Lepton number violation in Type II seesaw at the LHC

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

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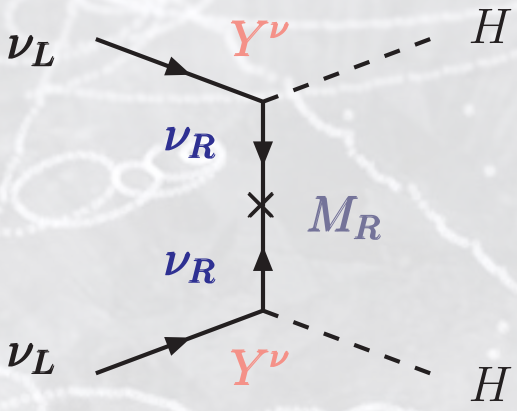
Making neutrino masses

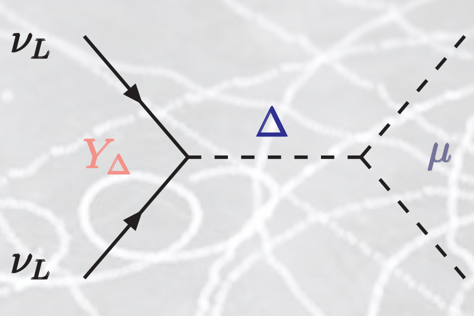
Effective mass term $\mathscr{L}_{\text{eff}} \sim \frac{m_{LL}}{2}\,\bar{\nu}_L\,\nu_L^C$ from Weinberg operator: $\mathscr{L}^{d=5} \sim \frac{h_{ij}}{2\Lambda}(H\,L_i\,H\,L_j)$

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



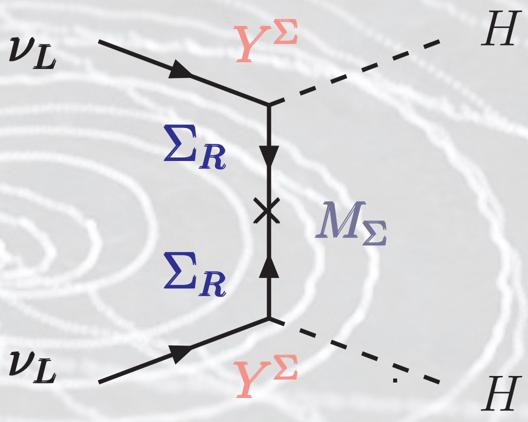
Type I (fermion singlet)

(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: $m_\nu^I \sim -\,v^2 Y_\nu^T \frac{1}{M_R} Y_\nu$, $\quad m_\nu^{II} \sim -\,v^2 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} \sim -\,Y_\Delta v_\Delta$, $\quad m_\nu^{III} \sim -\,Y_\Sigma^T \frac{v^2}{2M_\Sigma} Y_\Sigma$

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]

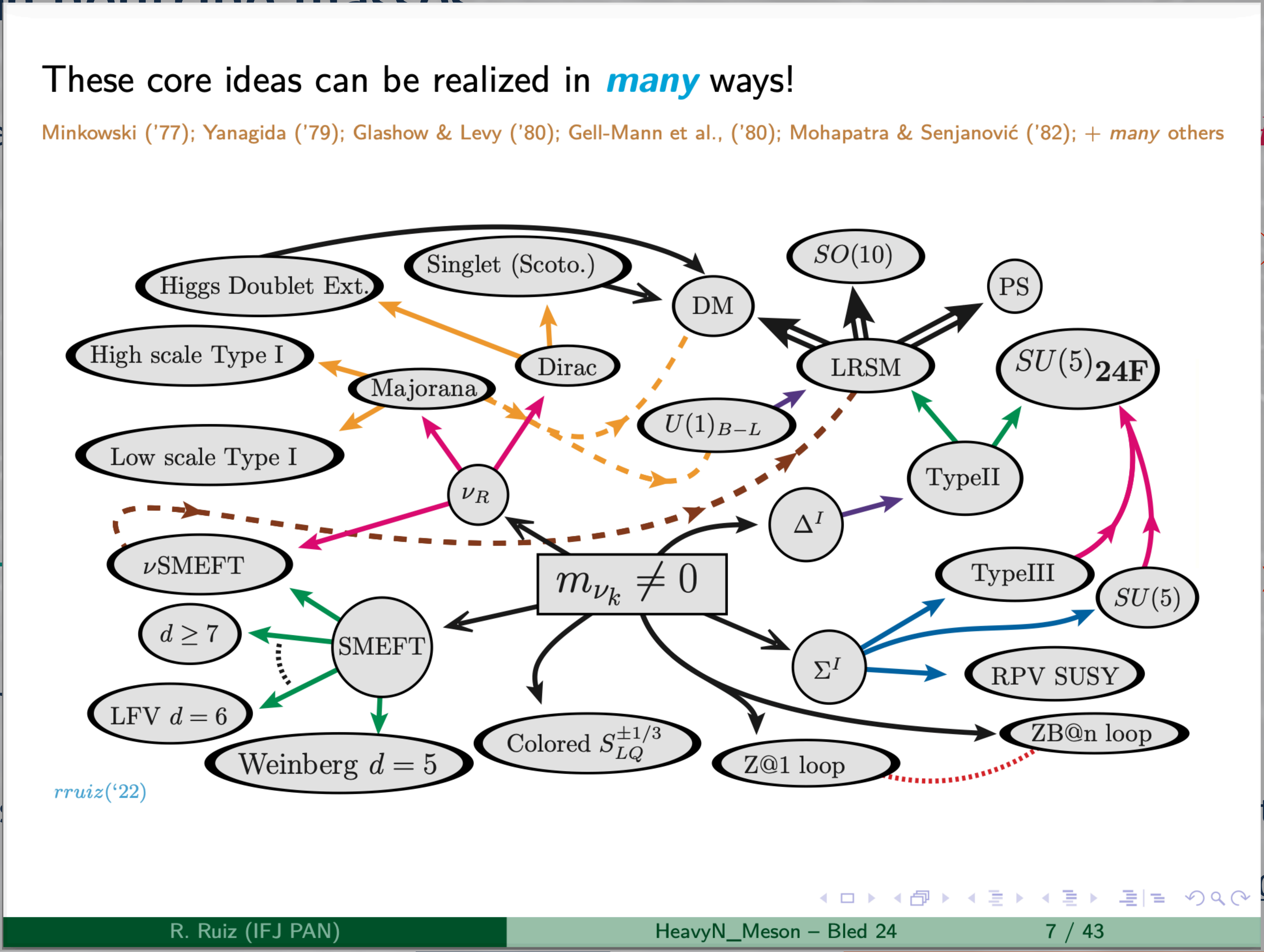
Making neutrino masses

Effective

$L_j)$

Different

$)(L_j^T \sigma_a H)$



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)

R. Ruiz (IFJ PAN) HeavyN_Meson – Bled 24 7 / 43

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Mass terr

Countless

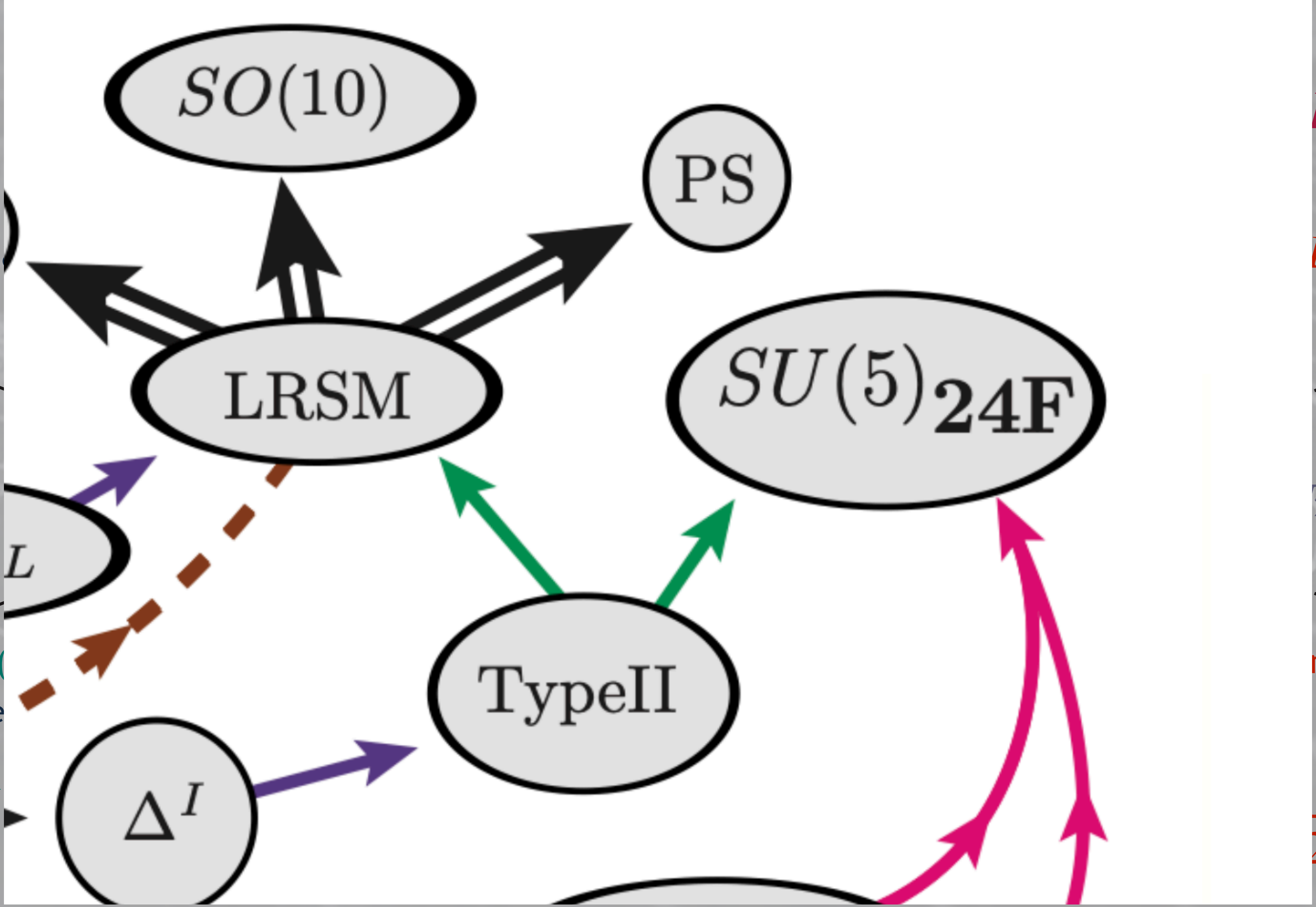
tions...

