Panel discussion:

BSM and LFV searches with τ's

Olcyr Sumensari

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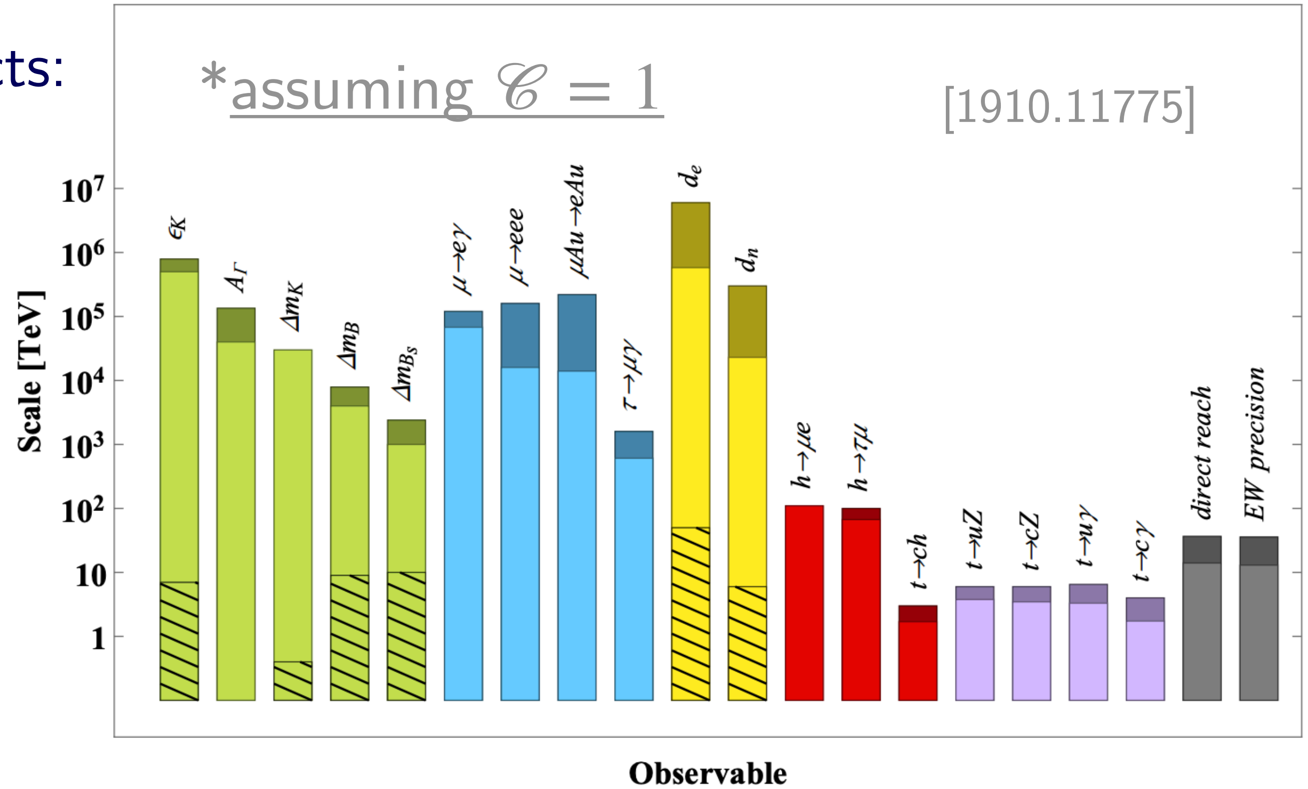
Belle II Physics Week, October, 2024

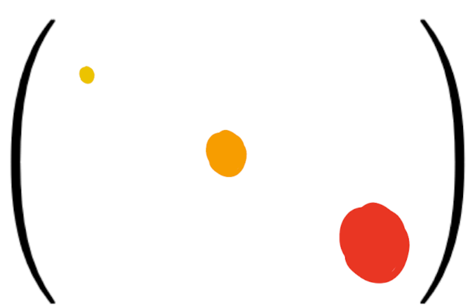
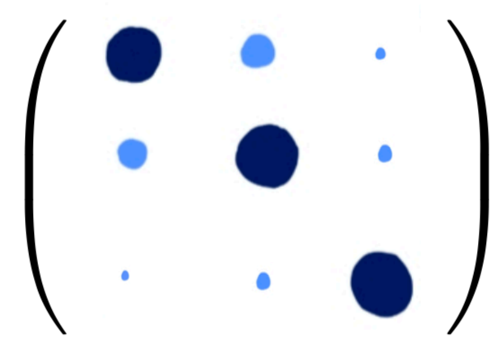
The Precision Frontier

- **Powerful indirect probe** of **New Physics** effects:



EFT constraints on the scale of New Physics (i.e., Λ/g_{NP})

- **What is the scale of New Physics?**
  - If we **naively** assume NP to be **flavor blind**, then constraints from $\mu \to e$ processes or $K^0 - \overline{K}^0$ mixing would be far more constraining than any τ observables...
  - However, the **SM Yukawa sector** has a very **peculiar structure** (Why? ⇒ Flavor Problem).

$M_{u,d,\ell} =$  $V_{\mathrm{CKM}} =$ 

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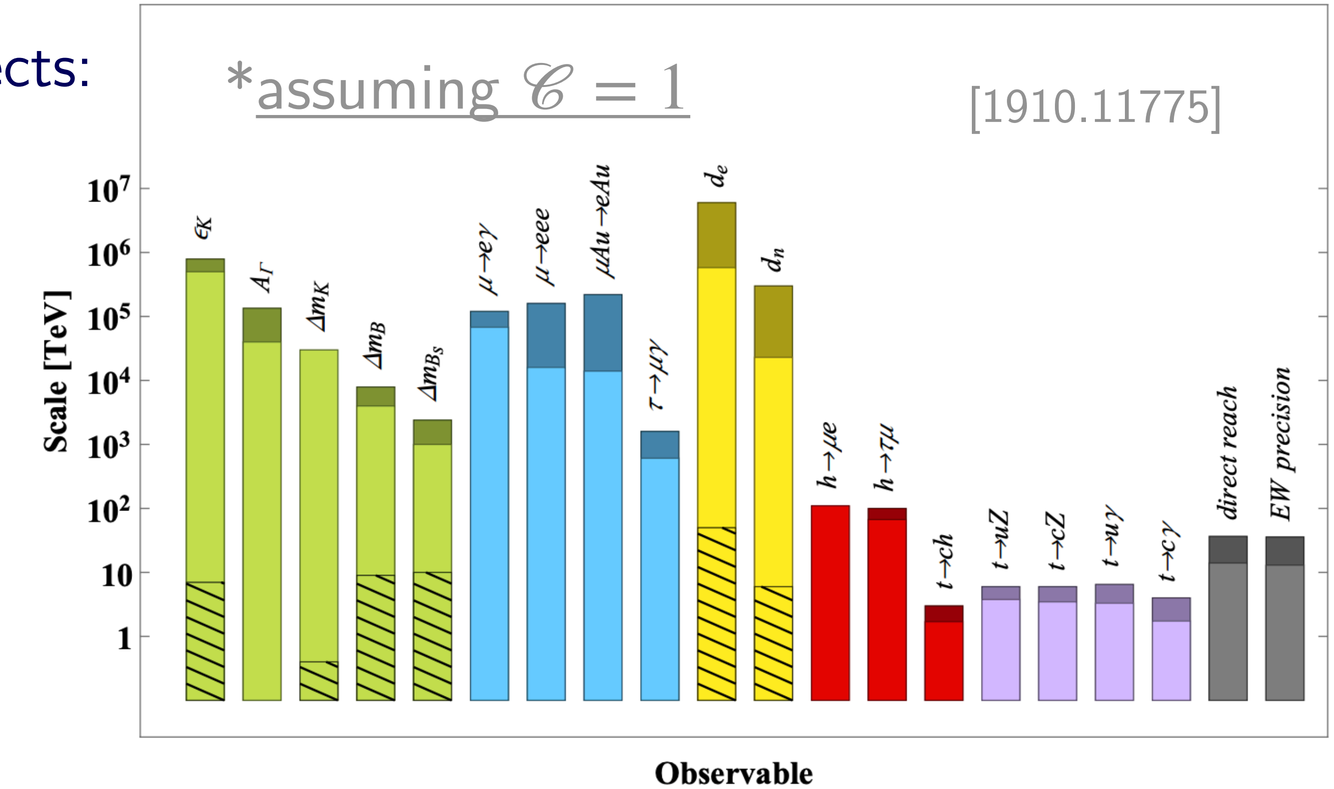

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NP could also have a **hierarchical flavor structure!** that would **suppress flavor-changing processes** with **light generations** *(e.g., in scenarios with an approximate $U(2)^5$ symmetry).*

