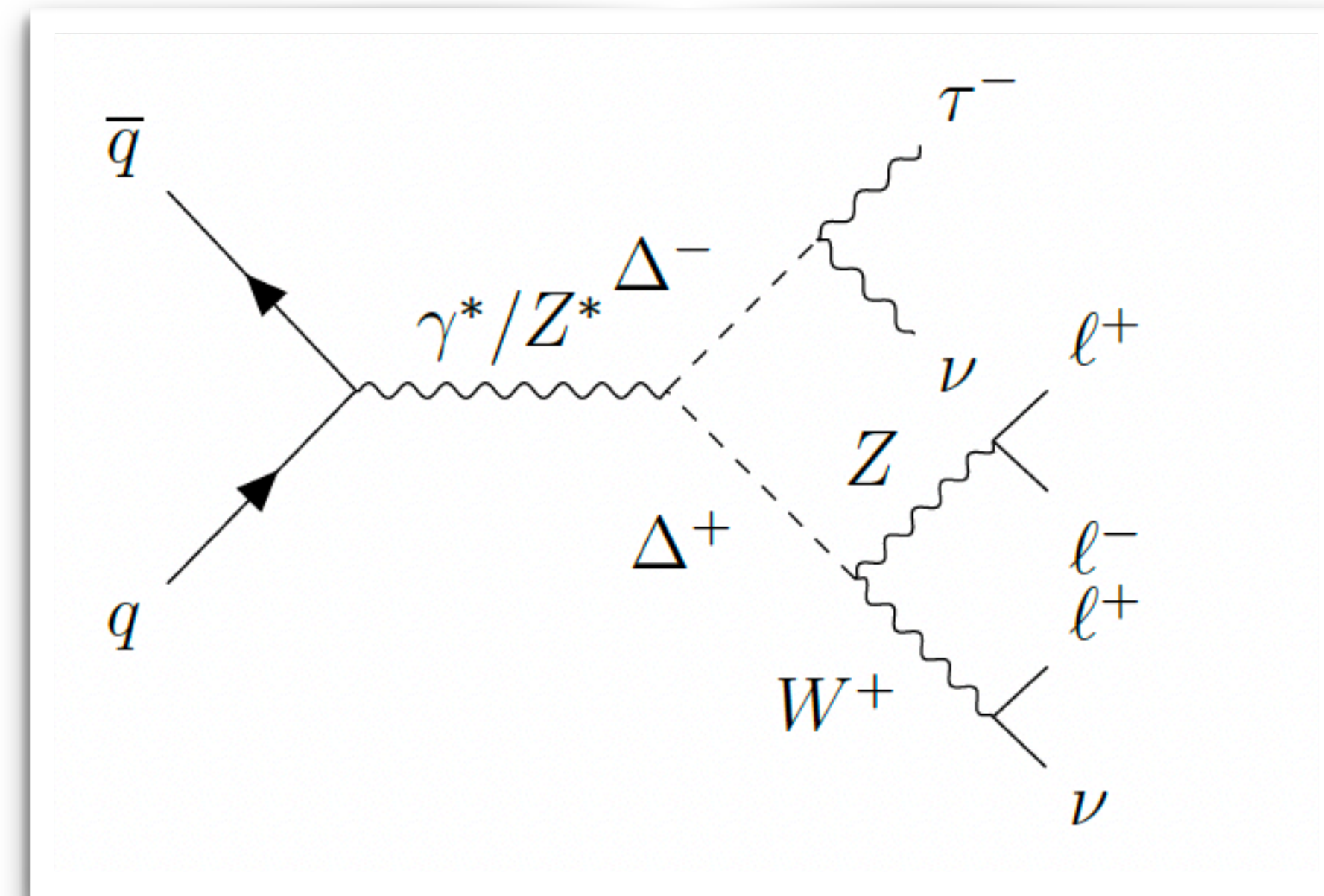
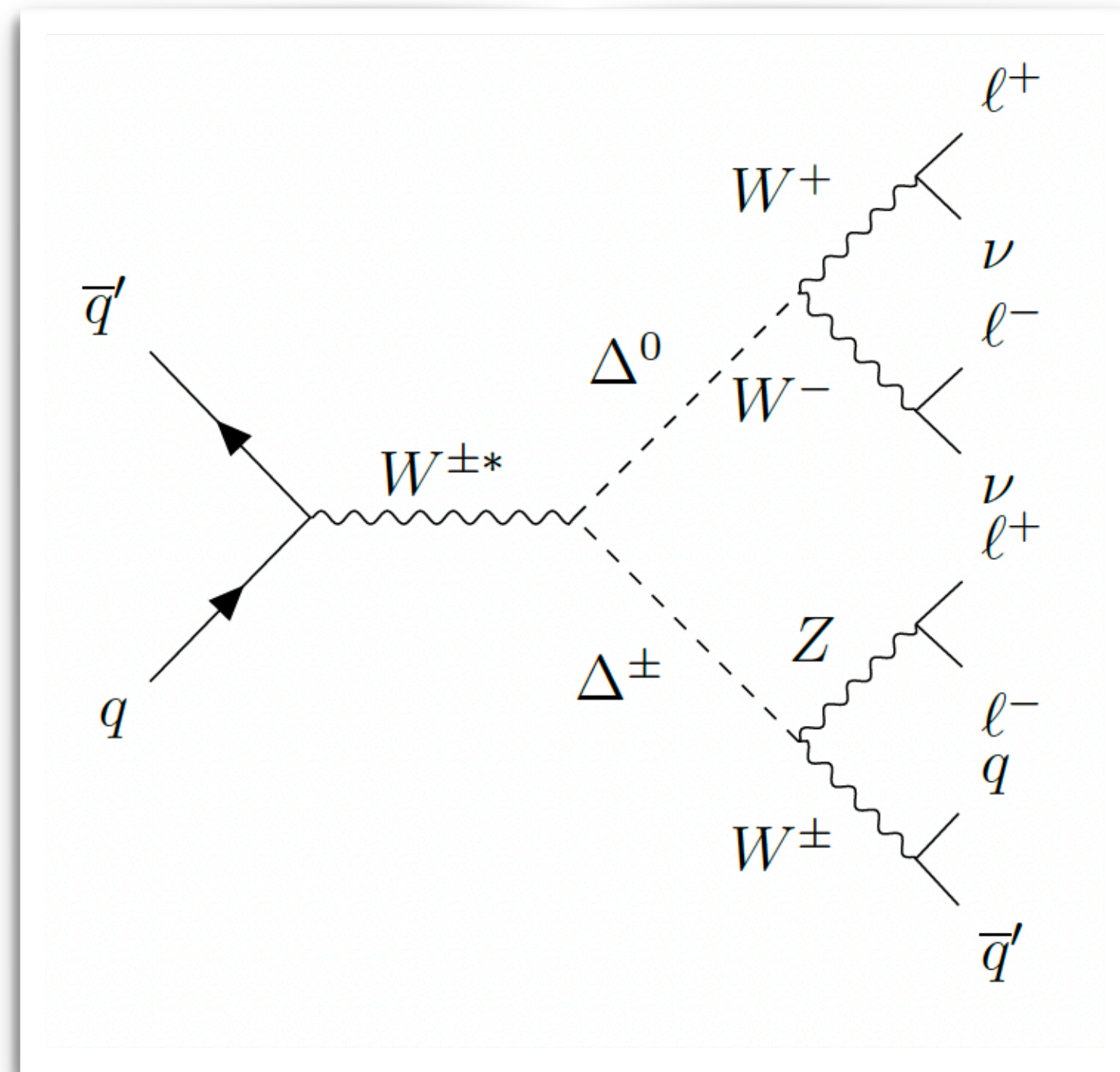


- $m_{\Delta^\pm} < 110$ GeV **excluded** at 95 % confidence level.

Explanation in Real Higgs Triplet

Model Constraints

- Triplet Higgs produces **multiple lepton final states** searched by ATLAS & CMS



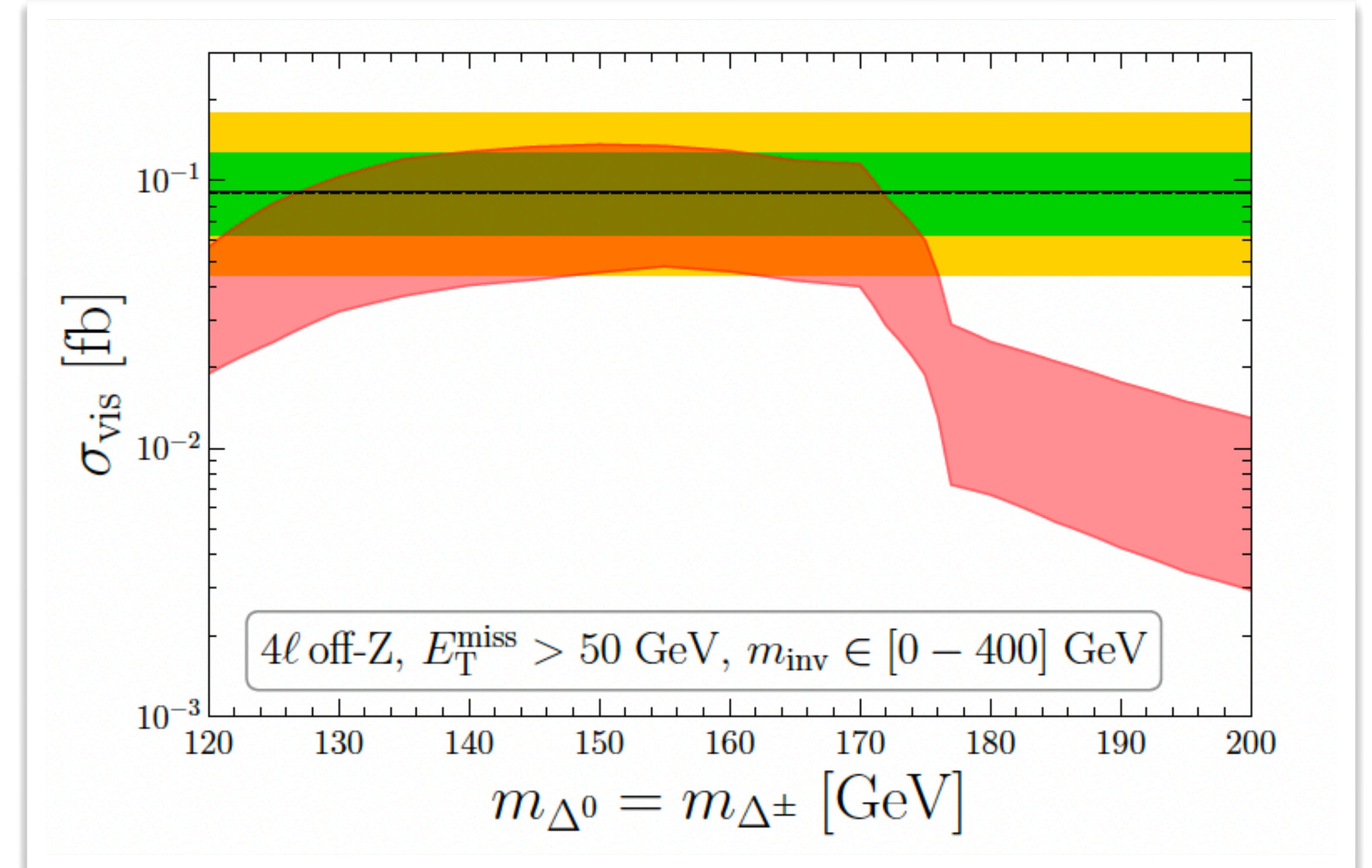
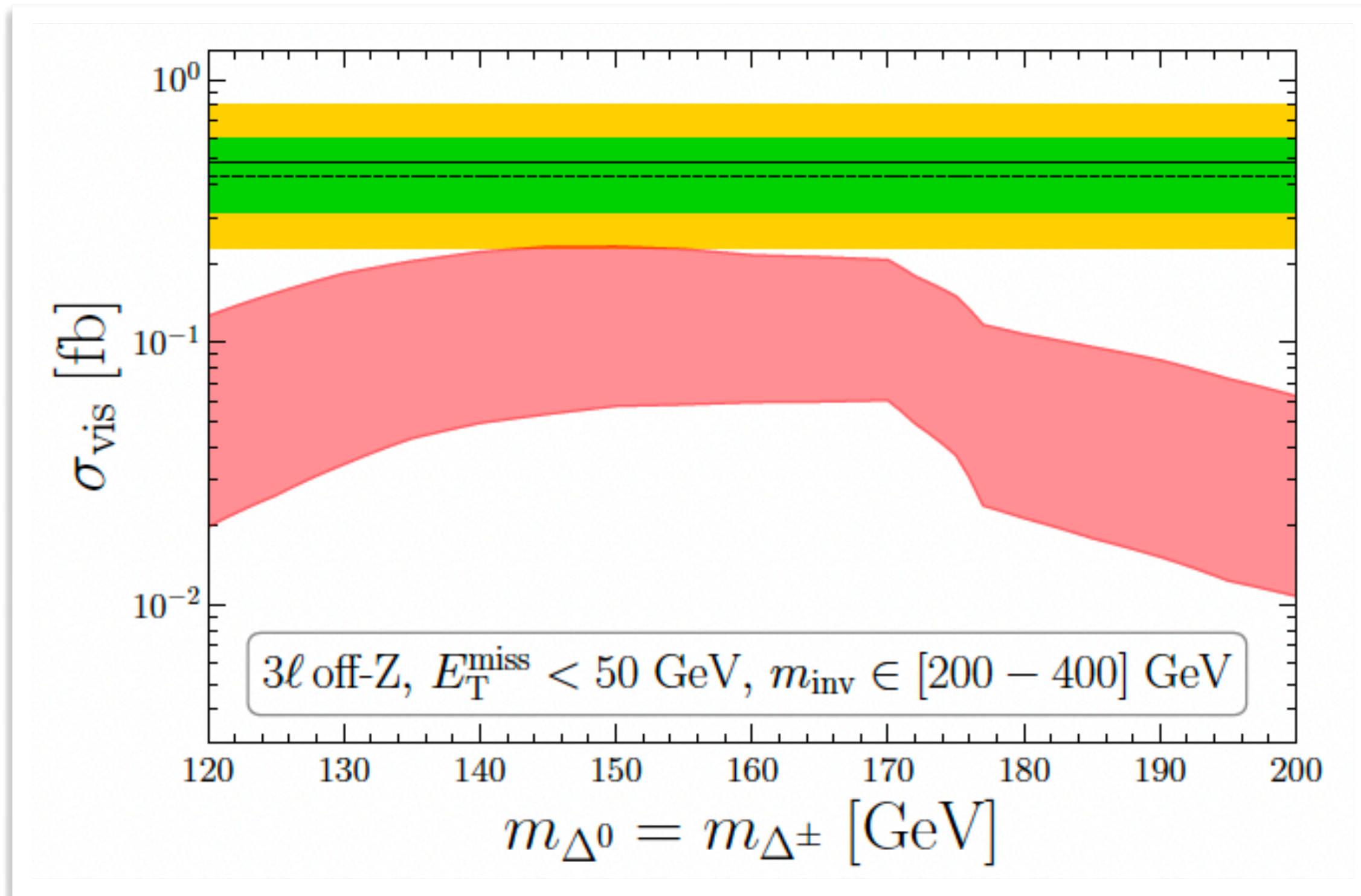
- ATLAS provides **upper limit** on visible cross-section for 22 SRs