09.13537]

Making neutrino masses

Effective mass … $H L_i H L_j)$

Different realis … $L_i^T \sigma_a H)(L_j^T \sigma_a H)$



ν_L … H

Σ

ν_L … H

Type I (… **n triplet)**

(e … 89)

Mass terms: m_ν^I … $\frac{v^2}{2M_\Sigma} Y_\Sigma$

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

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

⇒ 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 $v_\Delta \simeq 10^{-10}\,\mathrm{GeV}$

Complicated scalar potential, everything starts mixing… ⇒ rich EW pheno

Constraints on a $Y = 1$ scalar triplet

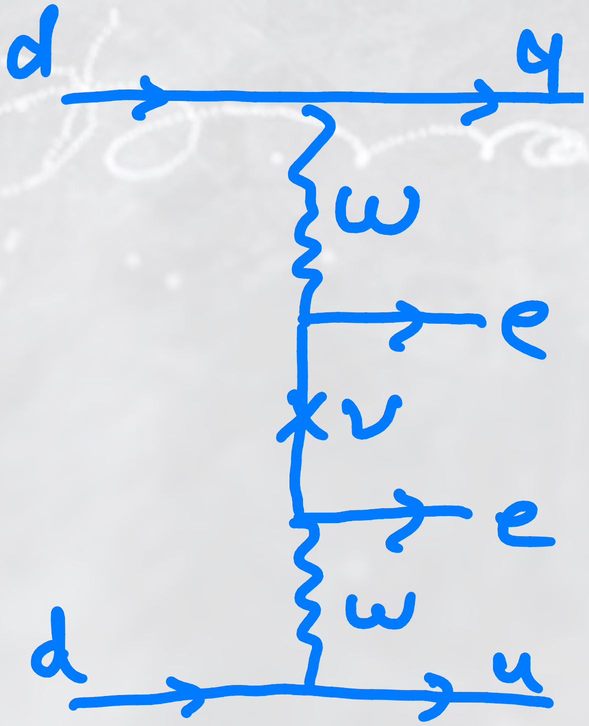
Yukawa Lagrangian $\mathscr{L}_{\text{yuk}} \supset Y_\Delta^{ij} L_{Li}^T \mathscr{C} i\sigma_2 \Delta_L L_{Lj} + \text{h.c.}$

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

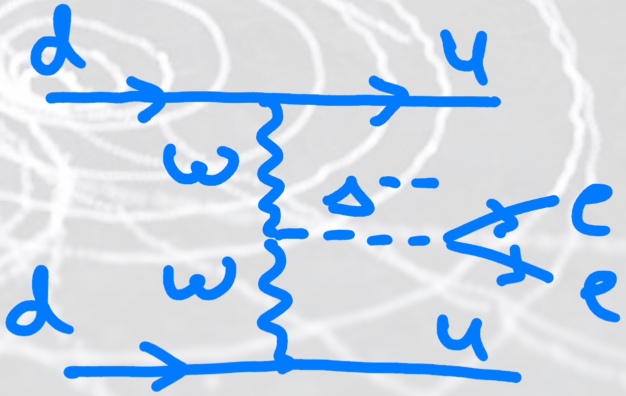
Yukawa structure completely fixed by oscillation data, $Y_\Delta \simeq \mathcal{O}(1)$ for $v_\Delta \simeq 10^{-10}\,\text{GeV}$

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

Neutrinoless double beta decay ($0\nu2\beta$):



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



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

Constraints on a $Y=1$ scalar triplet

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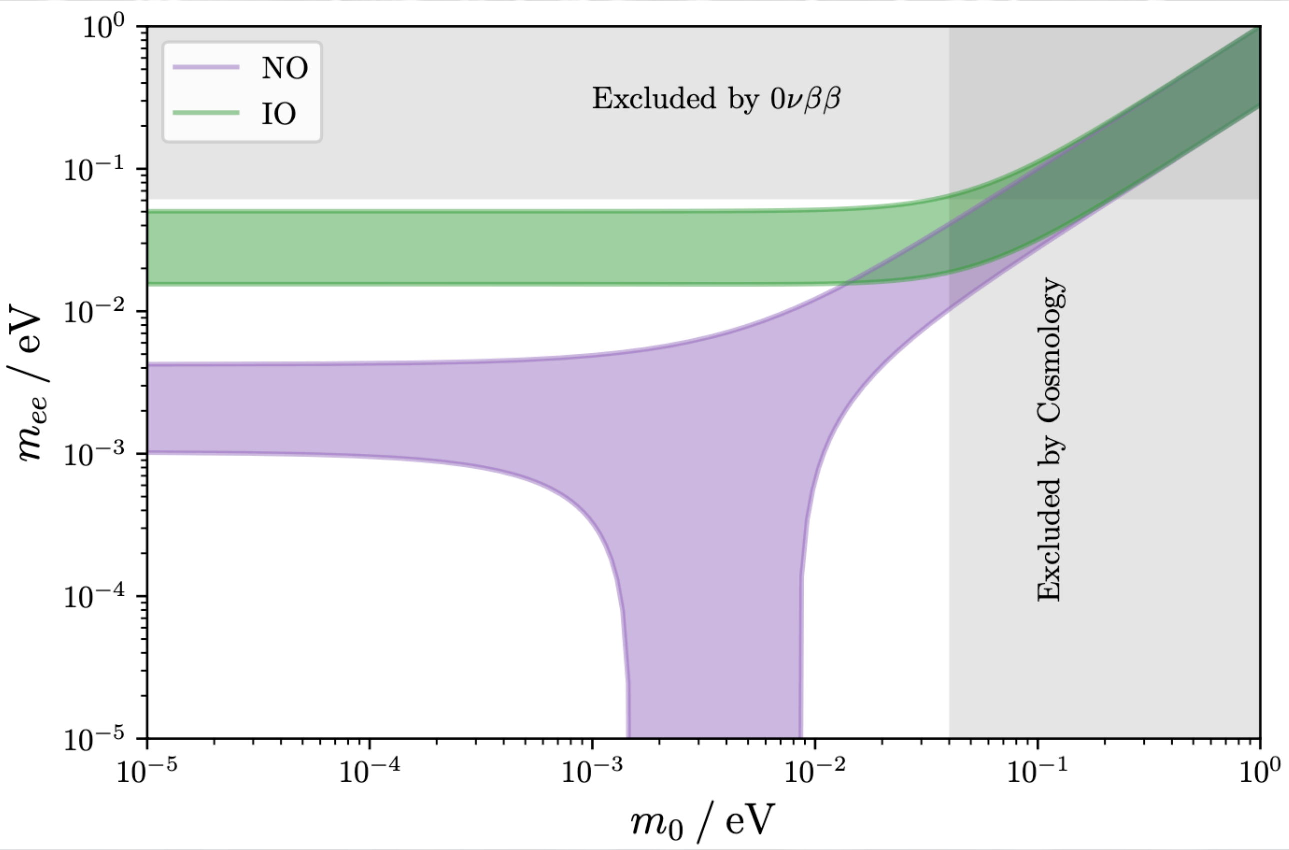


Long-range interaction fixed by U_P, m_{ν_i}

Constraints on a $Y = 1$ scalar triplet

Mixing with would-be Goldstones ⇜⇝ corrections to $M_W\,, M_Z\,, \rho$, **EWPO**

Testing solution to "M_W": 2210.13496

At **tree level**

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

From electroweak fit (see PDG)

Oblique parameters $S\,, T\,, U$ measure corrections to $W\,, Z\,, \gamma$ **self-energies (one-loop)**

[Peskin, Takeuchi '91]

⇒ 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 : $\quad m_{\Delta^{++,+,0}} \gtrsim \frac{M_Z}{2}$

Bi-quadratics $\quad \lambda_{h\Delta 1}\, \varphi^\dagger\varphi \mathrm{Tr}\left[\Delta^\dagger\Delta\right] + \lambda_{h\Delta 2}\, \mathrm{Tr}\left[\varphi\varphi^\dagger\Delta\Delta^\dagger\right]$ induce corrections to $h \to \gamma\gamma$ (and $h \to Z\gamma$)

Constraints on a $Y = 1$ scalar triplet

Yukawa Lagrangian $\mathscr{L}_{\rm yuk} \supset Y^{ij}_\Delta L^T_{Li} \mathscr{C} i\sigma_2 \Delta_L L_{Lj} + \rm h.c.$

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

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

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

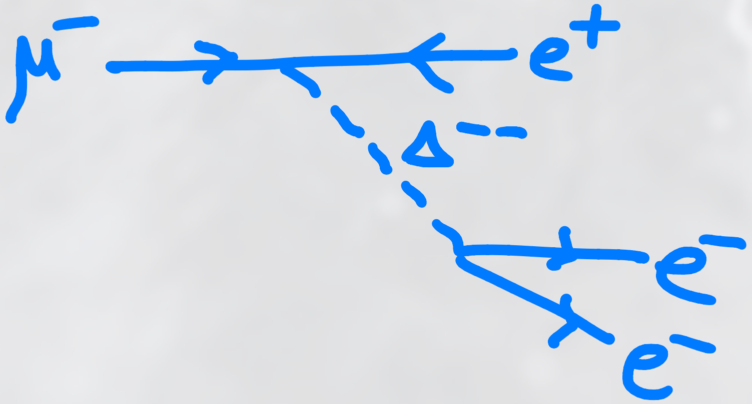
$\ell^-_\alpha \to \ell^+_i \ell^-_j \ell^-_k$ Tree

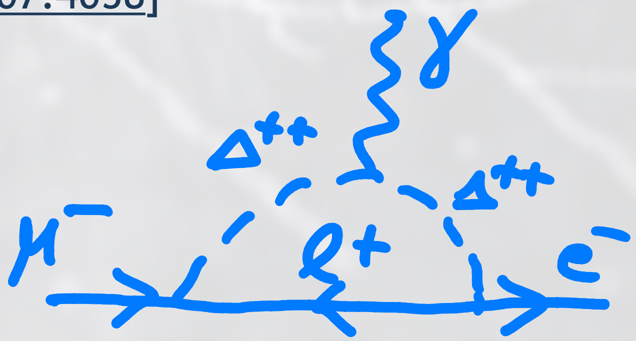
$\ell_\alpha \to \ell_\beta \gamma$ Loop

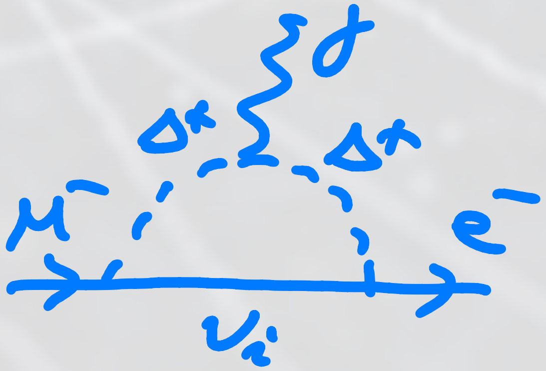
$$\Gamma \simeq \frac{m^5_{\ell_\alpha}}{(1+\delta_{jk}) 96 \pi^3 m^4_{\Delta^{++}}} |Y^{\alpha i}_\Delta|^2 |Y^{jk}_\Delta|^2$$

$$\Gamma \propto \frac{m^5_{\ell_\alpha}}{256 \pi^3 m^4_{\Delta^{++}}} |\sum Y^{\alpha i \dagger}_\Delta Y^{\beta i}_\Delta|^2$$

See e.g. [0707.4058]