[Barbieri et al. '11], [Faroughy et al. '20], [Allwicher et al. '23]

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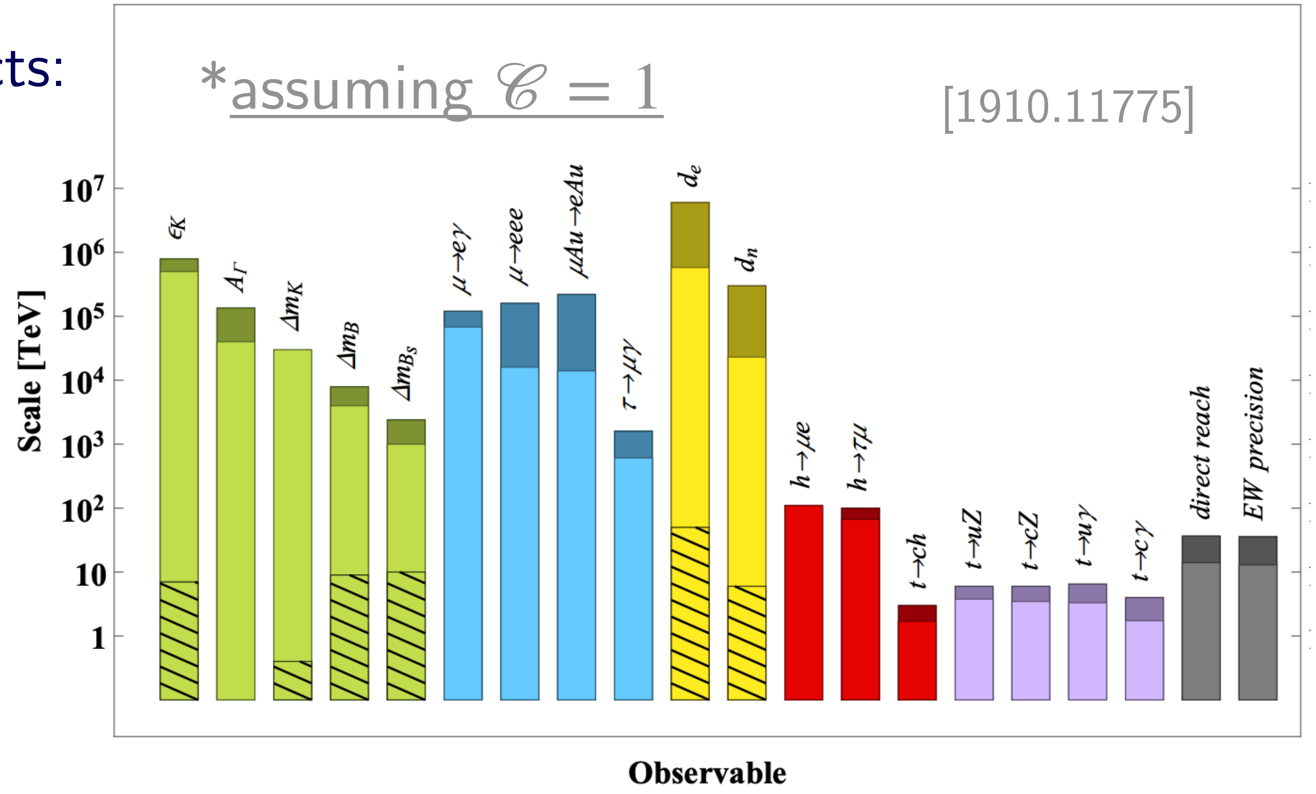

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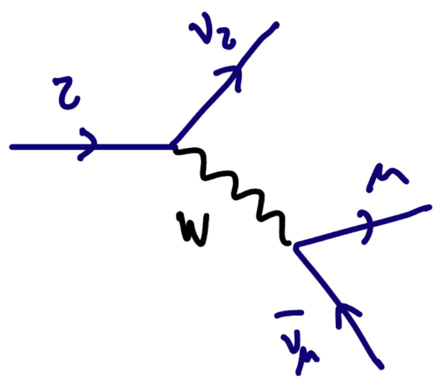
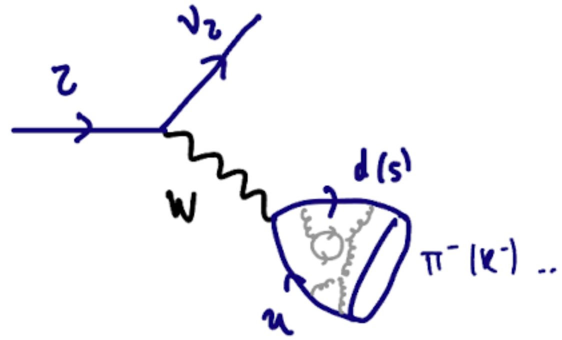
More generally, exploring τ-**lepton physics** is **fundamental** to **probe** the **(unknown) flavor structure** of physics **beyond the SM**!

Precision physics with τ's

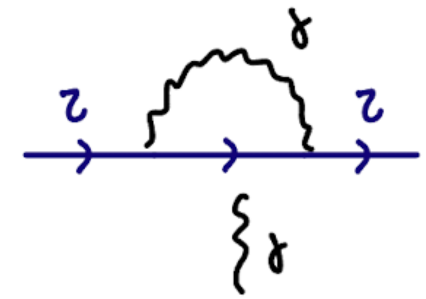
- **Search for deviations w.r.t. the SM predictions:**



$\tau \to \ell \nu \bar{\nu}$



$\tau \to \nu P$



τ-dipoles

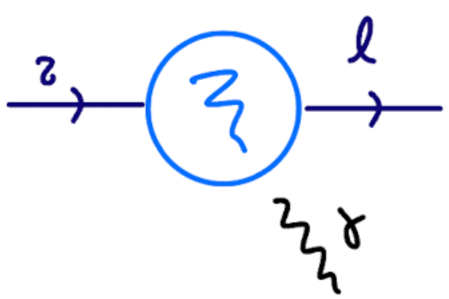
...

$$O_{exp} = O_{SM} \left(1 + \# \frac{C}{\Lambda^2} + \dots \right)$$

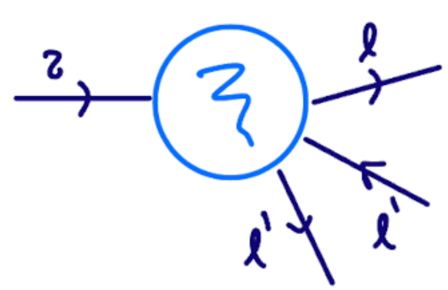
High precision/accuracy needed!

See talks by Roig, Bruno, Hoferichter and Passemar

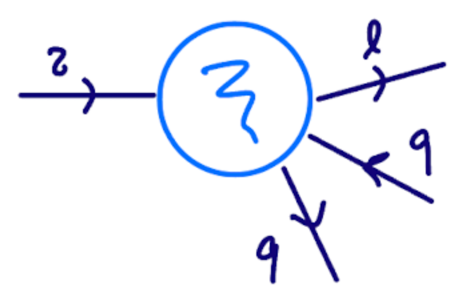
- **Search for forbidden SM processes *(by accidental symmetries)*:**



$\tau \to \ell \gamma$



$\tau \to \ell \ell' \ell'$



$\tau \to \ell + \text{had}$

...