[CMS: CERN-EP-EP-2021-063]

Explanation in Real Higgs Triplet

Model Constraints

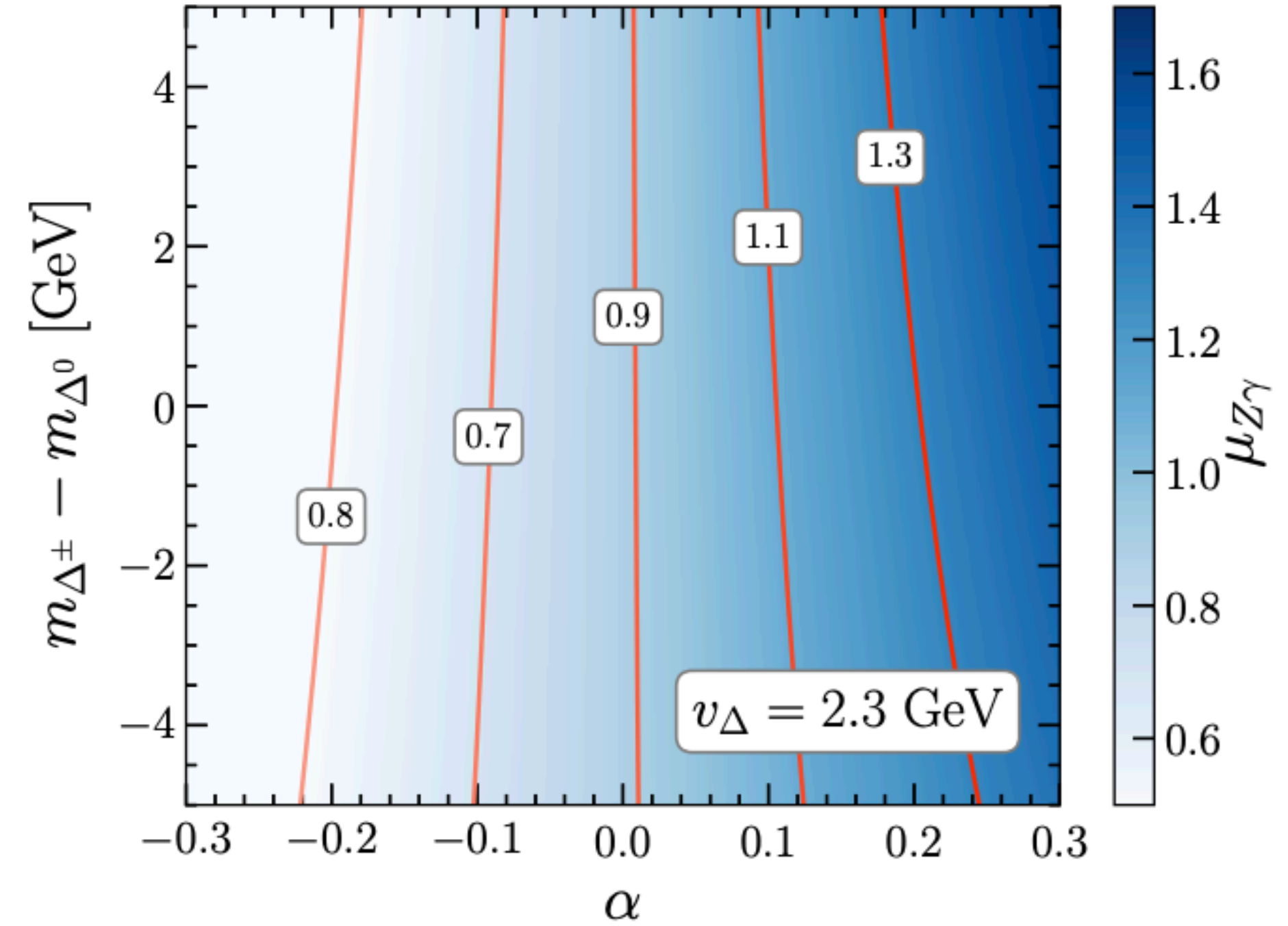
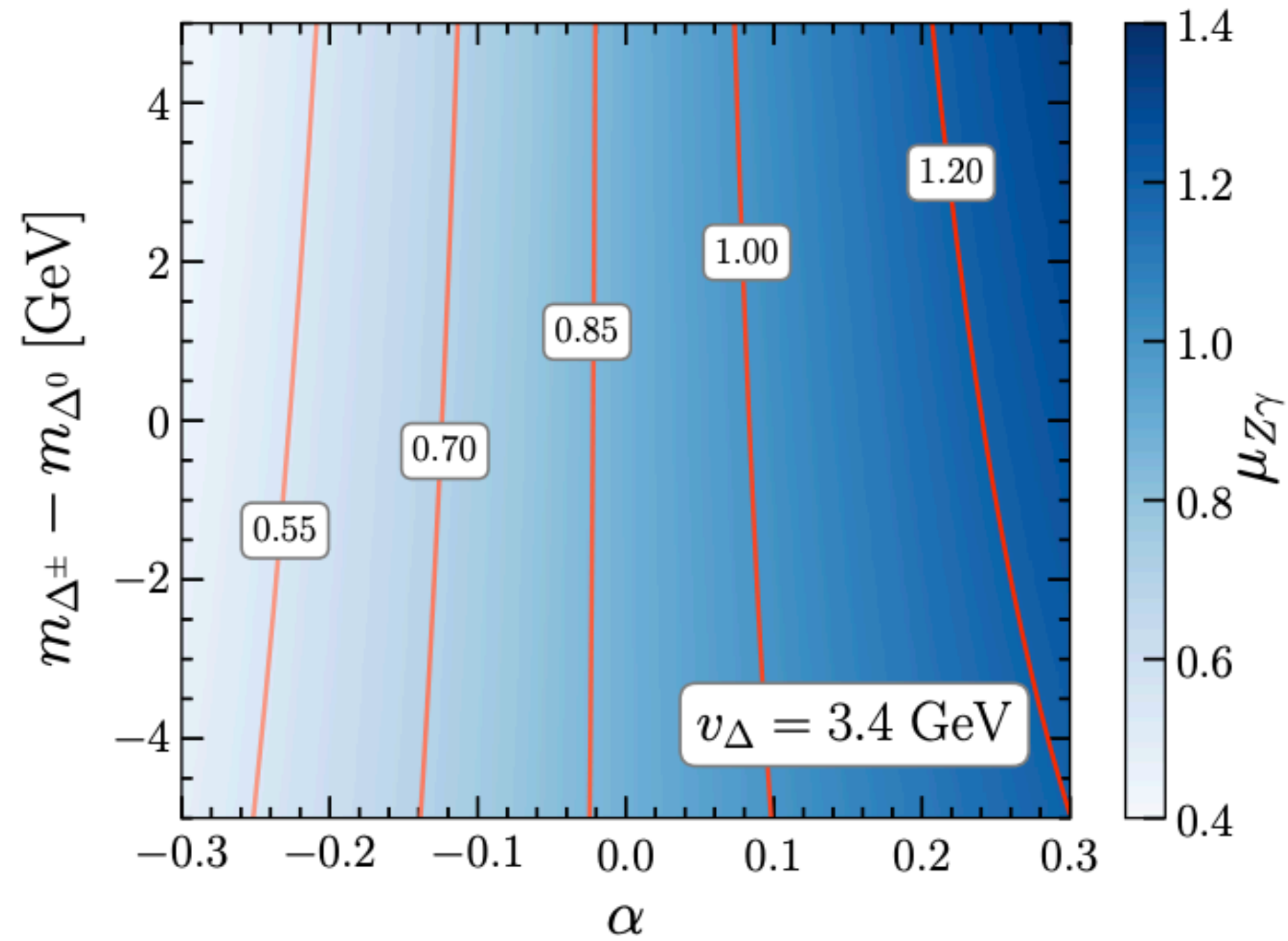
- Within 95 % CL upper limits of **ATLAS**



- Simulated $pp \rightarrow \Delta^0 \Delta^\pm$ and $pp \rightarrow \Delta^\mp \Delta^\pm$
- Upper band obtained for $\text{Br}(\Delta^0 \rightarrow WW) = 100\%$

