Effective field theory description of τ LFV decays

Topical workshop on LFV decays of the tau
Orsay, 11/04/2024

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Charged Lepton Flavour Violation (cLFV)

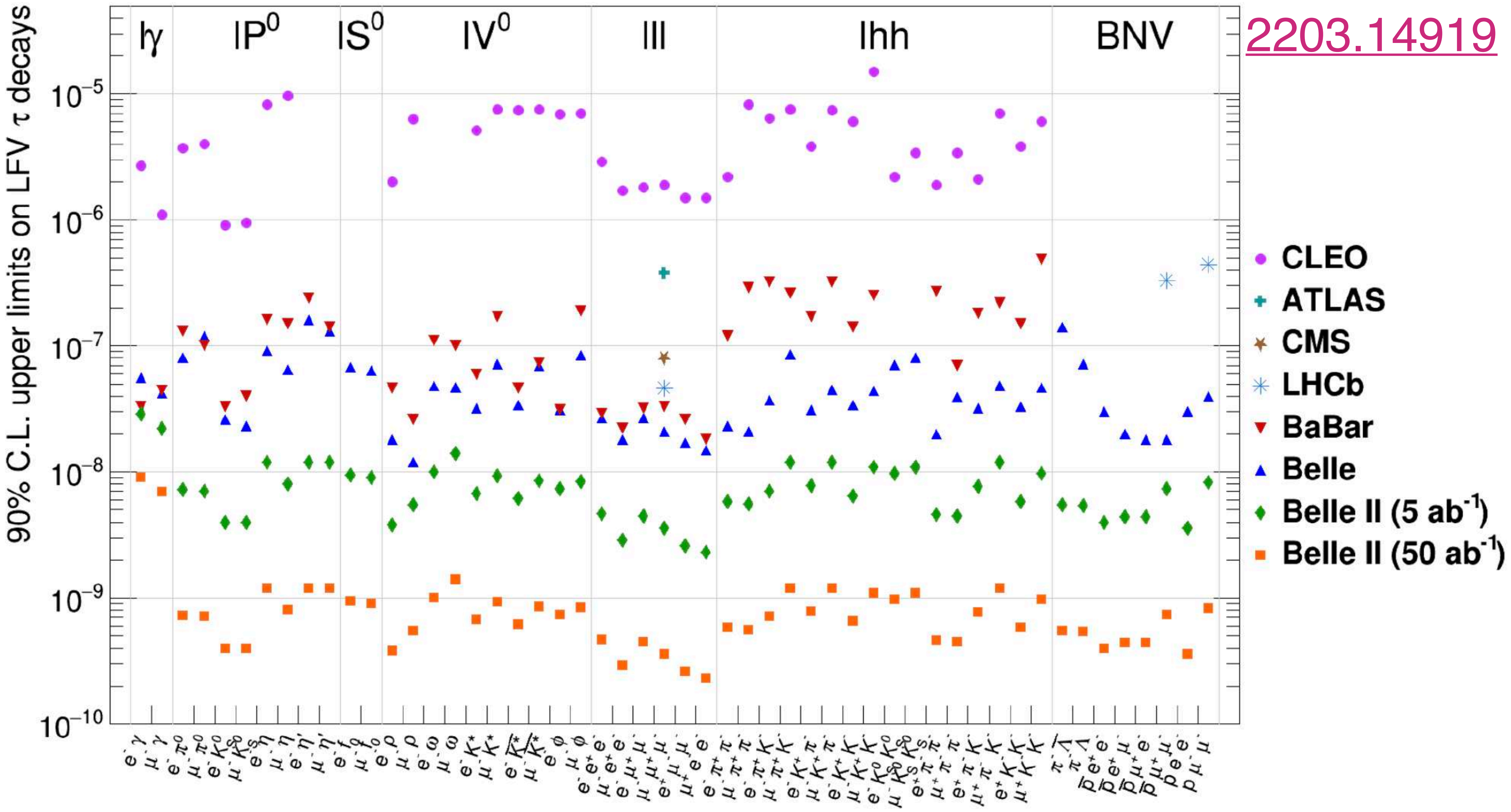
- cLFV ≡ contact interaction among the charged leptons that violates flavour
- Neutrino masses and oscillations imply lepton flavour violation
- Unambiguous signals of New Physics
- Accidental symmetries of the SM can be easily violated (cLFV is expected in many models)
- Can probe Beyond SM scenarios above the reach of colliders

Experimental searches

Process	Current bound on BR	Future Sensitivity
$\mu \to e\gamma$	$< 4.2 \times 10^{-13}$ MEG	10^{-14} MEGII
$\mu \to \bar{e}ee$	$< 1.0 \times 10^{-12}$ SINDRUM	10^{-16} Mu3e
$\mu A \to eA$	$< 7 \times 10^{-13}$ SINDRUMII	$10^{-16} \to 10^{-18}$ COMET, Mu2e

- $\mu \to e$ transitions

$K^0 \to \mu^\pm e^\mp$	$< 4.7 \times 10^{-12}$	
$B_d^0 \to \tau^\pm \mu^\mp$	$< 1.2 \times 10^{-5}$ LHCb	$\sim 10^{-6}$?
...	...	...
$h \to e^\pm \mu^\mp$	$< 6.1 \times 10^{-5}$ Atlas	2.1×10^{-5}
$h \to e^\pm \tau^\mp$	$< 2.2 \times 10^{-3}$ CMS	2.4×10^{-4}
$h \to \tau^\pm \mu^\mp$	$< 1.5 \times 10^{-3}$ CMS	2.3×10^{-4} ILC
$Z \to e^\pm \mu^\mp$	$< 7.5 \times 10^{-7}$ Atlas	
$Z \to l^\pm \tau^\mp$	$< 10^{-7}$ Atlas	



