

Long-lived neutral scalars in the Type-II seesaw

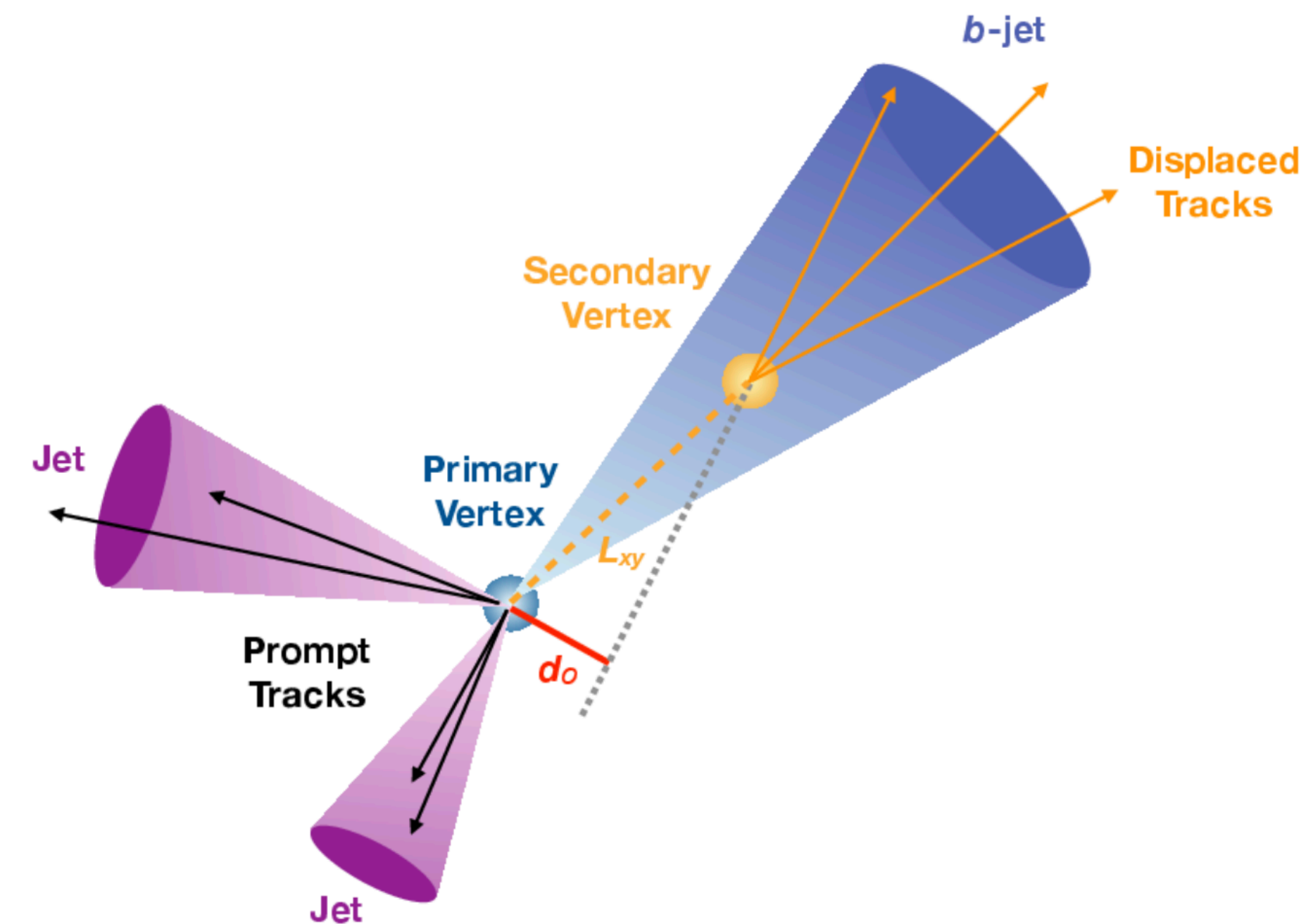
Can the Type-II seesaw produce viable neutral displaced signatures?

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Why look for long-lived neutral scalars?

- Neutrino masses motivate physics beyond the Standard Model.
- New particles can produce displaced, rather than prompt, signatures.
- Fully exploiting the LHC requires sensitivity to these signatures.

Our target: a neutral scalar decaying away from the collision point, potentially into $b\bar{b}$.



Configuration and performance of the ATLAS b -jet triggers in Run 2 - Aad, Georges et al - arXiv:2106.03584 CERN-EP-2021-032

A short route from the triplet to neutrino masses

Gauge quantum numbers:

- Higgs doublet $\phi \sim (1, 2, 1/2)$
- Scalar triplet $\Delta \sim (1, 3, 1)$

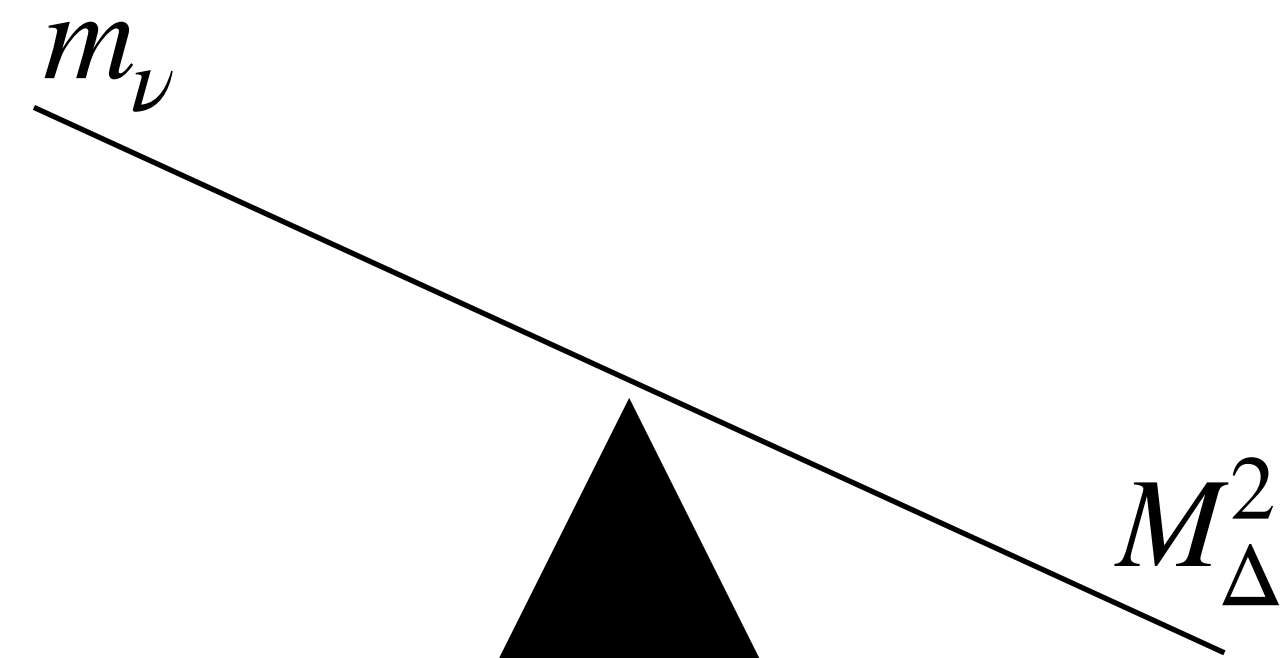
$$\mathcal{L}_\Delta = \mathcal{L}_{\Delta,kin} + \mathcal{L}_{\Delta,yuk} - V_\Delta$$

$$\mathcal{L}_{\Delta,yuk} = -Y_{ij}L_i^T C i\tau_2 \Delta L_j + h.c.$$

$$V_\Delta \supset i\mu_{h\Delta}\Phi^T \tau_2 \Delta^\dagger \Phi + h.c.$$

$$\Phi = \begin{pmatrix} \tilde{\phi}^+ \\ \frac{h+v+i\eta}{\sqrt{2}} \end{pmatrix} \quad \Delta = \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \frac{d_0+v_d+i\chi}{\sqrt{2}} & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix}$$

$$M_\nu = Y_\Delta v_\Delta \sqrt{2} = \frac{\mu v^2}{\sqrt{2} M_\Delta^2} Y_\Delta$$



The physical states and their mass splitting

After symmetry breaking:

h , $\rightarrow$ observed Higgs

$\Delta^{\pm\pm}, \Delta^{\pm}, \Delta^0, \chi$ $\rightarrow$ additional
scalar states

Δ^0 : CP-even neutral scalar

χ : CP-odd neutral scalar

Leading order masses ($\epsilon \rightarrow 0$):

$$M_{\Delta^{++}}^2 \simeq M_{\delta^{++}}^2 = m_{\Delta}^2 + \frac{1}{2}v^2\lambda_{h\Delta 1}$$

$$M_{\Delta^+}^2 \simeq M_{\delta^+}^2 = m_{\Delta}^2 + \frac{1}{2}v^2\lambda_{h\Delta 1} + \frac{1}{4}v^2\lambda_{h\Delta 2}$$

$$M_{\Delta^0}^2 \simeq M_{d_0}^2 = \frac{1}{2}(m_{\Delta}^2 + \frac{1}{2}v^2\lambda_{h\Delta 1} + \frac{1}{2}v^2\lambda_{h\Delta 2})$$

Sum rule:

Equal mass spacing between components

$$M_{\Delta^+}^2 - M_{\Delta^{++}}^2 \simeq M_{\Delta^0}^2 - M_{\Delta^+}^2 \simeq \frac{v^2\lambda_{h\Delta 2}}{4}$$

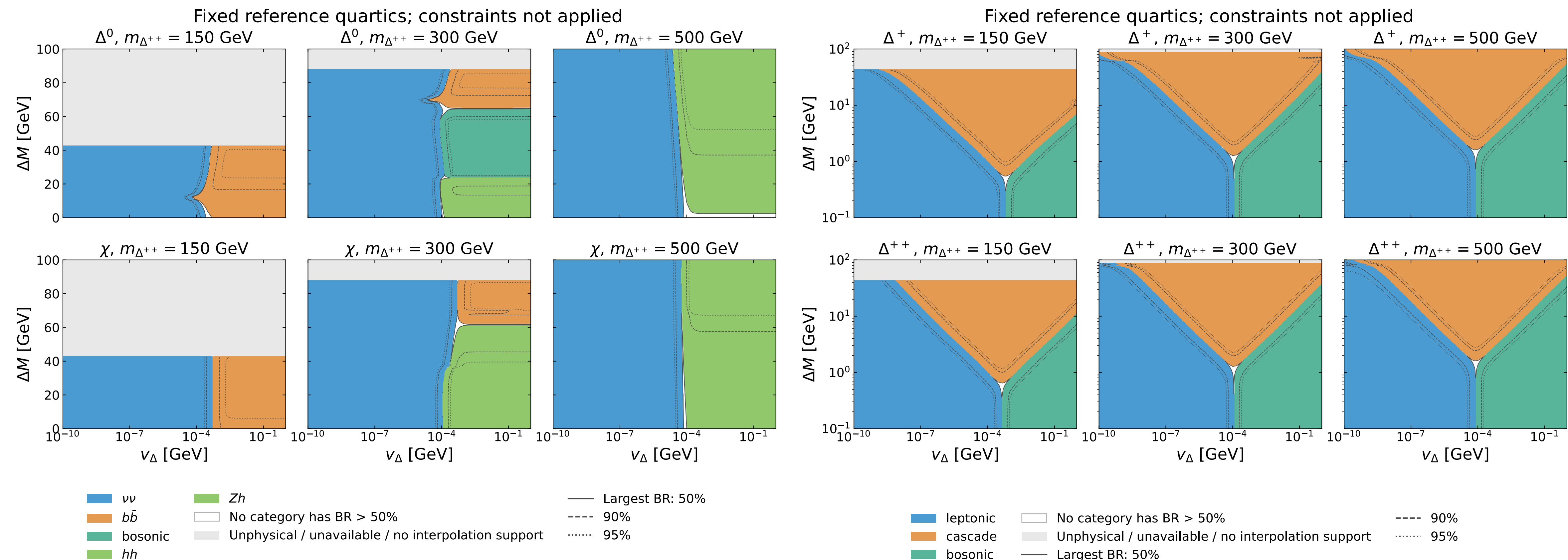
Two hierarchies:

$$M_{\Delta^{++}} < M_{\Delta^+} < M_{\Delta^0}, \quad \lambda_{h\Delta 2} > 0$$

$$M_{\Delta^0} < M_{\Delta^+} < M_{\Delta^{++}}, \quad \lambda_{h\Delta 2} < 0$$

$$\Delta M \equiv m_{\Delta^{++}} - m_{\Delta^+} > 0$$

What controls the decay regimes?