Real Higgs Triplet

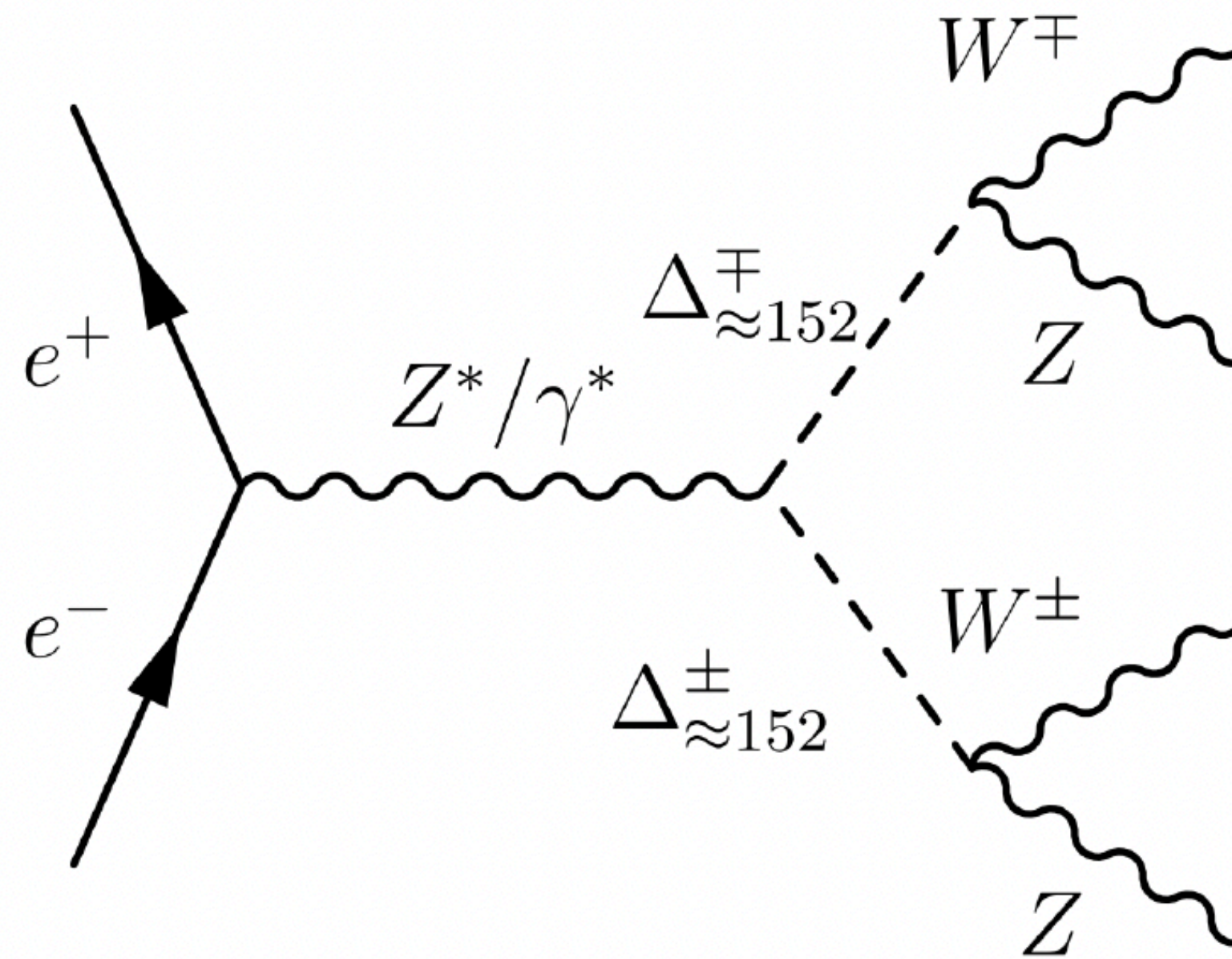
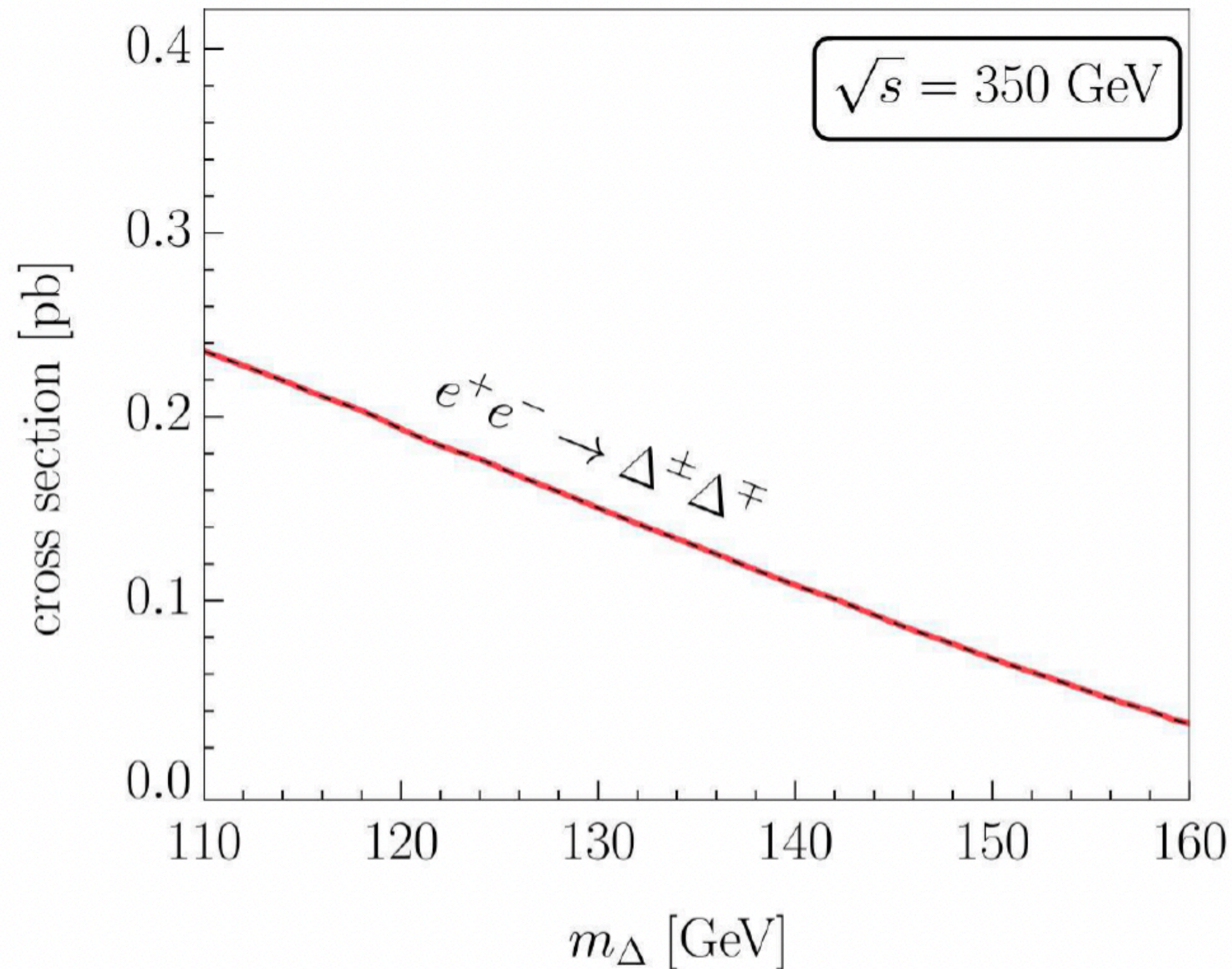
Z_γ



Real Higgs Triplet Prospects

FCC-ee

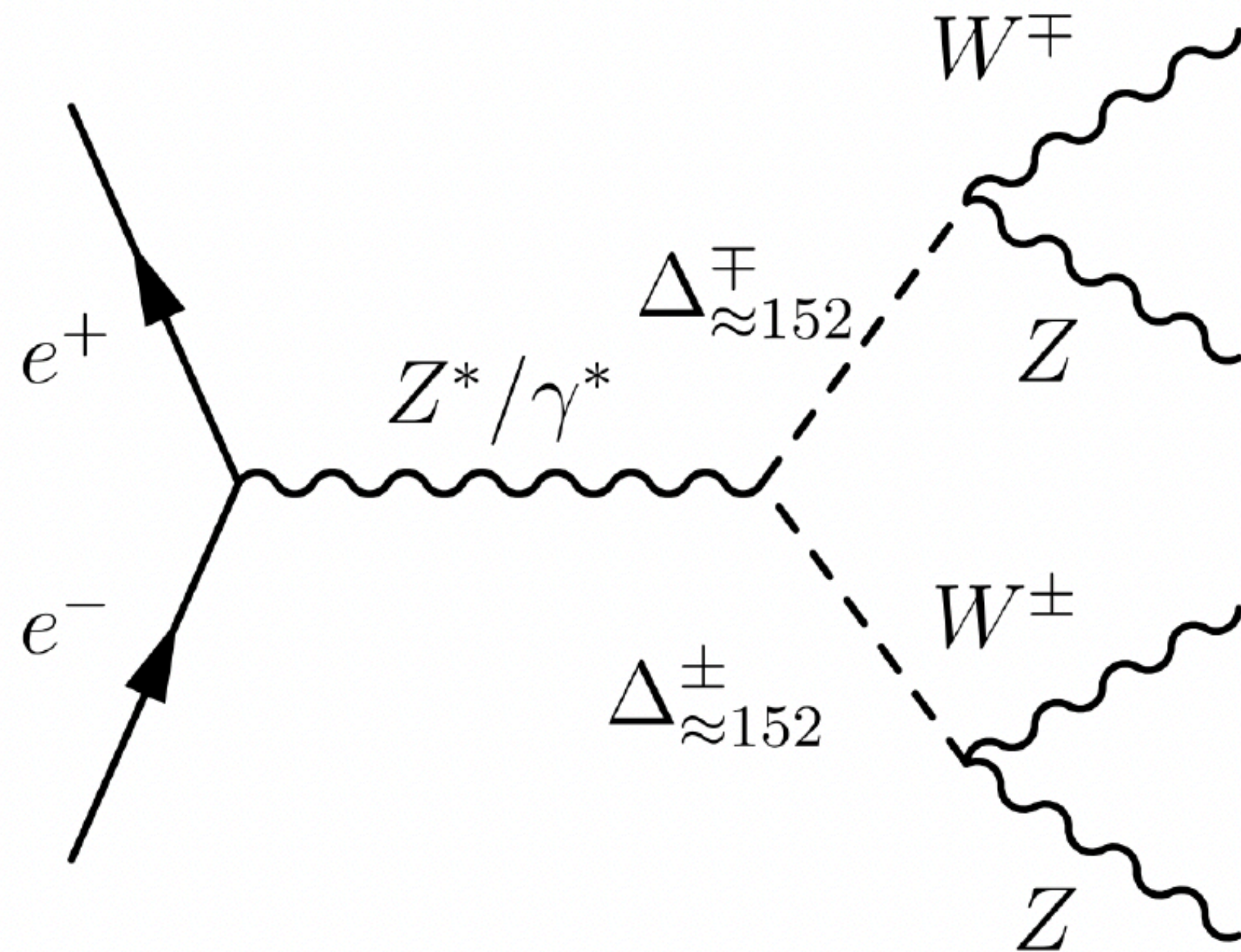
- Only Z^*/γ^* s-channel
- Suppressed $\Delta^0\Delta^0$ production for a real triplet
- Pair production of the charged components



Real Higgs Triplet Prospects

FCC-ee

- The decay $\Delta^\pm \rightarrow W^\pm Z$ leads to a $6\ell(+\text{MET})$ signature



Events expected in the Δ SM model

$$e^+e^- \rightarrow \Delta^\pm \Delta^\mp \rightarrow 6\ell + \text{MET} \approx 46$$

Events expected in the SM model

$$e^+e^- \rightarrow 6\ell(+\text{MET}) \approx 1$$

- Log-Likely-hood ratio yields $\chi^2 \approx 80$
- $\sigma(e^+e^- \rightarrow \Delta^\pm \Delta^\mp)$ could be measured at $\approx 9\sigma$