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- $\tau \to l$ decays

- Heavy particles decaying into LFV final states

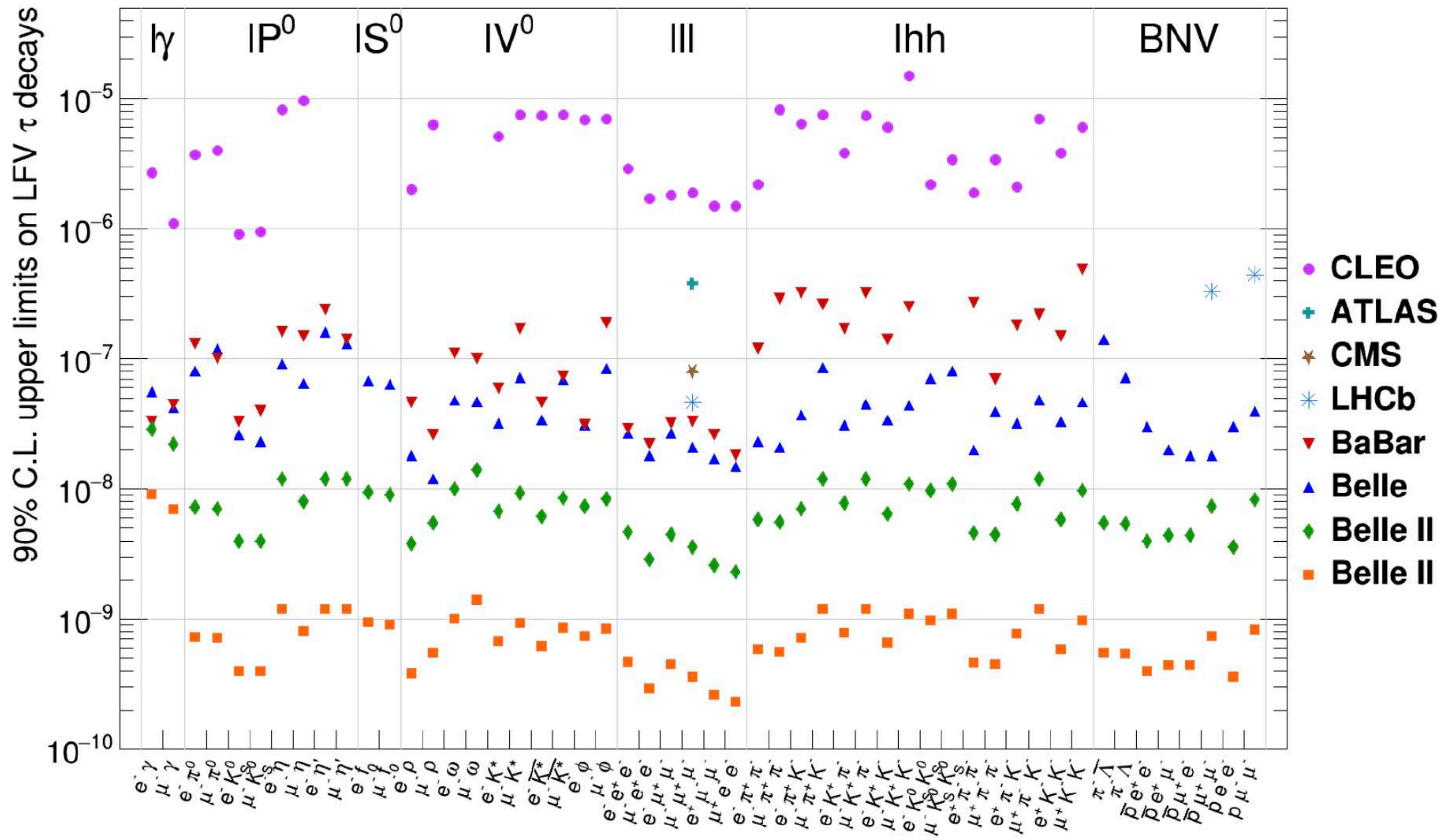
$\tau \to l$ transitions

- The sensitivities of $\tau \to l$ processes are $Br(\tau \to l) \lesssim 10^{-8} \to 10^{-10}$ (LHC(b), BaBar, Belle, Belle-II)

- If we see $\tau \to l$, it should be relatively large

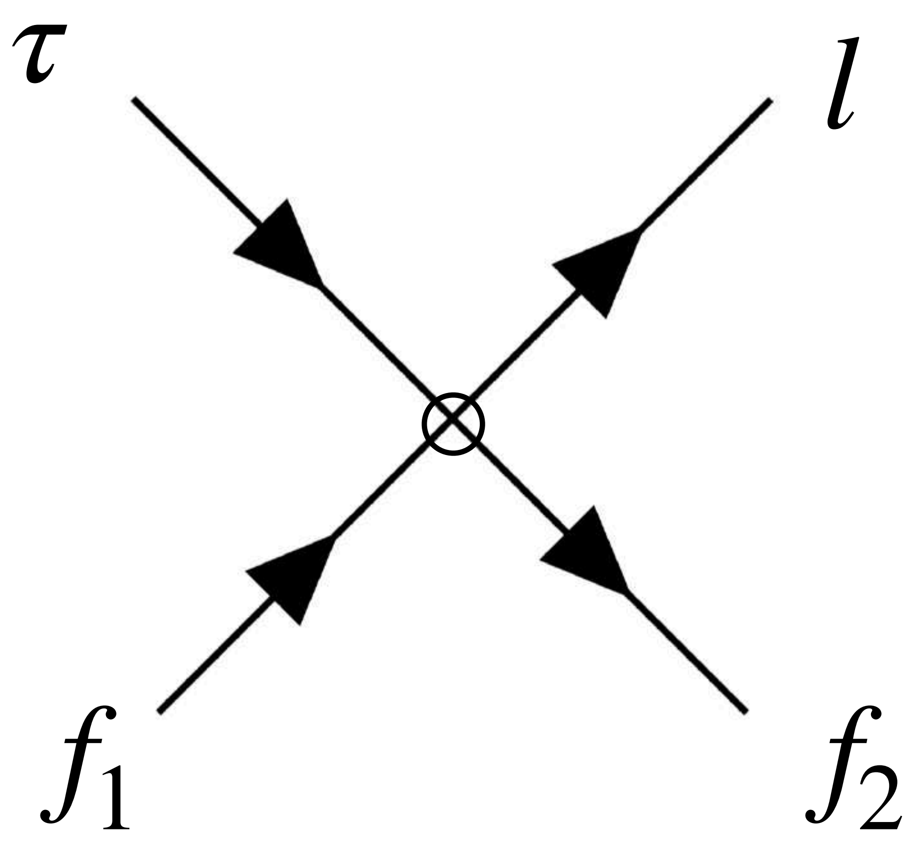
- The big phase available means there is a plethora of different channels (possible to overconstrain models = distinguish them)

- High energy probes (like the decay of heavy particles into final states with τ-s) are sometimes competitive with the decays



Effective Field Theories

- If LFV New Physics is heavy $(\Lambda \gtrsim \text{few TeV})$, it can be parametrised in terms of non-renormalizable operators



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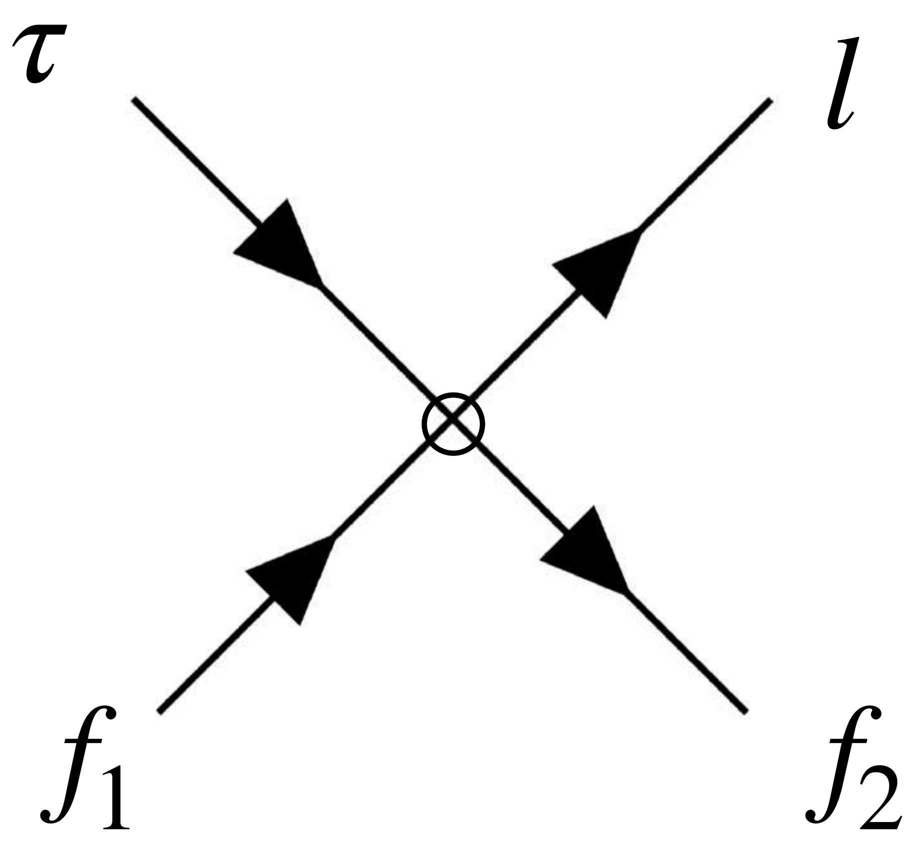

