Indications for New Higgs Bosons in Associated Di-Photon Production

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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

Full Run 2 Data

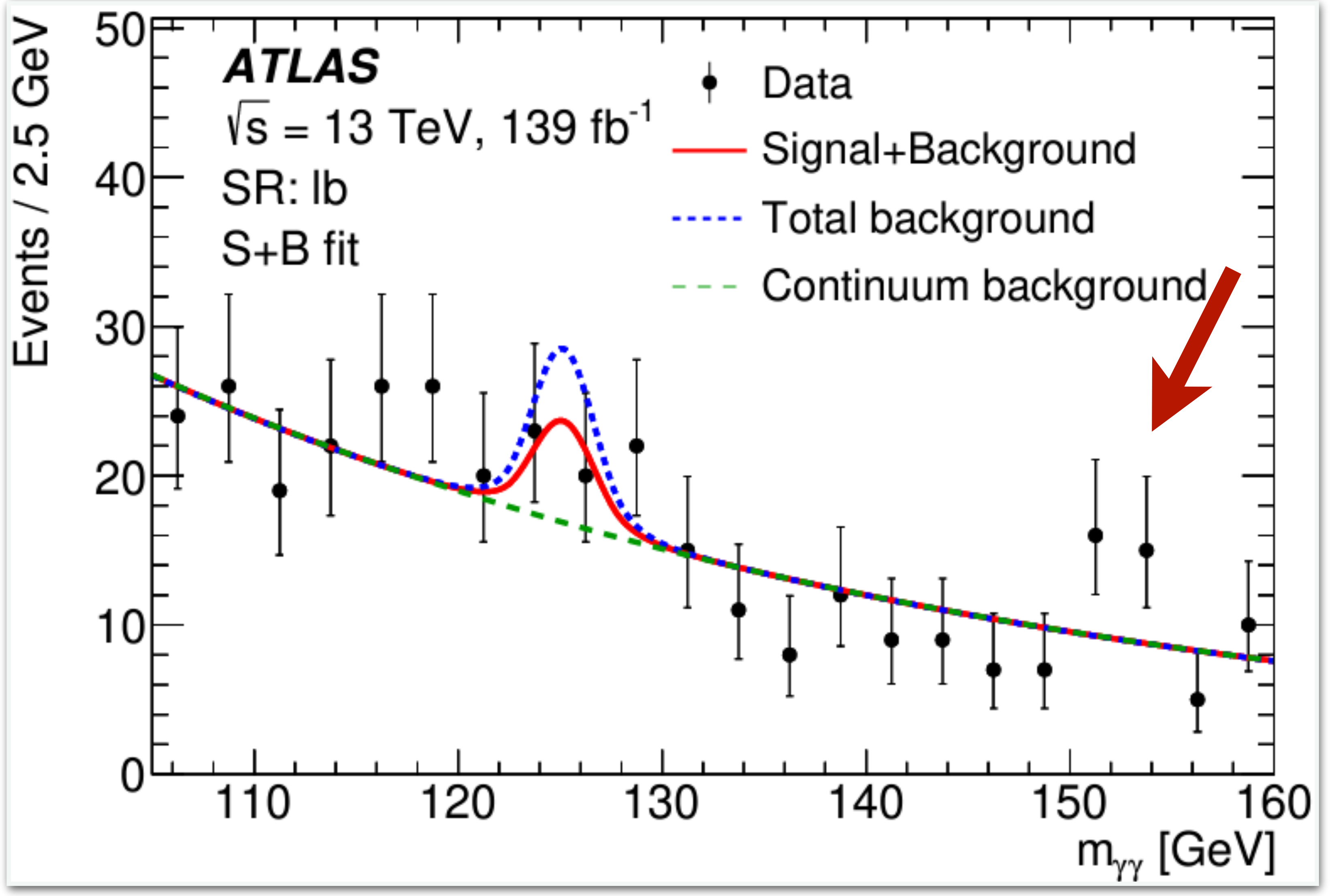
- Analysis involves 22 signal regions

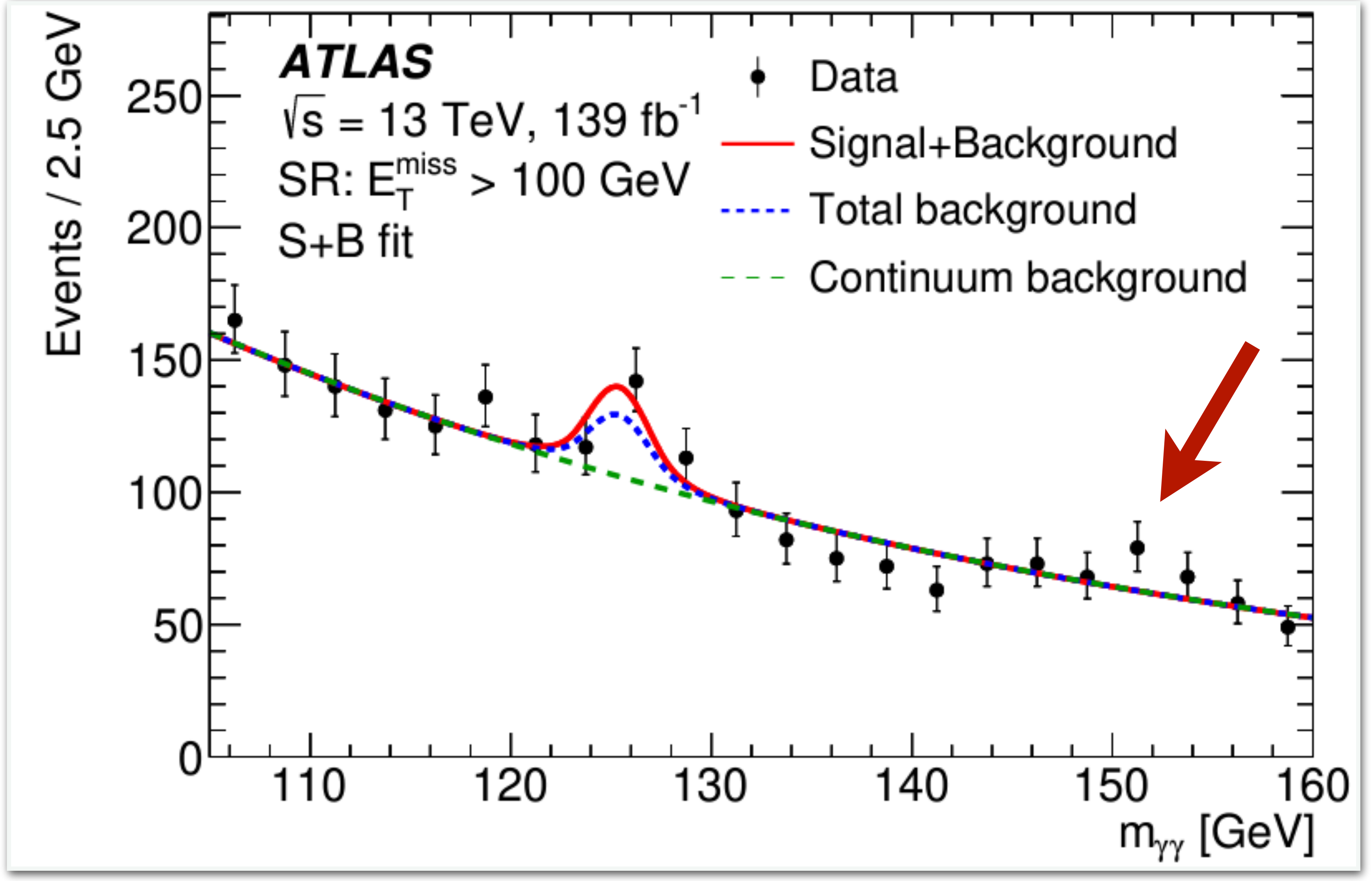
Heavy Flavor	Jets	Lepton	E_T^{miss}	Top	H_T	Photon
$\geq 3b$, $\geq 4b$	$\geq 4j$, $\geq 6j$, etc.	1ℓ, 2ℓ, $\geq 3\ell$, 1τ, 2τ	$E_T^{\text{miss}} > 100$ GeV, $E_T^{\text{miss}} > 200$ GeV	ℓb, t_{lep}, t_{had}	$H_T > 500$ GeV, $H_T > 1000$ GeV	$m_{\gamma\gamma}^{12}$, $m_{\gamma\gamma}^{13}$

Motivation

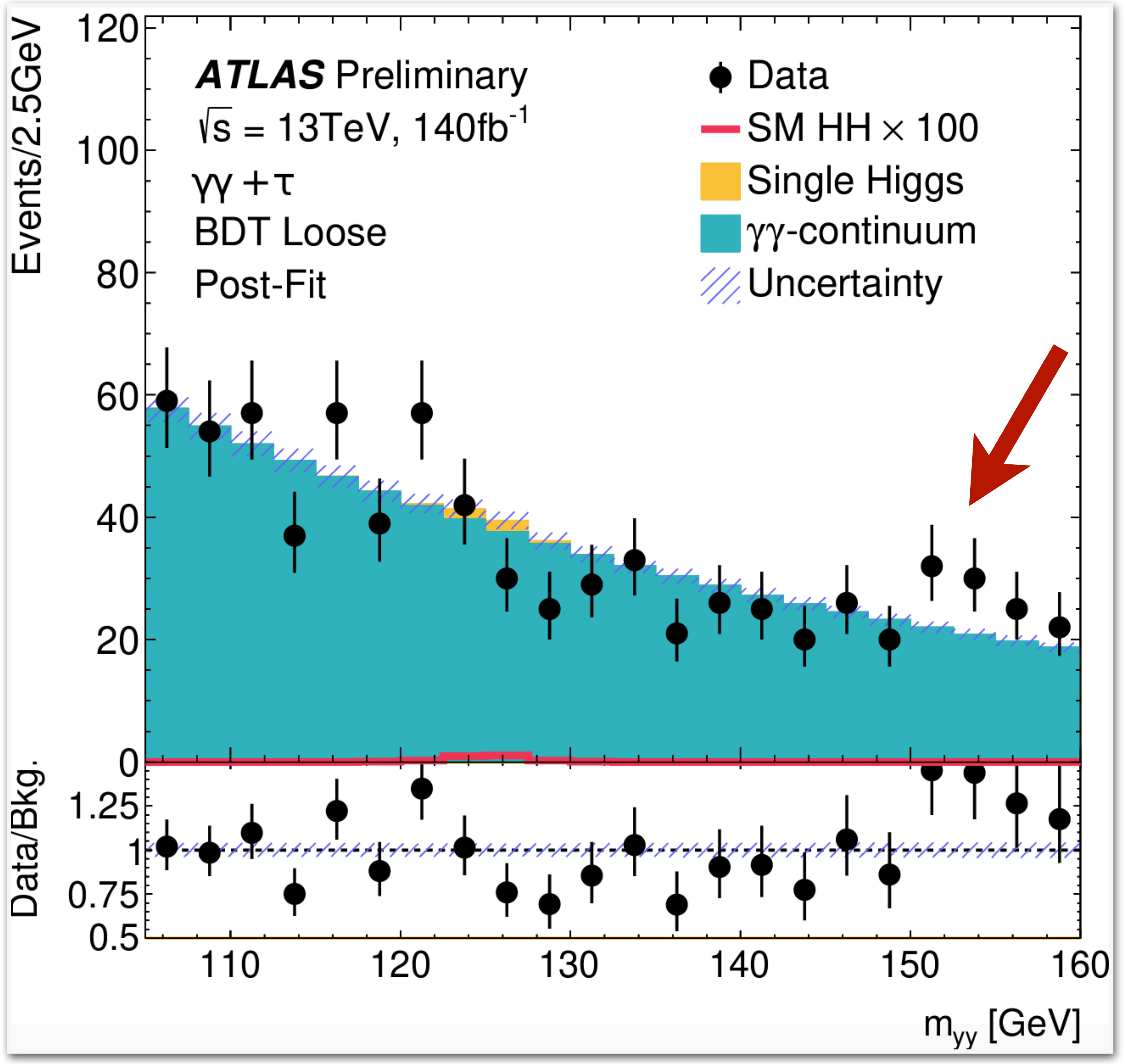
Hints for new Higgs Bosons

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





[ATLAS: CERN-EP-2022-232]



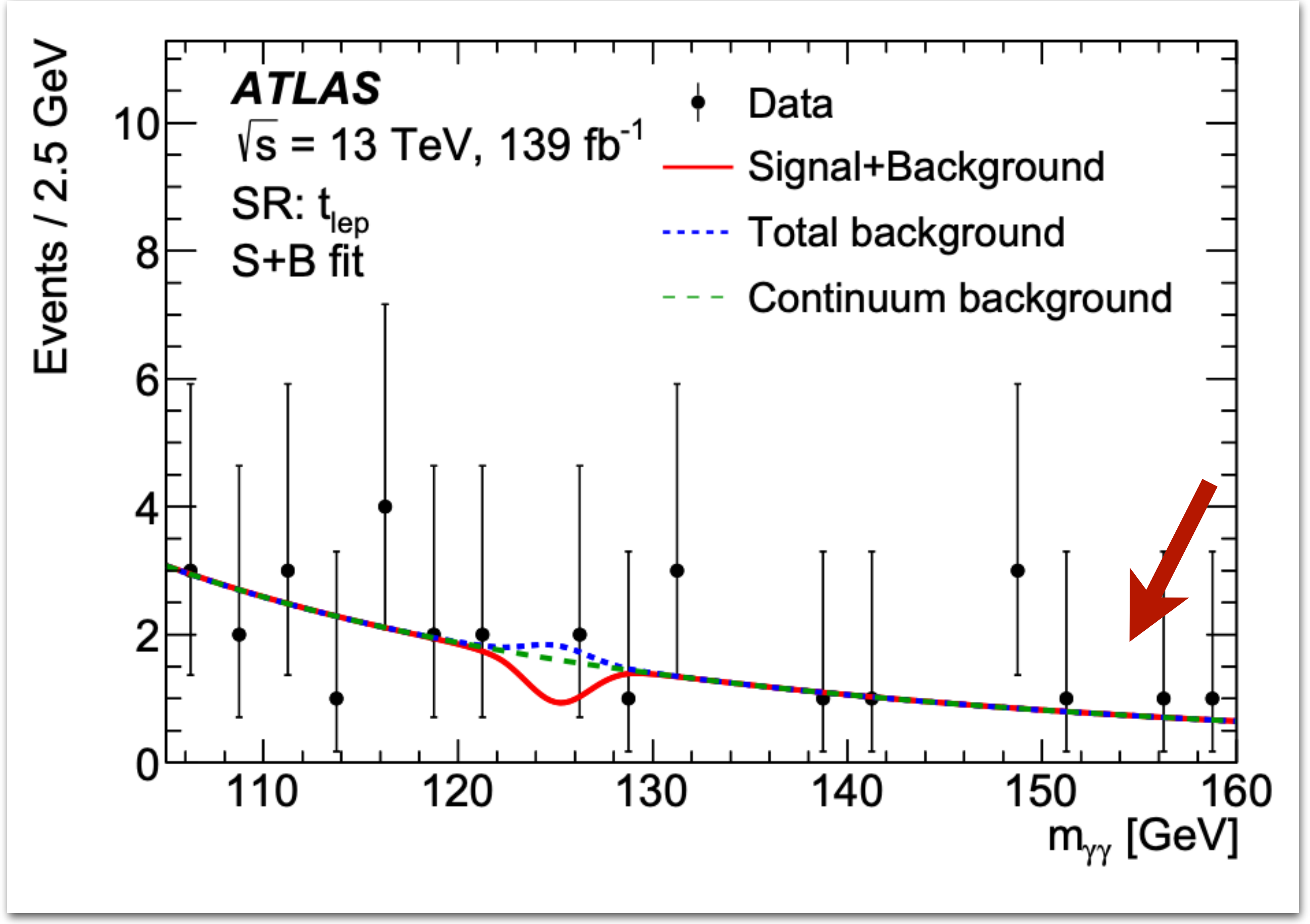
[ATLAS-CONF-2024-005]

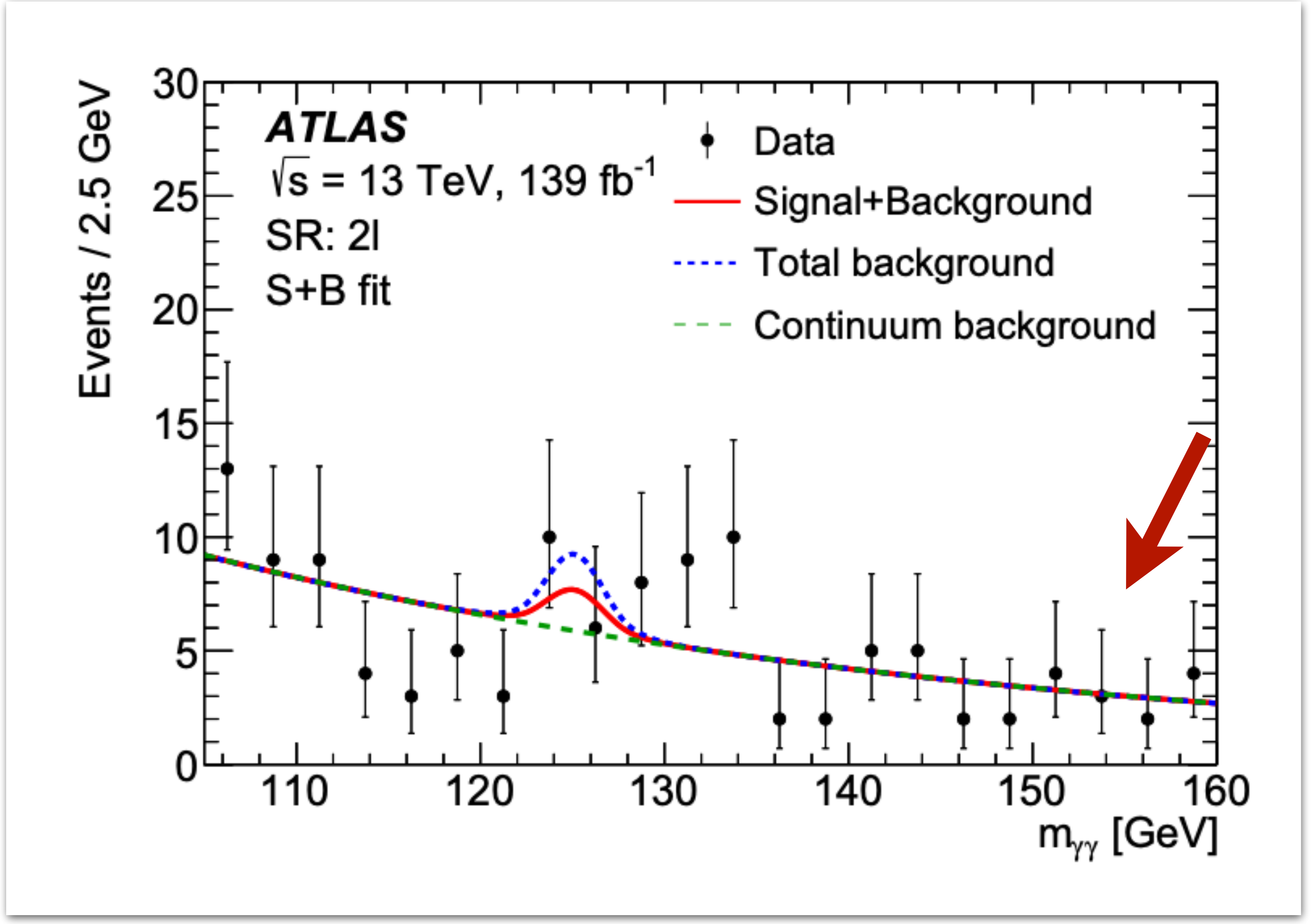
- Possible new Higgs Boson?

