Theory introduction on LFV and LFU

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Universidad de Valencia & IFIC

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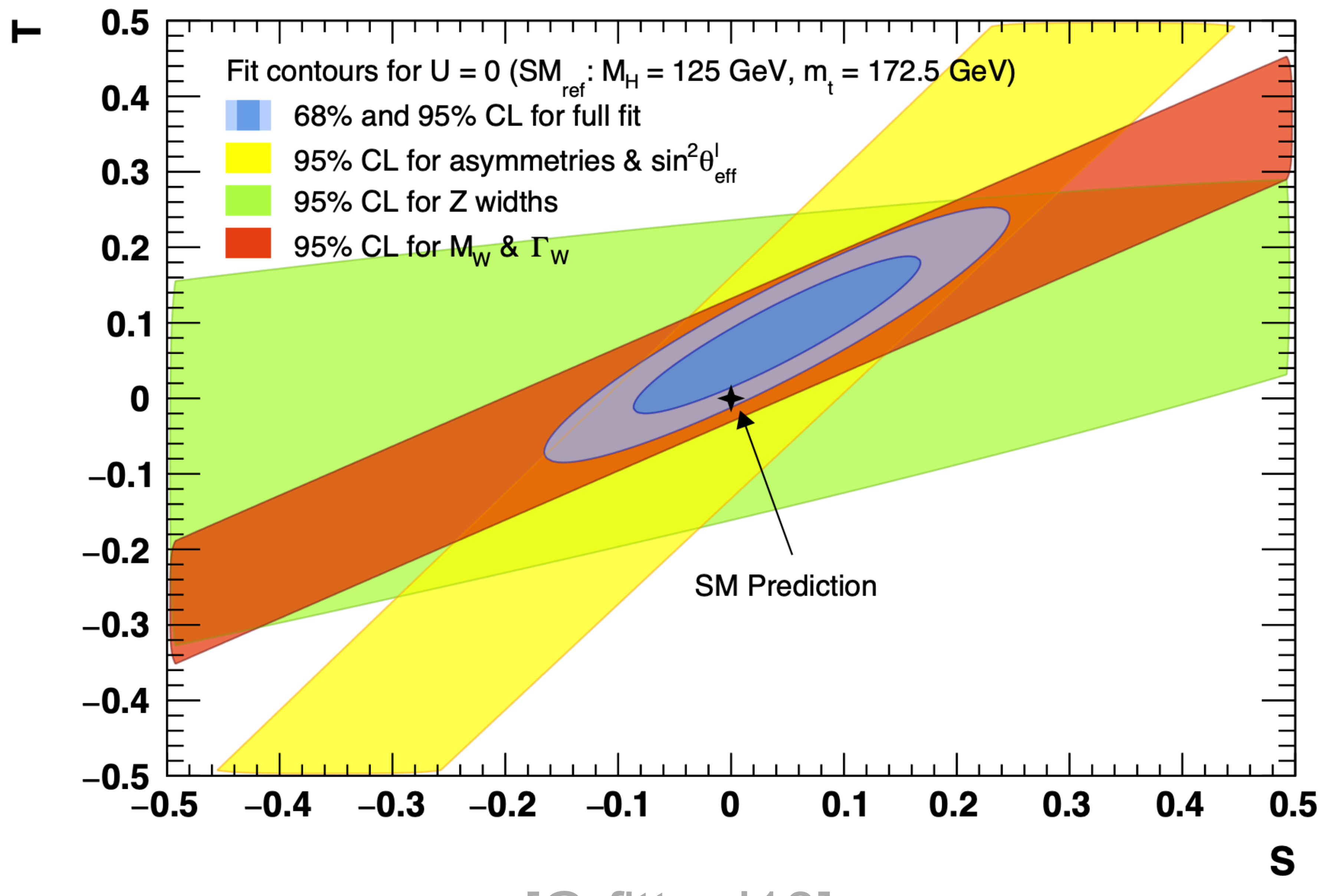

[G-fitter '18]

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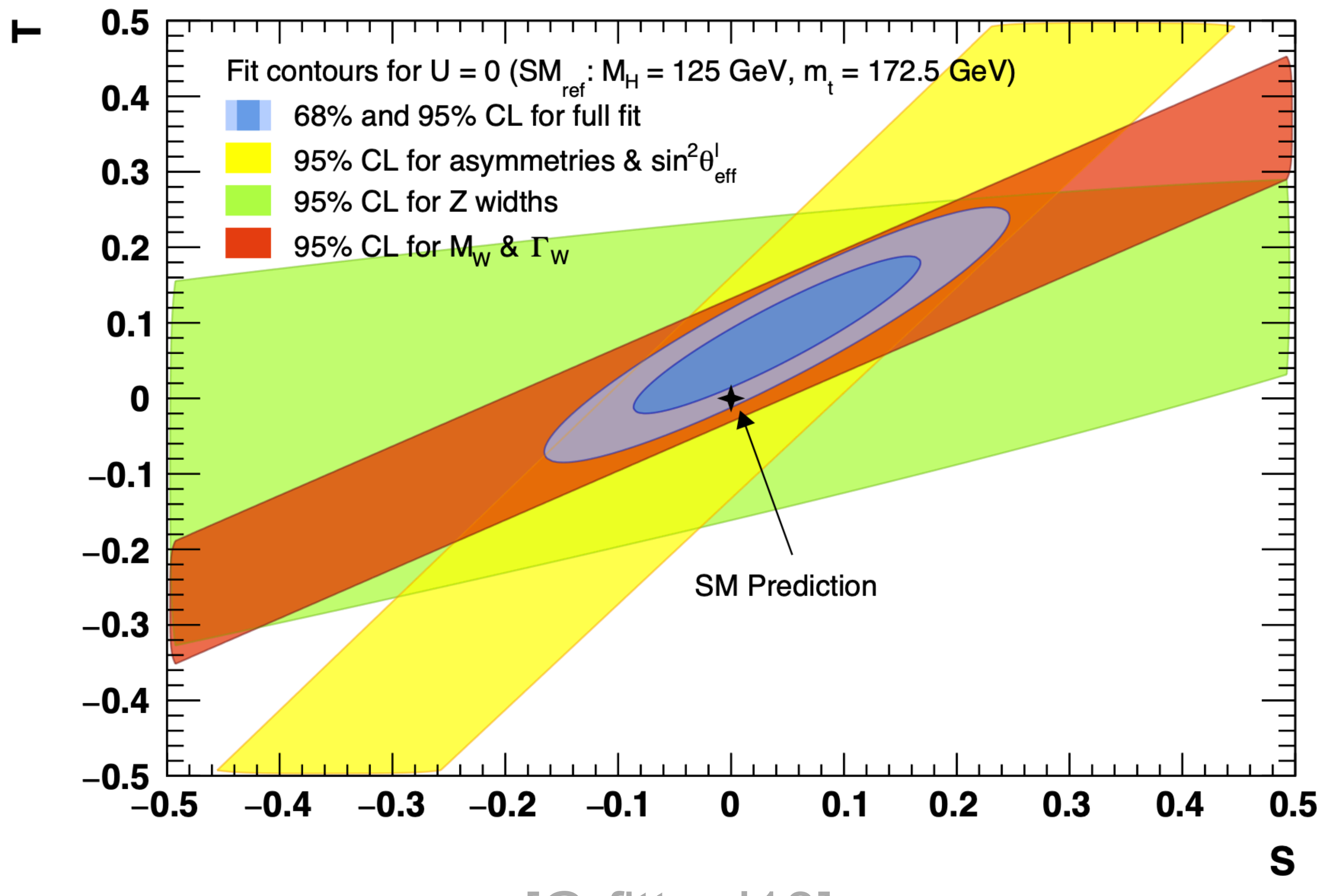

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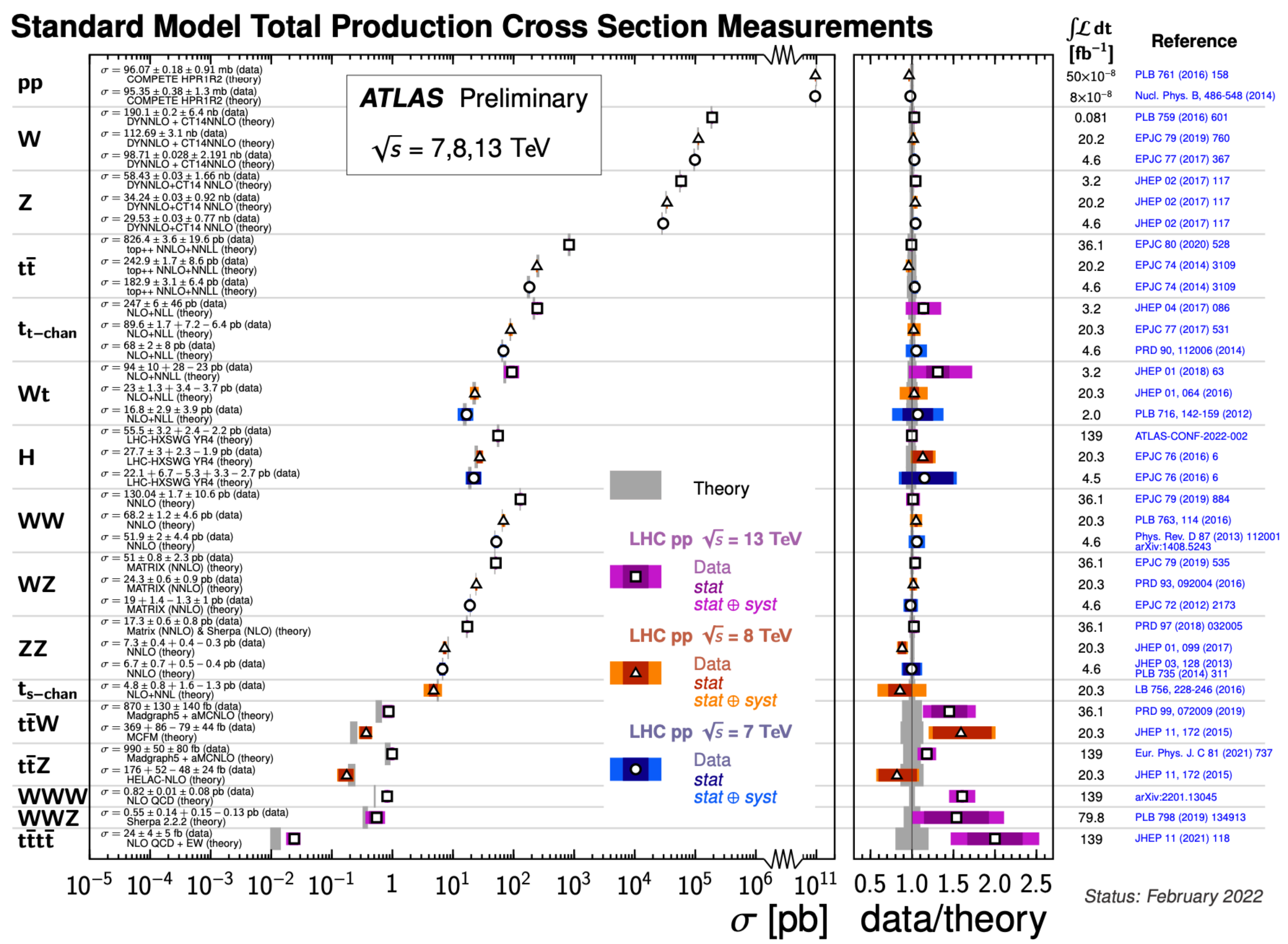

[Atlas Pub2022-009]

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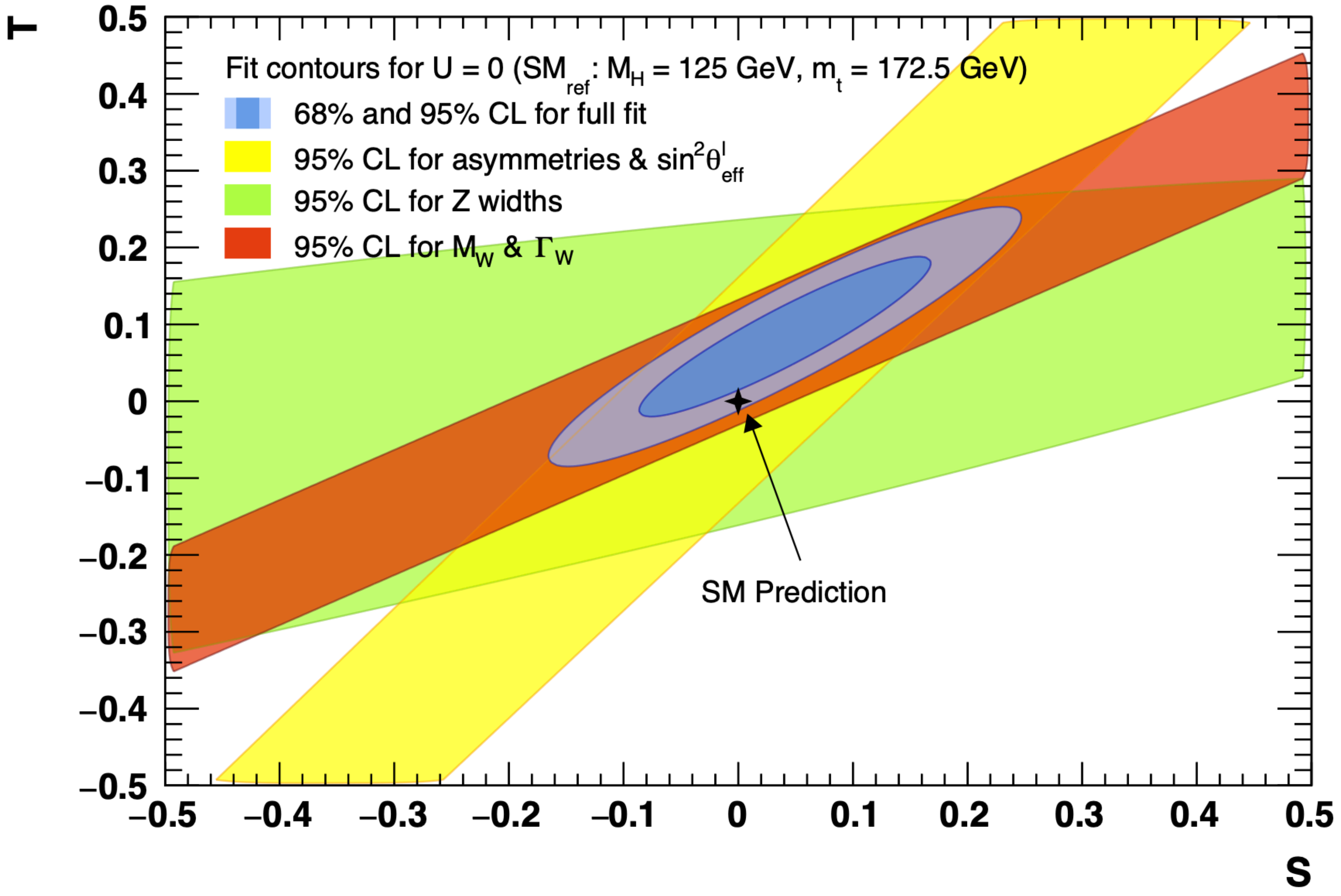

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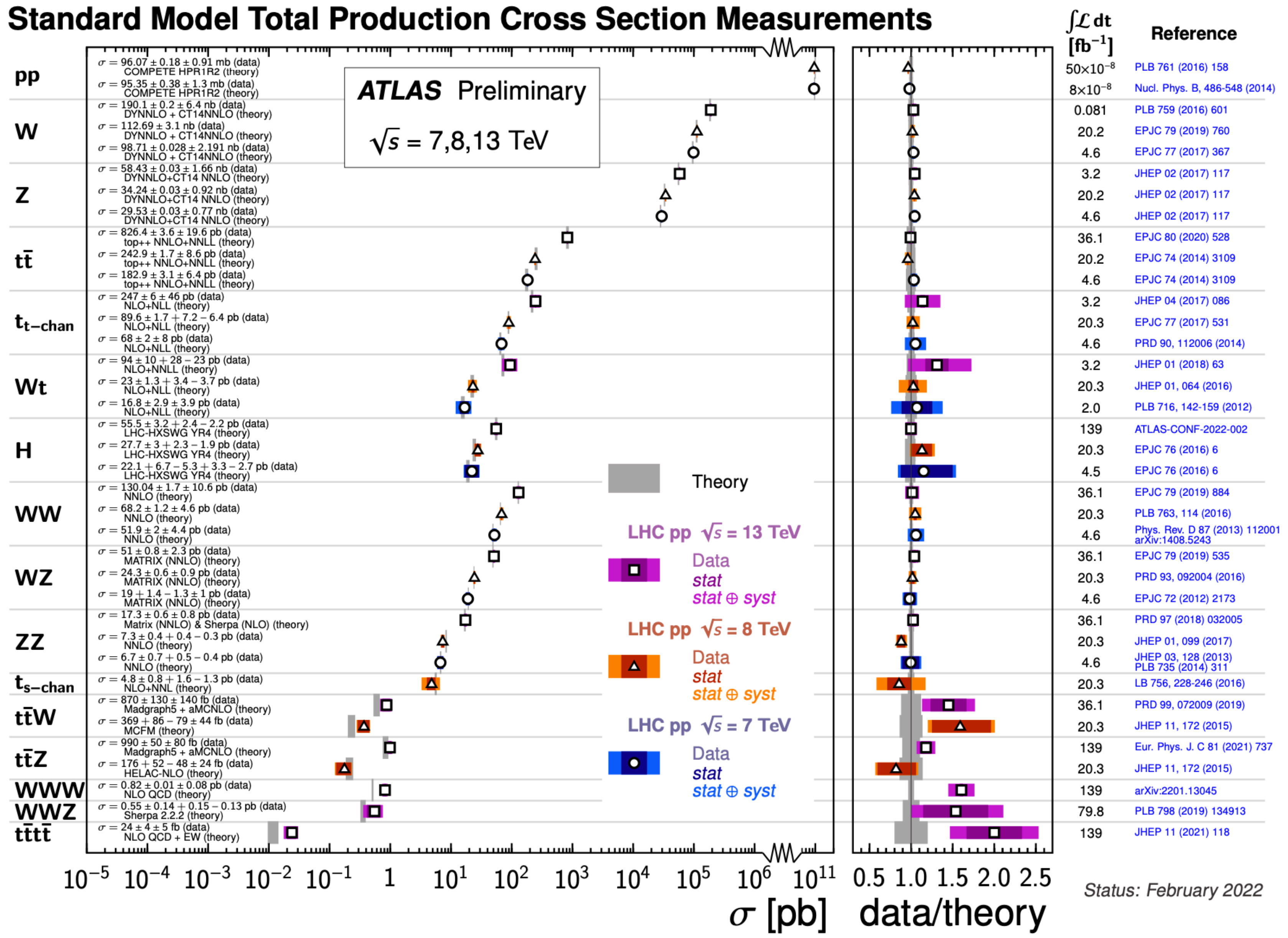

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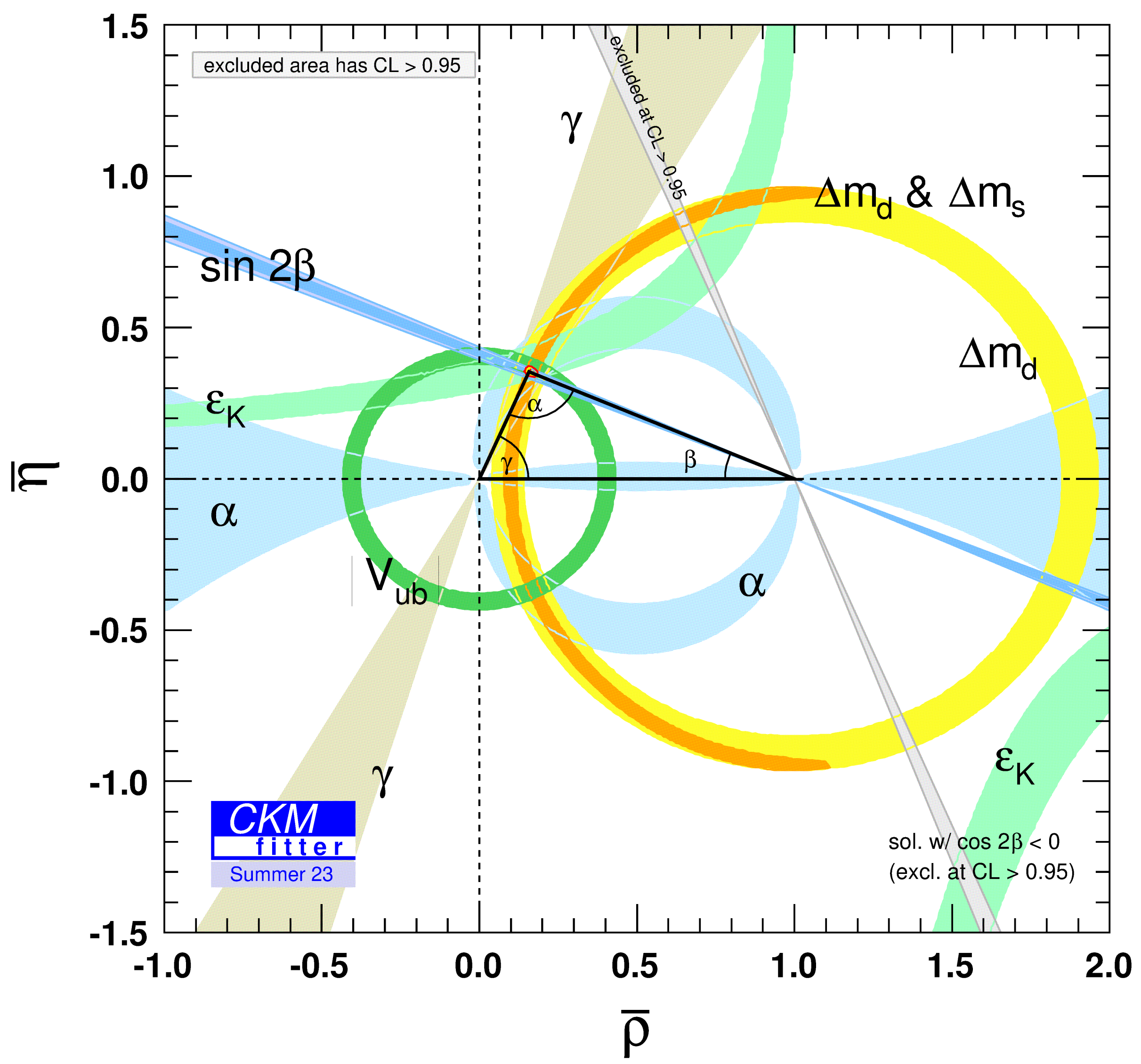