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- Add to the Lagrangian the relevant contact interactions (non-renormalizable operators) compatible with the symmetries

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{d\leq 4} + \sum_{n>4} \frac{C_n \mathcal{O}_n}{\Lambda^{n-4}}$$

and calculate observables…

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- Many channels = many operators can be probed (few flat directions in the EFT)
- Decays and high-energy probes sensitive to the same operators at a competitive level

Outline

- Leptonic decays ($\tau \to l_i \gamma$, $\tau \to l_i \bar{l}_k l_k$, $\tau \to \bar{l}_i l_k l_k$)

- Semi-leptonic decays (ex: $\tau \to \pi l_i$)

- Other processes

- Conclusion

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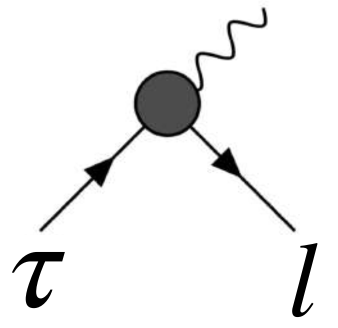
LFV Radiative decay: branching ratio



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

$$\frac{Br(\tau\to l\gamma)}{Br(\tau\to l\bar{\nu}\nu)} = 384\pi^2\left(\frac{v}{\Lambda}\right)^4(|C^{l\tau}_{D,R}|^2 + |C^{l\tau}_{D,L}|^2) < 2\times10^{-7} \longrightarrow \left(\frac{v}{\Lambda}\right)^2|C^{l\tau}_{D,X}| \lesssim 7\times10^{-6}$$

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

$\Lambda \gtrsim 4\times10^2 v$ (if $C_D \sim 1$)

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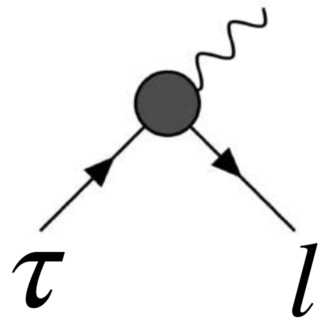

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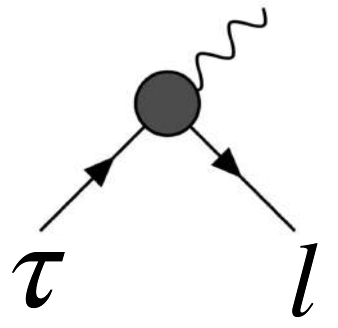

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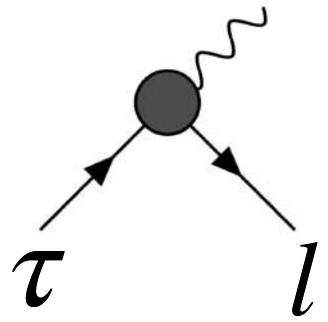

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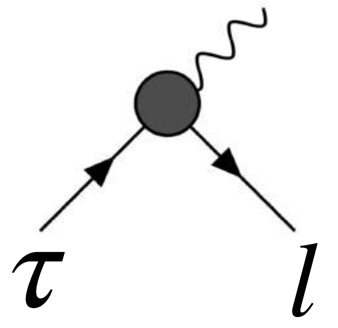

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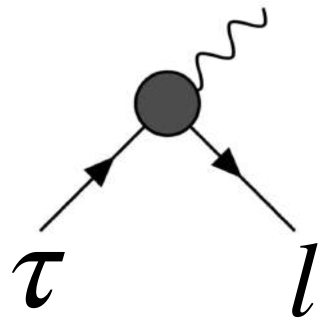