Motivation

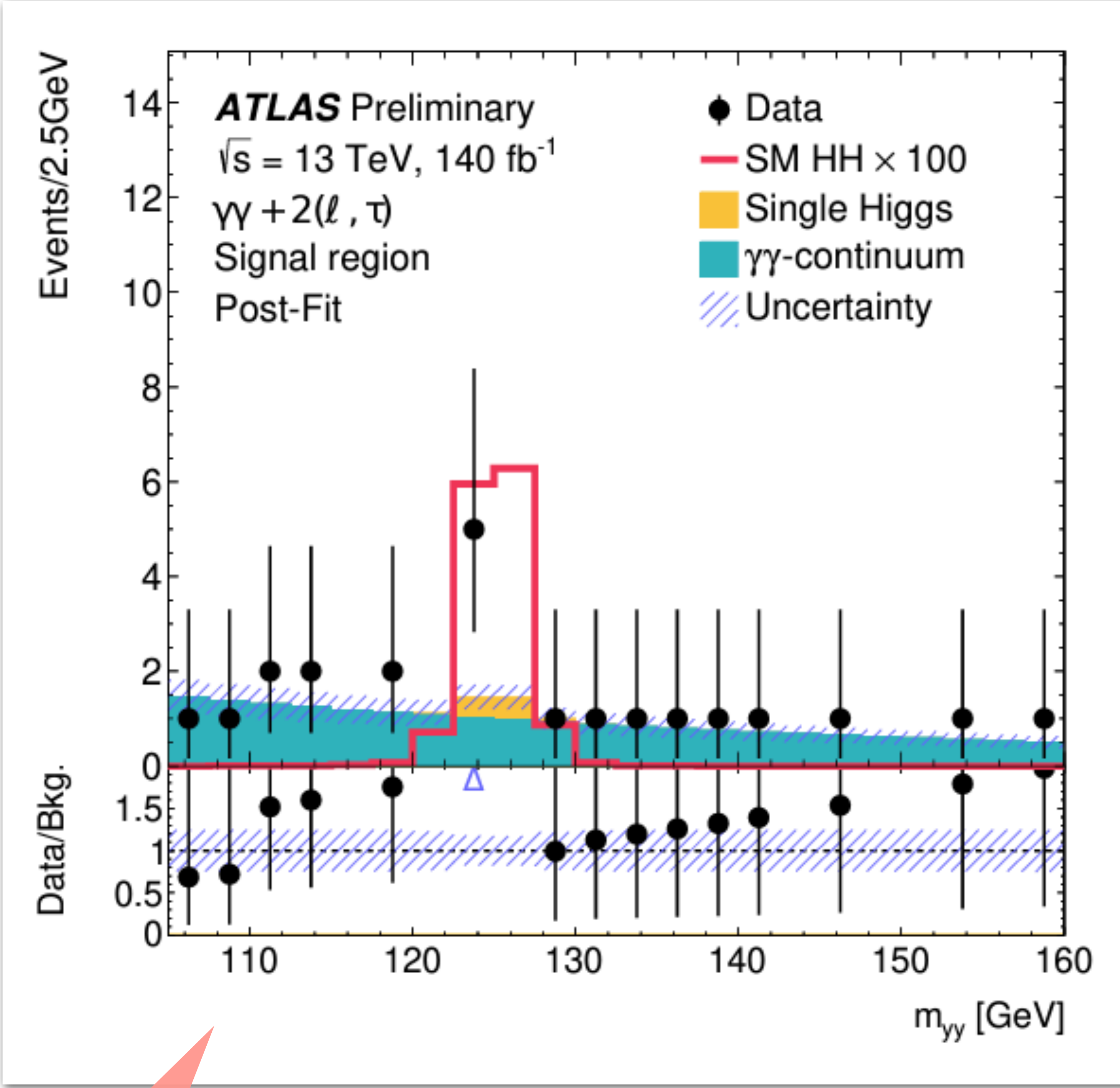
Hints for new Higgs Bosons

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





[ATLAS: CERN-EP-2022-232]



[ATLAS-CONF-2024-005]

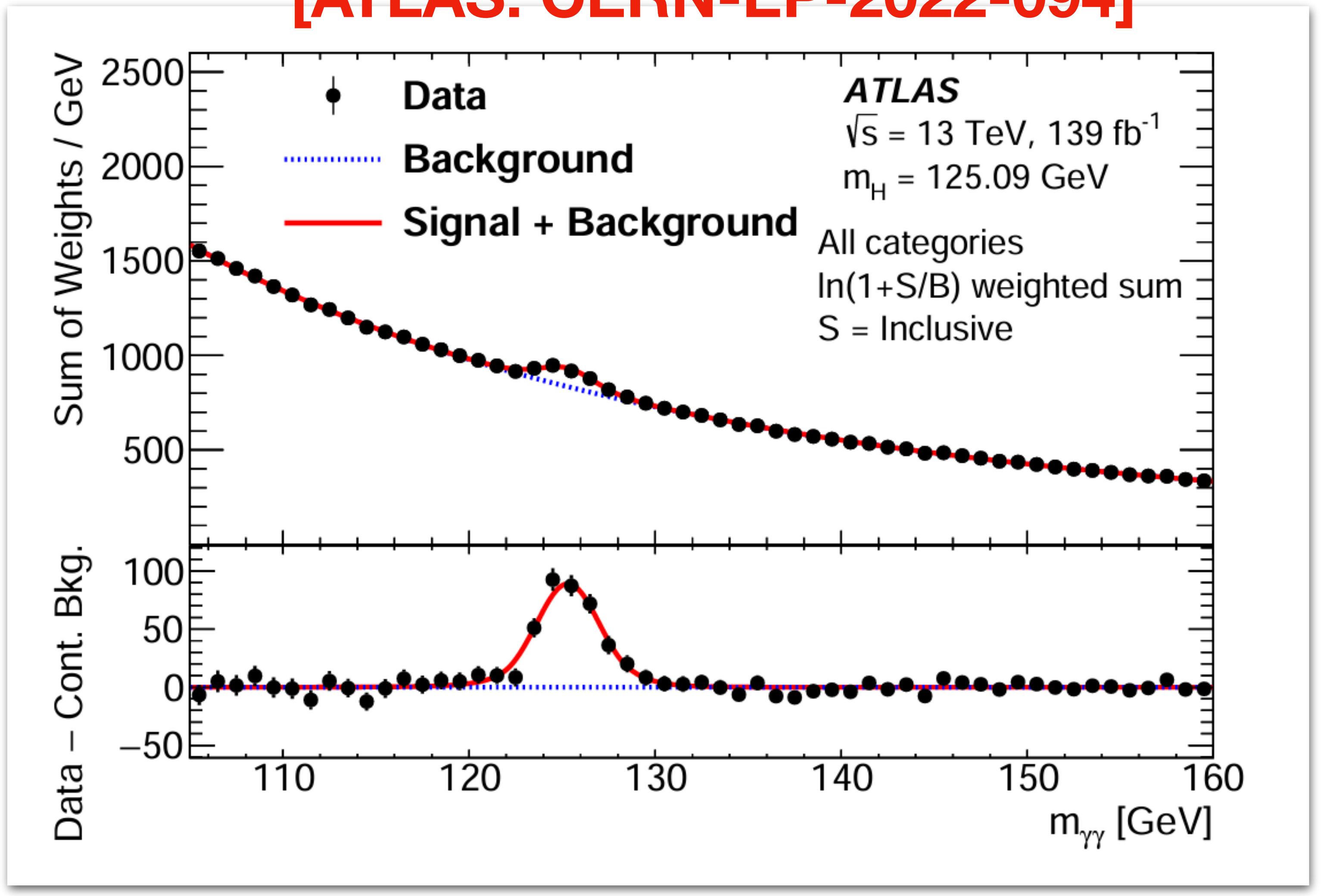
Point towards asssociated $H^{\pm}$

Motivation

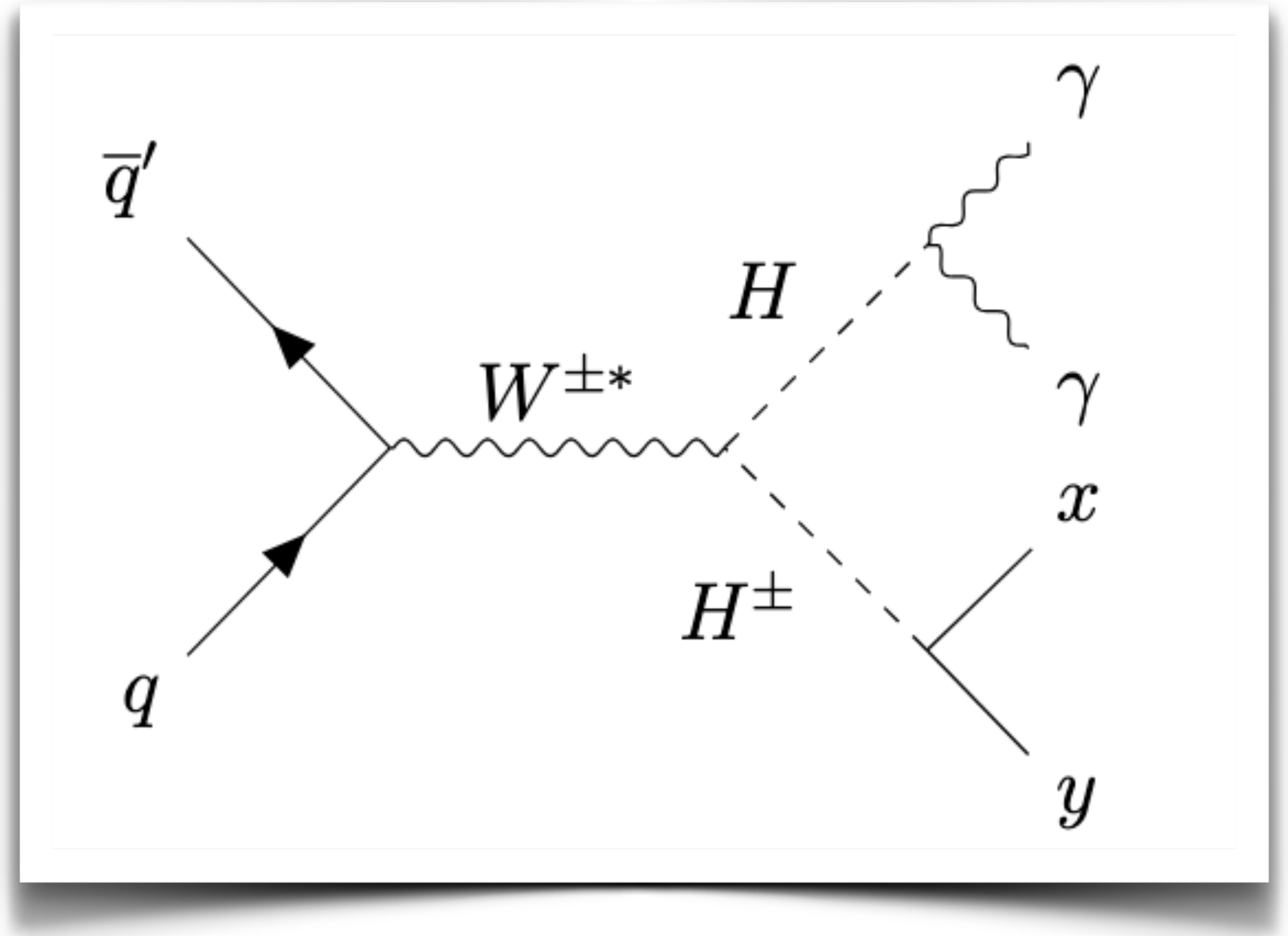
Hints for new Higgs Bosons

- No excess in Inclusive Searches

[ATLAS: CERN-EP-2022-094]



Dominant Production Process



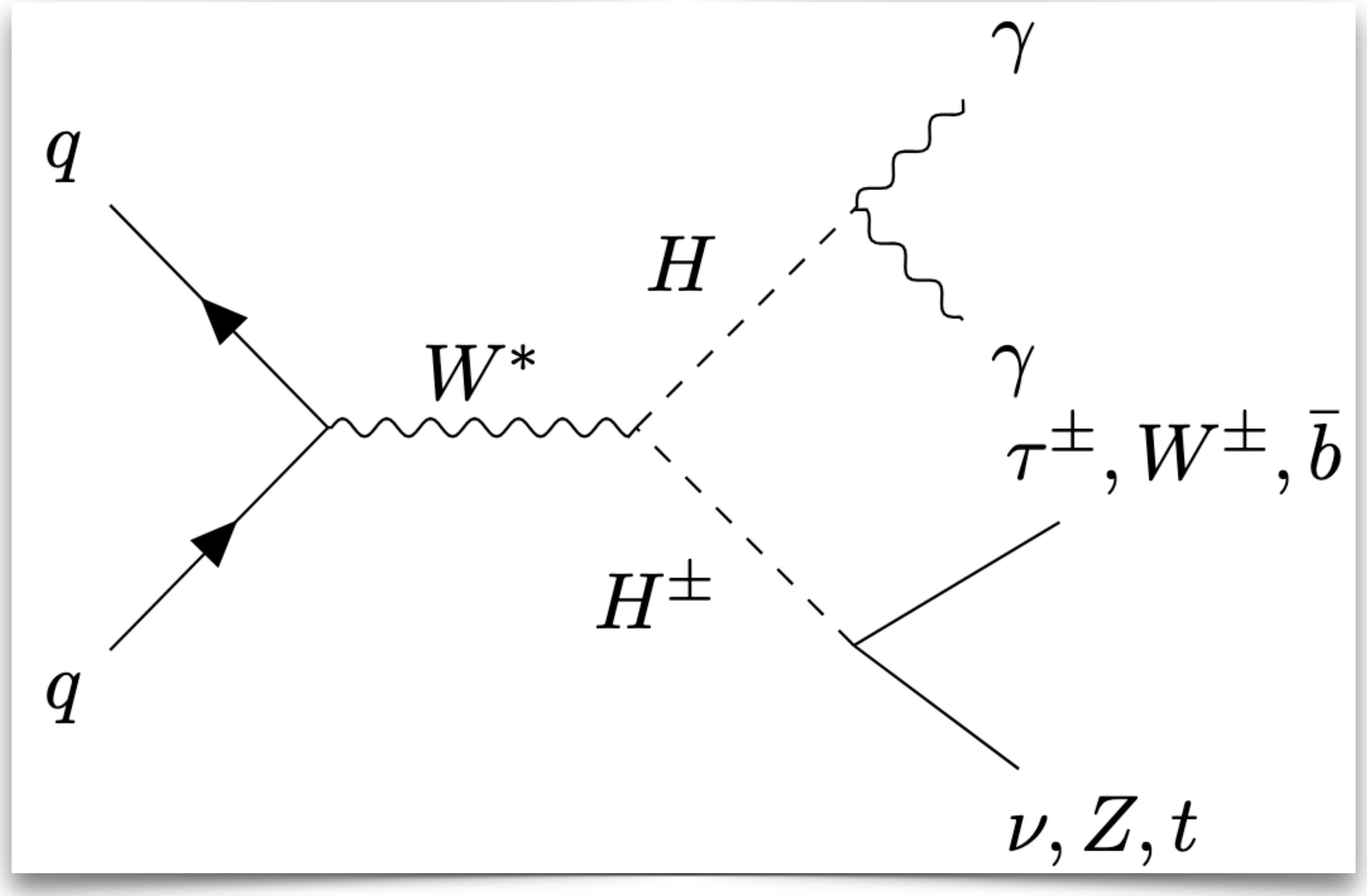
- Hints towards DY production of new Higgs at LHC

- Properties of $H^{\pm}$ unknown

Simplified Model

Model Description

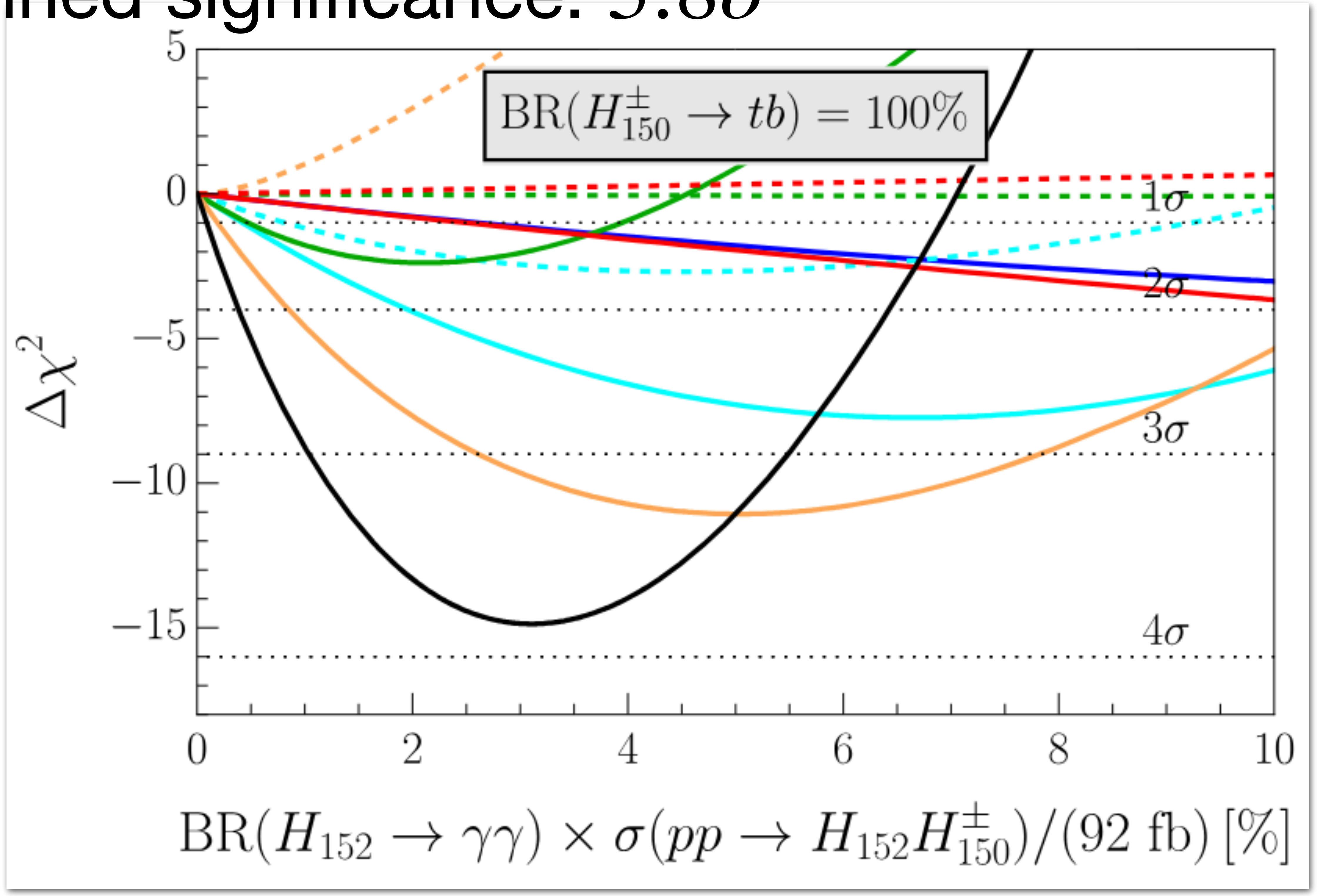
- Two New Particles: $H, H^{\pm}$
- H produced only via DY process
- Dominant decays of $H^{\pm}$: $tb, \tau\nu, WZ$
- Simulation Setup: MadGraph + Pythia + Delphes
- Log-Likelihood Fit performed using Poisson Statistics