Ingredient	Main effect
Small ν_Δ	Larger triplet Yukawa couplings, stronger leptonic/neutrino decays
Charged-neutral mass gaps	Open charged cascades
Neutral mixing and tresholds	Determine competition between visible and invisible decays

Small mixing can control visible decays

CP-even mixing:

$$h = \cos(\xi)\phi + \sin(\xi)d_0 \simeq \phi$$

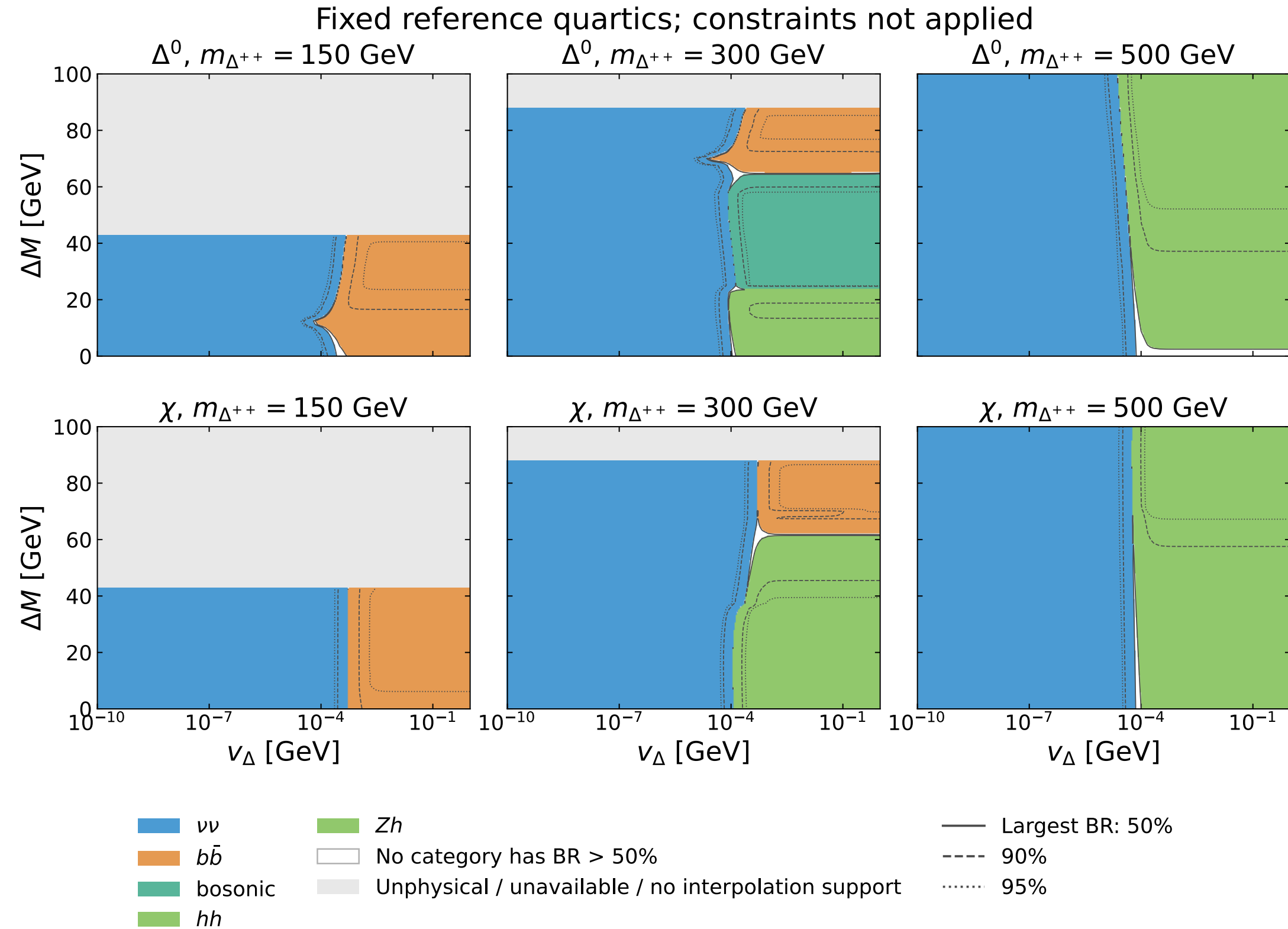
$$\Delta^0 = \cos(\xi)d_0 - \sin(\xi)\phi \simeq d_0$$

$$g_{\Delta^0\nu\nu} = \sqrt{2}Y_\Delta\cos(\xi) = \frac{M_\nu}{v_\Delta}\cos(\xi)$$

$$g_{\Delta^0 b\bar{b}} \sim \frac{m_b}{v}\sin(\xi)$$

$$g_{\Delta^0 WW} \sim v_\Delta\cos(\xi) - \frac{v}{2}\sin(\xi)$$

Visible branching fractions can change strongly even when the mixing angle is small.



The CP-odd state χ has a different mixing structure.

$$g_{\chi b\bar{b}} \sim \frac{2m_b v_\Delta}{v \sqrt{v^2 + 4v_\Delta^2}}$$

From a small width to a displaced signal

Three steps:

1. Proper decay length

$$c\tau = \frac{\hbar c}{\Gamma_{total}}$$

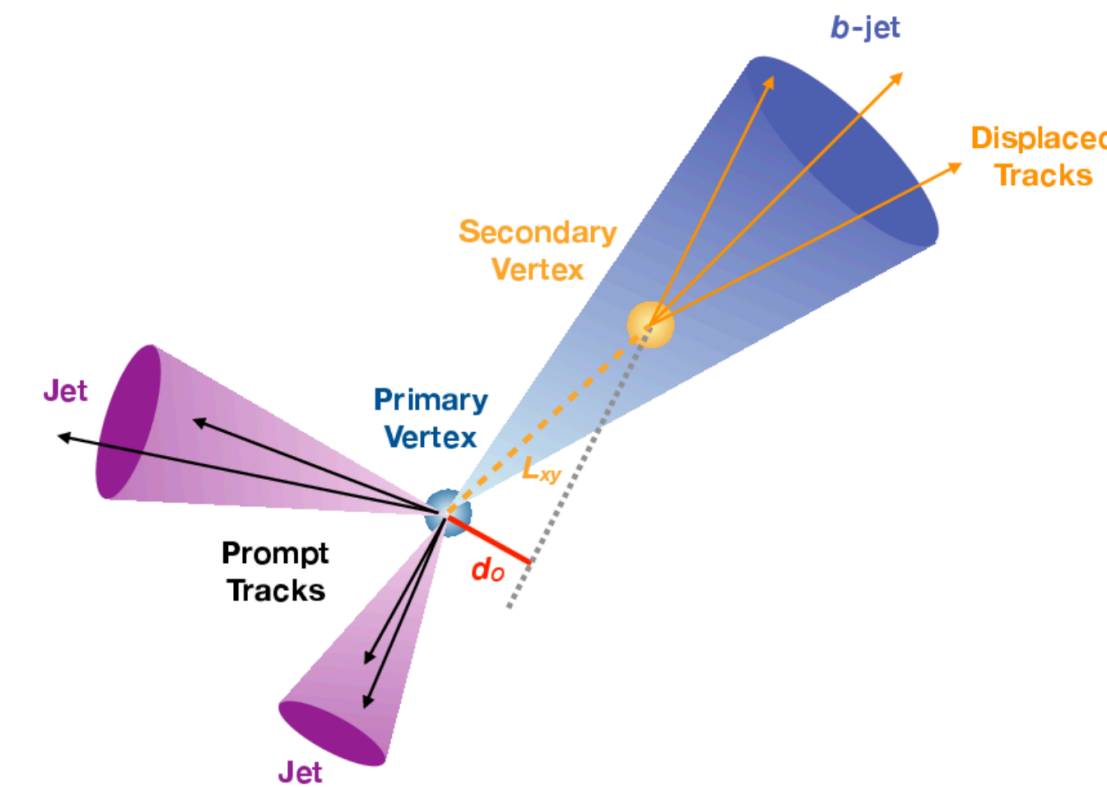
2. Laboratory transverse decay scale

$$\langle r \rangle = \frac{p_T}{m} c\tau$$

3. Probability of decay in radial interval

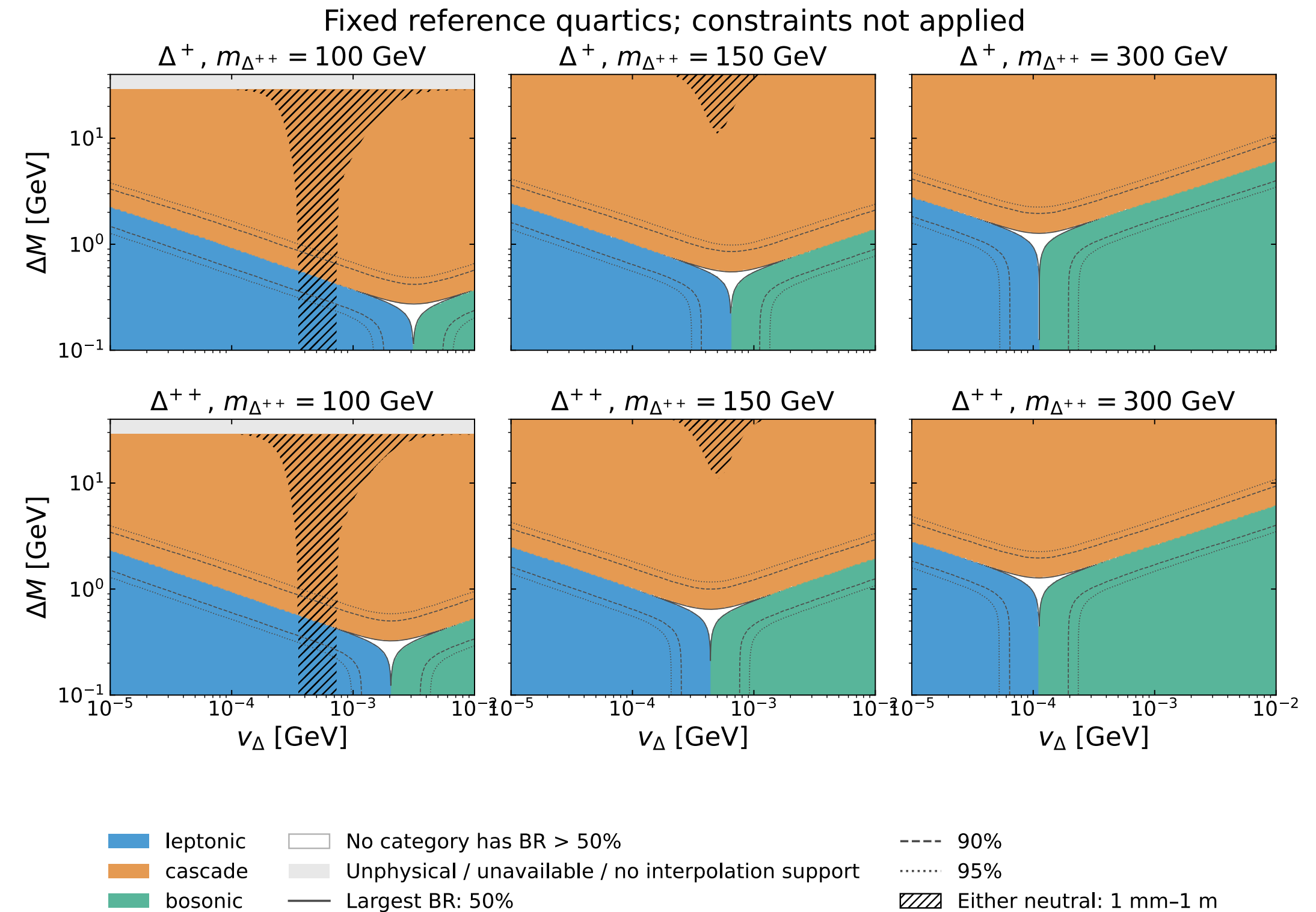
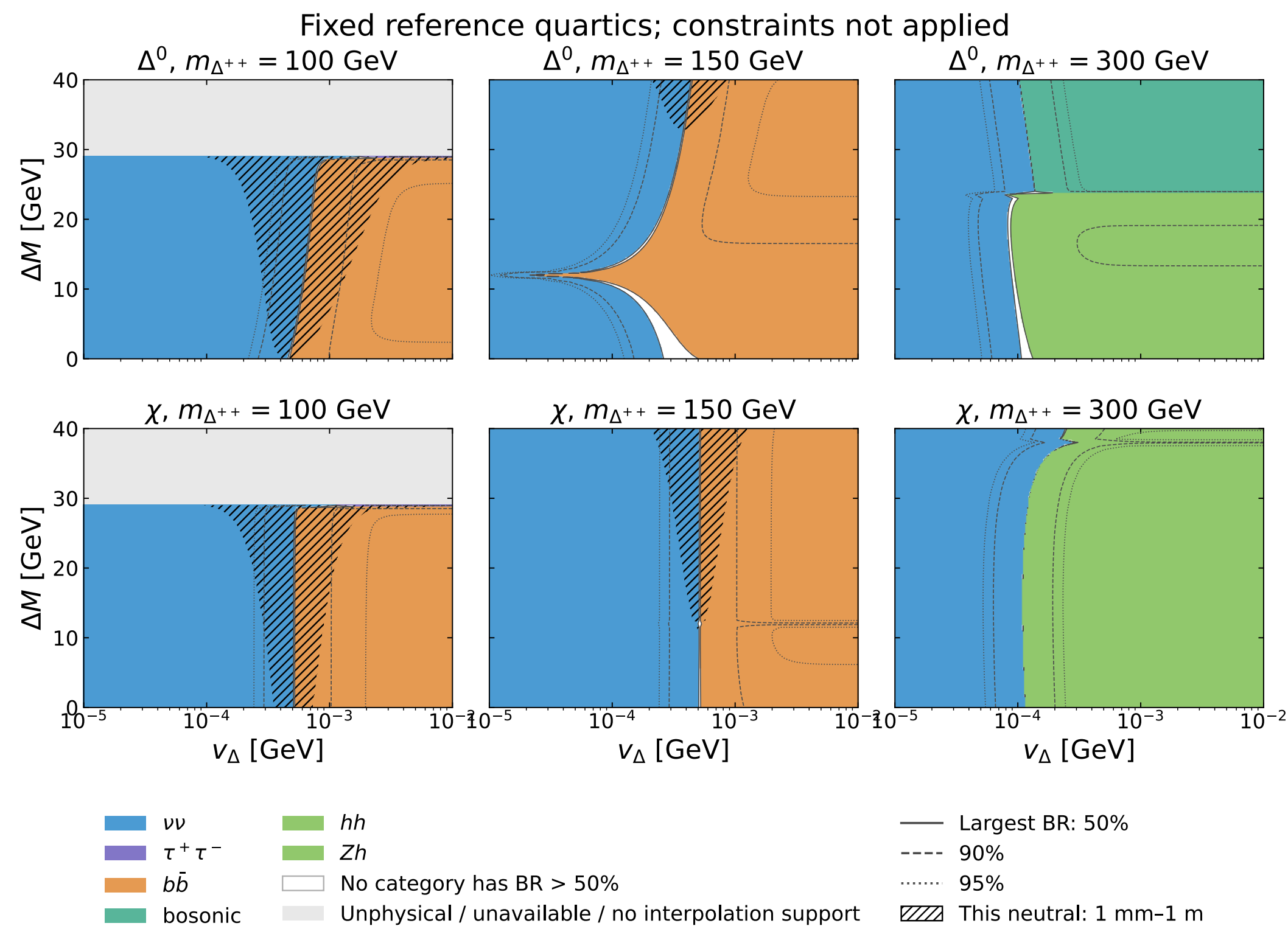
$$P(r_{min} < r < r_{max}) = e^{-r_{min}/\langle r \rangle} - e^{-r_{max}/\langle r \rangle}$$

Our map convention: $1mm \leq c\tau \leq 1m$. Detector acceptance also depends on boost and geometry.



$$N_{selected} = \mathcal{L} \sigma_{production} \langle P_{event,selection} \rangle$$

Where do visible displaced decays occur?



Hatching: $1\text{mm} \leq c\tau \leq 1\text{m}$

Visible target: overlap with $\Delta^0, \chi \rightarrow b\bar{b}$

Charged cascades: an additional source of neutral scalars

Proper-lifetime window: before constraint cuts and detector selection.

Charged panels: hatching represents either neutral's lifetime.

For displaced b-jet searches see: arXiv:2012.01581, arXiv:2409.10806

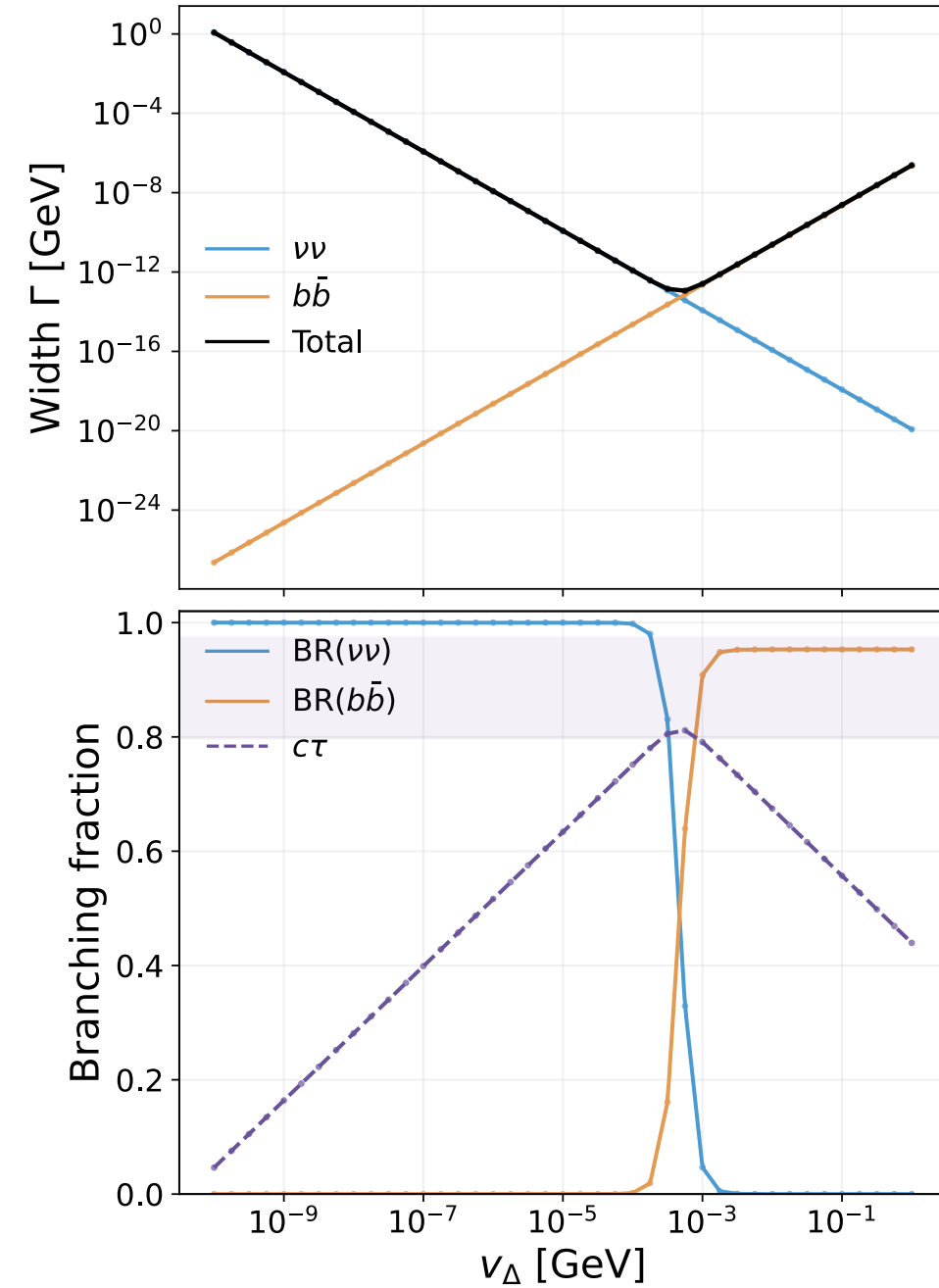
A long lifetime must coincide with a useful visible branching fraction.

Where does the lifetime peak?