[CKM-fitter '23]

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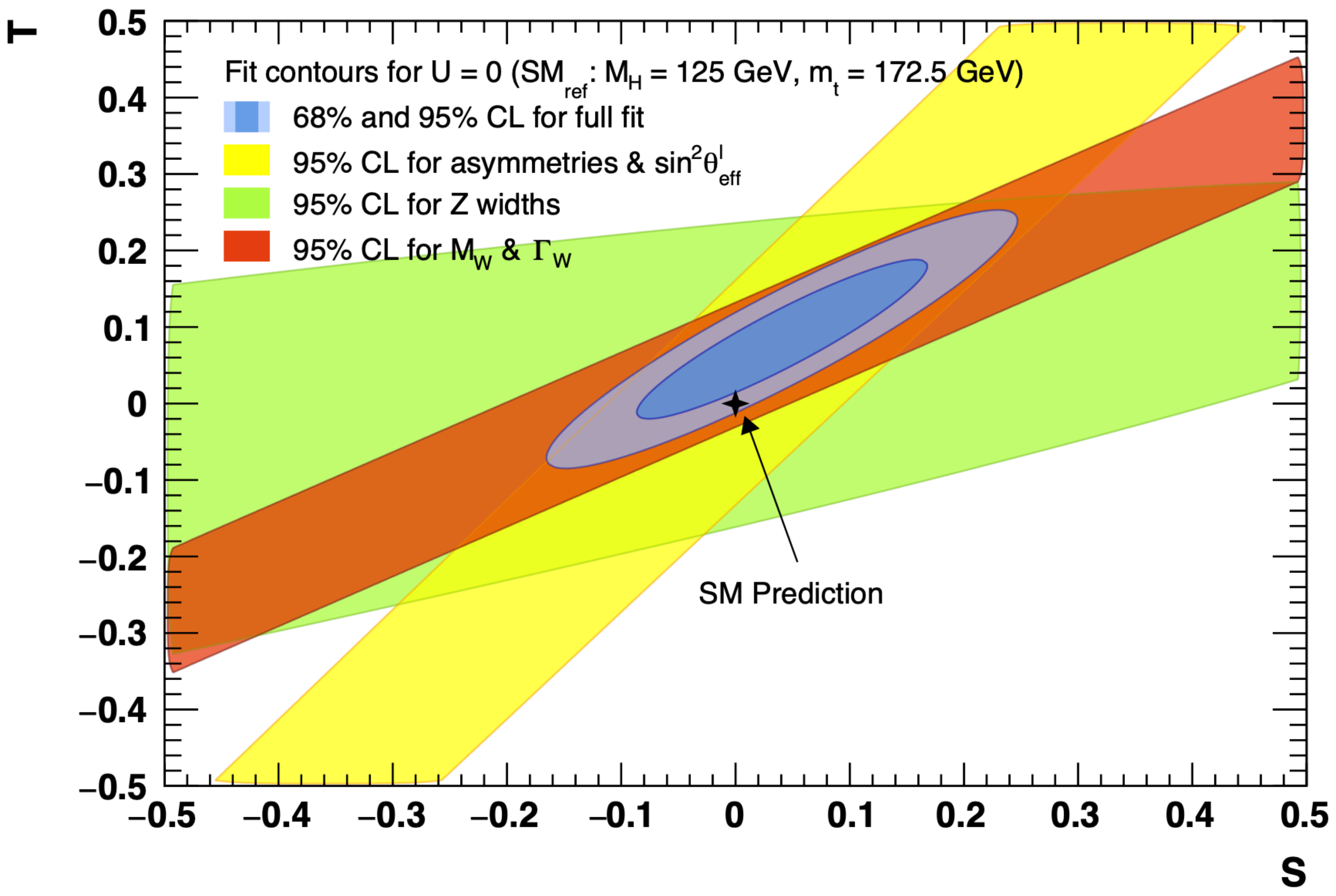

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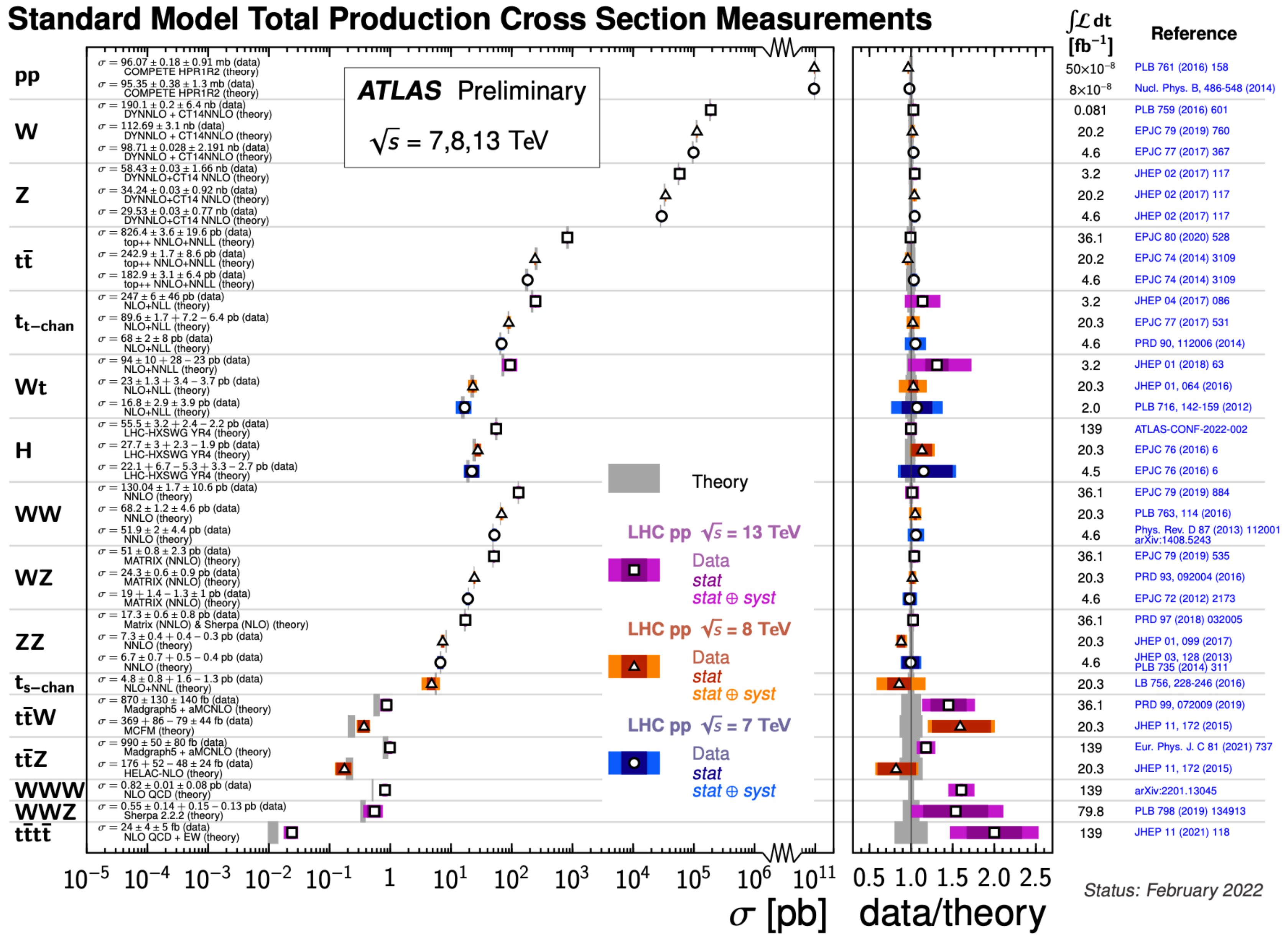

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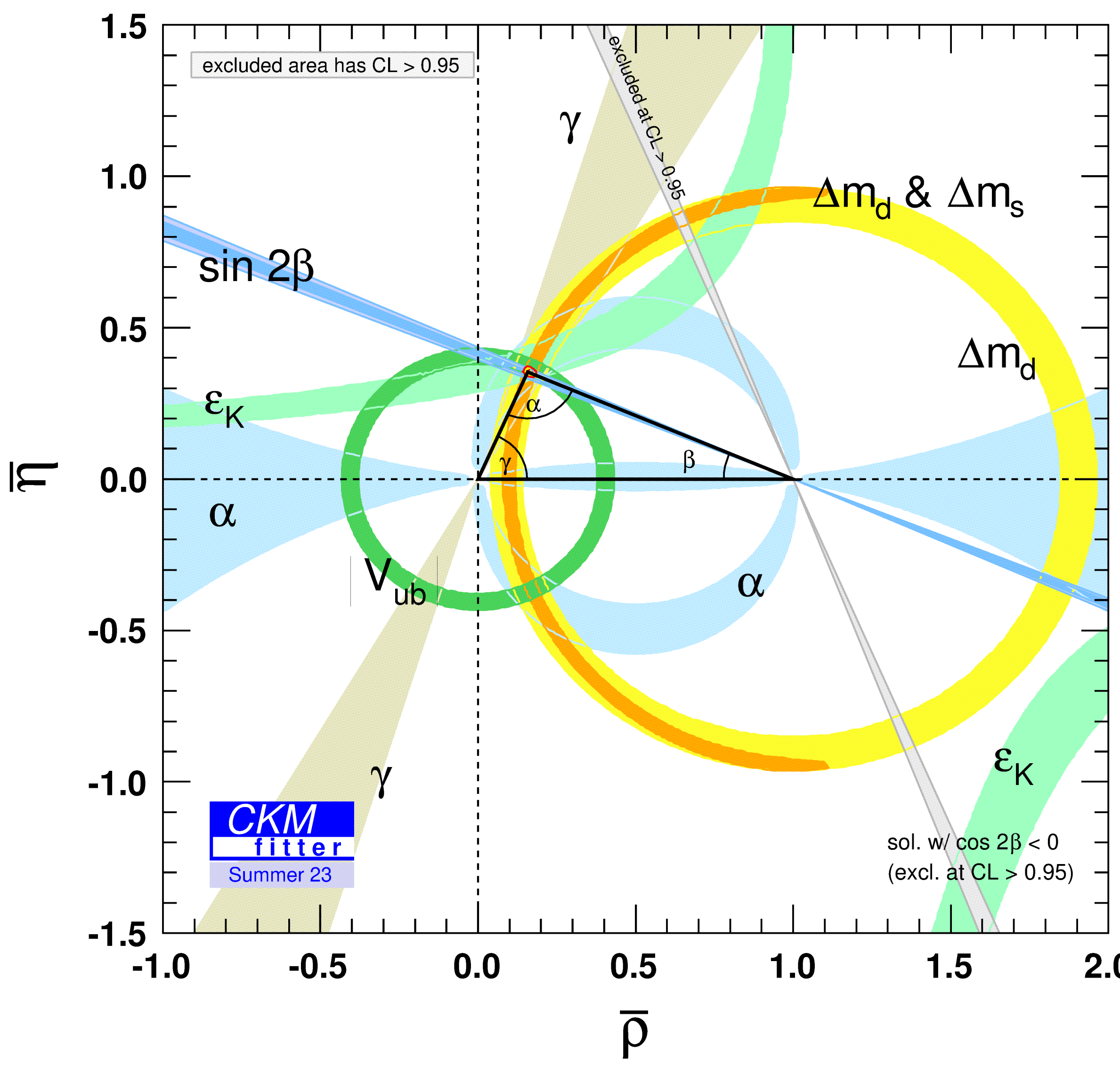
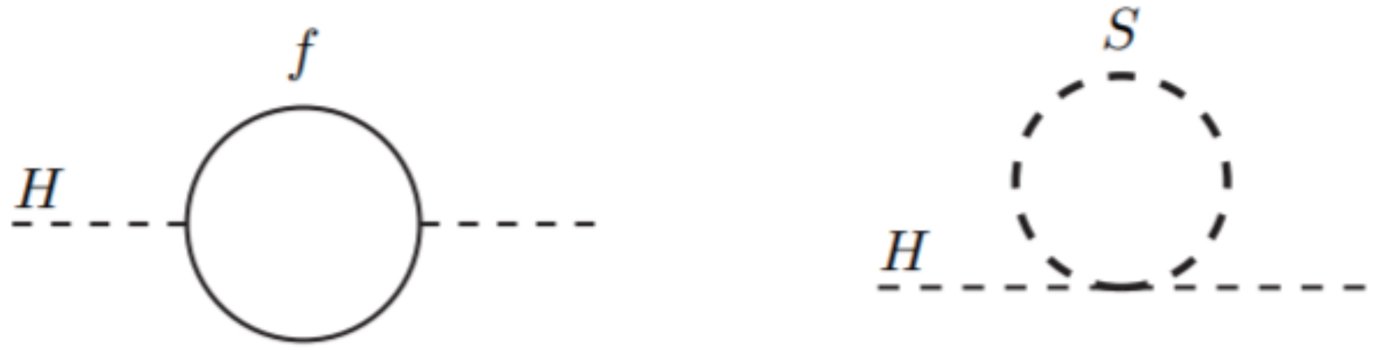


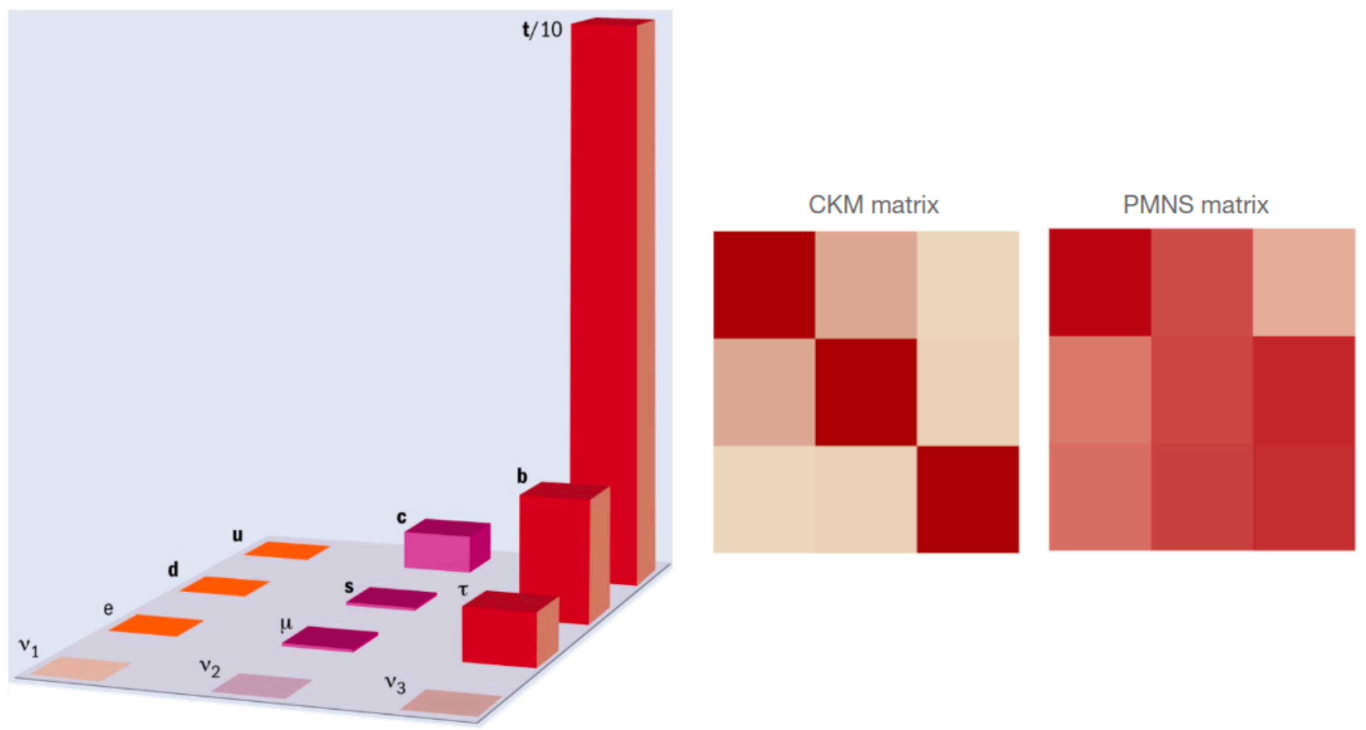
[CKM-fitter '23]

- The Standard Model of Particle Physics is extremely successful in explaining a wide variety of phenomena
- No evidence of new states
- **Yet we know that it cannot be the full story…**