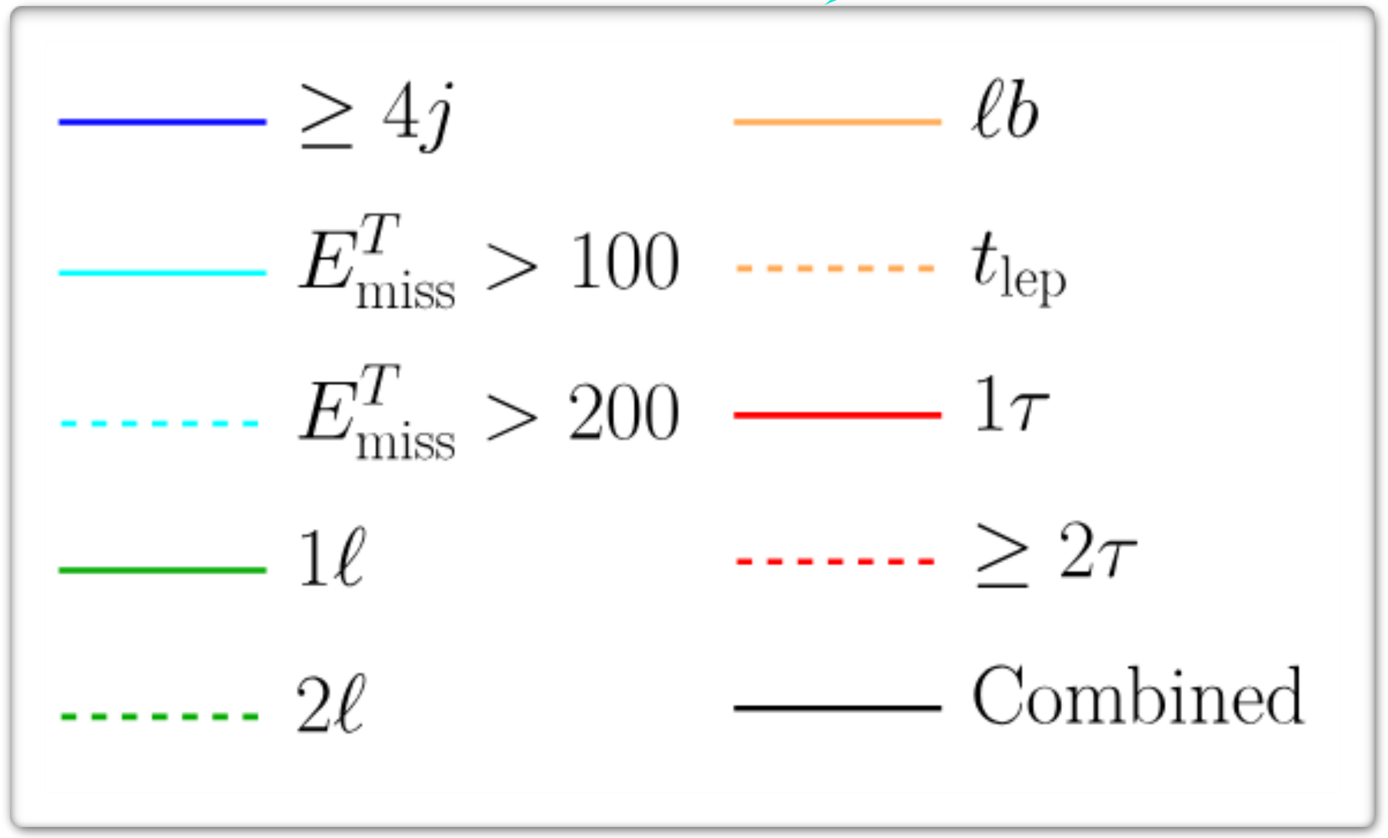


Simplified Model

Charged Higgs Decay

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





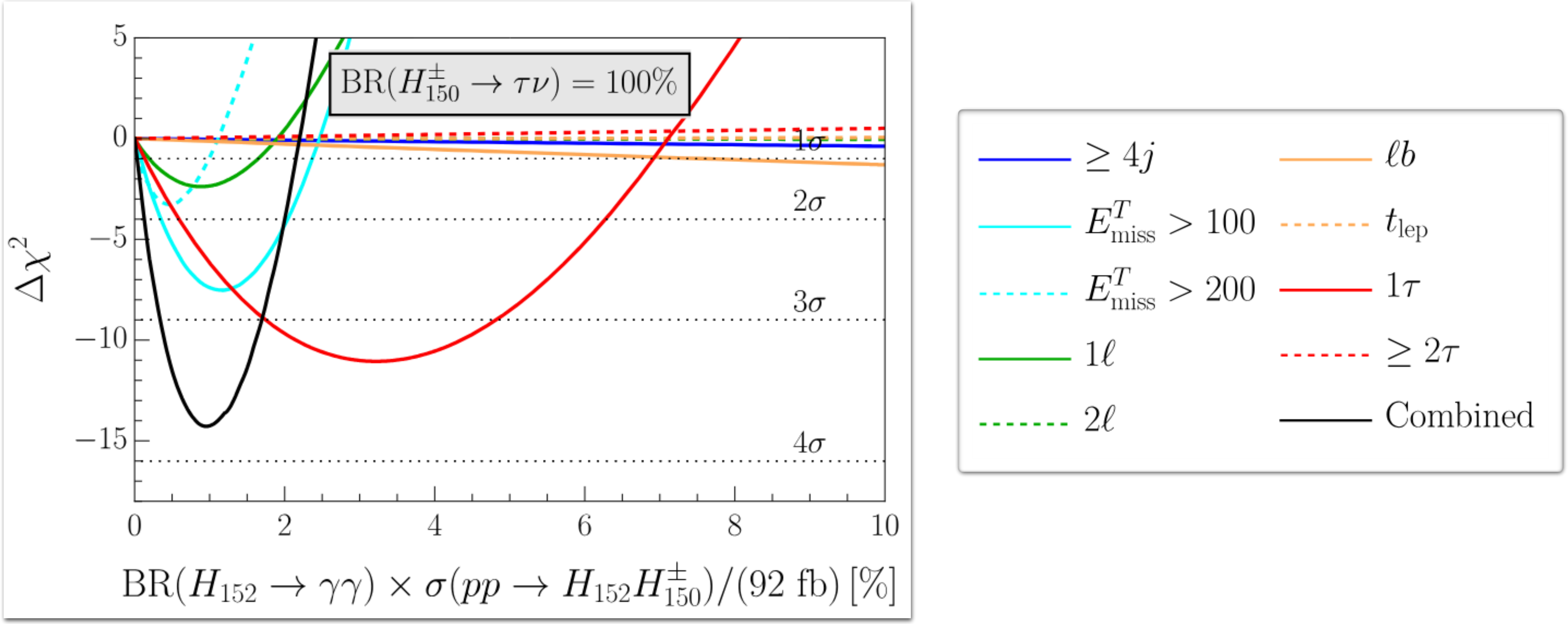
Relevant SRs

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

Simplified Model

Charged Higgs Decay

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

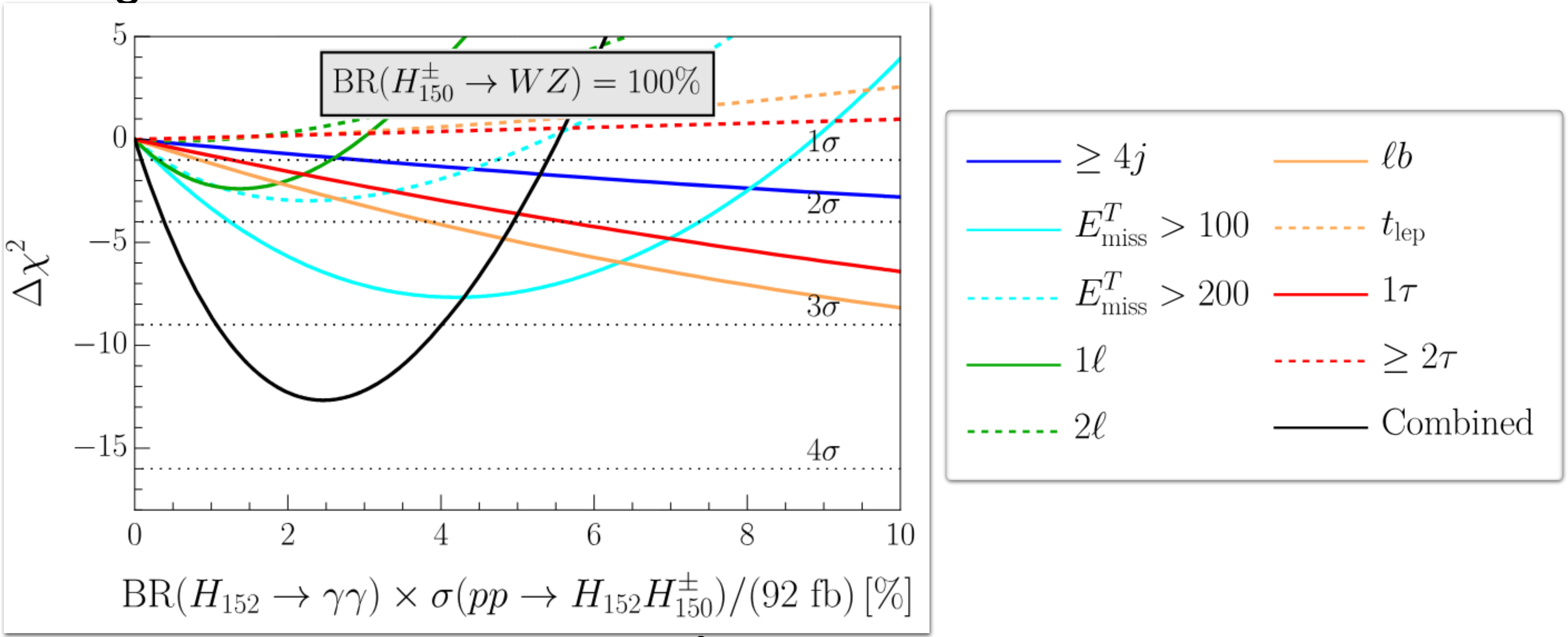


Simplified Model

Charged Higgs Decay

- $\mathrm{BR}(H^{\pm} \to WZ) = 100\,\%$
- 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



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 Real Higgs Triplet

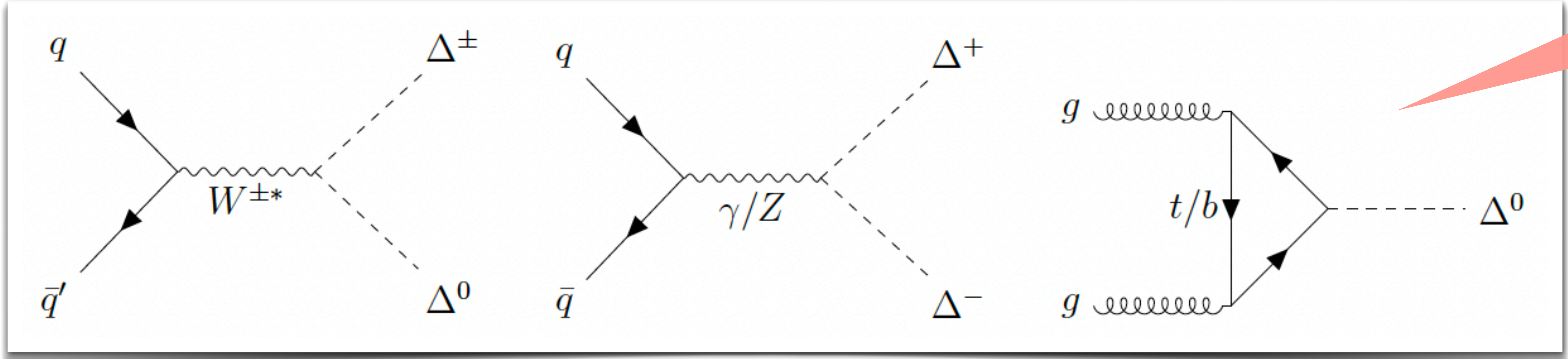
Model Description

- Scalar Particles: $h, \Delta^0, \Delta^\pm$
- Physical Parameters: $m_h, m_{\Delta^0}, m_{\Delta^\pm}, v_\Delta, \alpha$
- Theoretical constraints require $m_{\Delta^0} \approx m_{\Delta^\pm}$
- Triplet Higgs production channels at LHC

No Yukawa couplings

$m_h = 125$ **GeV**, $v_\Delta = 3.4$ **GeV**

Suppressed by mixing

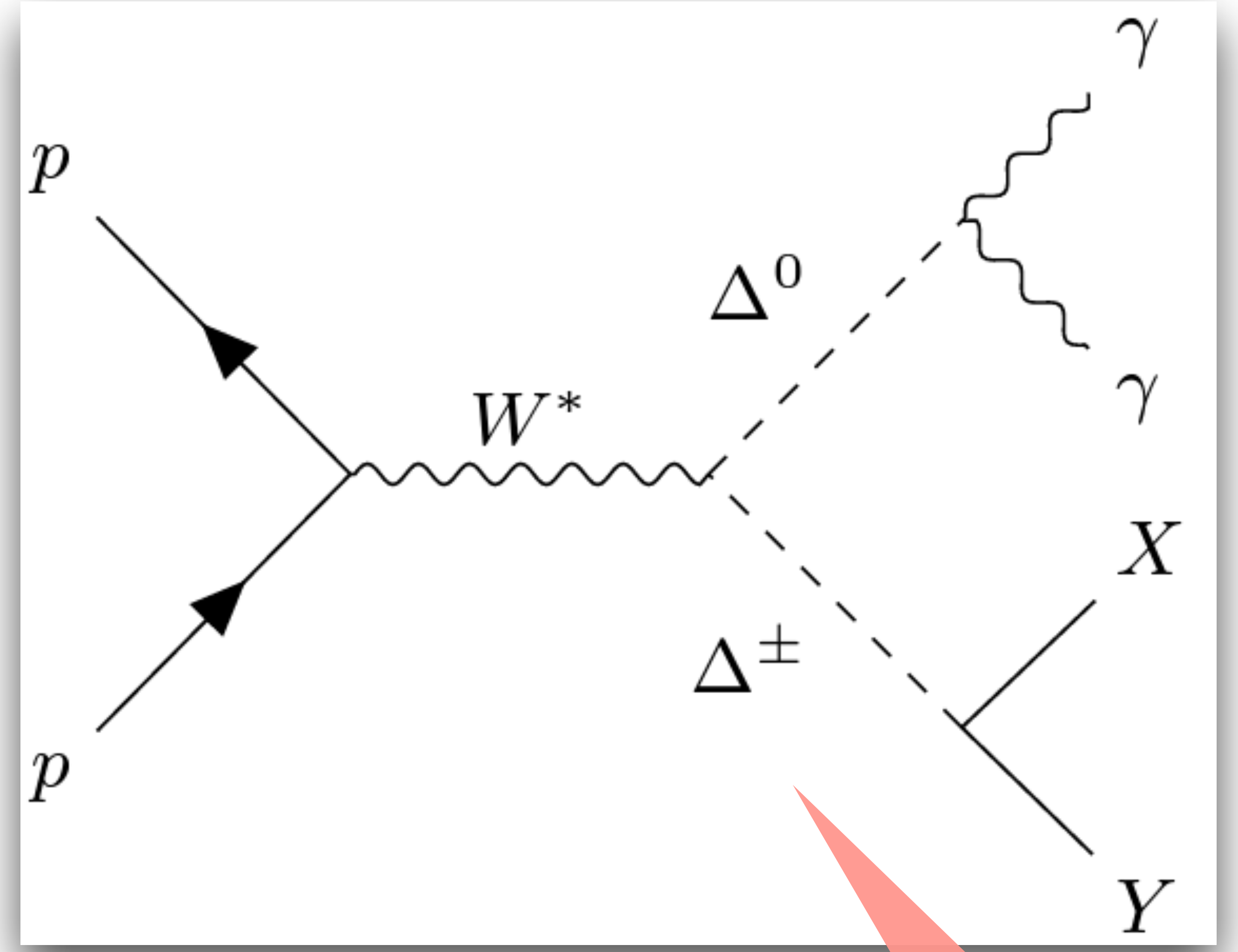


Explanation in Real Higgs Triplet

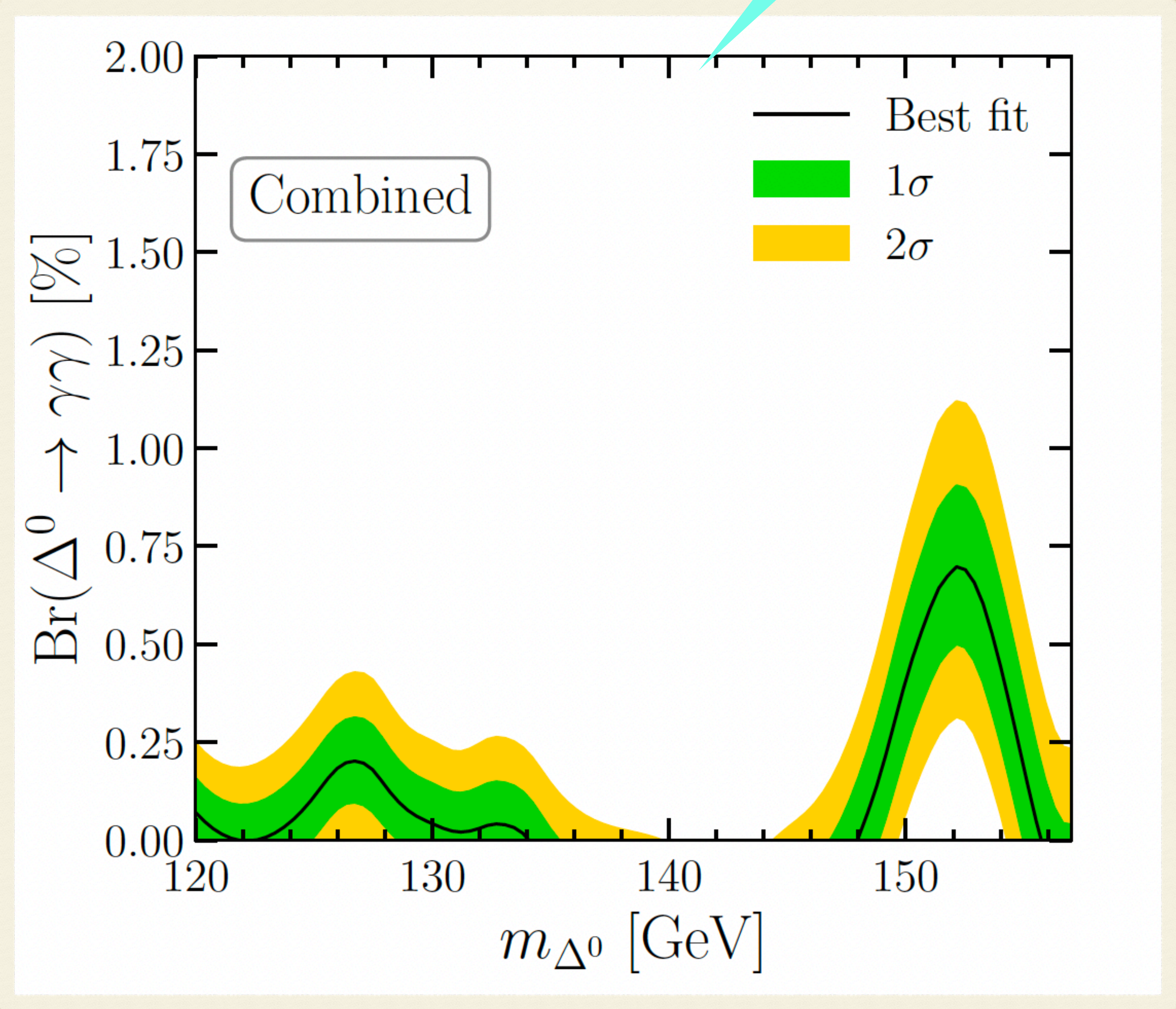
Explanation of $\gamma\gamma + X$ Excesses

- Model generated using SARAH
- Free Variables: m_{Δ_0}, Br $\left(\Delta_0 \to \gamma\gamma\right)$ instead of m_{Δ_0}, α

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



Process Simulated

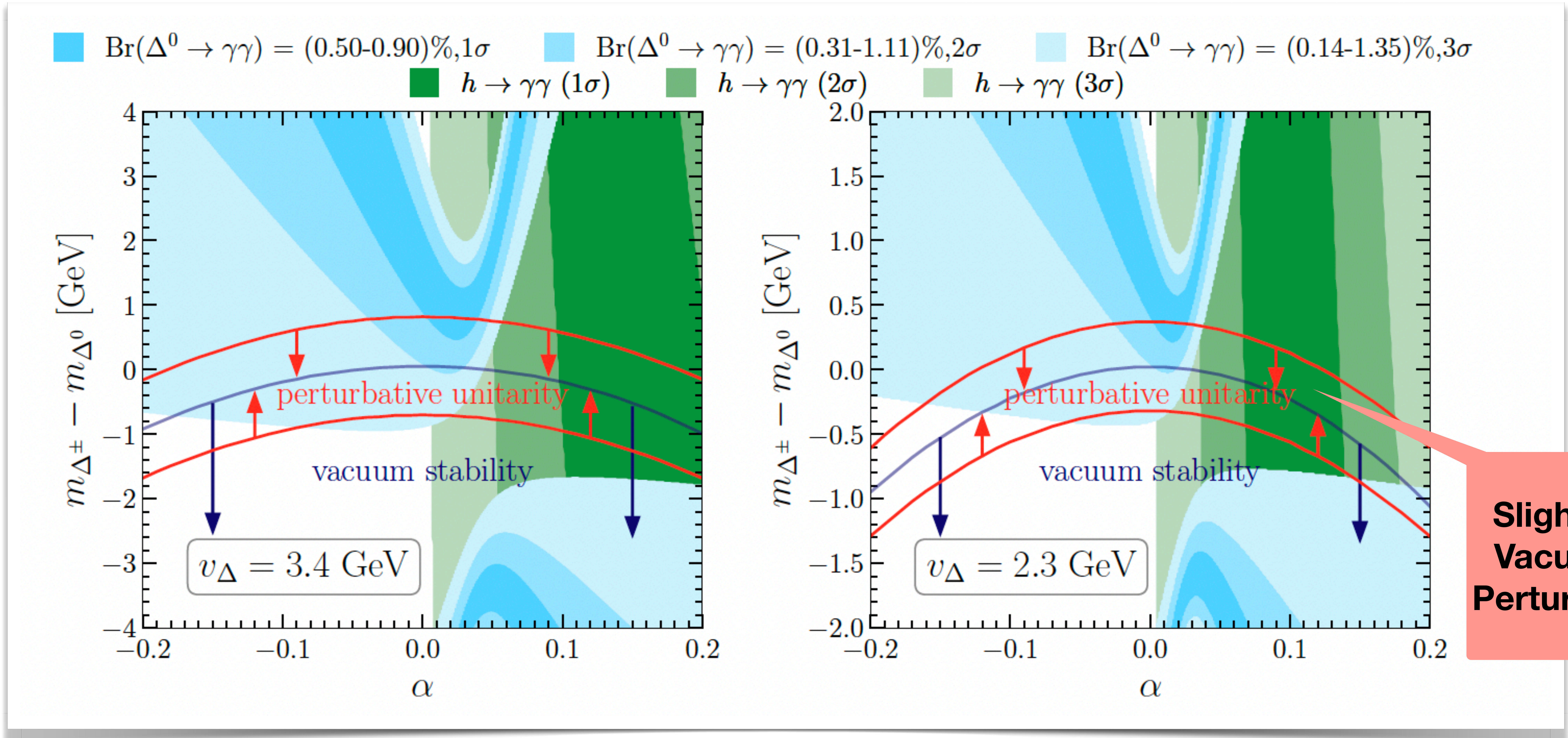


Br $\left(\Delta_0 \to \gamma\gamma\right) \approx 0.7\,\%$ at ≈ 151 GeV (3.9σ)

