

Lepton number **violation** in **Type II** seesaw at the LHC

Jonathan Kriewald

Jožef Stefan Institute

Based on [\[2408.00833\]](#) with Patrick D. Bolton, Miha Nemevšek, Fabrizio Nesti and Juan Carlos Vasquez
+ work in progress

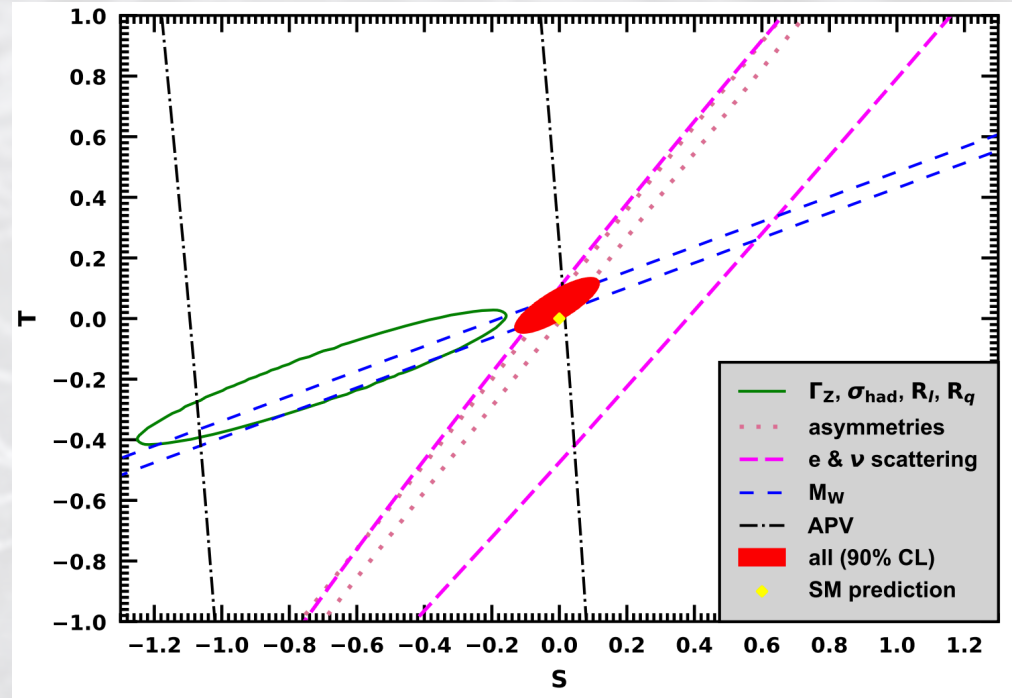
BLV2024 October 8th – October 11th

The Standard Model – A success story

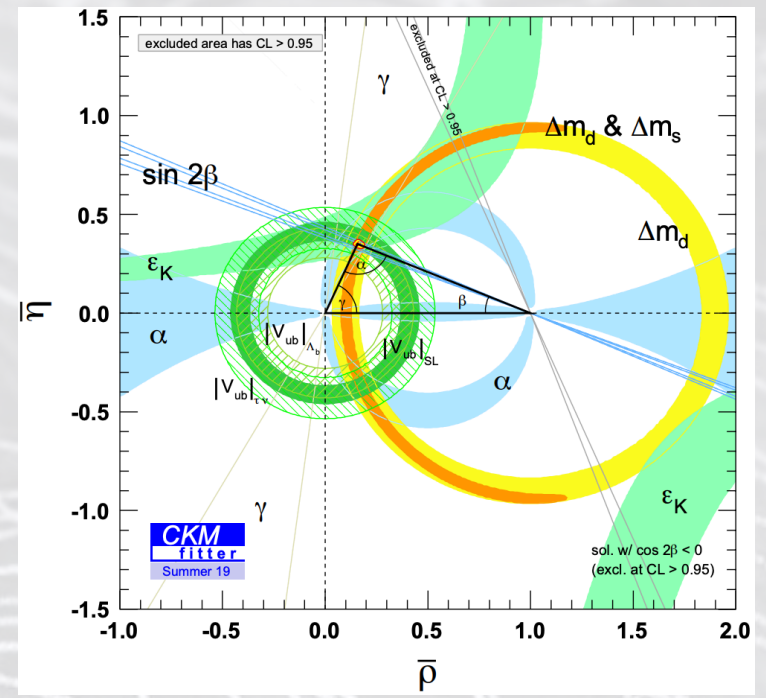
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \chi_i y_{ij} \chi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

$$\mathcal{G}_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

+ some *accidental* symmetries



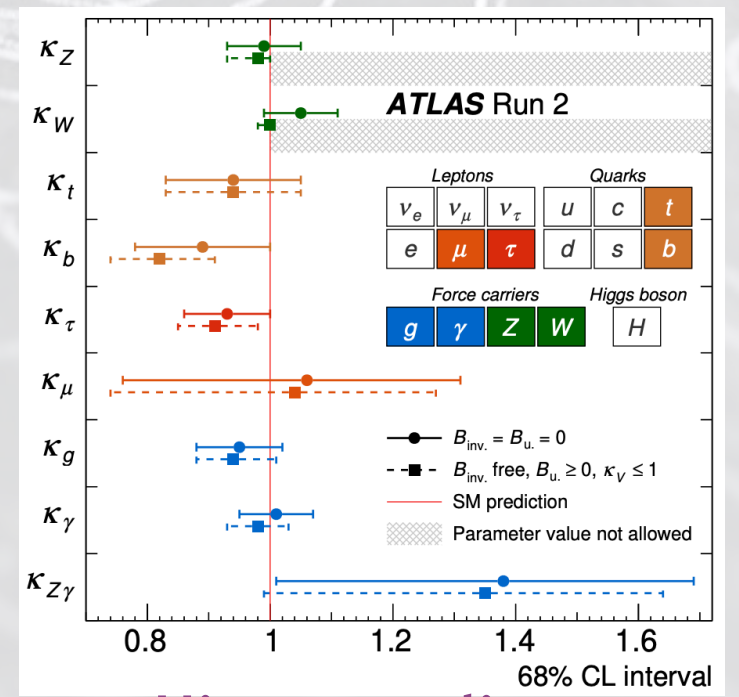
Electroweak fit



CKM paradigm of flavour mixing

Hundreds of experimental measurements overwhelmingly confirm the SM!

⇒ Just need to completely understand the Higgs sector now?



Higgs couplings

Strong arguments in **f(l)avour** of New Physics!

Observations **unaccounted** for in SM: ν -oscillations, Dark matter,

baryon asymmetry of the Universe

(also some theoretical caveats...)

How to unveil the NP model at work?

⇒ Test SM **symmetries** with flavour observables:

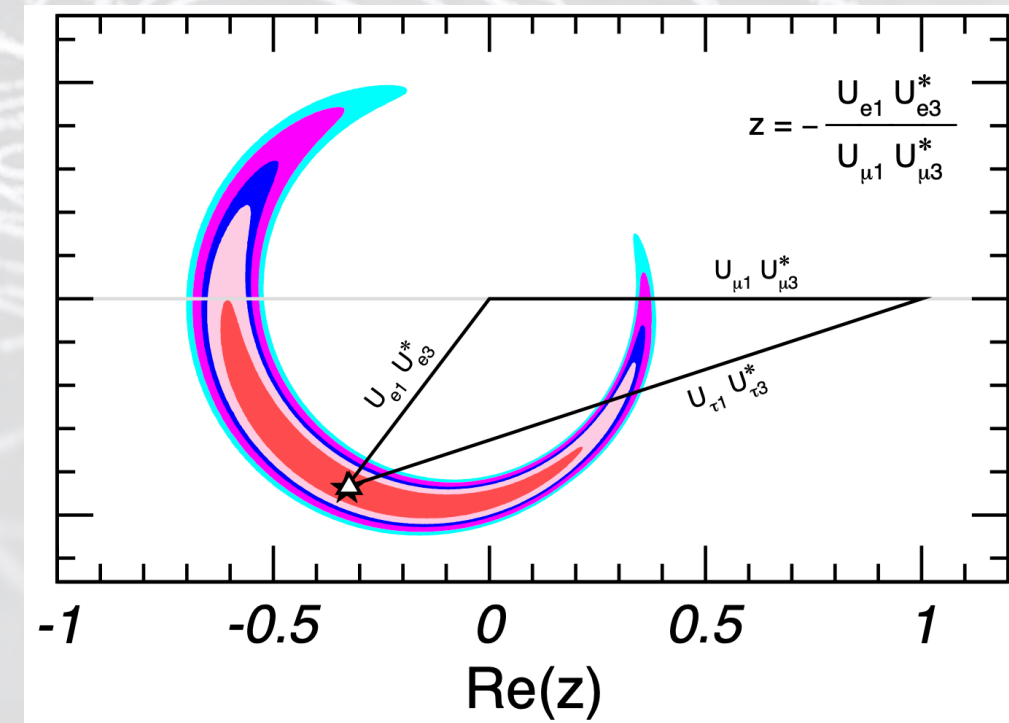
Lepton Flavour Violation, Baryon Number Violation, Lepton Number Violation, ...

ν -oscillations 1st laboratory *evidence* of New Physics!

- ▶ New mechanism of mass generation? **Majorana fields?**
- ▶ New sources of CP violation?

Several experimental puzzles remain:

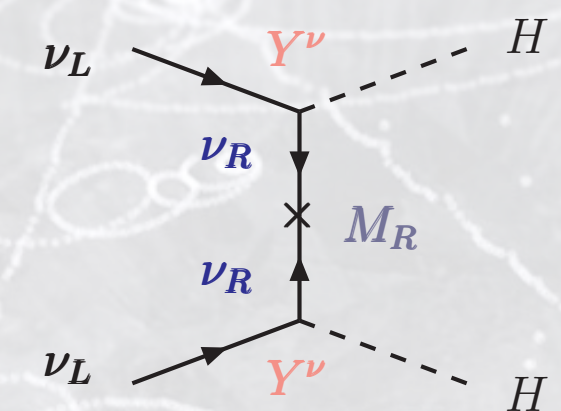
- ▶ Absolute mass scale?
- ▶ Mass ordering? (NO vs IO)
- ▶ CP violation maximal?



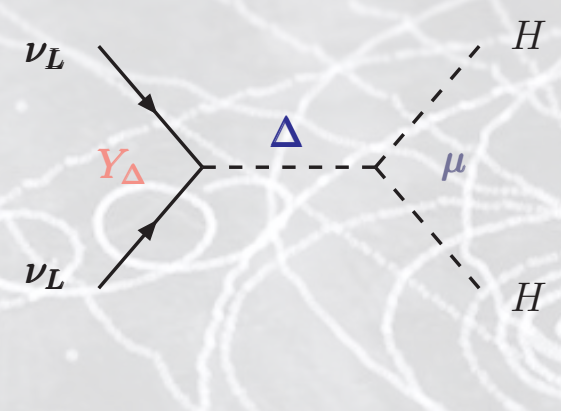
Making neutrino masses

Effective mass term $\mathcal{L}_{\text{eff}} \sim \frac{m_{LL}}{2} \bar{\nu}_L \nu_L^C$ from Weinberg operator: $\mathcal{L}^{d=5} \sim \frac{h_{ij}}{2\Lambda} (H L_i H L_j)$

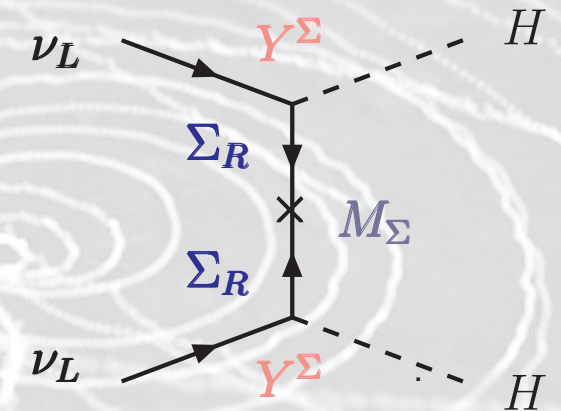
Different realisations: $\mathcal{O}_{\text{typeI}}^5 \sim (L_i^T H)(L_j^T H)$, $\mathcal{O}_{\text{typeII}}^5 \sim (L_i^T \sigma_a L_j)(H^T \sigma_a H)$, $\mathcal{O}_{\text{typeIII}}^5 \sim (L_i^T \sigma_a H)(L_j^T \sigma_a H)$



Type I (fermion singlet)
(e.g. Minkowski '77)



Type II (scalar triplet)
(e.g. Schechter & Valle '80)



Type III (fermion triplet)
(e.g. Foot et al. '89)

Mass terms: $m_\nu^I \sim -v^2 Y_\nu^T \frac{1}{M_R} Y_\nu$,

$m_\nu^{II} \sim -v^2 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} \sim -Y_\Delta v_\Delta$,

$m_\nu^{III} \sim -Y_\Sigma^T \frac{v^2}{2M_\Sigma} Y_\Sigma$

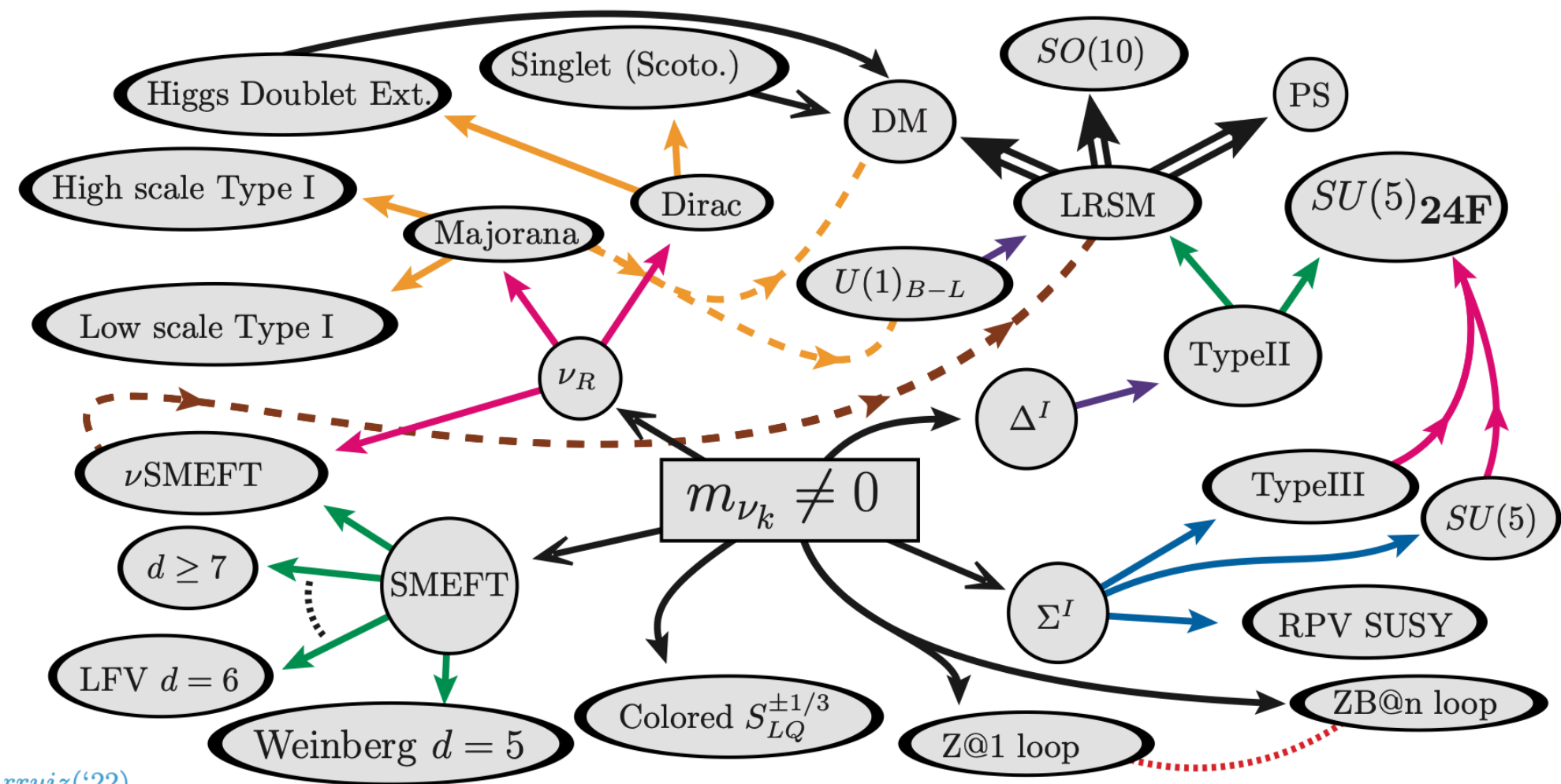
Countless more possibilities with higher odd-dimensional operators or loop-level realisations...

(Actually they are countable, see e.g. [John Gargalionis and Ray Volkas: [2009.13537](#)]

Making neutrino masses

These core ideas can be realized in *many* ways!

Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + many others



rruiz('22)

Making neutrino masses

Effective mass

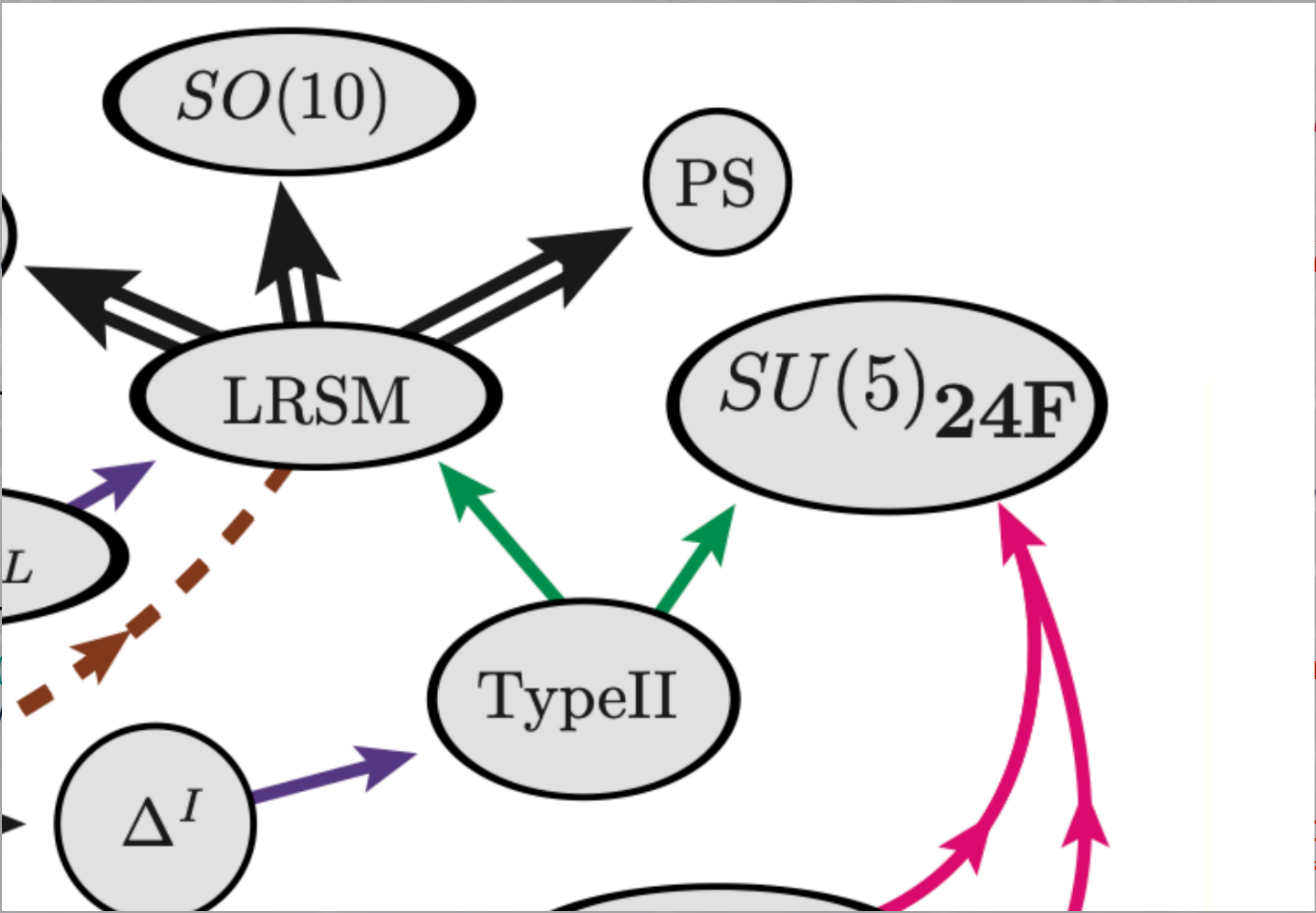
Different realisations

ν_L

ν_L

Type I

Mass terms: m_ν^I



$$H L_i H L_j$$

$$L_i^T \sigma_a H)(L_j^T \sigma_a H)$$

H

Σ

H

(n triplet)

(89)

$$\frac{v^2}{2M_\Sigma} Y_\Sigma$$

Countless more possibilities with higher odd-dimensional operators or loop-level realisations...