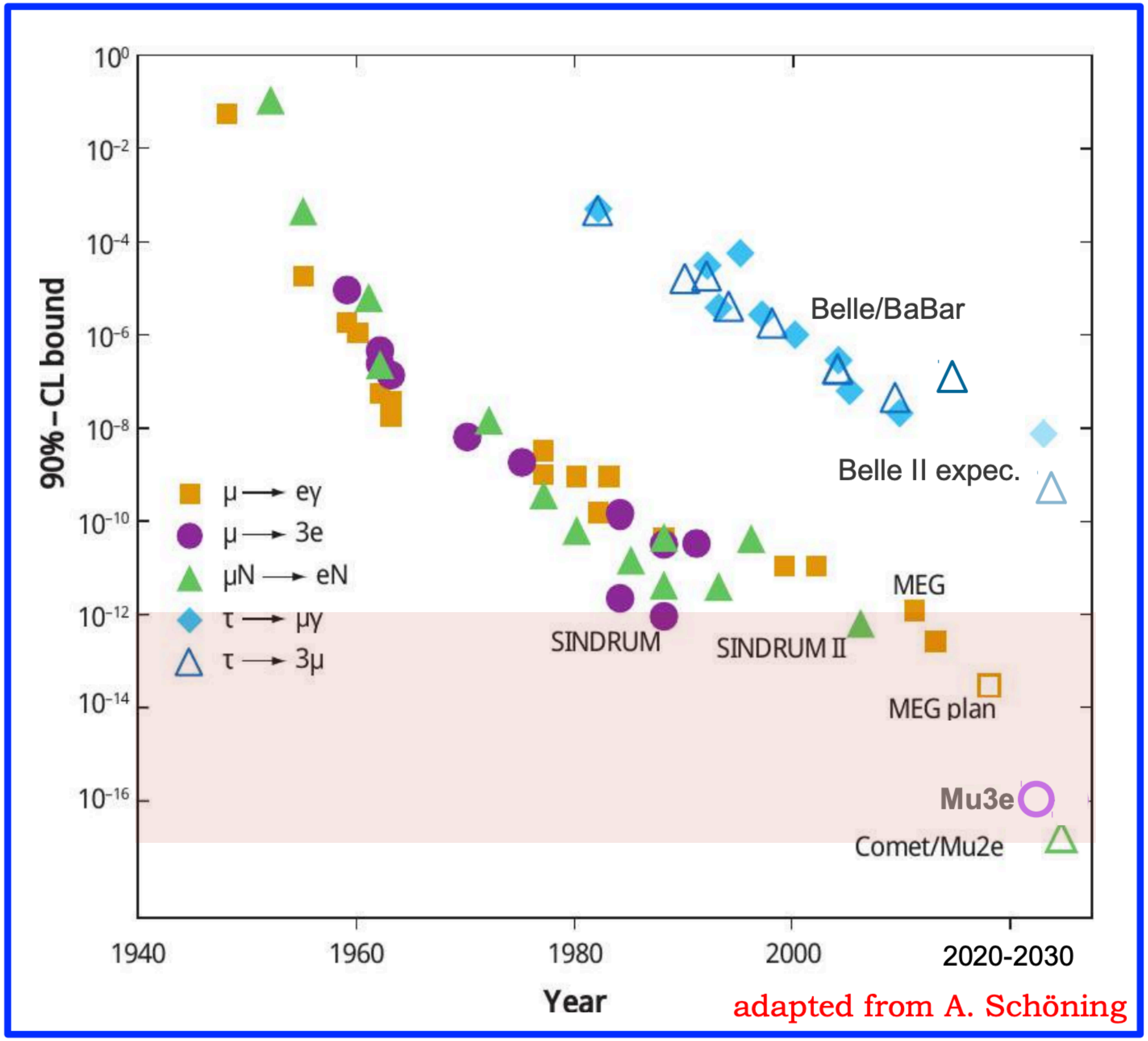
$U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

$\Rightarrow$ Very clean probes of New Physics!

See talks by Ardu, Calibbi and Zupan

Charged LFV searches

[From Calibbi's talk]



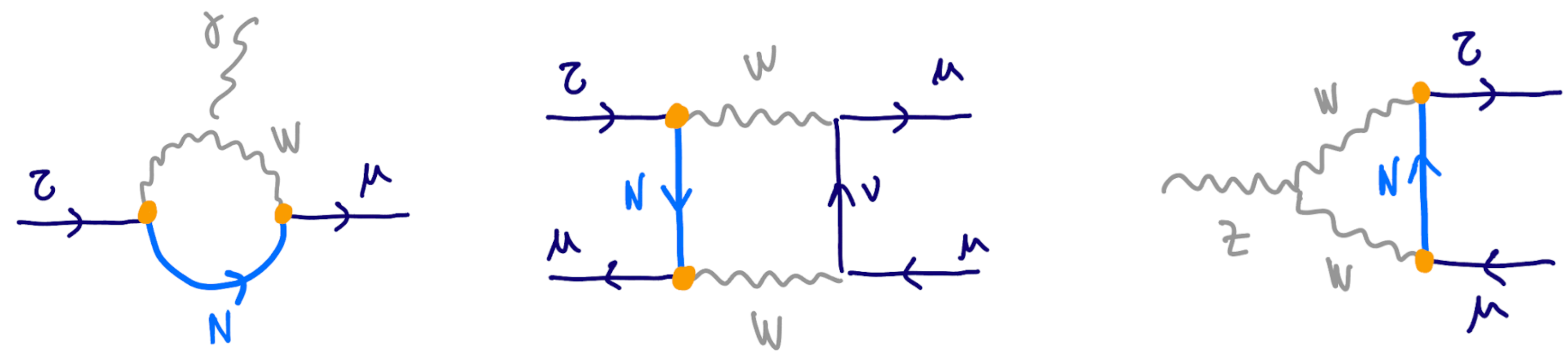
$\approx 10^3$ **improvement!**

There will be a **huge improvement** in sensitivity in $\mu \to e$ experiments — it is fundamental to improve τ**-data** too (complementarity)!

Complementarity

Concrete models predict **correlations** between different observables:

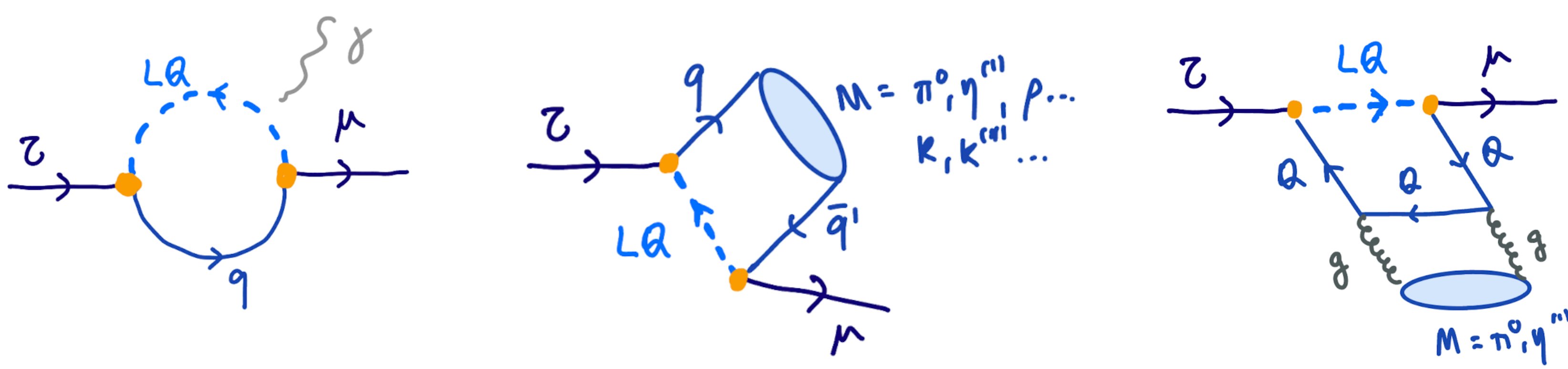
- **Heavy neutrinos:**



...

[Ilakovac et al. '94], [Abada et al. '14]...

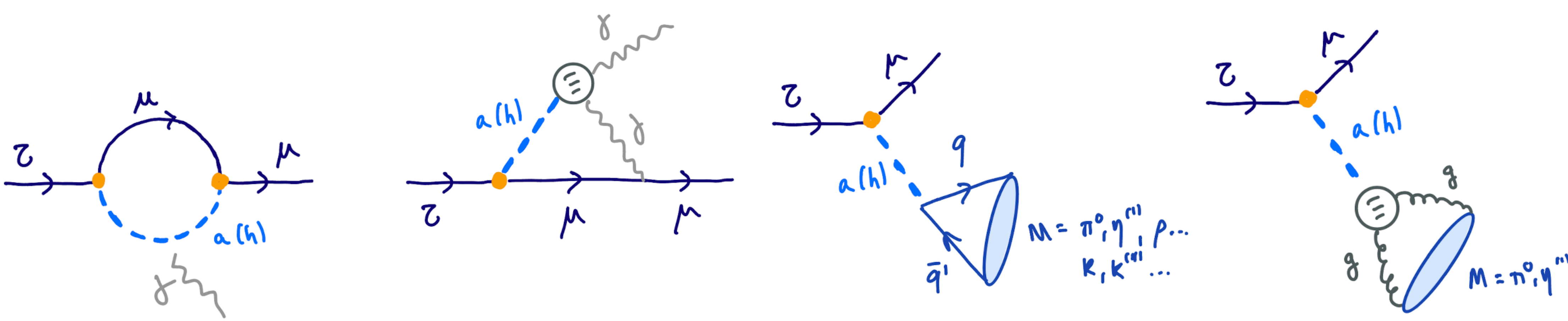
- **Leptoquarks:**



...

[Petrov et al. '13], [Becirevic et al. **(OS)**, '16], [Dorsner et al. '16]...