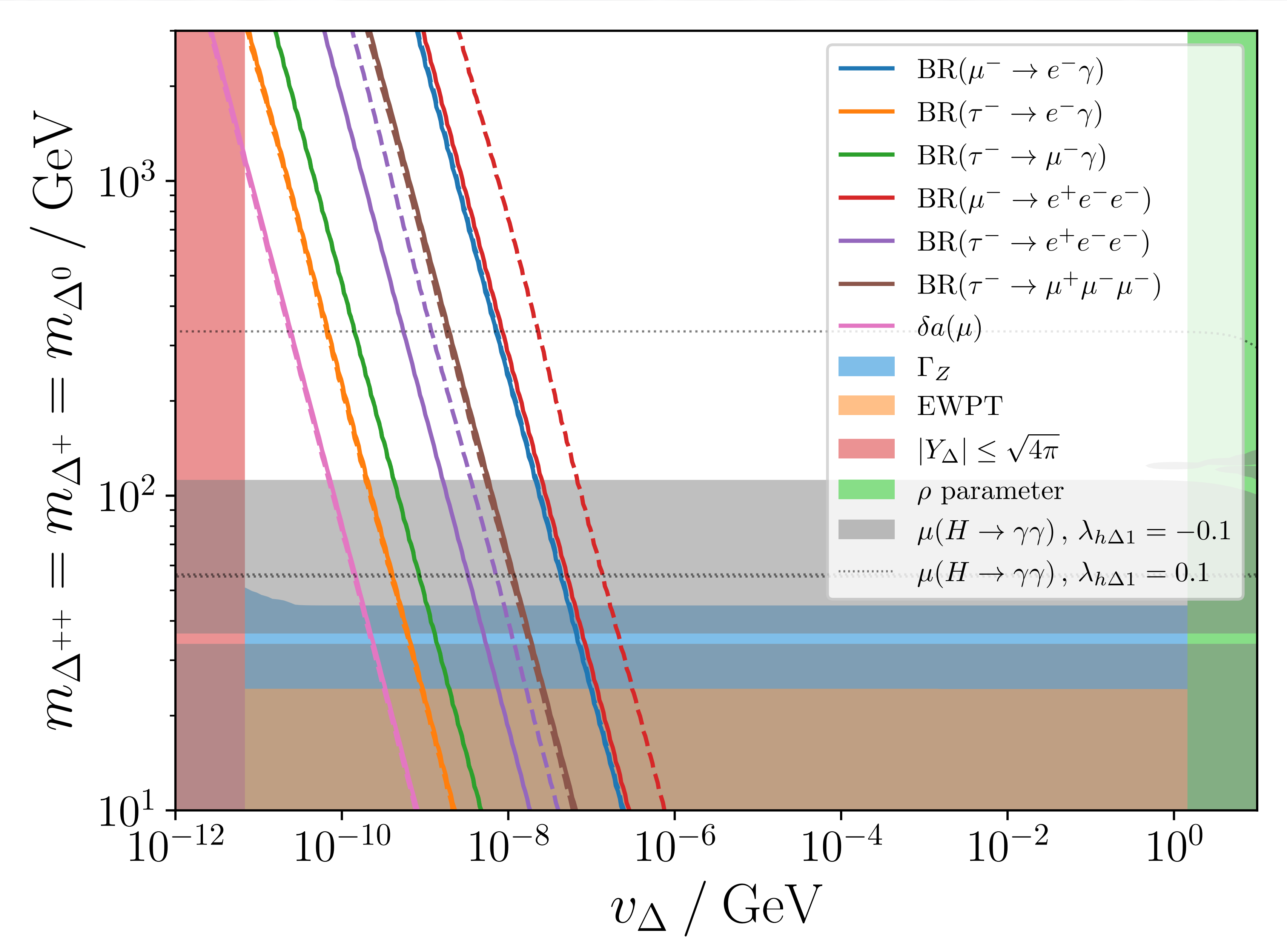






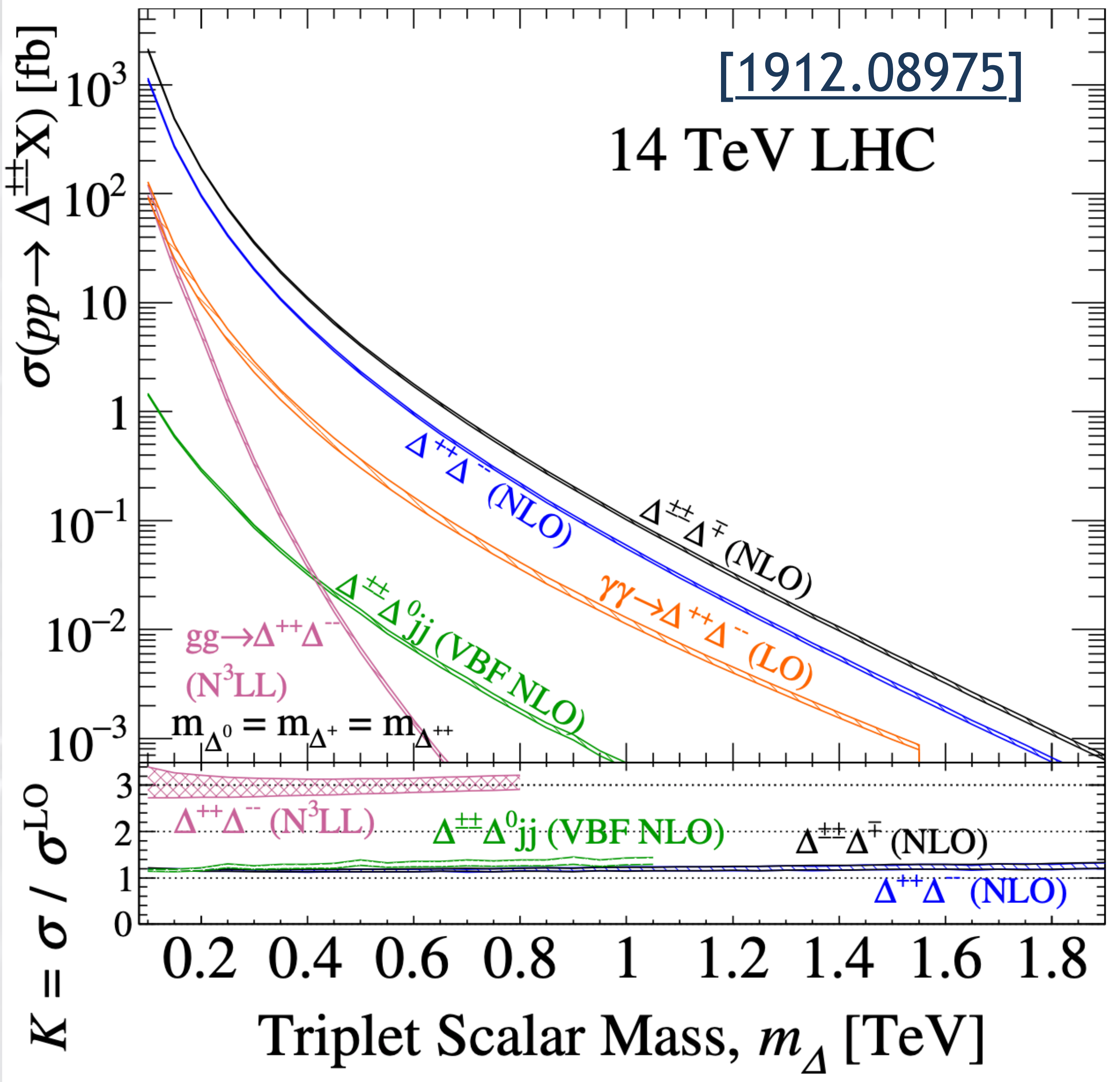
(Contributions to $(g-2)_\ell$ generically negative, weaker bound)