(Actually they are countable, see e.g. [John Gargalionis and Ray Volkas: [2009.13537](#)]

Type II seesaw mechanism

Extend Standard Model with a scalar $Y = 1$, $SU(2)_L$ -triplet

Assign lepton number $L = 2$ to Δ_L

$$\Delta_L = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \frac{v_\Delta + \Delta^0 + i\chi_\Delta}{\sqrt{2}} & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

⇒ Add to Yukawa Lagrangian $\mathcal{L}_{\text{yuk}} \supset Y_{\Delta}^{ij} L_{Li}^T \mathcal{C} i\sigma_2 \Delta_L L_{Lj} + \text{h.c.}$

⇒ Generate Majorana neutrino masses: $M_\nu = U_P^* m_\nu U_P^\dagger = \sqrt{2} v_\Delta Y_\Delta$

Yukawa structure completely fixed by oscillation data, $Y_\Delta \simeq \mathcal{O}(1)$ for $v_\Delta \simeq 10^{-10}$ GeV

Type II seesaw mechanism: the scalar spectrum

$$\Delta_L = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \frac{v_\Delta + \Delta^0 + i\chi_\Delta}{\sqrt{2}} & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

Extend Standard Model with a scalar $Y = 1$, $SU(2)_L$ -triplet

$$V(\varphi, \Delta) = -\mu_h^2 \varphi^\dagger \varphi + m_\Delta^2 \text{Tr}[\Delta^\dagger \Delta] + \lambda_h (\varphi^\dagger \varphi)^2 + \lambda_{\Delta 1} \text{Tr} [\Delta^\dagger \Delta]^2 + \lambda_{\Delta 2} \text{Tr} [(\Delta^\dagger \Delta)^2] \\ + \mu_{h\Delta} (\varphi^T i\sigma_2 \Delta^\dagger \varphi + \text{h.c.}) + \lambda_{h\Delta 1} \varphi^\dagger \varphi \text{Tr} [\Delta^\dagger \Delta] + \lambda_{h\Delta 2} \text{Tr} [\varphi \varphi^\dagger \Delta \Delta^\dagger]$$

Components of Δ_L have mass terms ($+\mathcal{O}(v_\Delta^2)$):

$$m_h^2 = 2\lambda_h v^2 \quad m_{\Delta^0}^2 = m_{\chi_\Delta}^2 = m_{\Delta^{++}}^2 + \frac{\lambda_{h\Delta 2}}{2} v^2 \quad m_{\Delta^+}^2 = m_{\Delta^{++}}^2 + \frac{\lambda_{h\Delta 2}}{4} v^2 \quad m_{\Delta^{++}}^2 = m_\Delta^2 + \frac{\lambda_{h\Delta 1}}{2} v^2$$

And mix with the SM-like doublet φ :

$$\sin \theta_{h\Delta} \simeq \frac{2m_\Delta^2}{m_h^2 - m_{\Delta^0}^2} \left(\frac{v_\Delta}{v} \right) \quad \sin \theta_{\Delta^+ \varphi^+} \simeq \sqrt{2} \left(\frac{v_\Delta}{v} \right) \quad \sin \theta_{\chi \varphi^0} \simeq 2 \left(\frac{v_\Delta}{v} \right)$$

Mixing induces couplings to pairs of quarks, W , Z

Mixing with would-be Goldstones \leftrightarrow corrections to M_W , M_Z , ρ , EWPO

Mass splittings follow sum-rule:

$$m_{\Delta^0}^2 - m_{\Delta^+}^2 = m_{\Delta^+}^2 - m_{\Delta^{++}}^2 = \frac{\lambda_{h\Delta 2}}{4} v^2$$

Mass splittings limited by Tachyon conditions & perturbative unitarity

See [1105.1925] for comprehensive analysis of the potential

Constraints on a $Y = 1$ scalar triplet

Mixing with would-be Goldstones \leftrightarrow corrections to M_W, M_Z, ρ , EWPO

At tree level

$$\rho^0 = \frac{M_W^2}{\cos^2 \theta_w M_Z^2} = \frac{v^2 + 2v_\Delta^2}{v^2 + 4v_\Delta^2} = 1.00031 \pm 0.00019 \Rightarrow \text{upper limit on } v_\Delta \lesssim \mathcal{O}(\text{few GeV})$$

From electroweak fit (see PDG)



Oblique parameters S, T, U measure corrections to W, Z, γ self-energies (one-loop)

[Peskin, Takeuchi '91]

\Rightarrow Limit mass-scale and mass-splittings between components

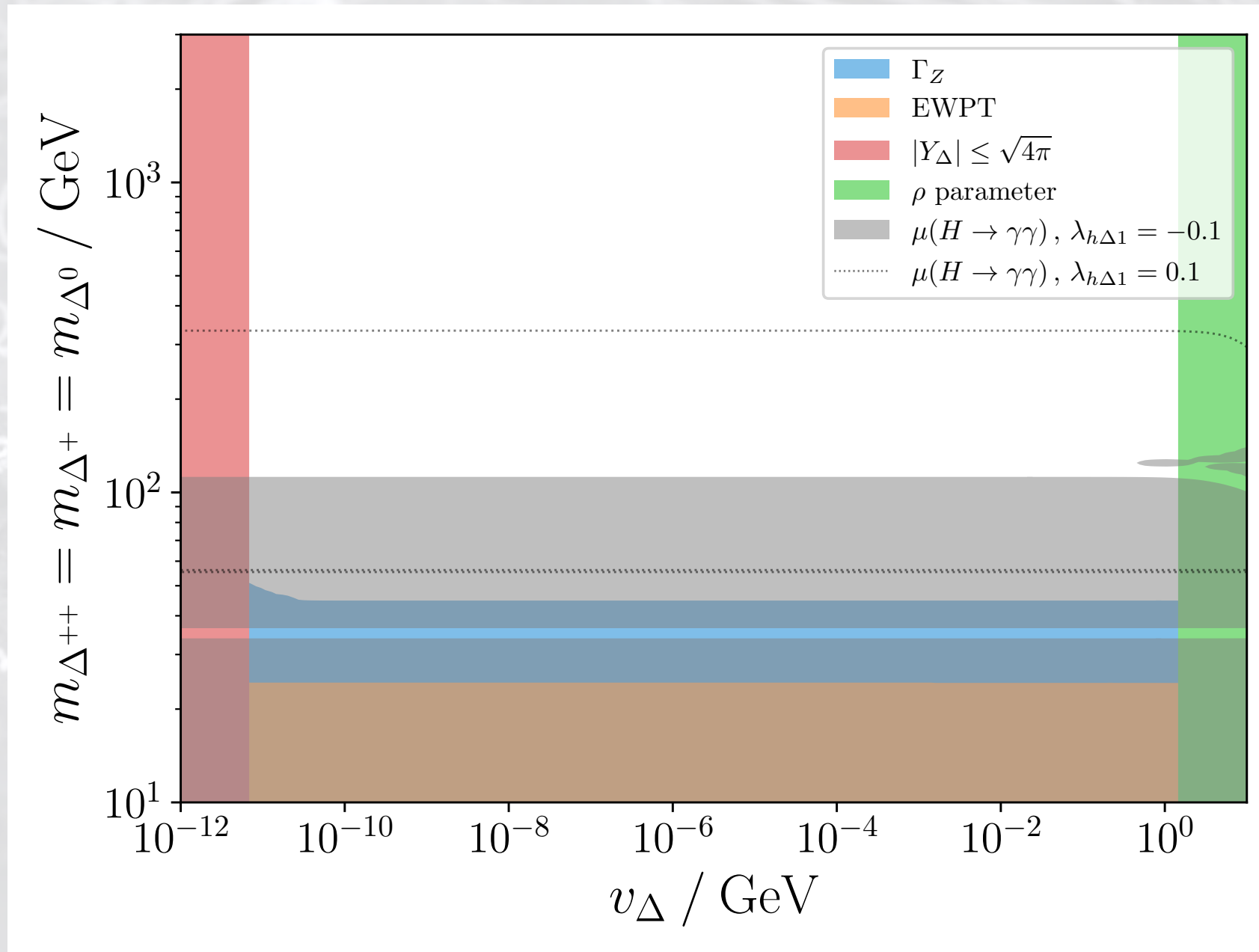
Computed for general $SU(2)_L$ multiplets in [hep-ph/9309262] for $v_\Delta = 0$

LEP measurements of Z line shape, Γ_Z : $m_{\Delta^{++,+,0}} \gtrsim \frac{M_Z}{2}$



Bi-quadratics $\lambda_{h\Delta 1} \varphi^\dagger \varphi \text{Tr} [\Delta^\dagger \Delta] + \lambda_{h\Delta 2} \text{Tr} [\varphi \varphi^\dagger \Delta \Delta^\dagger]$ induce corrections to $h \rightarrow \gamma\gamma$ (and $h \rightarrow Z\gamma$)

Constraints on a $Y = 1$ scalar triplet



⇒ **very small** and **very large** v_{Δ} excluded, still 11 orders of magnitude to play with

⇒ corrections to $h \rightarrow \gamma\gamma$ can be **tuned away** (with $\lambda_{h\Delta 1}$ and $\lambda_{h\Delta 2}$)

Constraints on a $Y = 1$ scalar triplet

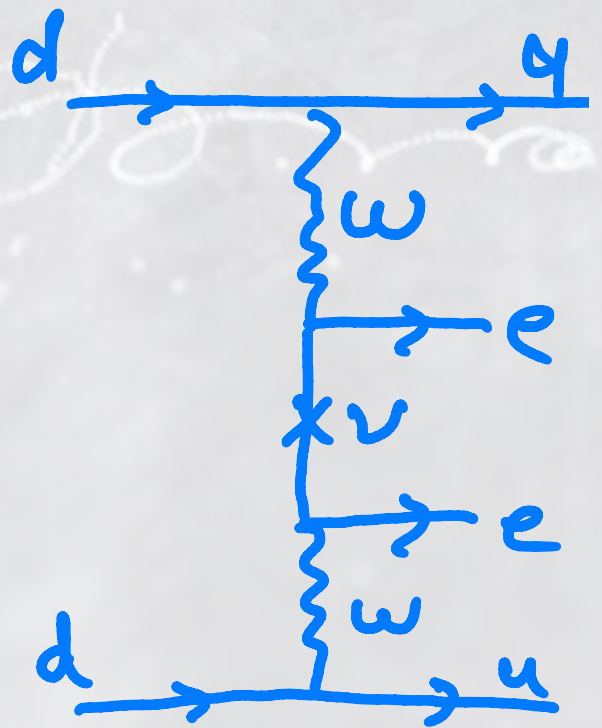
Yukawa Lagrangian $\mathcal{L}_{\text{yuk}} \supset Y_{\Delta}^{ij} L_{Li}^T \mathcal{C} i\sigma_2 \Delta_L L_{Lj} + \text{h.c.}$

\Rightarrow Generate Majorana neutrino masses: $M_{\nu} = U_P^* m_{\nu} U_P^{\dagger} = \sqrt{2} v_{\Delta} Y_{\Delta}$

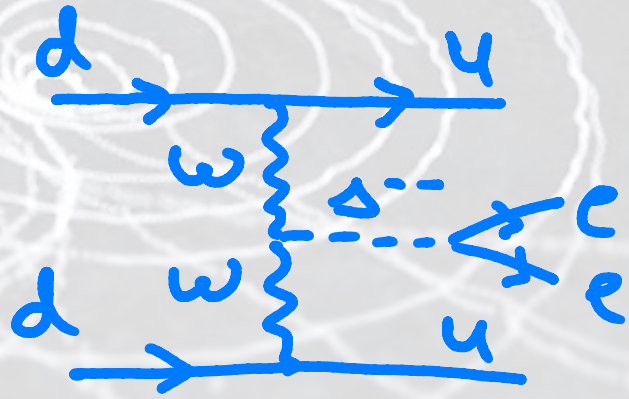
Yukawa structure completely fixed by oscillation data, $Y_{\Delta} \simeq \mathcal{O}(1)$ for $v_{\Delta} \simeq 10^{-10}$ GeV

\Rightarrow Combined presence of **Yukawa** and $\mu_{h\Delta}$ leads to **Lepton Number violating** interactions

Neutrinoless double beta decay ($0\nu 2\beta$):



Long range interaction from light **Majorana** mass insertion



Short range interaction strongly suppressed for $m_{\Delta} \gtrsim 100$ GeV, vertex: $\Delta^{++} WW \propto v_{\Delta}/v$

Constraints on a $Y = 1$ scalar triplet

Yukawa Lagrangian $\mathcal{L}_{\text{yuk}} \supset Y_{\Delta}^{ij} L_{Li}^T \mathcal{C} i\sigma_2 \Delta_L L_{Lj} + \text{h.c.}$

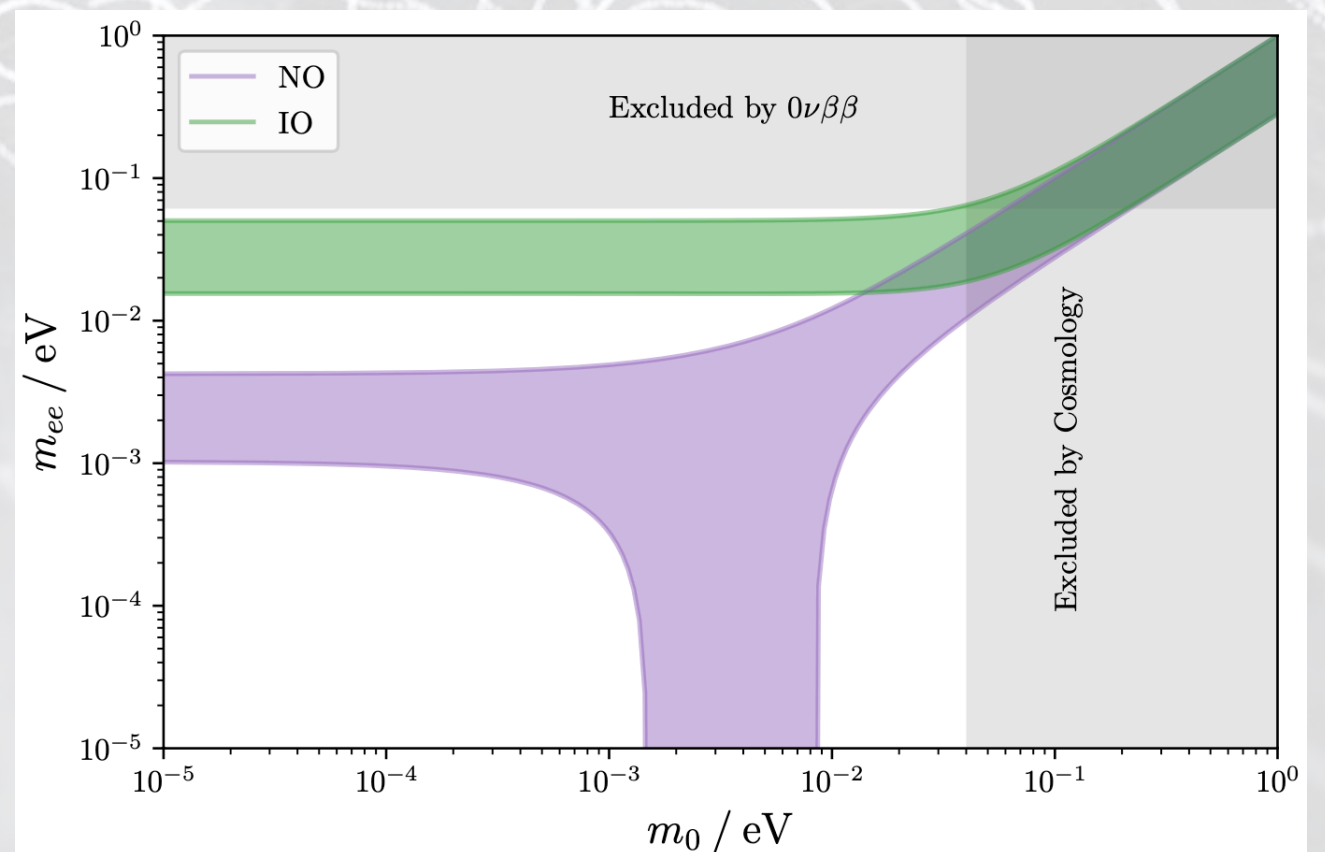
\Rightarrow Generate Majorana neutrino masses: $M_{\nu} = U_P^* m_{\nu} U_P^{\dagger} = \sqrt{2} v_{\Delta} Y_{\Delta}$

Yukawa structure completely fixed by oscillation data, $Y_{\Delta} \simeq \mathcal{O}(1)$ for $v_{\Delta} \simeq 10^{-10}$ GeV

\Rightarrow Combined presence of **Yukawa** and $\mu_{h\Delta}$ leads to **Lepton Number violating** interactions

Neutrinoless double beta decay ($0\nu 2\beta$):

Long-range interaction fixed by U_P, m_{ν_i}



Constraints on a $Y = 1$ scalar triplet

Yukawa Lagrangian $\mathcal{L}_{\text{yuk}} \supset Y_{\Delta}^{ij} L_{Li}^T \mathcal{C} i\sigma_2 \Delta_L L_{Lj} + \text{h.c.}$

\Rightarrow Generate Majorana neutrino masses: $M_{\nu} = U_P^* m_{\nu} U_P^{\dagger} = \sqrt{2} v_{\Delta} Y_{\Delta}$

Yukawa structure completely fixed by oscillation data, $Y_{\Delta} \simeq \mathcal{O}(1)$ for $v_{\Delta} \simeq 10^{-10}$ GeV