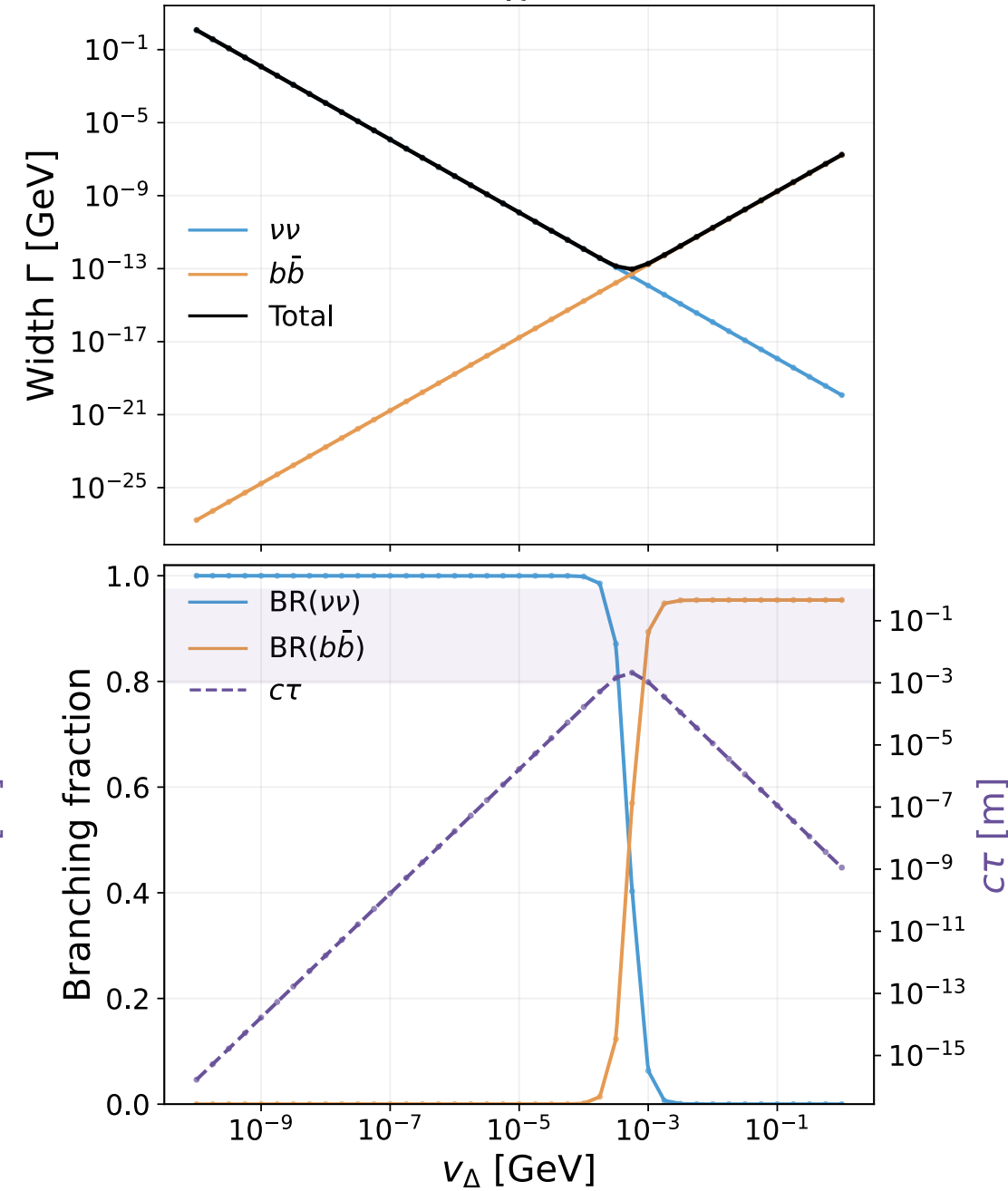
v6 catalogue: $m_{\Delta^{++}} = 200$ GeV, $\Delta M = 52.5475$ GeV

Markers: calculated points; lines: interpolation

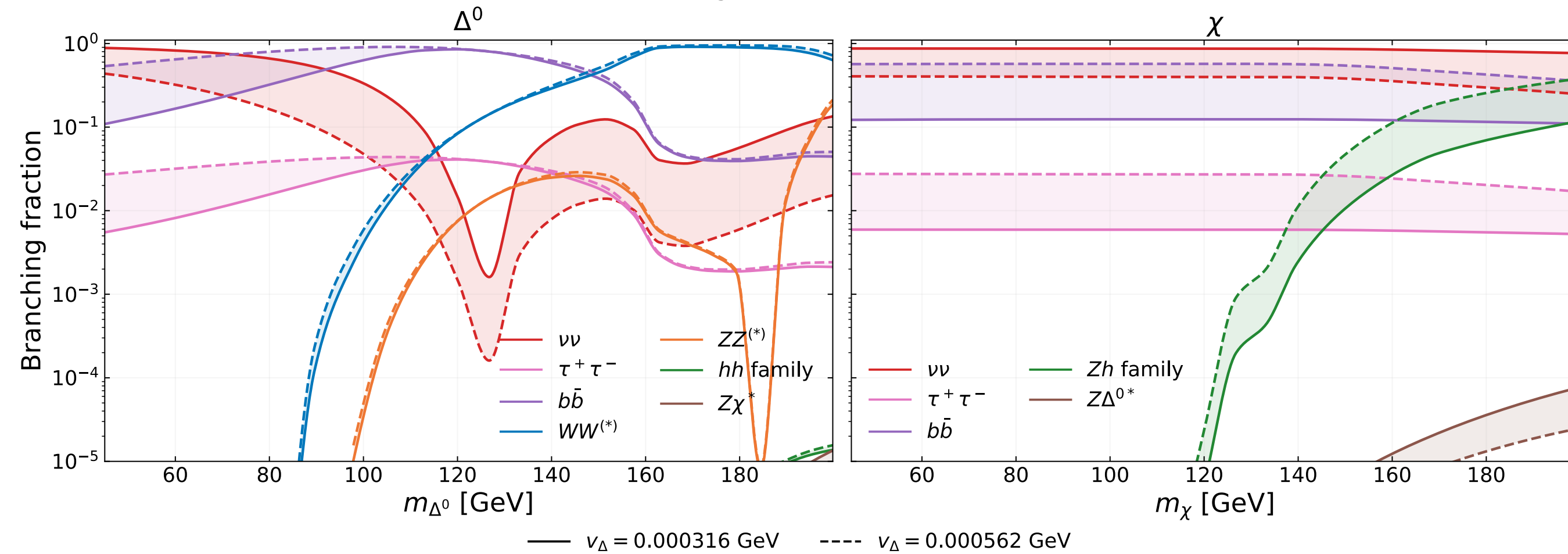
Δ^0



χ



v6 catalogue: $m_{\Delta^{++}} = 200$ GeV



$$g_{\Delta^0 \nu \nu} = \sqrt{2} Y_\Delta \cos(\xi) = \frac{M_\nu}{v_\Delta} \cos(\xi) \rightarrow \Gamma(\Delta^0 \rightarrow \nu \nu) \sim v_\Delta^{-2}$$

$$g_{\Delta^0 b \bar{b}} \sim \frac{m_b}{v} \sin(\xi) \rightarrow \Gamma(\Delta^0 \rightarrow b \bar{b}) \sim v_\Delta^2, \quad \sin(\chi) \sim K v_\Delta$$

$$\Gamma_{total} = \frac{A}{v_\Delta^2} + B v_\Delta^2, \quad c\tau = \frac{\hbar c}{\Gamma_{total}}$$

Schematic small-mixing behaviour at fixed spectrum and quartics; thresholds and cancellations can modify it.

Displaced decays can therefore probe the triplet vev within a specified model parameter family.

Neutral production: direct and through cascades

DY cross-sections:

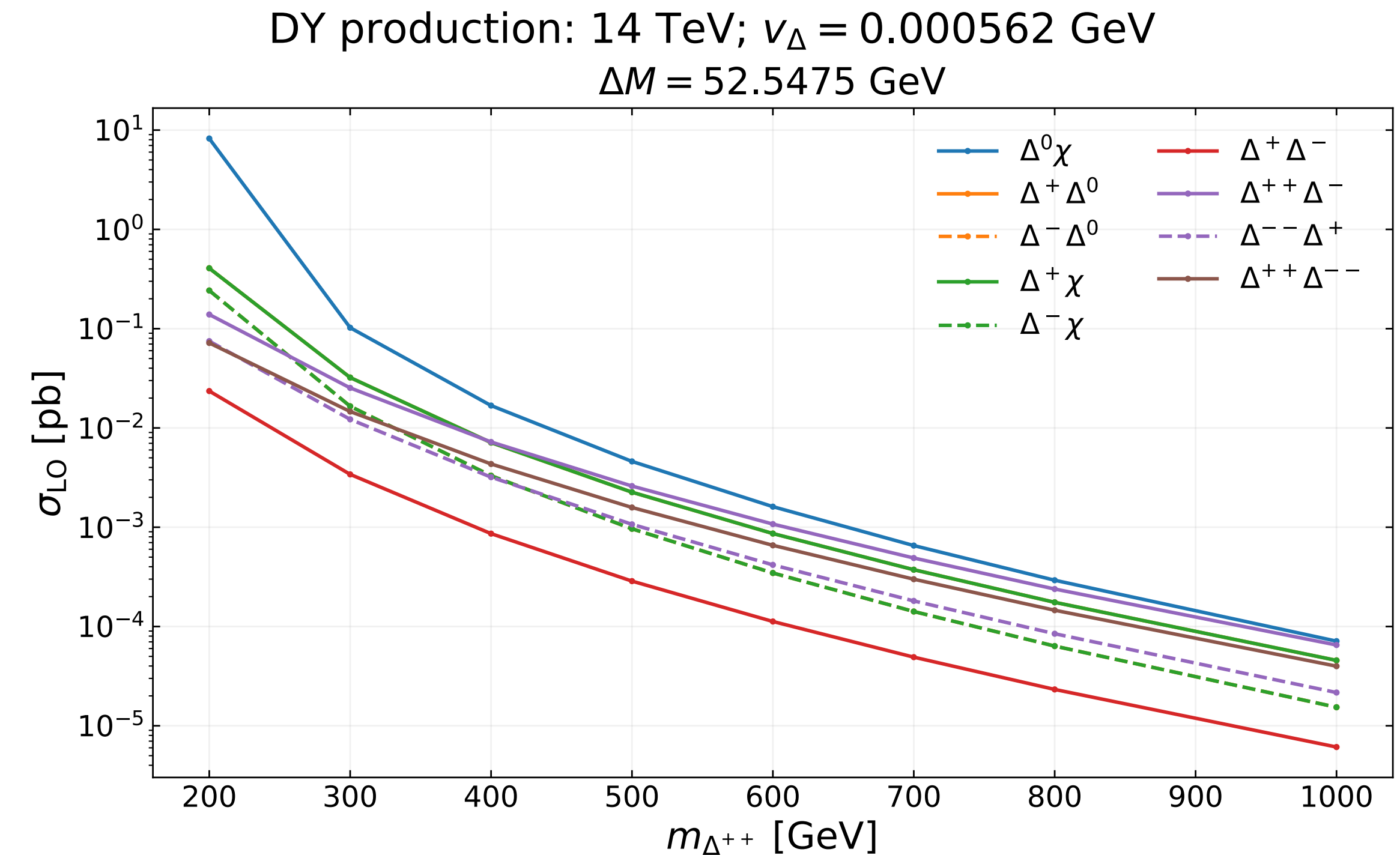
$pp \rightarrow Z^* \rightarrow \Delta^0 \chi$ direct production