Explanation in 2HDM

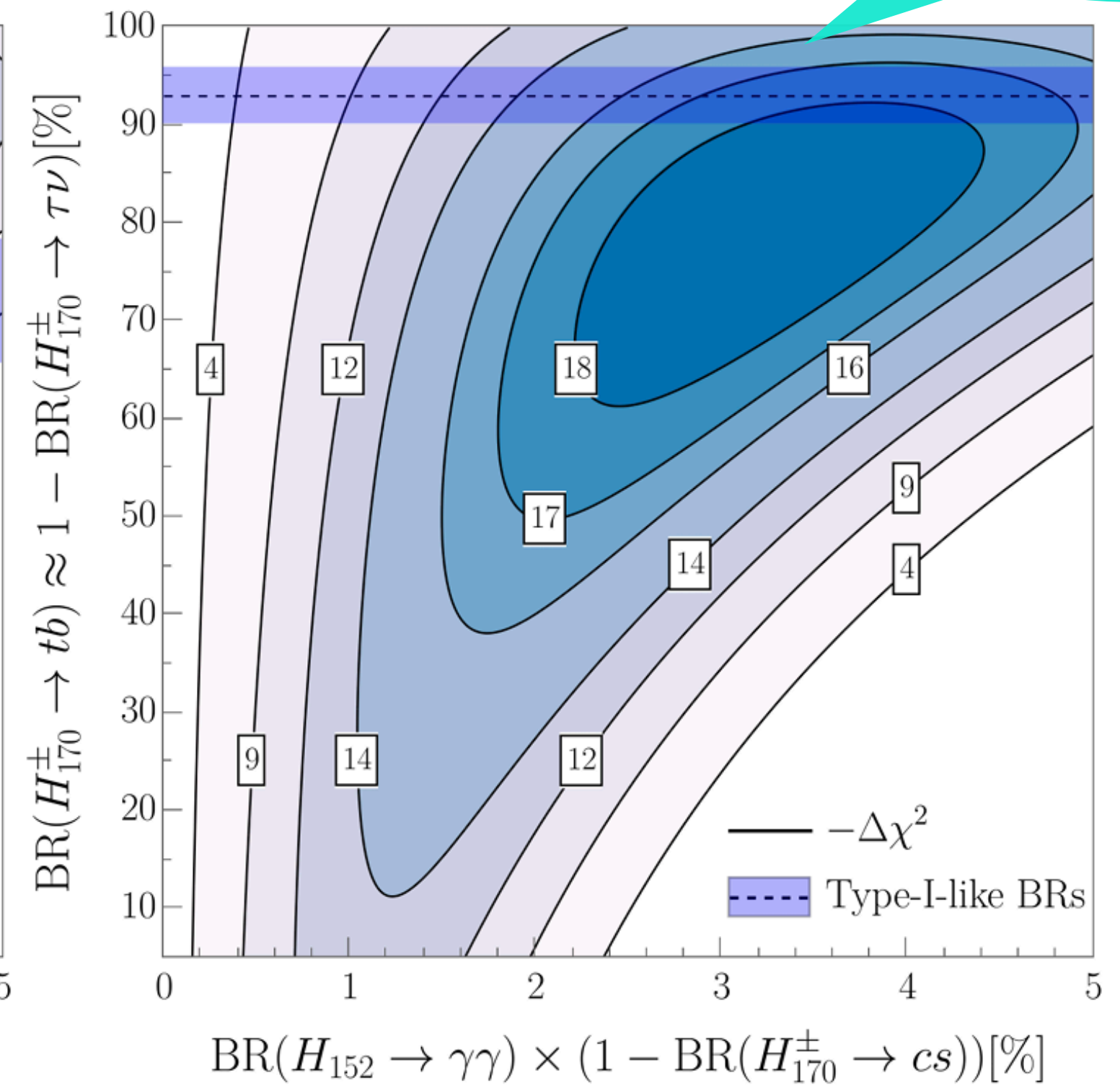
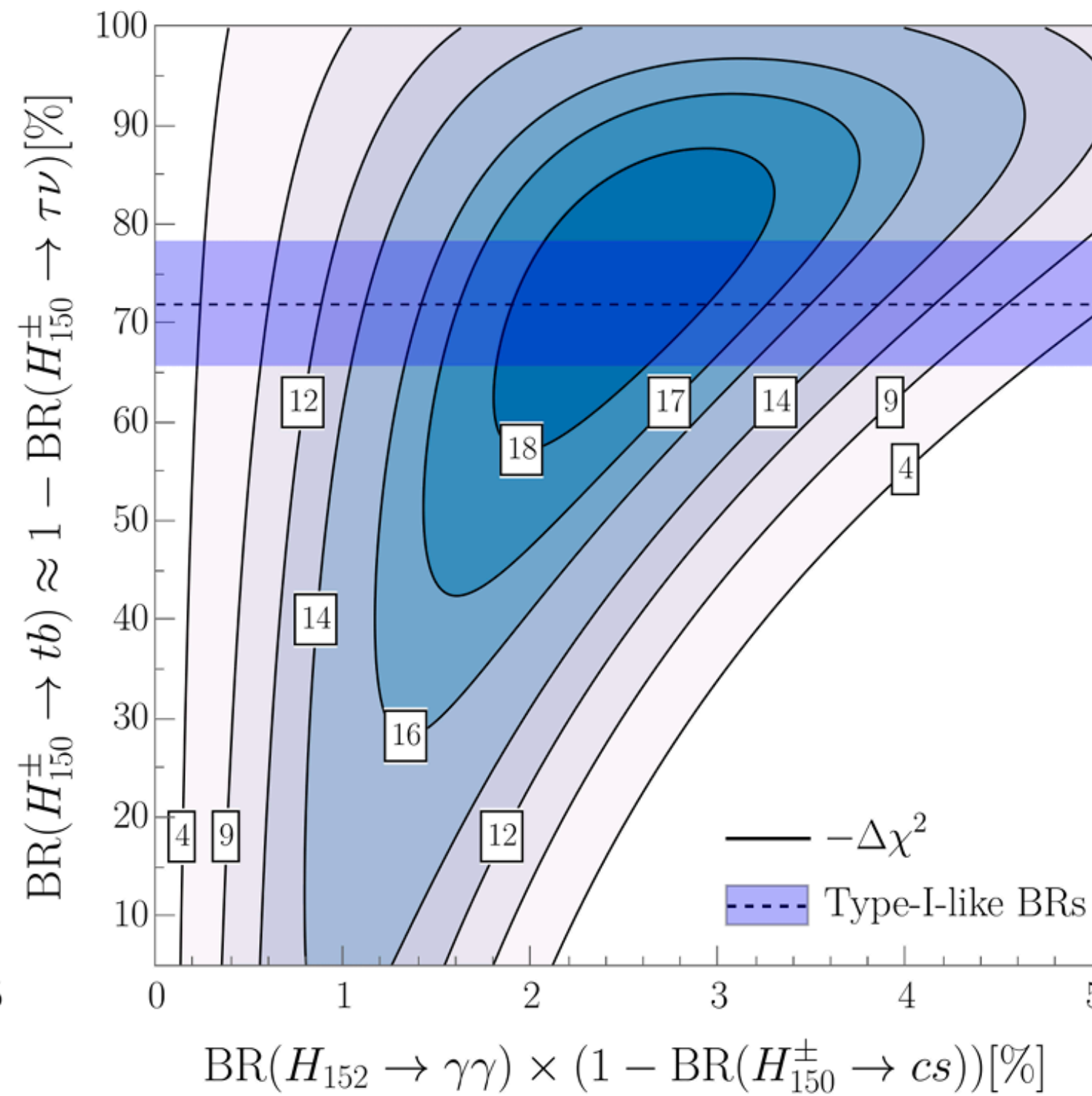
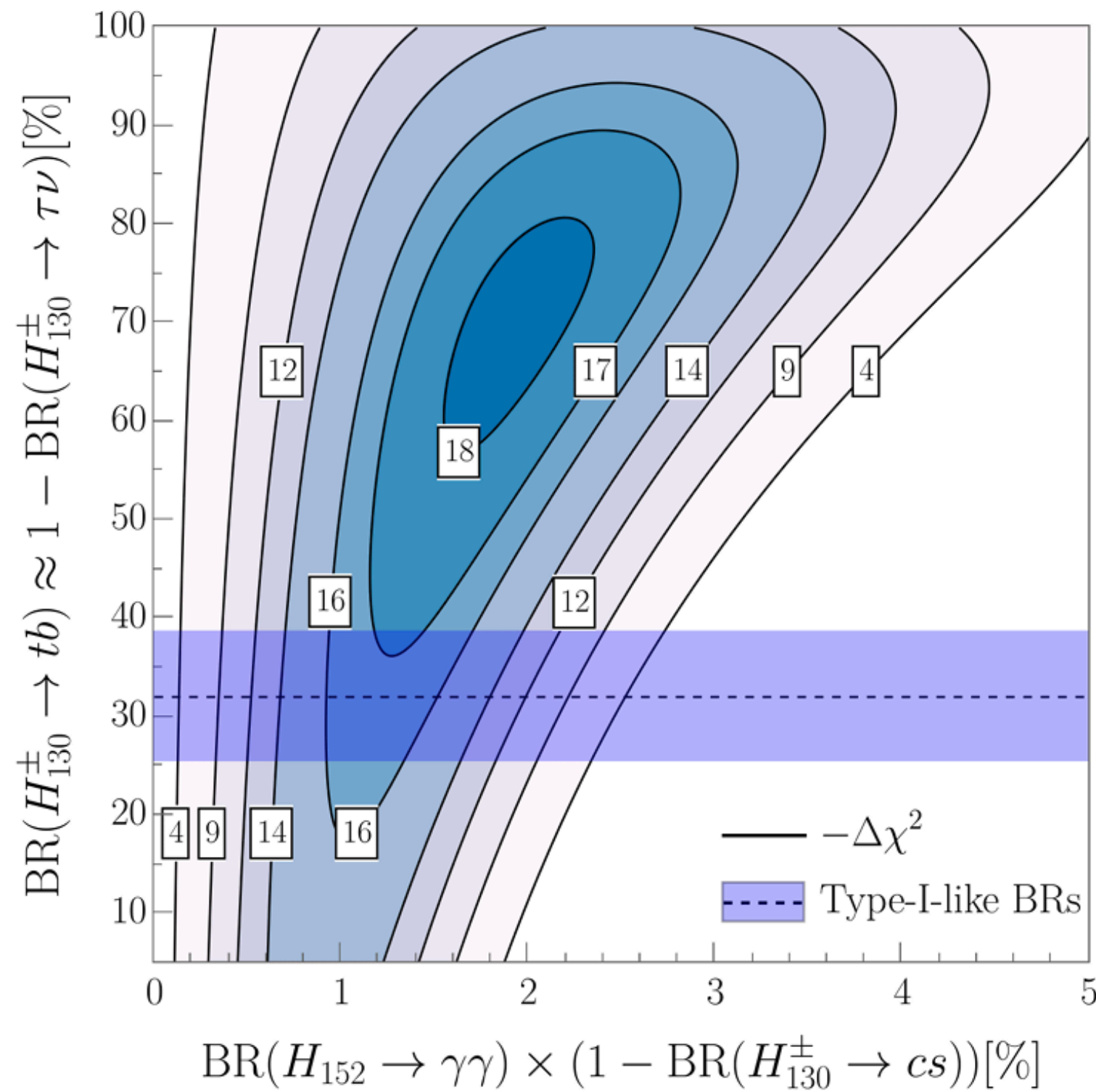
Type-I

○ Combined decay modes: $H^\pm \rightarrow tb$, $H^\pm \rightarrow \tau\nu$

$H^\pm \rightarrow W^\pm Z$
suppressed in
2HDM

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

$H^\pm \rightarrow cs$ has
small impact

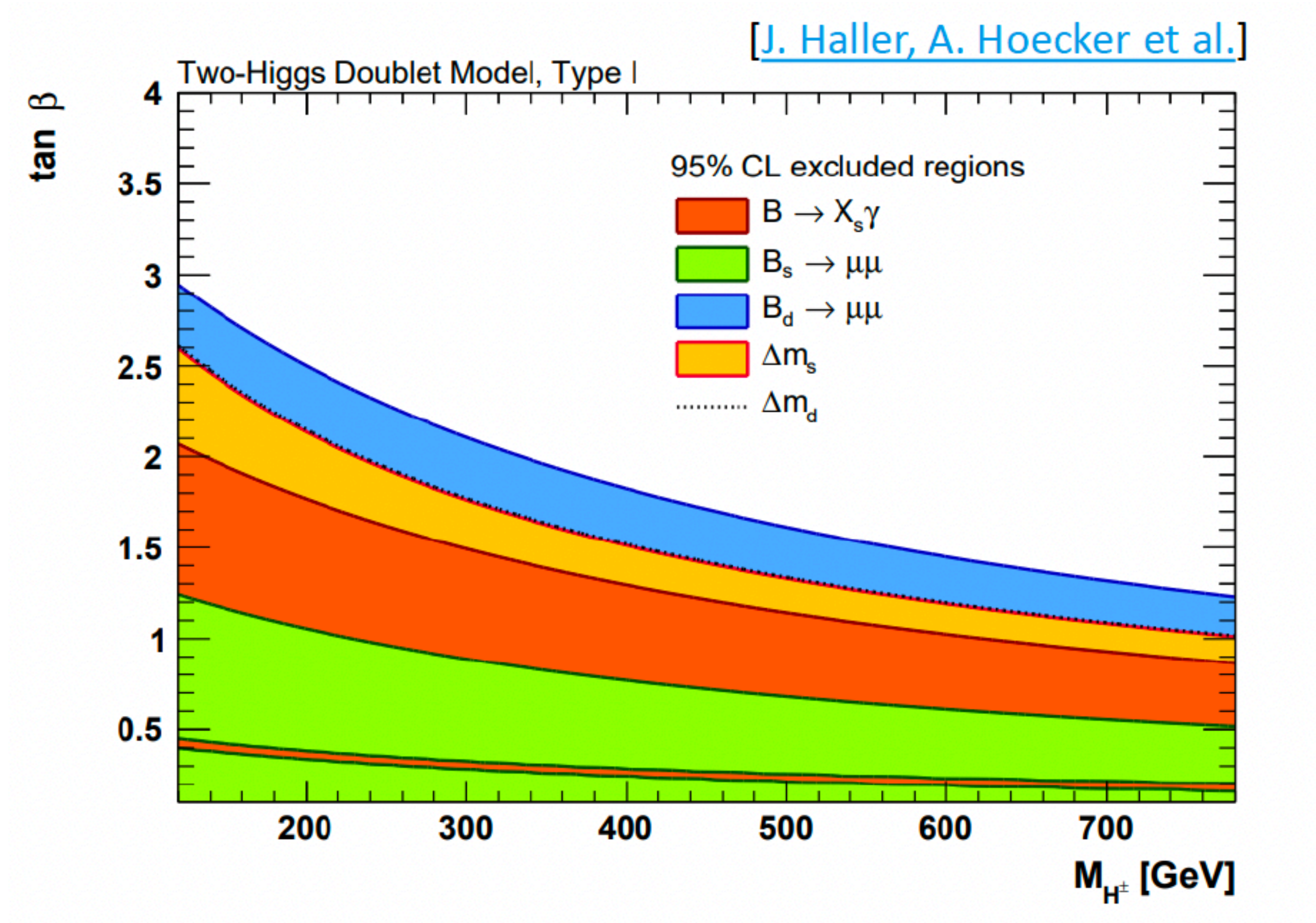


○ $BR(H \rightarrow \gamma\gamma)$ increases with m_{H^\pm}

Explanation in 2HDM

Explanation of $\gamma\gamma + X$ Excesses

- Bounds on $\tan(\beta)$



Explanation in Real Higgs Triplet

Model Description

○ Scalar Particles: h, Δ^0, Δ^\pm

No Yukawa couplings

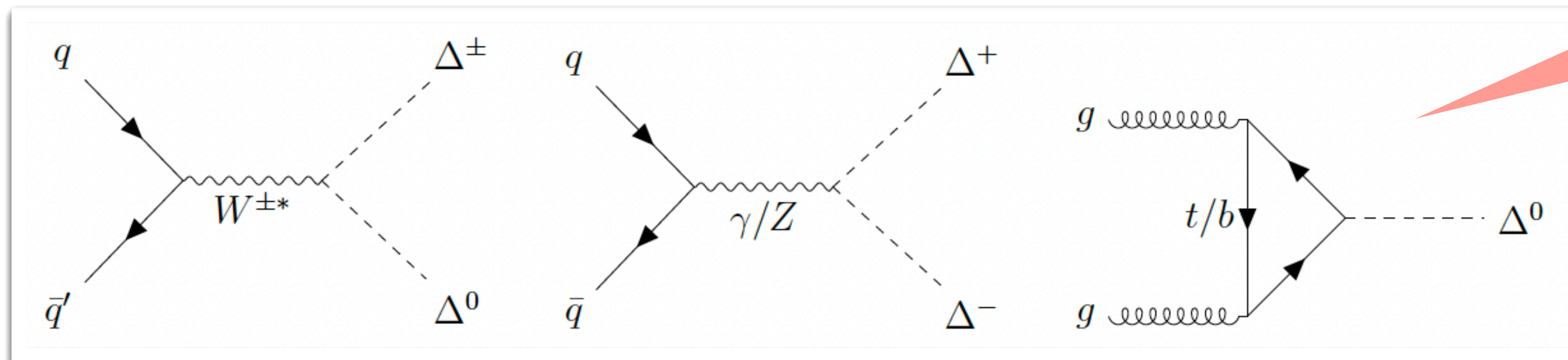
○ Physical Parameters: $m_h, m_{\Delta^0}, m_{\Delta^\pm}, v_\Delta, \alpha$