Explanation in Real Higgs Triplet

Explanation of $\gamma\gamma + X$ Excesses

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



Slight Tension with Vacuum Stability & Perturbative Unitarity

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

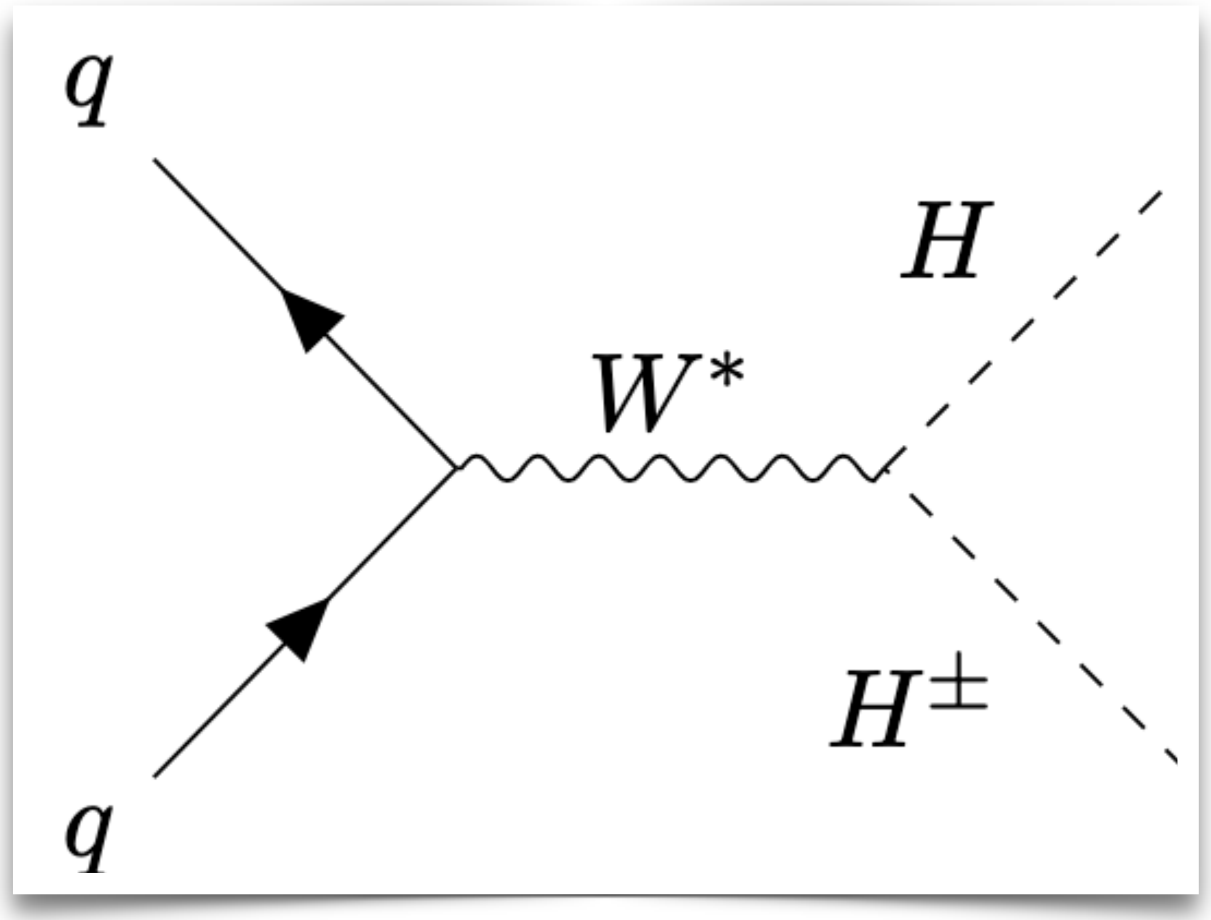
Explanation in 2HDM

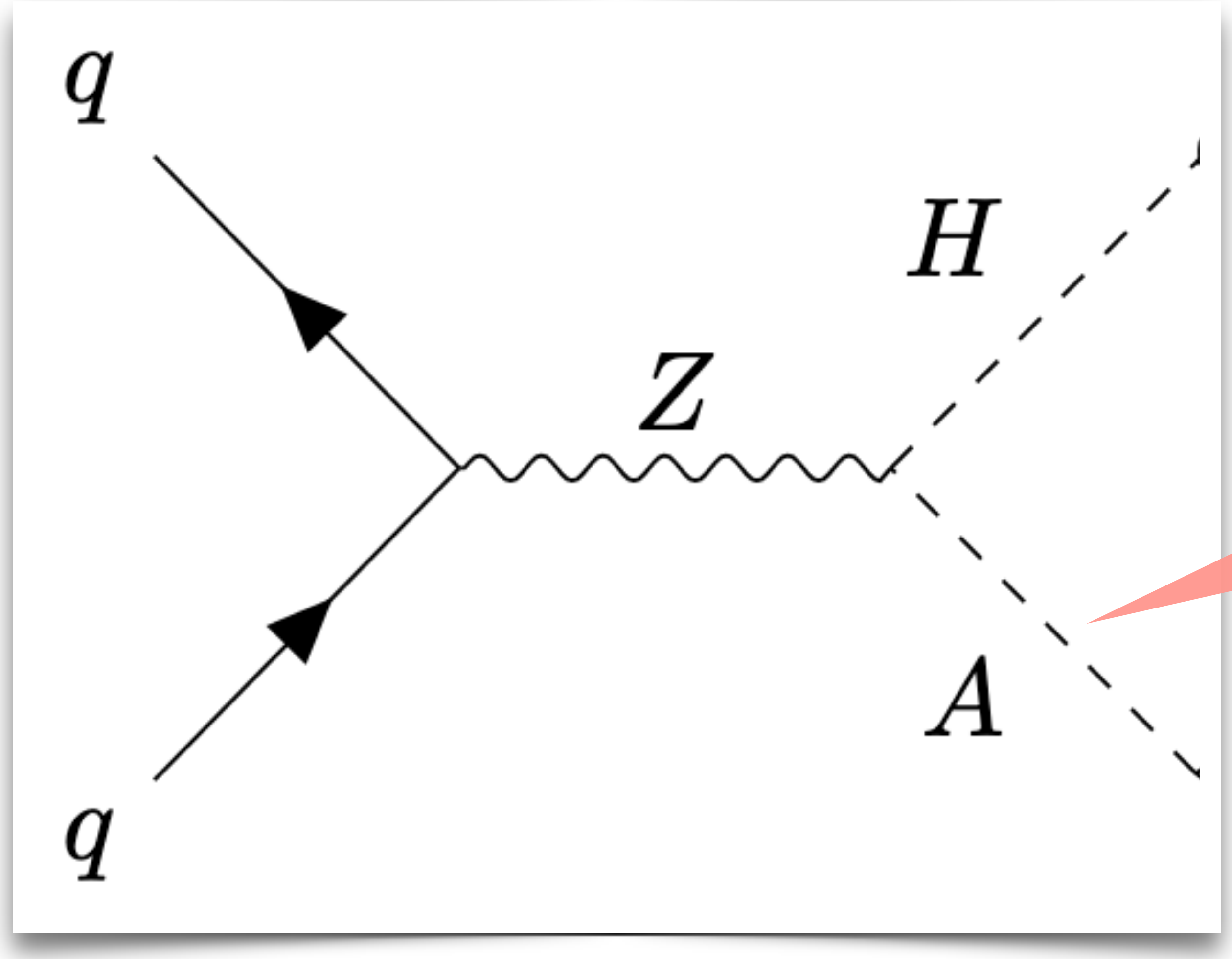
Type-I

- 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

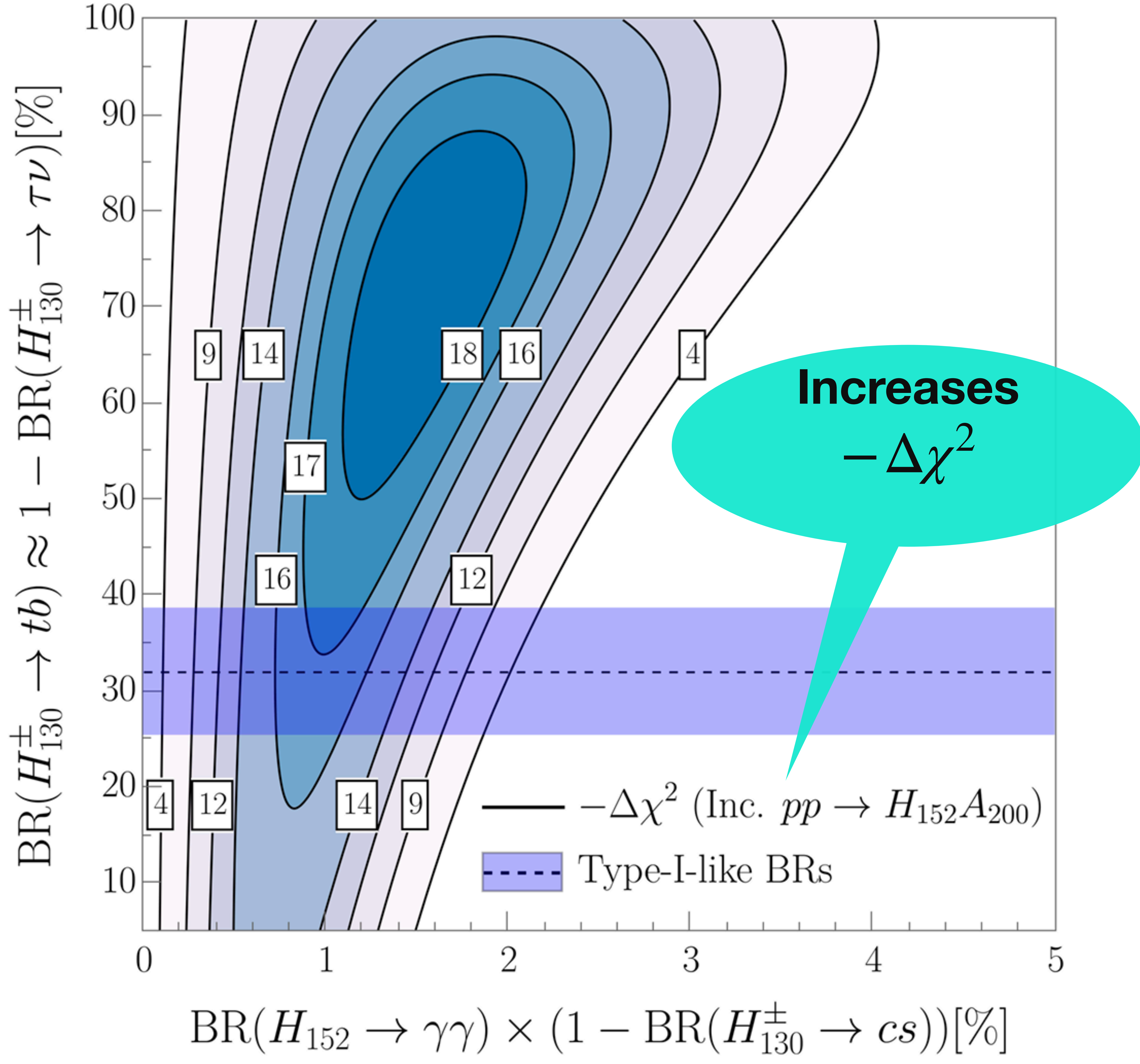
Type-I

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

- Considered Benchmark Point:

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

- Br$(H \to \gamma\gamma)$ required at the percent level



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

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 ΔSM and 2HDM
- Large Br$(H \to \gamma\gamma)$ 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

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

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

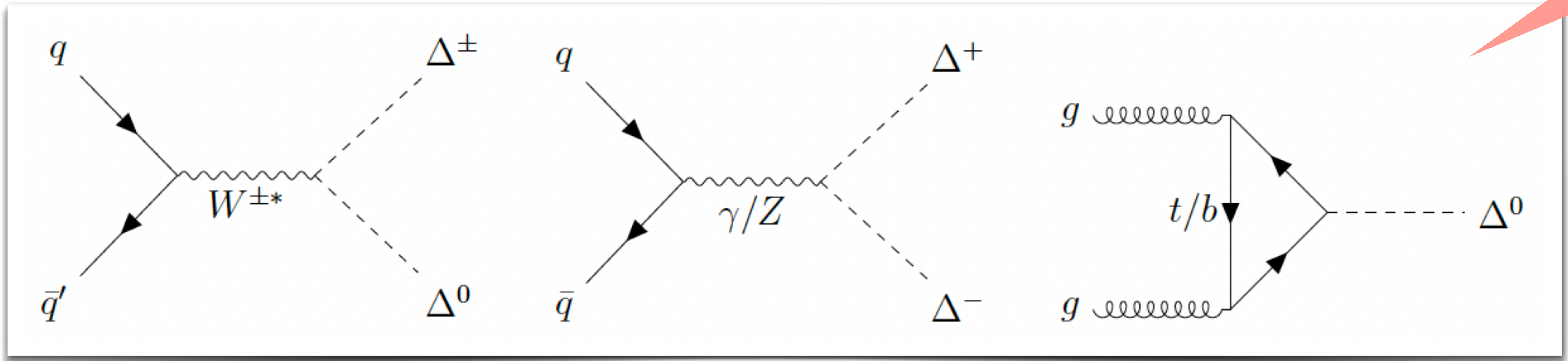
where ϕ is the SM doublet.

Explanation in Real Higgs Triplet

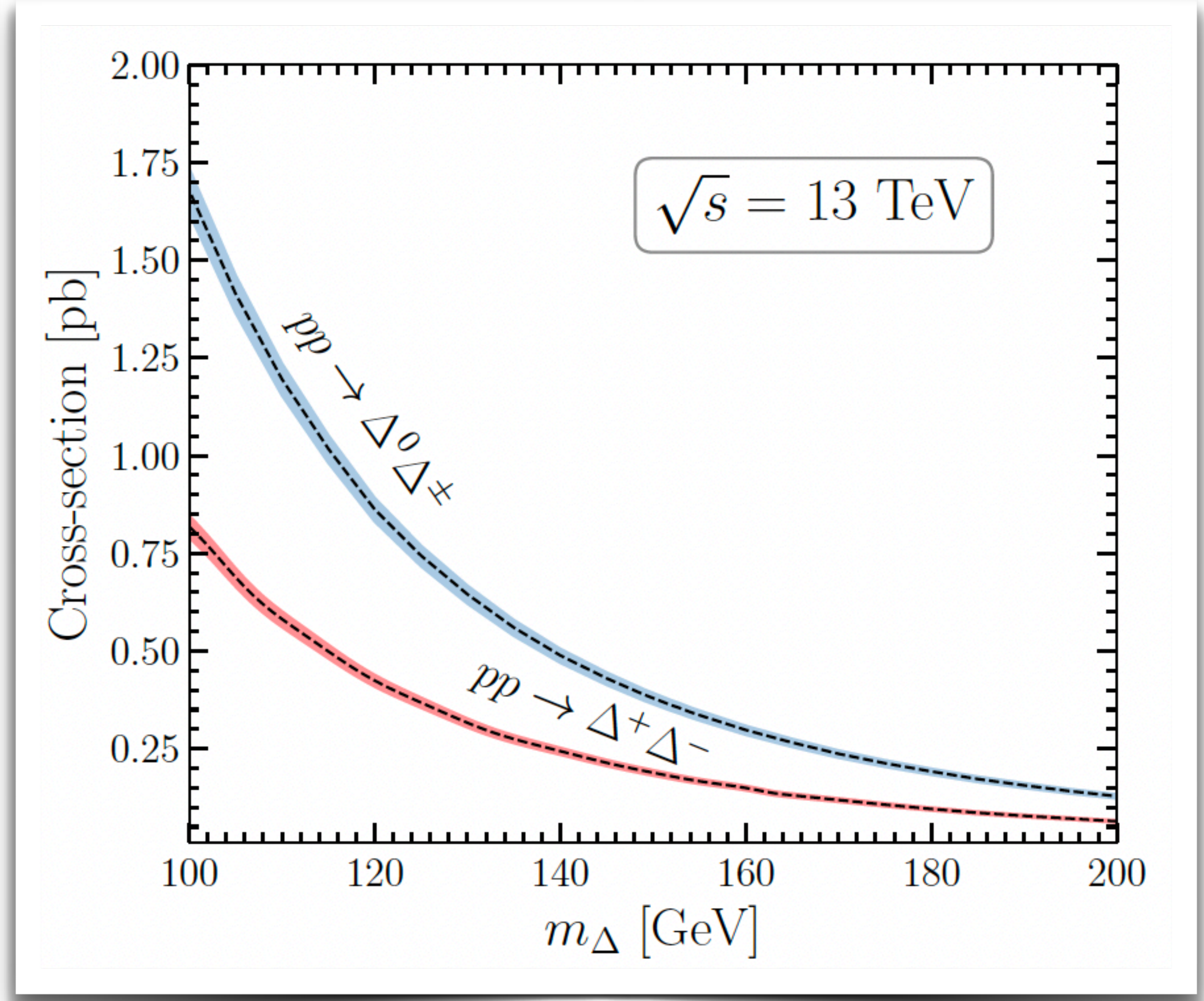
Model Description

- Triplet Higgs production channels at LHC

Suppressed by mixing



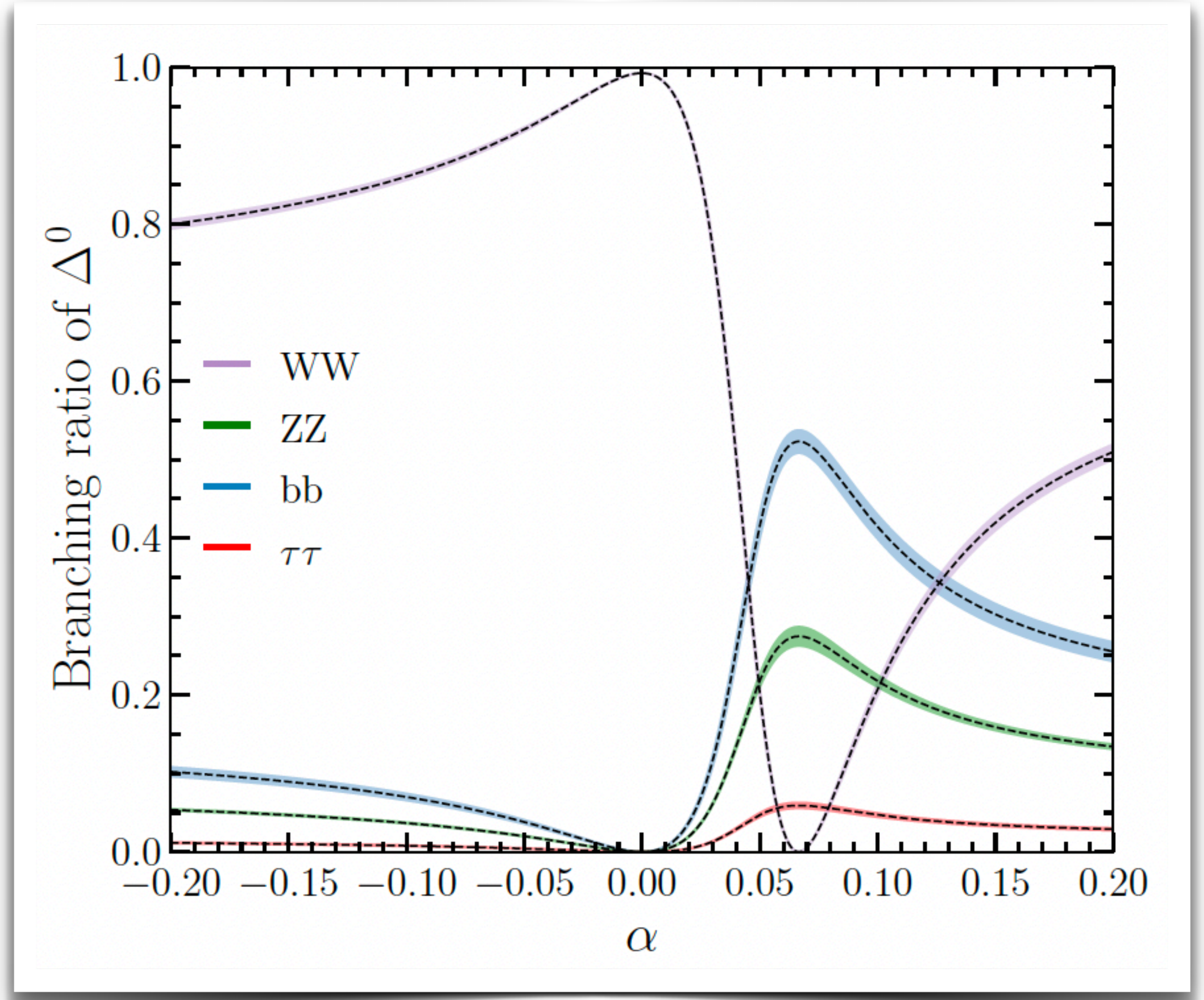
- Triplet Higgs DY production cross-section



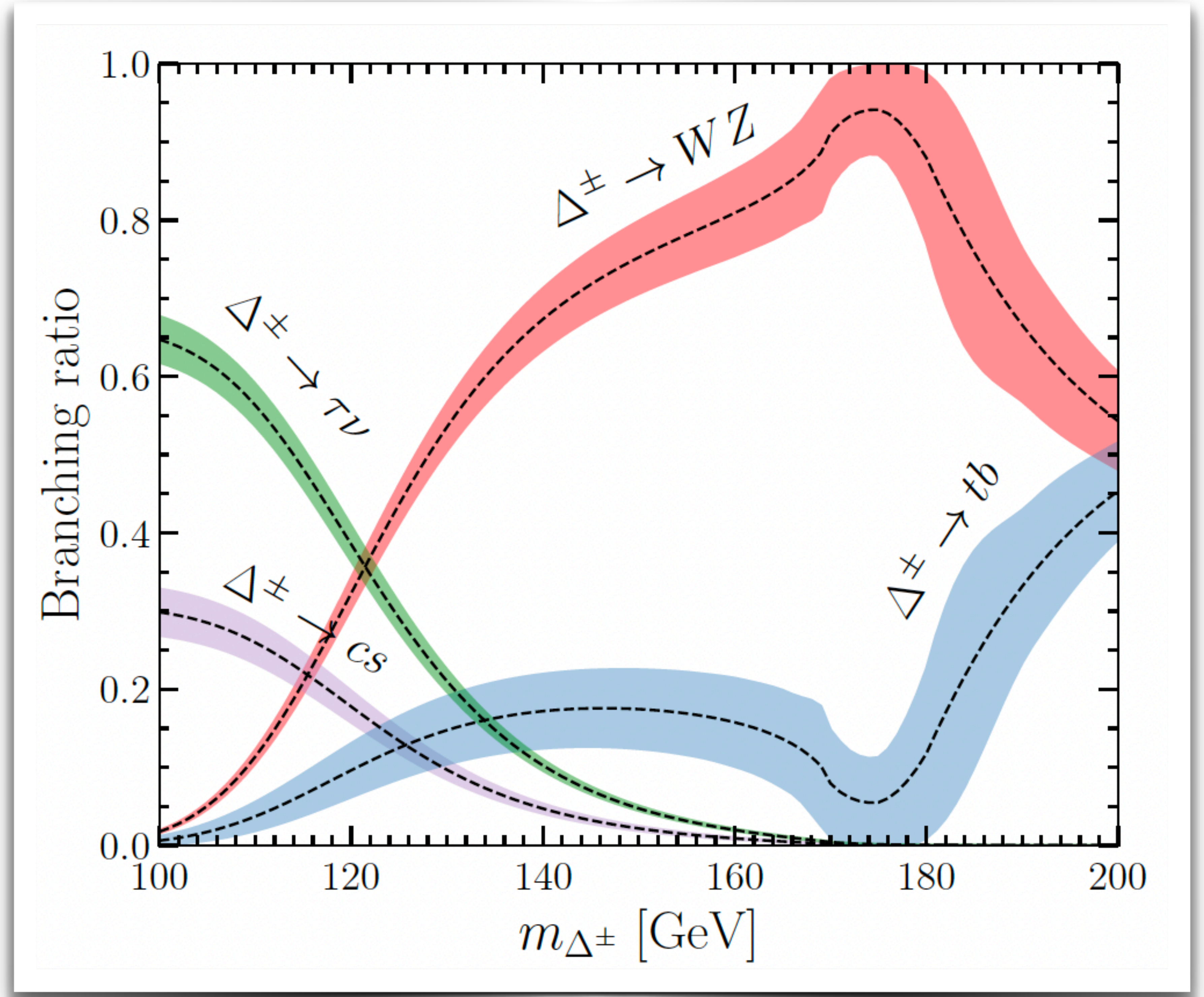
Explanation in Real Higgs Triplet

Model Description

- Dominant Triplet Higgses decay channels



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



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

Real Higgs Triplet

Basis Transformation

Physical to Lagrangian Basis

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

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

$$m_{\Delta^\pm}^2 = A\frac{v_\Phi^2 + 4 v_\Delta^2}{4 v_\Delta},$$

Lagrangian to Physical Basis

$$\lambda_\Phi = \frac{2 m_h^2}{v^2},$$

$$\lambda_\Delta = \frac{2}{v_\Delta^2}\left[m_{\Delta^0}^2 - m_{\Delta^\pm}^2\right],$$