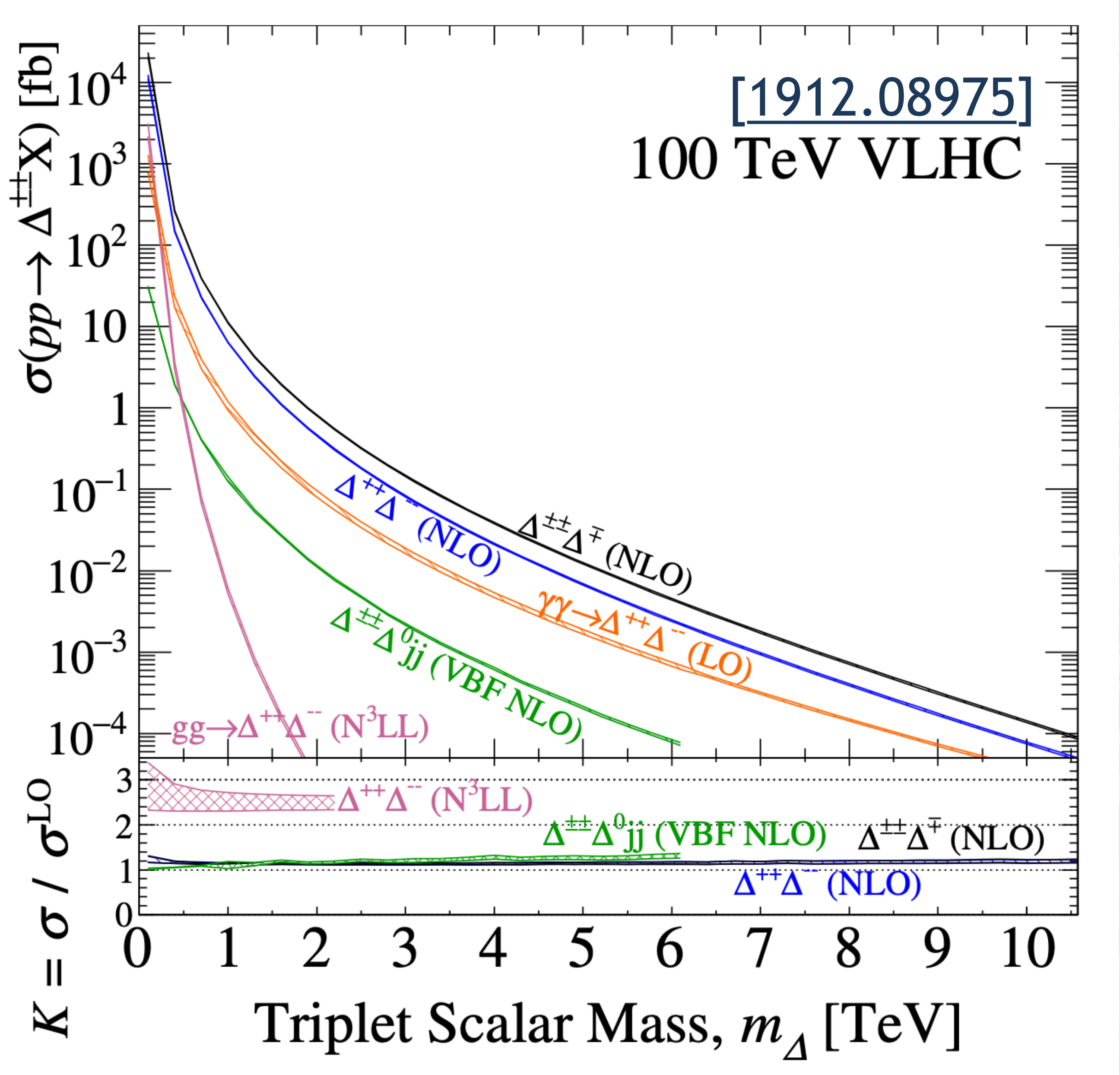
Constraints on a $Y = 1$ scalar triplet



⇒ Bounds on $\mu \to eee$ and $\mu \to e\gamma$ strongest, further push v_Δ

Direct searches — production modes





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

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

Decay modes of the triplet components

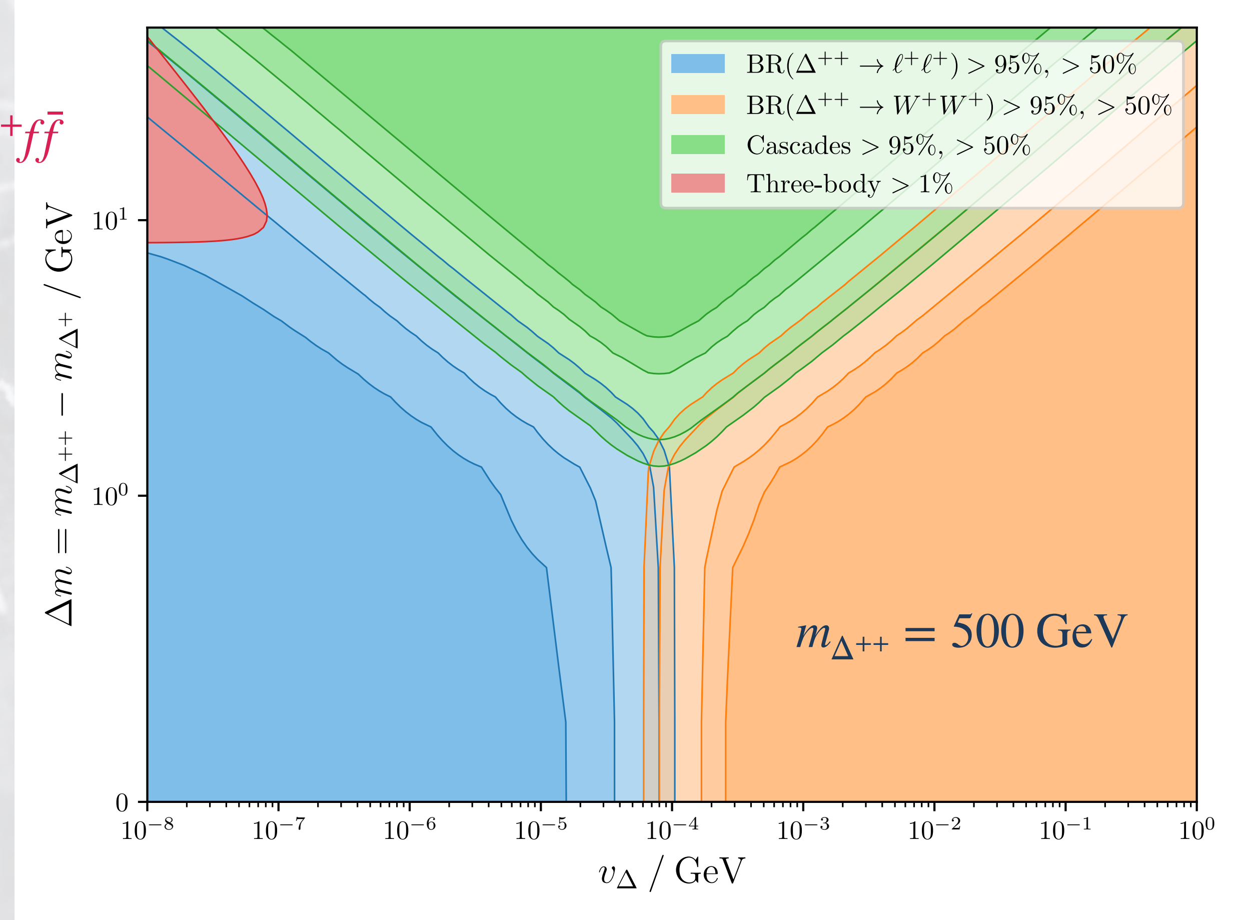
Smoking gun signal: resonance in the same-sign di-lepton invariant mass from $\Delta^{\pm\pm}$ decay

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

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

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

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



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

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

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

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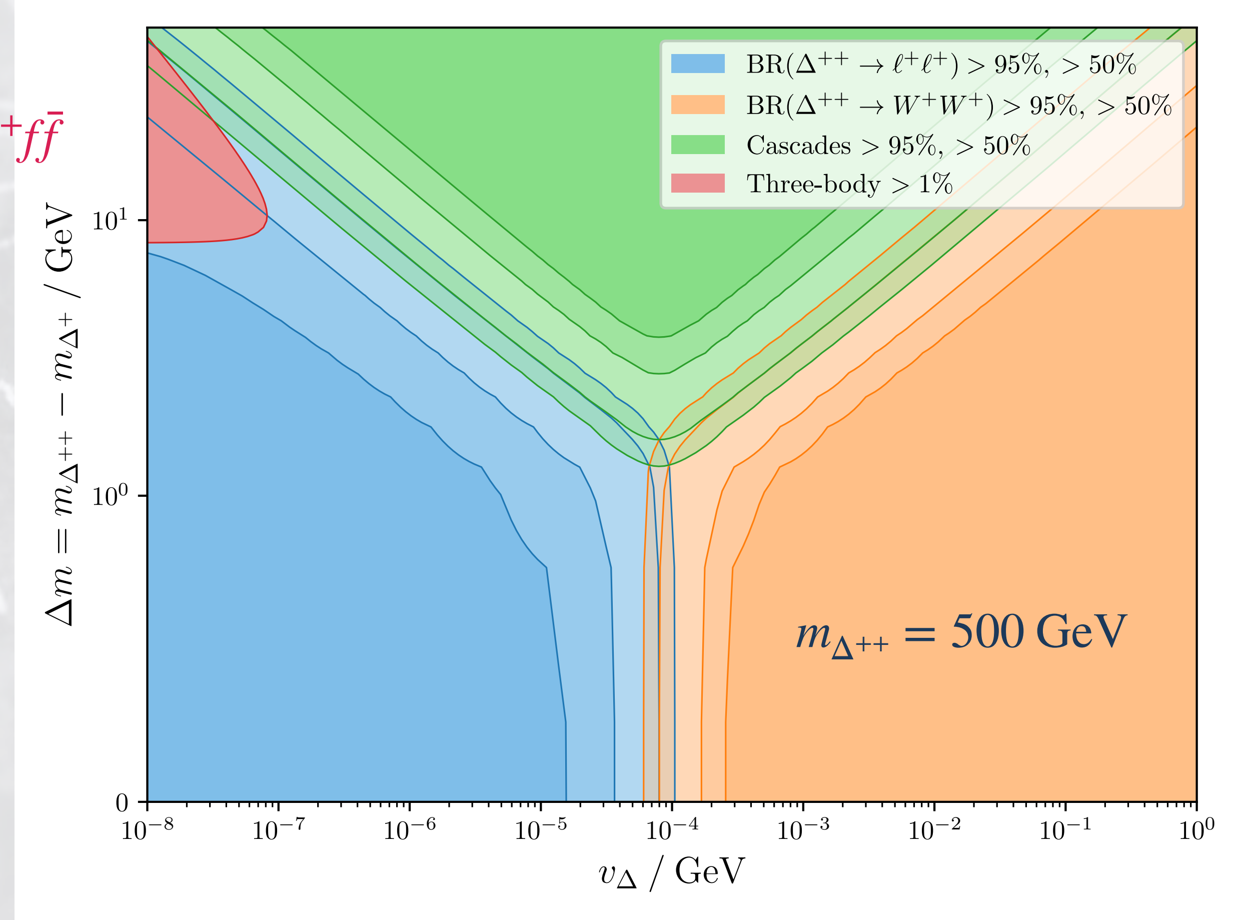
$$\Gamma_{\Delta^{++}\to\ell_i^+\ell_j^+} = \frac{m_{\Delta^{++}}}{8\pi\left(1+\delta_{ij}\right)} \left|\frac{M_{\nu ij}}{v_\Delta}\right|^2$$

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



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

Some ATLAS searches for **di-boson**

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

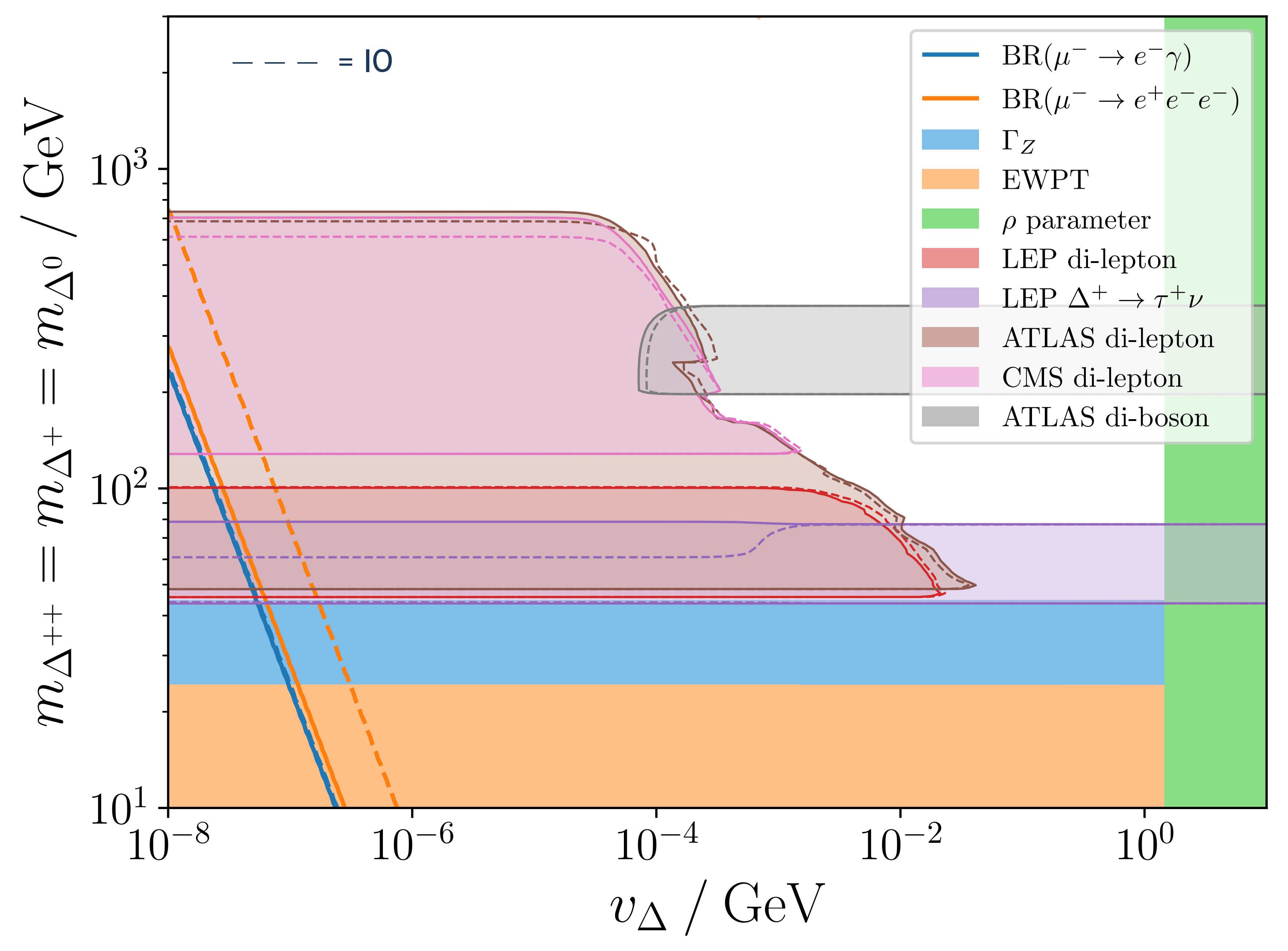
LEP/LHC searches mostly focus on **di-lepton** channel

LEP searches for $\Delta^\pm \to \tau^\pm\nu$, LHC searches only for sub-dominant production/decay channels