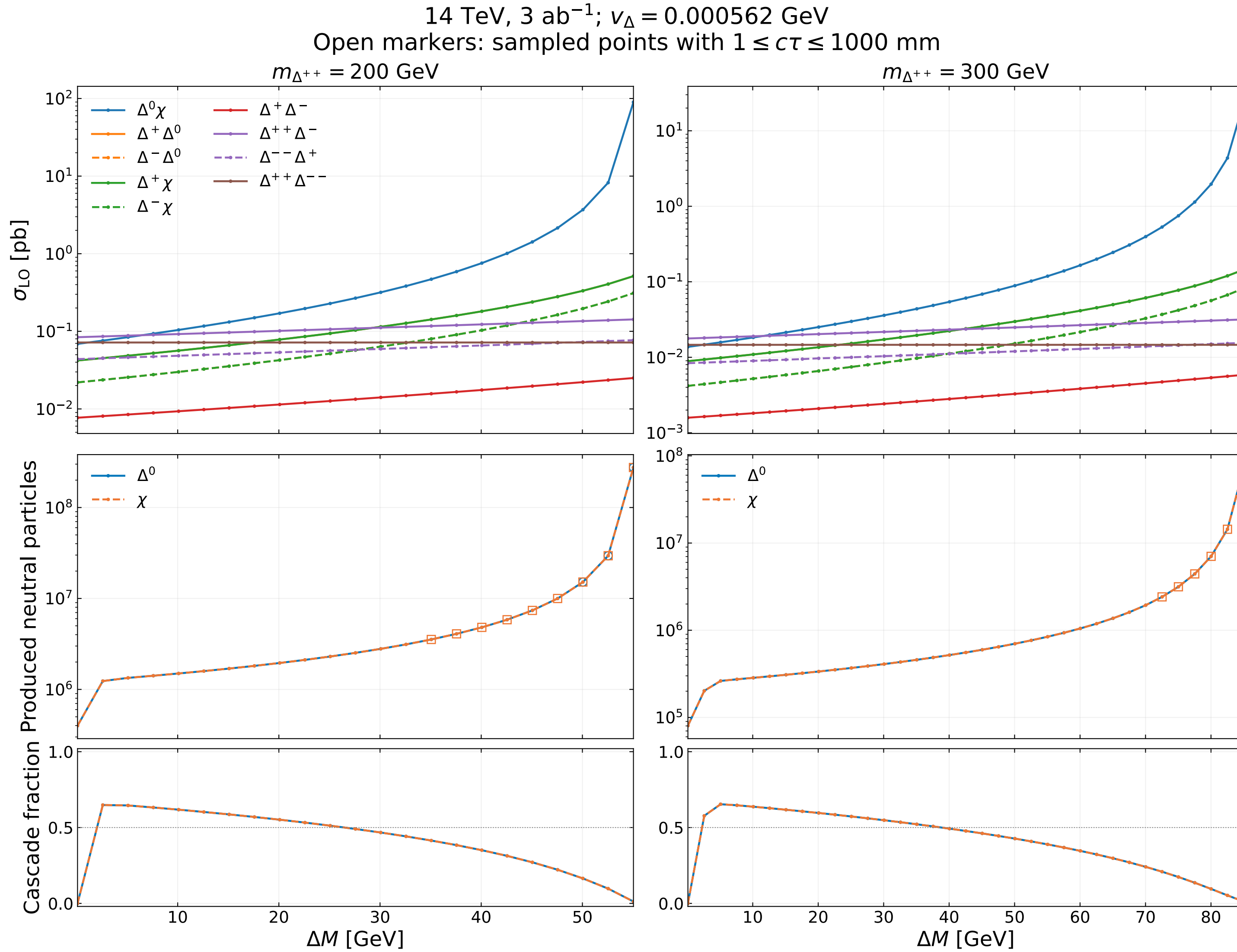
$pp \rightarrow \Delta^\pm(\Delta^0, \chi), \Delta^+ \Delta^-, \Delta^{++} \Delta^-, \Delta^{++} \Delta^{--}$

charged production can supply additional neutrals

Cascade chain:

$\Delta^{++} \rightarrow \Delta^+ W^{+(*)}, \Delta^+ \rightarrow (\Delta^0, \chi) W^{+(*)}$





Mass splitting controls both the spectrum and the cascade contribution.

Cascades can enhance the neutral yield, but a larger splitting does not guarantee a larger total yield. Production rates and branching fractions change together.

$$N_S = \mathcal{L} \sum_p \sigma_p \langle n_s \rangle_p$$

Electroweak precision tests restrict the neutral LLP window

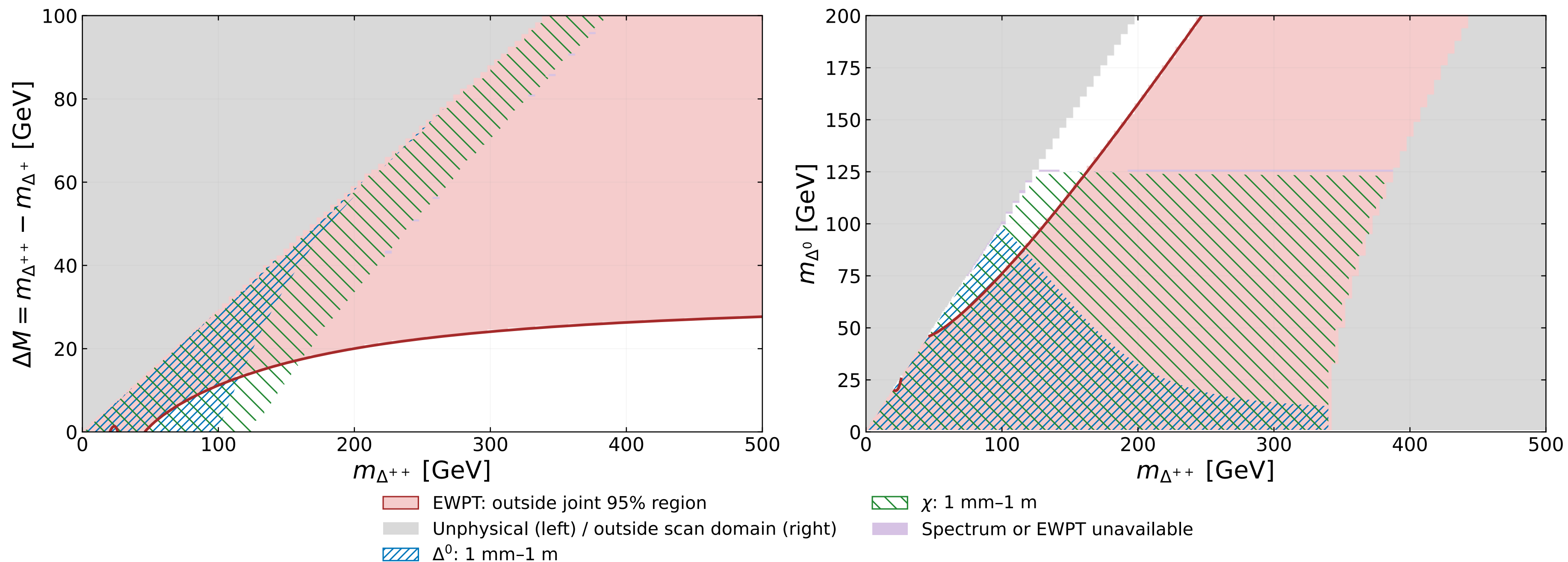
Electroweak precision tests

- S, T, U : new-physics corrections to electroweak gauge-boson propagators.
- Triplet mass splittings contribute to these corrections.
- Correlated **PDG 2026 fit**, joint **95% CL**.

Direct charged-scalar searches $\Delta^{++} \rightarrow l^+l^+, W^+W^+$

- Cascades reduce these branching fractions.

PDG 2026 EWPT and neutral LLP windows; $v_\Delta = 0.000562$ GeV
 $(\lambda_{D1}, \lambda_{D2}, \lambda_{HD1}) = (0.11, 0.15, 0.10)$



EWPT removes part of the LLP window; the remaining region requires searches matched to its decay modes and lifetimes.

Reinterpreting existing displaced-jet searches

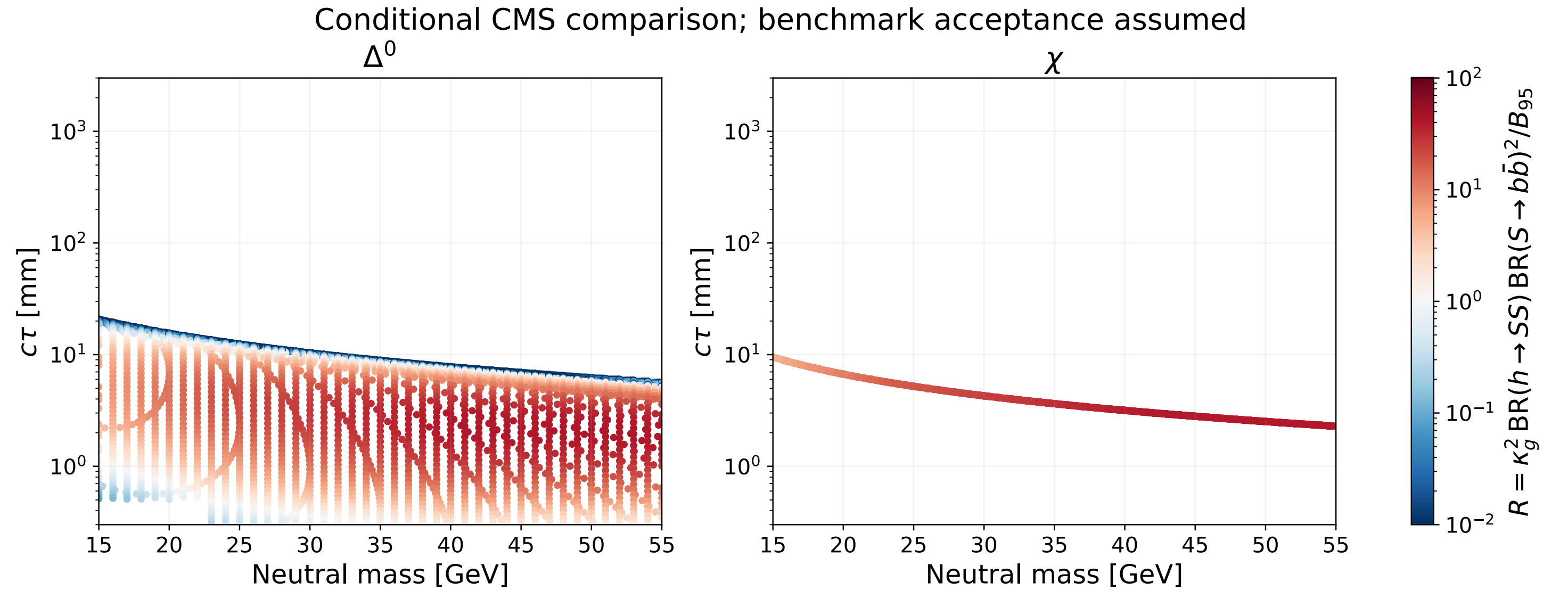
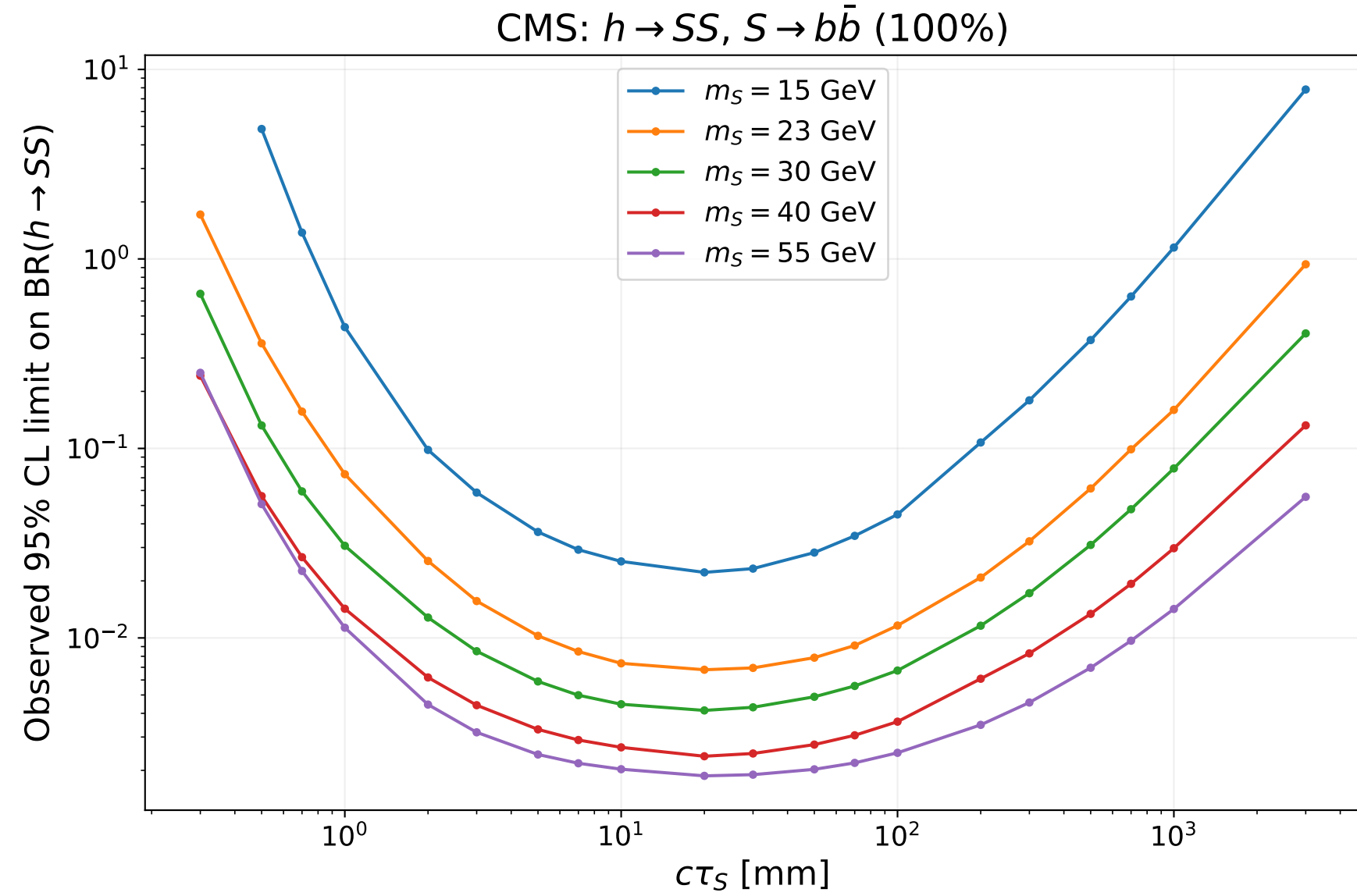
Light LLPs from Higgs decays