The need for Beyond SM physics

- Strong CP Problem
- Hierarchy Problem
- Flavour puzzle
- …





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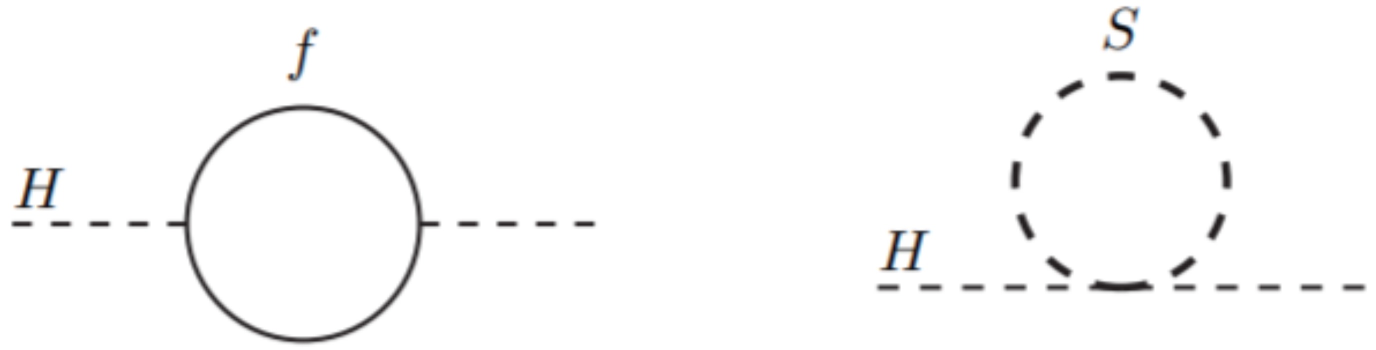
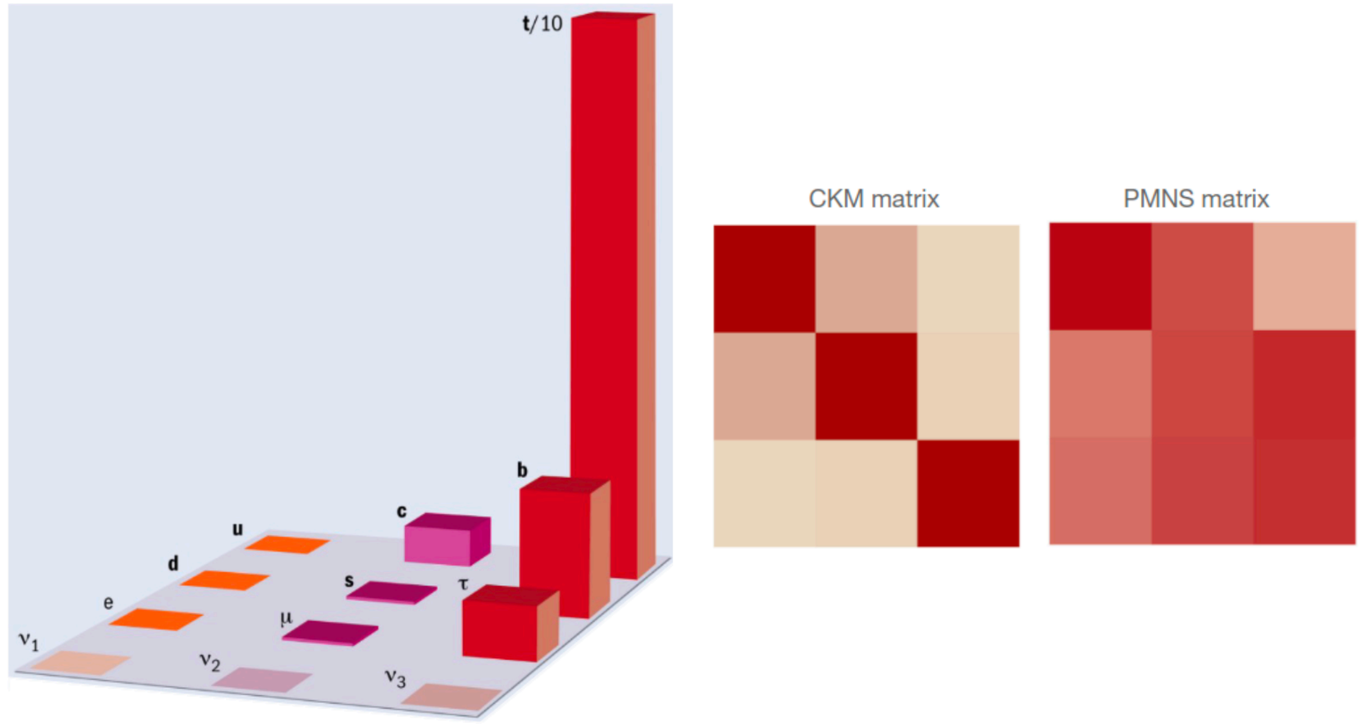
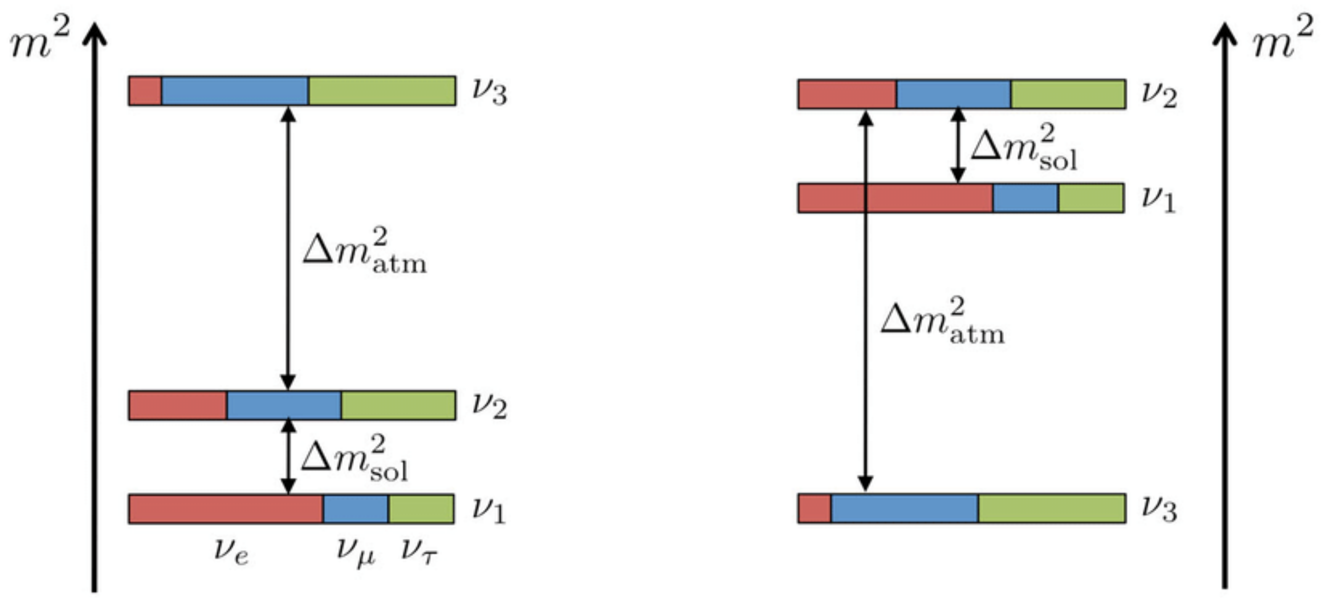
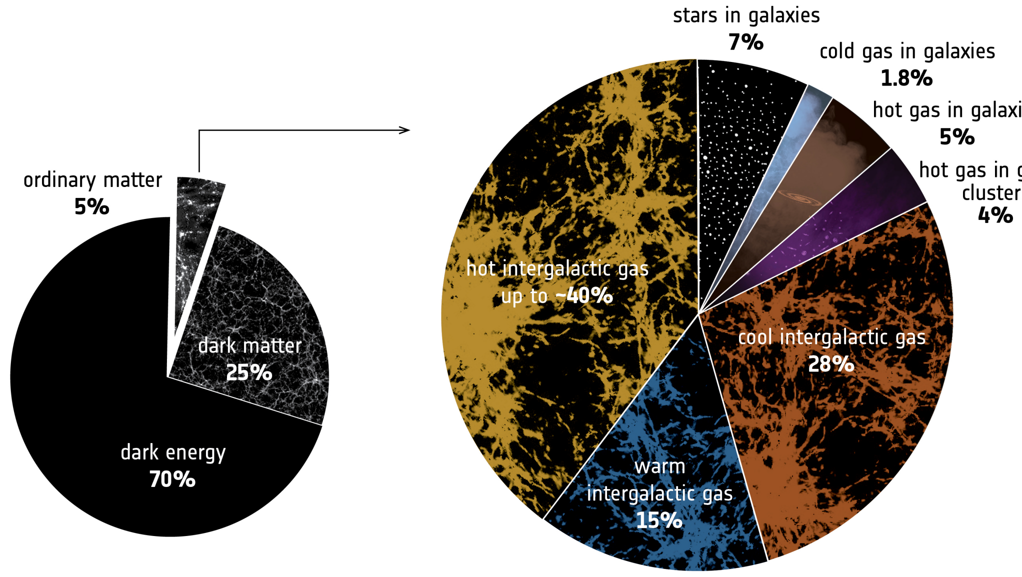




- Neutrino masses
- Dark matter
- Baryon asymmetry of the Universe

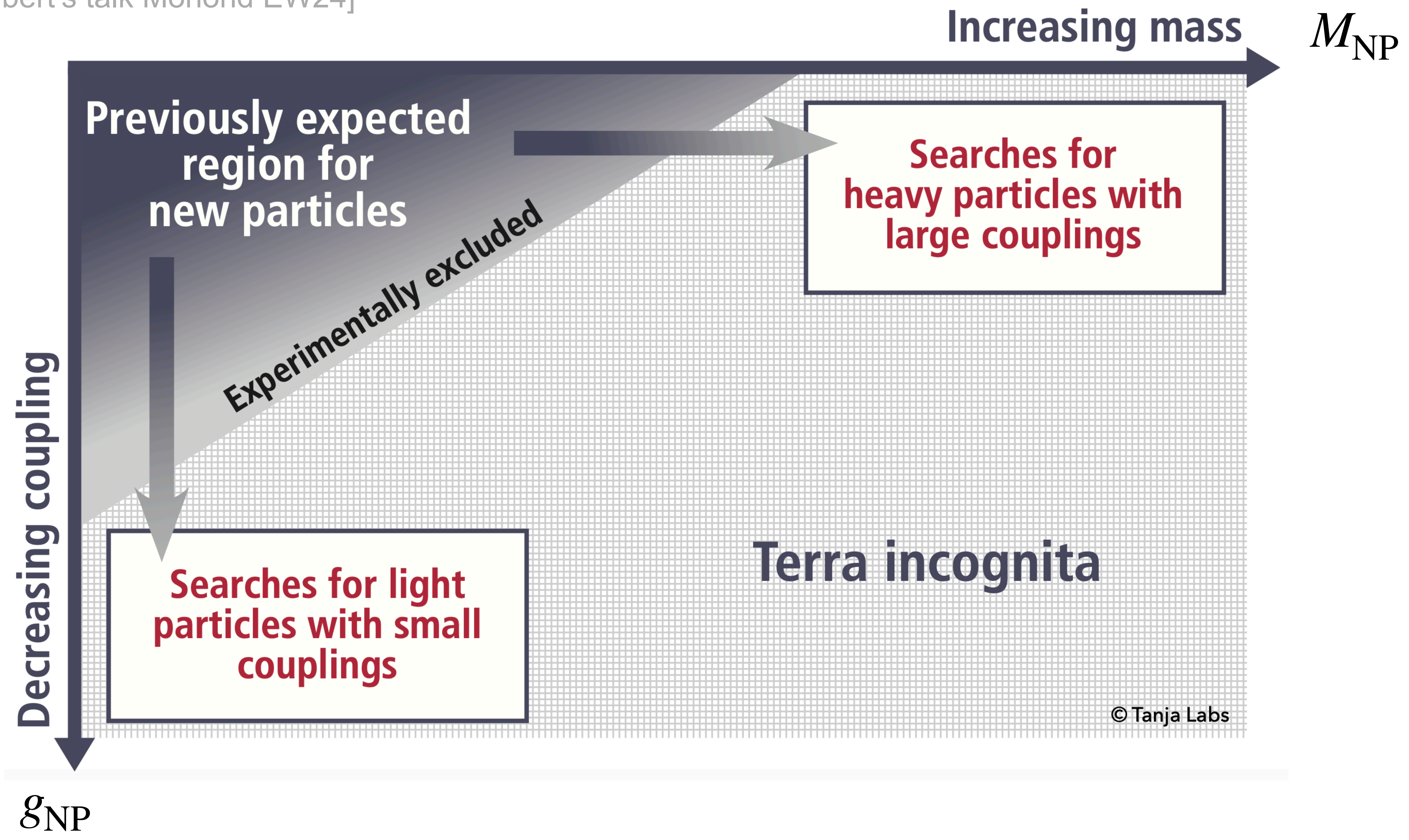




$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

New Physics searches

[Neubert's talk Moriond EW24]



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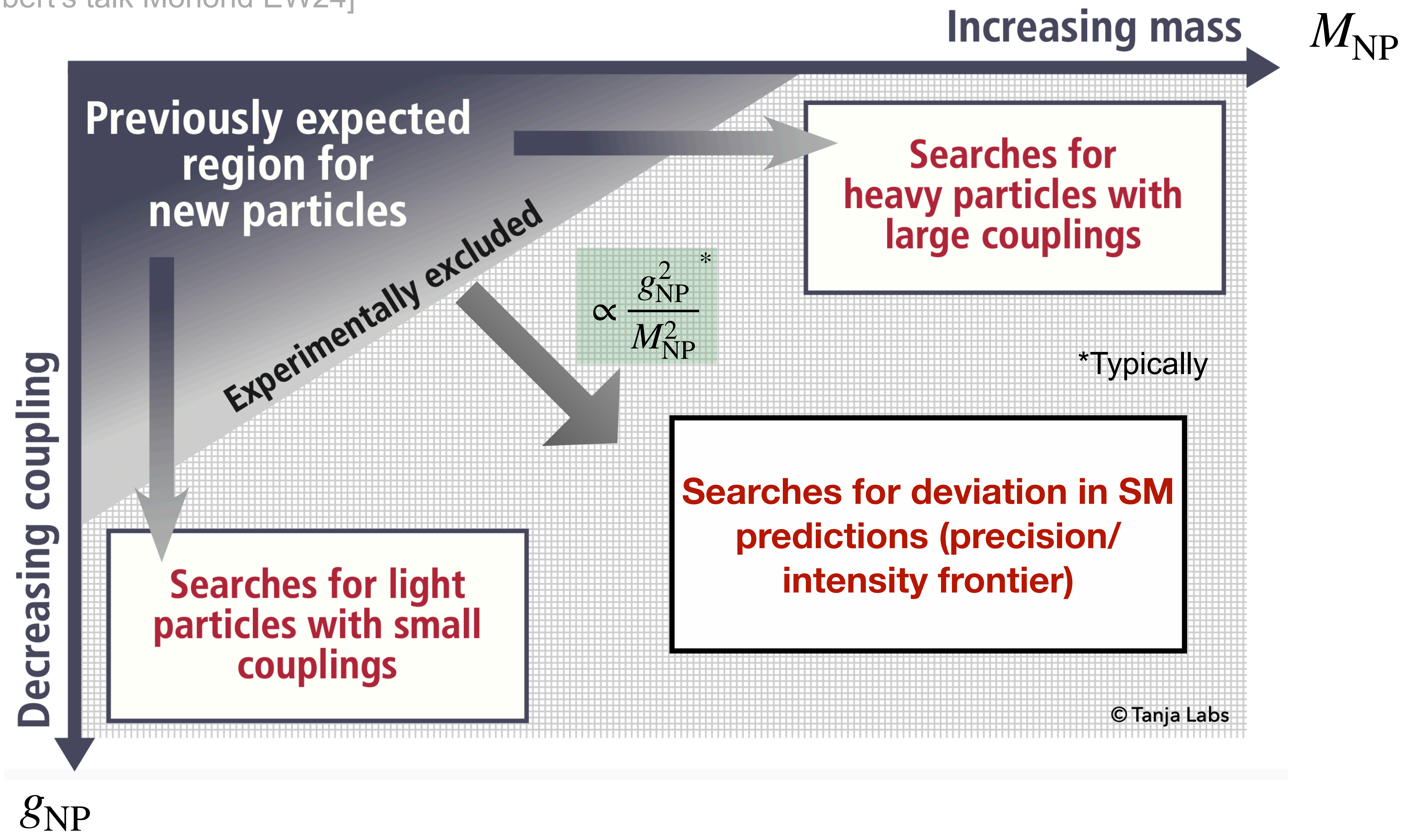

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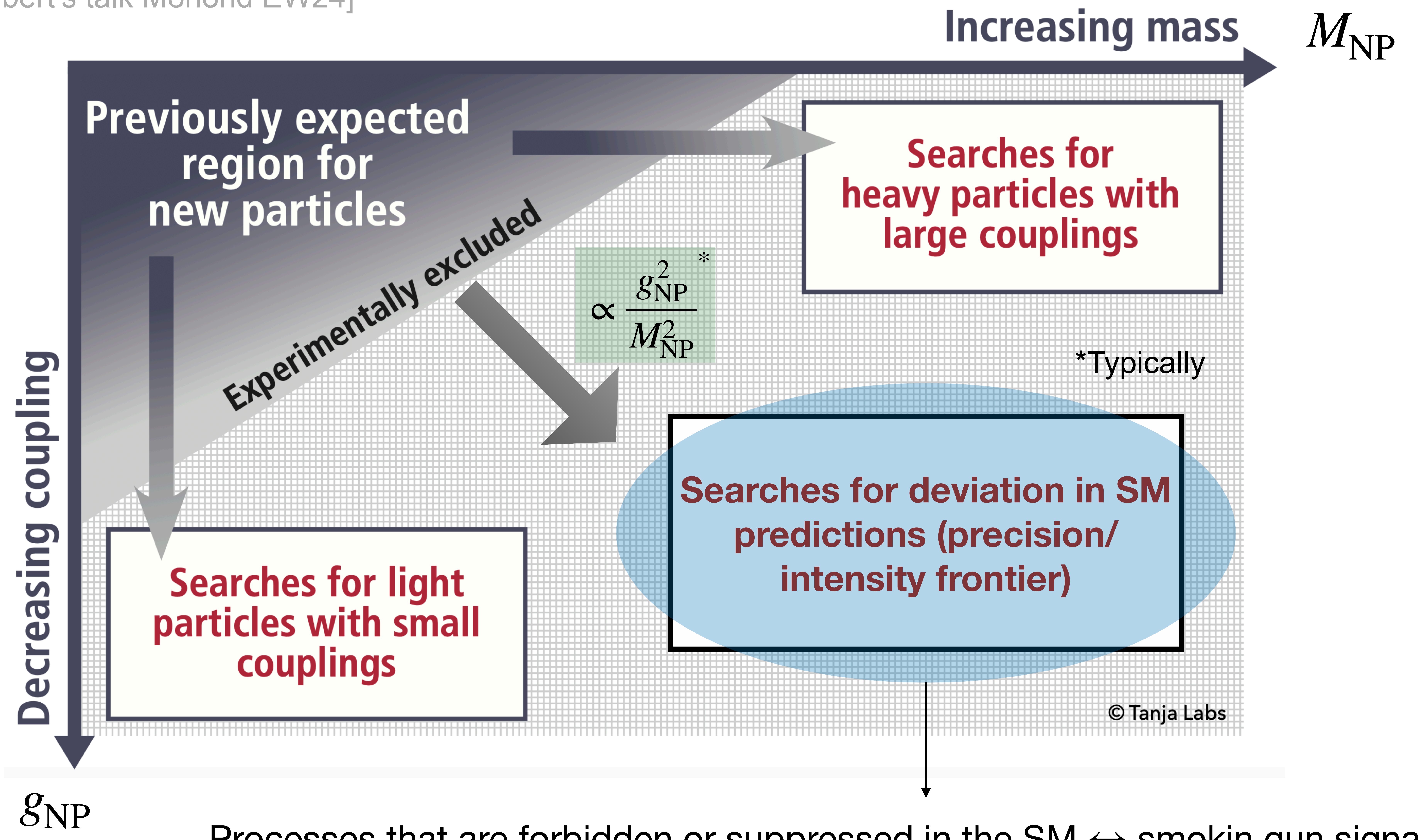

Processes that are forbidden or suppressed in the SM ↔ smokin gun signals of NP

Lepton symmetries in the SM

$$\ell_i = \begin{pmatrix} \nu_i \\ e_{iL} \end{pmatrix}, \quad e_i = e_{iR}$$

$$\mathcal{L}_{\text{gauge}} \supset i \sum_{i=1,2,3} (\bar{\ell}_i \, \not{D} \ell_i + \bar{e}_i \, \not{D} e_i)$$

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$$\alpha = e, \mu, \tau$$

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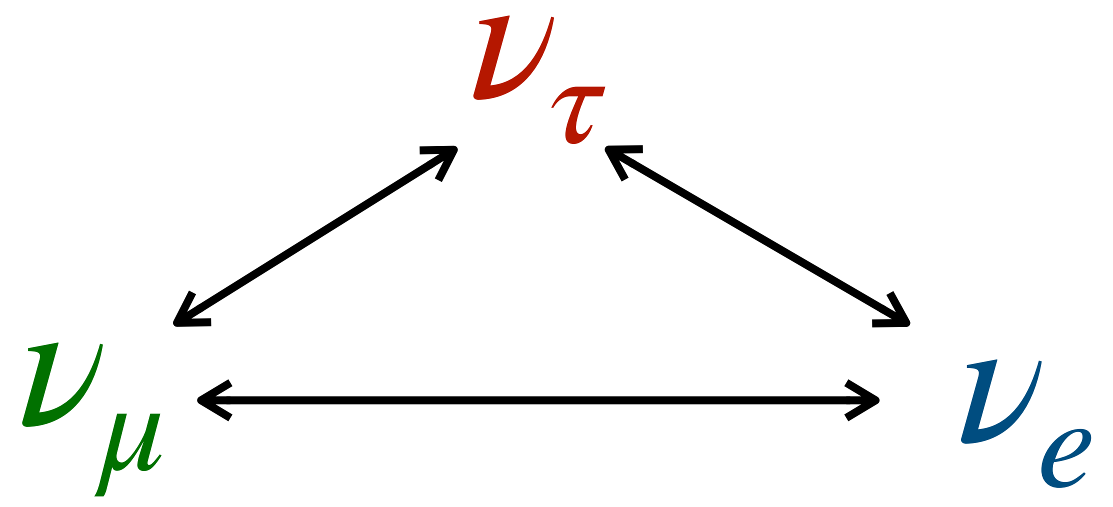
Lepton Flavour Conservation and **Lepton Flavour Universality** (LFU) up to Yukawa/mass effects

Neutrino masses imply Lepton Flavour Violation

The Standard Model Lagrangian (without right-handed neutrinos) is accidentally invariant under a phase rotation of each **lepton flavor**