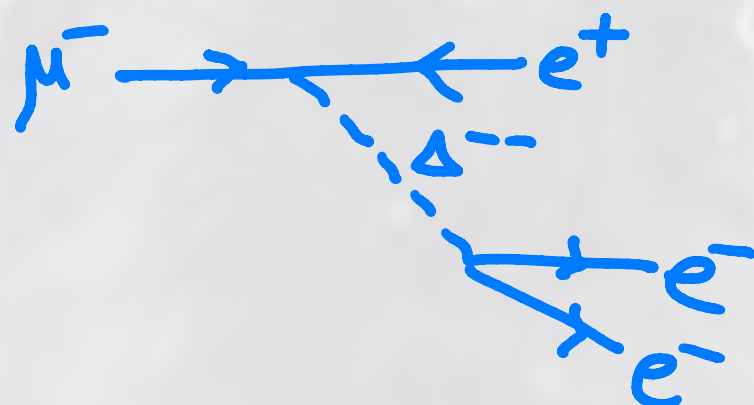
Off-diagonal Yukawas induce **lepton flavour-violating** interactions:

See also [Ana's talk](#)

$\ell_{\alpha}^{-} \rightarrow \ell_i^{+} \ell_j^{-} \ell_k^{-}$ Tree

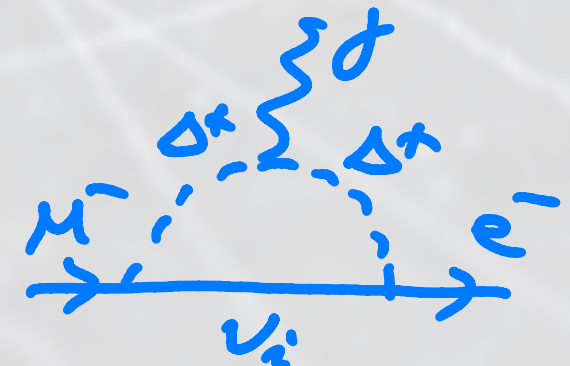
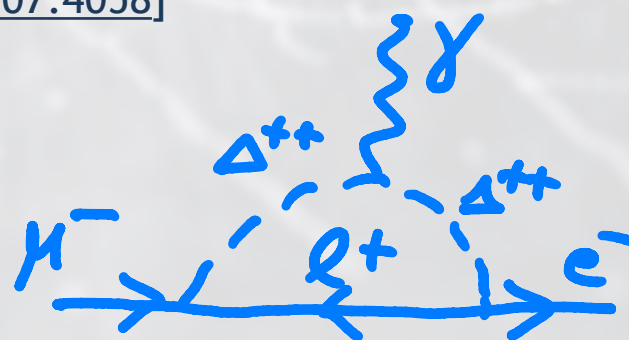
$$\Gamma \simeq \frac{m_{\ell_{\alpha}}^5}{(1 + \delta_{jk}) 96 \pi^3 m_{\Delta^{++}}^4} |Y_{\Delta}^{\alpha i}|^2 |Y_{\Delta}^{jk}|^2$$

See e.g. [\[0707.4058\]](#)



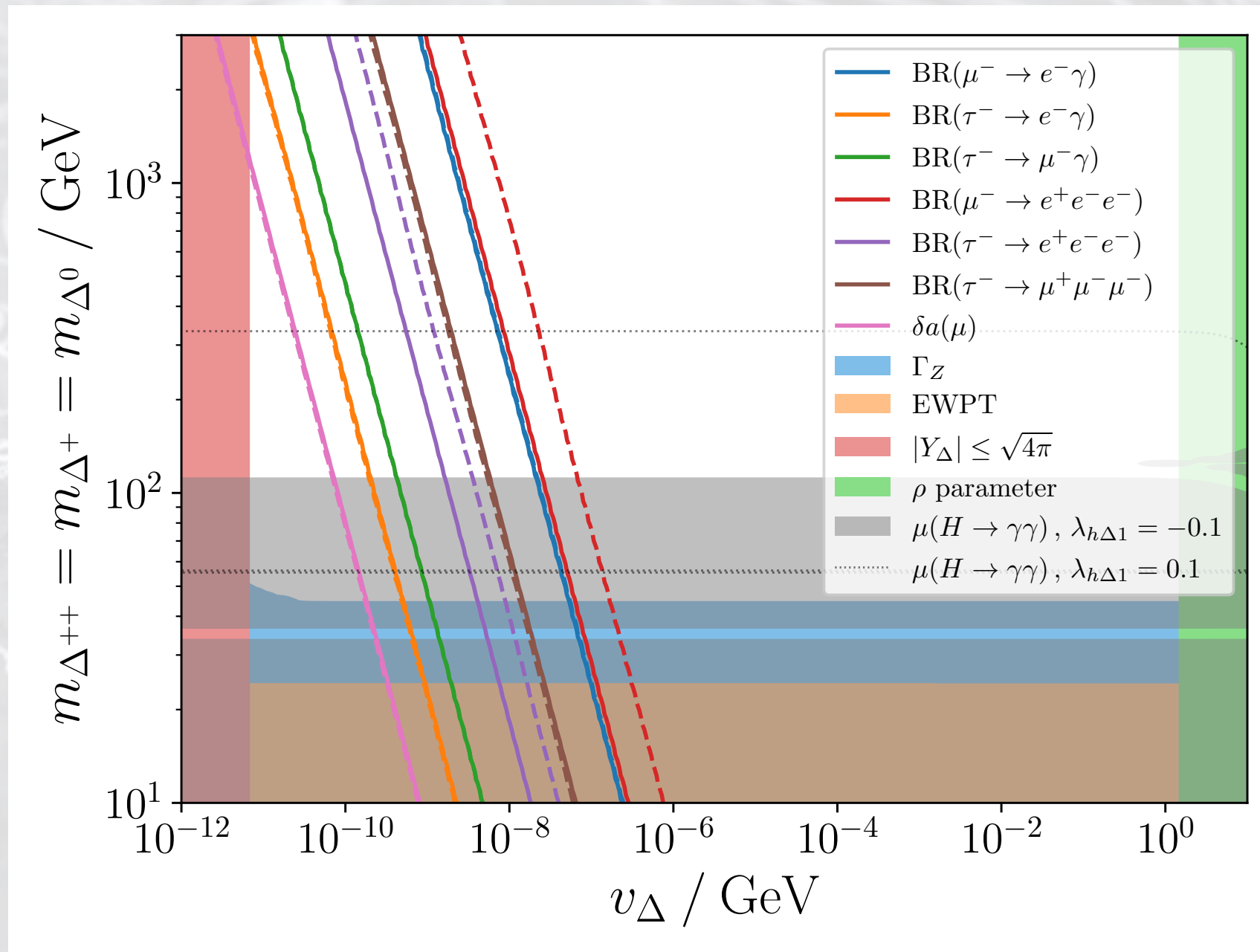
$\ell_{\alpha} \rightarrow \ell_{\beta} \gamma$ Loop

$$\Gamma \propto \frac{m_{\ell_{\alpha}}^5}{256 \pi^3 m_{\Delta^{++}}^4} \left| \sum Y_{\Delta}^{\alpha i \dagger} Y_{\Delta}^{\beta i} \right|^2$$



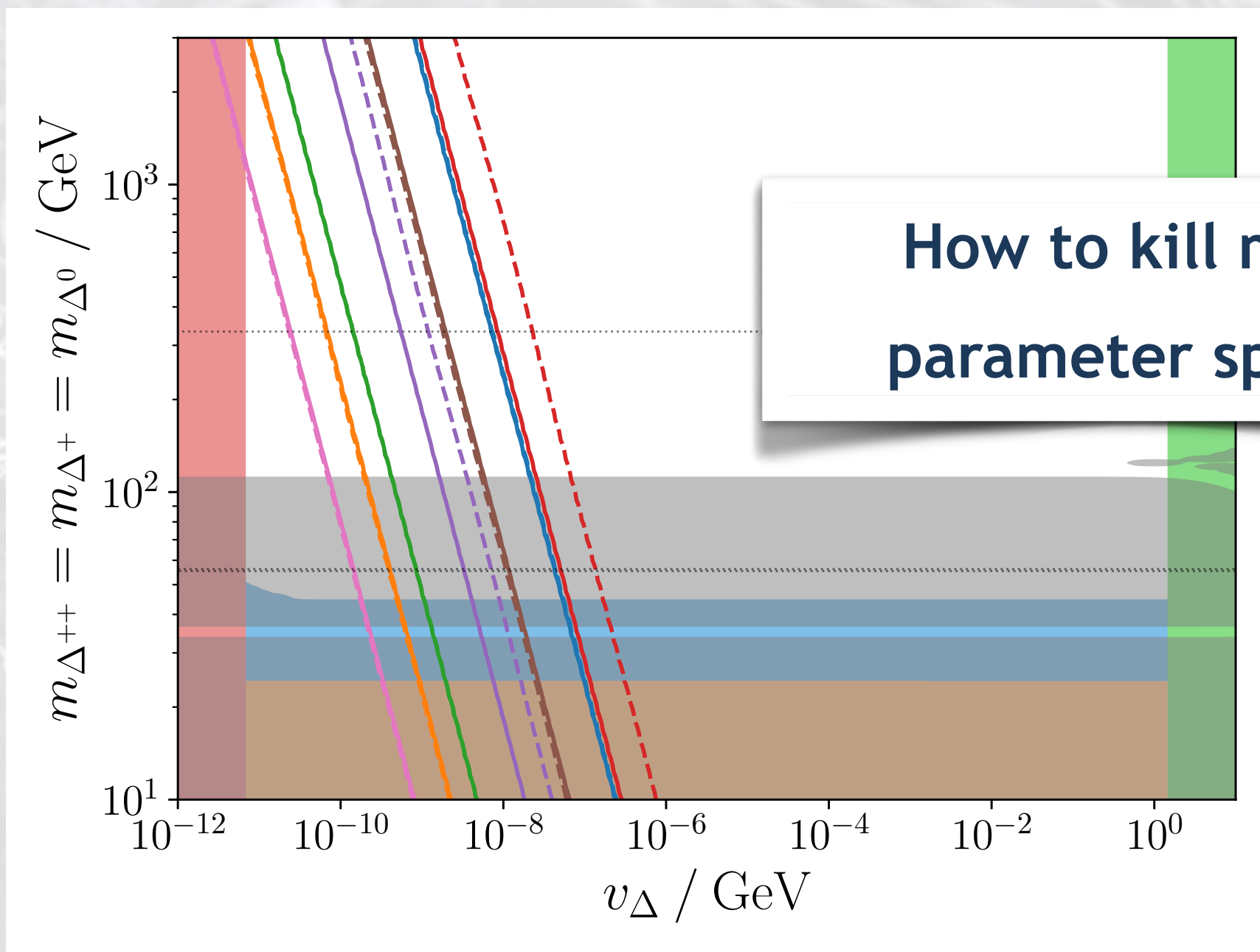
(Contributions to $(g - 2)_{\ell}$ generically negative, weaker bound)

Constraints on a $Y = 1$ scalar triplet



⇒ Bounds on $\mu \rightarrow eee$ and $\mu \rightarrow e\gamma$ strongest, further push v_{Δ}

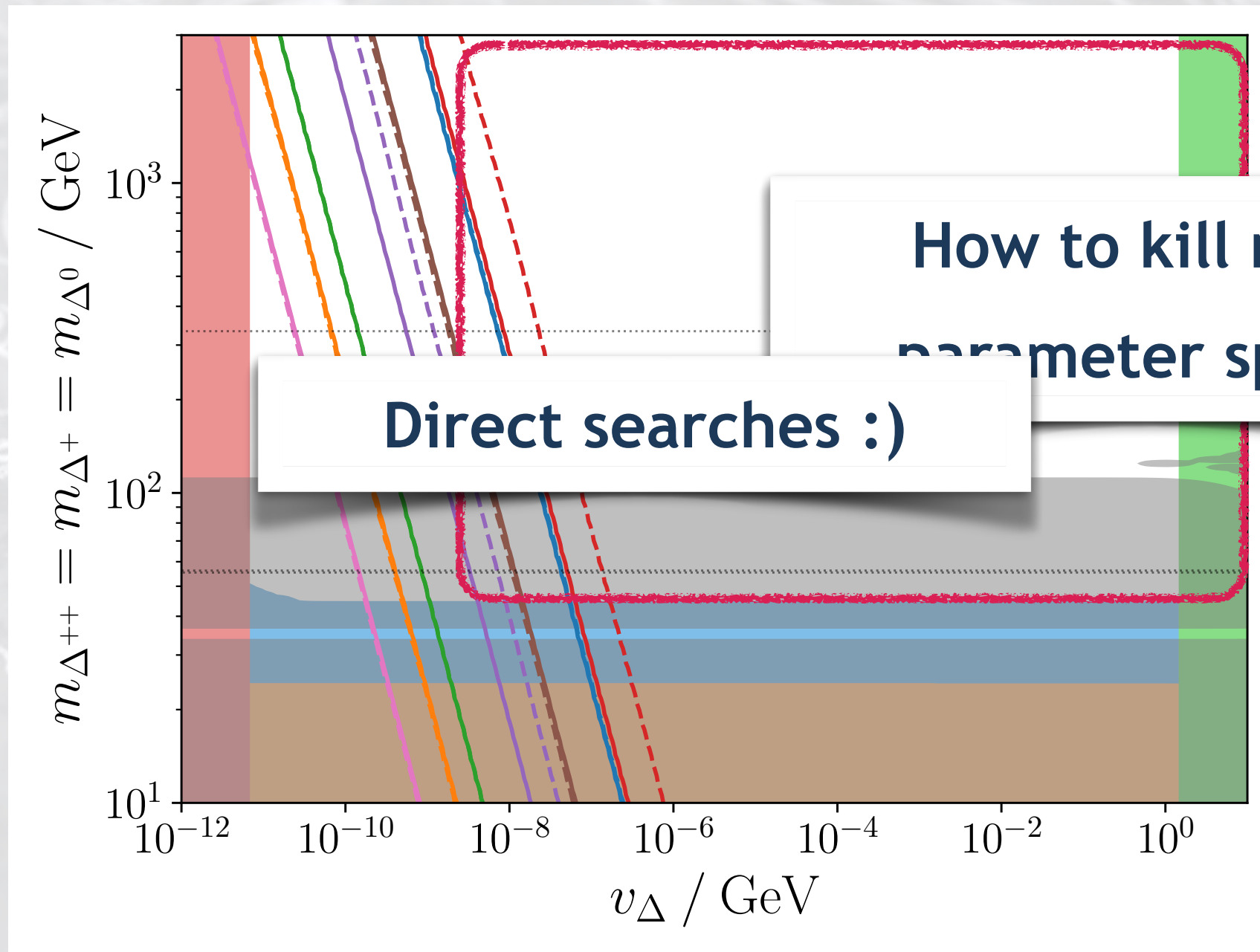
Constraints on a $Y = 1$ scalar triplet



How to kill more parameter space?

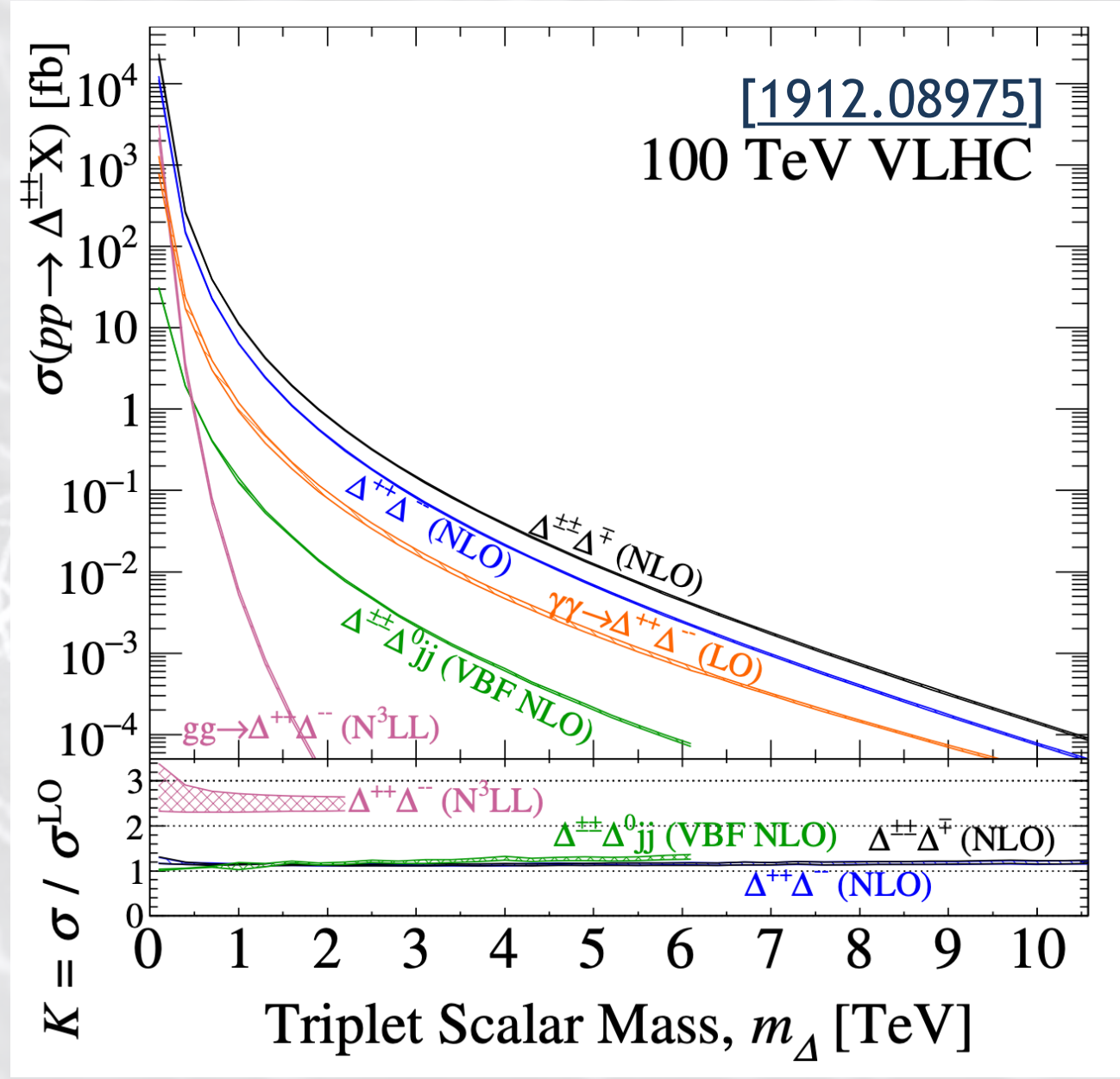
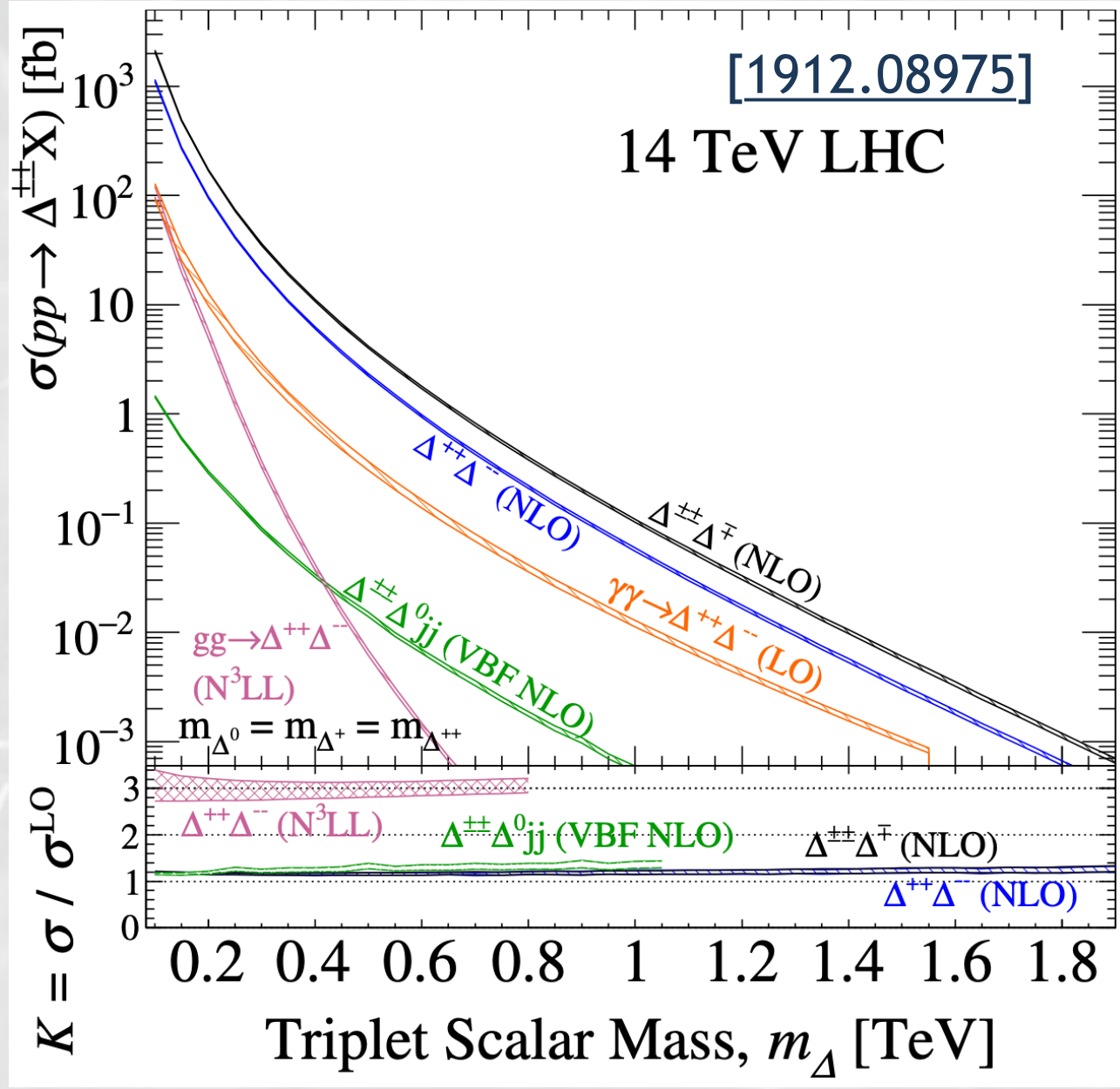
⇒ Bounds on $\mu \rightarrow eee$ and $\mu \rightarrow e\gamma$ strongest, further push v_{Δ}