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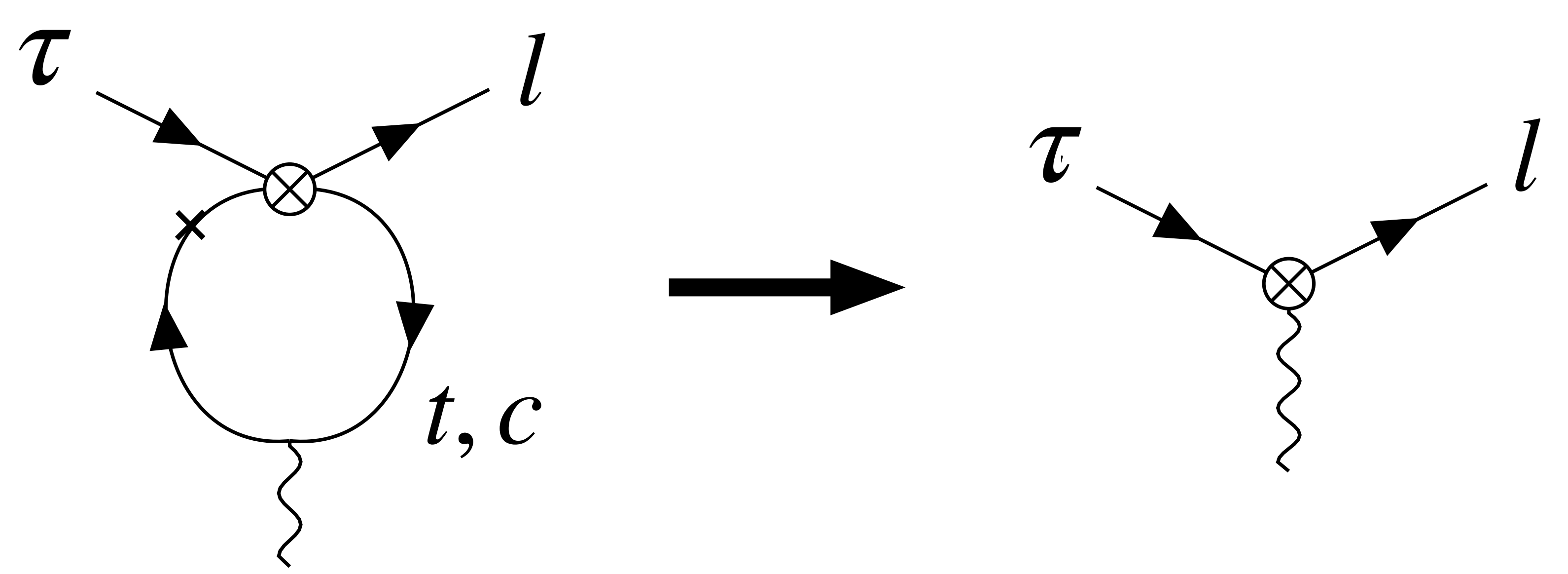
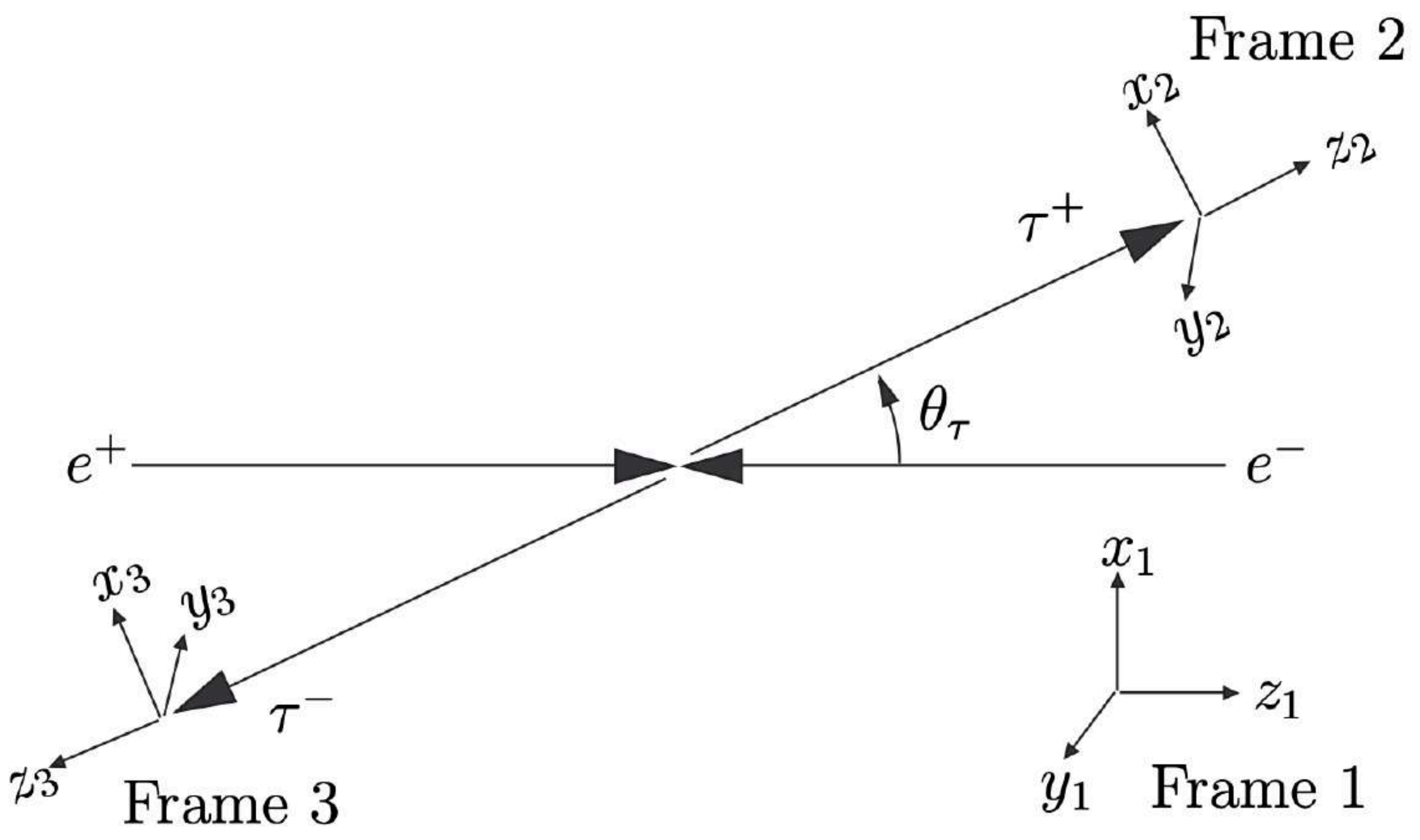
$C^{qq}_{T,X}(\bar{l}\sigma P_X\tau)(\bar{q}\sigma P_X q)$



LFV Radiative decay: distinguishing chiralities

Kitano, Okada hep-ph/0012040



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- Angles in Frame 2, and taking the normalization $\Lambda = v$ for the dipoles

$$dR_a^{\tau^-\to l^-\bar{\nu}\nu} = \frac{d\Omega_l}{4\pi}dx\frac{1}{\Gamma}\frac{G_F^2 m_\tau^5}{192\pi^3}2x^2(1-2x)\begin{pmatrix}\sin\theta_{l^-}\cos\phi_{l^-}\\ \sin\theta_{l^-}\sin\phi_{l^-}\\ \cos\theta_{l^-}\end{pmatrix}$$

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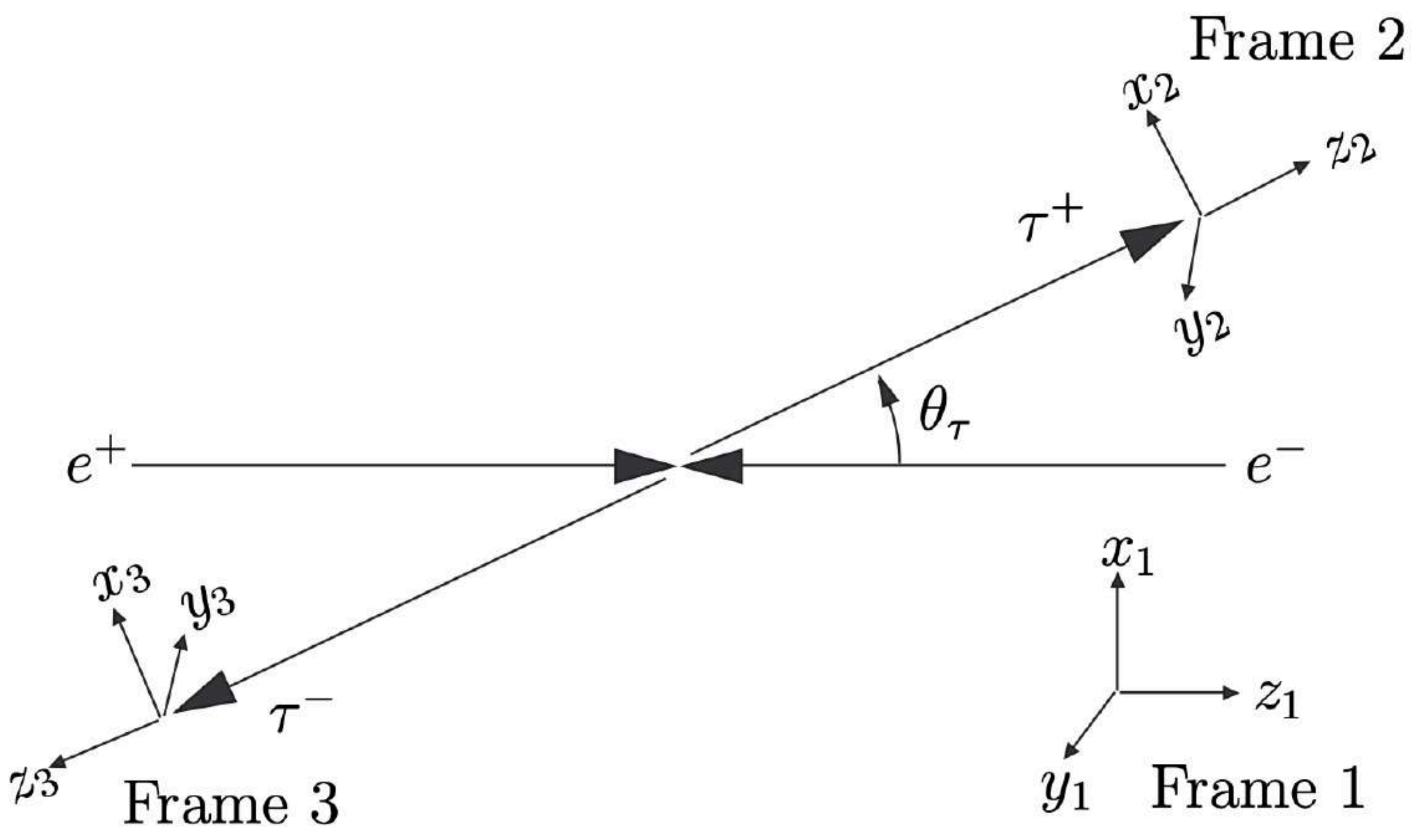