Neutrino masses break all three symmetries



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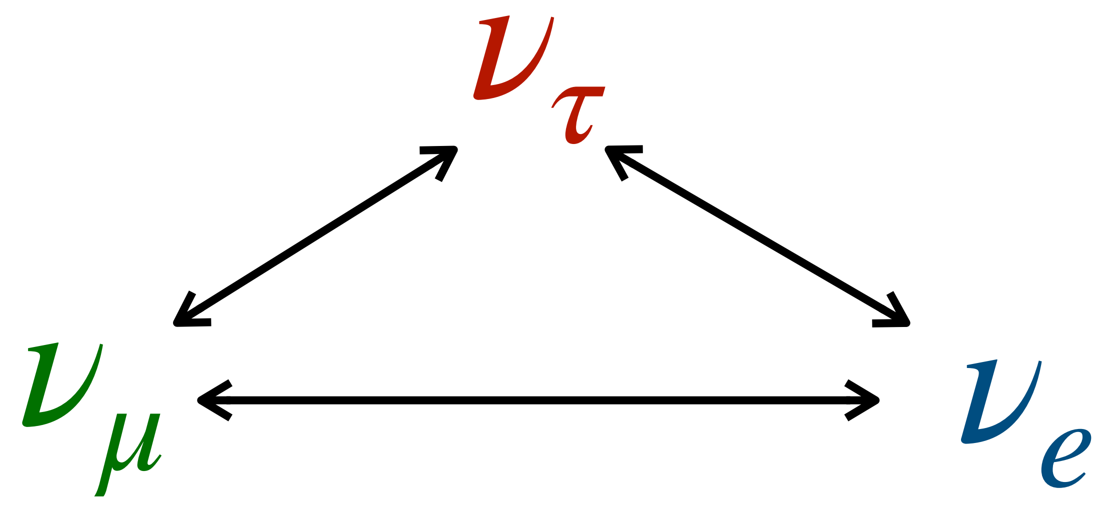
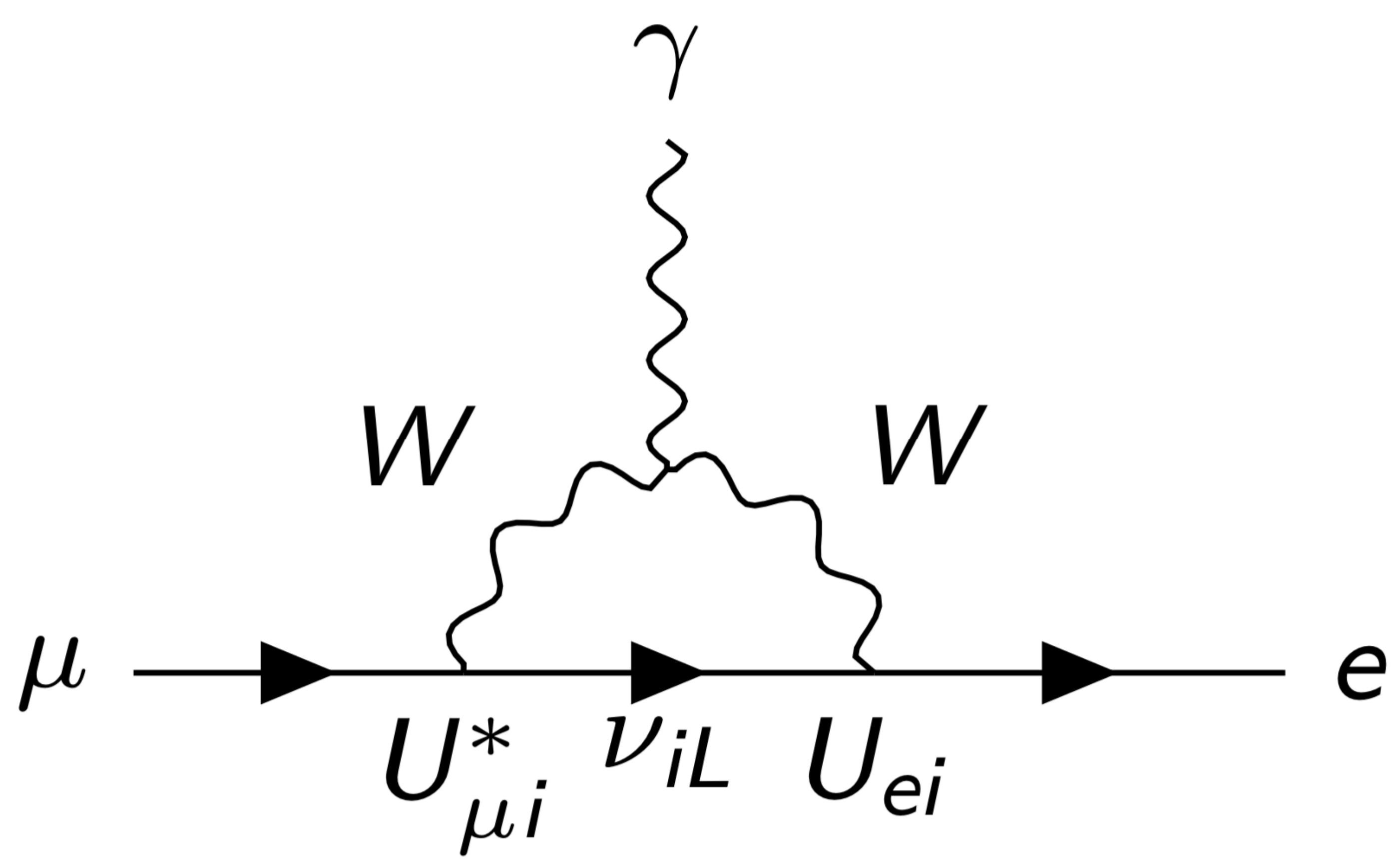


Since there is no symmetry that forbids it, **lepton flavour violation in the charged sector is inevitable**:

$$\mu^{\pm} \rightarrow e^{\pm}\gamma \qquad \tau^{\pm} \rightarrow e^{\pm}e^{+}e^{-} \qquad h \rightarrow \tau^{\pm}\mu^{\mp}\ldots$$

must happen, but at what rates?

Charged Lepton Flavour Violation (cLFV)



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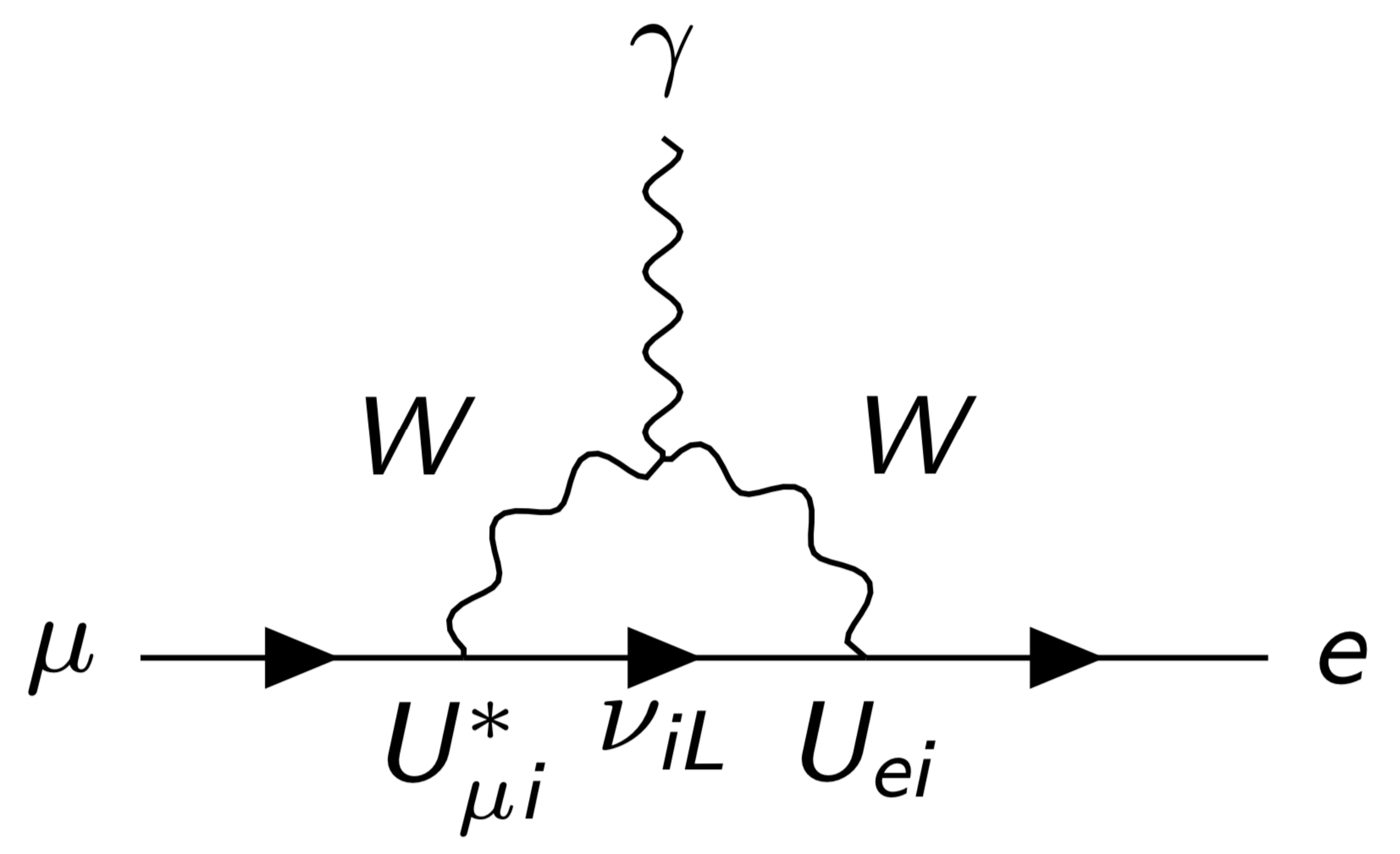

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- **An observation of LFV would be a clear signature of new physics**
- **It could shed light on the mechanism behind neutrino masses**
- **Many models** that address unresolved puzzles (independently from neutrino masses) **predict potentially observable LFV signals**

Outline

1. LFV with muons

2. LFV in tau decays

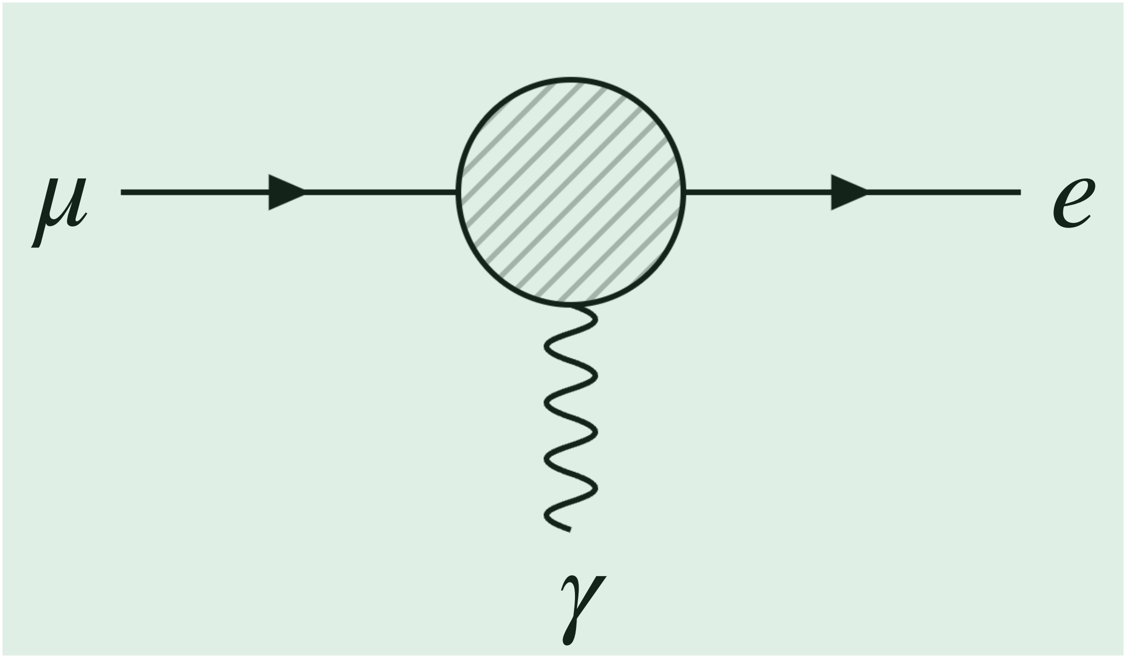
3. LFU tests with tau decays

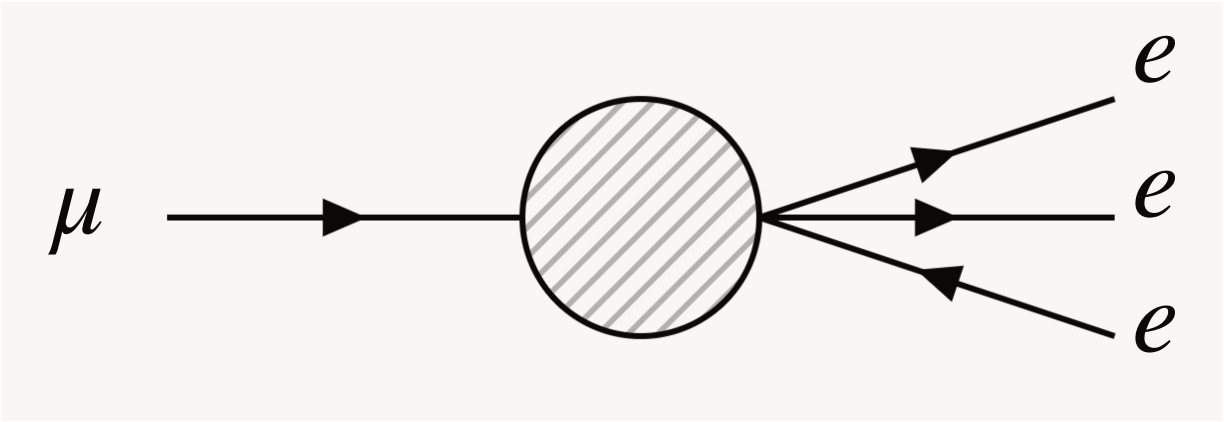
Hopefully covered in other theory talks

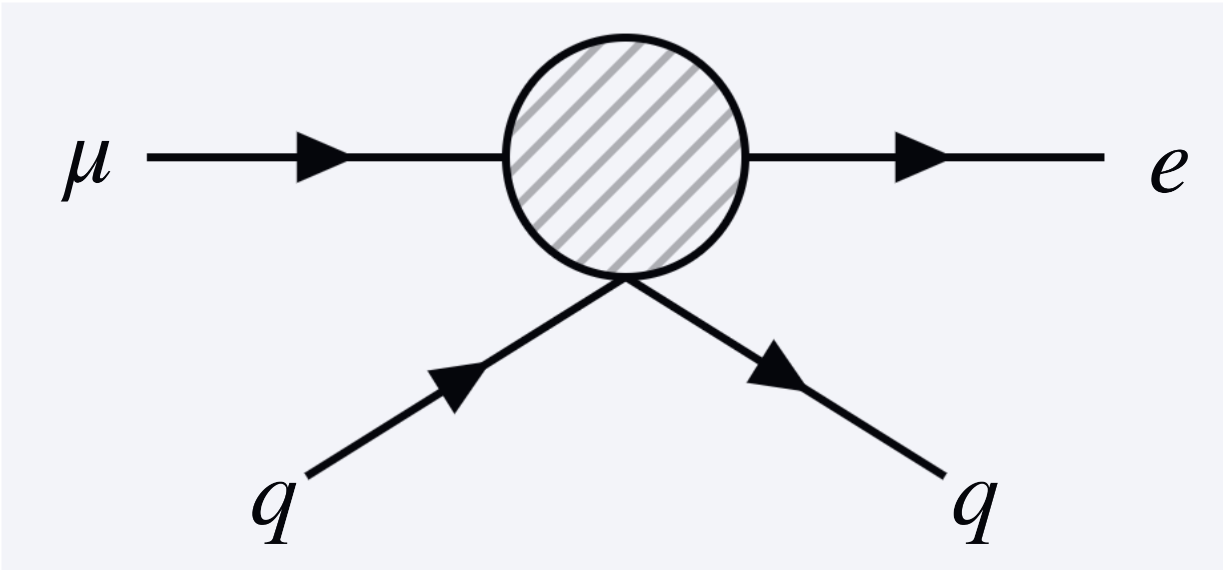
- LFV and LFU violation in B and Kaon (semi)leptonic decays
- LFU violation in Pion decays
- $R(D)/R(D^*)$

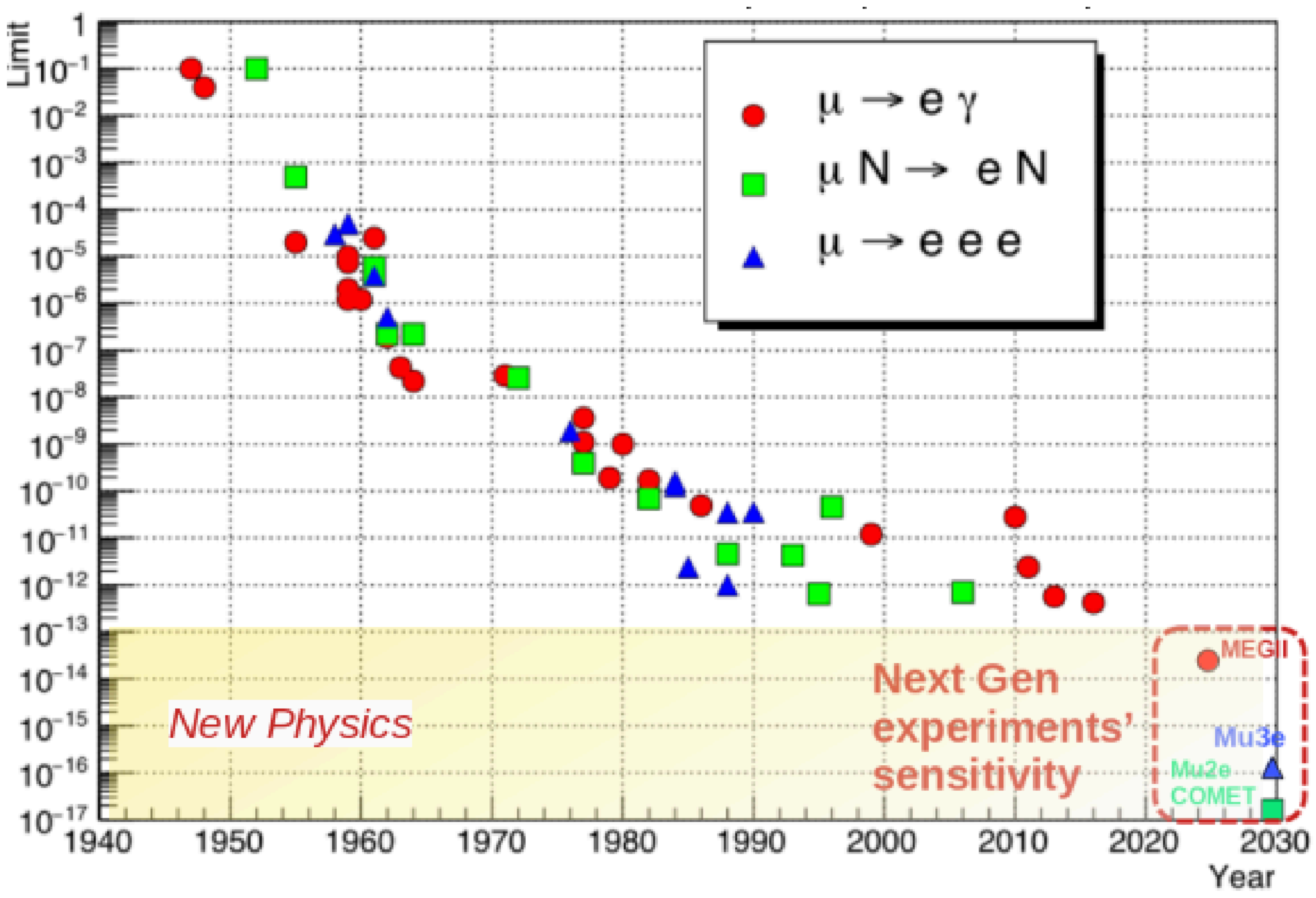
$\mu \to e\gamma$, $\mu \to 3e$, $\mu A \to eA$

- The possibility of extremely intense muon beams make these the **most sensitive probes of LFV**
- Experimental sensitivities are expected to be **improved by up to five orders of magnitude**









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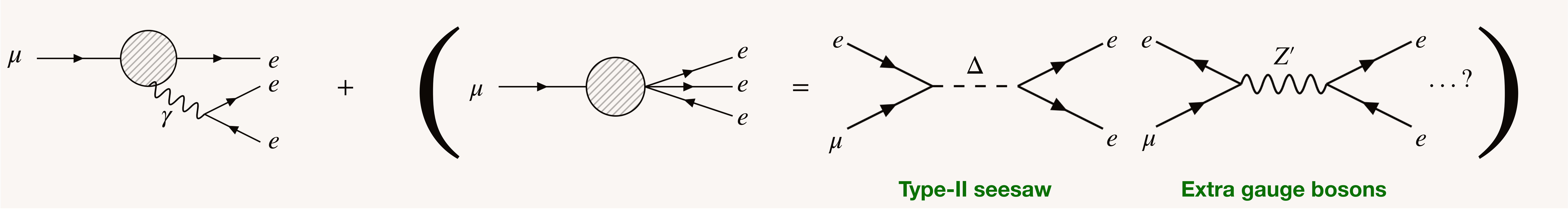
- $\mu \to e + \bar{e} + e$ $\quad Br(\mu \to e\bar{e}e) < 10^{-12}$ (SINDRUM) $\to$ $Br(\mu \to e\bar{e}e) \sim 10^{-16}$ (Mu3e)