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

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

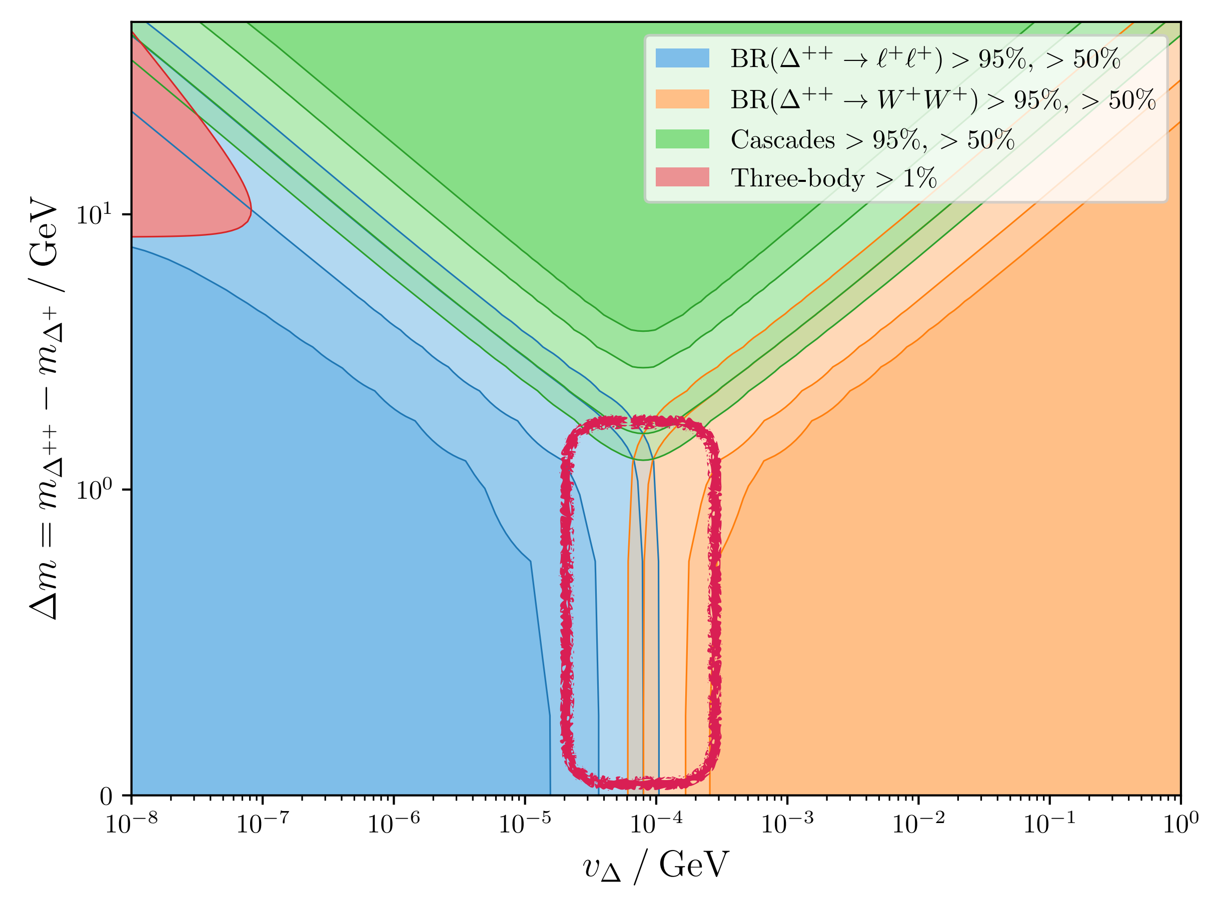
Current state of the art

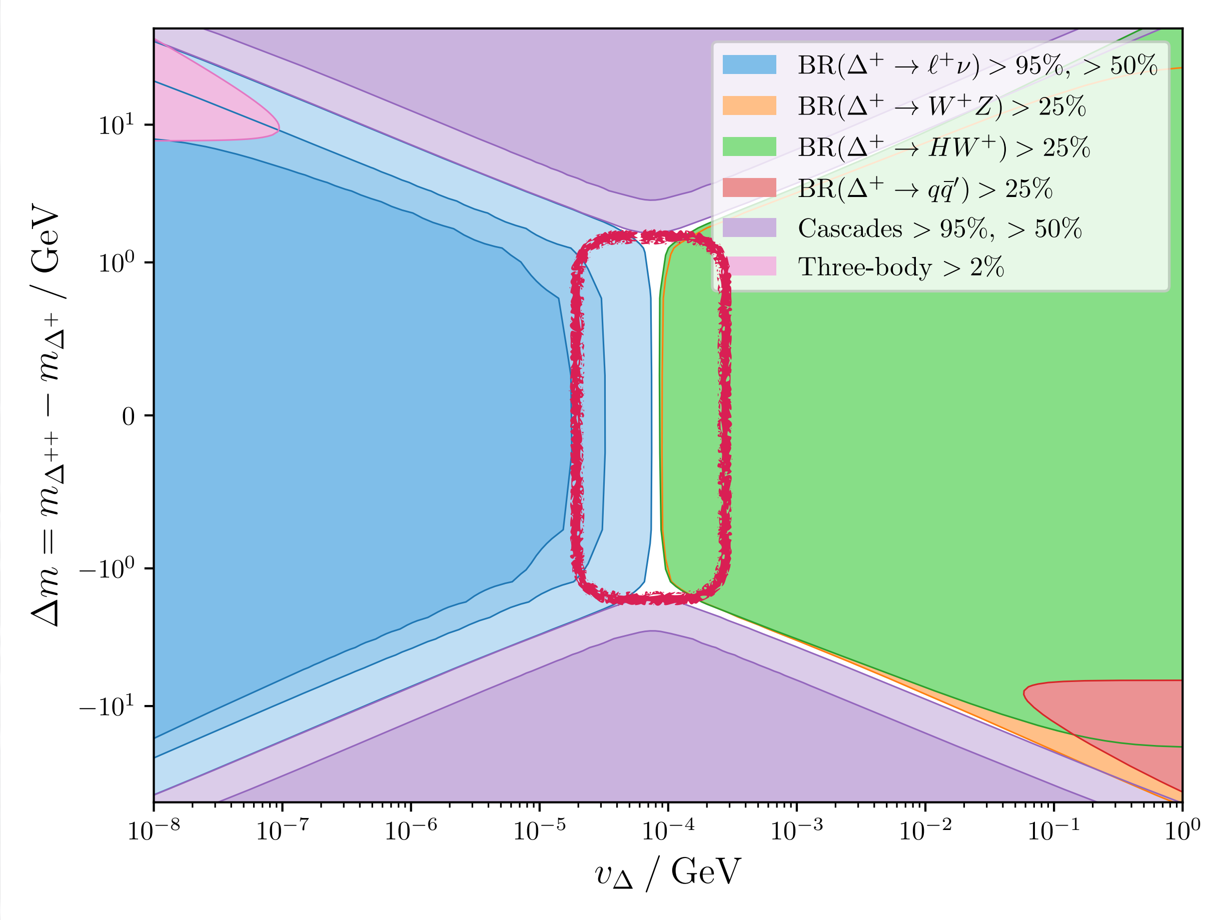


$\Rightarrow$ LHC searches exclude $m_{\Delta^{++}} \lesssim 700\,\mathrm{GeV}$ for small v_Δ

$\Rightarrow$ Di-boson final states harder to reconstruct, smaller efficiencies

Decay modes of the triplet components





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

Intermediate region: "**LNV window**"