- CMS — arXiv:2409.10806
- $h \rightarrow SS, S \rightarrow b\bar{b}$
- Displaced-jet and muon-assisted triggers
- Track/vertex identification using **graph neural networks**
- **First target:** light neutral LLPs

Directly produced LLP pairs

- CMS — arXiv:2012.01581
- $Z^* \rightarrow XX, X \rightarrow q\bar{q}$
- Displaced-jet triggers with larger H_T requirements
- Track/vertex identification using **boosted decision trees**
- **Next:** direct-production benchmark

Existing displaced-jet searches can test Higgs-produced triplet neutrals



$$h \rightarrow SS \rightarrow (b\bar{b})(b\bar{b}), S = \Delta^0 \chi$$

$$R_S = \frac{k_g^2 BR(h \rightarrow SS) BR(S \rightarrow b\bar{b})^2}{B_{95}^{CMS}(m_S, c\tau_S)}$$

$R_S > 1$: predicted rate exceeds the published limit, assuming benchmark acceptance.

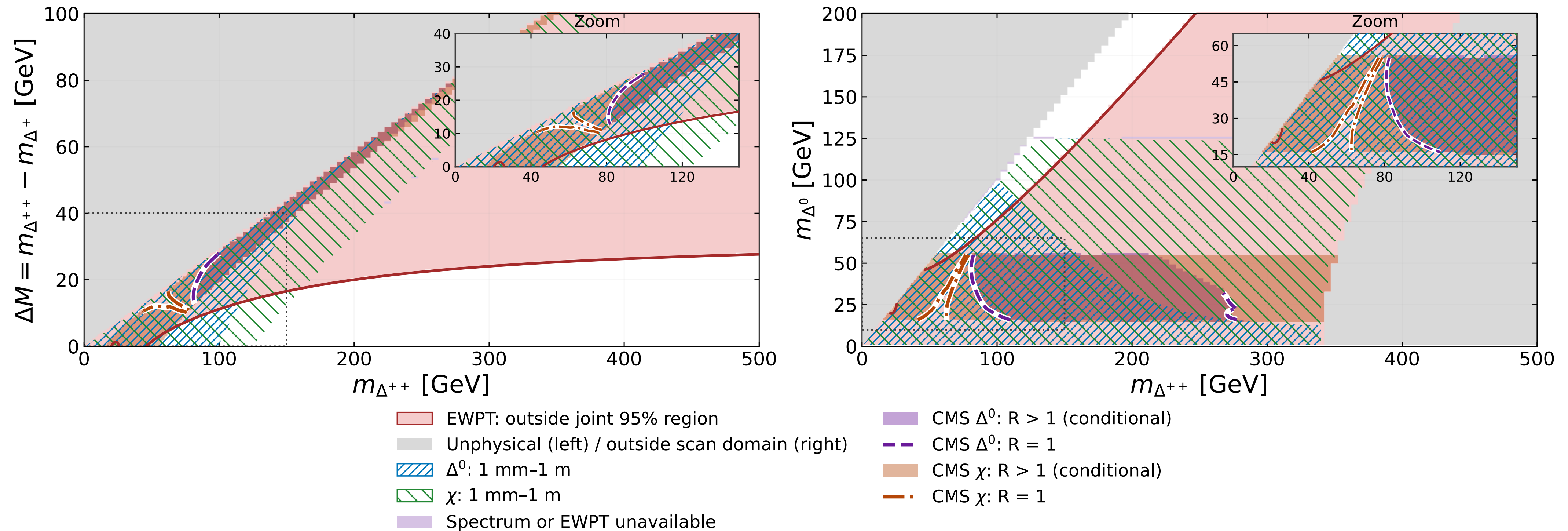
CMS arXiv:2409.10806; observed limits from HEPData.
Interpolation within published coverage; scalar-pair contributions included in the approximate Higgs total width.

Precision constraints and displaced searches probe complementary regions

PDG 2026 EWPT and neutral LLP windows; $v_\Delta = 0.000562$ GeV

$(\lambda_{D1}, \lambda_{D2}, \lambda_{HD1}) = (0.11, 0.15, 0.1)$

CMS Higgs $\rightarrow$ 4b: benchmark acceptance assumed



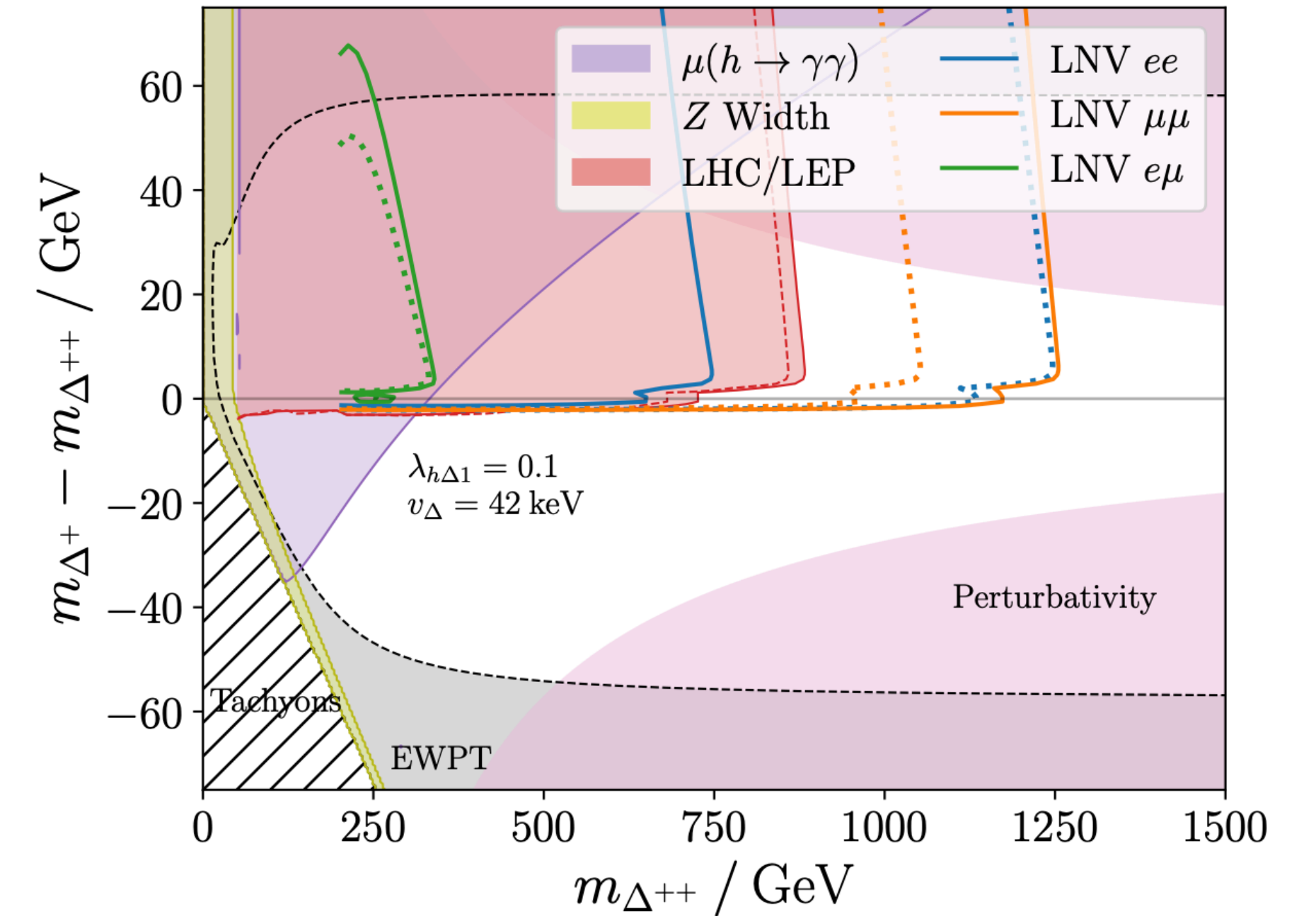
EWPT restricts the charged-neutral mass splitting.

The CMS comparison additionally probes light neutrals produced in Higgs decays.

Conclusions and outlook

- **Neutral triplet scalars can develop displaced signatures**, with lifetimes and visible decays controlled by the spectrum, v_Δ , and mixing.
- **EWPT and existing displaced-jet searches provide complementary tests.** Our Higgs-mediated comparison indicates substantial coverage under the benchmark-acceptance assumption.
- **Next:** extend reinterpretations, assess acceptance uncertainties, and develop searches for the remaining neutral LLP regimes.
- **Beyond LLPs:** investigate prompt neutral signatures in regions not covered by the constraints considered here.

Fully exploiting the LHC means testing the neutrino-mass mechanism across its different signatures.