$\mu \to e$ conversion in nuclei

- The muon gets captured by the (Z, A) nucleus and tumbles down to the 1s state

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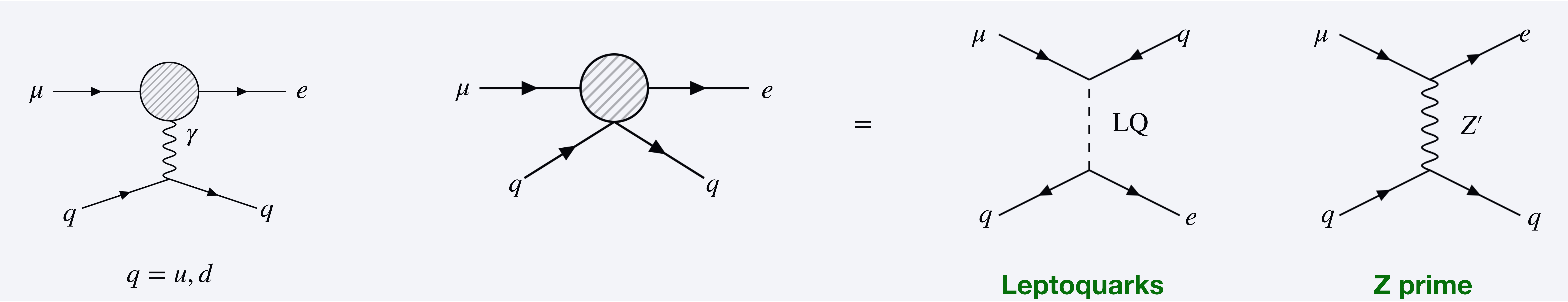
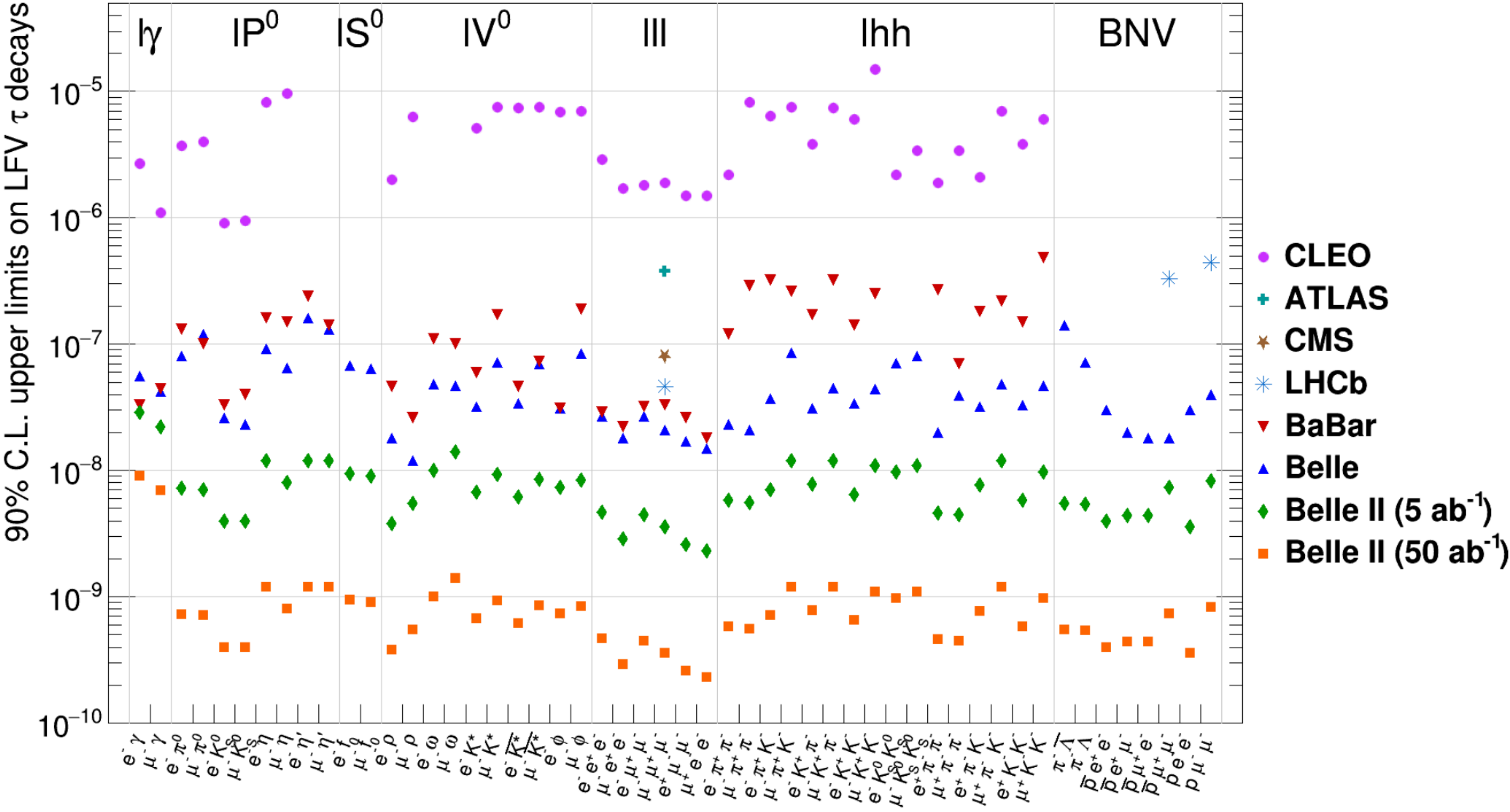


$\tau \to (e, \mu)$ transitions



[Snowmass tau CLFV, 2203.1419]

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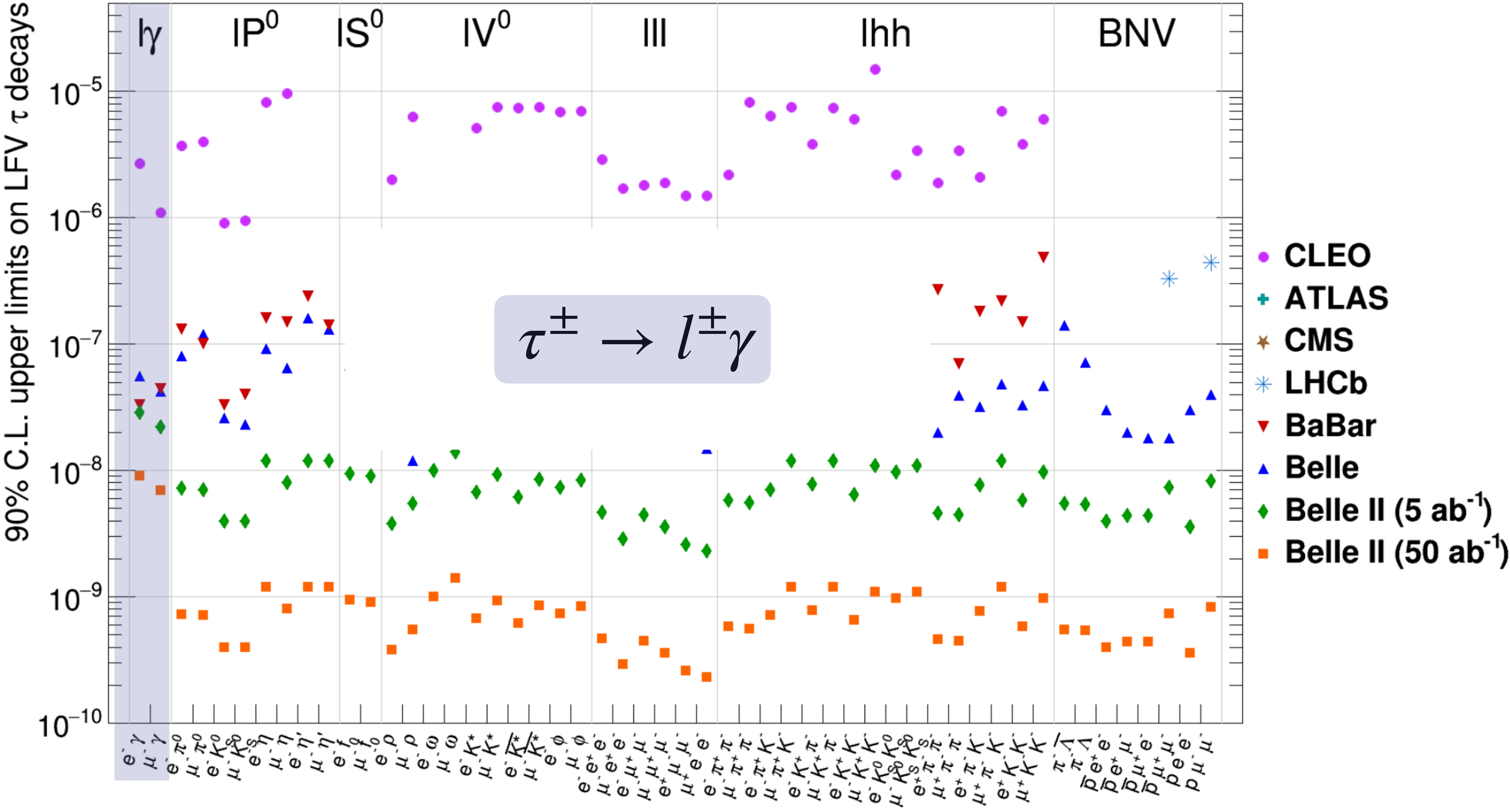

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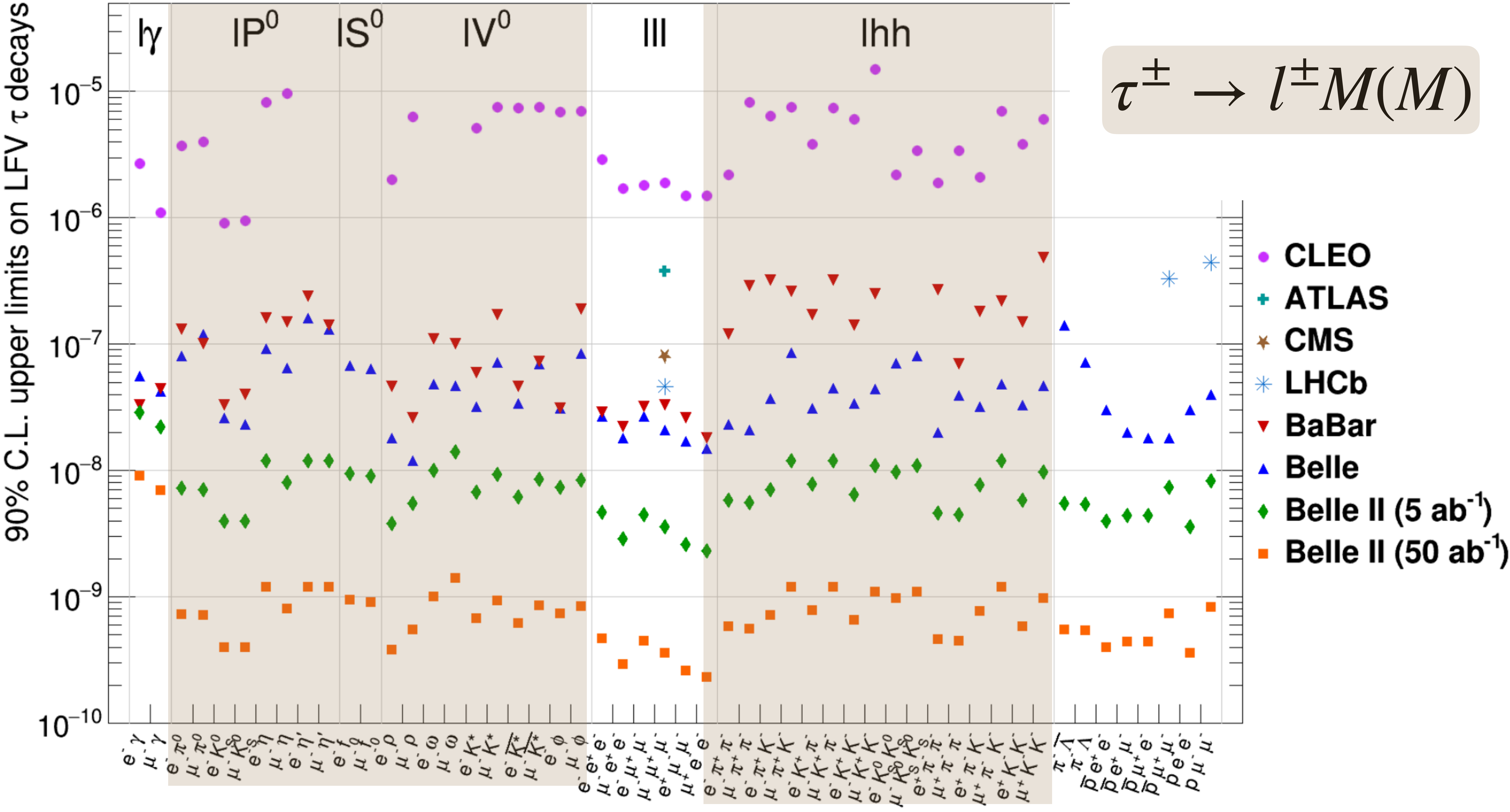
$$\tau^\pm \to l^\pm M(M)$$



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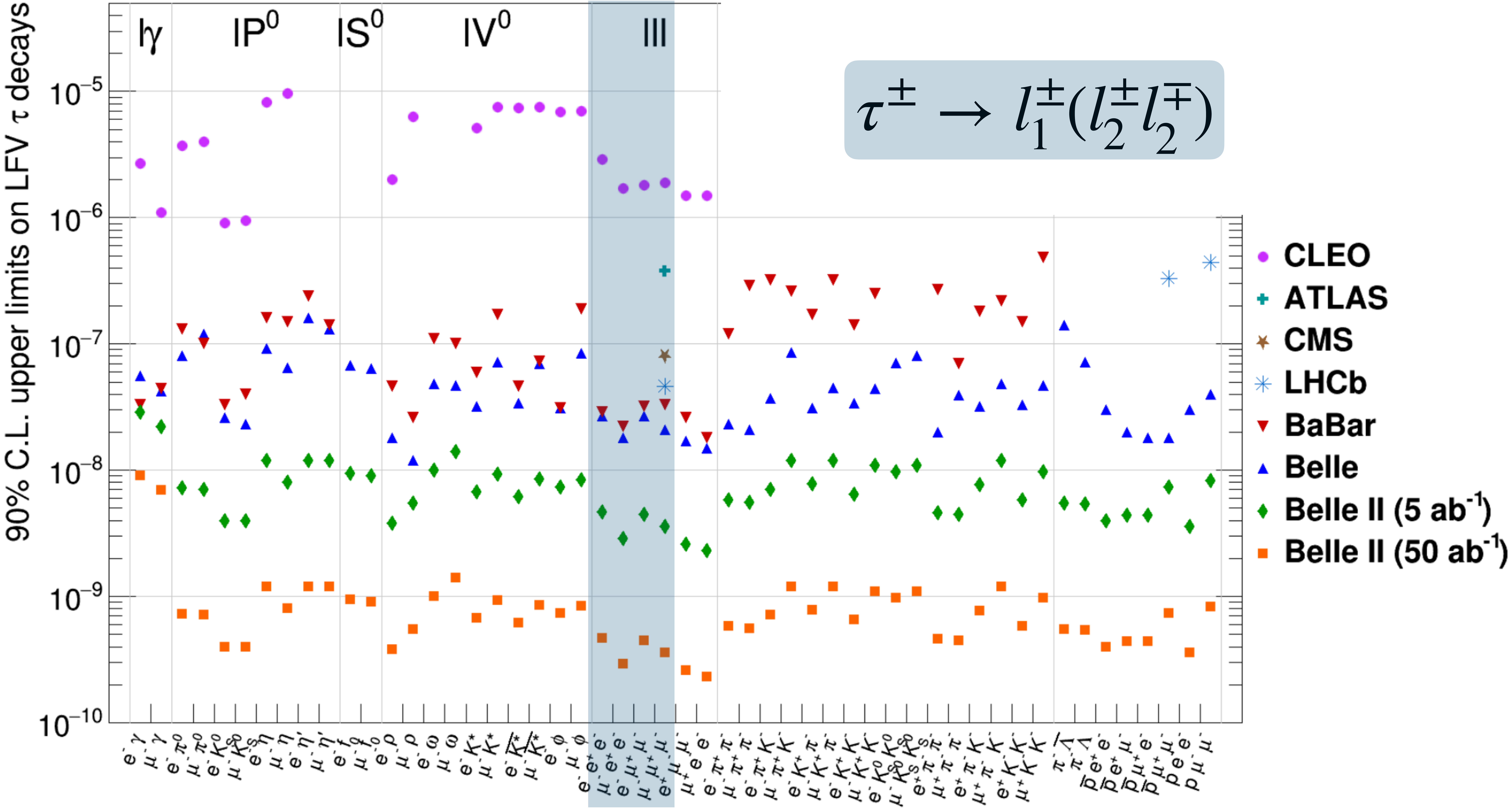

$\tau^{\pm} \to l_1^{\pm}(l_2^{\pm} l_2^{\mp})$

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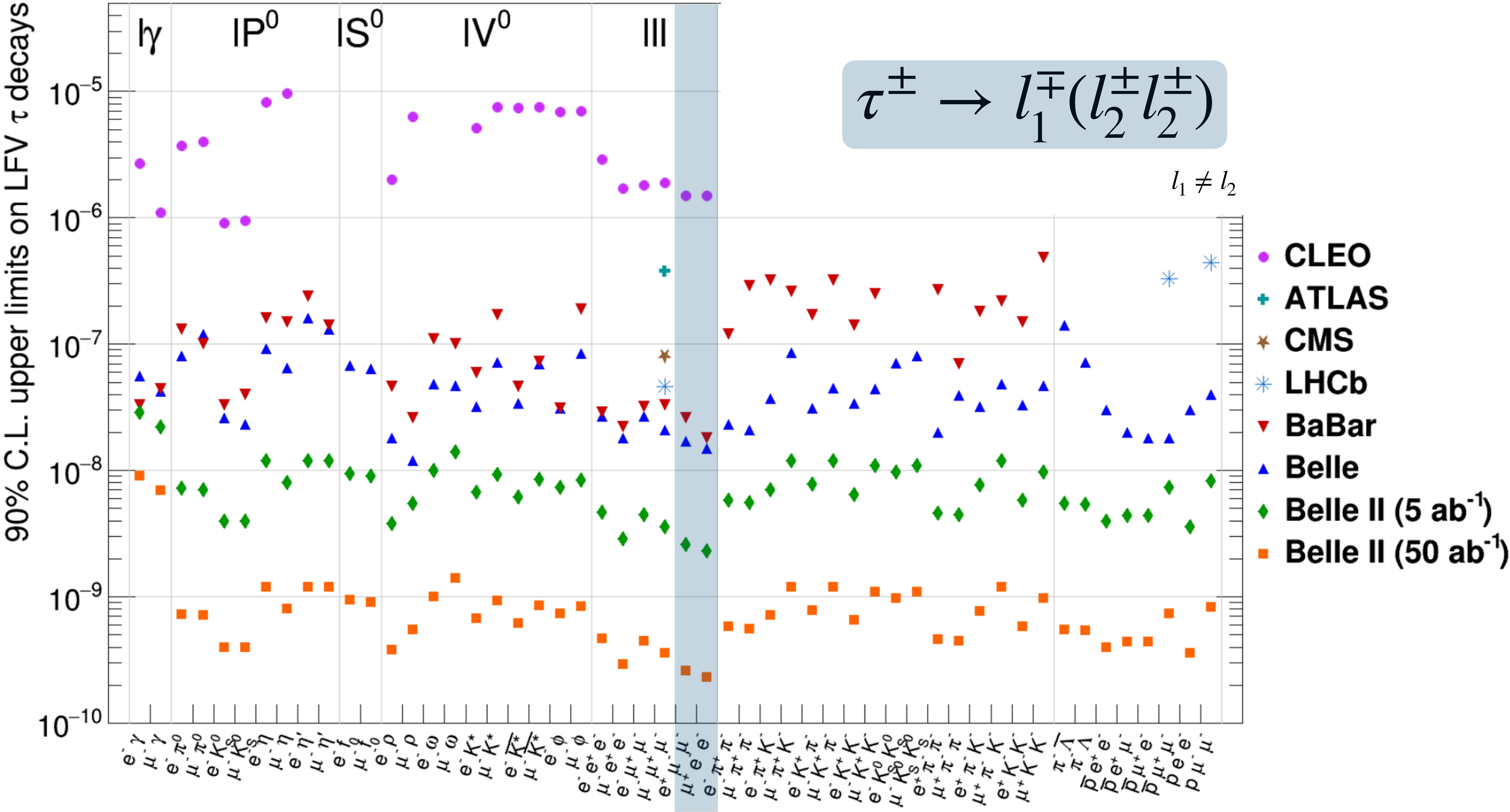

$$\tau^{\pm} \to l_1^{\mp}(l_2^{\pm} l_2^{\pm})$$

$l_1 \neq l_2$

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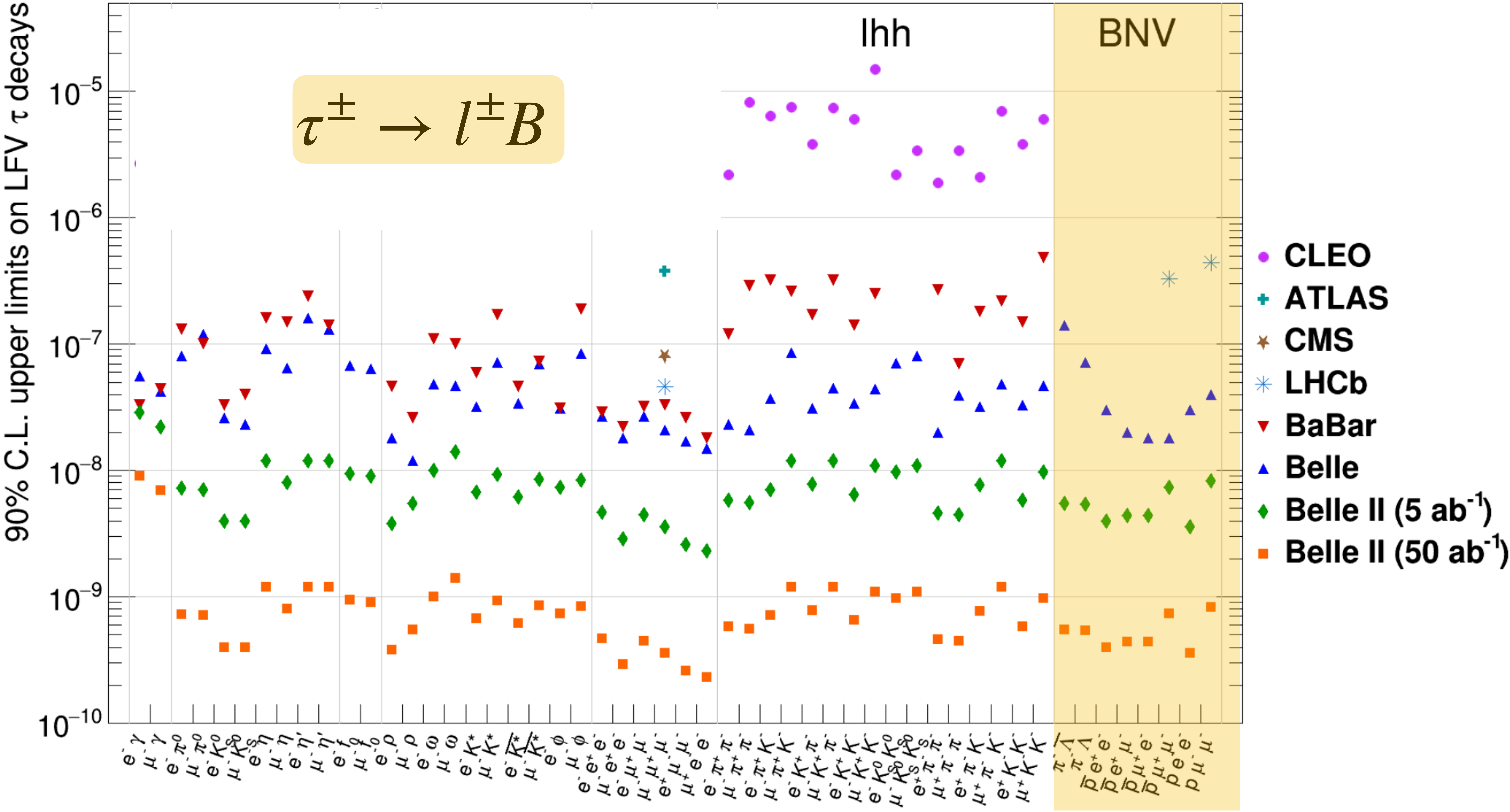