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$$d\sigma\left(e^+e^- \to \tau^+\tau^- \to l^+\gamma + l^-\bar{\nu}\nu\right)$$
$$= \sigma\left(e^+e^- \to \tau^+\tau^-\right) B\left(\tau^+ \to l^+\gamma\right) B\left(\tau^- \to l^-\bar{\nu}\nu\right)\frac{d\cos\theta_{l^+}}{2}\frac{d\cos\theta_{l^-}}{2}dx2x^2$$
$$\times\left\{3 - 2x - \frac{s-2m_\tau^2}{s+2m_\tau^2}(1-2x)A_P\cos\theta_{l^+}\cos\theta_{l^-}\right\}$$

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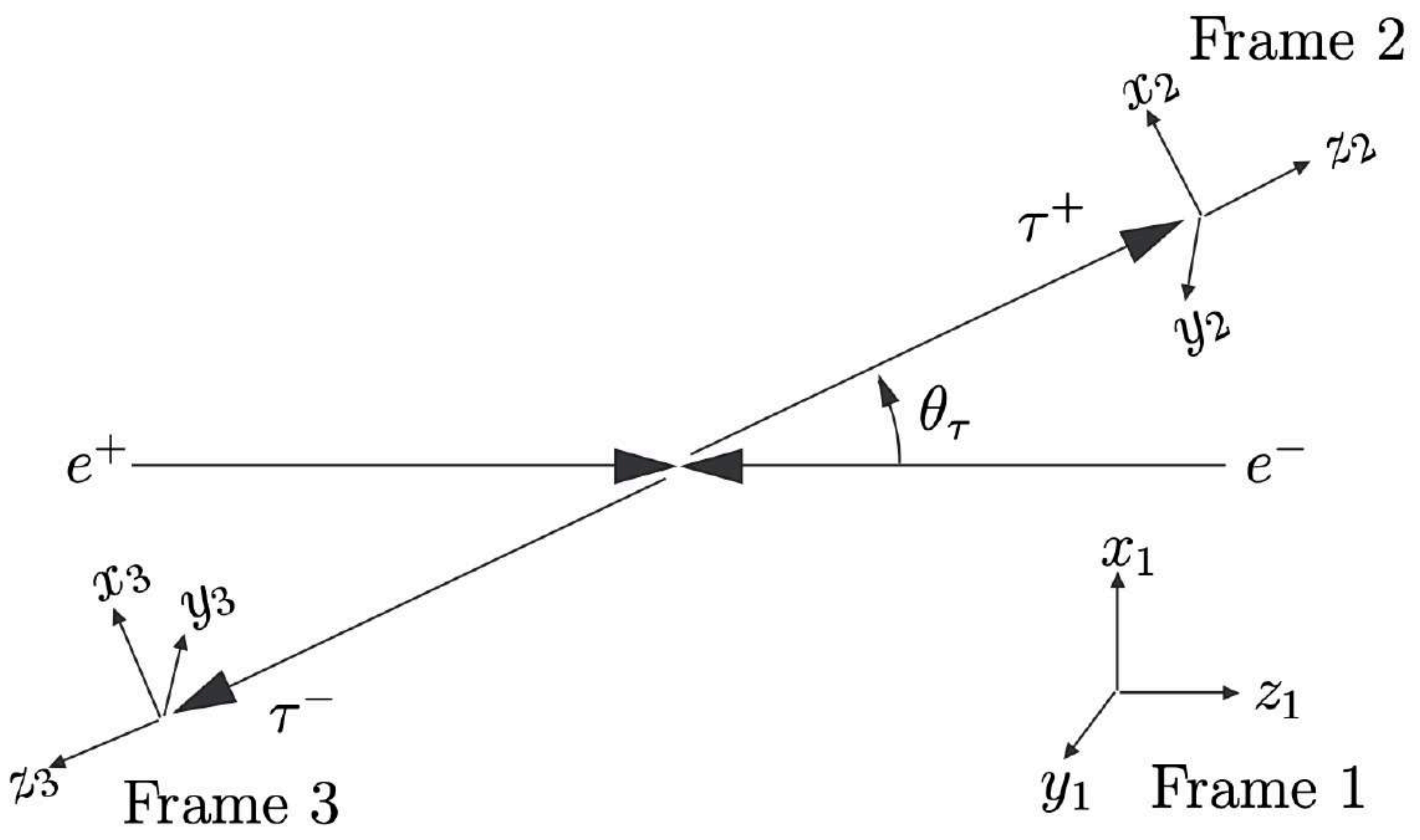