- **ALPs (or Higgs):**



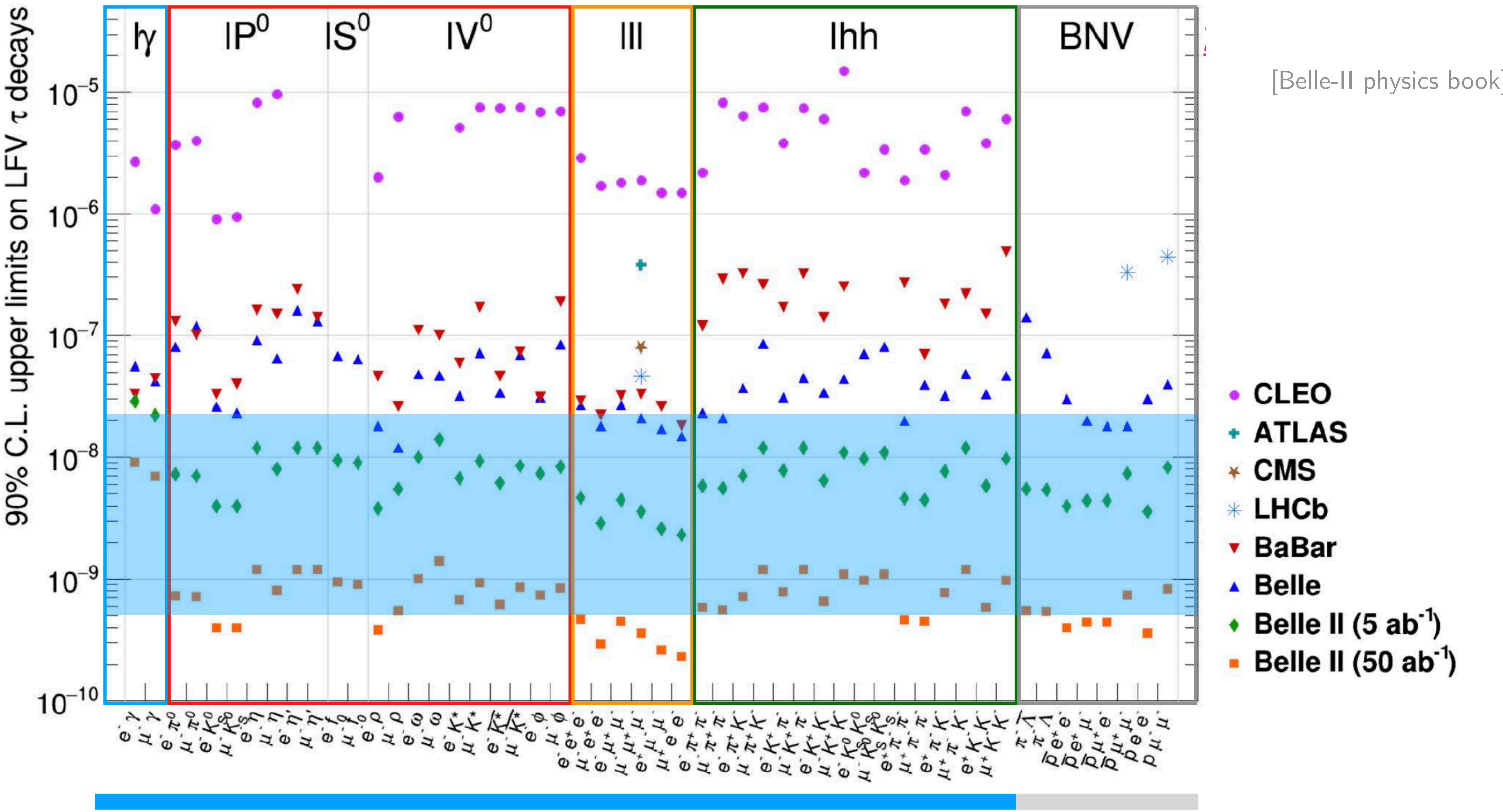
...

...

[Han et al. '08], [Harnik et al. '12], [Blankenburg et al. '13]... [Cornella, Paradisi, **OS**. '19]...

Belle-II and τ-decays

Belle-II will **improve** the **sensitivity** on $\tau \to e$ and $\tau \to \mu$ decays by a **factor** $\mathcal{O}(10)$:



LFV decays **BNV decays**

Discussion

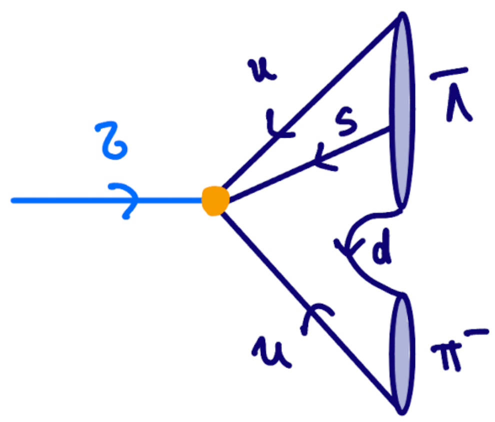
I. Should we look for BNV in τ-decays?

The lowest-order operators that violate B in the SM appear at $d = 6$: [Weinberg, '79]

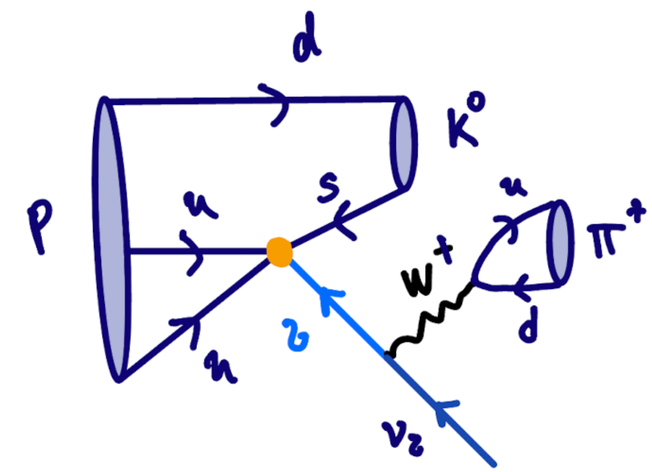
$O_1 \sim QQQL$ $\quad$ $O_2 \sim QQue$ $\quad$ $O_3 \sim Qu_R d_R L$ $\quad$ $O_4 \sim u_R u_R d_R e_R$

They could *in principle* induce BNV τ-decays depending on their flavor content:

e.g.,



vs.



$$\mathscr{B}(\tau^- \to \overline{\Lambda}\pi^-) \simeq \tau_\tau \frac{m_\tau^5}{(4\pi)^2} \frac{|\mathscr{C}|^2}{\Lambda^4} \overset{\text{exp}}{\lesssim} 1.8 \times 10^{-8}$$

[Belle, '20]

$$\Rightarrow \quad \Lambda/|\mathscr{C}| \gtrsim 20~\text{TeV}$$

$$\Gamma(p \to K^0\pi^+\nu) \simeq \frac{m_p^{11}}{(4\pi)^3} \frac{G_F^2}{m_\tau^2} \frac{|\mathscr{C}|^2}{\Lambda^4} \overset{\text{exp}}{\gtrsim} (10^{30}~\text{year})^{-1}$$

[PDG]

$$\Rightarrow \quad \Lambda/|\mathscr{C}| \gtrsim 10^9~\text{TeV}$$

Caution: the same operators that generate **BNV τ-decays** may also induce the **proton decay** *(via an insertion of G_F or EW loops)* — **potentially much more constraining**!