Constraints on a $Y = 1$ scalar triplet



⇒ Bounds on $\mu \rightarrow eee$ and $\mu \rightarrow e\gamma$ strongest, further push v_{Δ}

Direct searches – production modes



⇒ Drell-Yan pair and associate production always dominate for $m_{\Delta} \gtrsim 100$ GeV, regime for resonant $gg \rightarrow h \rightarrow \Delta\Delta$ already covered (excluded) by LEP searches

⇒ Production at LEP: $e^+e^- \rightarrow Z^*, \gamma^* \rightarrow \Delta^{++,+} \Delta^{--,-}$

Decay modes of the triplet components

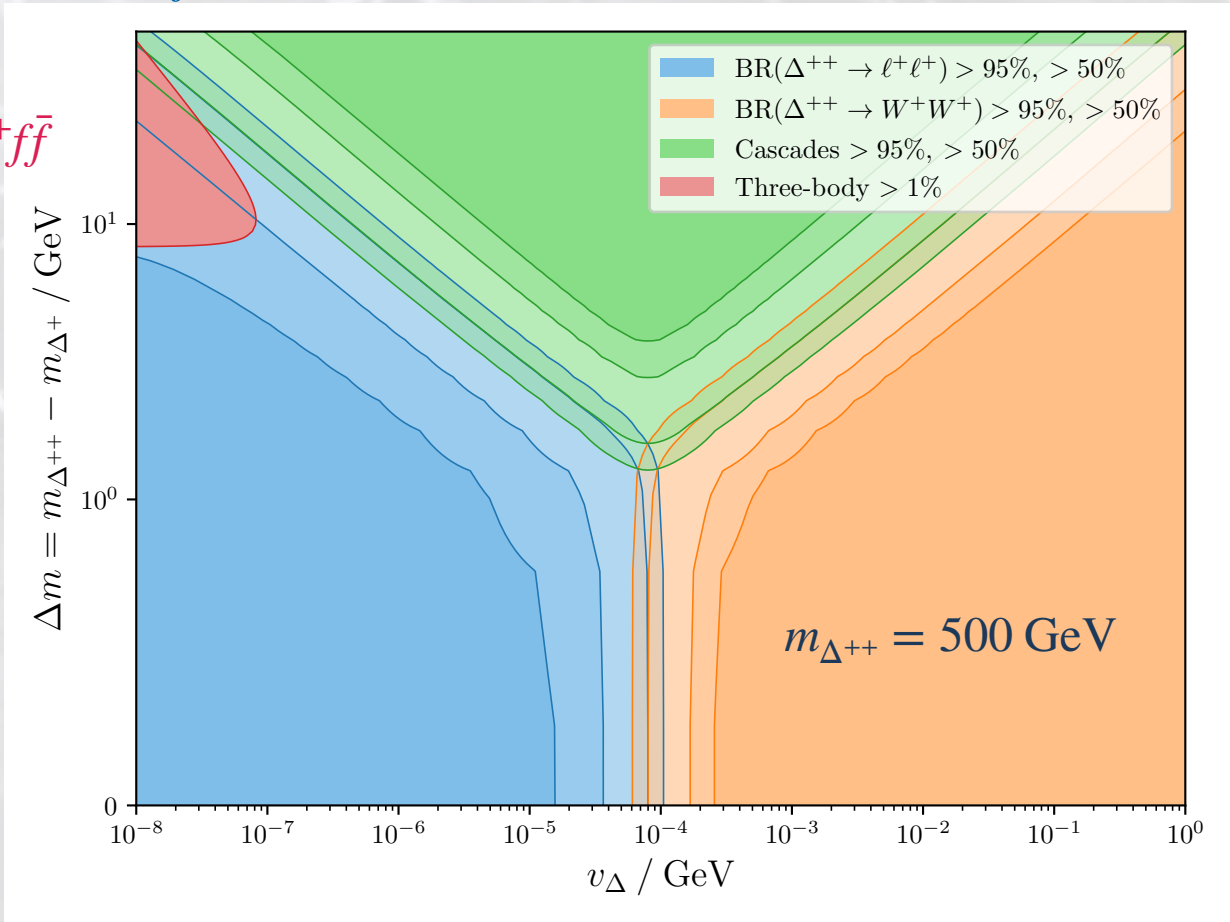
Smoking gun signal: resonance in the same-sign di-lepton invariant mass from $\Delta^{\pm\pm}$ decay

$v_\Delta \lesssim 10^{-4}$ GeV: $\Delta^{\pm\pm} \rightarrow \ell_i^\pm \ell_j^\pm$ dominant

Larger v_Δ : $\Delta^{\pm\pm} \rightarrow W^\pm W^\pm$ quickly dominates

Three-body decays subdominant $\Delta^{++} \rightarrow W^+ f \bar{f}$

$$\Gamma_{\Delta^{++} \rightarrow \ell_i^+ \ell_j^+} = \frac{m_{\Delta^{++}}}{8\pi(1 + \delta_{ij})} \left| \frac{M_{\nu ij}}{v_\Delta} \right|^2$$



$$\Gamma_{\Delta^{++} \rightarrow W^+ W^+} \propto \alpha_2^2 \frac{v_\Delta^2}{v^2} \frac{m_{\Delta^{++}}}{M_W^2}$$

If $m_{\Delta^{++}} > m_{\Delta^+}$: $\Delta^{\pm\pm} \rightarrow \Delta^\pm + X$ cascades dominate

$$\Gamma_{\Delta^{++} \rightarrow \Delta^+ f \bar{f}} \simeq \frac{3\alpha_2^2}{5\pi} \frac{\Delta m_\Delta^5}{M_W^4}$$

Decay modes of the triplet components

Smoking gun signal: resonance in the same-sign di-lepton invariant mass from $\Delta^{\pm\pm}$ decay

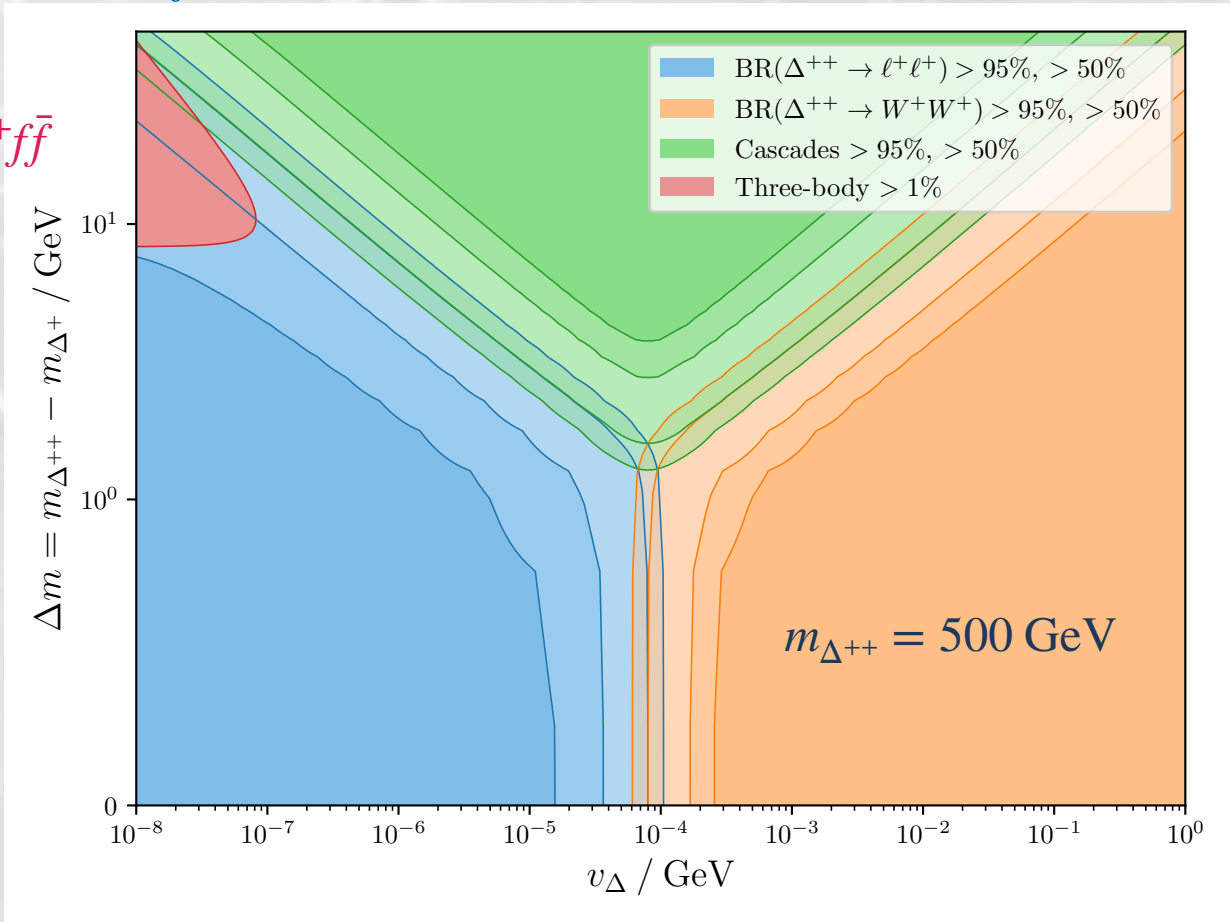
$v_\Delta \lesssim 10^{-4}$ GeV: $\Delta^{\pm\pm} \rightarrow \ell_i^\pm \ell_j^\pm$ dominant

Larger v_Δ : $\Delta^{\pm\pm} \rightarrow W^\pm W^\pm$ quickly dominates

Three-body decays subdominant $\Delta^{++} \rightarrow W^+ f \bar{f}$

$$\Gamma_{\Delta^{++} \rightarrow \ell_i^+ \ell_j^+} = \frac{m_{\Delta^{++}}}{8\pi(1 + \delta_{ij})} \left| \frac{M_{\nu ij}}{v_\Delta} \right|^2$$

Searches for pair & associate production: $\ell^+ \ell^+ \ell^- \ell^-$ and $\ell^+ \ell^+ \ell^- \nu$ final states



$$\Gamma_{\Delta^{++} \rightarrow W^+ W^+} \propto \alpha_2^2 \frac{v_\Delta^2}{v^2} \frac{m_{\Delta^{++}}}{M_W^2}$$

Some ATLAS searches for **di-boson**

Searches for pair & associate production: $W^+ W^+ W^- W^-$ and $W^+ W^+ W^- Z$

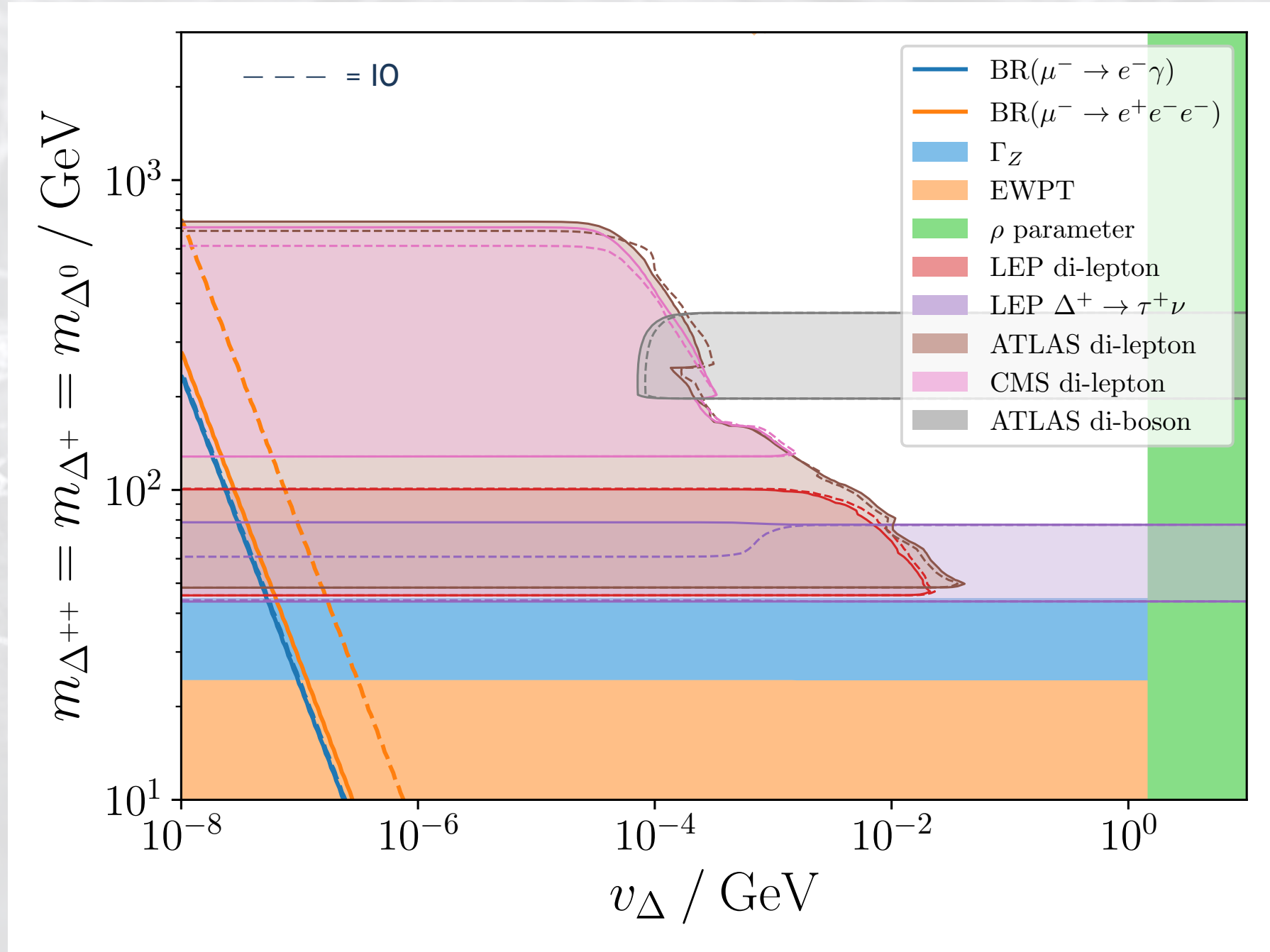
LEP/LHC searches mostly focus on **di-lepton** channel

LEP searches for $\Delta^\pm \rightarrow \tau^\pm \nu$, LHC searches only for subdominant production/decay channels

$$\Gamma_{\Delta^+ \rightarrow \ell_i^+ \nu} \simeq \frac{m_{\Delta^+}}{16\pi} \frac{\sum_\nu m_\nu^2 |V_{i\nu}|^2}{v_\Delta^2}$$

Prospects for displaced vertex searches see e.g. [1811.03476]

Current state of the art

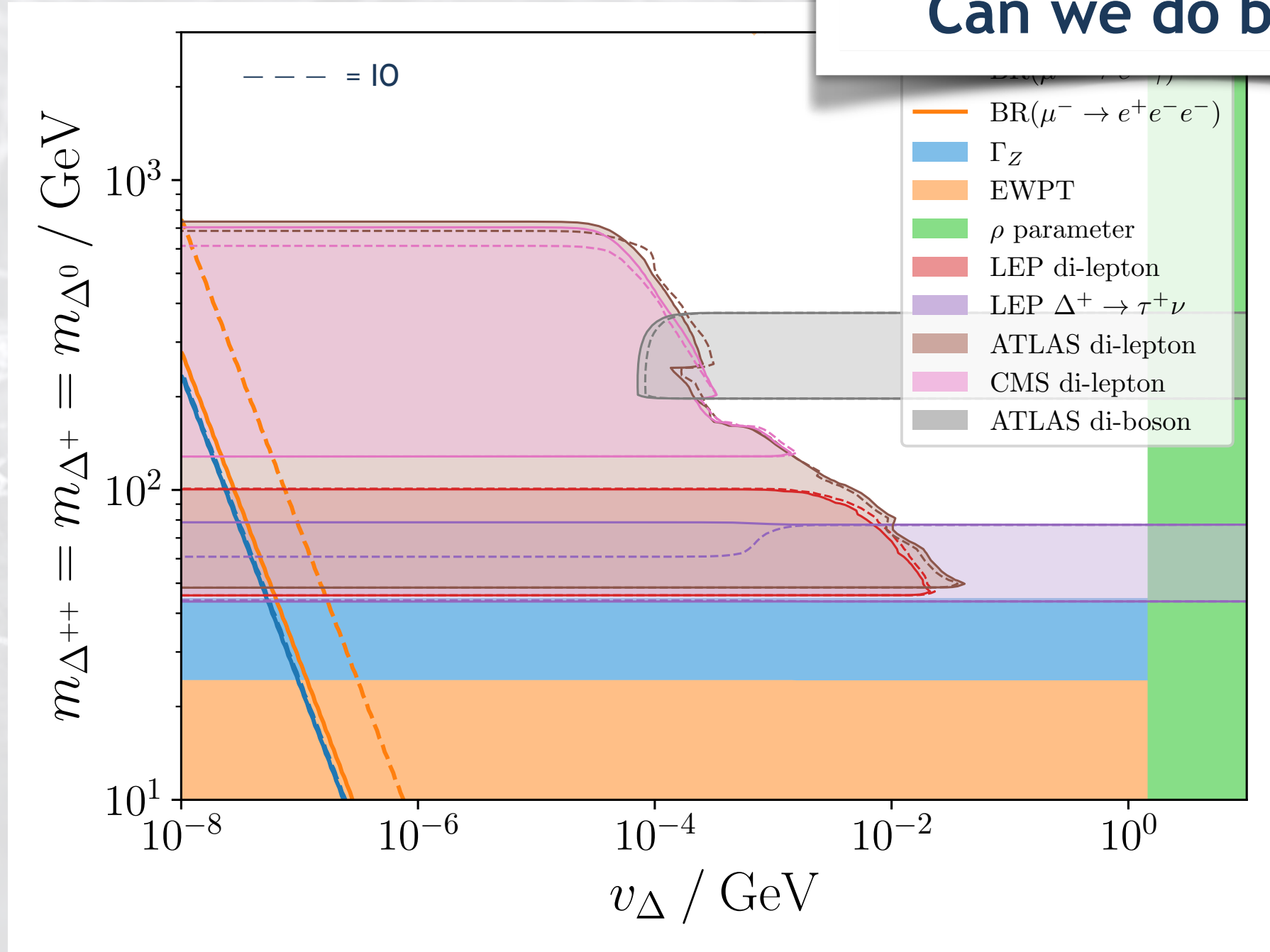


⇒ LHC searches exclude $m_{\Delta^{++}} \lesssim 700 \text{ GeV}$ for small v_{Δ}

⇒ Di-boson final states harder to reconstruct, smaller efficiencies

Current state of the art

Can we do better?