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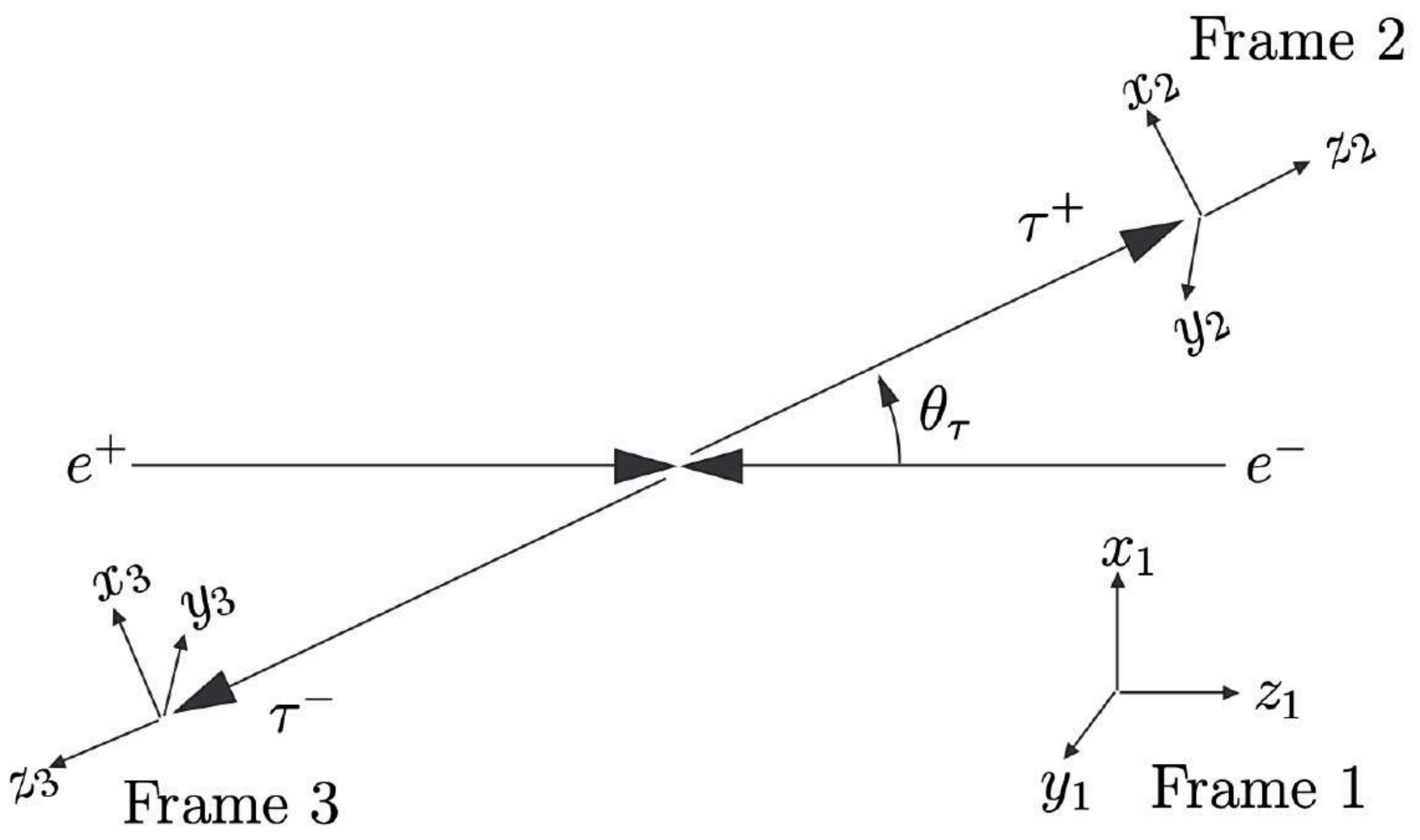

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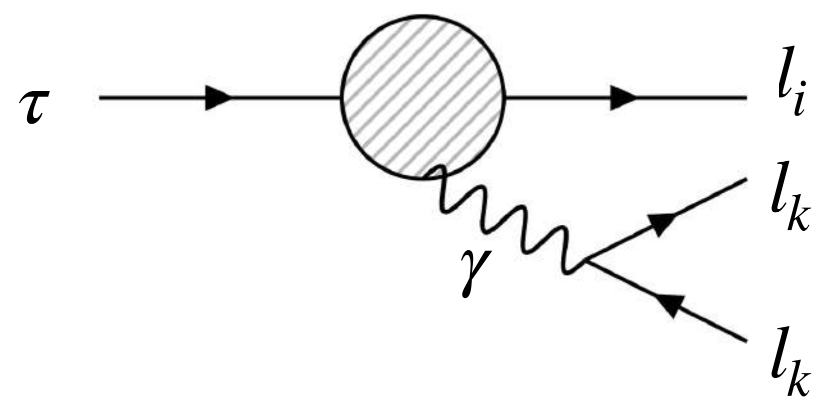
$$A_P = \frac{|C_{D,L}^{l\tau}|^2 - |C_{D,R}^{l\tau}|^2}{|C_{D,L}^{l\tau}|^2 + |C_{D,R}^{l\tau}|^2}$$

LFV three body decays ($\Delta F = 1$)

- All decays with only one flavour changing current: $\tau \to \mu\bar{\mu}\mu$, $\tau \to \mu\bar{e}e$, $\tau \to e\bar{e}e$, $\tau \to e\bar{\mu}\mu$



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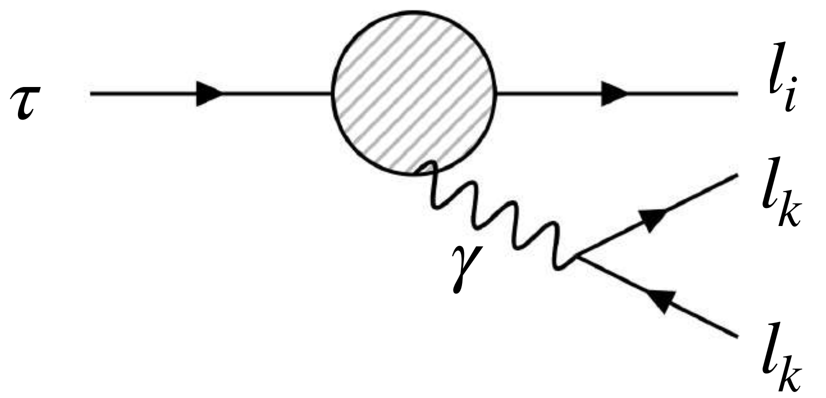

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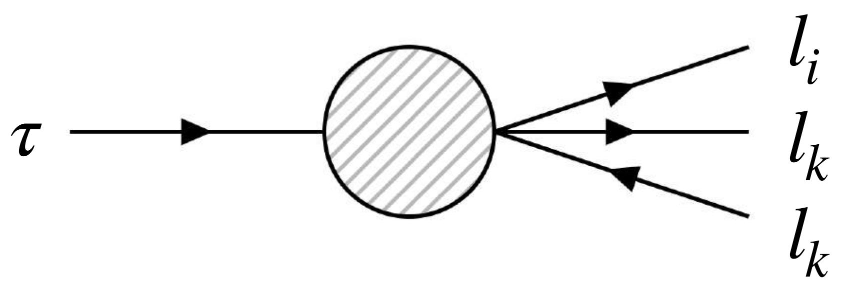