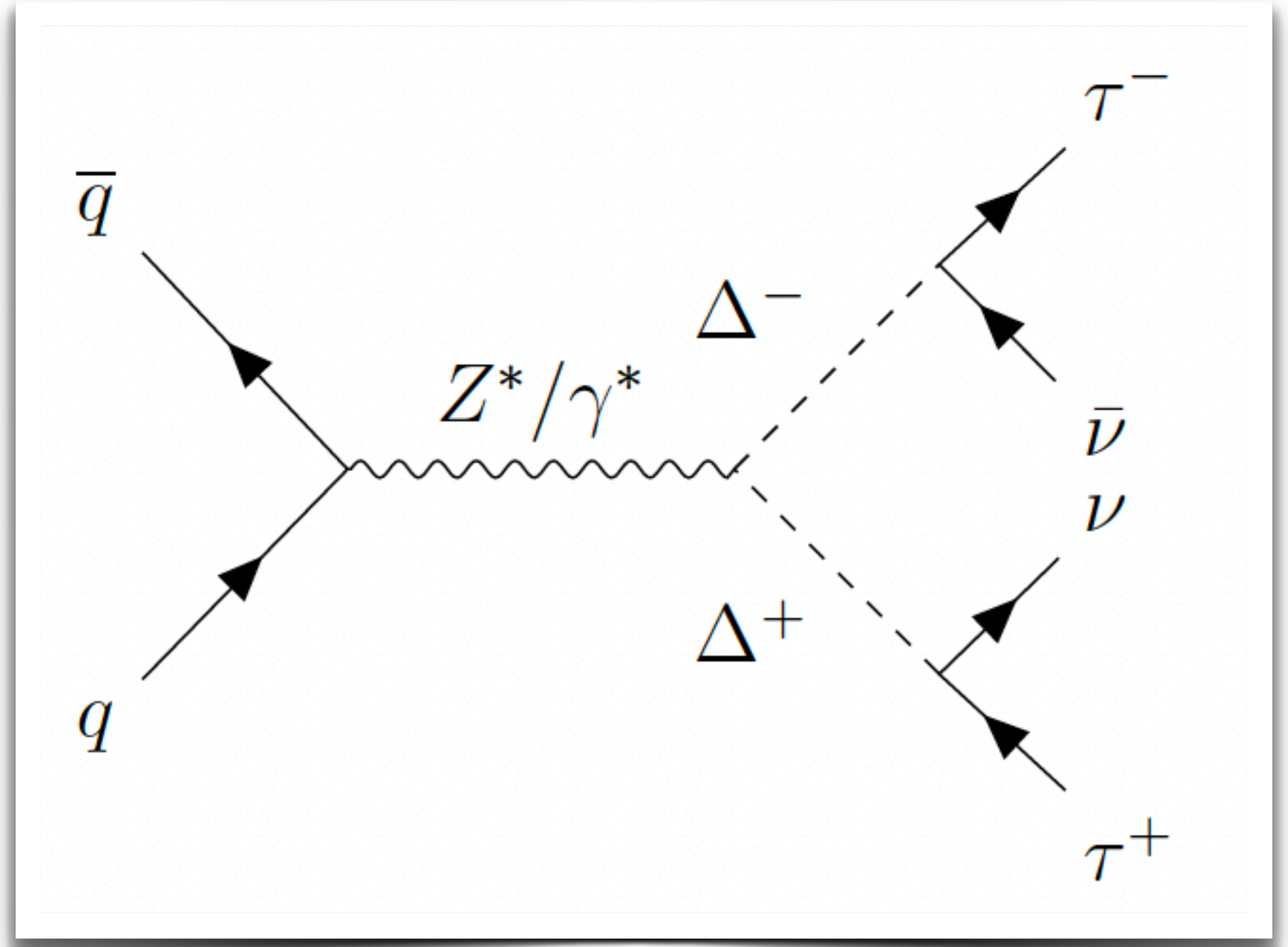
$$\lambda_{\Phi\Delta} = \frac{\alpha}{v v_\Delta}\left(m_{\Delta^0}^2 - m_{\Delta^\pm}^2\right) + \frac{2}{v^2} m_{\Delta^\pm}^2,$$

$$A = \frac{4 v_\Delta}{v^2} m_{\Delta^\pm}^2 .$$

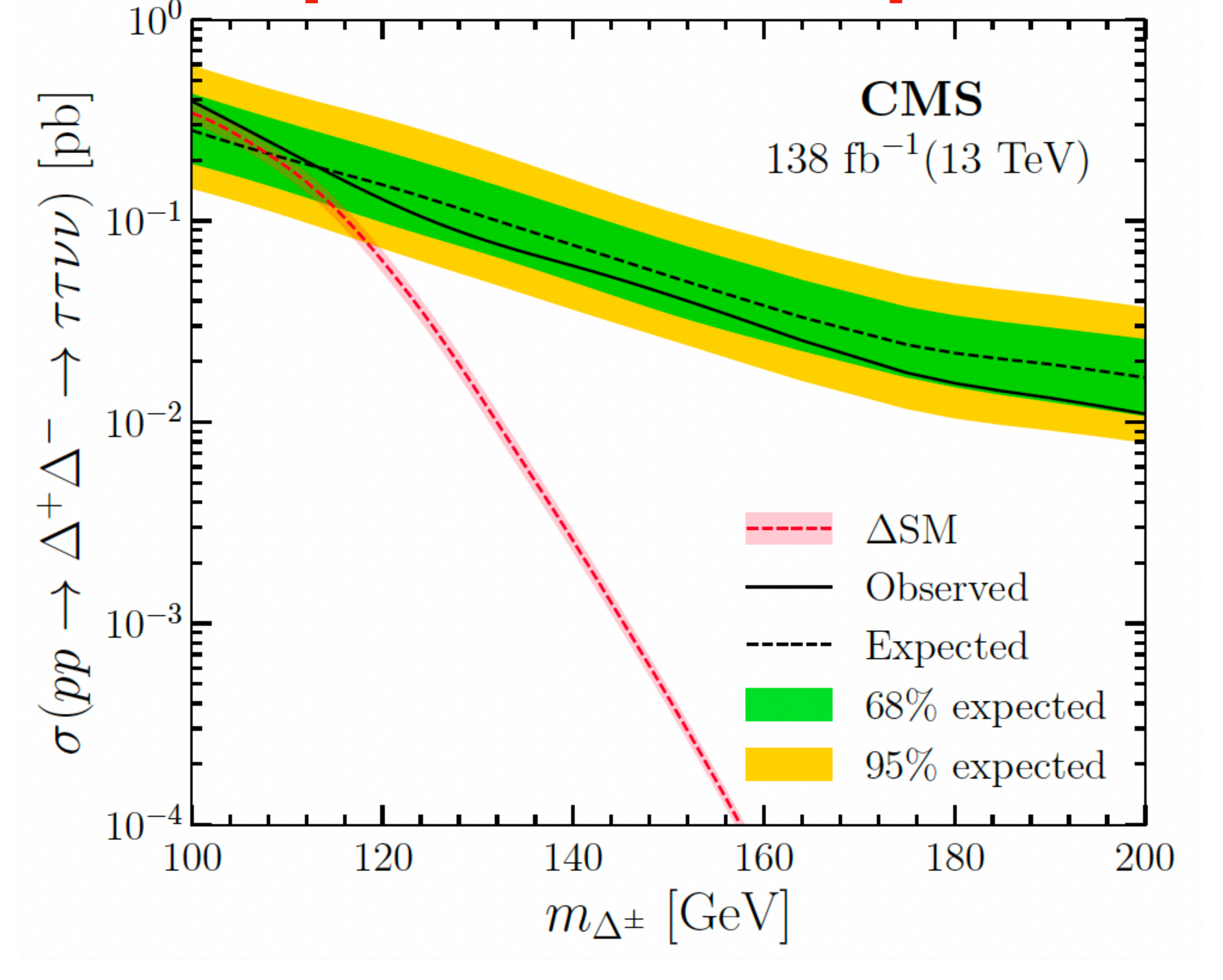
Explanation in Real Higgs Triplet

Model Constraints

- Mass of $\Delta^{\pm}$ constrained from stau-like searches



[CMS: CERN-EP-2022-032]

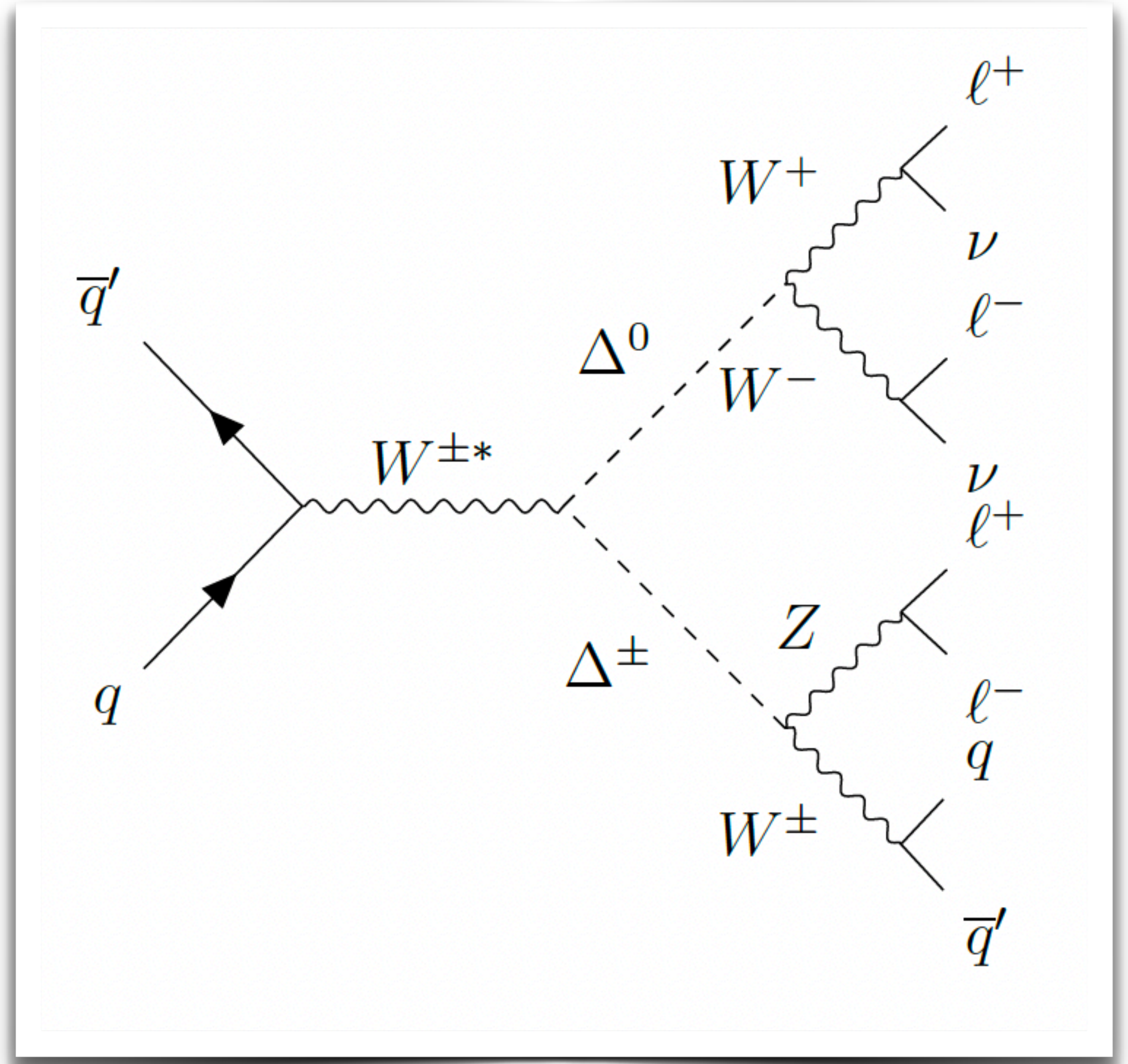


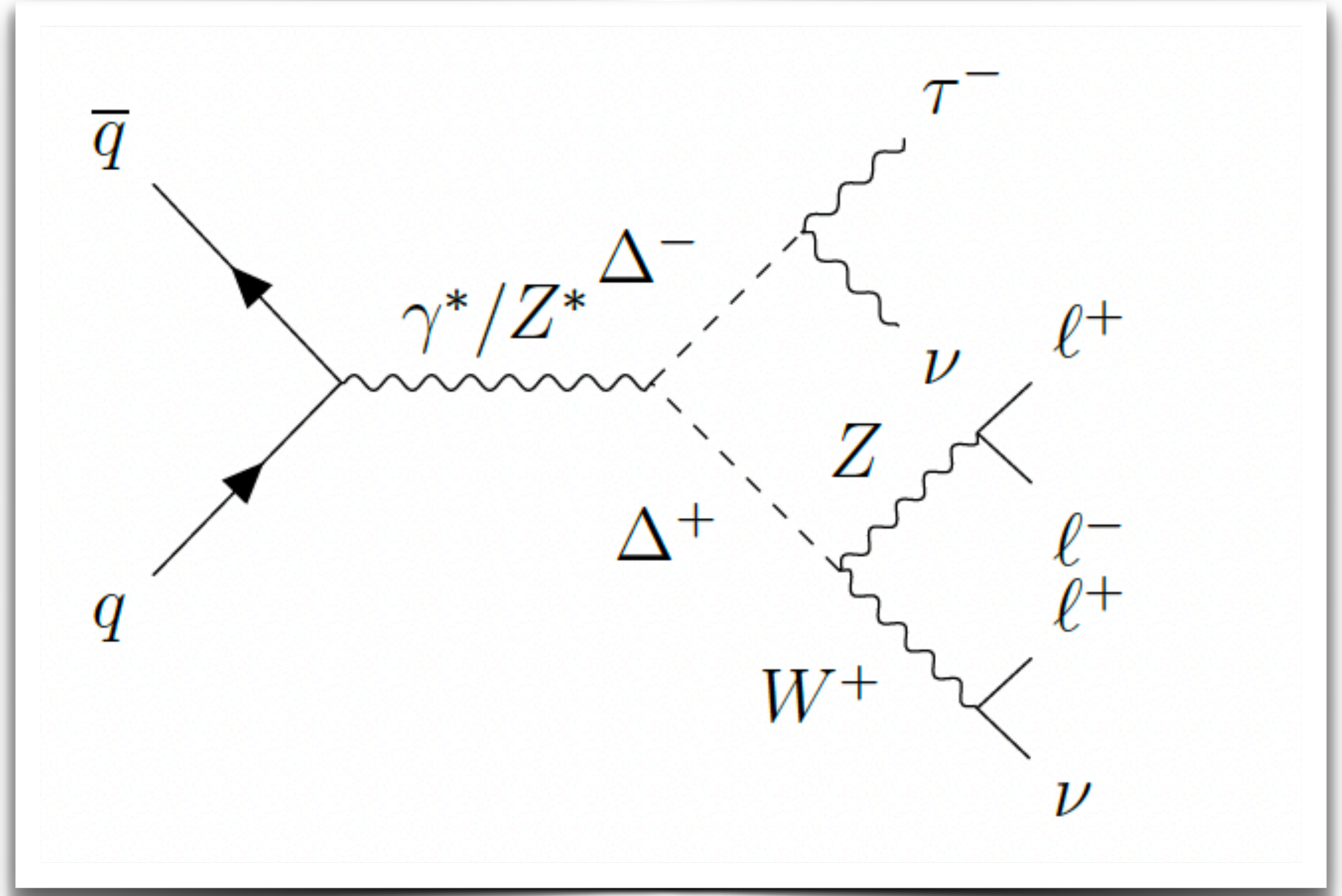
- $m_{\Delta^{\pm}} < 110$ GeV excluded at $95\ \%$ confidence level.

Explanation in Real Higgs Triplet

Model Constraints

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





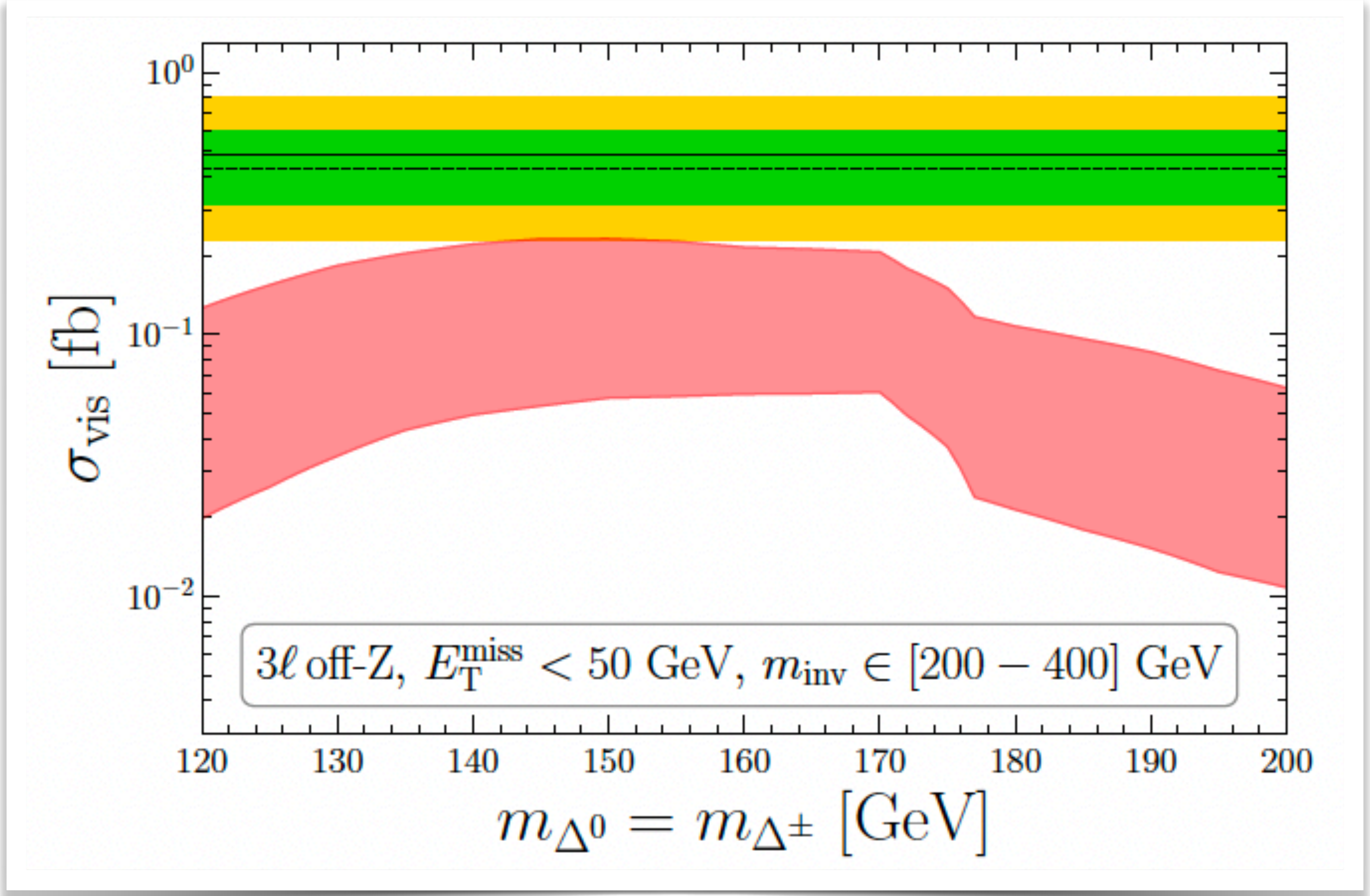
- ATLAS provides upper limit on visible cross-section for 22 SRs