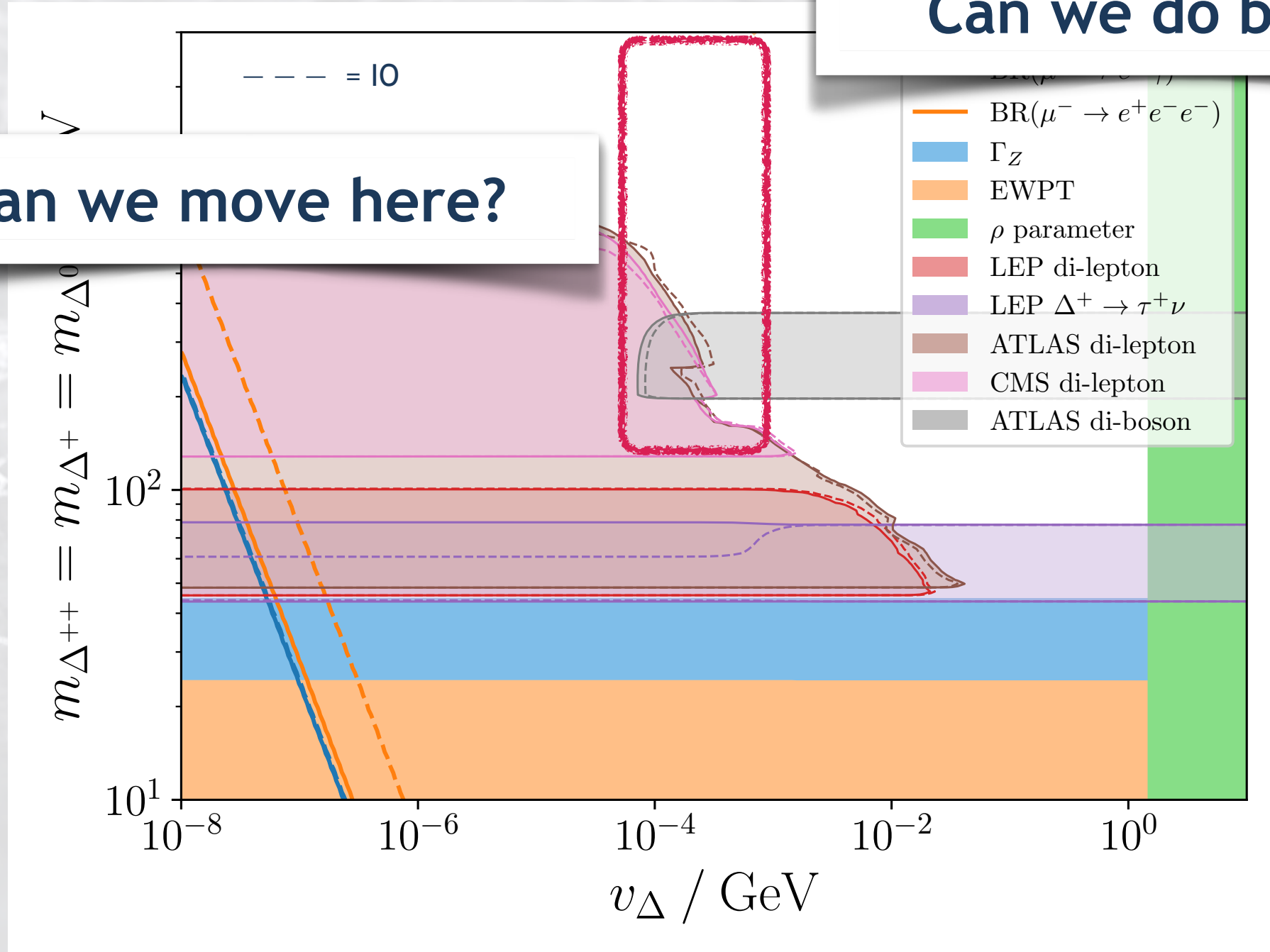
⇒ LHC searches exclude $m_{\Delta^{++}} \lesssim 700 \text{ GeV}$ for small v_{Δ}

⇒ Di-boson final states harder to reconstruct, smaller efficiencies

Current state of the art

Can we do better?

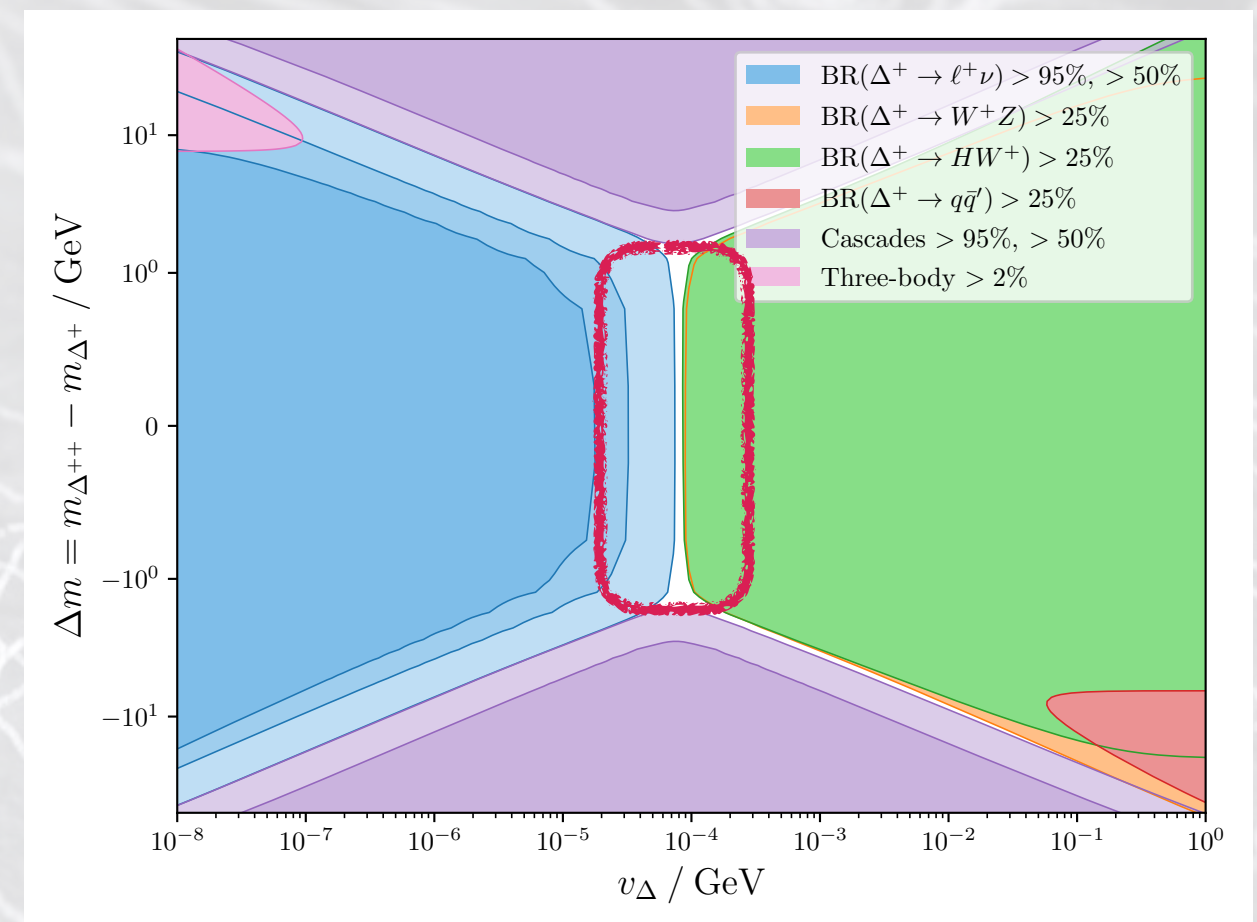
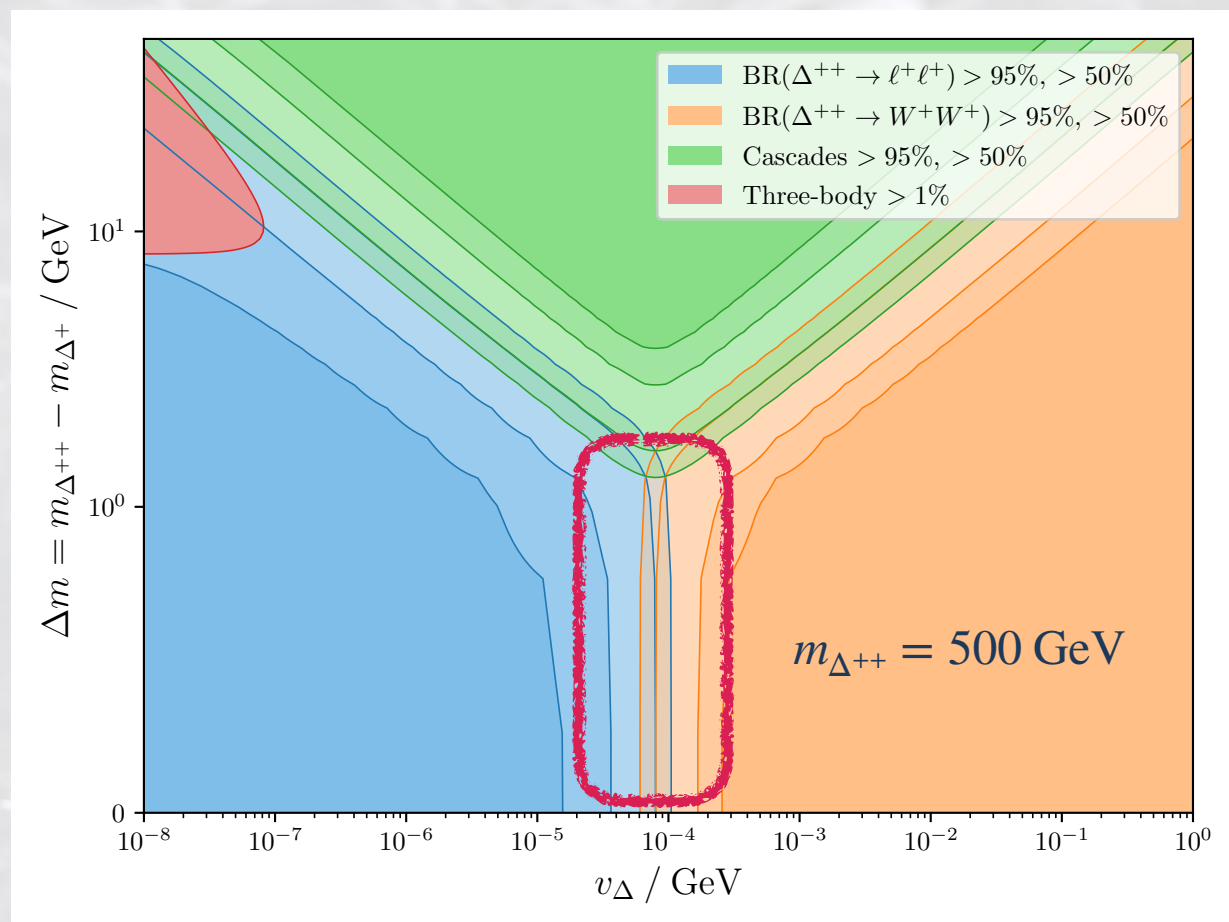
Can we move here?



⇒ LHC searches exclude $m_{\Delta^{++}} \lesssim 700 \text{ GeV}$ for small v_{Δ}

⇒ Di-boson final states harder to reconstruct, smaller efficiencies

Decay modes of the triplet components



Larger v_{Δ} : $\Delta^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ quickly dominates

Intermediate region: “**LNV window**”

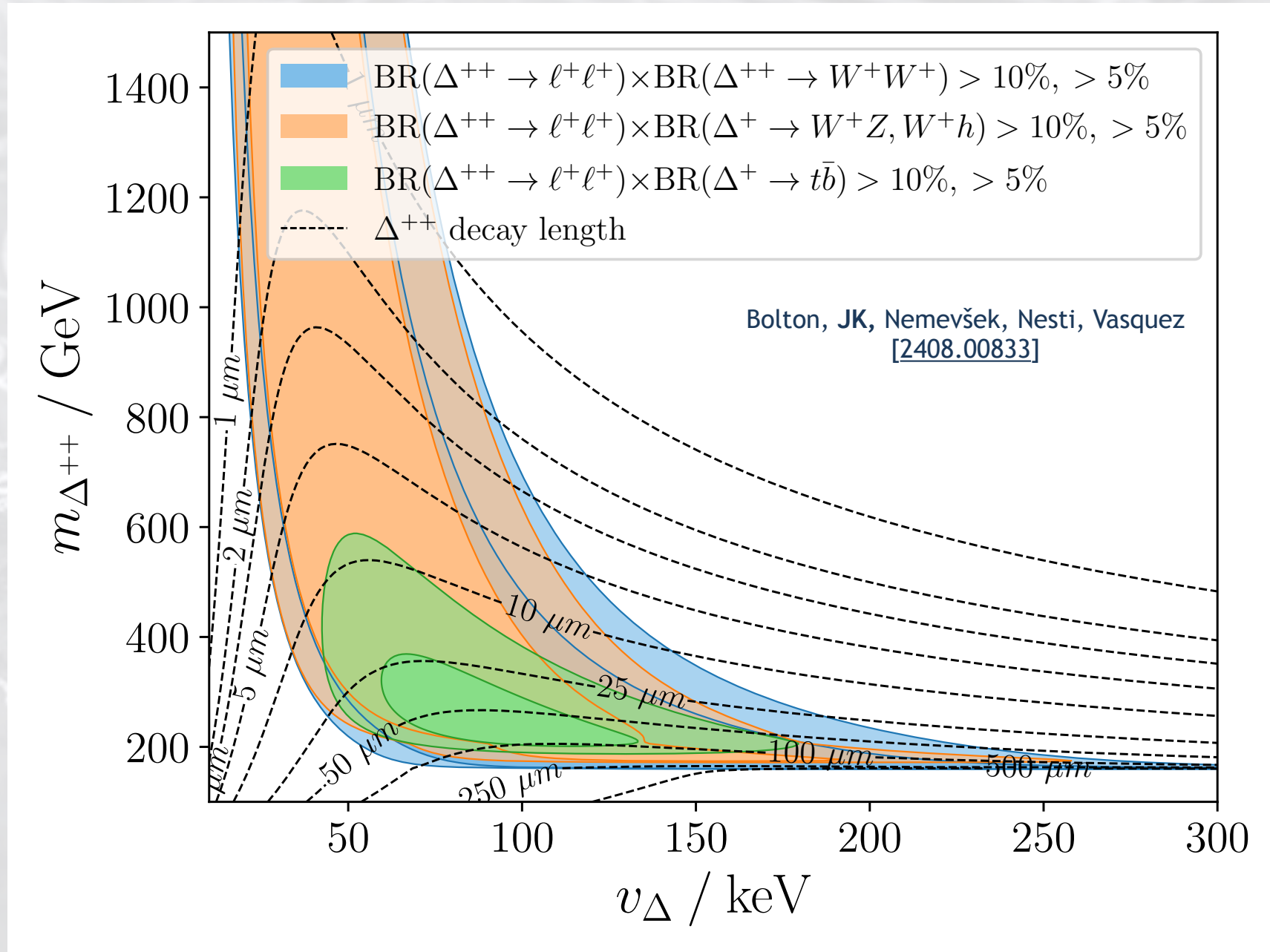
See also [2212.08025] for first glimpse

Maeizza, Nemevšek, Nesti '16

Narrow window where $BR(\Delta^{++} \rightarrow \ell_i^+ \ell_j^+) \simeq BR(\Delta^{++} \rightarrow W^+ W^+)$

Leading to **manifestly lepton number violating** final states at colliders: $pp \rightarrow \ell_i^+ \ell_j^+ W^{\mp} W^{\mp}$

The LNV window



⇒ Identify three different **signal processes**

⇒ Mass reach maximal for $v_{\Delta} \simeq 40 - 50 \text{ keV}$

⇒ Decays mostly prompt (except at W threshold)

Accessing the LNV window at (HL)-LHC

Event selection:

- ▶ (At least) **2 same-sign leptons** $\ell^\pm \ell'^\pm$, $\ell, \ell' = e, \mu$
- ▶ (At least) **2 matched jets** $\Delta R = 0.3$, $p_{Tj\min} = 20$ GeV
- ▶ Demand $p_{Tj,\ell} > 50$ GeV on **leading lepton/jet**
- ▶ Demand leading leptons $m_{\ell\ell} \in [0.9, 1.1] m_{\Delta^{++}}$
- ▶ Reject $m_{j_1 j_2} > 1.1 m_{\Delta^{++}}$

Dominant backgrounds:

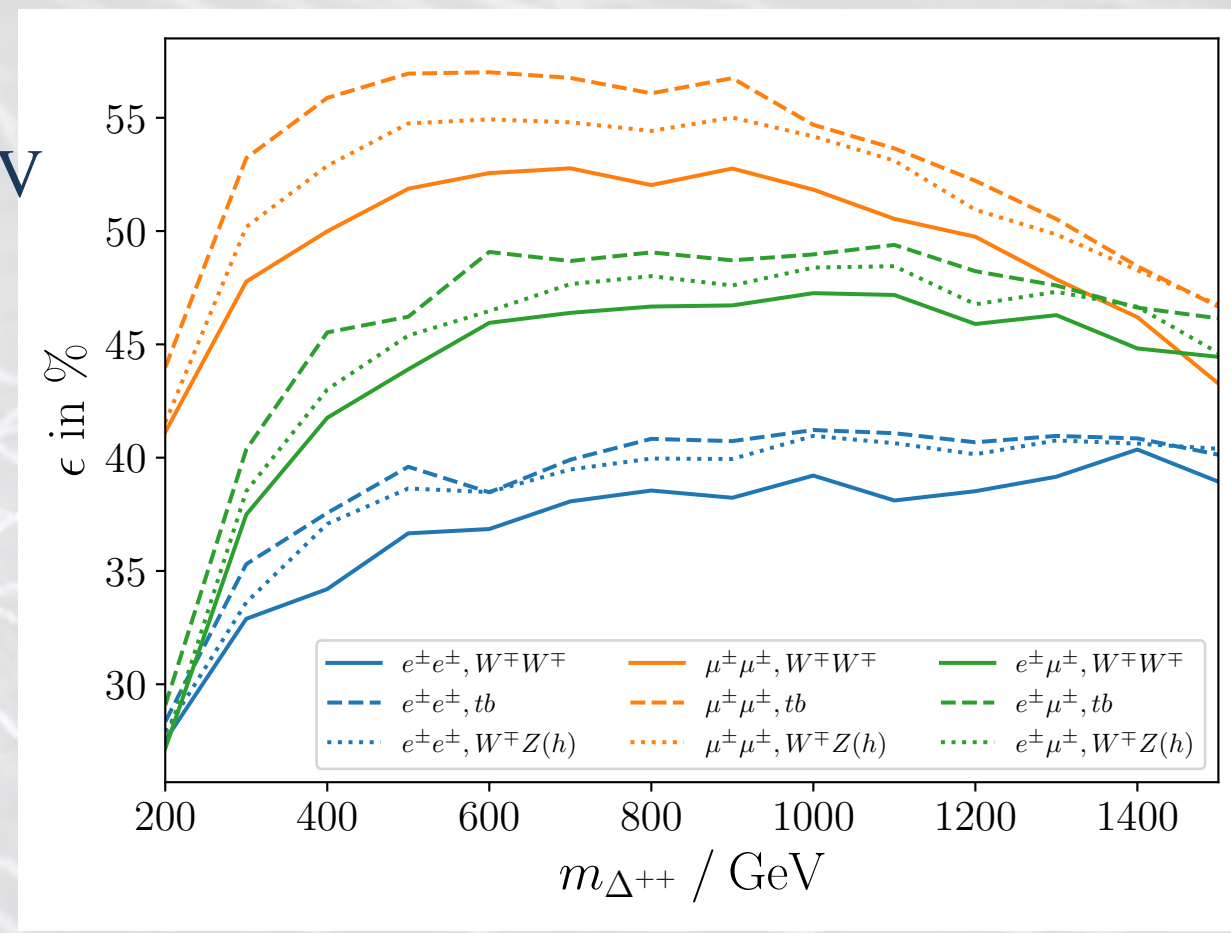
- ▶ $pp \rightarrow V + 012j$, $pp \rightarrow VV + 012j$, $V = W^\pm, Z$
- ▶ $pp \rightarrow t\bar{t} + 012j$, ($pp \rightarrow VVV + 012j$ found to subdominant)

Event simulation:

Model file adapted from Fuks, Nemevšek, Ruiz [[1912.08975](#)]

- ▶ Use *MadGraph5* (at LO) + *Pythia8* + *Delphes* (default card) + *MadAnalysis5* chain
- ▶ Rescaled to NLO in QCD, signals and backgrounds simulated to 100 fb^{-1}

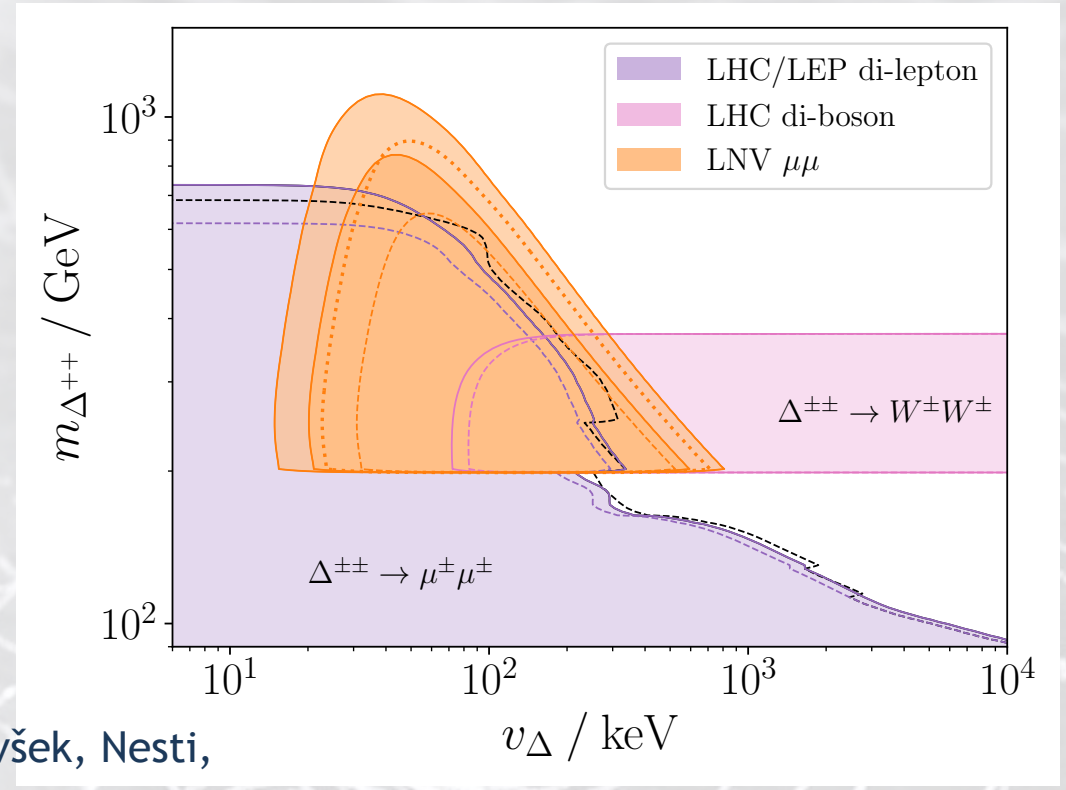
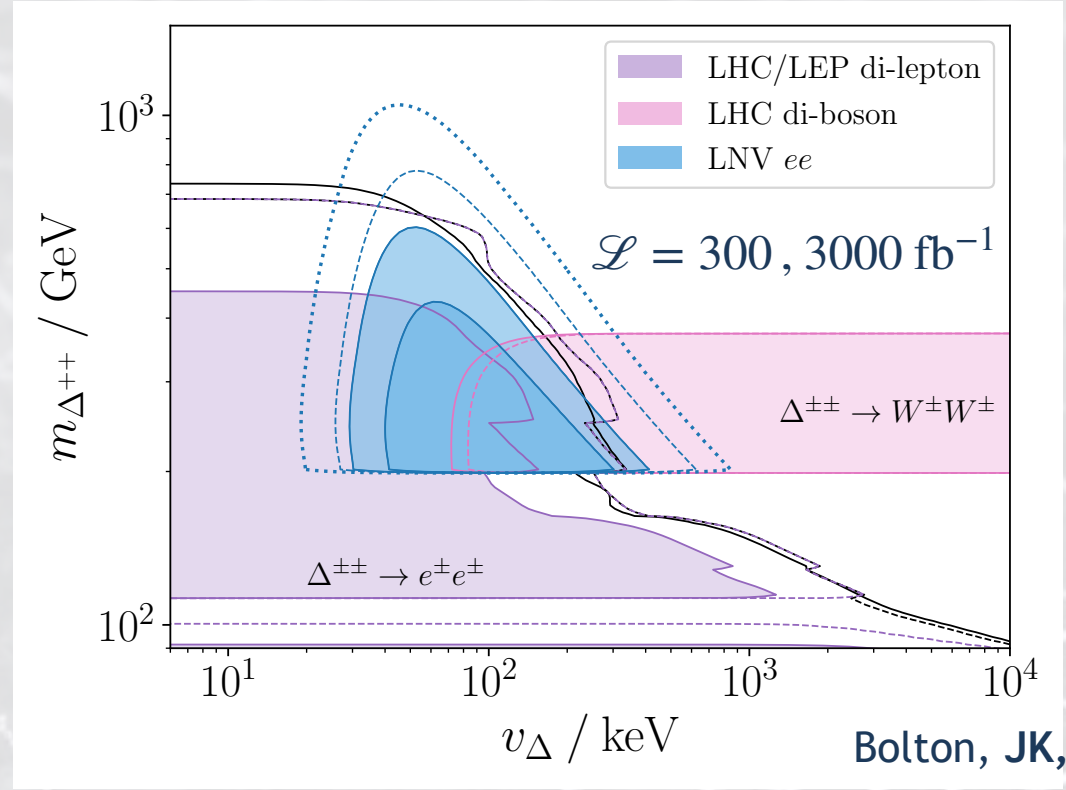
Signal efficiencies after cuts



⇒ Muon final state highest efficiency



The LNV window – sensitivities

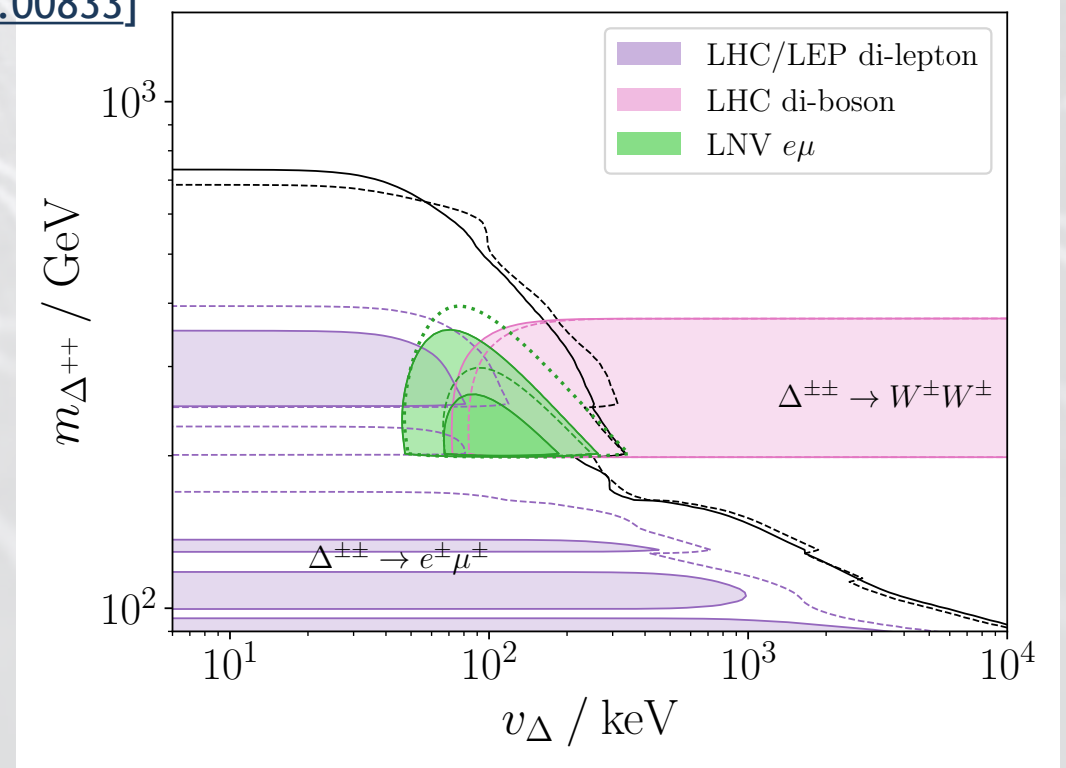


Bolton, JK, Nemevšek, Nesti, Vasquez [2408.00833]

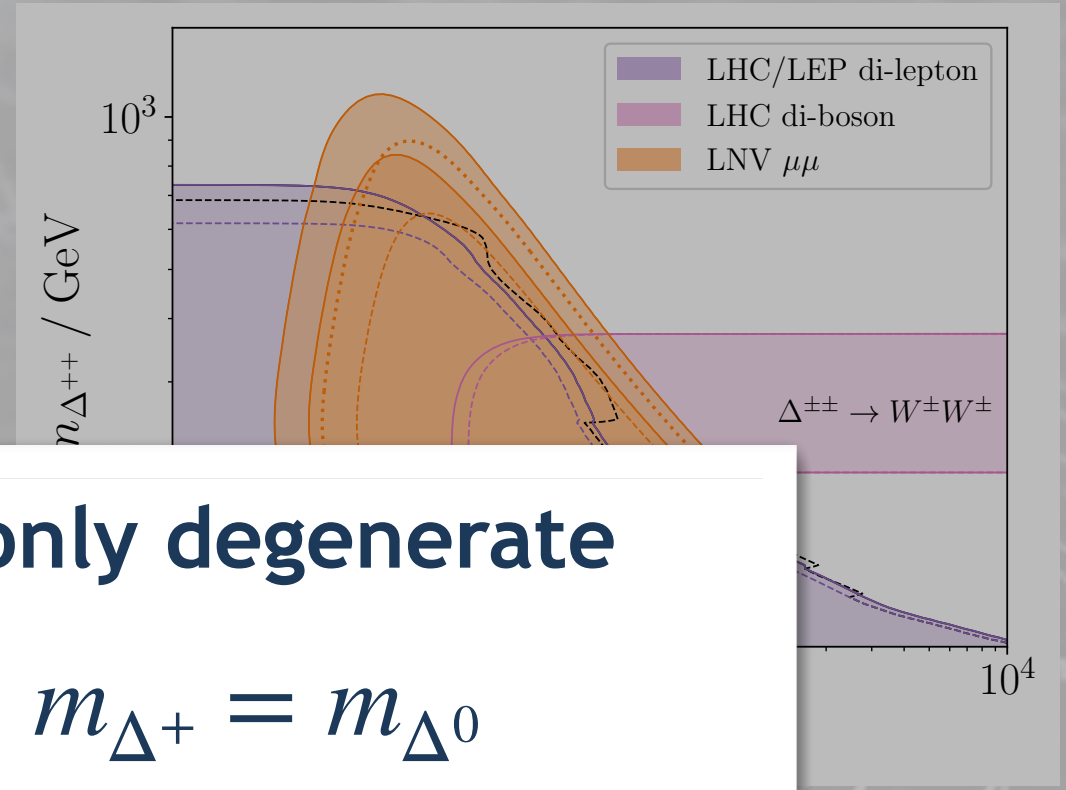
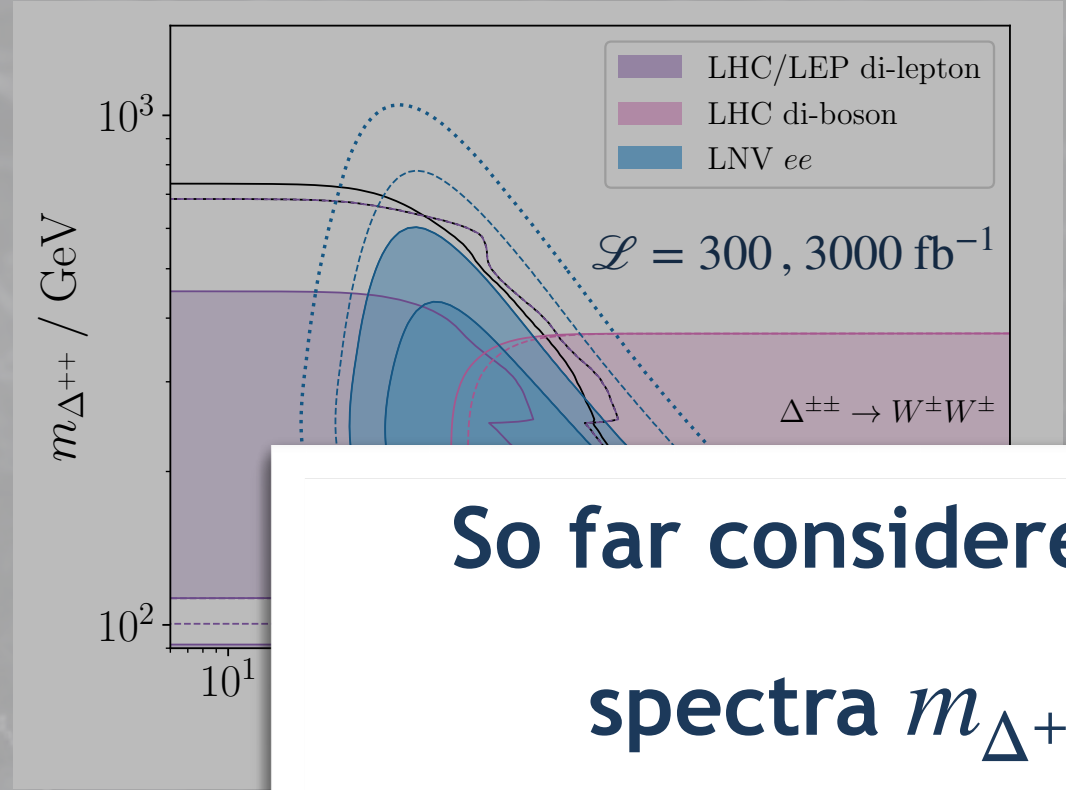
Cover region towards larger m_{Δ} and v_{Δ}

$e^{\pm}e^{\pm}/\mu^{\pm}\mu^{\pm}$ reach strongly depends on **ordering**

$e\mu$ final state suffers from larger backgrounds



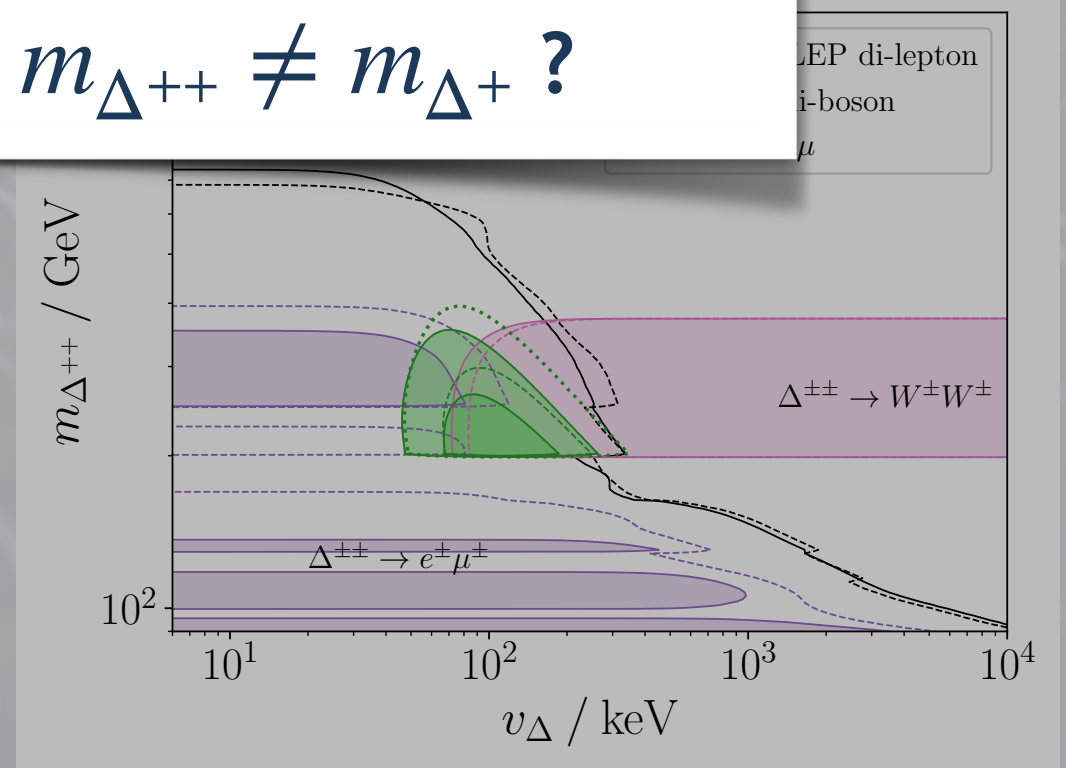
The LNV window – sensitivities



So far considered only degenerate spectra $m_{\Delta^{++}} = m_{\Delta^+} = m_{\Delta^0}$

What happens for $m_{\Delta^{++}} \neq m_{\Delta^+}$?