see [Beneke et al. '24] for a discussion of B-meson BNV decays

II. EFTs and Dalitz plot

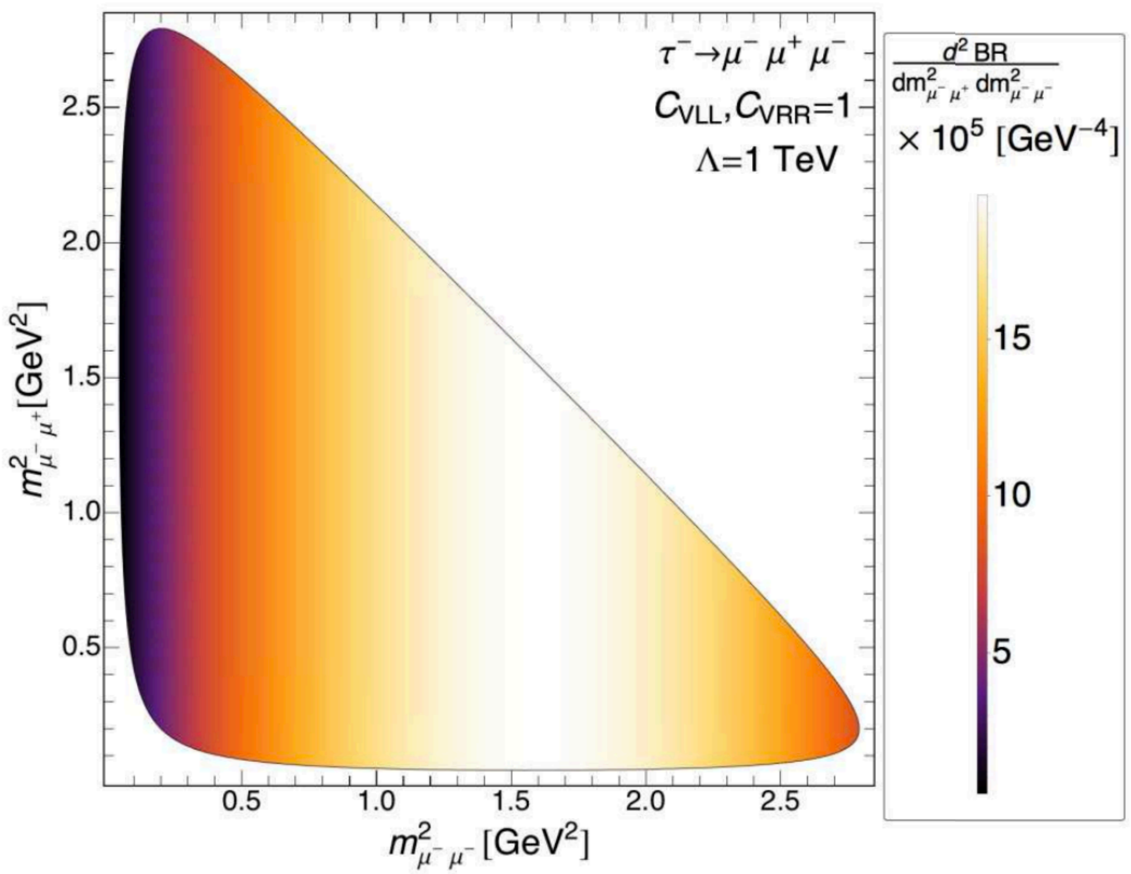
See talk by Ardu!

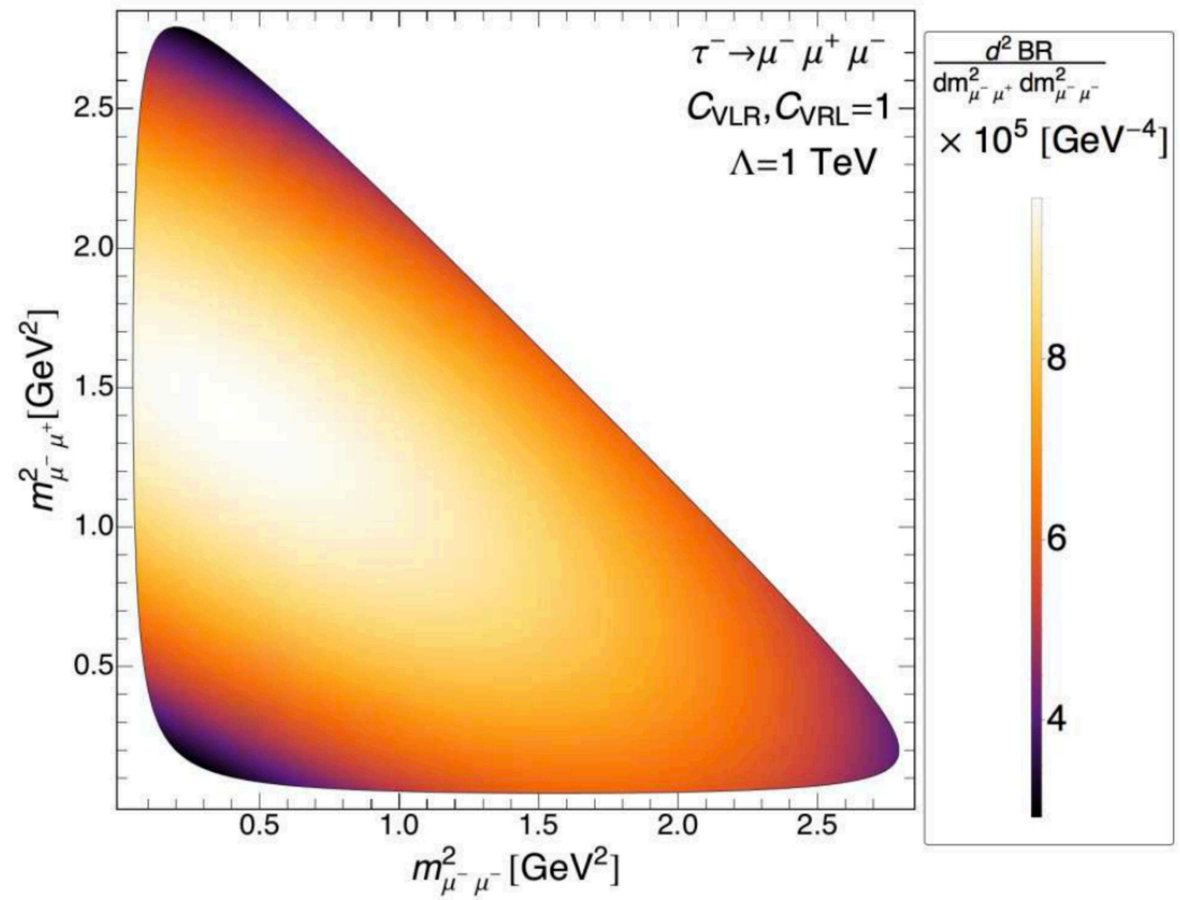
Which Lorentz structure?

[Dassinger et al. '07]

$$\mathscr{L}_{\text{EFT}} \supset \frac{1}{v^2}\Big[C_{VLL}\,(\bar{\mu}\gamma^{\mu}P_L\tau)(\bar{\mu}\gamma_{\mu}P_L\mu) + C_{VLR}\,(\bar{\mu}\gamma^{\mu}P_L\tau)(\bar{\mu}\gamma_{\mu}P_R\mu)\Big] + (L \leftrightarrow R) + \text{h.c.}$$

[Celis et al. '14]





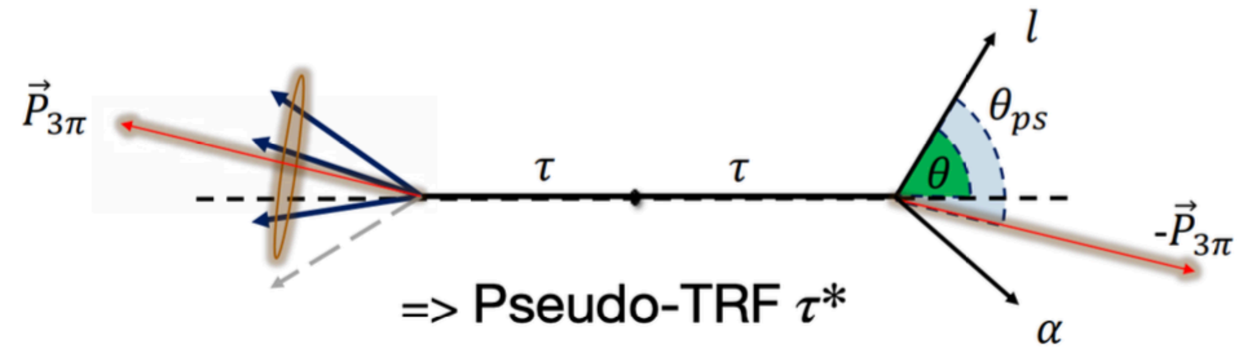
Question: Which **EFT scenario** is used in the **MC simulation**? Can/should we further exploit this information experimentally?