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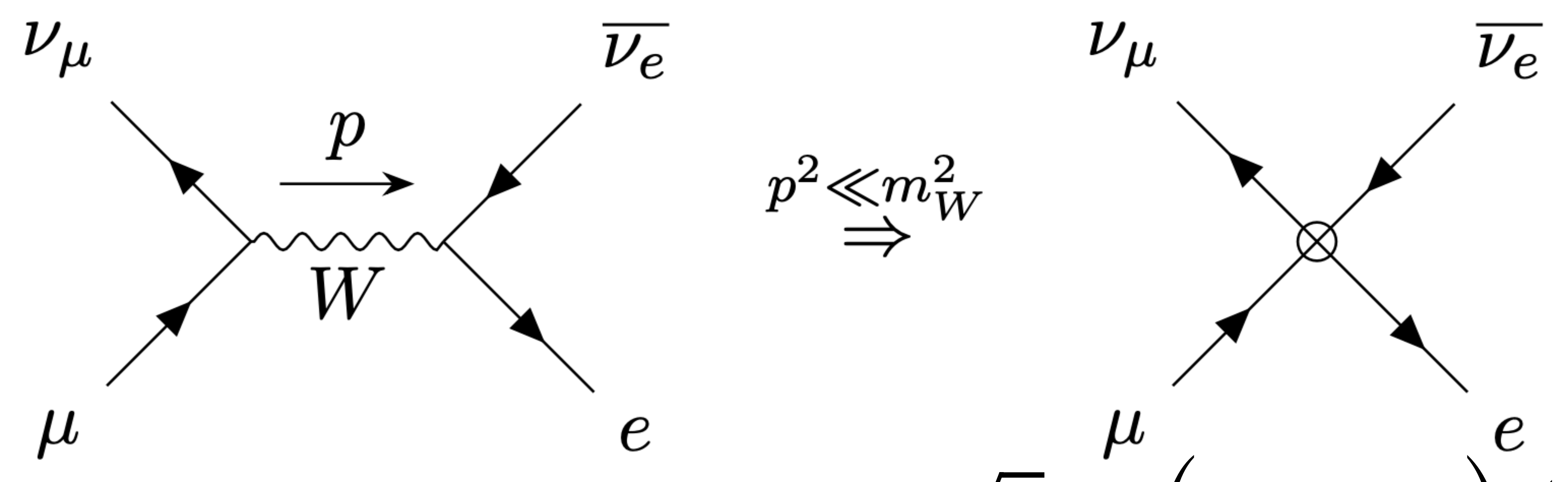

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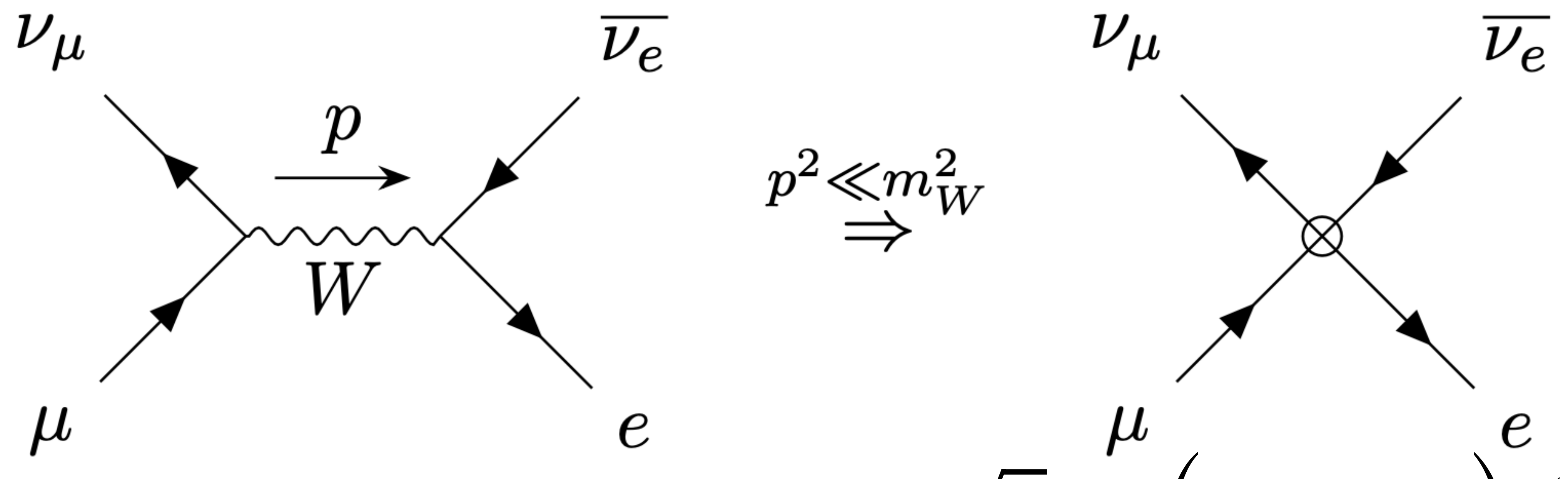

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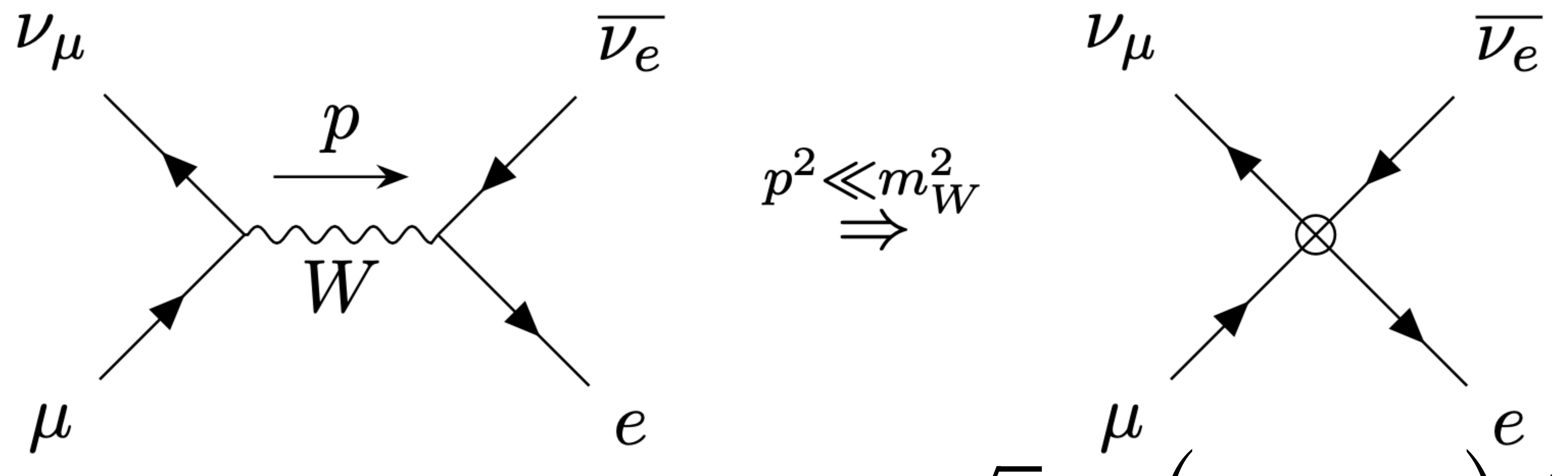

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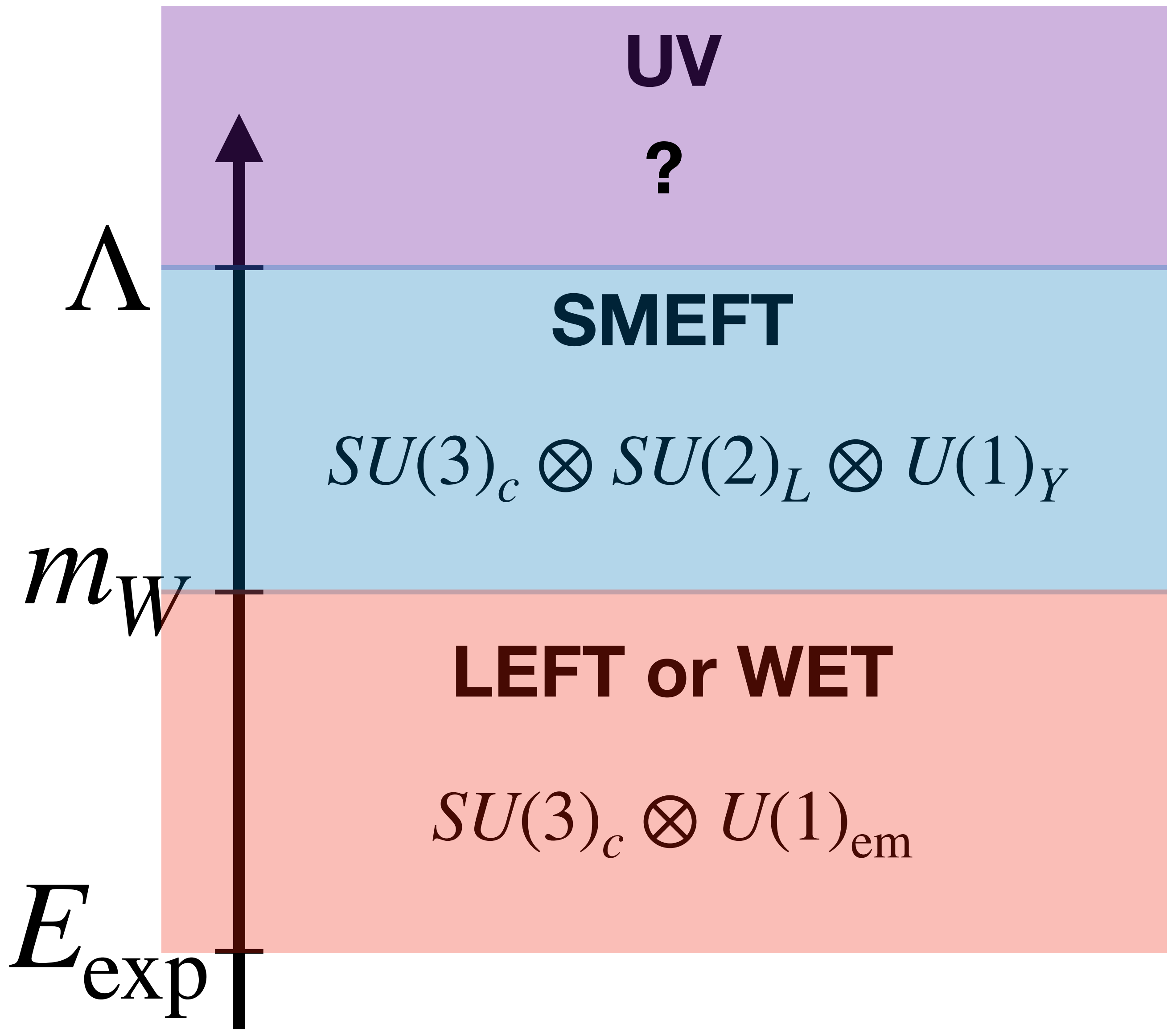

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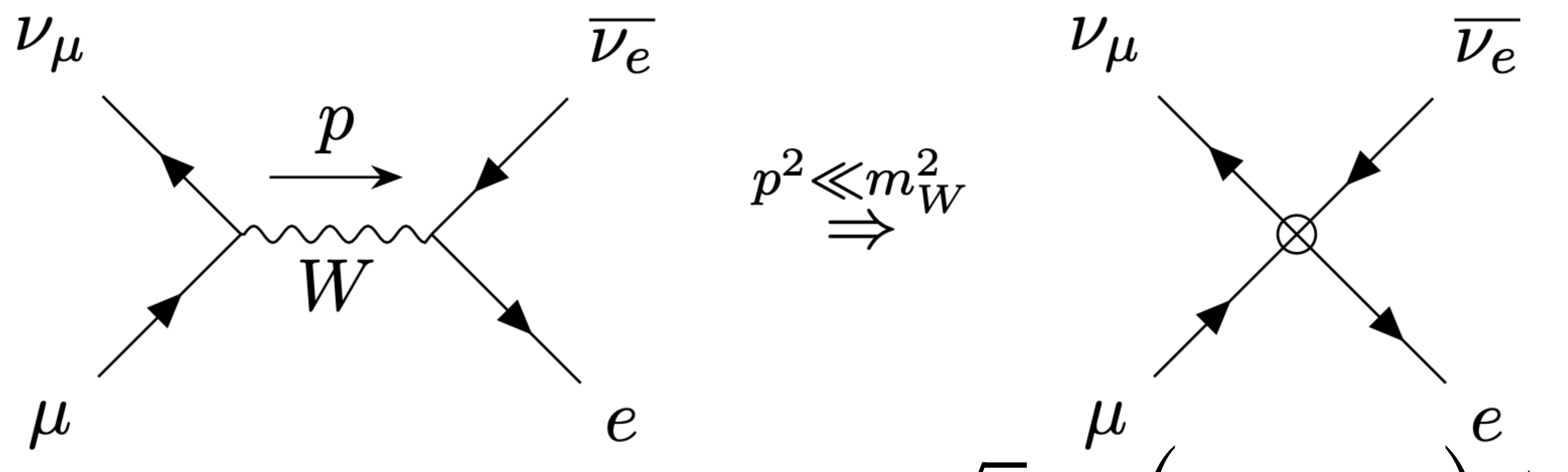

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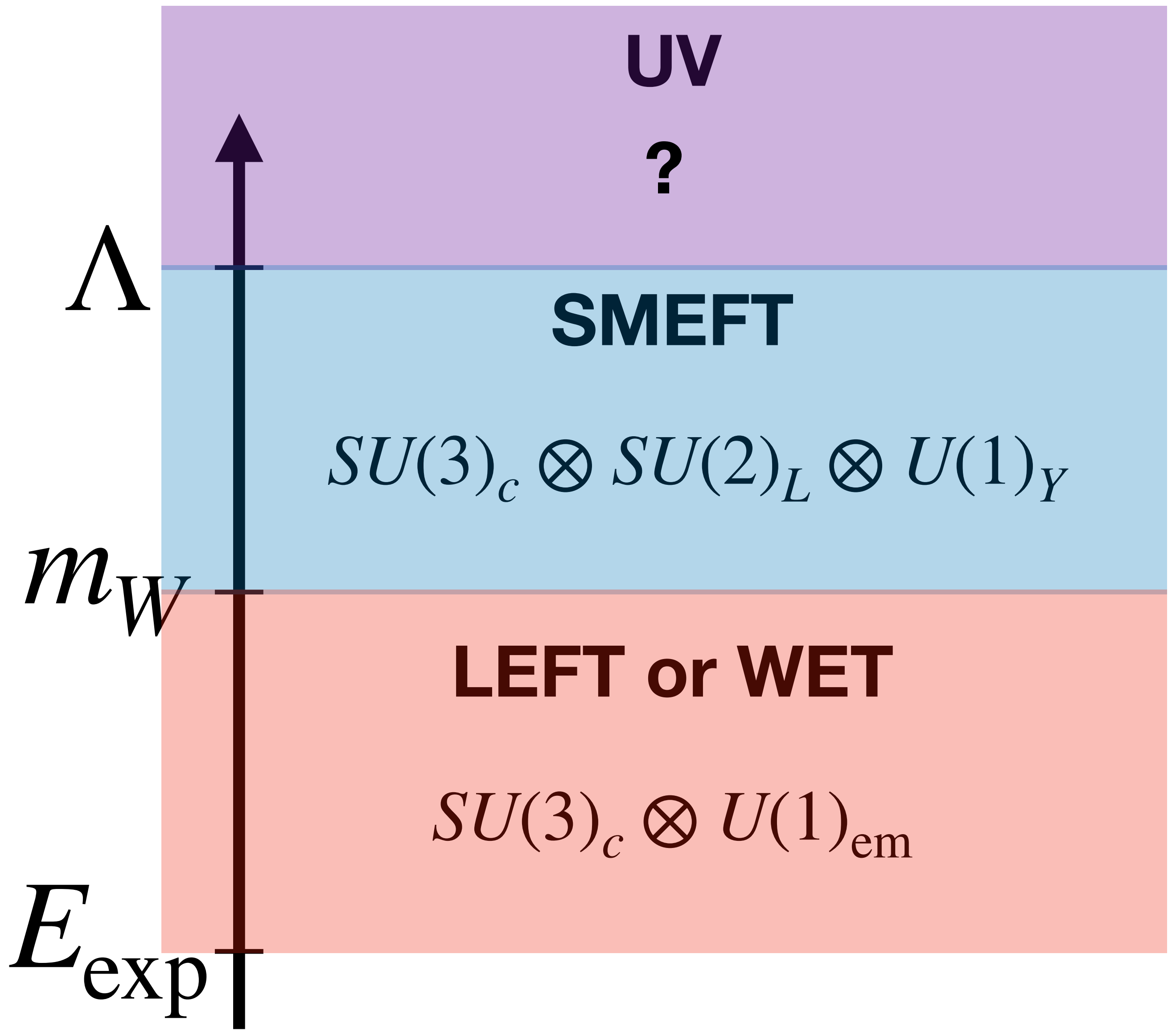
C_n **: Wilson Coefficients = short-distance heavy physics**

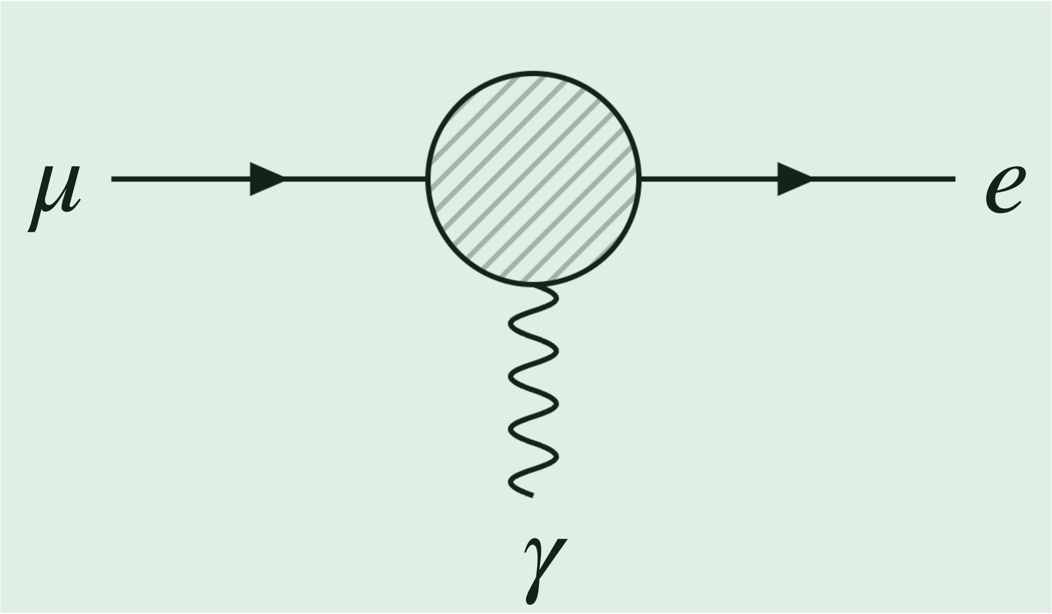
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{n>4} \frac{C_n \mathscr{O}_n}{\Lambda^{n-4}}$$

$\mathscr{O}_n$ **: Contact interactions among light fields**



EFT and LFV observables

- **Observables calculated in terms of the operator coefficients**



$$\delta\mathscr{L}_{\mu\to e\gamma} = \frac{m_\mu}{\Lambda^2}(C^{e\mu}_{D,R}\bar{e}\sigma_{\alpha\beta}P_R\mu + C^{e\mu}_{D,L}\bar{e}\sigma_{\alpha\beta}P_L\mu)F^{\alpha\beta}$$