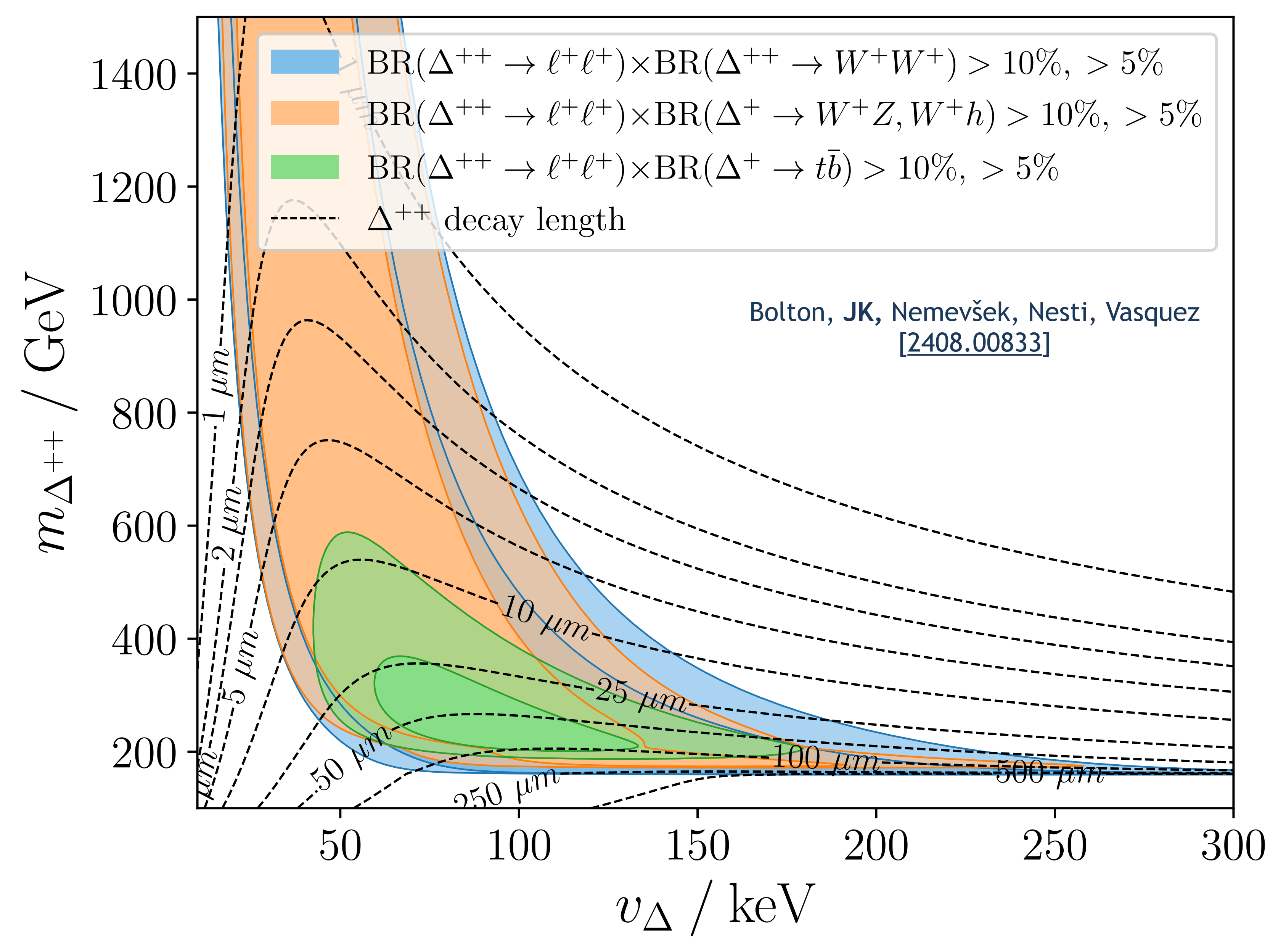
See also [2212.08025] for first glimpse

Maeizza, Nemevšek, Nesti '16

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

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

The LNV window



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

⇒ Identify three **different** **signal processes**

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

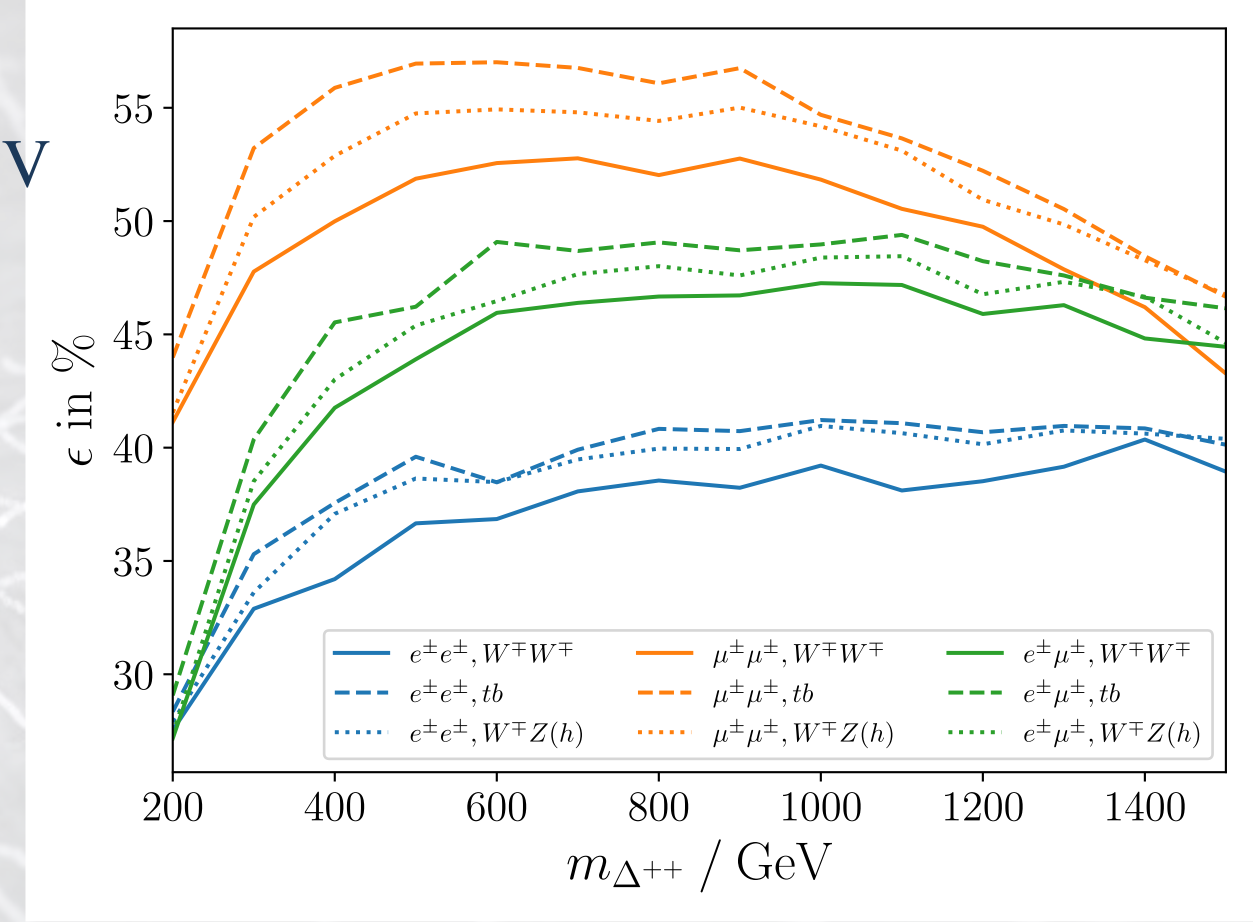
⇒ Decays mostly prompt (except at W threshold)

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** $\Delta R = 0.3\,, p_{T j\mathrm{min}} = 20\ \mathrm{GeV}$
- Demand $p_{T j,\ell} > 50\ \mathrm{GeV}$ on **leading lepton/jet**
- **Demand leading leptons** $m_{\ell\ell} \in [0.9, 1.1]\, m_{\Delta^{++}}$
- Reject $m_{j_1 j_2} > 1.1\, m_{\Delta^{++}}$

Signal efficiencies after cuts



Dominant backgrounds:

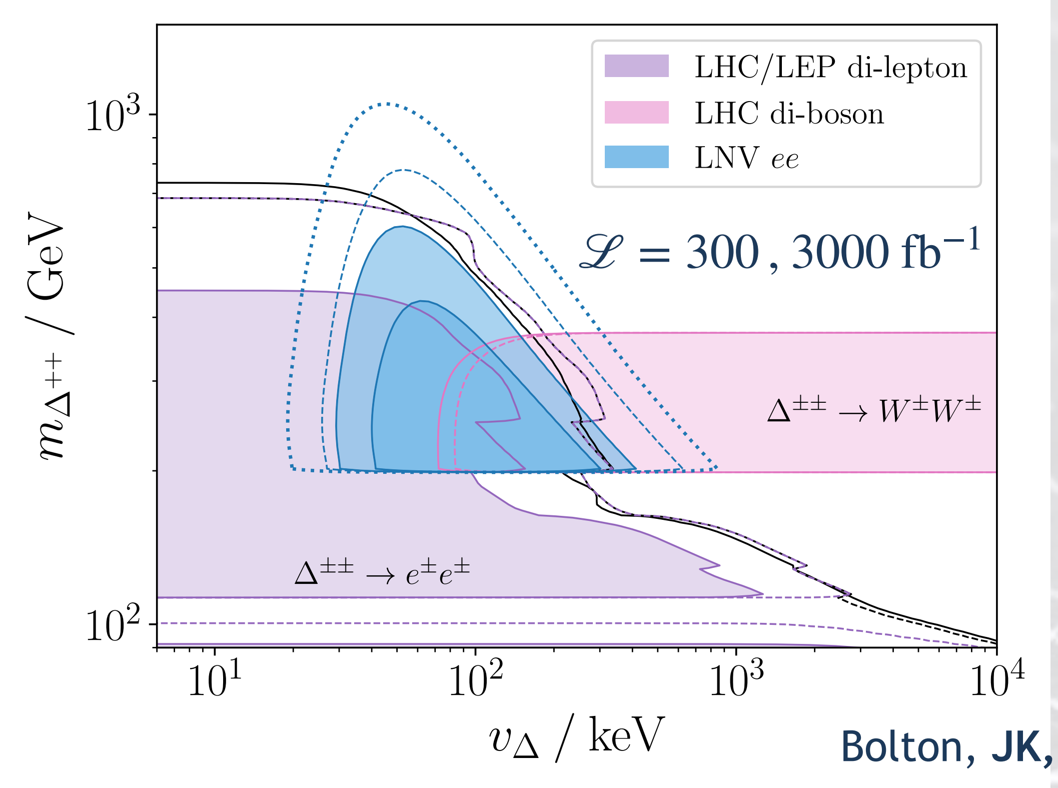
- $pp \to V + 012j,\ pp \to VV + 012j\,,\ V = W^\pm, Z$
- $pp \to t\bar{t} + 012j$, ($pp \to VVV + 012j$ found to subdominant)

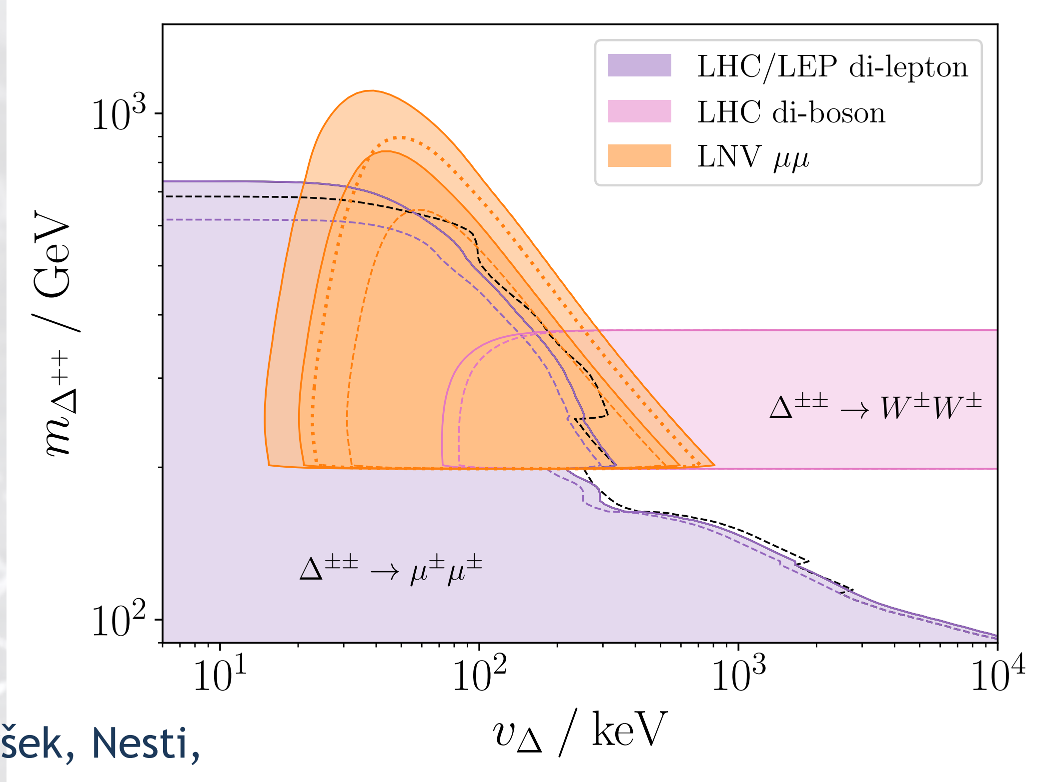
$\Rightarrow$ Muon final state highest efficiency

Event simulation: Model file adapted from Fuks, Nemevšek, Ruiz [1912.08975]

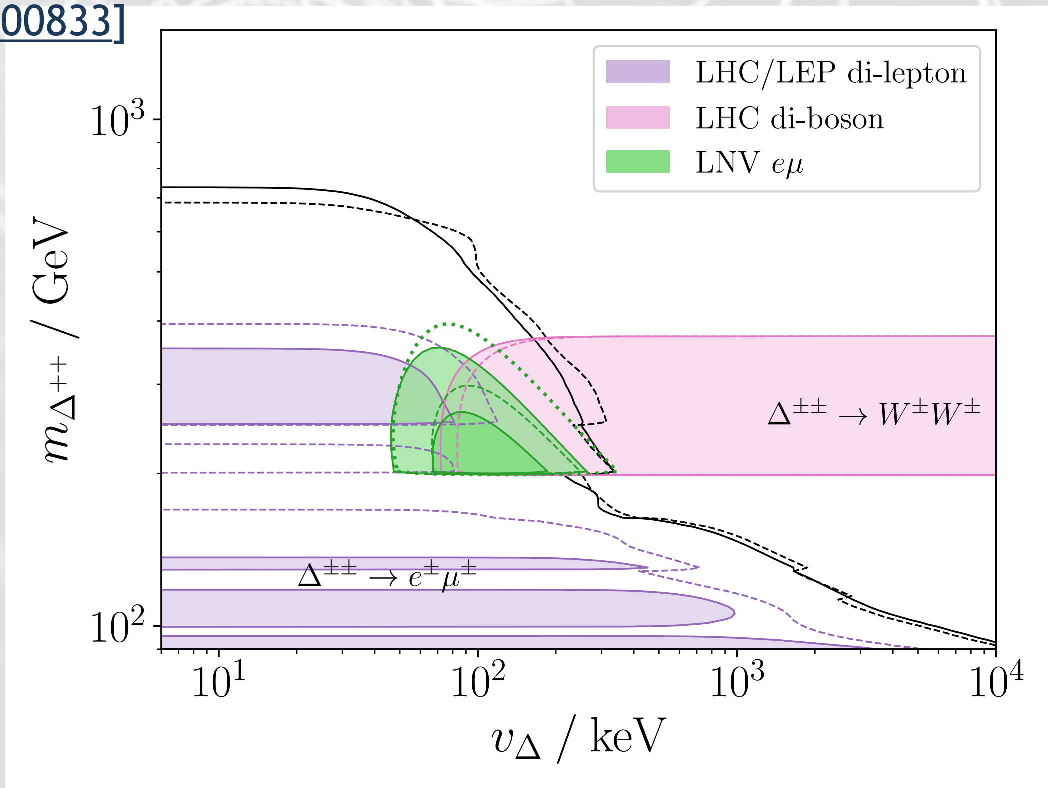
- Use ***MadGraph5*** (at LO) + ***Pythia8*** + ***Delphes*** (default card) + ***MadAnalysis5*** chain
- Rescaled to NLO in QCD, signals and backgrounds simulated to $100\ \mathrm{fb}^{-1}$