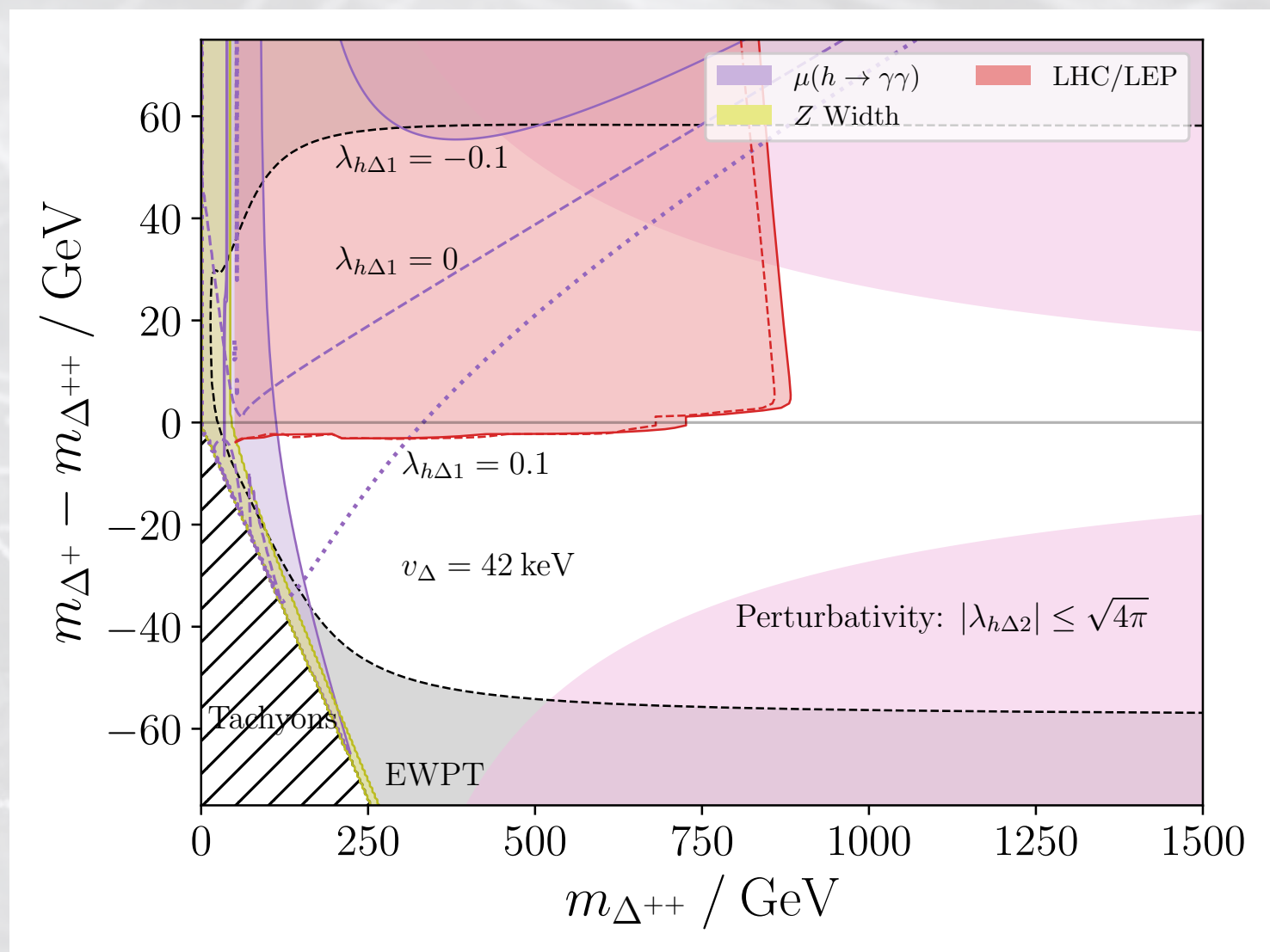
Cover region



$e^{\pm}e^{\pm}/\mu^{\pm}\mu^{\pm}$ reach strongly depends on **ordering**

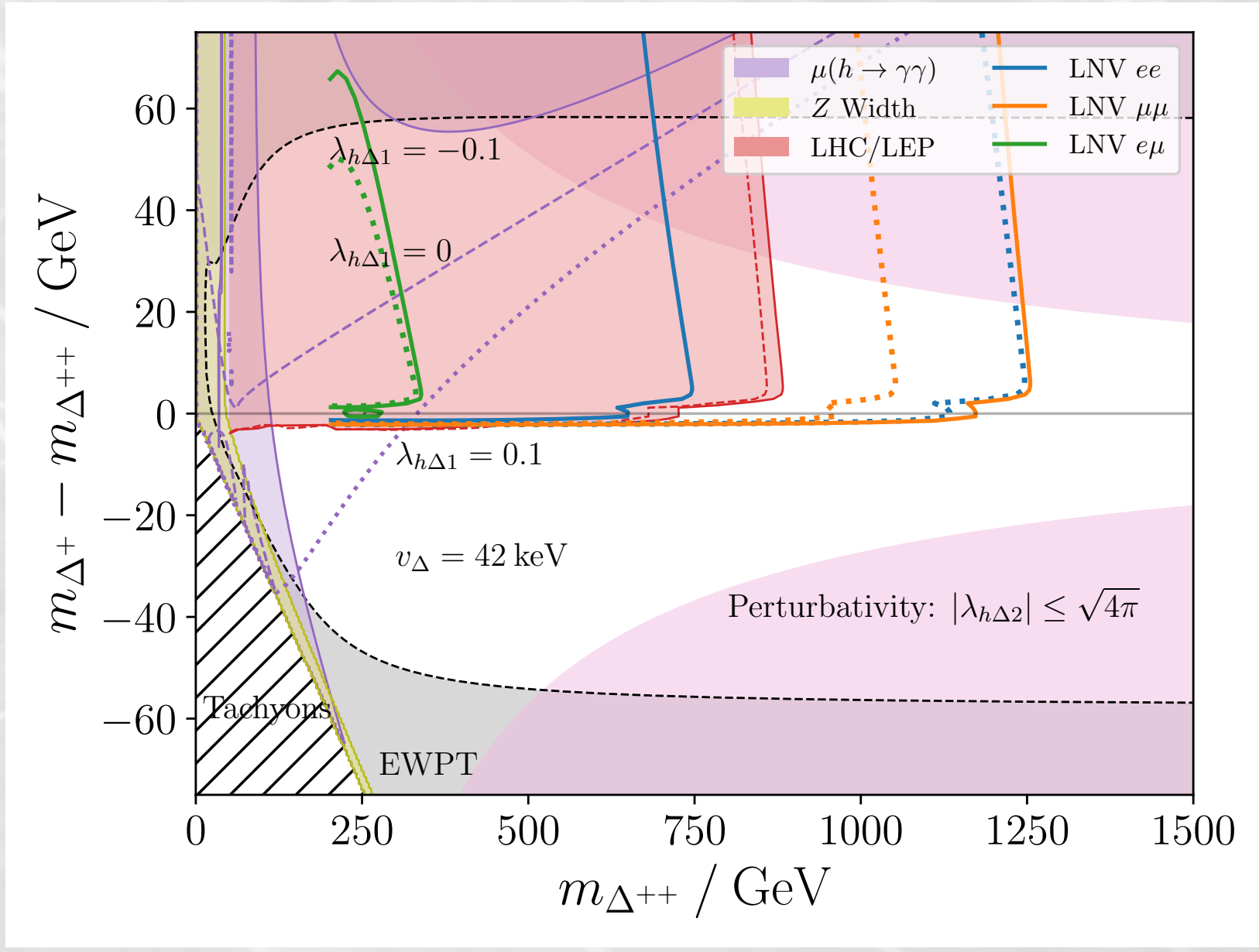
$e\mu$ final state suffers from larger backgrounds

Switching on cascades



- ⇒ Oblique parameters (EWPT) and $h \rightarrow \gamma\gamma$ strongly depend on **mass splitting**
- Perturbativity** of the potential & **absence of tachyonic modes** become constraining
- ⇒ Cascade decays open **new production channels**: e.g. $pp \rightarrow \Delta^0 (\rightarrow \Delta^- jj \rightarrow \Delta^{--} jjjj) \Delta^+ (\rightarrow \Delta^{++} jj)$
- ⇒ **Increase mass reach** for positive mass splittings; negative: $\sigma \times \text{BR}$ **tends quickly to 0**
- ⇒ Direct searches **don't exclude anything** if $m_{\Delta^{++}} > m_{\Delta^+}$

Switching on cascades



⇒ Cascade decays open **new production channels**: e.g. $pp \rightarrow \Delta^0 (\rightarrow \Delta^- jj \rightarrow \Delta^{--} jjjj) \Delta^+ (\rightarrow \Delta^{++} jj)$

⇒ **Increase mass reach** for positive mass splittings; negative: $\sigma \times \text{BR}$ **tends quickly to 0**

Existing searches: $m_{\Delta^{++}} \gtrsim 900 \text{ GeV}$

LNV window: $m_{\Delta^{++}} \gtrsim 1300 \text{ GeV}$

Conclusions & Outlook

- ▶ Minimal **Type II seesaw** is a *cool* model that gives an origin to neutrino masses
 Appears e.g. in the left-right symmetric model on the way to GUTs
- ▶ Collider searches start to gradually **exclude the low-scale** parameter space
 Small ν_Δ : di-lepton Large ν_Δ : di-boson
- ▶ Suggest new search strategy for intermediate ν_Δ region: the **LVN window**
 Could be first discovery of **Lepton Number Violation** (before $0\nu 2\beta$)
- ▶ Cascade decays can **strengthen searches** or **kill them completely**
 Need to recast/design new searches for Δ^0, χ_Δ final states

Conclusions & Outlook

- ▶ Minimal **Type II seesaw** is a *cool* model that gives an origin to neutrino masses
Appears e.g. in the left-right symmetric model on the way to GUTs
- ▶ Collider searches start to gradually **exclude the low-scale** parameter space

Small ν_Δ : di-lepton	Large ν_Δ : di-boson
--------------------------------	-------------------------------
- ▶ Suggest new search strategy for intermediate ν_Δ region: the **LVN window**
 Could be first discovery of **Lepton Number Violation** (before $0\nu 2\beta$)
- ▶ Cascade decays can **strengthen searches** or **kill them completely**
 Need to recast/design new searches for Δ^0, χ_Δ final states

Thanks for your
attention!

Bonus content

Type II seesaw mechanism: the induced vev

Extend Standard Model with a scalar $Y = 1$, $SU(2)_L$ -triplet

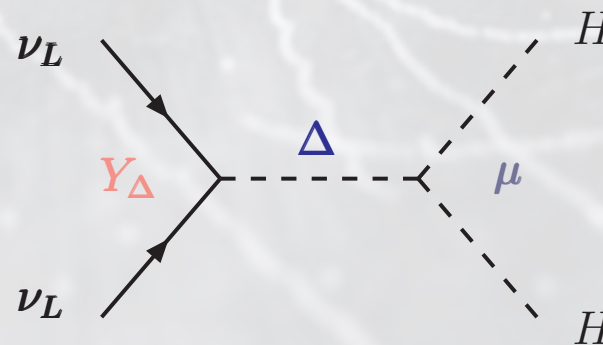
$$\Delta_L = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \frac{v_\Delta + \Delta^0 + i\chi_\Delta}{\sqrt{2}} & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

$$V(\varphi, \Delta) = -\mu_h^2 \varphi^\dagger \varphi + m_\Delta^2 \text{Tr}[\Delta^\dagger \Delta] + \lambda_h (\varphi^\dagger \varphi)^2 + \lambda_{\Delta 1} \text{Tr}[\Delta^\dagger \Delta]^2 + \lambda_{\Delta 2} [(\Delta^\dagger \Delta)^2] \\ + \mu_{h\Delta} (\varphi^T i\sigma_2 \Delta^\dagger \varphi + \text{h.c.}) + \lambda_{h\Delta 1} \varphi^\dagger \varphi \text{Tr}[\Delta^\dagger \Delta] + \lambda_{h\Delta 2} \text{Tr}[\varphi \varphi^\dagger \Delta \Delta^\dagger]$$

$\varphi = \text{SM-like } SU(2)_L\text{-doublet}$

Minimise **potential**: $\mu_h^2 \simeq v^2 \lambda_h$, $\mu_{h\Delta} \simeq \frac{v_\Delta (2m_\Delta^2 + v^2 \lambda_{h\Delta})}{\sqrt{2} v^2}$

\Rightarrow Triplet vev v_Δ **induced** by SM-like electroweak vev and $\mu_{h\Delta} \neq 0$ (stability condition $\mu_{h\Delta} > 0$)

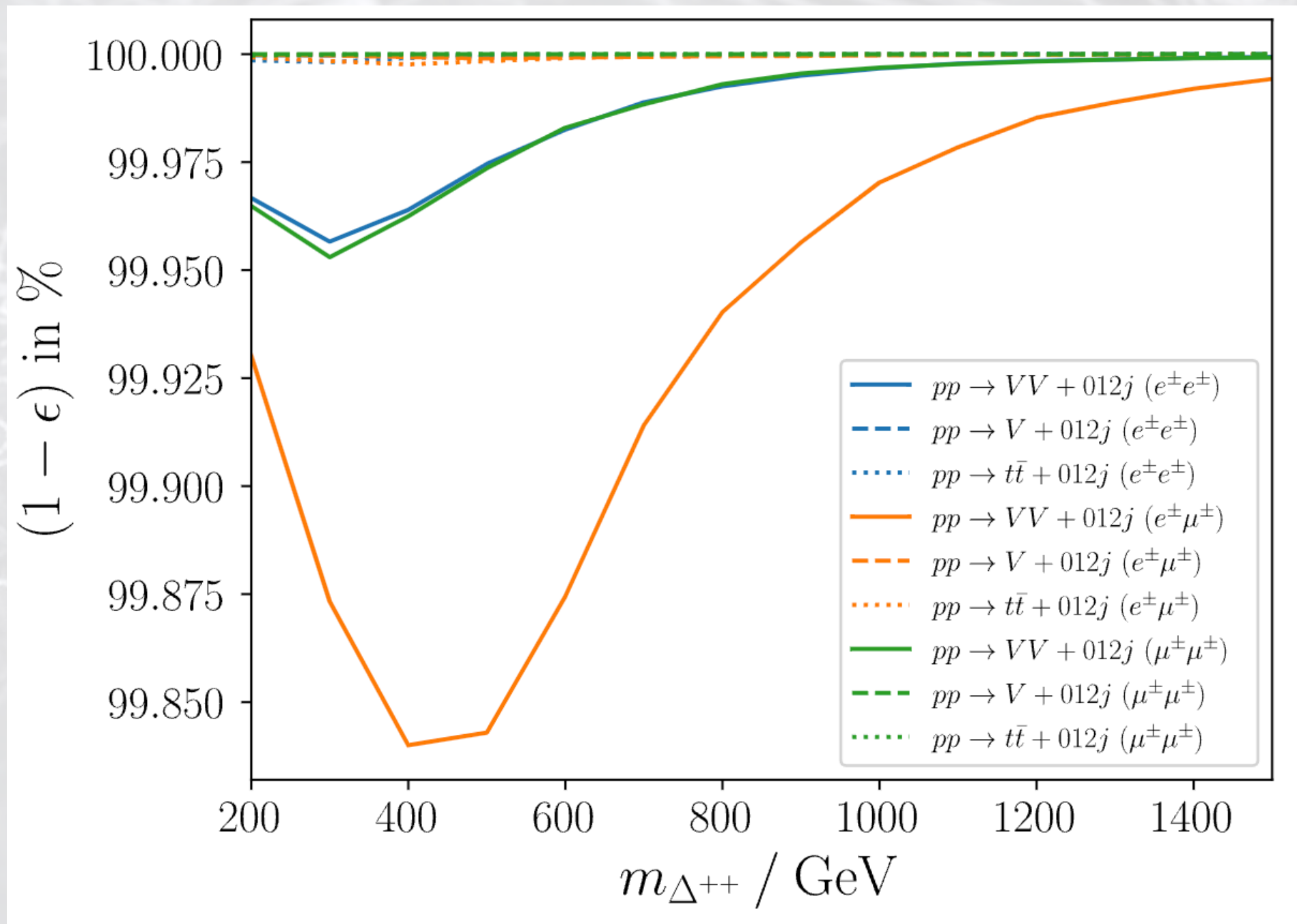


See e.g. [1105.1925]

\Rightarrow Combined presence of **Yukawa** and $\mu_{h\Delta}$ leads to **Lepton Number violating** interactions