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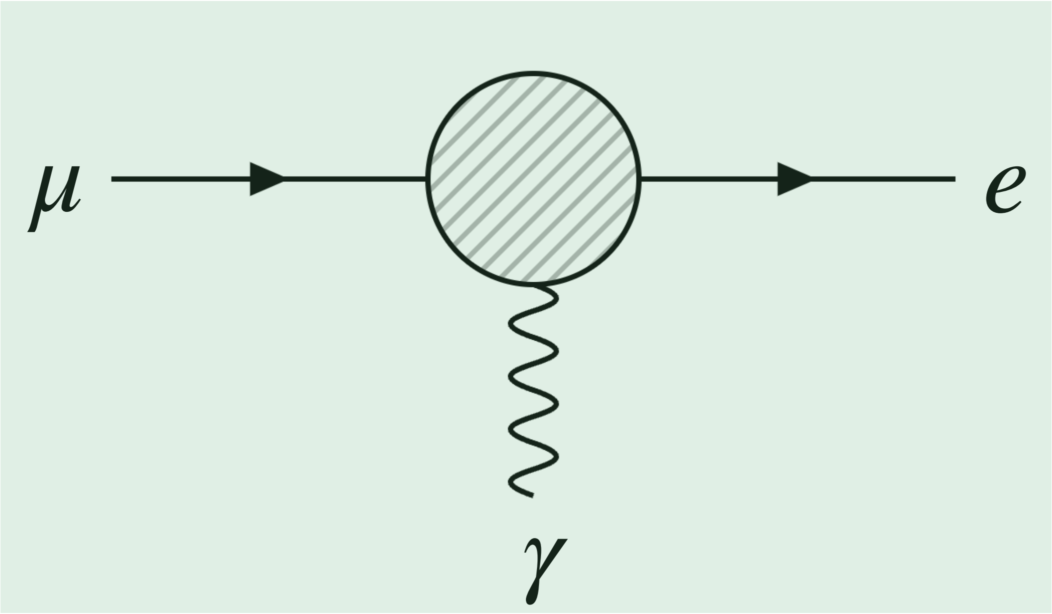

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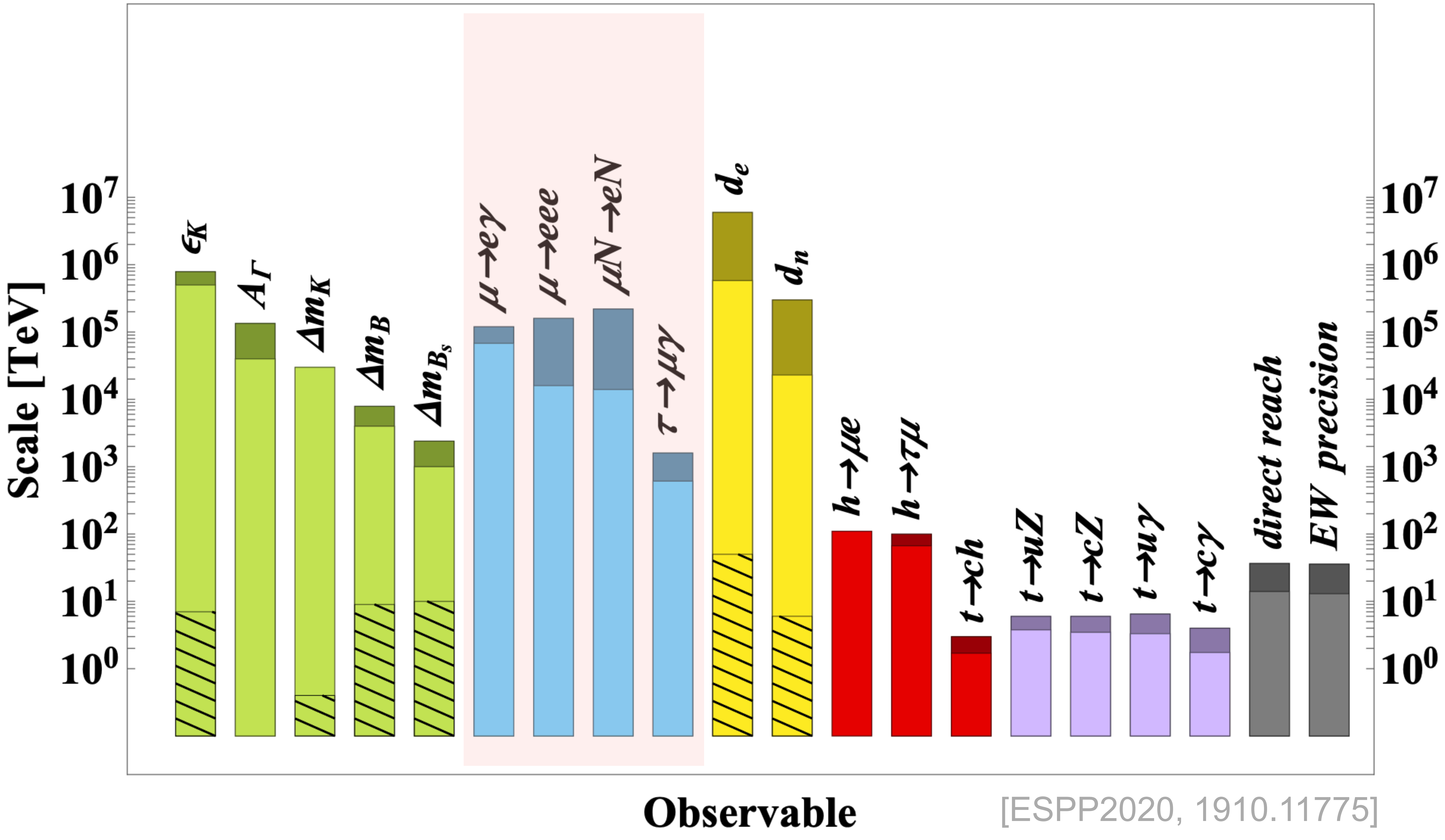
$$Br(\mu\to e\gamma) = 384\pi^2\left(\frac{v}{\Lambda}\right)^4(|C^{e\mu}_{D,R}|^2 + |C^{e\mu}_{D,L}|^2) < 1.5\times 10^{-13} \longrightarrow \left(\frac{v}{\Lambda}\right)^2|C^{e\mu}_{D,X}| < 10^{-8}$$

$v^2 = (2\sqrt{2}G_F)^{-1} \sim (174\text{ GeV})^2$

$\Lambda \gtrsim 10^4 v$ (if $C_D \sim 1$)

EFT and LFV observables

LFV observables sensitive to large New Physics scale



[ESPP2020, 1910.11775]

If NP is light

- Well motivated BSM scenarios predict **new states with light masses** (sub-electroweak)

- For instance, axions or ALPs are pseudo-Goldstones boson of spontaneously broken $U(1)$s = naturally light

- ALPs arise in many extension of the SM (and can be DM candidates or mediator)

- Flavour violating couplings arise when the $U(1)$ are non-universal (e.g flaxion/axiflavon)

[Ema et al, 1612.05492]
[Calibbi et al, 1612.08040]

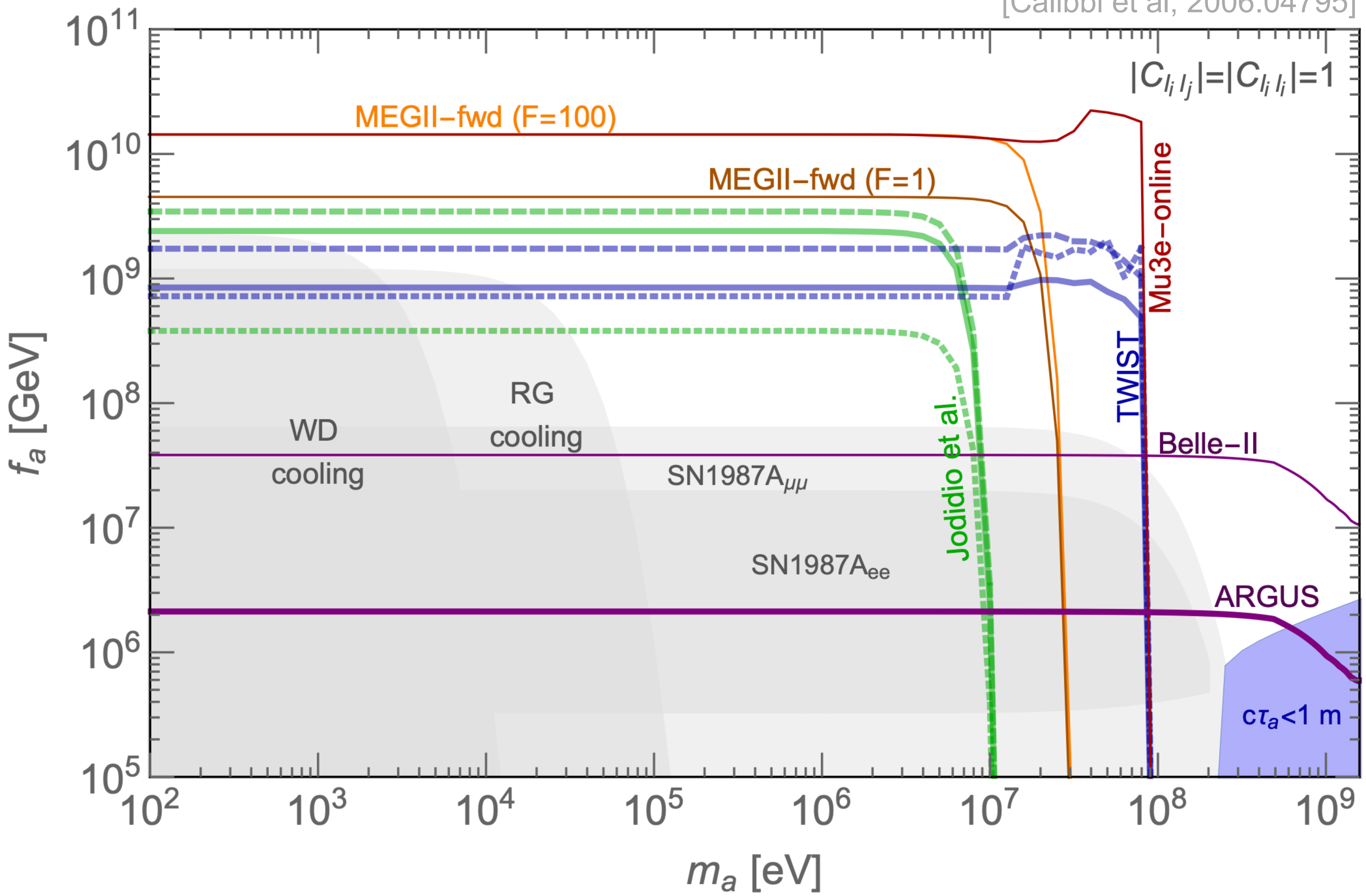
$$\mathscr{L}_{aff} = \frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu \left(C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5 \right) f_j$$

- If produced on shell (and does not decay visibly inside the detectors) possible signatures are

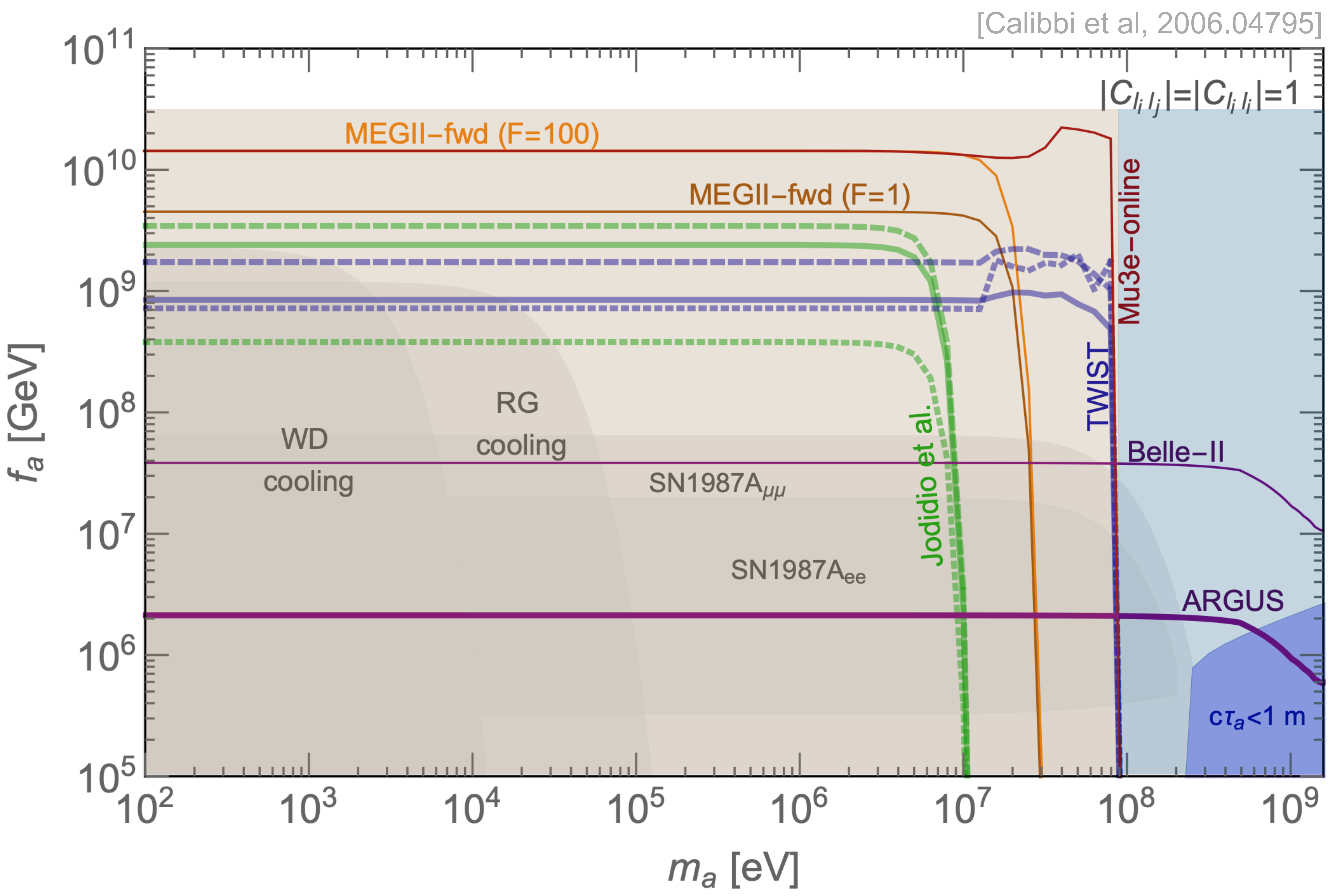
$$\tau \to l + \text{inv} \qquad \mu \to e + \text{inv}$$

LFV ALP Searches

[Calibbi et al, 2006.04795]



LFV ALP Searches



$\mu \to ea$

$\tau \to la$

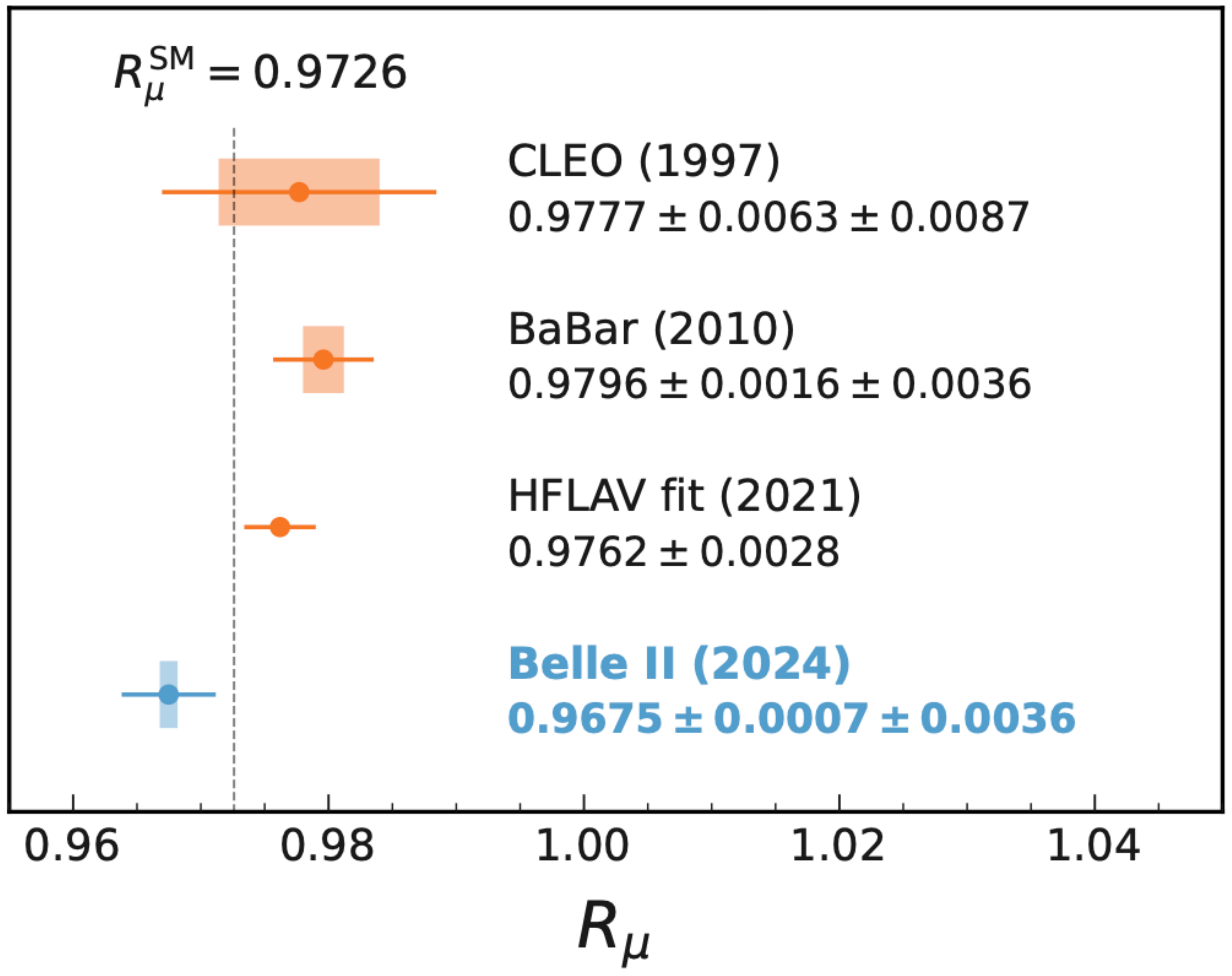
Lepton Flavour Universality in τ decays

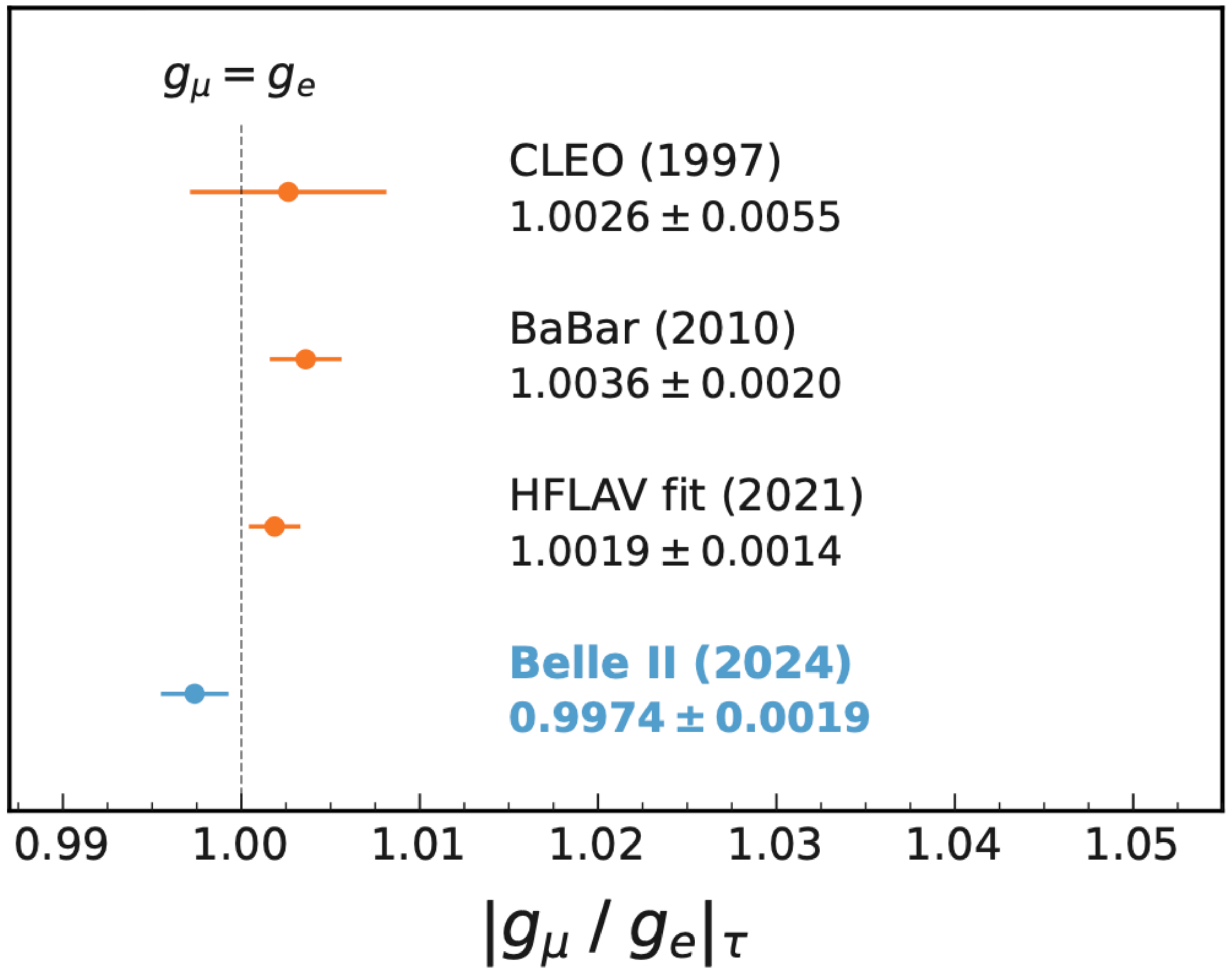
- Test $\mu - e$ universality in tau decays