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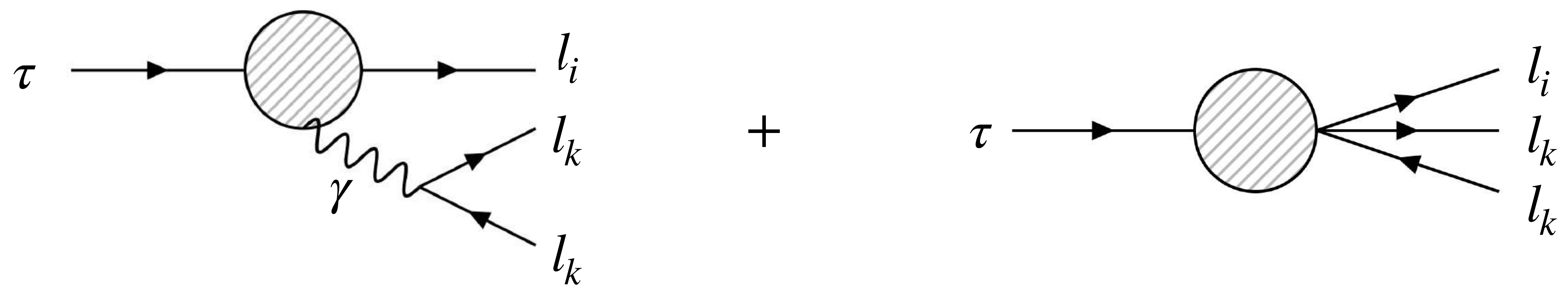

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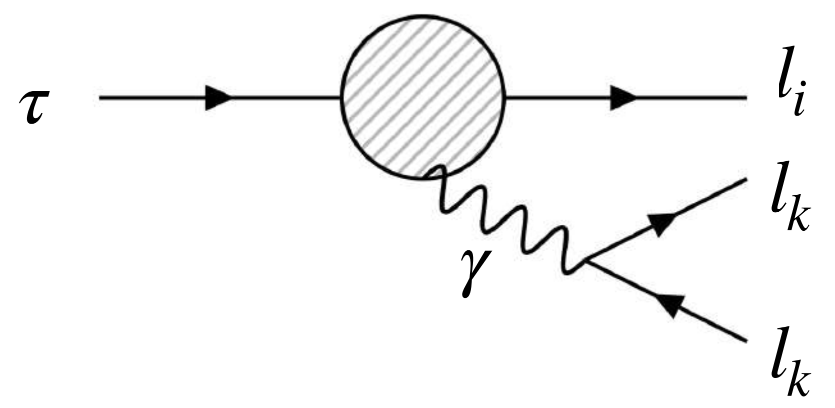

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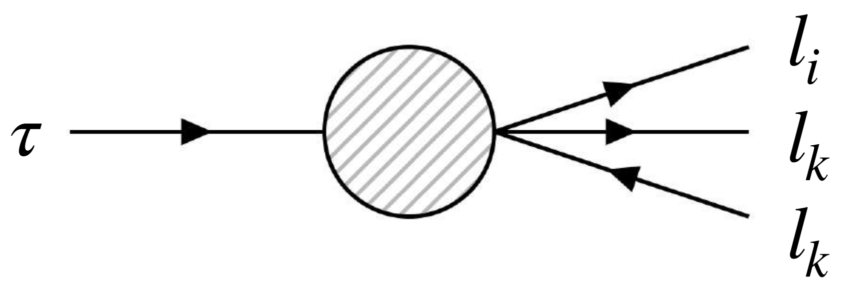

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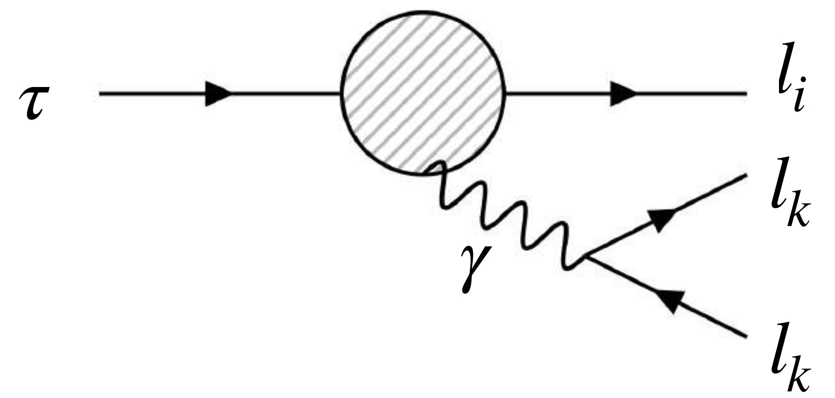
$$\delta\mathscr{L}_{\tau\to l_i\bar{l}_k l_k} = \frac{1}{\Lambda^2}\sum_{X,Y=L,R}[C_{V,XY}(\bar{l}_i\gamma^\alpha P_X\tau)(\bar{l}_k\gamma_\alpha P_Y l_k) + C_{S,X}(\bar{l}_i P_X\tau)(\bar{l}_k P_X l_k) + C_{T,X}(\bar{l}_i\sigma P_X\tau)(\bar{l}_k\sigma P_X l_k)]$$

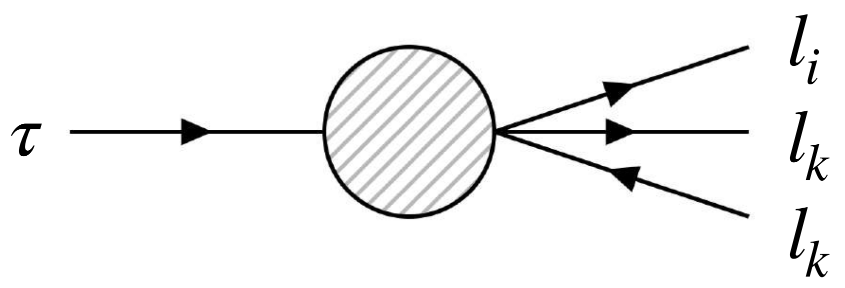
$$\frac{Br(\tau\to\mu\mu\mu)}{Br(\tau\to\mu\bar{\nu}_\mu\nu_\tau)} = \left(\frac{v}{\Lambda}\right)^4\left[2|C_{V,LL}+4eC_{D,R}|^2 + |C_{V,LR}+4eC_{D,R}|^2 + |C_{S,R}|^2/8 + (64\log(m_\tau/m_\mu) - 136)|eC_{D,R}|^2 + L\leftrightarrow R\right]$$

LFV three body decays ($\Delta F = 1$)

- All decays with only one flavour changing current: $\tau \to \mu\bar{\mu}\mu,\ \tau \to \mu\bar{e}e,\ \tau \to e\bar{e}e,\ \tau \to e\bar{\mu}\mu$



+



Can be neglected because of $\tau \to l\gamma$

Can include four-lepton scalars, vectors and tensors*

* four-lepton tensors are at dimension eight in SMEFT
four-lepton scalars are Yukawa suppressed or at dimension eight

$$\delta\mathscr{L}_{\tau\to l_i\bar{l}_k l_k} = \frac{1}{\Lambda^2}\sum_{X,Y=L,R}\left[C_{V,XY}(\bar{l}_i\gamma^\alpha P_X\tau)(\bar{l}_k\gamma_\alpha P_Y l_k) + C_{S,X}(\bar{l}_i P_X\tau)(\bar{l}_k P_X l_k) + C_{T,X}(\bar{l}_i\sigma P_X\tau)(\bar{l}_k\sigma P_X l_k)\right]$$