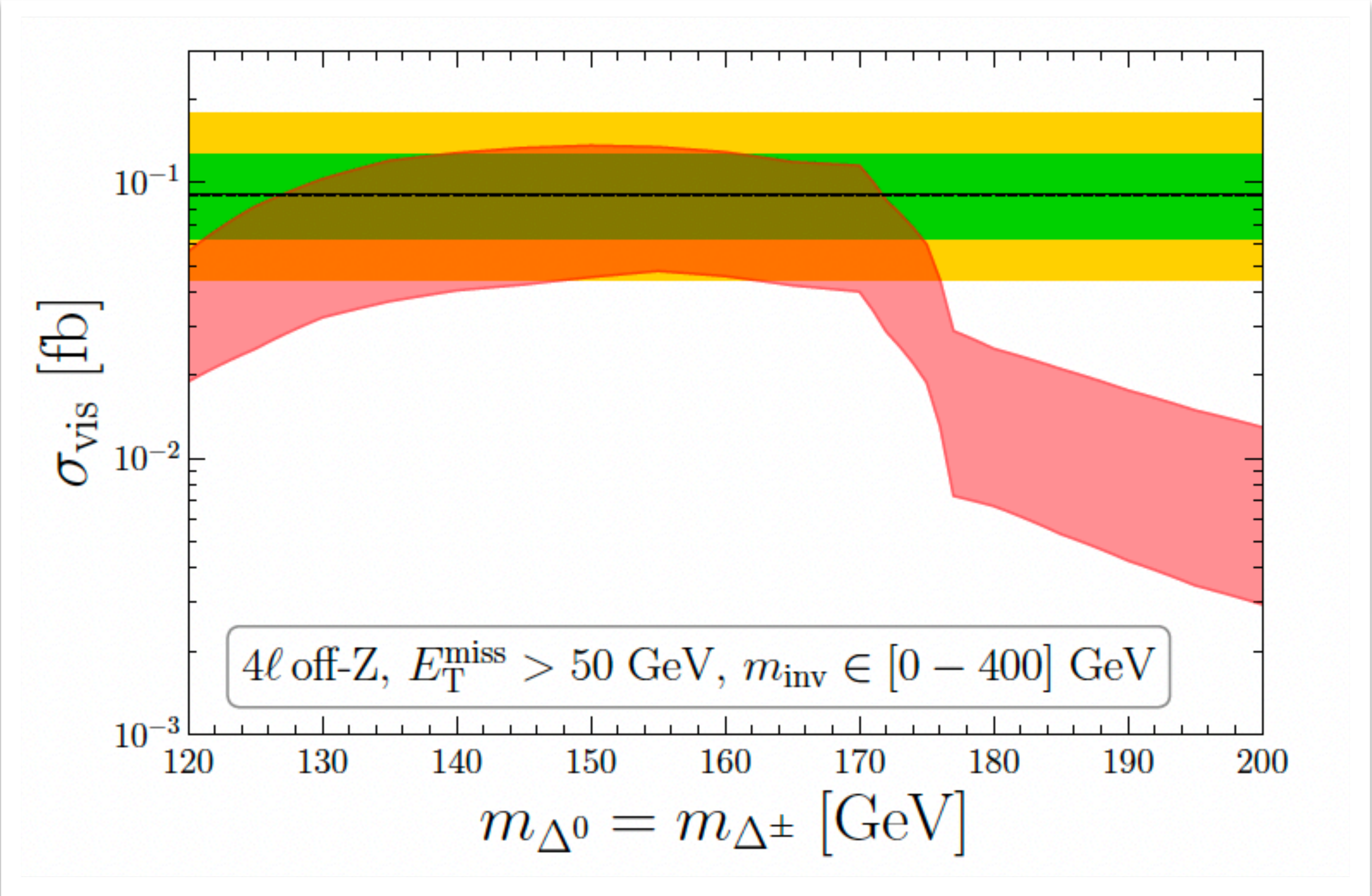
[CMS: CERN-EP-EP-2021-063]

Explanation in Real Higgs Triplet

Model Constraints

- Within $95\,\%$ CL upper limits of ATLAS

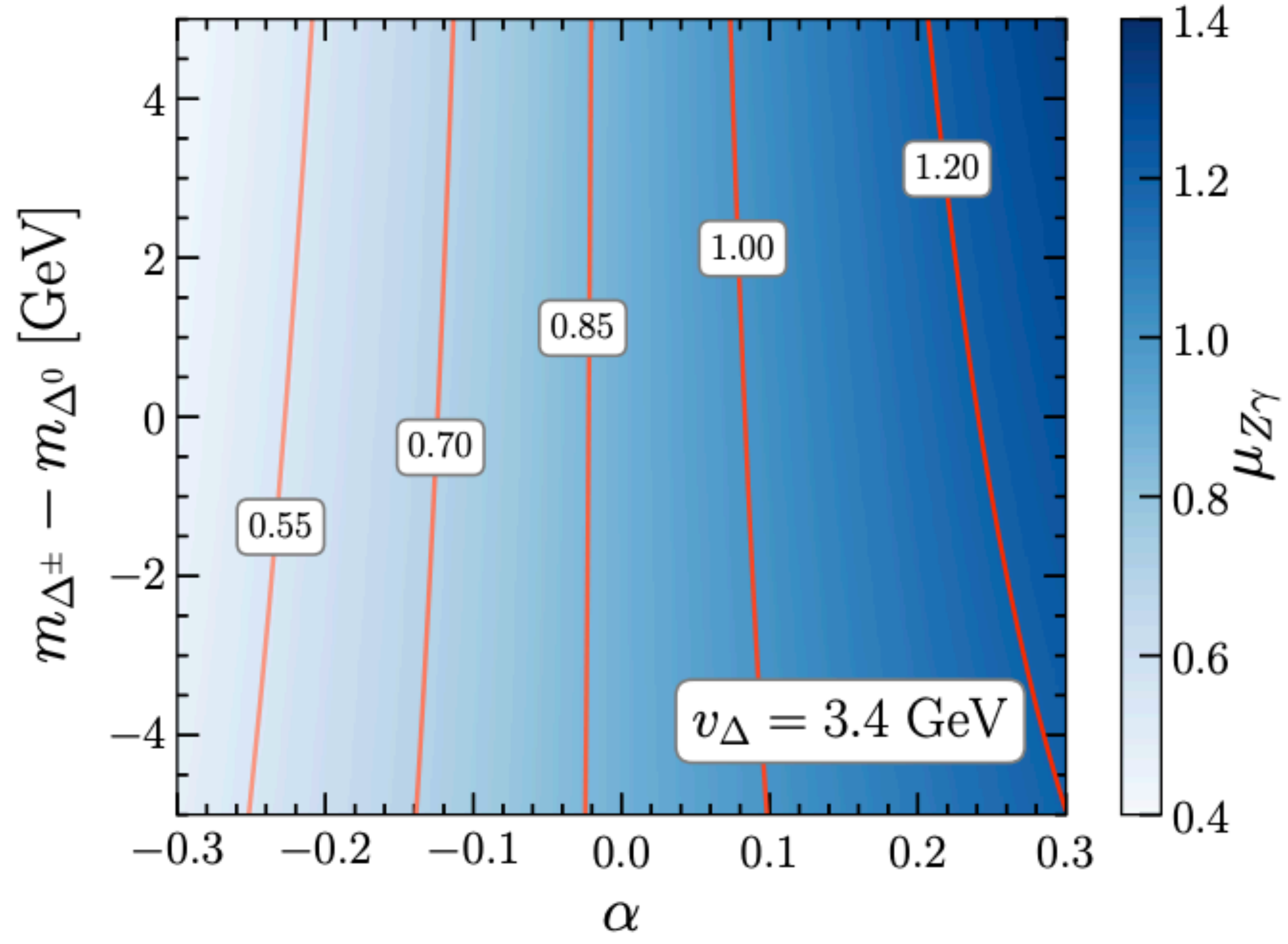


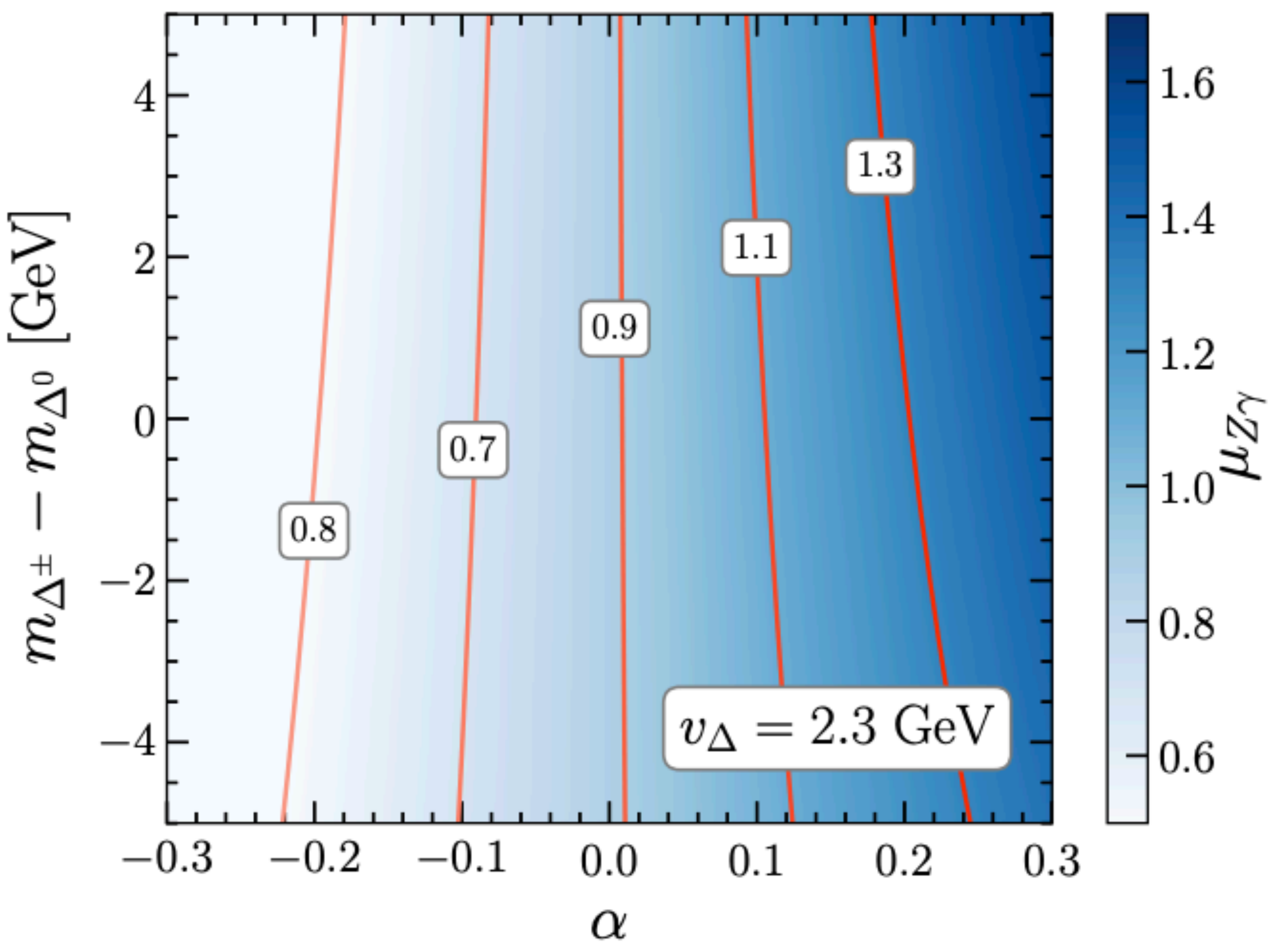


- Simulated $pp \to \Delta^0\Delta^\pm$ and $pp \to \Delta^\mp\Delta^\pm$
- Upper band obtained for Br$(\Delta^0 \to WW) = 100\,\%$

Real Higgs Triplet

$Z\gamma$

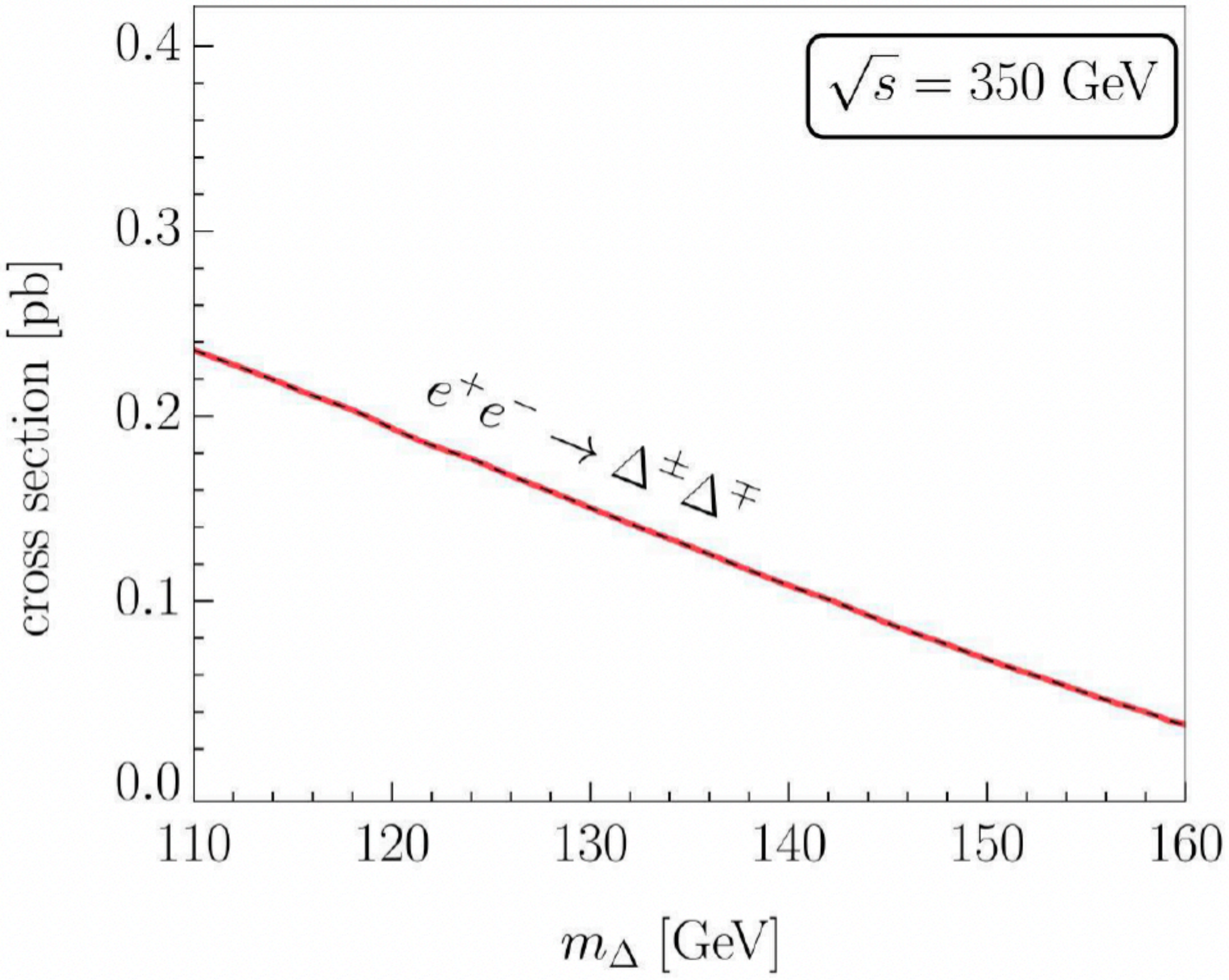


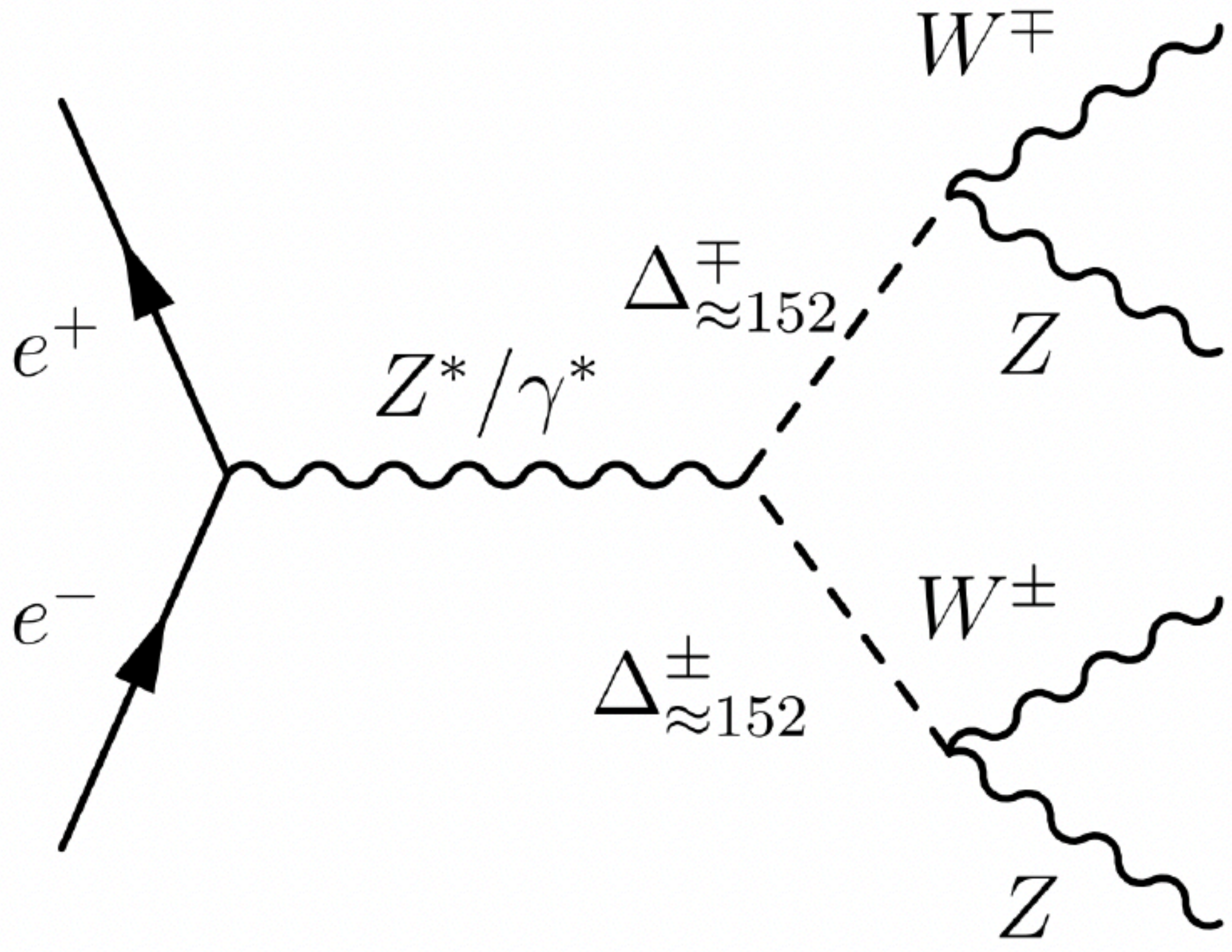


Real Higgs Triplet Prospects

FCC-ee

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

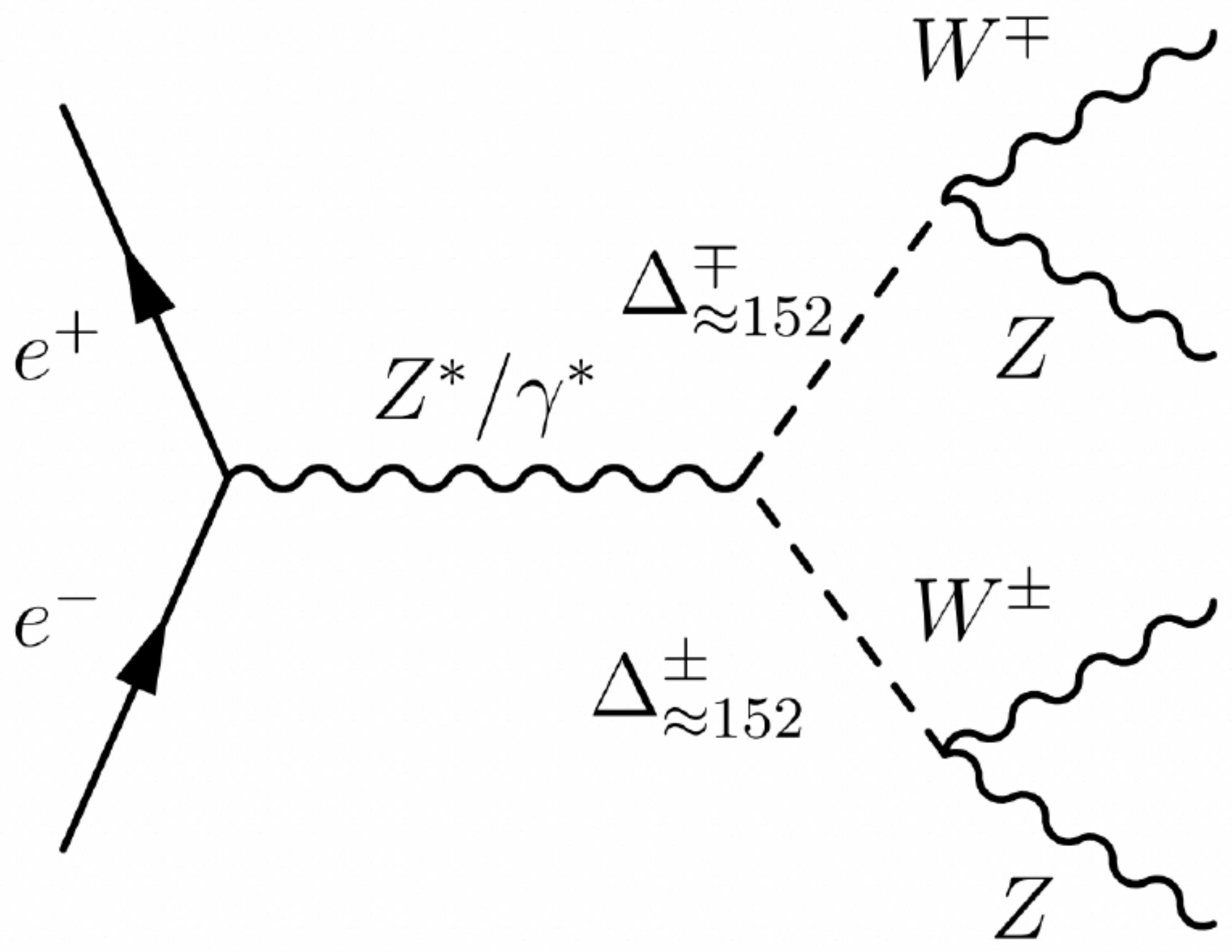




Real Higgs Triplet Prospects

FCC-ee

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



Events expected in the ΔSM model

$$e^{+}e^{-} \to \Delta^{\pm}\,\Delta^{\mp} \to 6\ell + \mathrm{MET} \approx 46$$