P. D. Bolton, J. Kriewald, M. Nemevšek, F. Nesti, and J. C. Vasquez, arXiv:2408.00833 [hep-ph]

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Backup: production couplings

$$s_W = \sin \theta_W, \quad c_W = \cos \theta_W, \quad s_\xi = \sin \xi, \quad c_\xi = \cos \xi, \quad N_+ = \sqrt{v^2 + 2v_\Delta^2}, \quad N_0 = \sqrt{v^2 + 4v_\Delta^2}$$

$$C_{ZD^0\chi} = -\frac{e(vc_\xi + v_\Delta s_\xi)}{s_W c_W N_0},$$

$$C_{WD^+D^0} = -\frac{ie(vc_\xi + v_\Delta s_\xi)}{\sqrt{2}s_W N_+},$$

$$C_{WD^+\chi} = \frac{eN_+}{\sqrt{2}s_W N_0},$$

$$C_{WD^{++}D^-} = \frac{iev}{s_W N_+}.$$

$$C_{\gamma D^+D^-} = e,$$

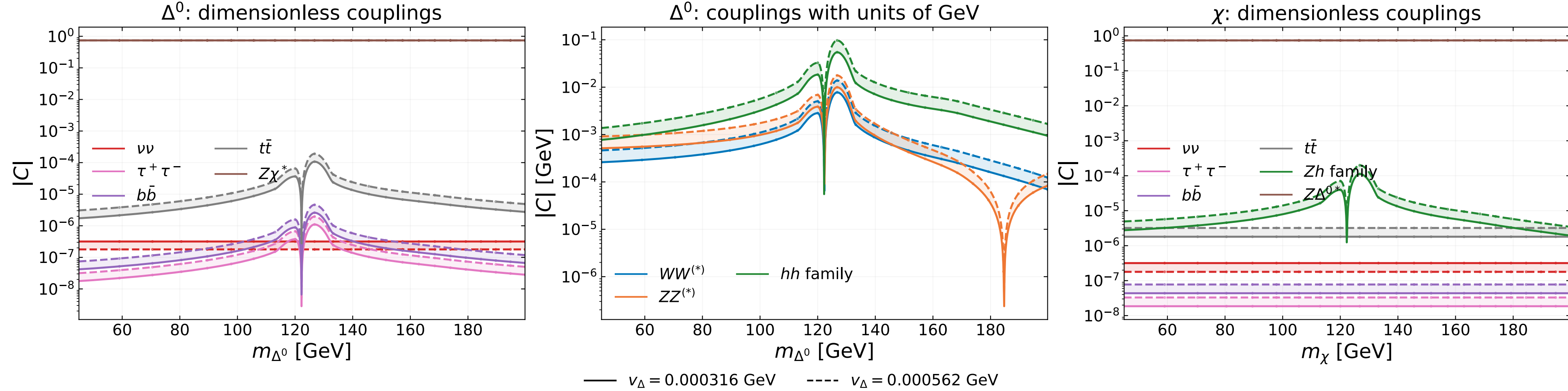
$$C_{\gamma D^{++}D^{--}} = 2e,$$

$$C_{ZD^+D^-} = \frac{e[-s_W^2 v^2 + (c_W^2 - s_W^2)v_\Delta^2]}{s_W c_W (v^2 + 2v_\Delta^2)},$$

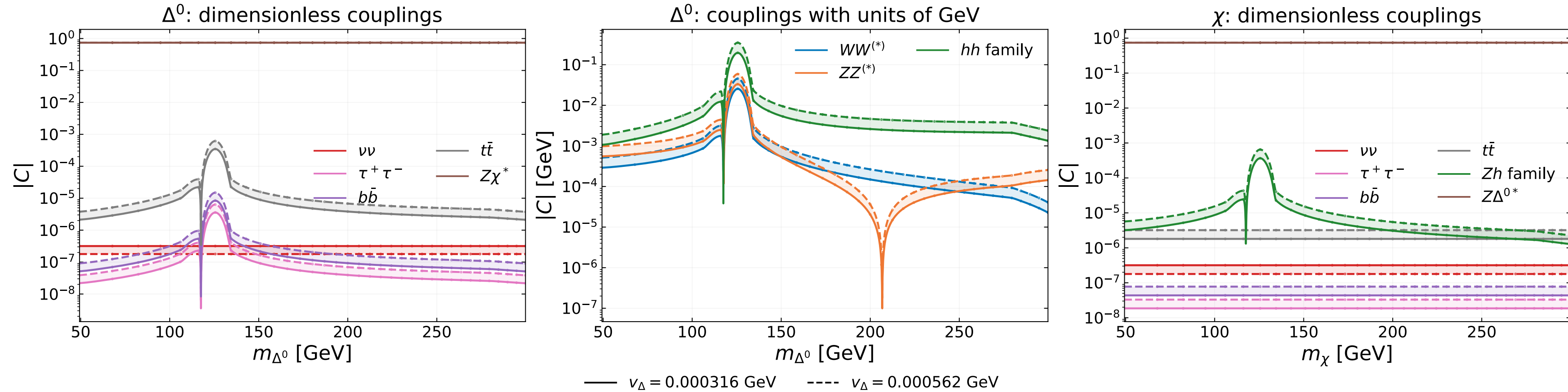
$$C_{ZD^{++}D^{--}} = \frac{e(c_W^2 - s_W^2)}{s_W c_W}.$$

Backup: BR dips explained

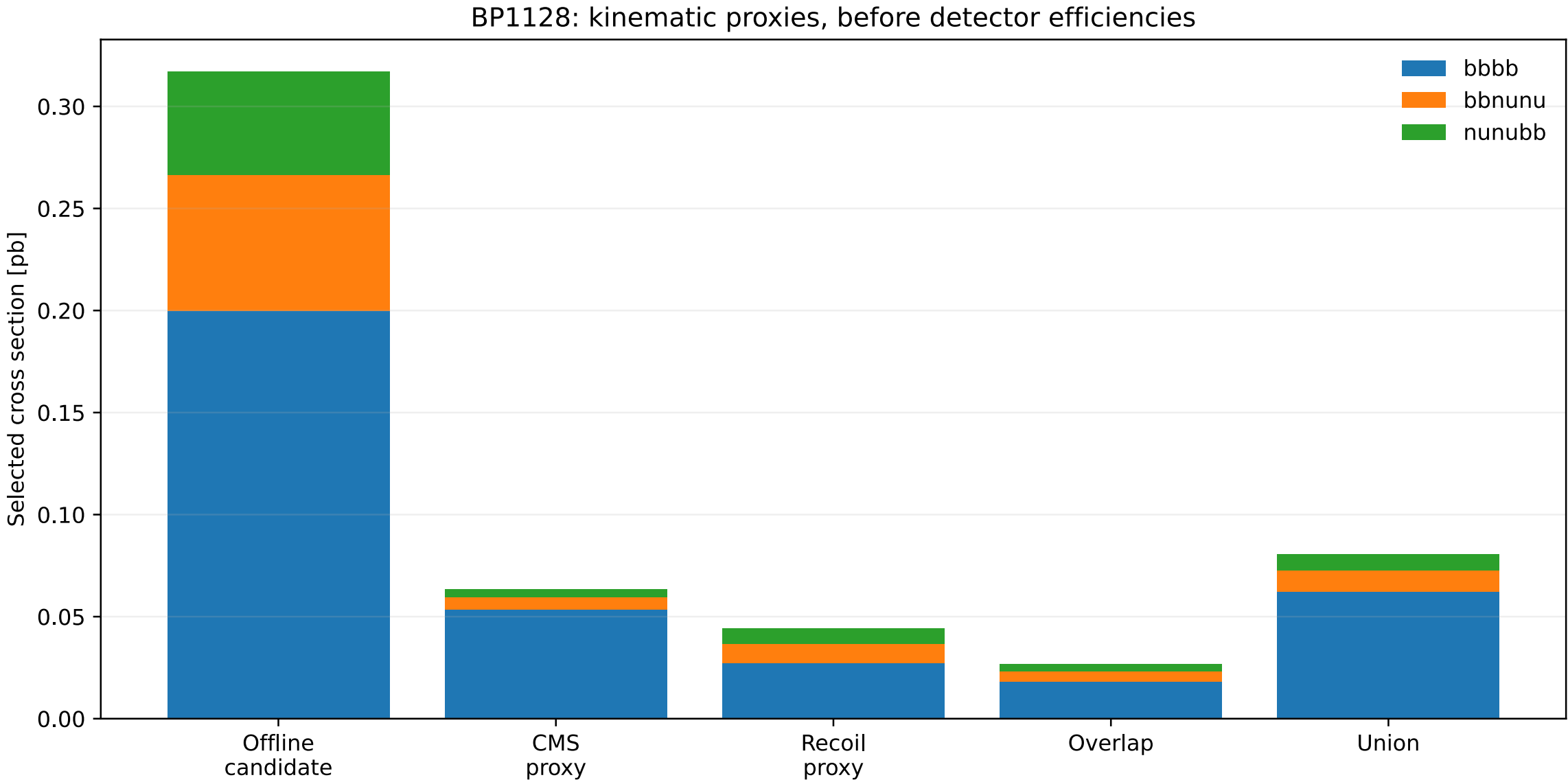
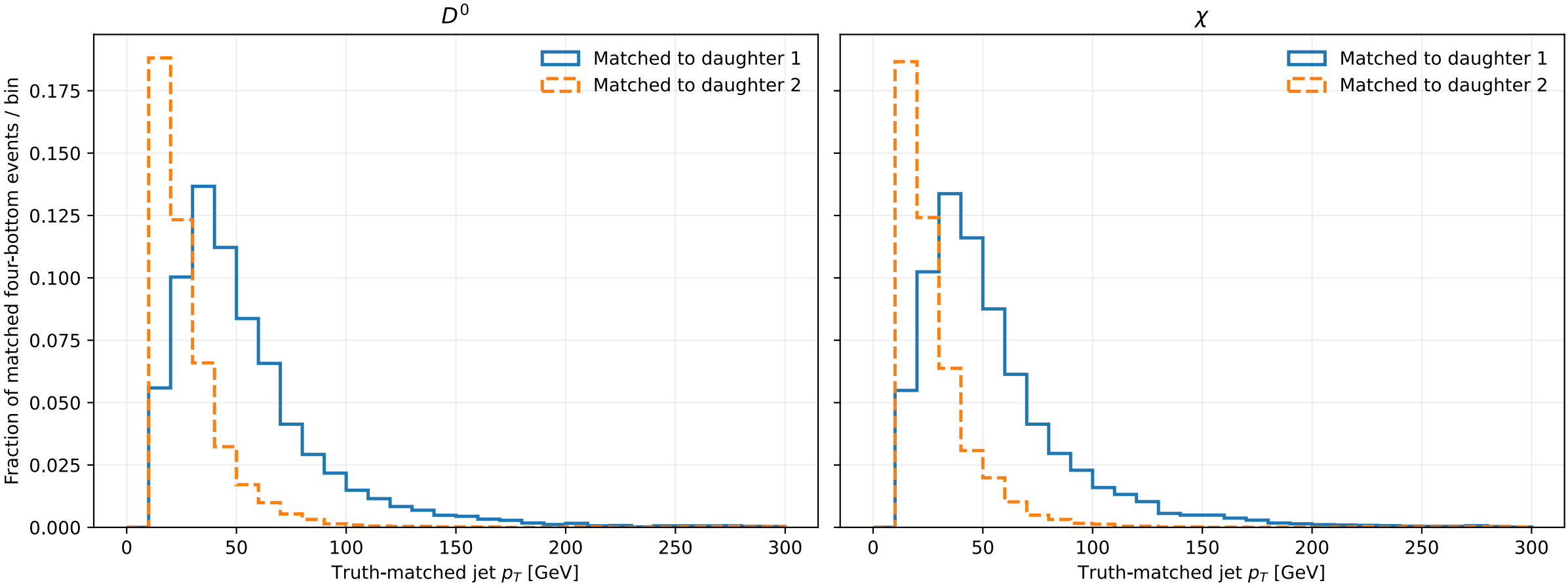
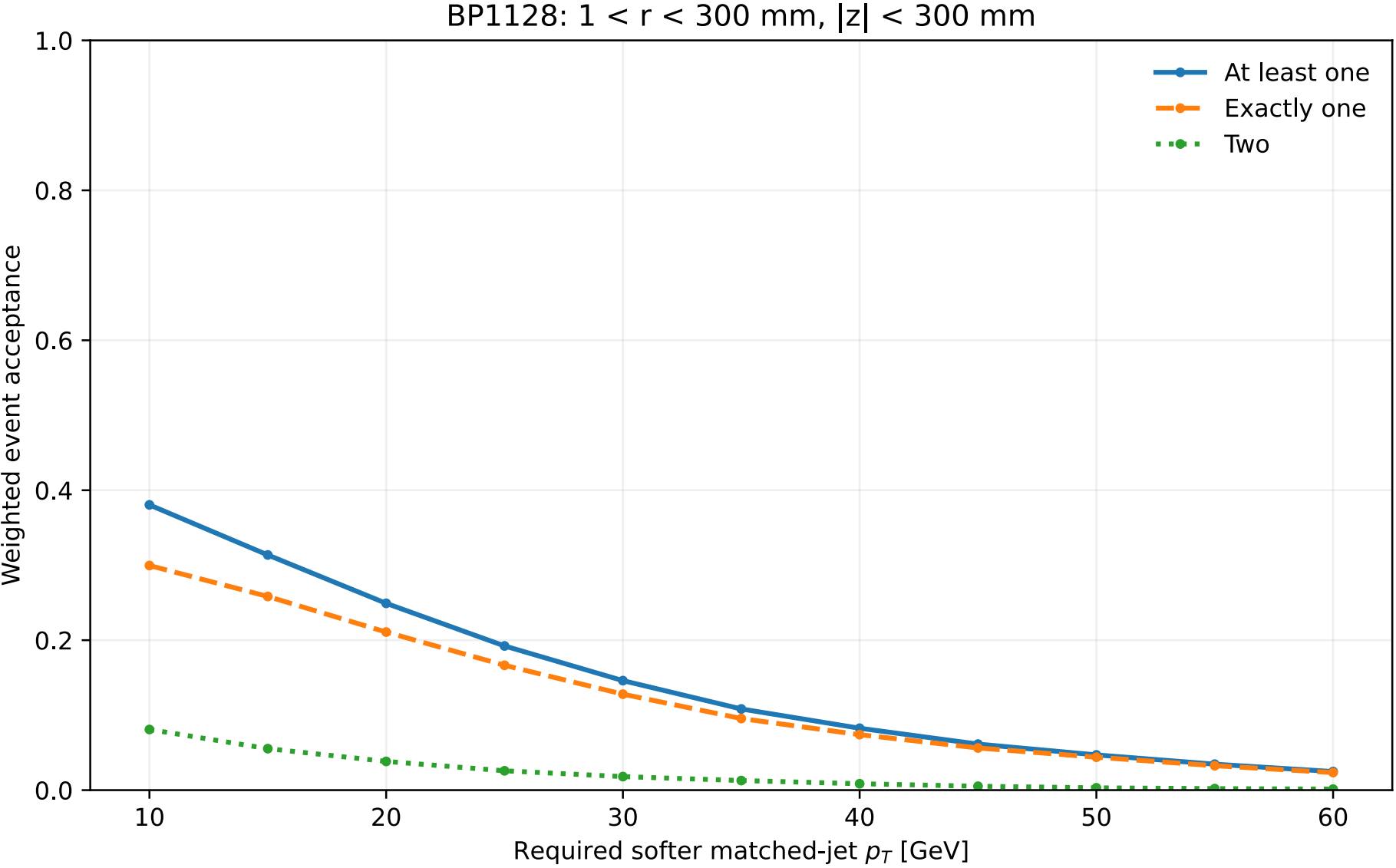
v6 coupling magnitudes: $m_{\Delta^{++}} = 200$ GeV
Dots: calculated points; curves and shading: interpolation