\Rightarrow small $\mu_{h\Delta}$ & v_Δ technically natural

Background rejection

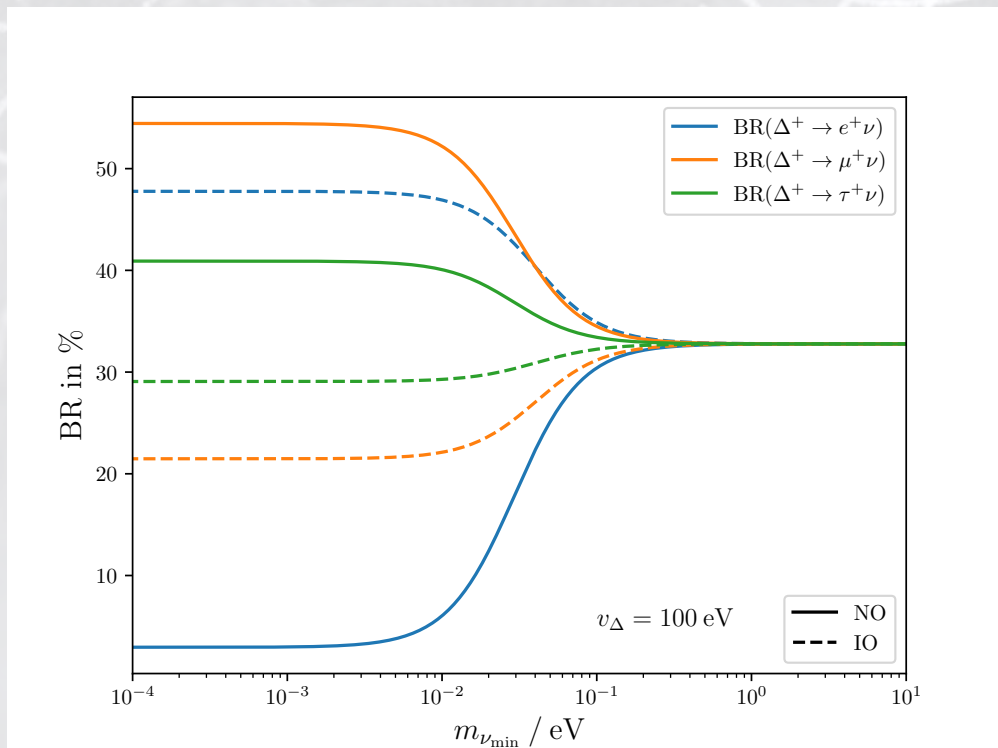
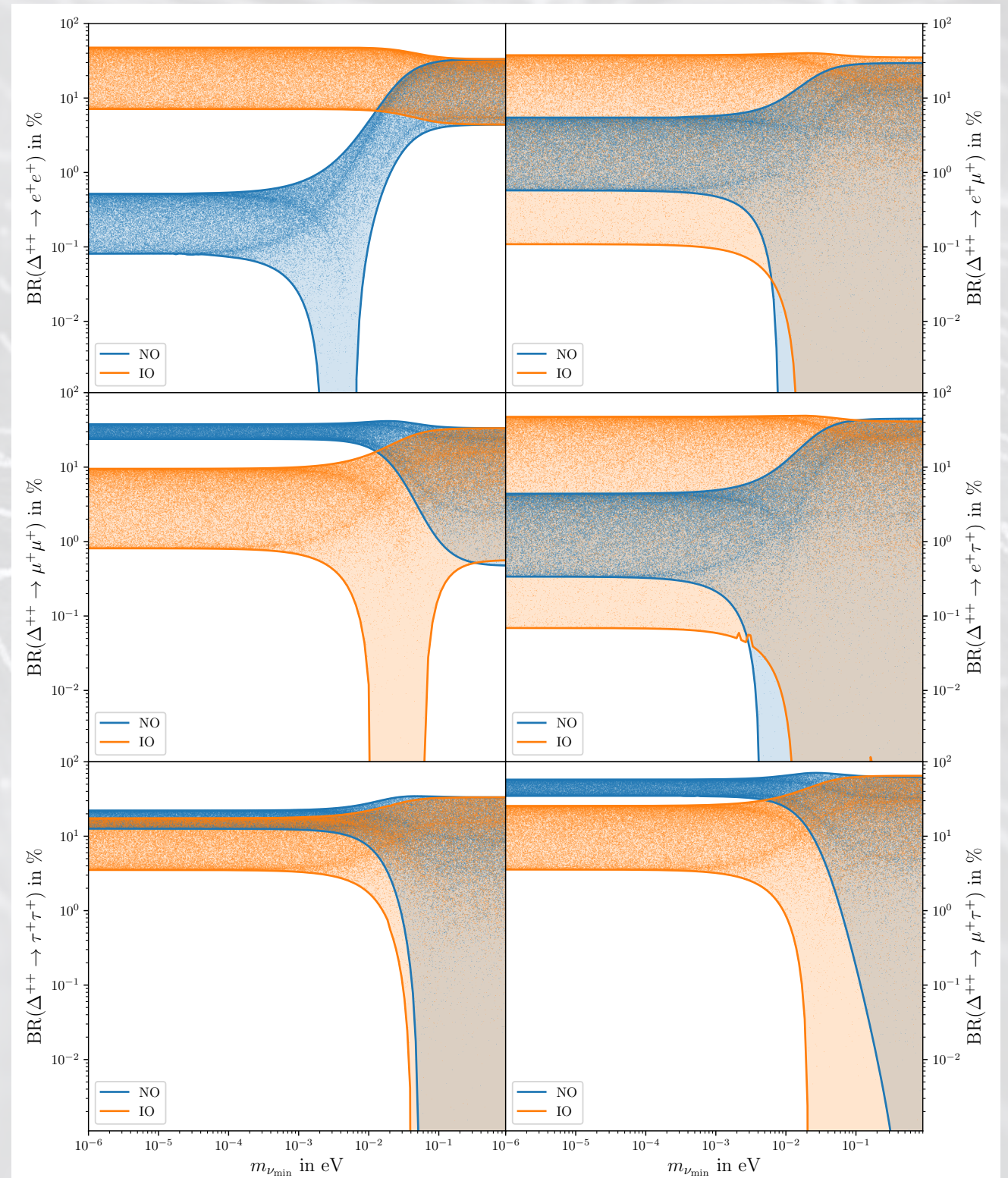


Decay modes of the triplet components

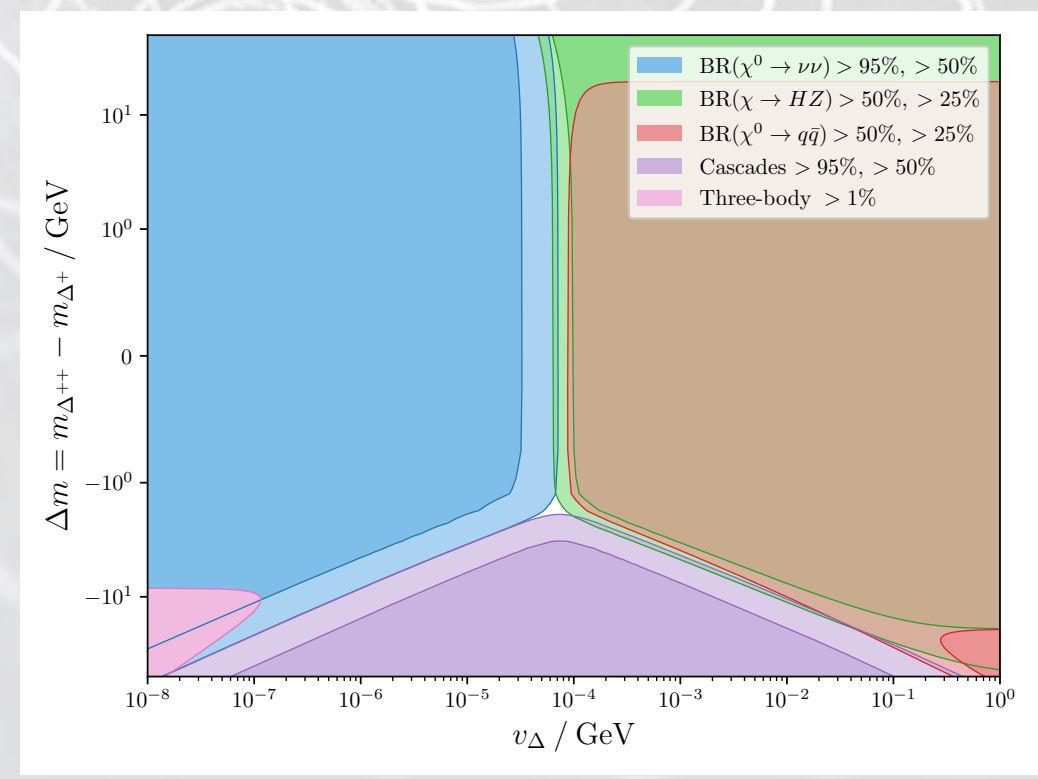
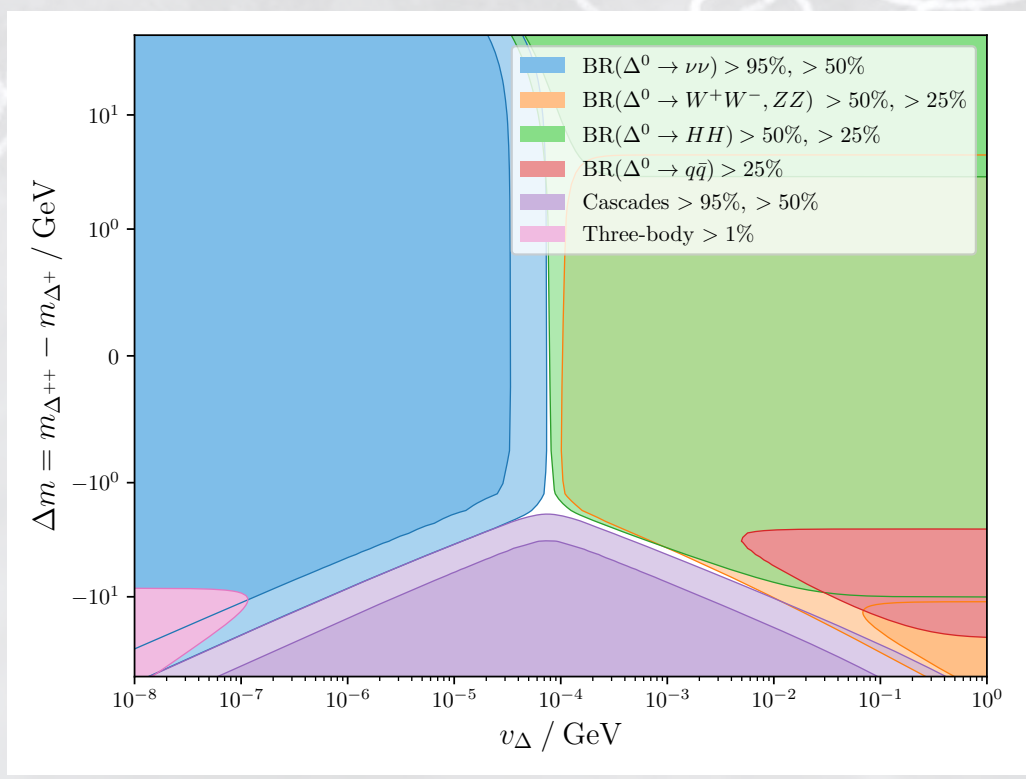
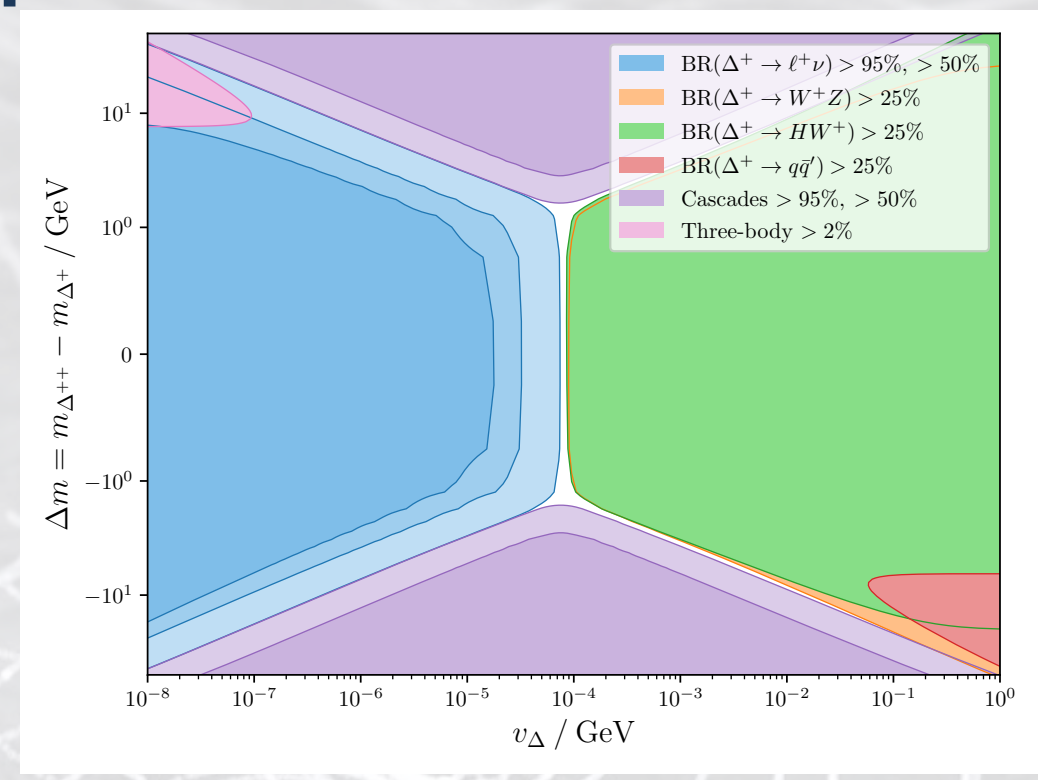
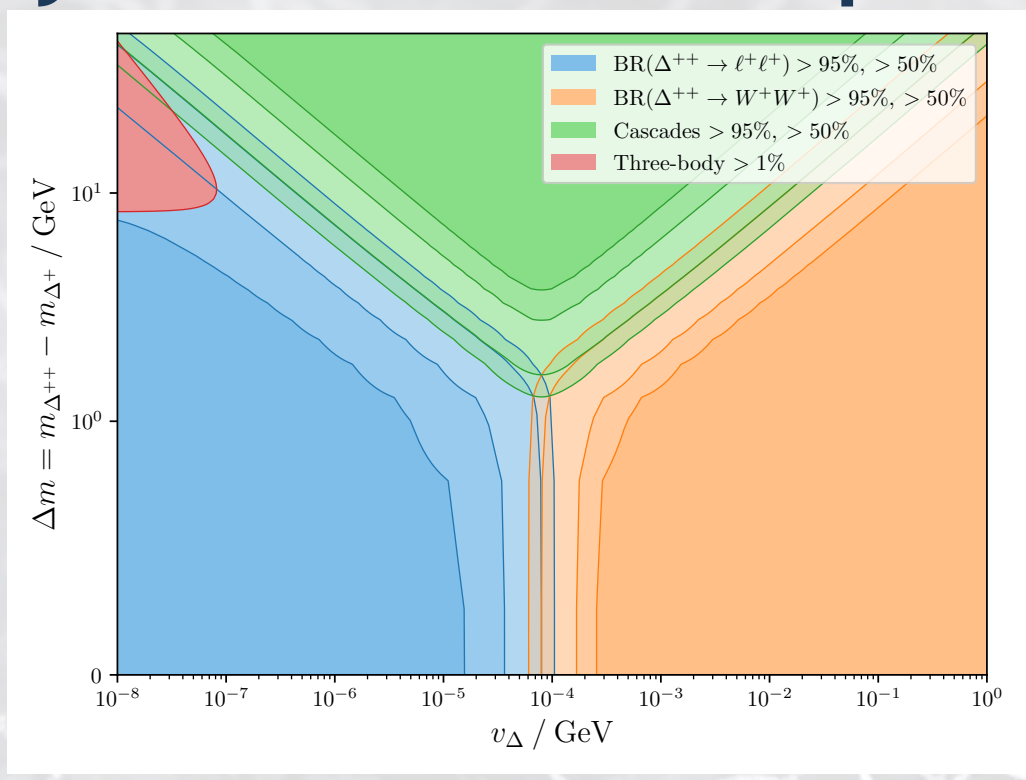
Flavour composition of $\Delta^{++} \rightarrow \ell_i^+ \ell_j^+$ strongly depends on the PMNS input and neutrino mass spectrum/ordering

$$\Gamma_{\Delta^{++} \rightarrow \ell_i^+ \ell_j^+} = \frac{m_{\Delta^{++}}}{8\pi(1 + \delta_{ij})} \left| \frac{M_{\nu ij}}{v_{\Delta}} \right|^2$$

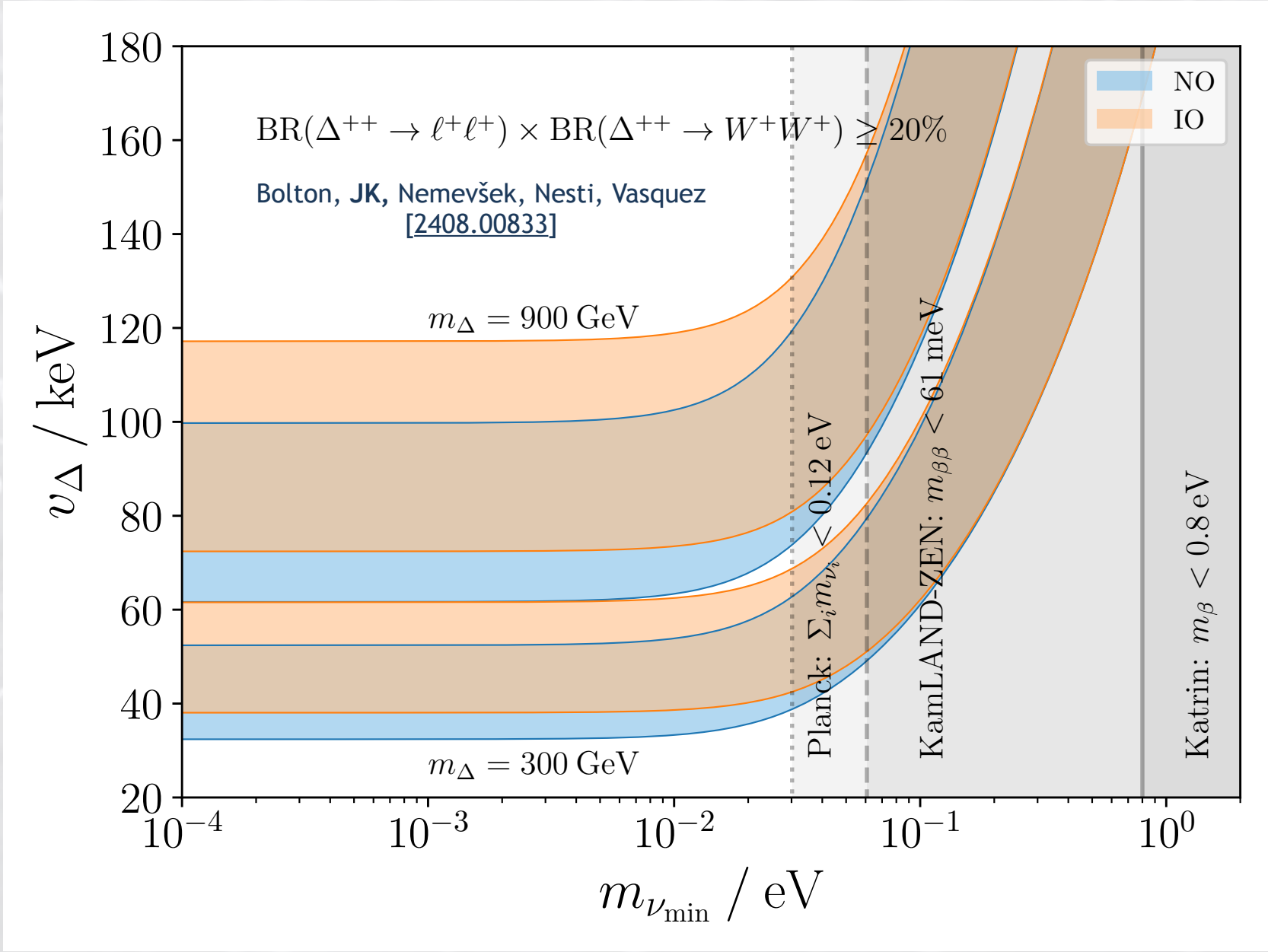
Interference of **PMNS phases** can lead to funnel regions



Decay modes of the triplet components



The LNV window



⇒ In phenomenologically viable region: only mild dependence on $m_{\nu_{\min}}$ and ordering

(Stronger dependence on ordering in flavour channels)