○ Theoretical constraints require $m_{\Delta^0} \approx m_{\Delta^\pm}$

$m_h = 125 \text{ GeV}, v_\Delta = 3.4 \text{ GeV}$

○ Triplet Higgs production channels at LHC

Suppressed by mixing

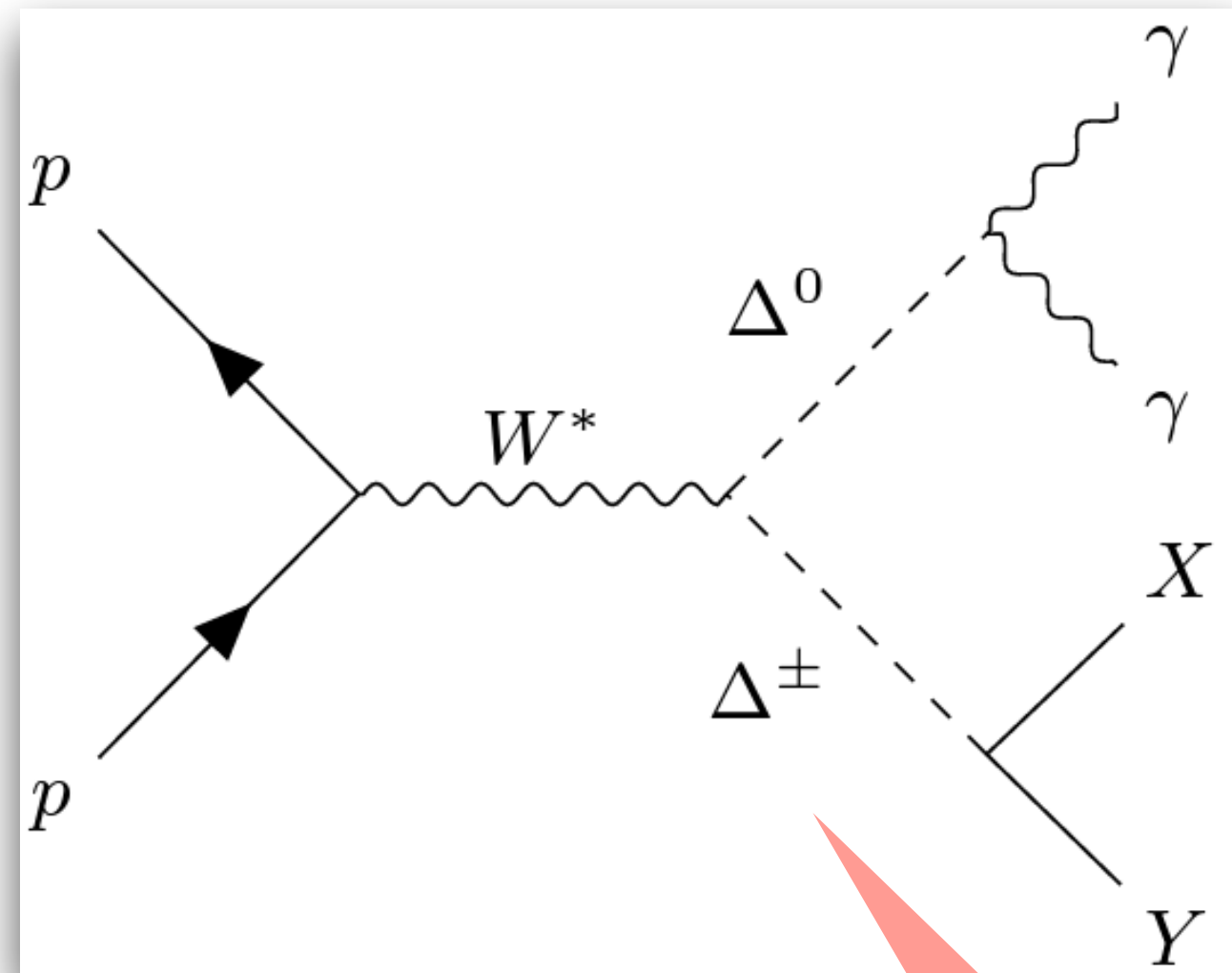


Explanation in Real Higgs Triplet

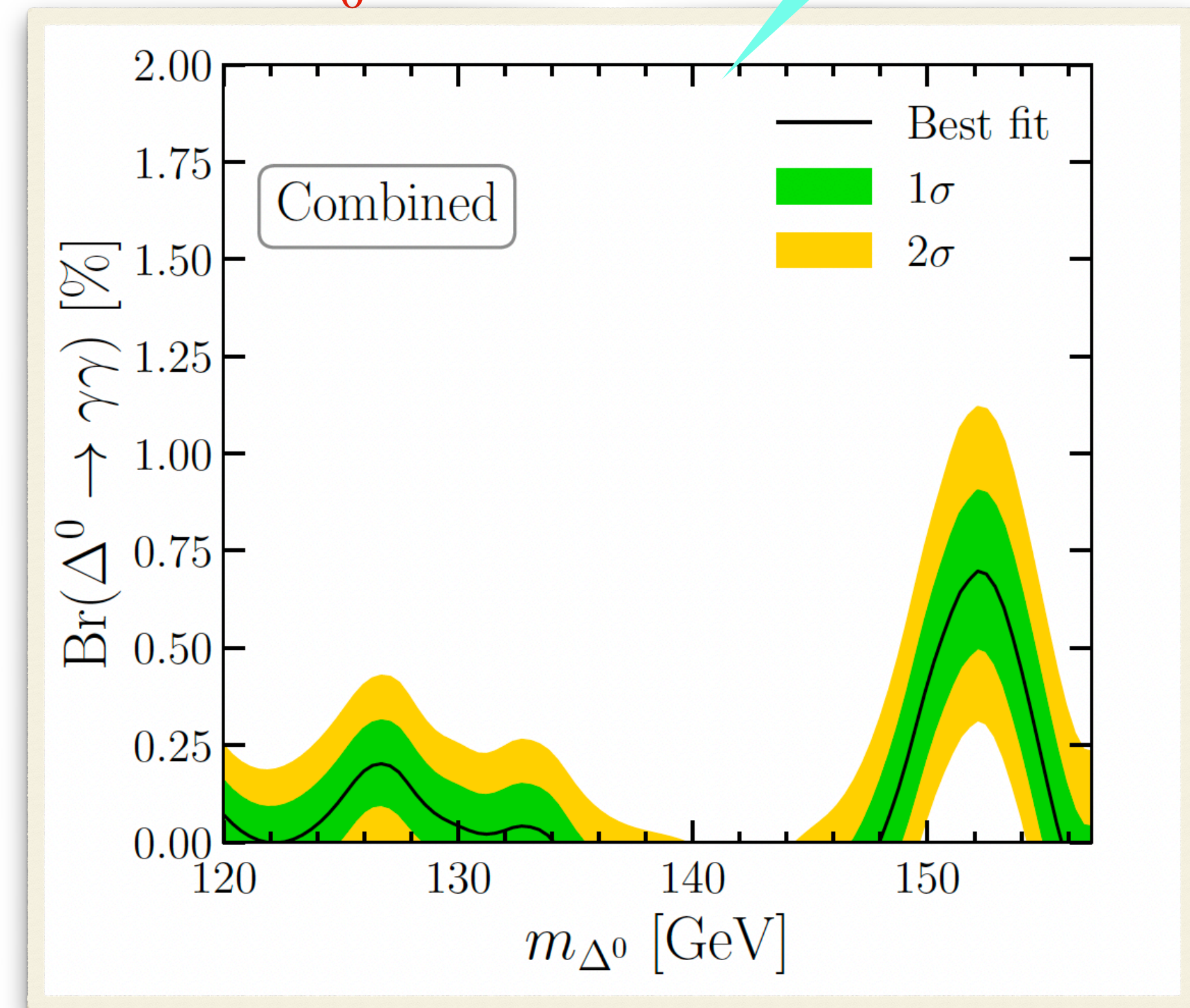
Explanation of $\gamma\gamma + X$ Excesses

- Model generated using **SARAH**
- Free Variables: m_{Δ_0} , $\text{Br}(\Delta_0 \rightarrow \gamma\gamma)$ instead of m_{Δ_0} , α

(S. Ashanujaman, SB et al.)
[2404.14492]



Process Simulated

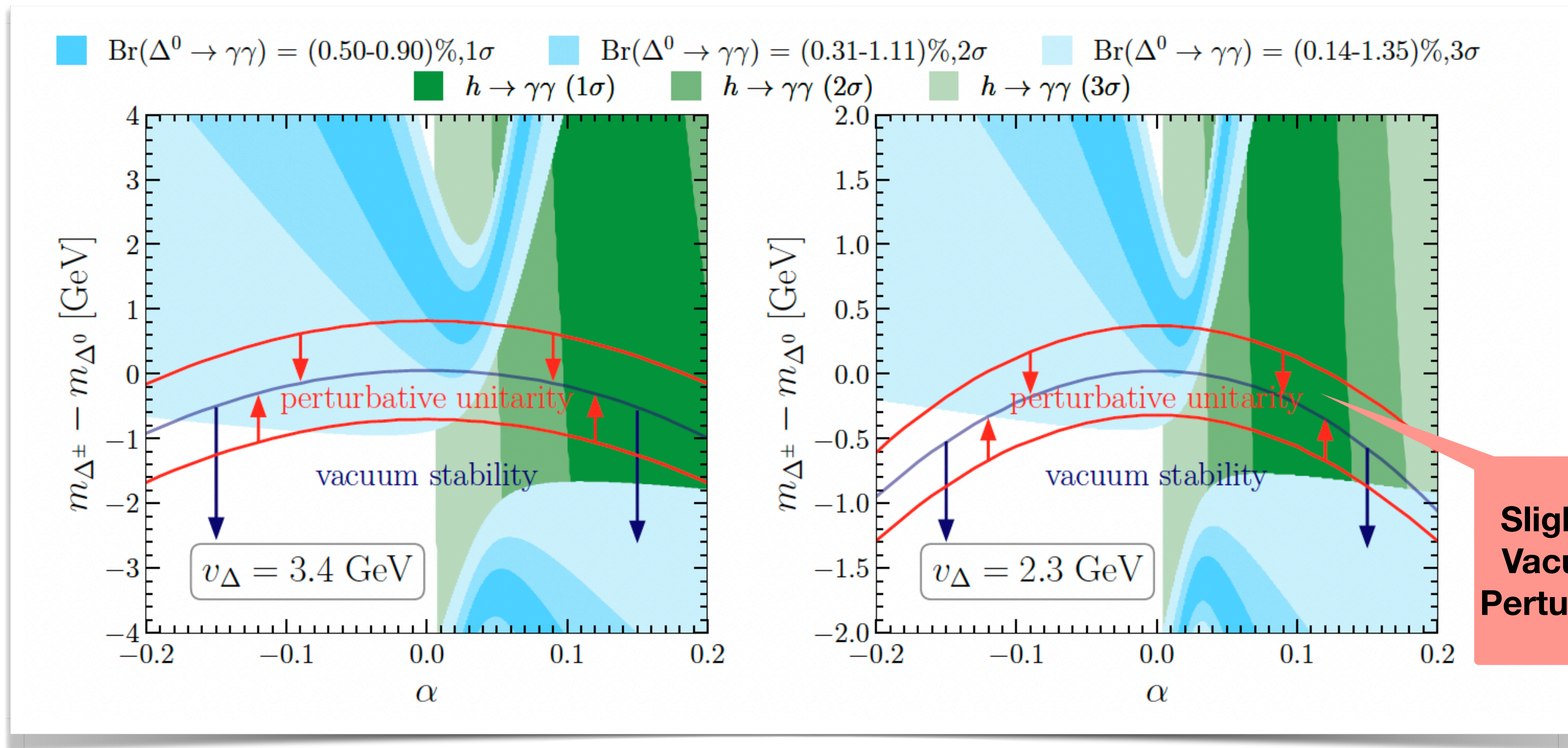


$\text{Br}(\Delta_0 \rightarrow \gamma\gamma) \approx 0.7\%$ at ≈ 151 GeV (3.9σ)