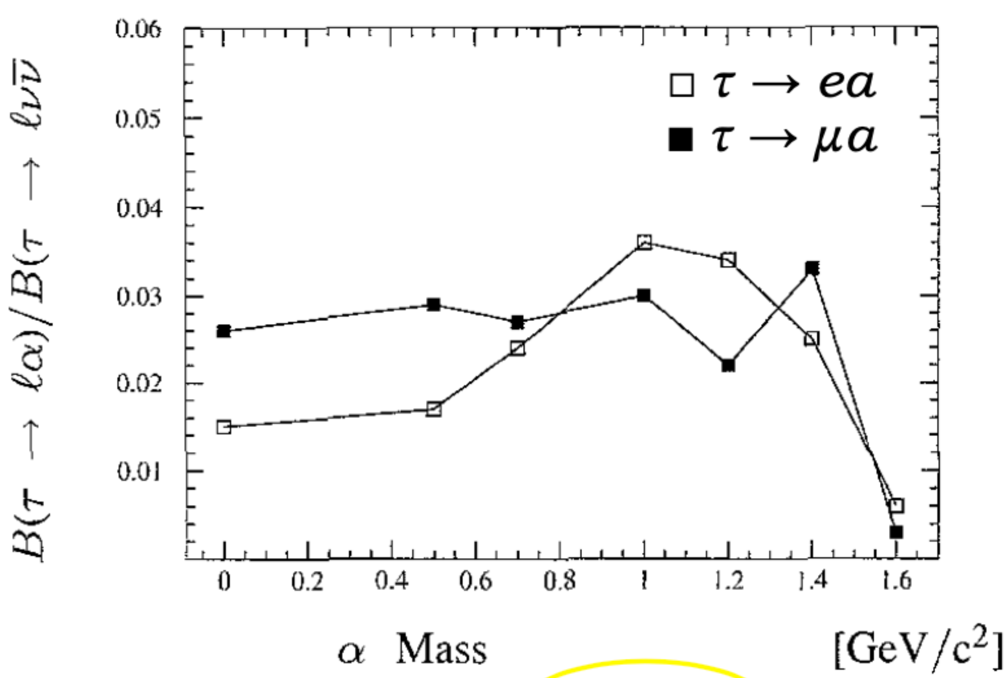
III. Beyond the SMEFT

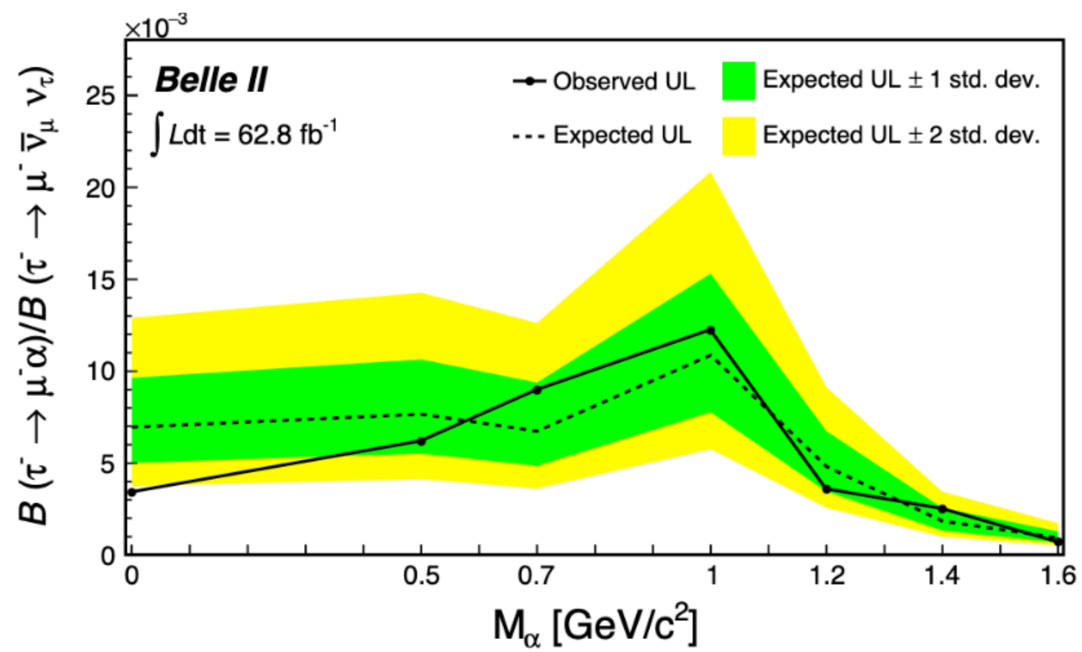
See talk by Lorenzo!

Present limits on $\tau \to e\, a$, $\tau \to \mu\, a$ (invisible a)

A challenging search:
tau momentum / rest frame
cannot be exactly reconstructed
BG: ordinary $\tau \to \ell\nu\bar{\nu}$







ARGUS 1995 (472 pb^{-1}) → Belle II 2023 (62.8 fb^{-1})

up to O(10) improvement!

$m_a \approx 0$:

$$\mathrm{BR}(\tau \to \mu\, a) < 4.7 \times 10^{-4}\ (90\%\ \mathrm{CL}) \quad \Rightarrow \quad f_a/C^{V,A}_{\mu\tau} > 5.1 \times 10^6\ \mathrm{GeV}$$

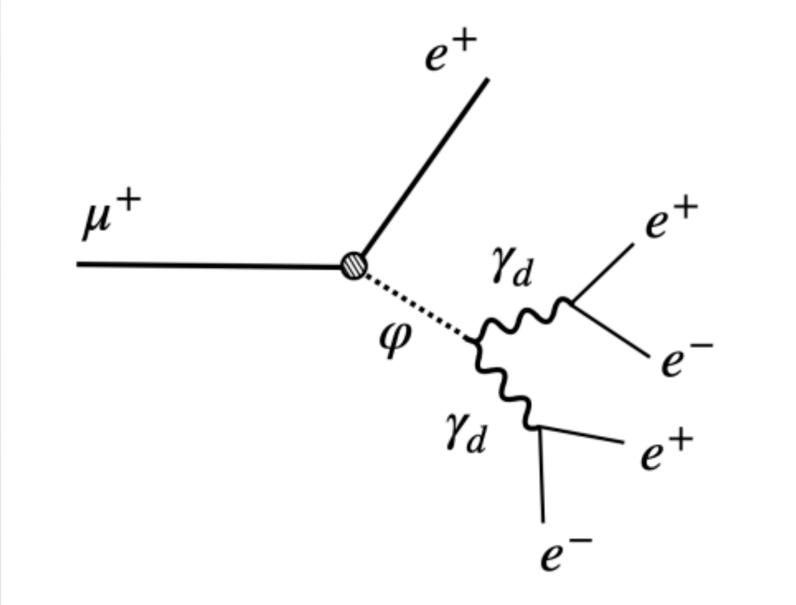
$$\mathrm{BR}(\tau \to e\, a) < 7.6 \times 10^{-4}\ (90\%\ \mathrm{CL}) \quad \Rightarrow \quad f_a/C^{V,A}_{e\tau} > 4.0 \times 10^6\ \mathrm{GeV}$$

Other channels to be explored?

IV. New ideas

$\mu \to 5e$

- if $\frac{m_\mu}{\Lambda}\phi(\bar{e}\mu)$ coupling $\Rightarrow$ mediates $\mu \to e\varphi$
  - if φ QCD axion $\Rightarrow$ escapes the detector $\mu \to e + \text{inv}$
    - MEG-II, Mu3e, Mu2e-X, COMET-X can search for it
  - if φ can decay $\Rightarrow$ sensitivity to even higher scales
    - example: $\mu \to 5e$ can probe $f_a \gtrsim 10^{13}$GeV



Hostert, Menzo, Pospelov, JZ, 2306.1563

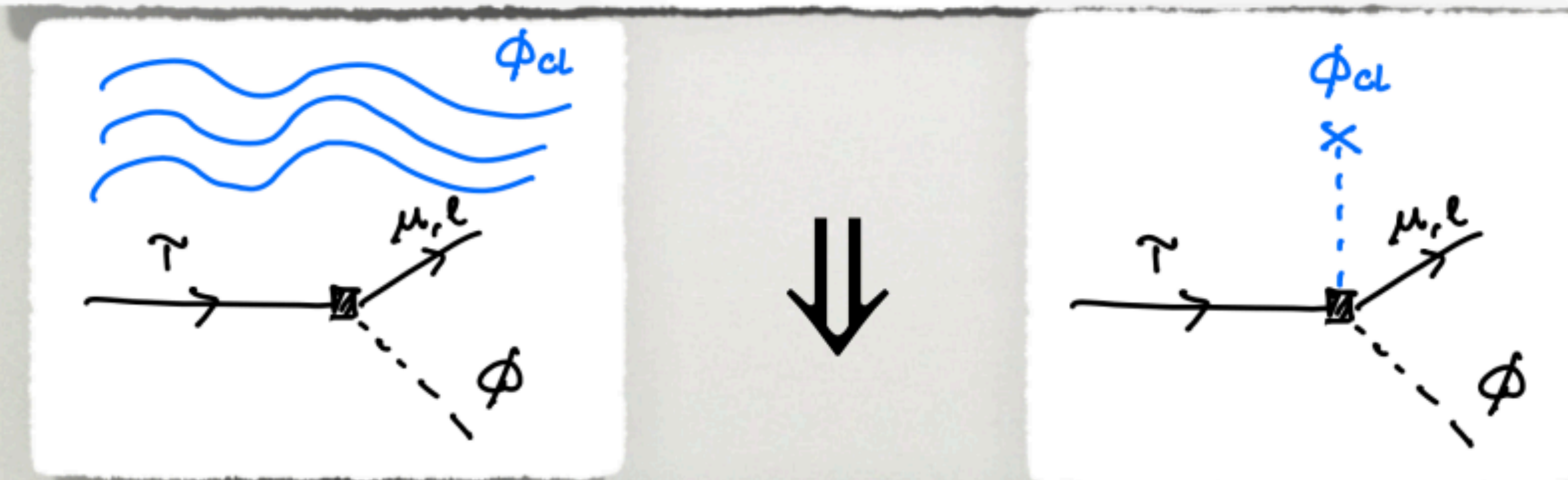
Can we do the same for τ's?