v6 coupling magnitudes: $m_{\Delta^{++}} = 300$ GeV
Dots: calculated points; curves and shading: interpolation

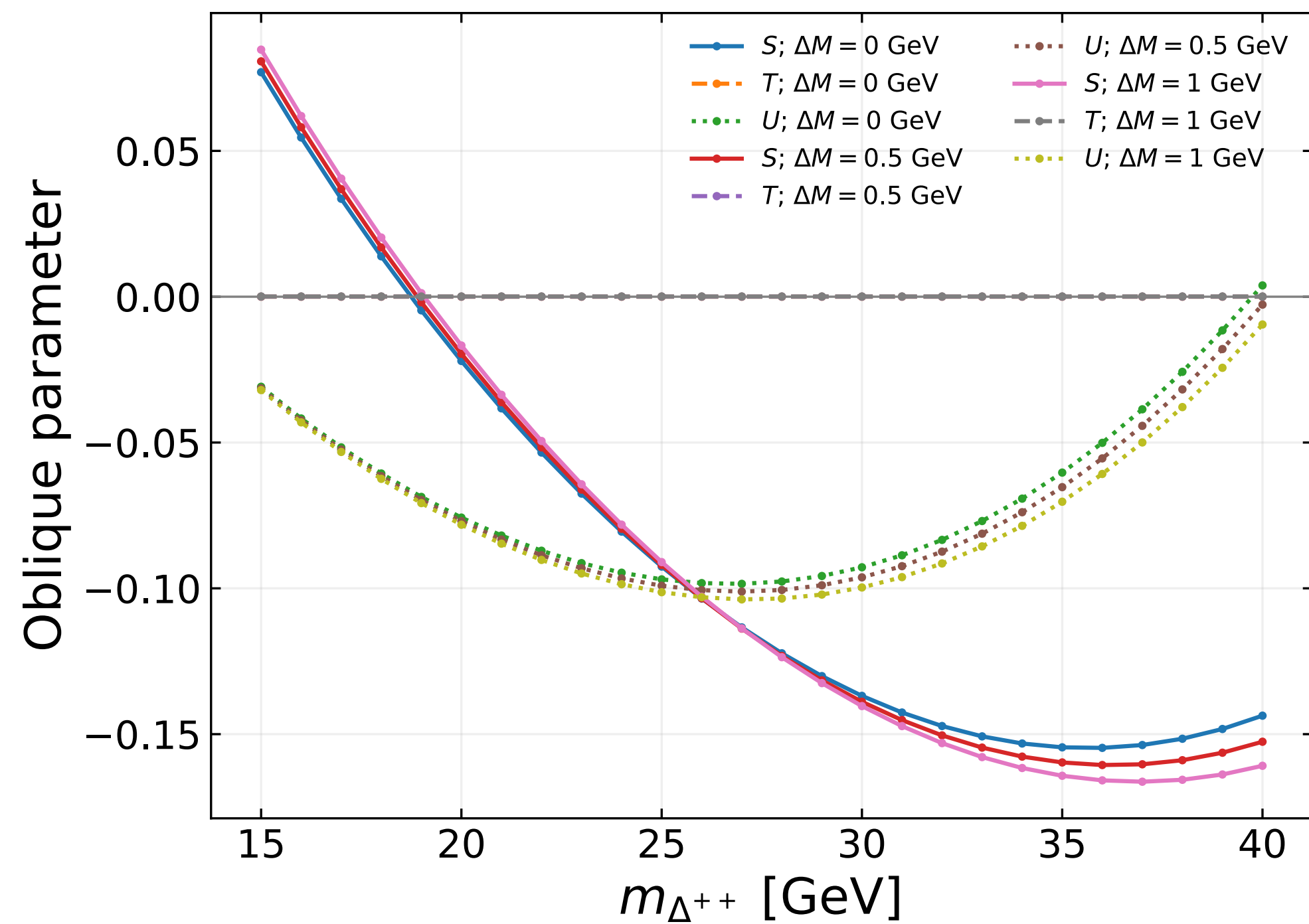
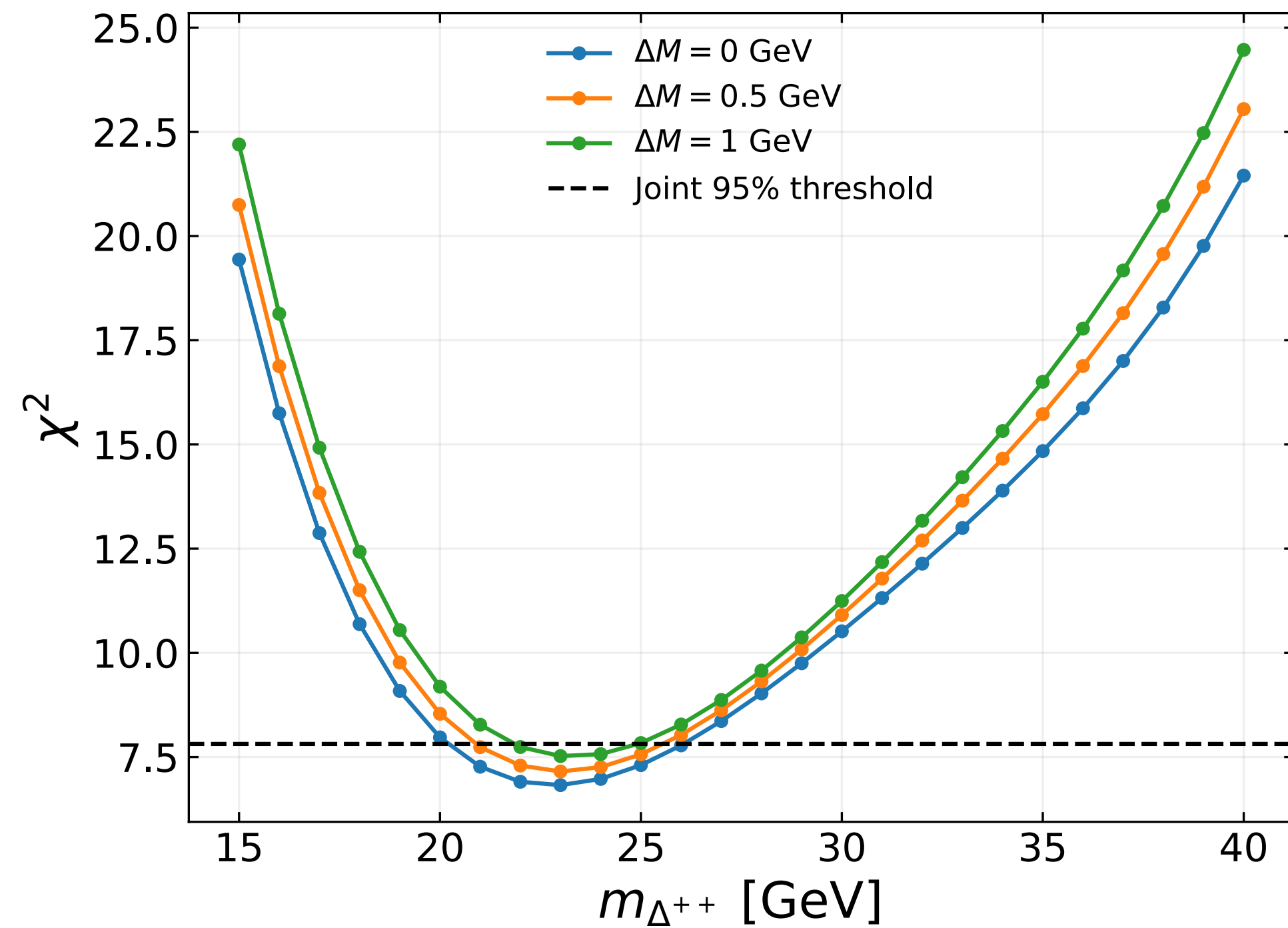


Backup: b-jet simulations



Backup: EWPT diagnostics

EWPT diagnostic: calculated low-mass points



Backup: CMS b-jet