Explanation in Real Higgs Triplet

Explanation of $\gamma\gamma + X$ Excesses

- $\text{BR}(\Delta^0 \rightarrow \gamma\gamma)$ compatible with SM Higgs signal strength to $\gamma\gamma$



Explanation in 2HDM

FCNC & CP-Violation

- General 2HDM may lead to FCNC at tree-level
- Avoided in flavour aligned 2HDM

$$Y = -\bar{Q}_L Y_d (\phi_2 + \zeta_d \phi_1) d_R - \bar{Q}_L Y_u (\phi_2^c + \zeta_u^* \phi_1^c) u_R - \bar{L}_L Y_l (\phi_2 + \zeta_l \phi_1) e_R$$

- Complex parameters leads to CP-violation

Yukawa Sector: $\zeta_u, \zeta_d, \zeta_l$

Higgs Sector: $\lambda_5, \lambda_6, \lambda_7$

We take them
real

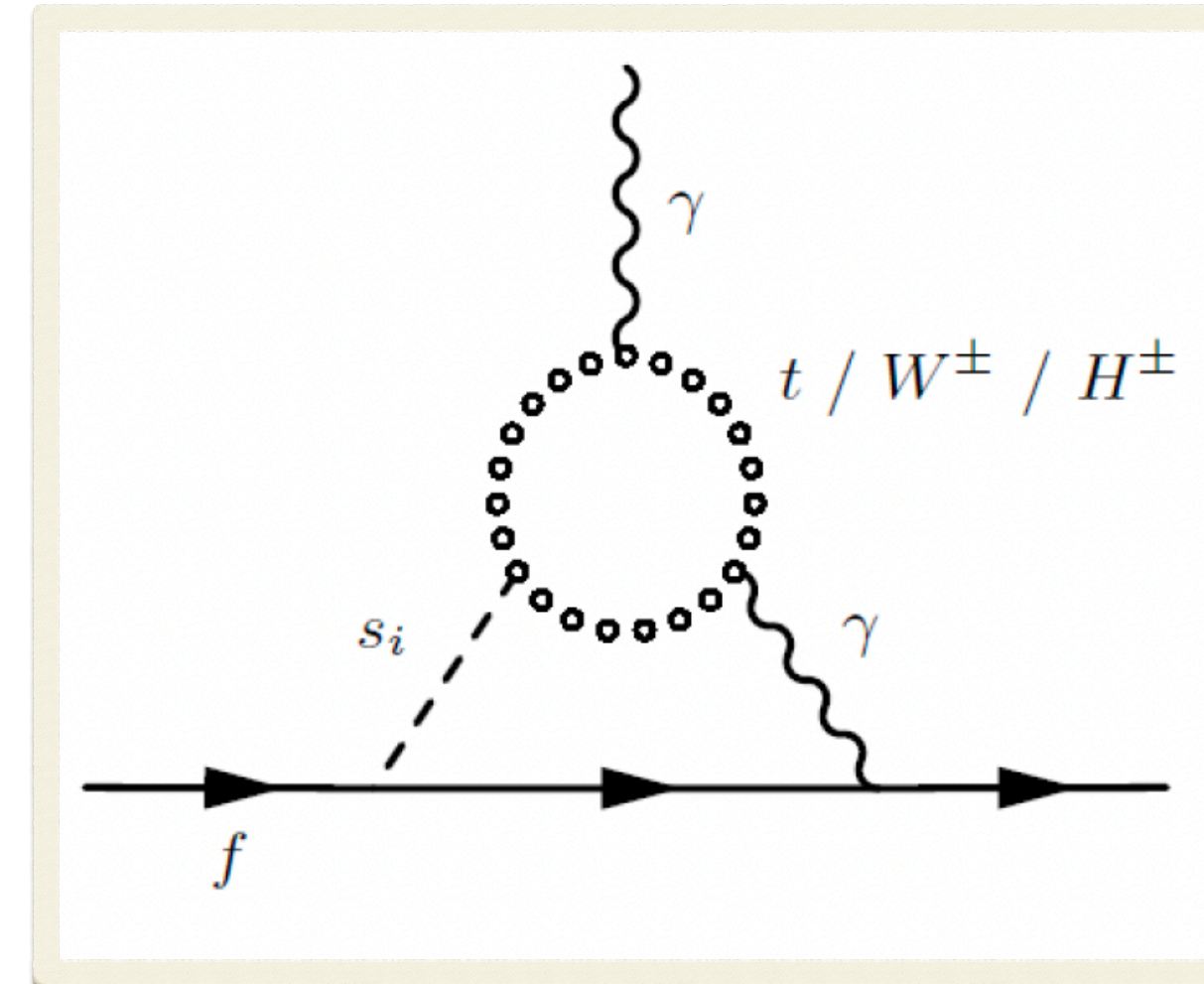
Explanation in 2HDM

EDM Constraints

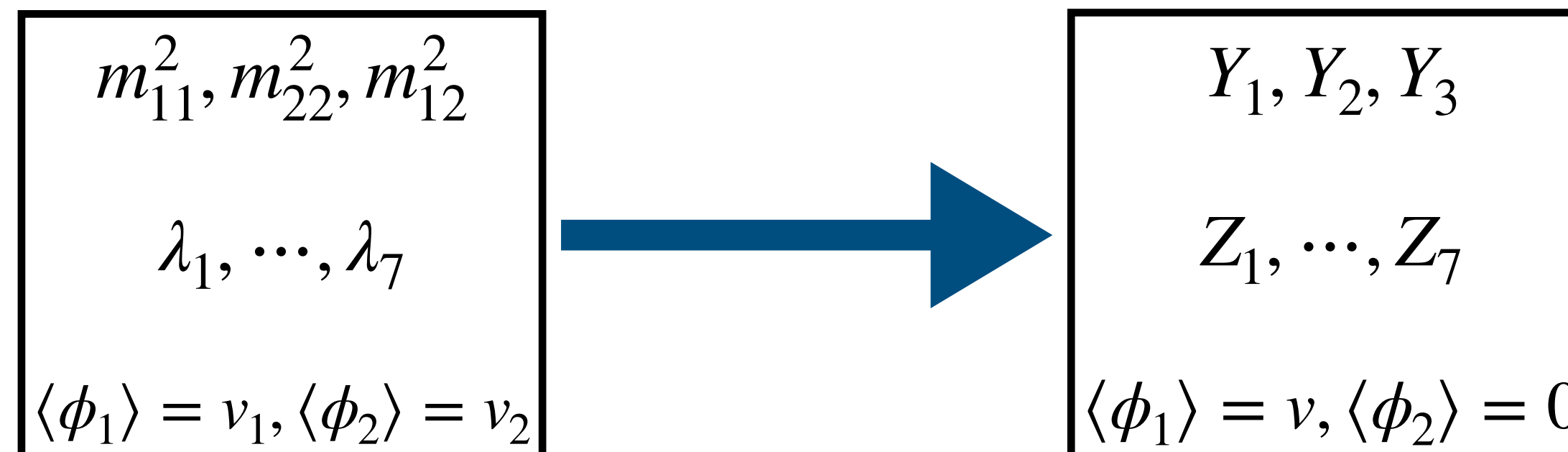
○ $\text{Im}(\lambda_6)$ drives $\text{Br}(A \rightarrow \gamma\gamma)$

○ Correlate with EDM constraints

○ Transform Lagrangian to Higgs Basis



$$\supset id_f \bar{u} \sigma^{\mu\nu} q_\nu \gamma_5 u$$



○ Used analytic expressions of [\[arXiv: 2009.01258\]](#)

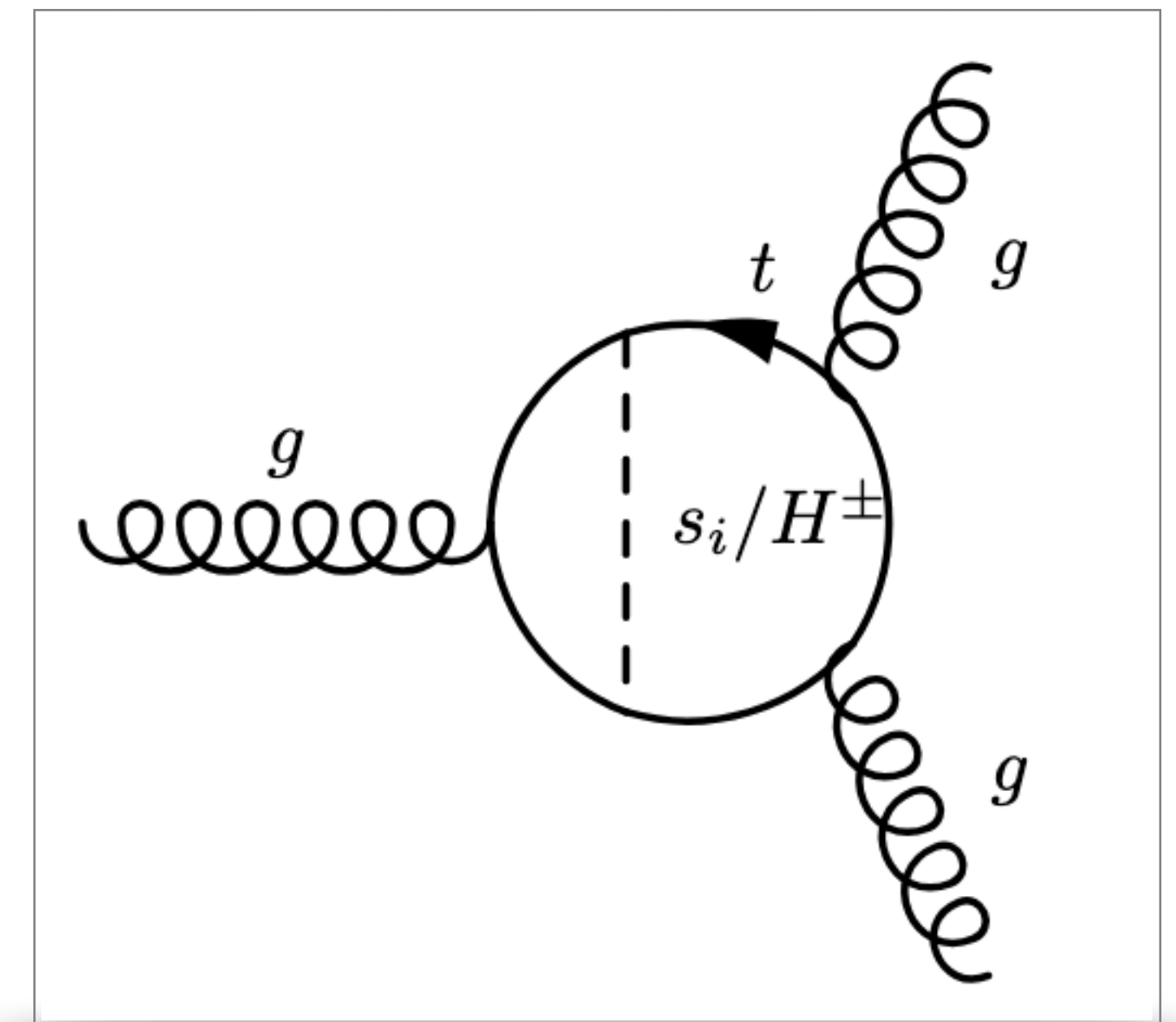
Explanation in 2HDM

nEDM

- nEDM is expressed as

$$d_n = - (0.20 \pm 0.01)d_u + (0.78 \pm 0.03)d_d - (0.55 \pm 0.28)e\tilde{d}_u \\ - (1.1 \pm 0.55)e\tilde{d}_d + (50 \pm 40) \text{ MeV } e\tilde{d}_G$$

- d_q is the quark EDM and \tilde{d}_q is the chromo EDM
- d_G contribution from **Weinberg** operator