See talk by Jure!

NON-ABELIAN PNGB

- in the light DM background

$$\mathcal{L}_{\rm int} \supset \sum_a \frac{\phi_a}{f}\frac{i\partial_\mu \phi_a}{f}\bar{\psi}_i\gamma^\mu(C^V_{\psi_i\psi_j} + C^A_{\psi_i\psi_j}\gamma_5)\psi_j + \text{h.c.},$$



$$\mathcal{L}_{\rm int} \supset \frac{\phi_{a,\rm cl}}{f}\frac{i\partial_\mu \phi_a}{2f}\bar{\psi}_i\gamma^\mu(C^V_{\psi_i\psi_j} + C^A_{\psi_i\psi_j}\gamma_5)\psi_j + \text{h.c.}$$

- induces time dependent FCNCs
- example: $Br(\tau \to \mu\phi) \propto \cos^2(m_\phi t)$

Feasible?

Take-home

Improving the sensitivity of **LFV τ decays** is **fundamental** to **constraining** the flavor **structure beyond the SM** and is a **powerful approach** to probe **high-energy scales** *(otherwise inaccessible...) — in particular, in models that couple hierarchically to leptons.*

These decays also provide **key information** to **indirectly constrain potential** NP explanations of discrepancies in low-energy data (e.g., B-***physics***) and to probe scenarios with **light particles**.

Questions:

I. Does it really make sense to look for **BNV decays of τ's**? How to avoid p-decay bounds?

II. Which model is used to simulate the signal in $\tau \to \ell\ell\ell$ searches? Can we further exploit the **kinematical distributions**?

III. Are there searches for **displaced vertices** ($\tau \to \ell\varphi(\to \gamma\gamma, \ell\ell)$) in LFV decays?

IV. **Time-modulation** of $\tau \to \ell\varphi$: Which are the main challenges experimentally?

V. What can we learn if the e^+e^- **beam** is **polarized** — *both in models with light/heavy particles?*

Back-up

EFT for $\tau \to \ell\gamma$ and $\tau \to \ell\ell\ell$

see e.g. [Kuno, Okada. 99]

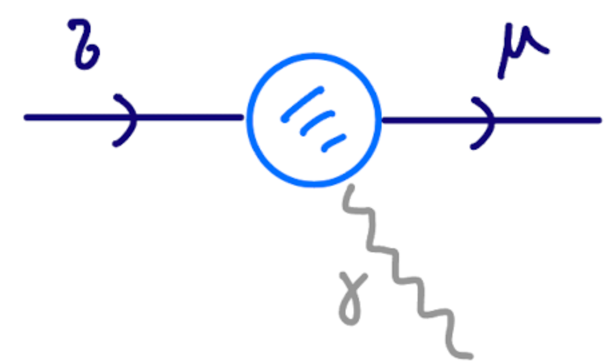
See talk by Ardu!

$$\mathscr{L}_{\text{LEFT}} \supset \frac{1}{v^2} \sum_a C_a O_a$$

Operators invariant under $SU(3)_c \times U(1)_{\text{em}}$

- **Dipoles:**

$$O^{\ell}_{D_L} = e m_\tau \bar{\ell}_R \sigma_{\mu\nu} \tau_L F^{\mu\nu}$$



… and $(L \leftrightarrow R)$

- **Four-leptons:**

Vector

$$O^{\ell}_{V_{LL}} = \left(\bar{\ell}\,\gamma^\mu P_L \tau\right)\left(\bar{\ell}\,\gamma_\mu P_L \ell\right)$$

$$O^{\ell}_{V_{LR}} = \left(\bar{\ell}\,\gamma^\mu P_L \tau\right)\left(\bar{\ell}\,\gamma_\mu P_R \ell\right)$$

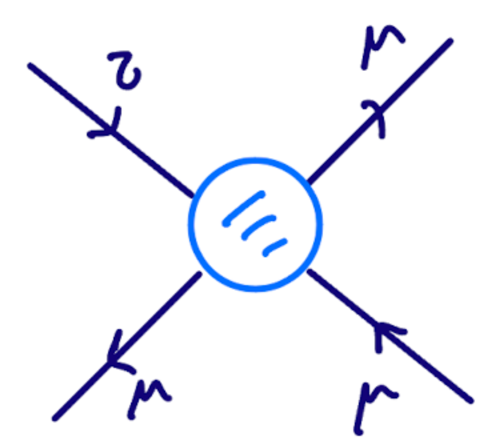
Scalar

$$O^{\ell}_{S_{LL}} = \left(\bar{\ell}\,P_L \tau\right)\left(\bar{\ell}\,P_L \ell\right)$$

$$O^{\ell}_{S_{LR}} = \left(\bar{\ell}\,P_L \tau\right)\left(\bar{\ell}\,P_R \ell\right)$$

Tensor

$$O^{\ell}_{T_L} = \left(\bar{\ell}\,\sigma^{\mu\nu} P_L \tau\right)\left(\bar{\ell}\,\sigma_{\mu\nu} P_L \ell\right)$$



… and $(L \leftrightarrow R)$

SMEFT for $\tau \to \ell\gamma$ and $\tau \to \ell\ell\ell$

[Buchmuller et al. '86, Grzadkowski et al. '10]

See talk by Ardu!

$$\mathscr{L}_{\text{SMEFT}} \supset \frac{1}{\Lambda^2} \sum_a \mathscr{C}_a \mathscr{O}_a$$

Operators invariant under $SU(3)_c \times SU(2)_L \times U(1)_Y$

- **Dipoles:**

$$\mathscr{O}_{\underset{ij}{B}} = \left(\bar{L}_i \sigma^{\mu\nu} e_{Rj}\right) H\, B_{\mu\nu}$$

$$\mathscr{O}_{\underset{ij}{W}} = \left(\bar{L}_i \tau^I \sigma^{\mu\nu} e_{Rj}\right) H\, W^I_{\mu\nu}$$

- **Four-leptons:**

$$\mathscr{O}_{\underset{ijkl}{ll}} = \left(\bar{L}_i \gamma^\mu L_j\right)\left(\bar{L}_k \gamma_\mu L_l\right)$$

$$\mathscr{O}_{\underset{ijkl}{le}} = \left(\bar{L}_i \gamma^\mu L_j\right)\left(\bar{e}_{Rk} \gamma_\mu e_{Rl}\right)$$

$$\mathscr{O}_{\underset{ijkl}{ee}} = \left(\bar{e}_{Ri} \gamma^\mu e_{Rj}\right)\left(\bar{e}_{Rk} \gamma_\mu e_{Rl}\right)$$

Matching @ tree-level:

*Flavor indices omitted...

Dipole

$$C_{D_L} \propto \frac{v^2}{\Lambda^2}\left[\cos\theta_W \mathscr{C}_{eW} - \sin\theta_W \mathscr{C}_{eB}\right]$$

Vector

$$C_{V_{LL}} \propto \frac{v^2}{\Lambda^2}\mathscr{C}_{ll} + \ldots$$

$$C_{V_{LR}} \propto \frac{v^2}{\Lambda^2}\mathscr{C}_{le} + \ldots$$

... and $(L \leftrightarrow R)$

Scalar

$$C_{S_{LL}} = \mathscr{O}(\Lambda^{-4})$$

$$C_{S_{LR}} = \mathscr{O}(\Lambda^{-4})$$

Tensor

$$C_{T_L} = \mathscr{O}(\Lambda^{-4})$$

Suppressed in the SMEFT!