Events expected in the SM model

$$e^{+}e^{-} \to 6\ell(+\mathrm{MET}) \approx 1$$

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

Explanation in 2HDM

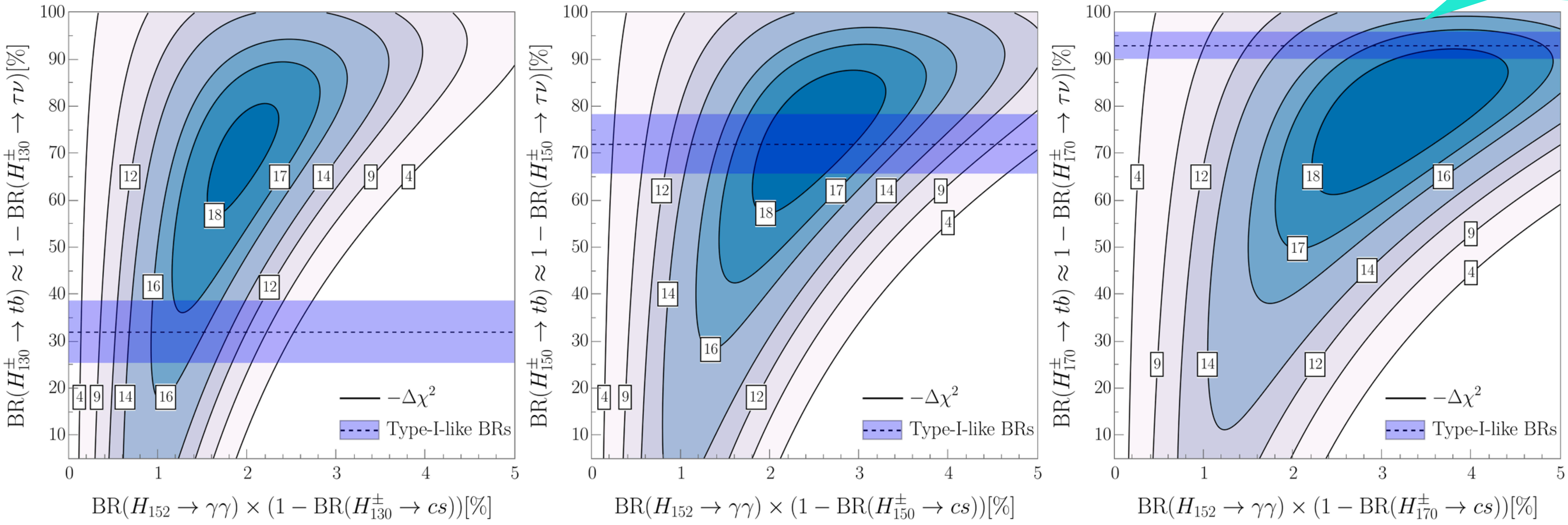
Type-I

- 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 $\gamma\gamma + t_{\text{lep}}$

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



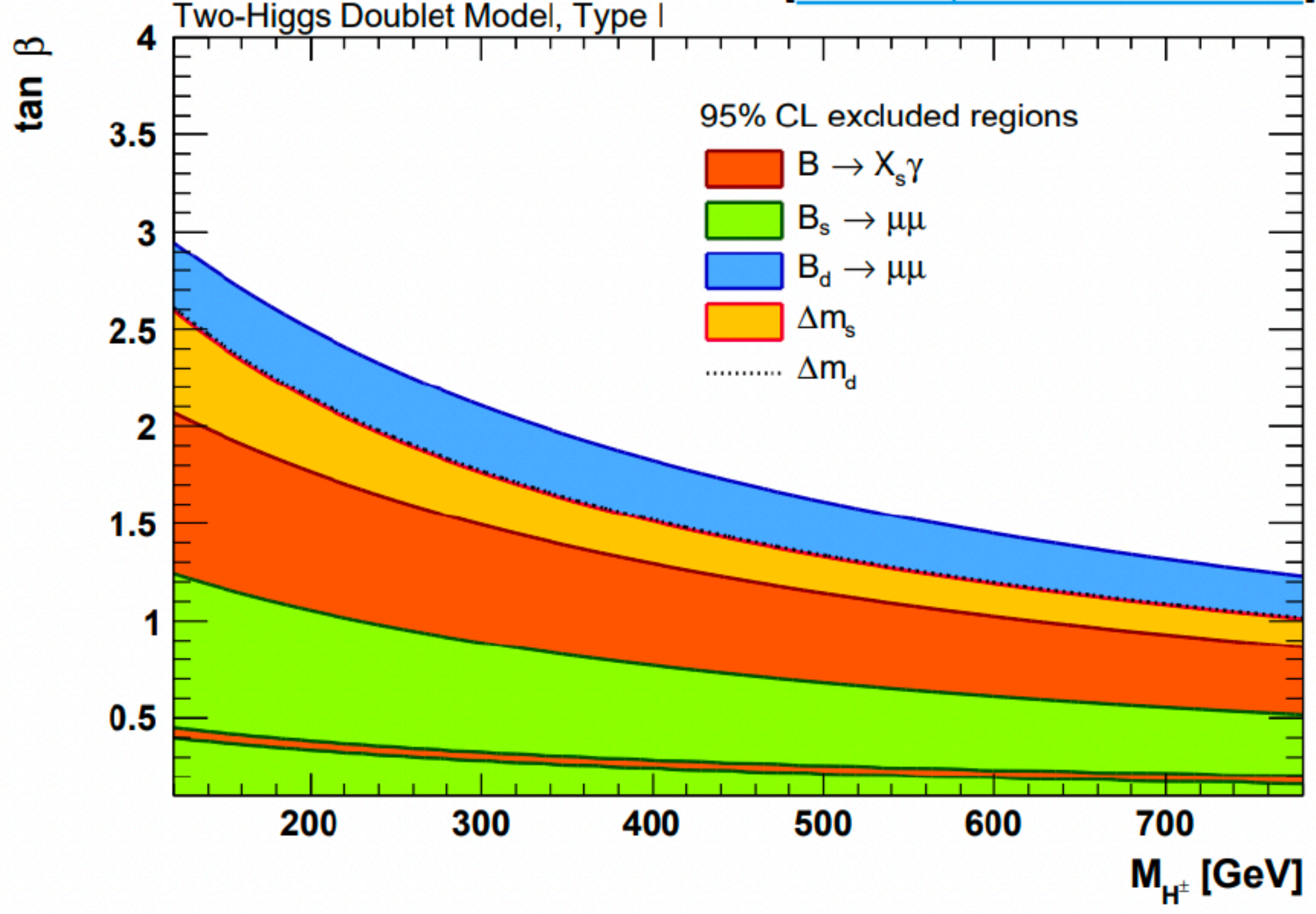
- $\mathrm{BR}(H \to \gamma\gamma)$ increases with $m_{H^{\pm}}$

Explanation in 2HDM

Explanation of $\gamma\gamma + X$ Excesses

- Bounds on $\tan(\beta)$

[J. Haller, A. Hoecker et al.]



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

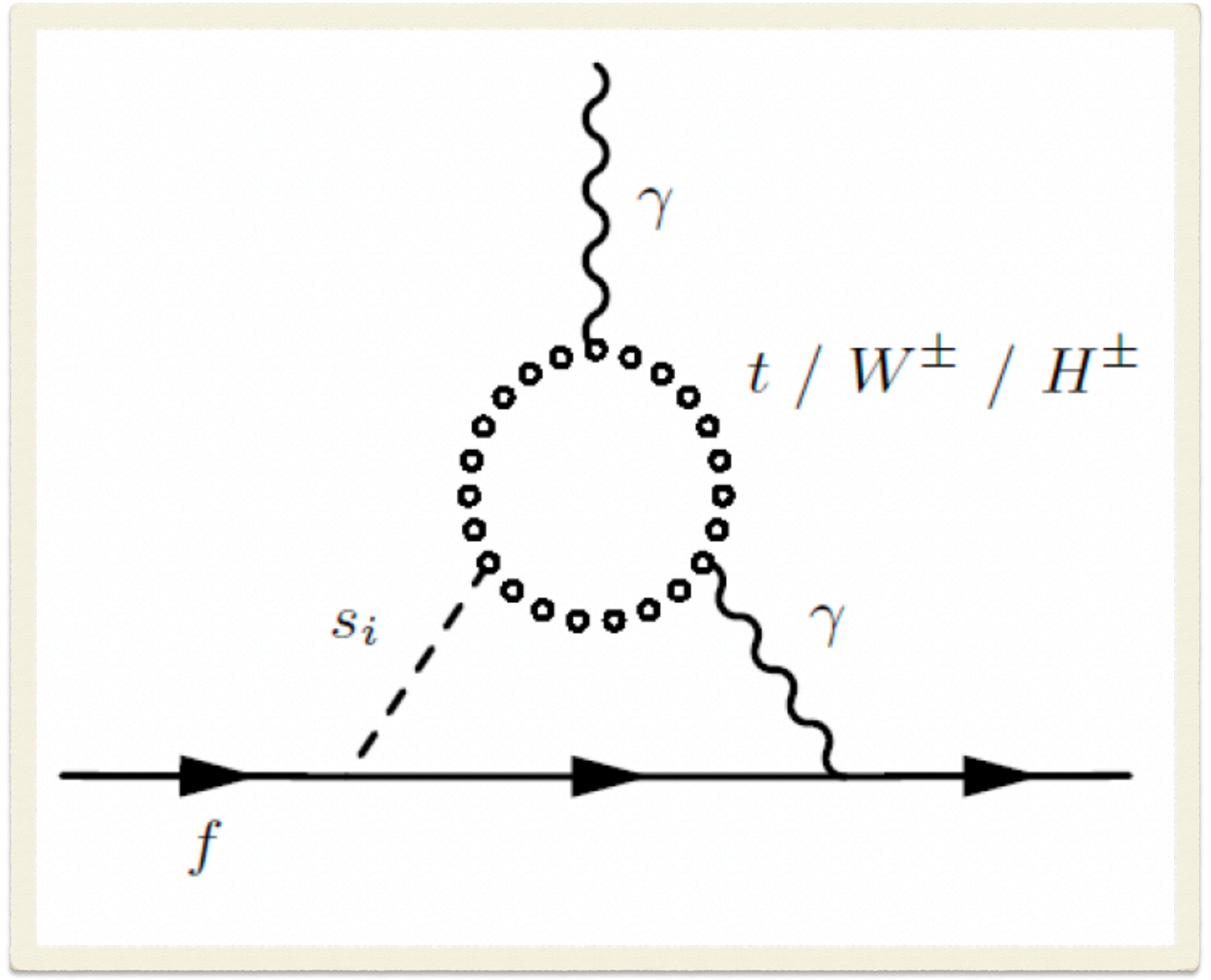
Yukawa Sector: $\zeta_u, \zeta_d, \zeta_l$ Higgs Sector: $\lambda_5, \lambda_6, \lambda_7$

We take them real

Explanation in 2HDM

EDM Constraints

- $\mathrm{Im}(\lambda_6)$ drives $\mathrm{Br}(A \to \gamma\gamma)$



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

- Correlate with EDM constraints

- Transform Lagrangian to Higgs Basis

$m_{11}^2, m_{22}^2, m_{12}^2$ $\lambda_1, \cdots, \lambda_7$ $\langle\phi_1\rangle = v_1, \langle\phi_2\rangle = v_2$	→	Y_1, Y_2, Y_3 $Z_1, \cdots, Z_7$ $\langle\phi_1\rangle = v, \langle\phi_2\rangle = 0$

- Used analytic expressions of [arXiv: 2009.01258]

Explanation in 2HDM

EDM Constraints

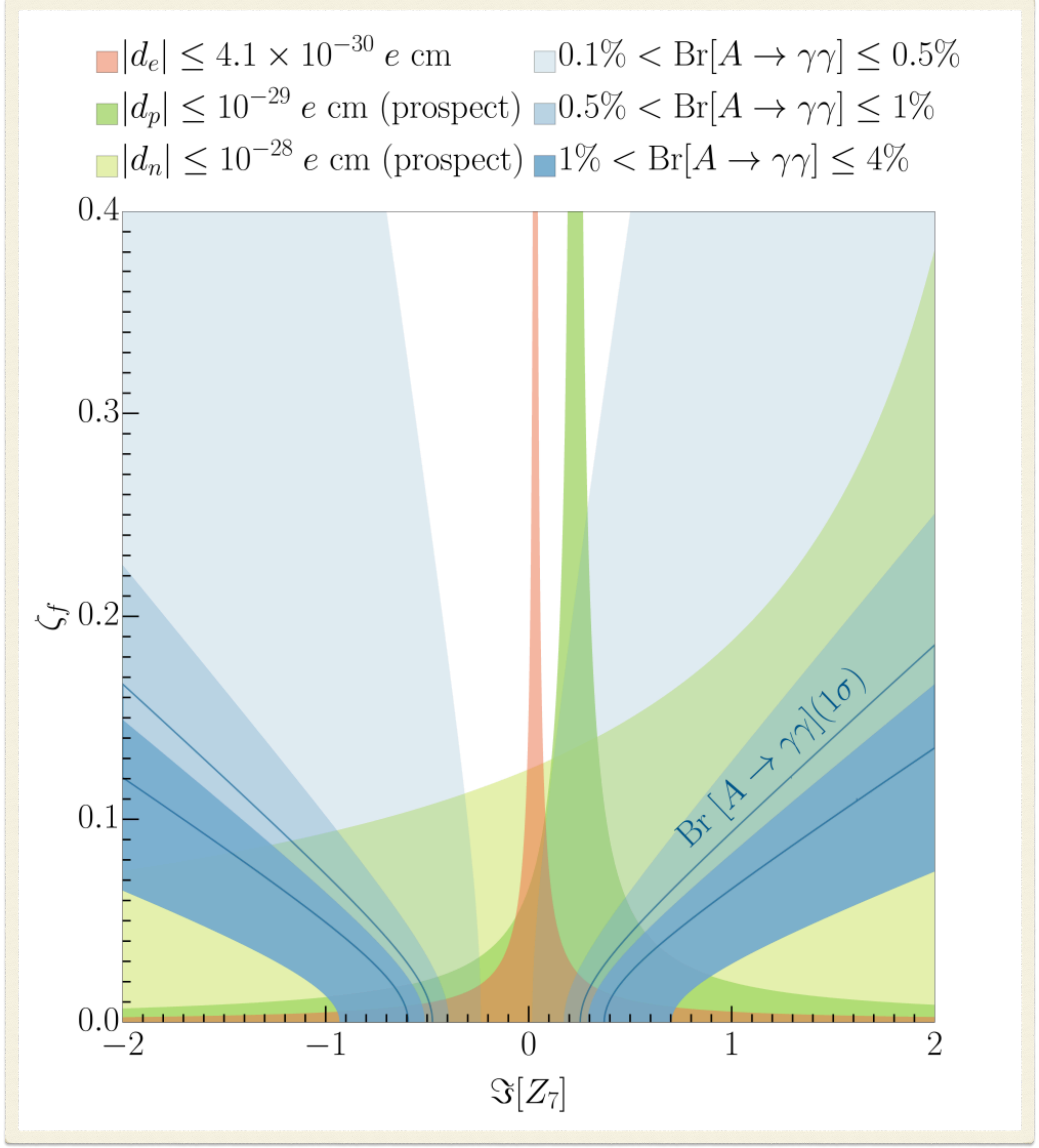
- eEDM gives stringent bounds: $10^{-30} e\, cm^{-1}$
  [arXiv:2212.11841]

- Projection for nEDM and pEDM considered

  nEDM $\leq 10^{-28} e\, cm^{-1}$; pEDM $\leq 10^{-29} e\, cm^{-1}$
  [EPJ Web Conf. 262 (2022) 01015] [arXiv:2007.10332]

- Benchmark Point:

$$m_H = 200 \text{ GeV}, m_{H\pm} = 130 \text{ GeV}, m_A = 152 \text{ GeV}$$
$$Z_2 = -Z_3 = 0.2, \text{Re}(Z_7) = 0.1, \theta_{12} = 0.001$$
$$\theta_{13} = \theta_{23} = 0.01, \zeta_l = \zeta_u = \zeta_d = \zeta_f$$



Explanation in 2HDM

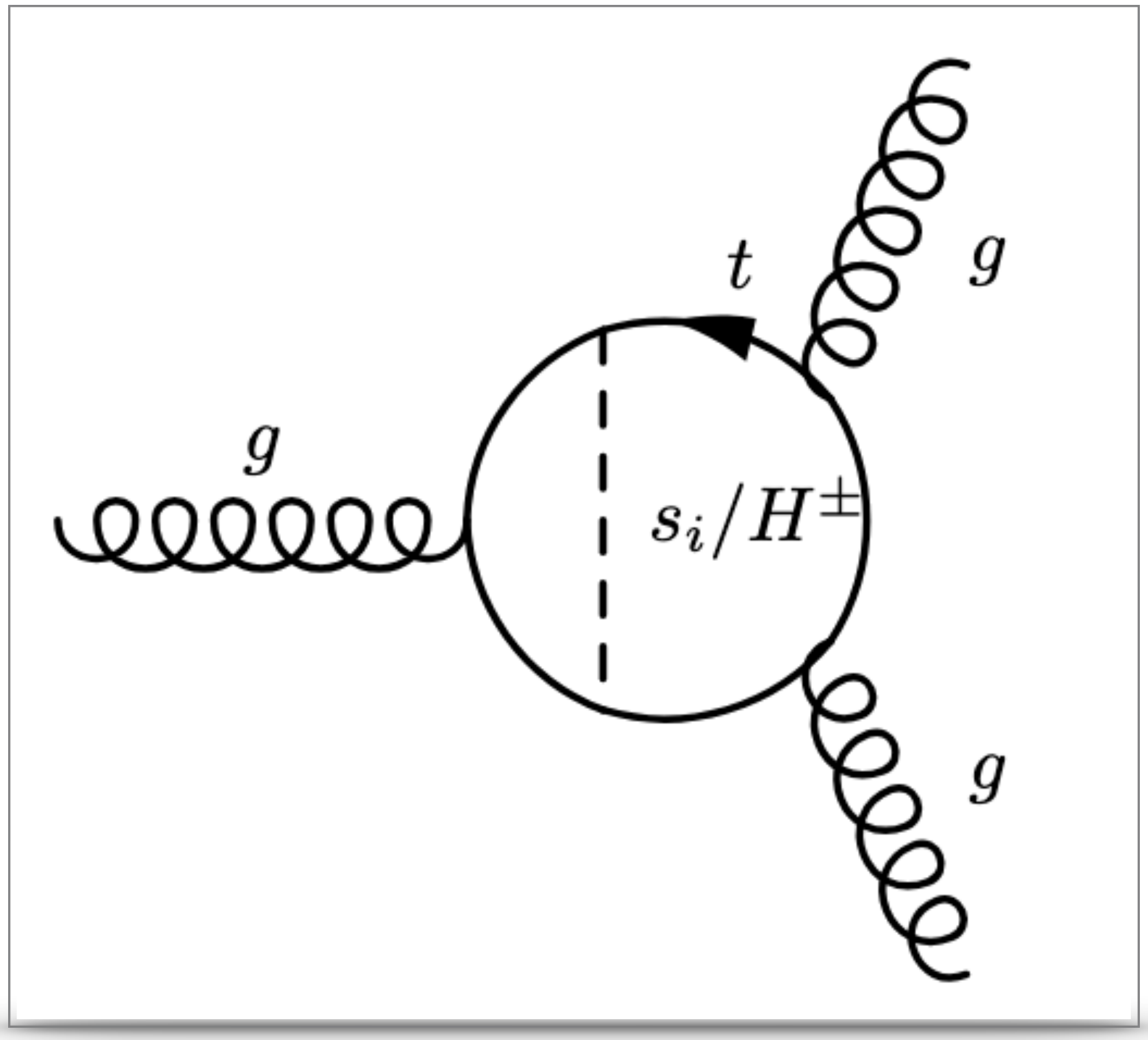
nEDM

- 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 $H \to \gamma\gamma$

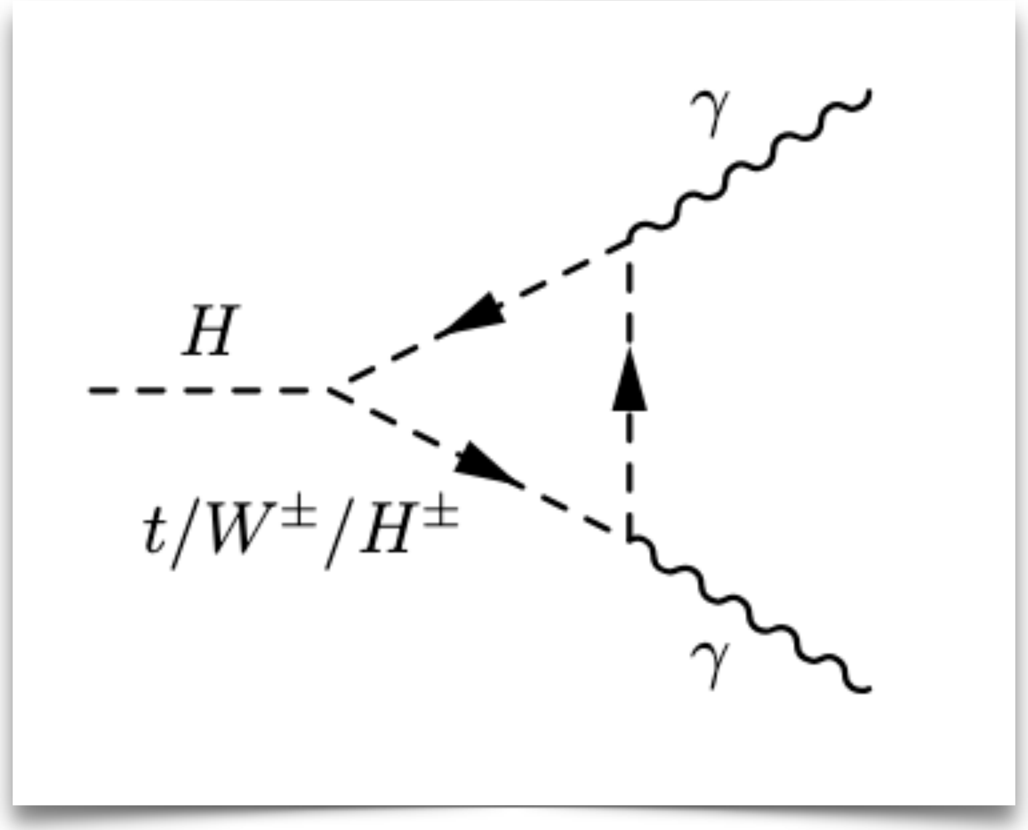
- Large Br$(H \to \gamma\gamma)$ possible in general 2HDM