General 2HDM

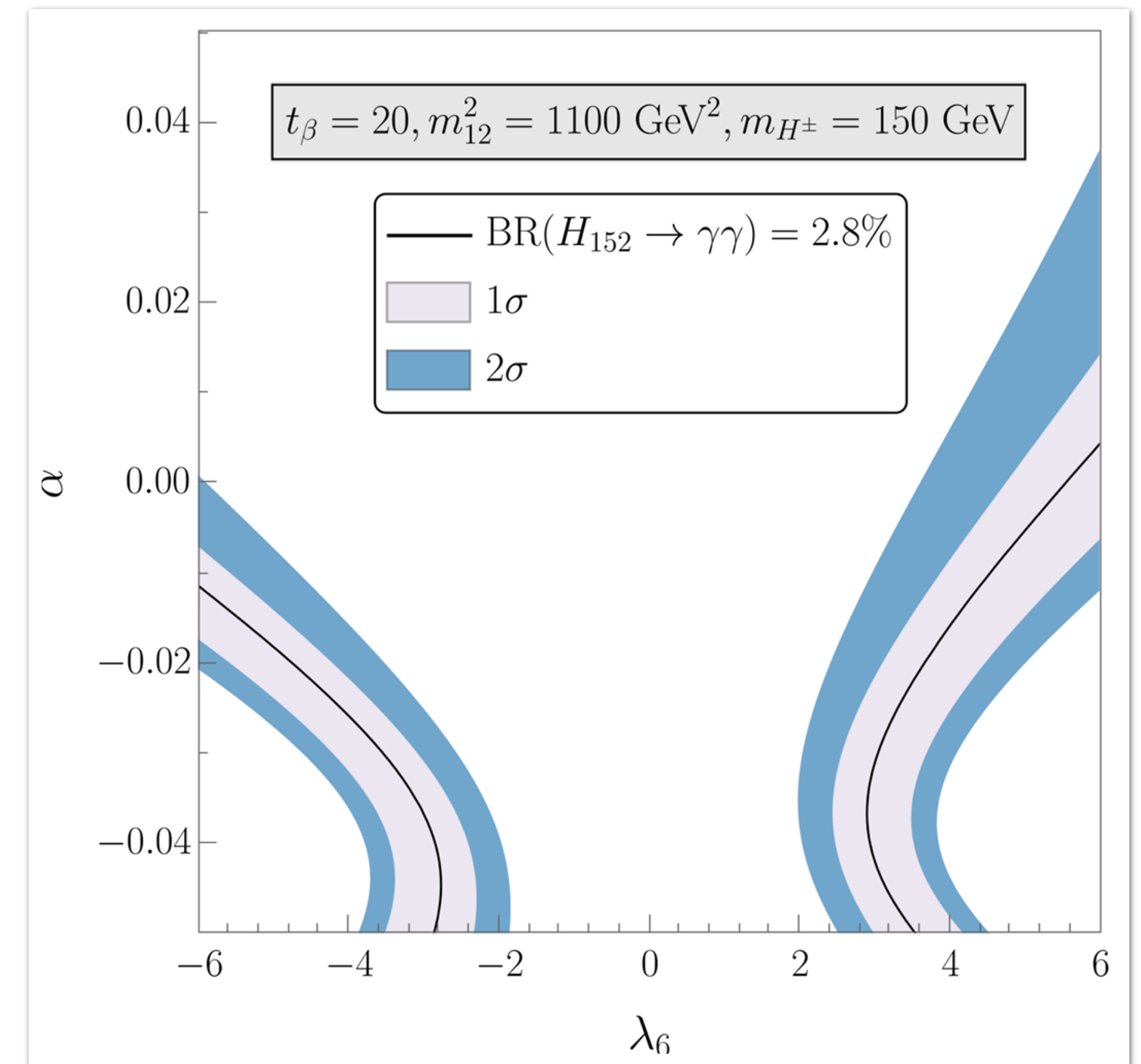
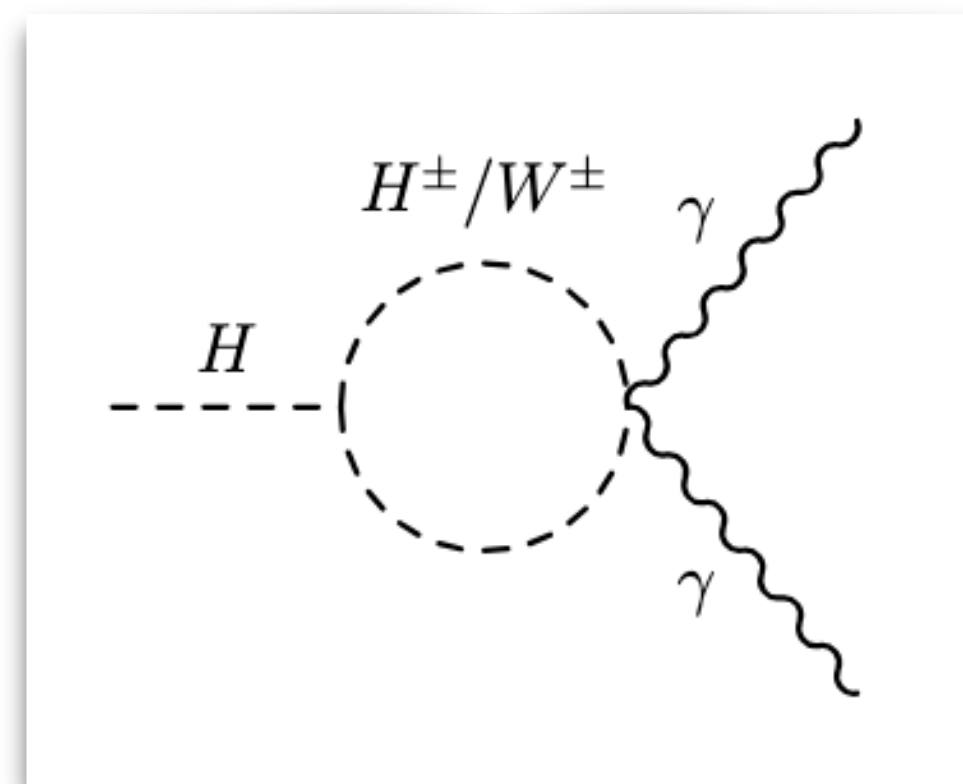
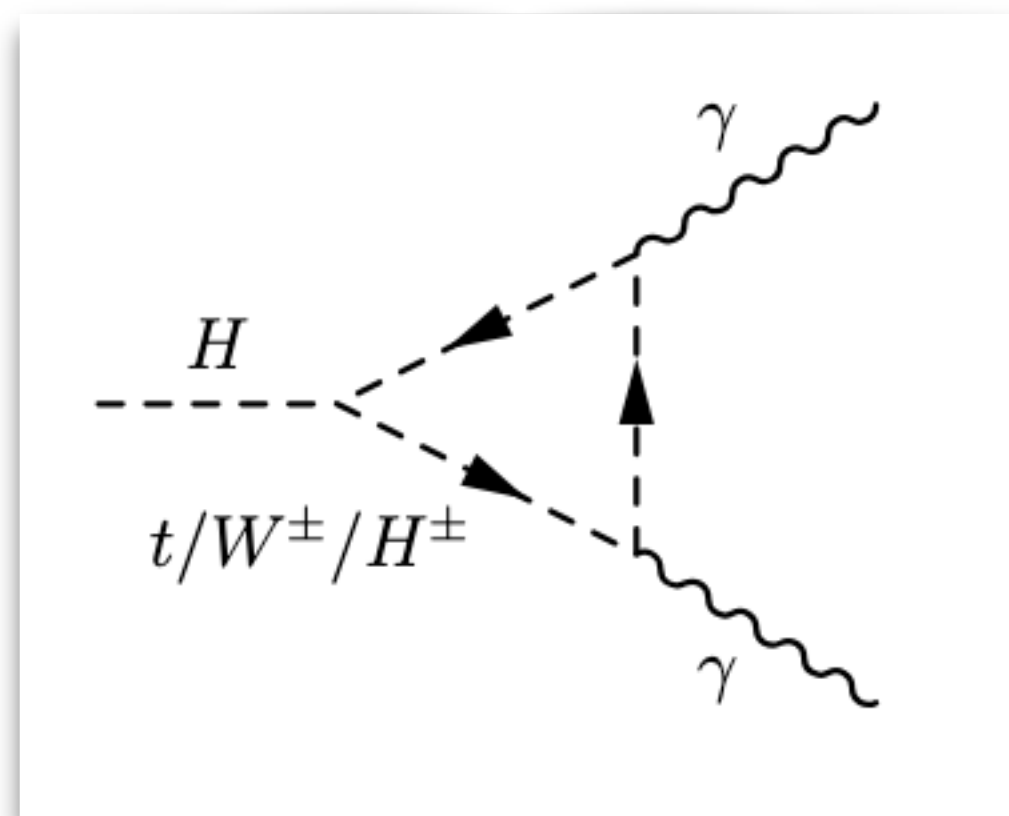
Large $H \rightarrow \gamma\gamma$

- Large $\text{Br}(H \rightarrow \gamma\gamma)$ possible in **general 2HDM**

Z_2 symmetry broken

$$\mathcal{L} \in -\lambda_6 H_1^\dagger H_1 H_2^\dagger H_2 + \text{h.c.}, \dots$$

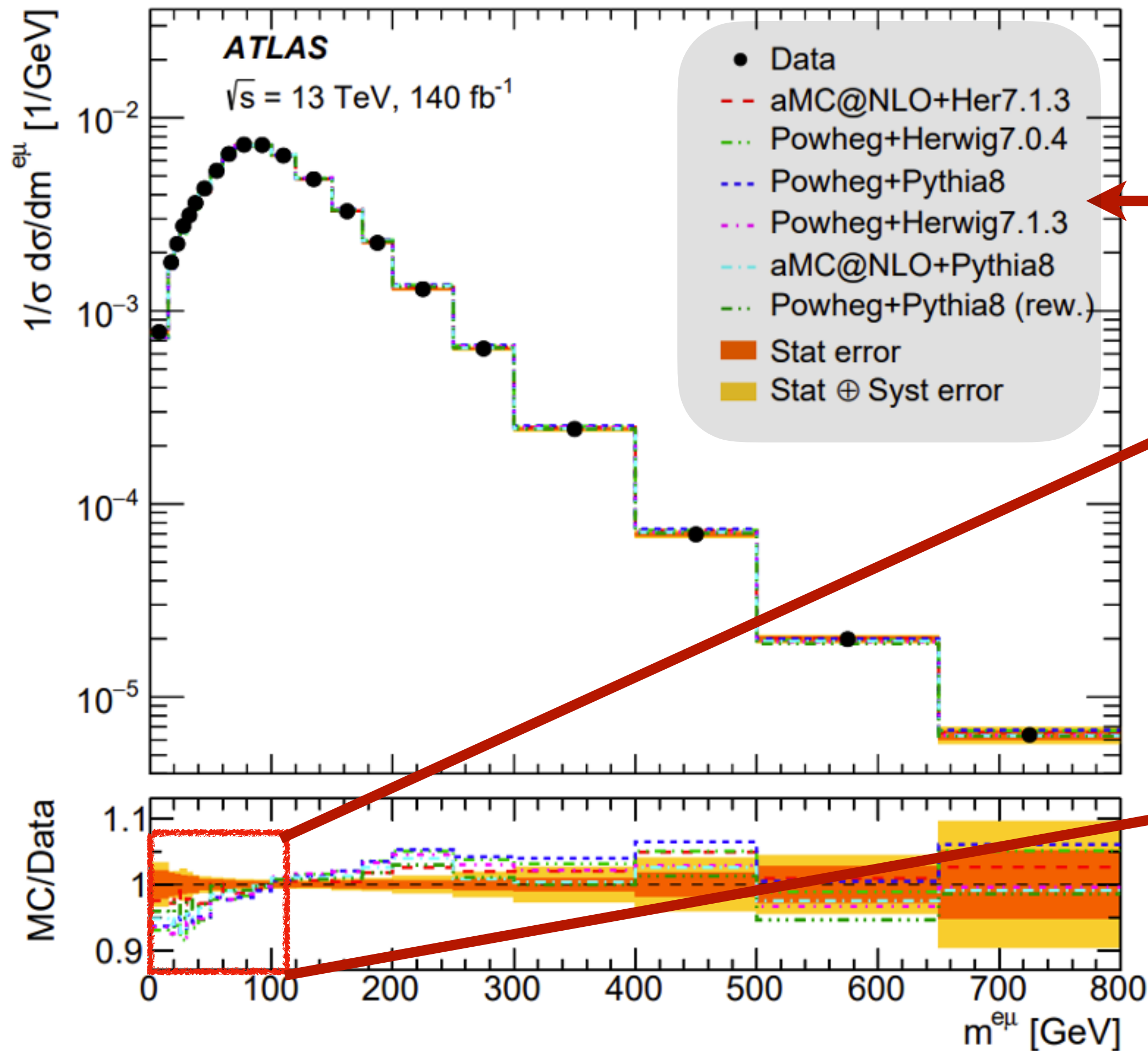
- Modifies the $HH^\pm H^\mp$ vertex
- **Enhanced** $\text{Br}(H \rightarrow \gamma\gamma)$ via H^\pm loop