The LNV window — sensitivities





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

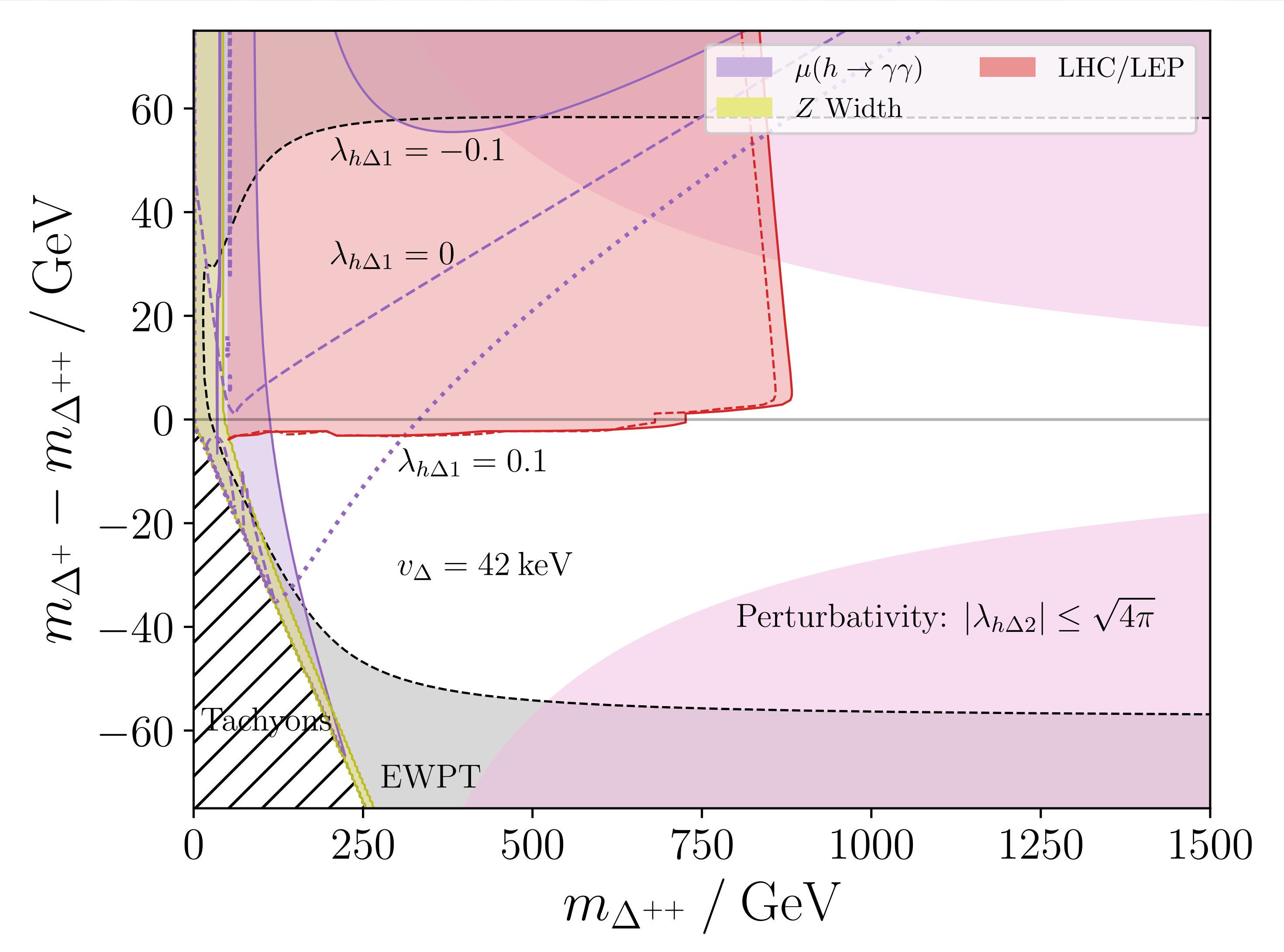


Cover region towards larger m_Δ and v_Δ

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

$e\mu$ final state suffers from larger backgrounds

Switching on cascades



⇒ Oblique parameters (EWPT) and $h \to \gamma\gamma$ strongly depend on **mass splitting**

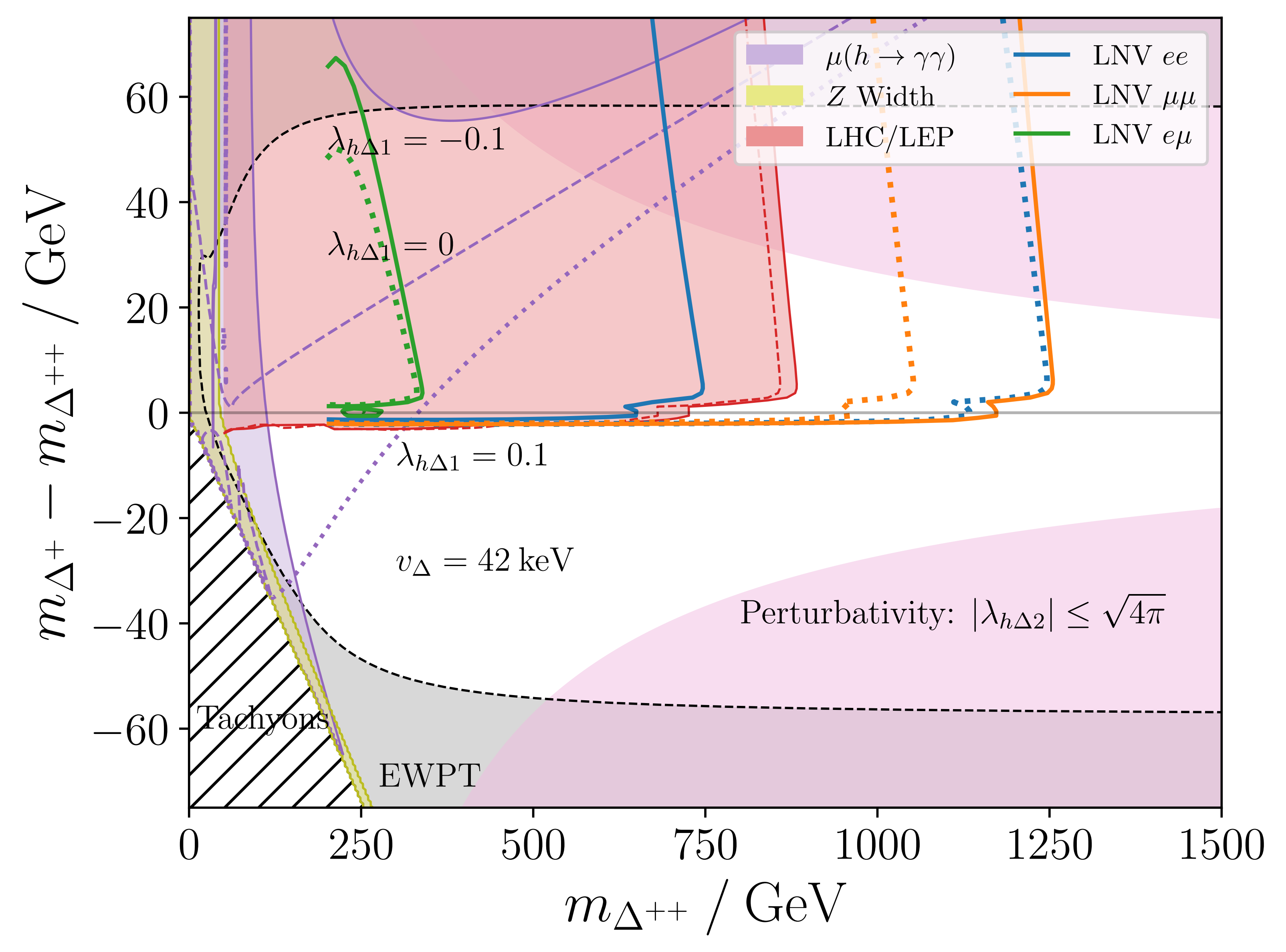
Perturbativity of the potential & **absence of tachyonic modes** become constraining

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

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

⇒ Direct searches **don't exclude anything** if $m_{\Delta^{++}} > m_{\Delta^+}$

Switching on cascades



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

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

LNV window: $m_{\Delta^{++}} \gtrsim 1300$ 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 v_Δ: di-lepton

  Large v_Δ: di-boson

- Suggest new search strategy for intermediate v_Δ region: the **LNV 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

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Thanks for your attention!

Bonus content

Type II seesaw mechanism: the induced vev

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

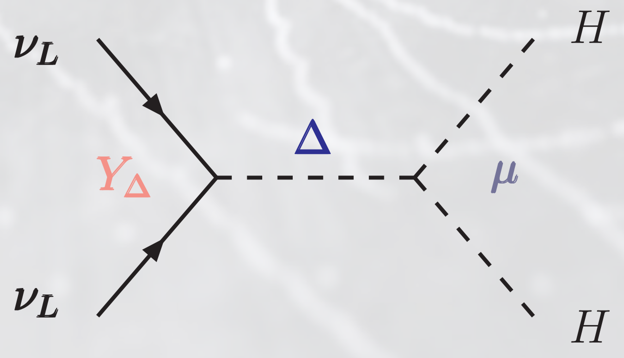
Extend Standard Model with a **scalar** $Y = 1$, $SU(2)_L$-triplet

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

φ = **SM-like $SU(2)_L$-doublet**

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

⇒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]

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

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

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

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

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

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

And mix with the SM-like doublet φ:

$$\sin\theta_{h\Delta} \simeq \frac{2m_\Delta^2}{m_h^2 - m_{\Delta_0}^2} \left(\frac{v_\Delta}{v}\right) \qquad \sin\theta_{\Delta^+\varphi^+} \simeq \sqrt{2} \left(\frac{v_\Delta}{v}\right) \qquad \sin\theta_{\chi\varphi^0} \simeq 2 \left(\frac{v_\Delta}{v}\right)$$

Mixing induces couplings to pairs of quarks, W, Z

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

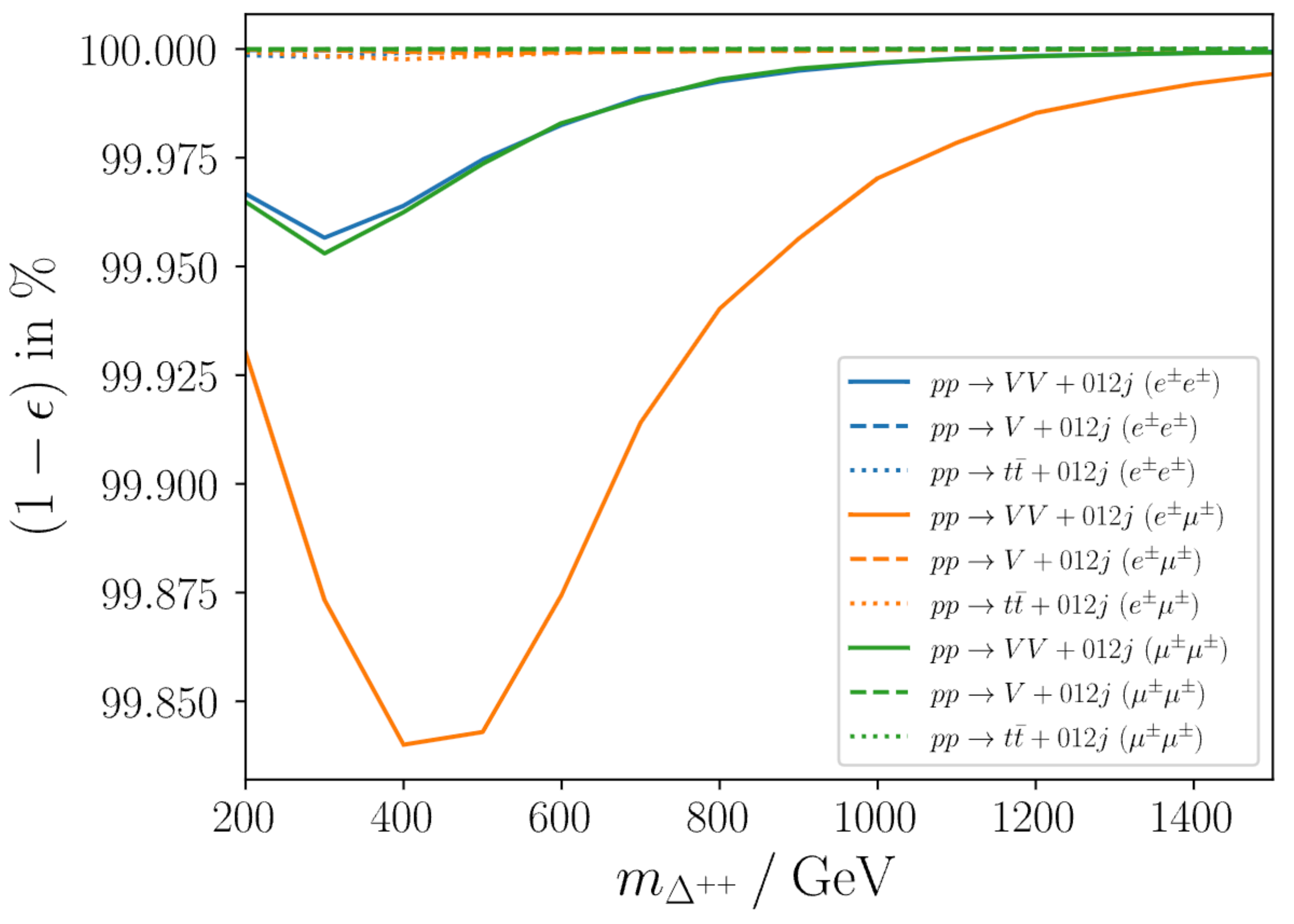
Mass splittings follow sum-rule:

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

Mass splittings limited by Tachyon conditions & perturbative unitarity

See [1105.1925] for comprehensive analysis of the potential

Background rejection

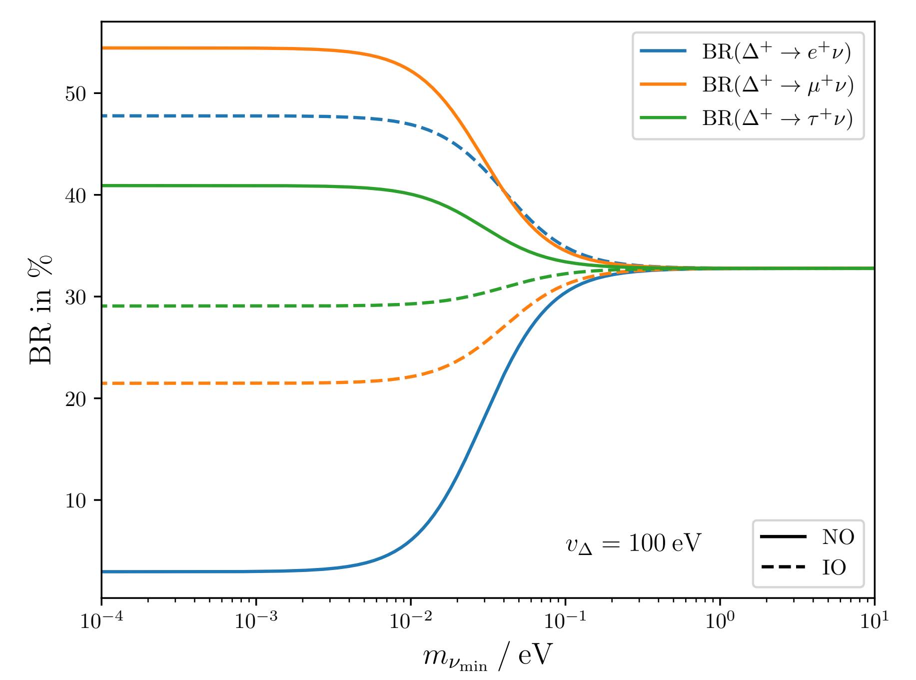


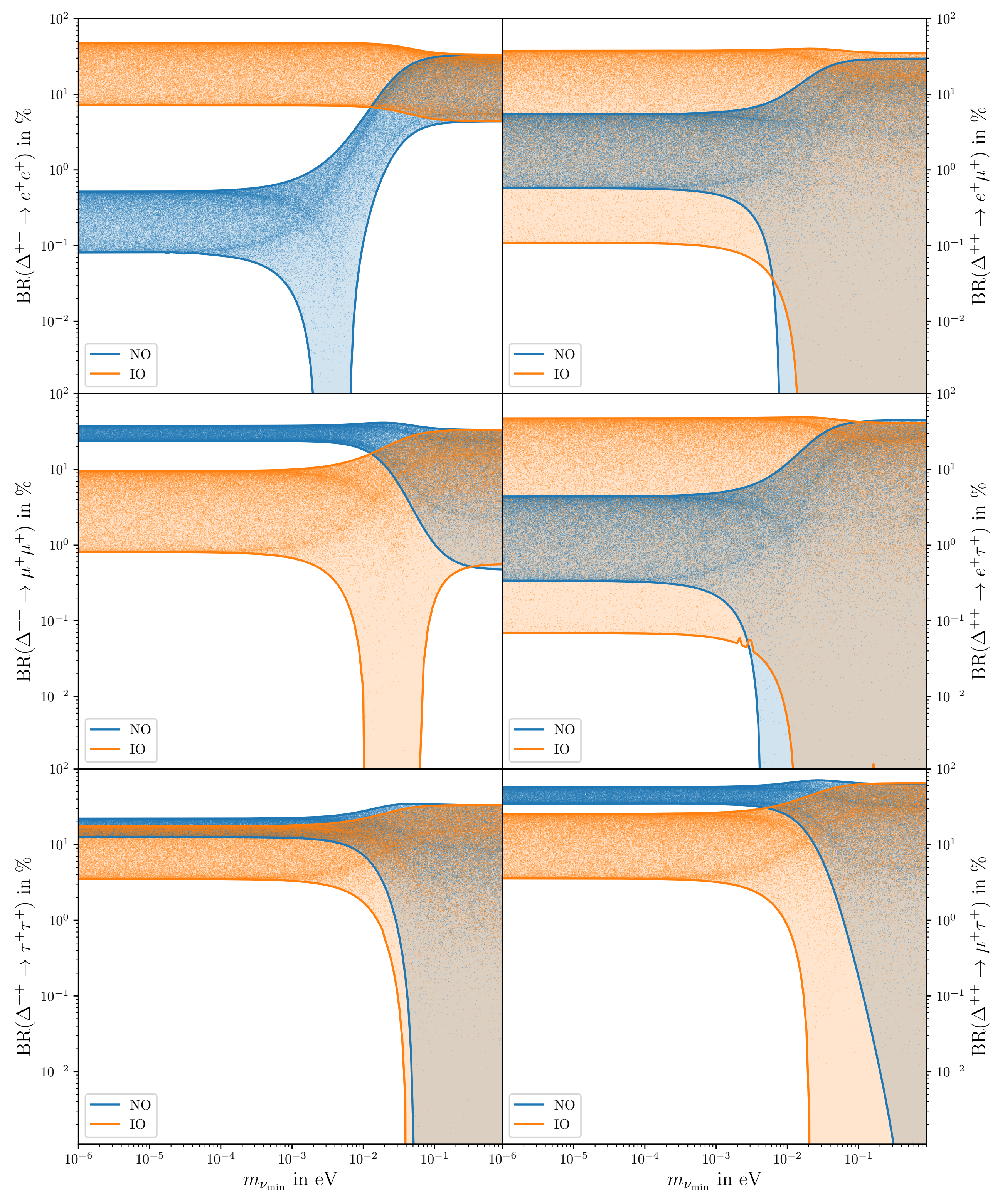
Decay modes of the triplet components

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

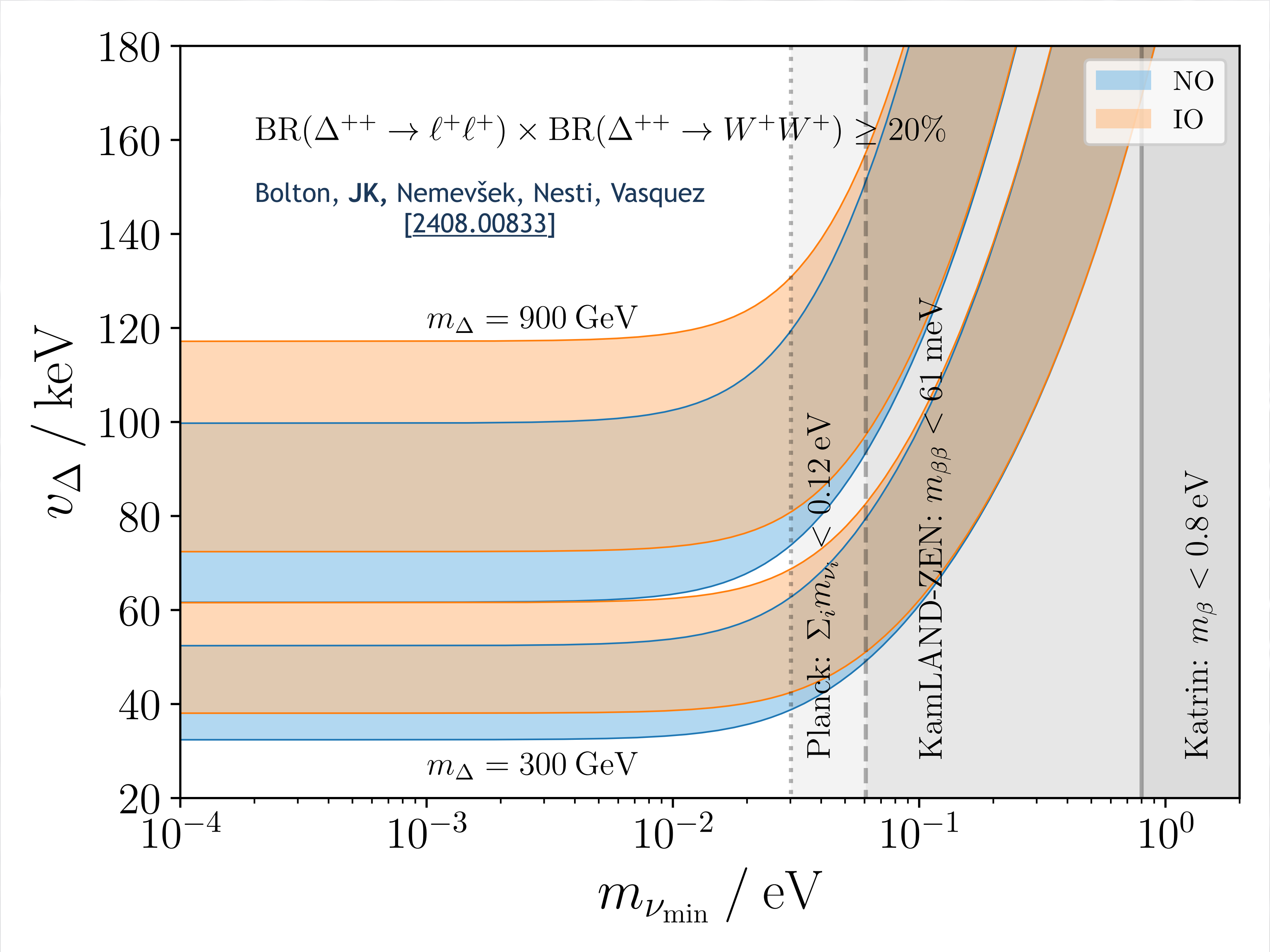
$$\Gamma_{\Delta^{++}\to\ell_i^+\ell_j^+} = \frac{m_{\Delta^{++}}}{8\pi\left(1+\delta_{ij}\right)}\left|\frac{M_{\nu ij}}{v_\Delta}\right|^2$$

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





The LNV window



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

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

(Stronger dependence on ordering in flavour channels)

Decay modes of the triplet components