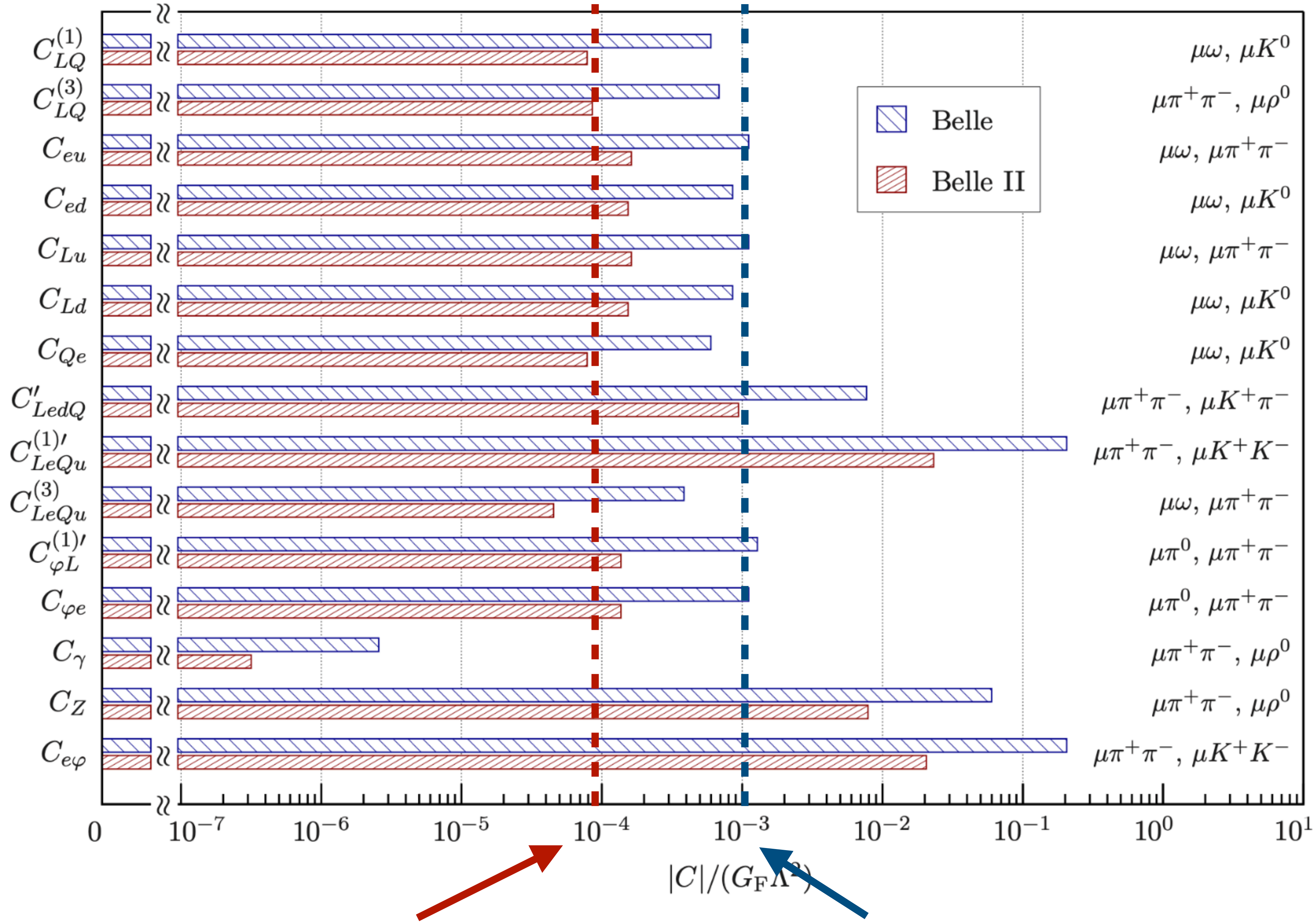
Gauge invariance is useful for constraining the possible operators

EFT for $\tau \to \ell + \text{had}$

[Ardu]

New Physics scale of SMEFT operators probed by **hadronic τ-decays**:

[2203.14919]



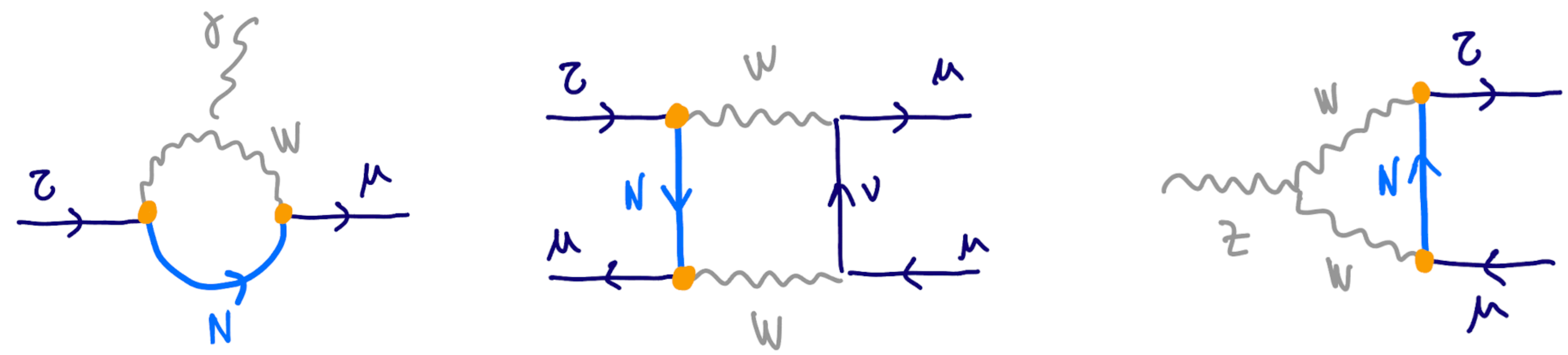
Belle-II: $\Lambda/|\mathscr{C}| \gtrsim 30$ TeV

Belle: $\Lambda/|\mathscr{C}| \gtrsim 10$ TeV

From EFTs to concrete models

Concrete models can also be used to establish **correlations** between different observables:

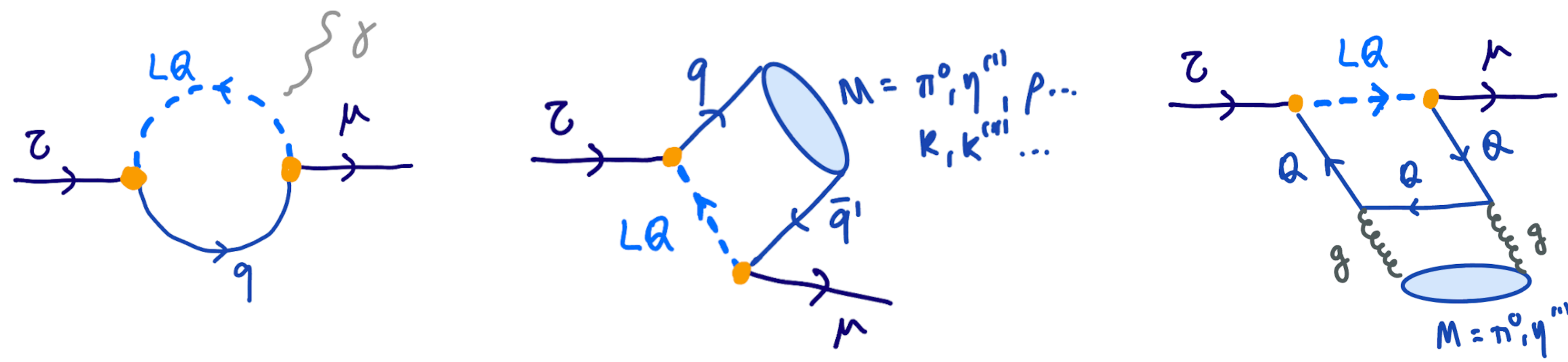
- **Heavy neutrinos:**



...

[Ilakovac et al. '94], [Abada et al. '14]...

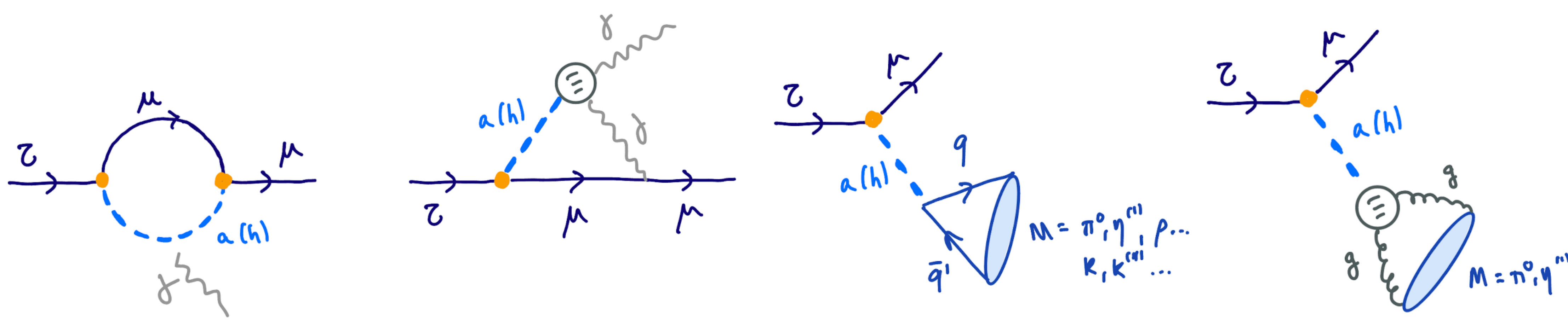
- **Leptoquarks:**



...

[Petrov et al. '13], [Becirevic et al. **(OS)**, '16], [Dorsner et al. '16]...

- **ALPs (or Higgs):**



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...

[Han et al. '08], [Harnik et al. '12], [Blankenburg et al. '13]... [Cornella, Paradisi, **OS**. '19]...