Deviations in $t\bar{t}$ Differential cross-section

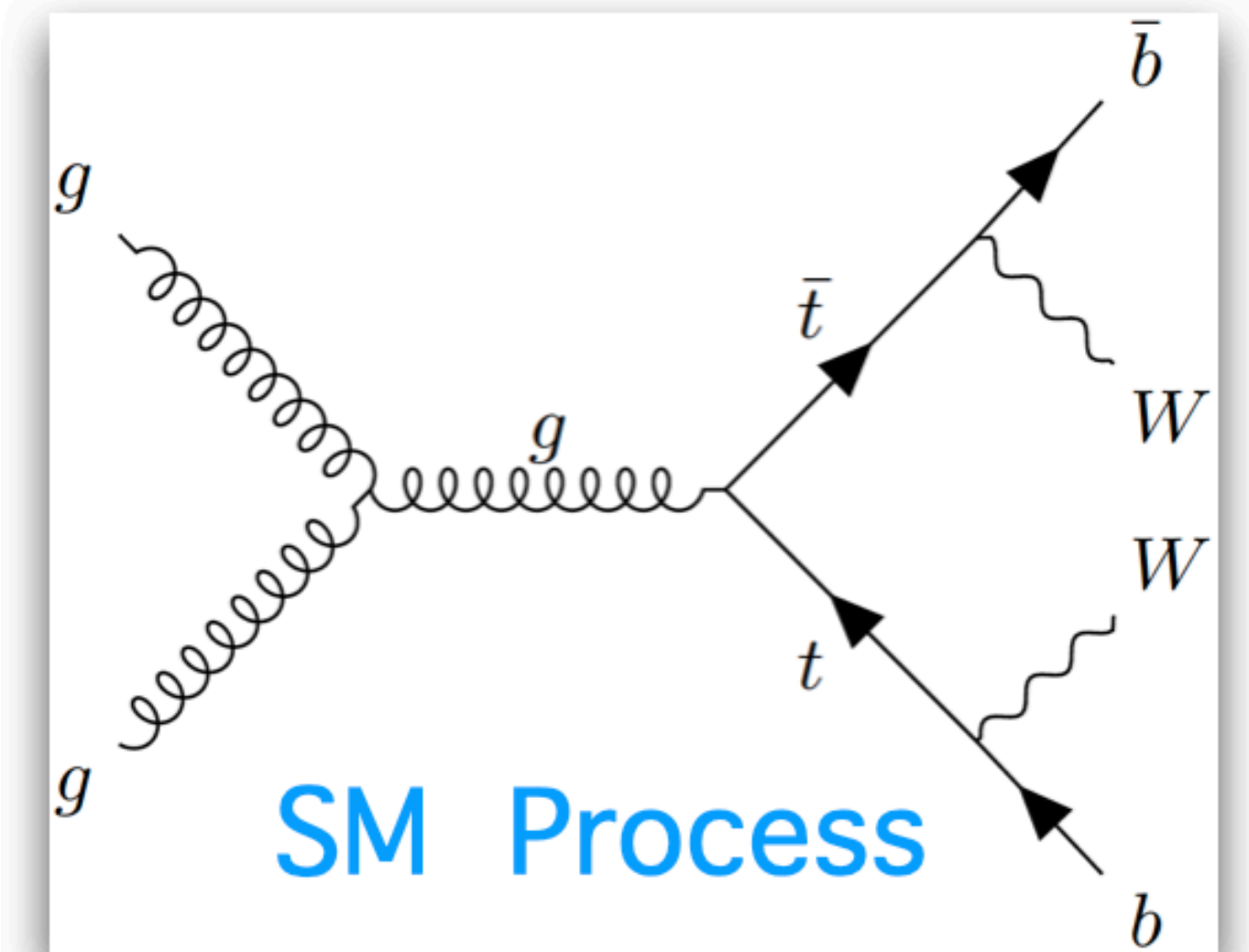
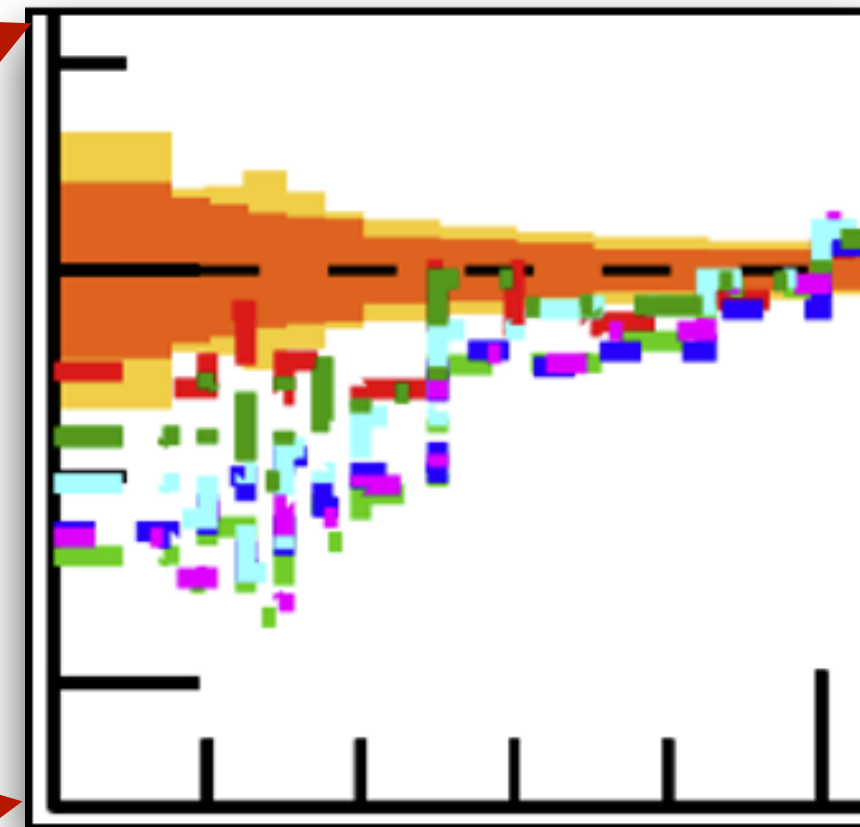
No match with SM

[ATLAS: CERN-EP-2023-016]



[ATLAS: CERN-EP-2023-016]

The precision of the measurements is typically 2% for the absolute differential cross-sections and at the 1% level for the normalised differential cross-sections, except in the highest energy bins where the $t\bar{t}/Wt$ interference uncertainty contribution increases. The measurements are compared with a wide range of models for $t\bar{t}$ production in pp collisions. No model can describe all measured distributions within their uncertainties.

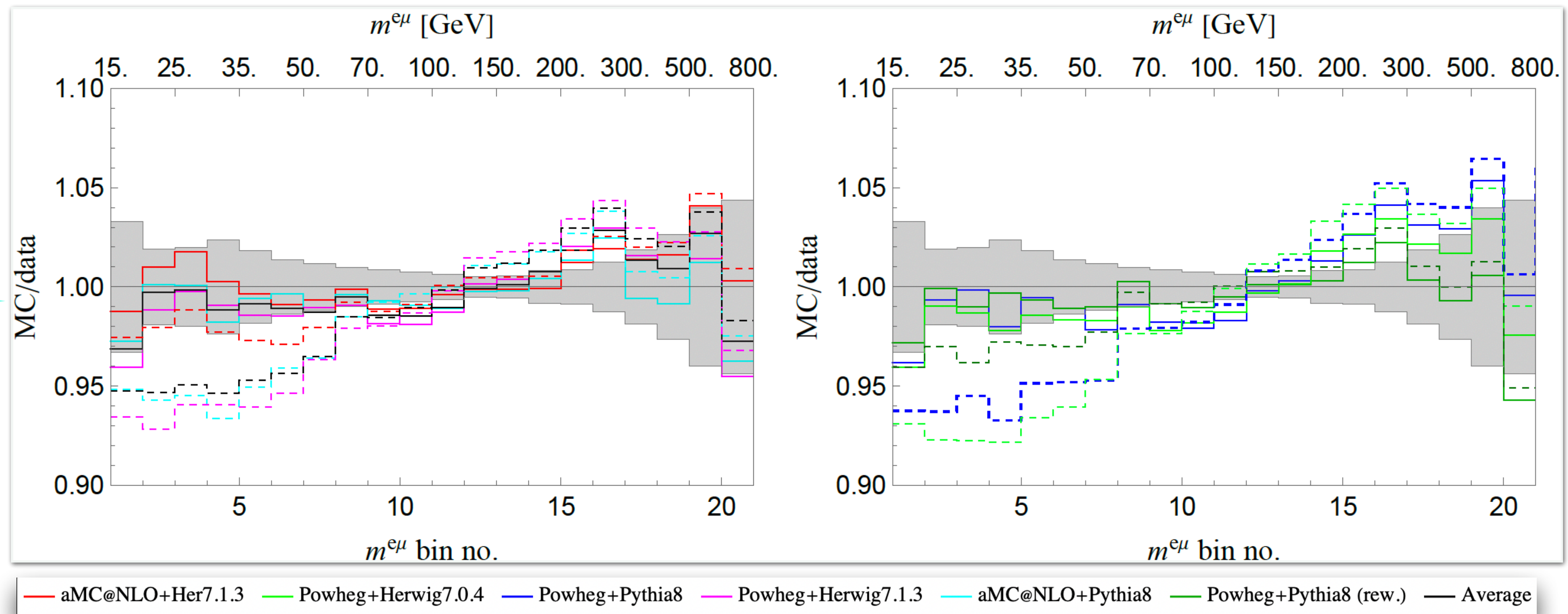
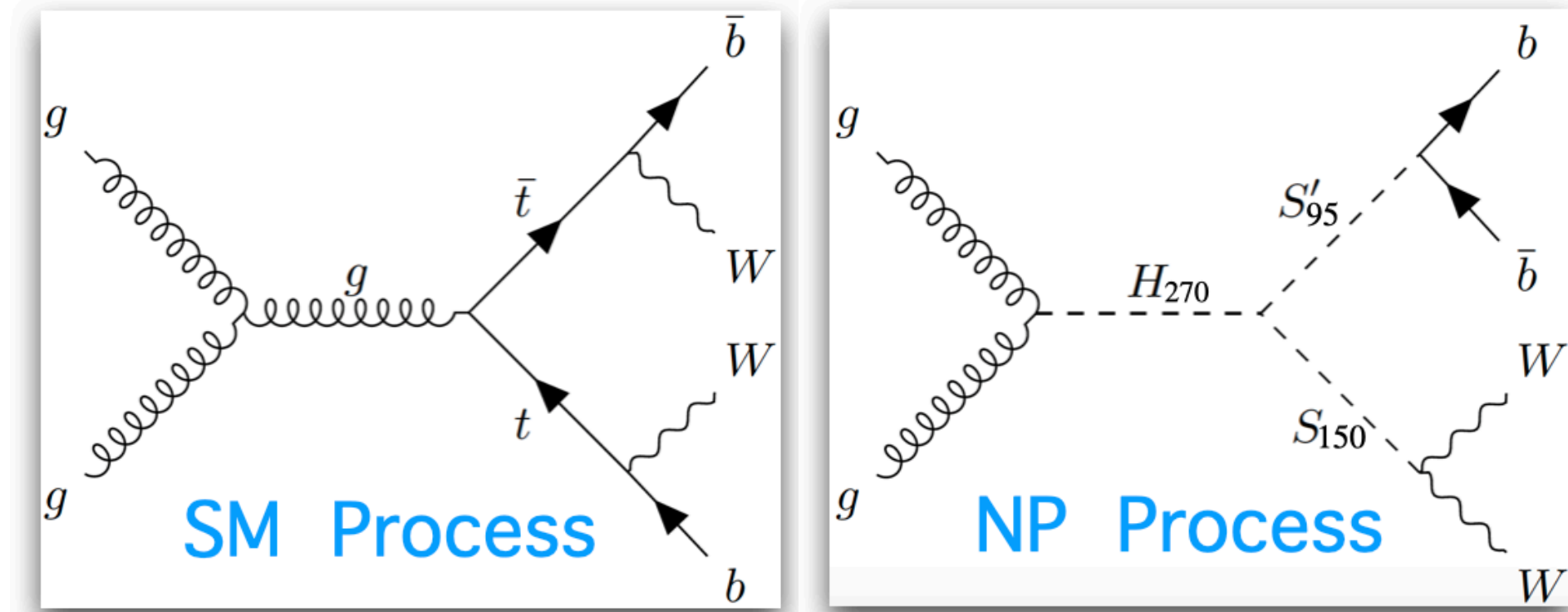


Mismodelling of SM or NP effects?

Deviations in $t\bar{t}$ Differential cross-section

NP Results

- *Simplified model* with **three Higgs bosons**
- Preferred over SM by at least **5.8σ**
- **Compatible** with 95 GeV and 152 GeV Excesses



(SB, A. Crivellin et al.)
[2308.07953]