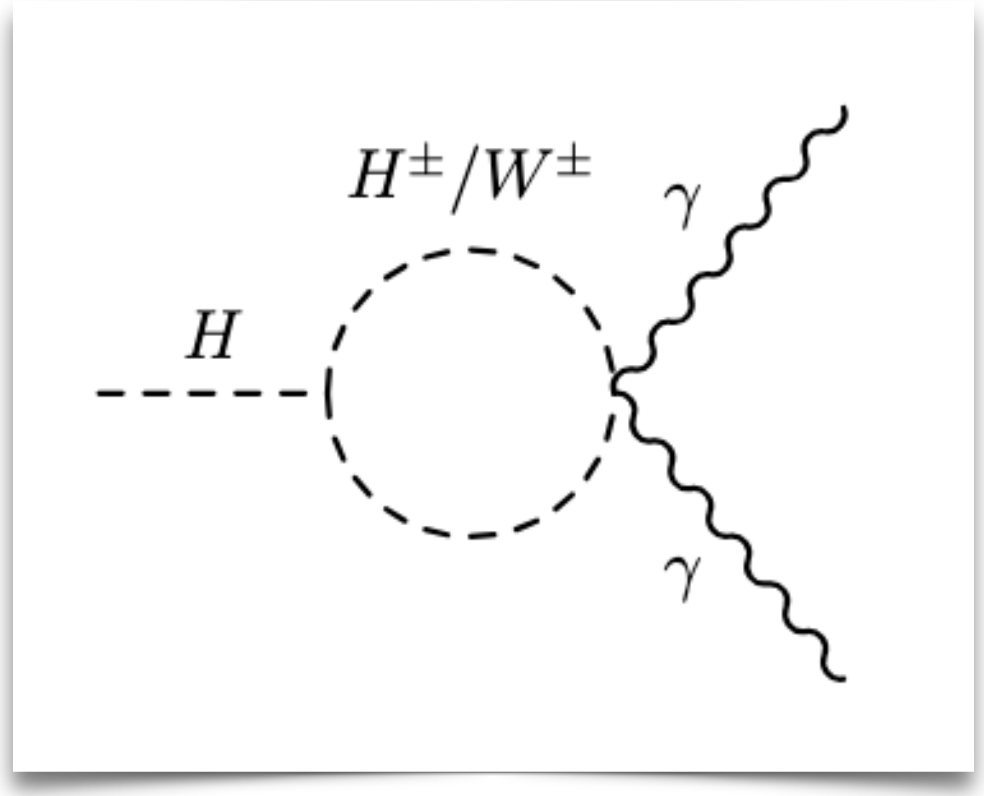
Z_2 symmetry broken

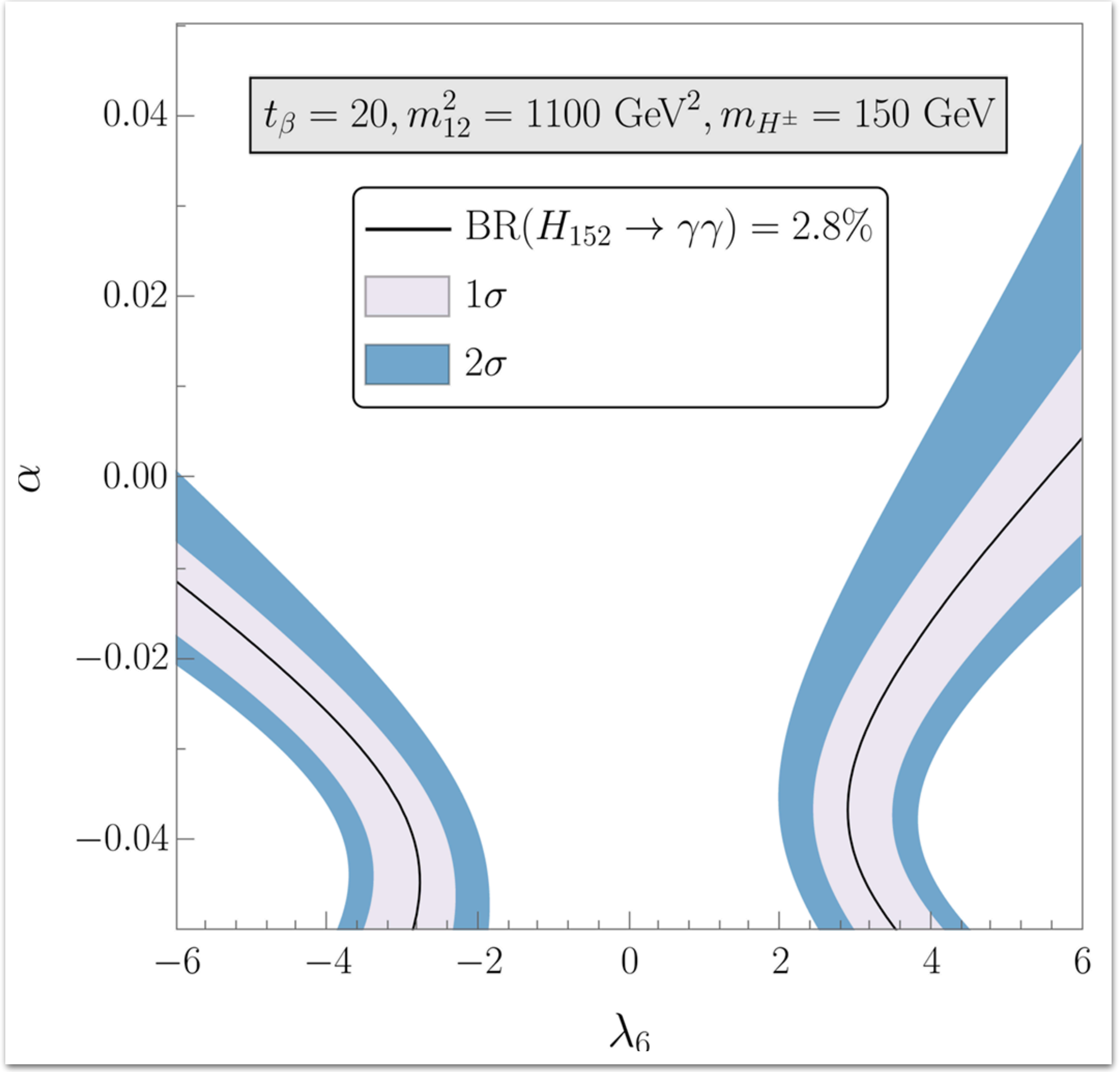
$$\mathscr{L} \in -\lambda_6 H_1^\dagger H_1 H_2^\dagger H_1 + \mathrm{h.c.},.$$

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

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



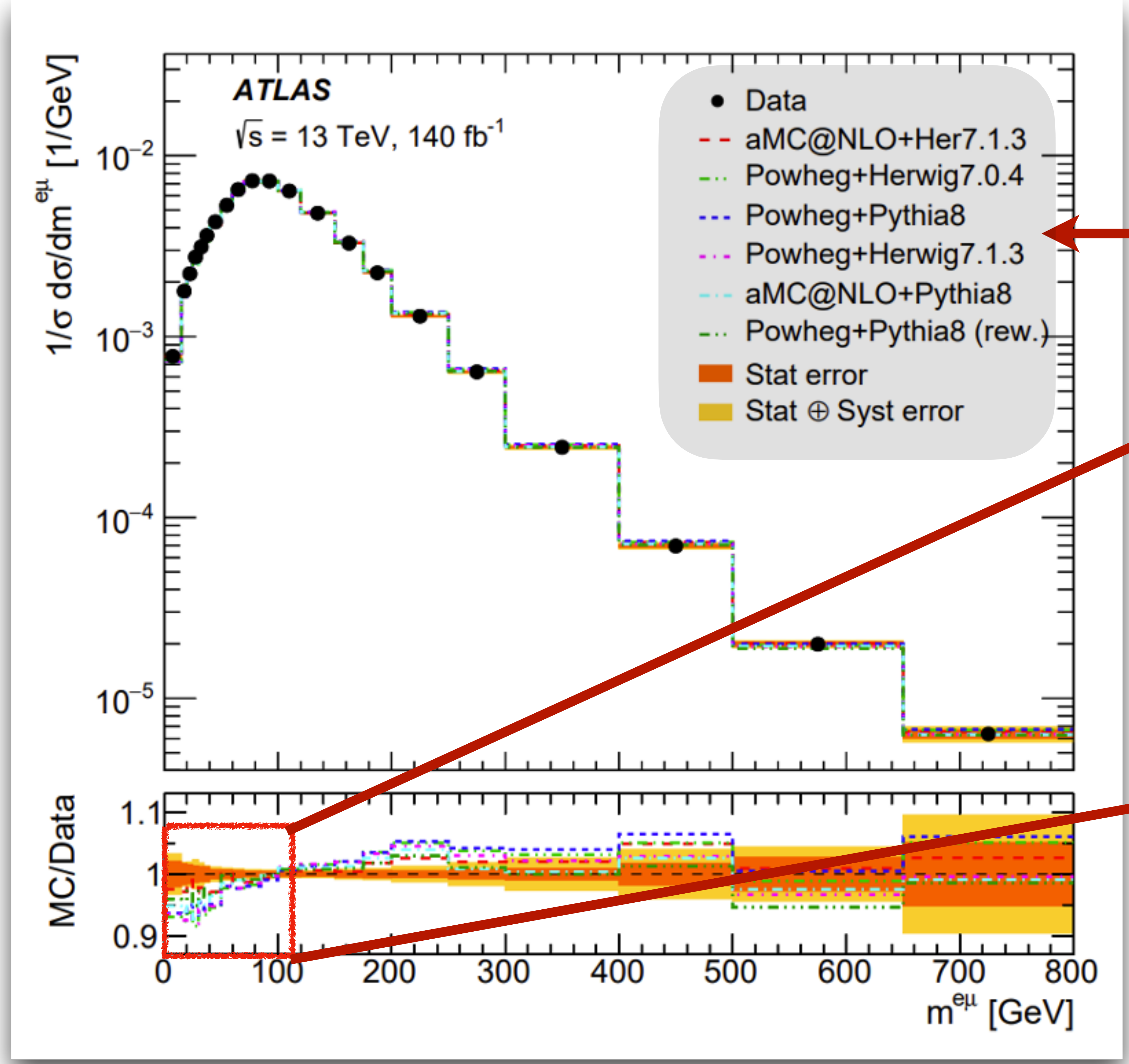




Deviations in $t\bar{t}$ Differential cross-section

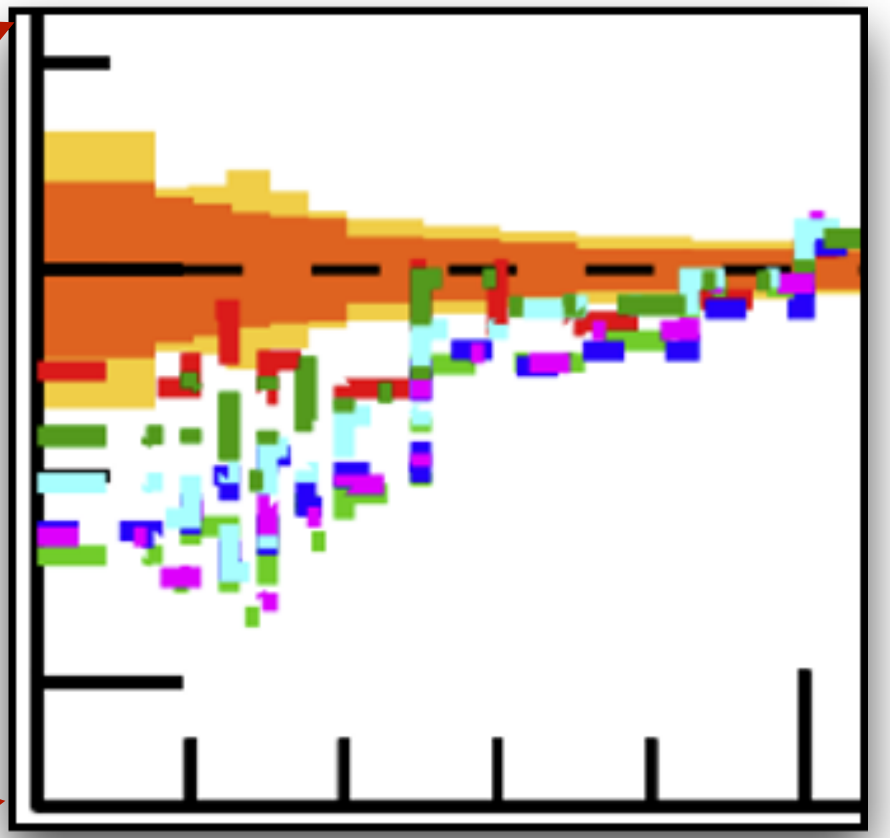
No match with SM

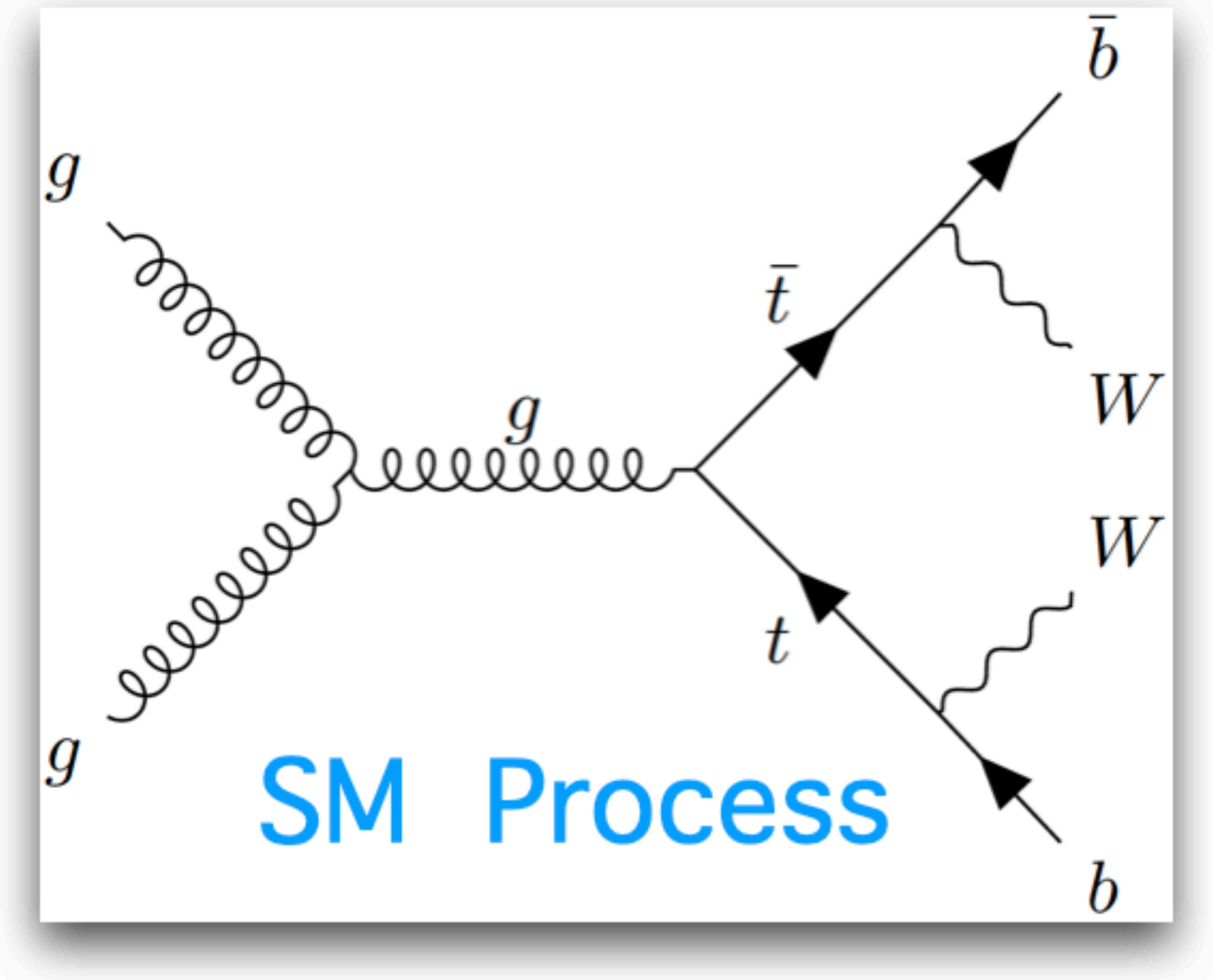
[ATLAS: CERN-EP-2023-016]



[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.



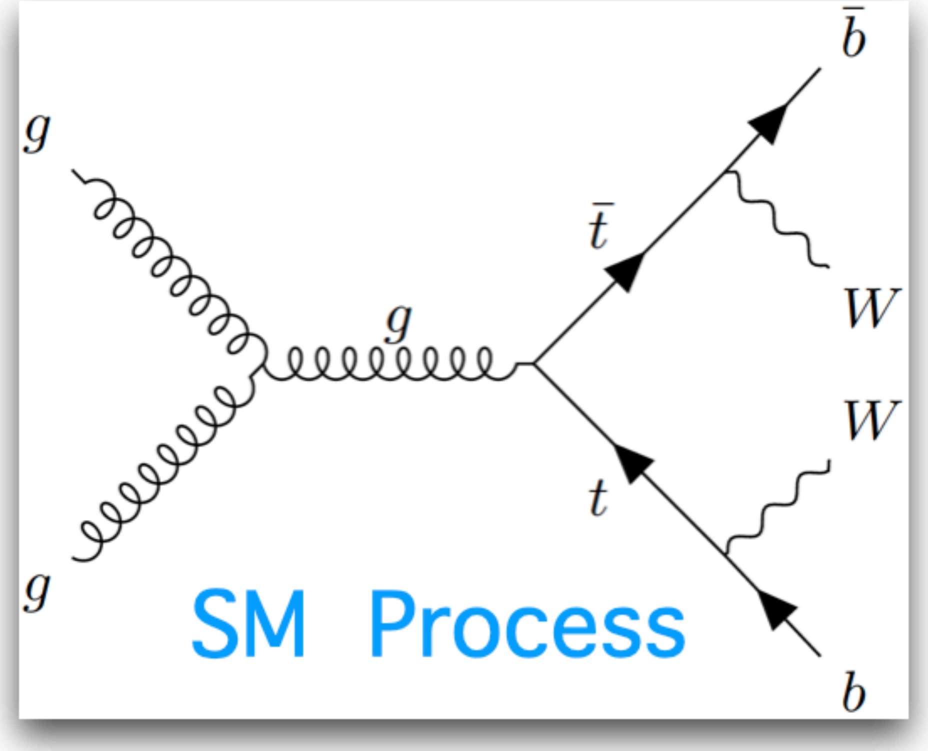


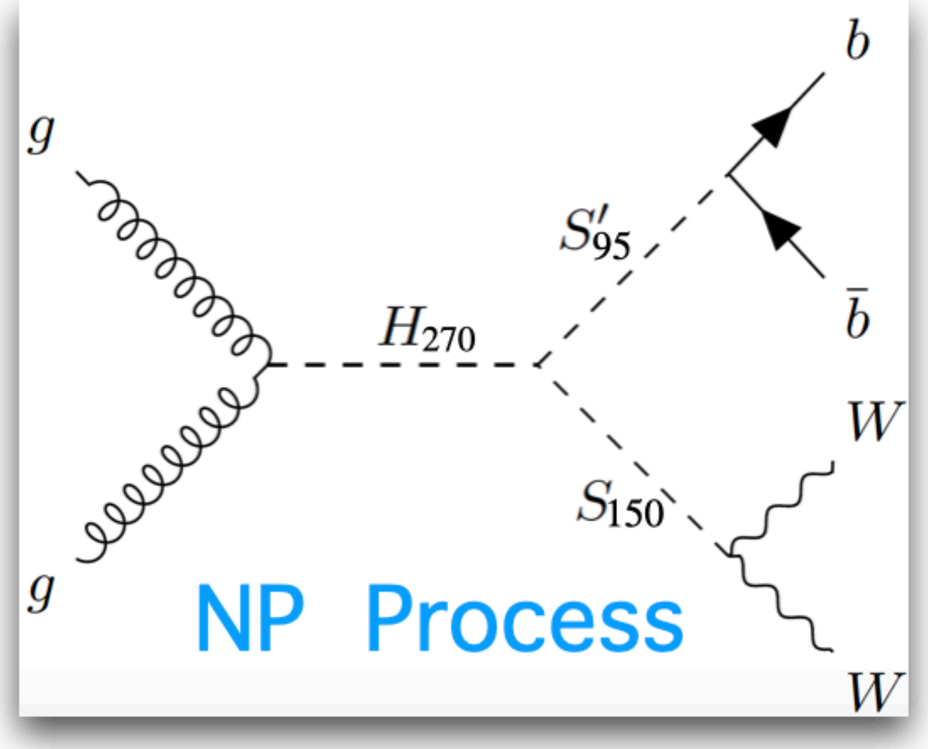
Mismodelling of SM or NP effects?

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

NP Results

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





(SB, A. Crivellin et al.)
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