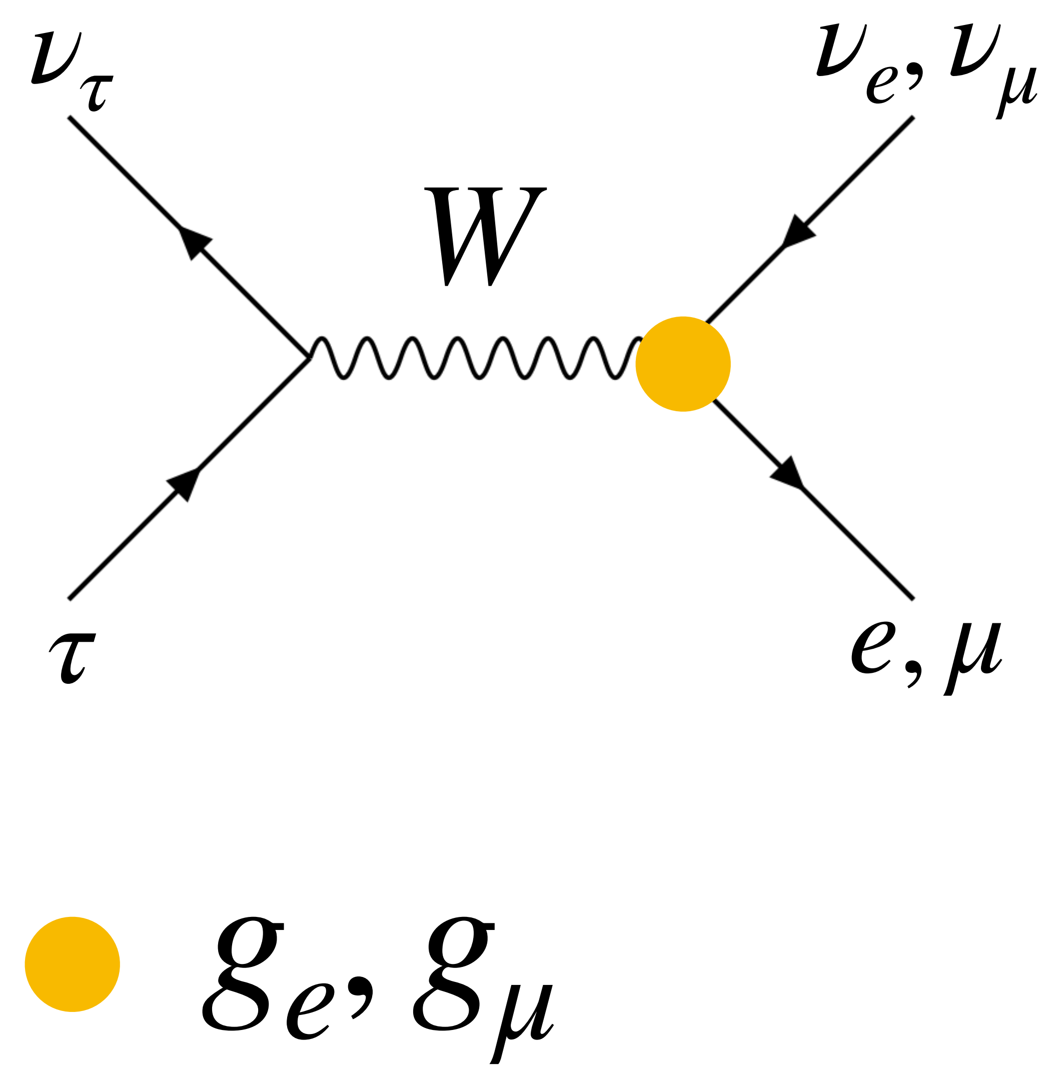
$$R_\mu = \frac{\mathrm{BR}(\tau \to \mu\nu\nu)}{\mathrm{BR}(\tau \to e\nu\nu)} = \frac{f\left(m_e^2/m_\tau^2\right)}{f\left(m_\mu^2/m_\tau^2\right)}\left(1 + \Delta_{\mathrm{QED}}\right)$$

- Phase space and QED corrections are known with incredible precision

[Belle II, 2405.14625]



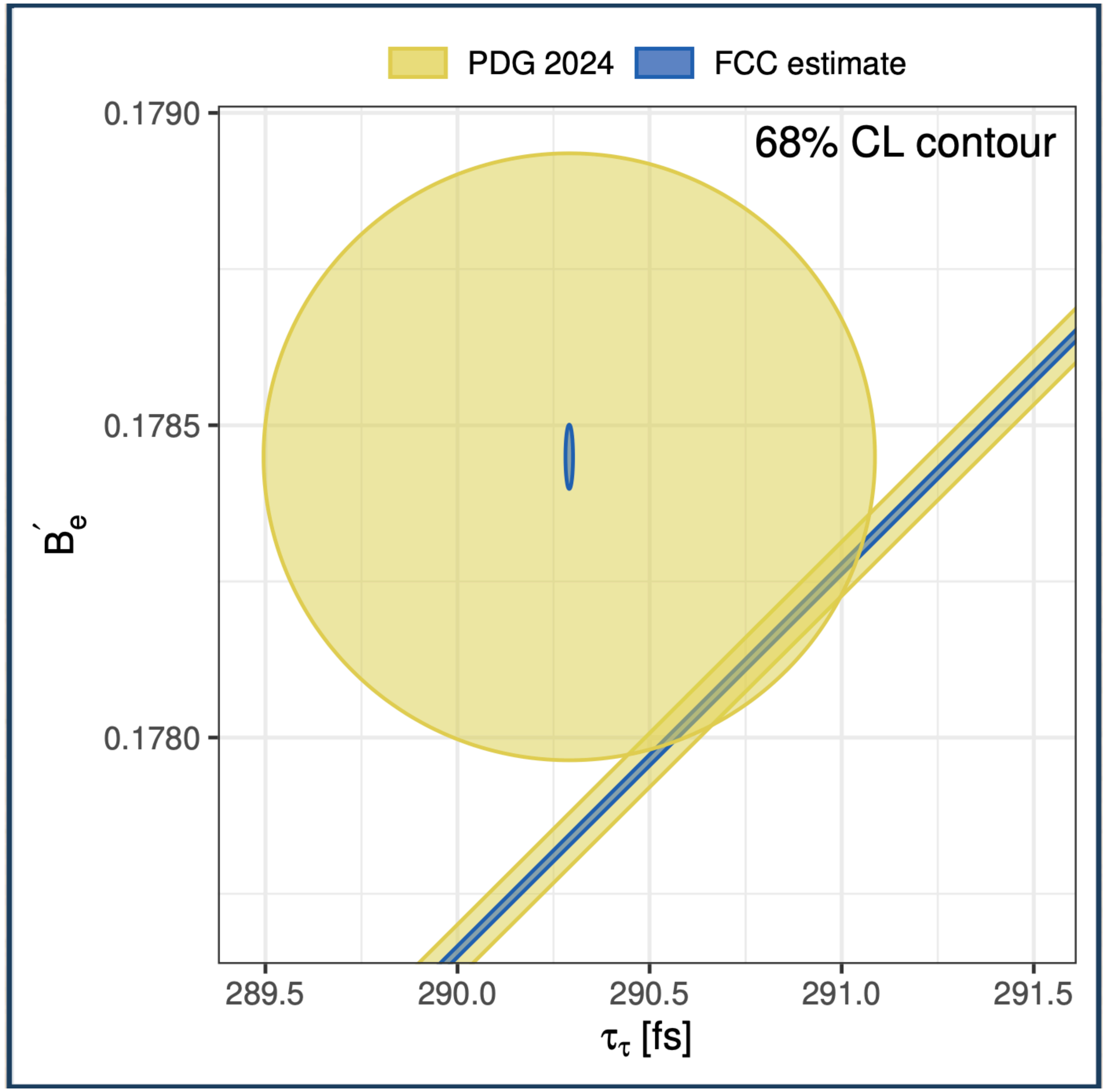




Lepton Flavour Universality in τ decays

- Can also test universality by normalizing to muon decays

[Lusiani @FCC Italy & France Workshop 2024]



$$B'_e = \mathrm{Br}(\tau \to e\bar{\nu}\nu) \sim \mathrm{Br}(\mu \to e\bar{\nu}\nu)\frac{m_\tau^5}{m_\mu^5}\frac{\tau_\tau}{\tau_\mu} \times \left(\frac{g_\tau}{g_\mu}\right)^2$$

- Consistent with universality

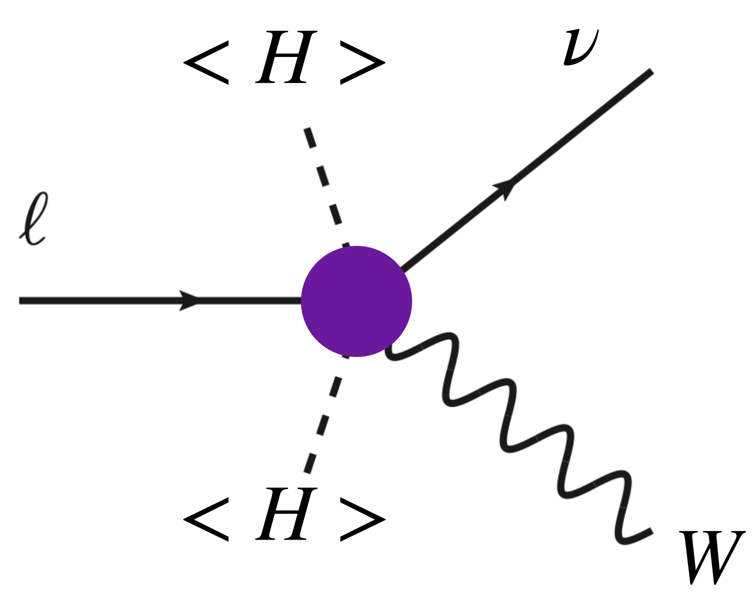
[HFLAV 2023]

$$(g_\tau/g_\mu) = 1.0017 \pm 0.0013$$

- FCC could significantly improve the precision on the tau mass, lifetime and decay branching ratios

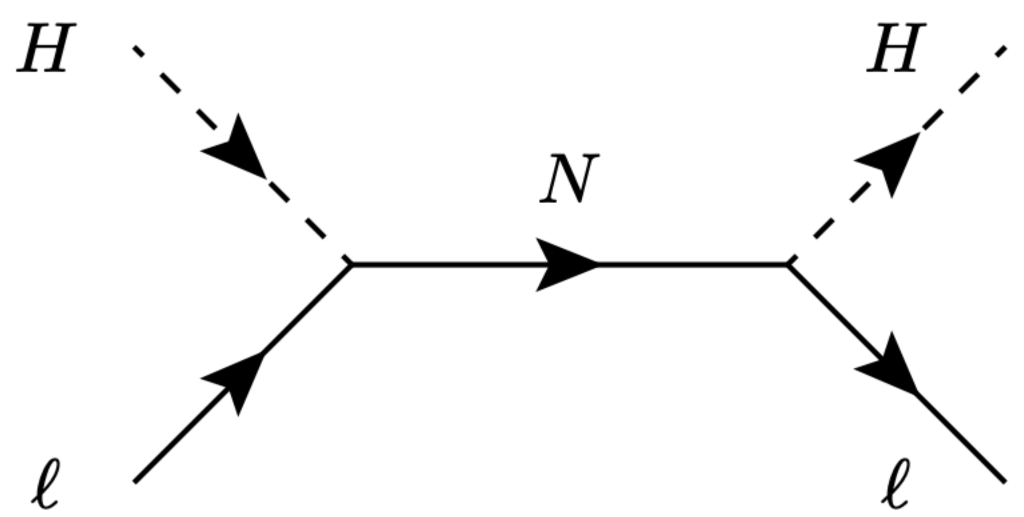
LFU tests with τ-s and NP models

- They can probe modified W couplings

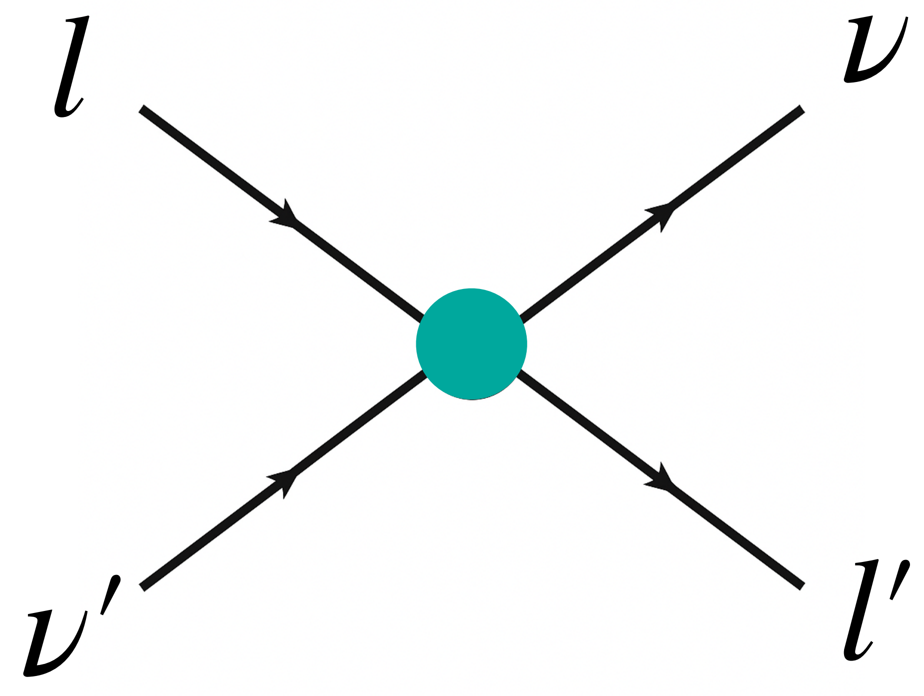


$\Leftarrow$

Ex: Type-I seesaw



- But can also be sensitive to new four fermion interactions



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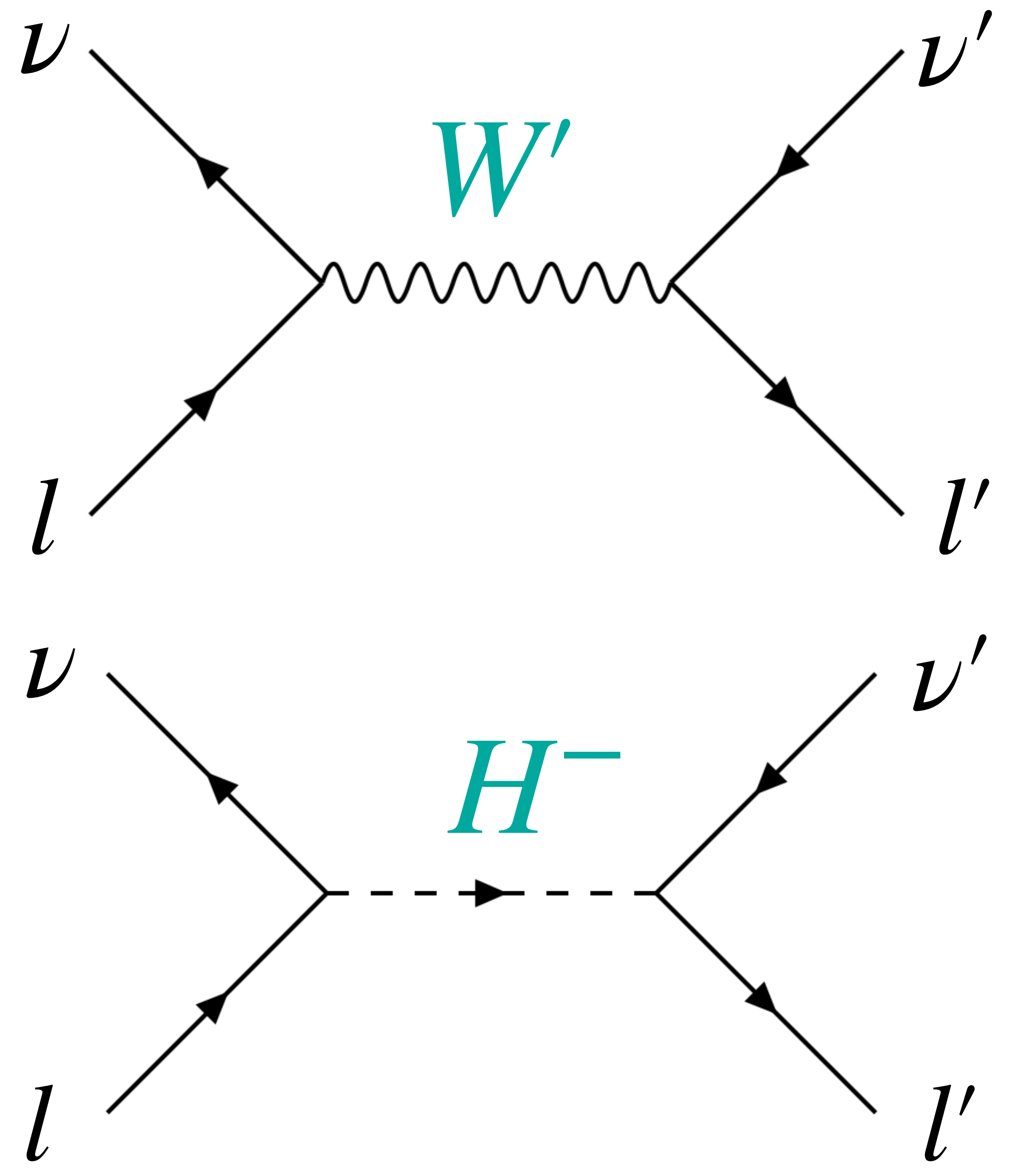

Ex: 331 or Left-Right Sym model

Ex: Two Higgs Doublet model

Conclusions

- **Lepton Flavour Violation** must exist, as established by neutrino oscillations.
- **Observation of LFV in the charged lepton sector** would be a clear, smoking-gun signature of new physics.
- **Muon LFV experiments** will improve sensitivities by several orders of magnitude in the coming years.
- **Tau LFV decays** are being probed at Belle II with enhanced sensitivity, and are expected in scenarios where NP couples preferentially to the third generation.
- **Lepton Flavour Universality tests** provide complementary probes of NP, and in combination with LFV searches can help discriminate among different models.

LFU Violation and LFV

$U(3)_\ell \times U(3)_e \to U(1)_e \times U(1)_\mu \times U(1)_\tau$ By the **LFU violating SM Yukawa**

- Any source of additional LFU violation that is misaligned with the Yukawa leads to LFV

$$U(1)_e \times U(1)_\mu \times U(1)_\tau \to \text{LFV}$$

- But NP may be:
  - (approximately) aligned (Minimal Flavour Violation-like or $U(2)$ symmetric)
    [Greljo, Isidori, Marzocca 1506.01705, …]
  - Or stem from gauge invariant extension that share the same accidental symmetry
    Eg. Models with gauged $L_i - L_j$ [Alonso, Grinstein, Martin-Camalich 1505.05164] [Altmannshofer, Davighi, Nardecchia 1909.02021]

- **LFU≠LFV**, but could be related. **Searches are highly completementary and can distinguish NP scenarios**

$\tau \to (e, \mu)$ LFV

$\mathscr{L}_{\text{Yukawa}} \supset y_\alpha \bar{\ell}_\alpha H e_\alpha + \text{h.c}$ **But** $y_e, y_\mu \ll y_\tau$

SM Lagrangian respect an approximate $U(2)$ symmetry acting on the first two generation

If the **NP respect this symmetry** (couples dominantly to third generation), **may expect preferably τ LFV**

Flavour symmetries in connection to the Flavour Puzzle **may lead to residual symmetries that favor $\tau \to l$**

Ex: **Lepton Flavour Triality** [Ma, 1006.3524]

$\ell_\alpha \to \left(e^{i\frac{2\pi}{3}}\right)^{T_\alpha} \ell_\alpha$

$T_e = 1$

$T_\mu = 2$

$T_\tau = 3$

$\mu^- \to e^- \gamma$: $T_\mu = 2$, $T_e = 1$, $\Delta T \neq 0$

$\tau^- \to \mu^+ e^- e^-$: 3, -2, $+1$, $+1$, $\Delta T = 0 \mod 3$

See also [Calibbi et al, 2505.24350]