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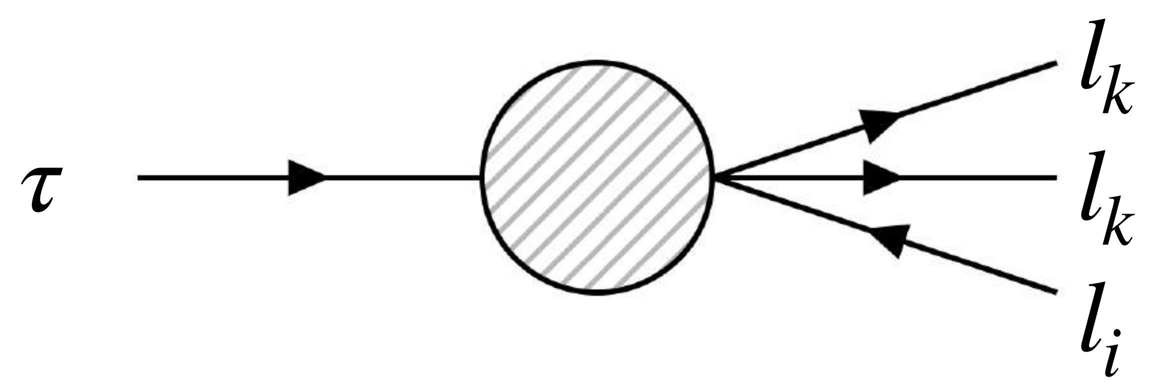
$$\frac{Br(\tau\to\mu\mu\mu)}{Br(\tau\to\mu\bar{\nu}_\mu\nu_\tau)} \lesssim 1.5\times10^{-7} \quad\to\quad \frac{v^2}{\Lambda^2}\begin{pmatrix}C_{D,X} & C_{V,XX} & C_{V,XY} & C_{S,X}\end{pmatrix} \lesssim \begin{pmatrix}8.3\times10^{-5} & 2.4\times10^{-4} & 3.4\times10^{-4} & 9.7\times10^{-4}\end{pmatrix}$$

LFV three body decays ($\Delta F = 2$)

- All decays with two flavour changing currents: $\tau \to \bar{\mu} ee$, $\tau \to \bar{e}\mu\mu$,



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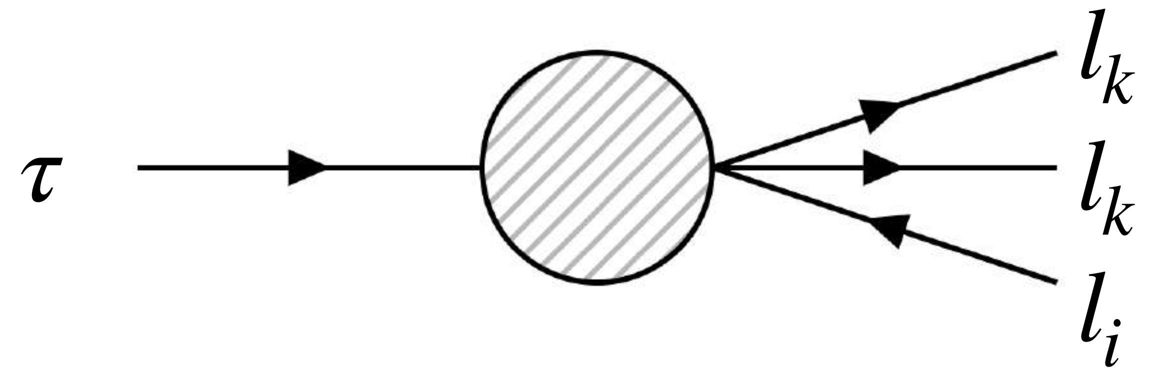

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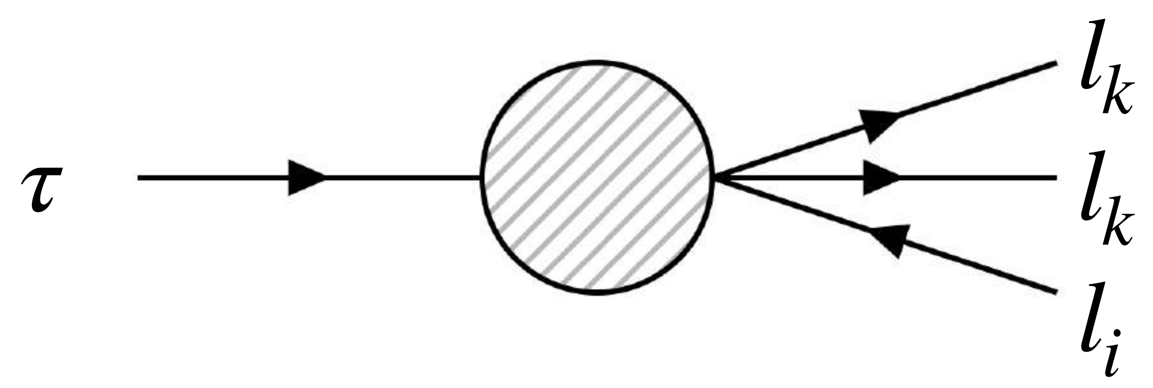

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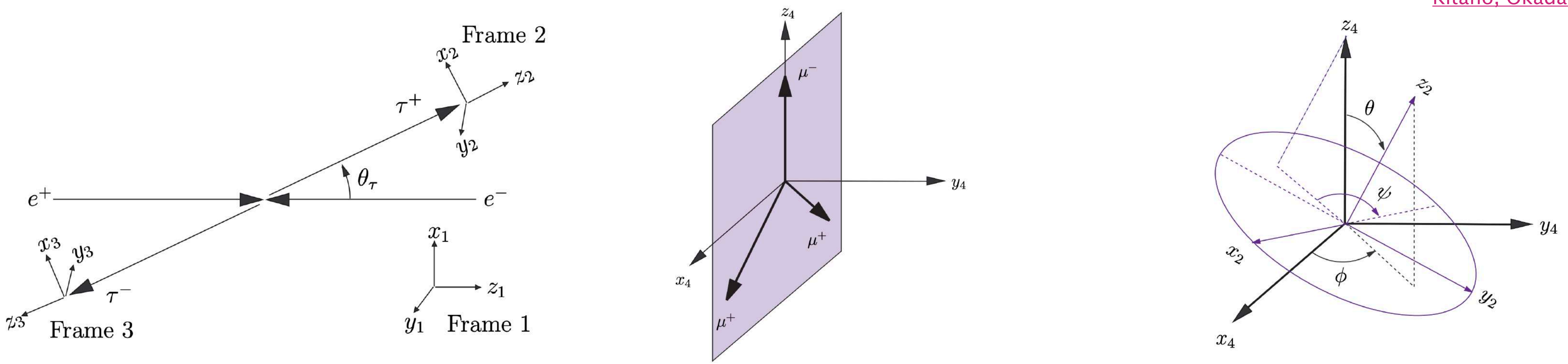
Three body decay: lepton angular asymmmetries

Kitano, Okada hep-ph/0012040



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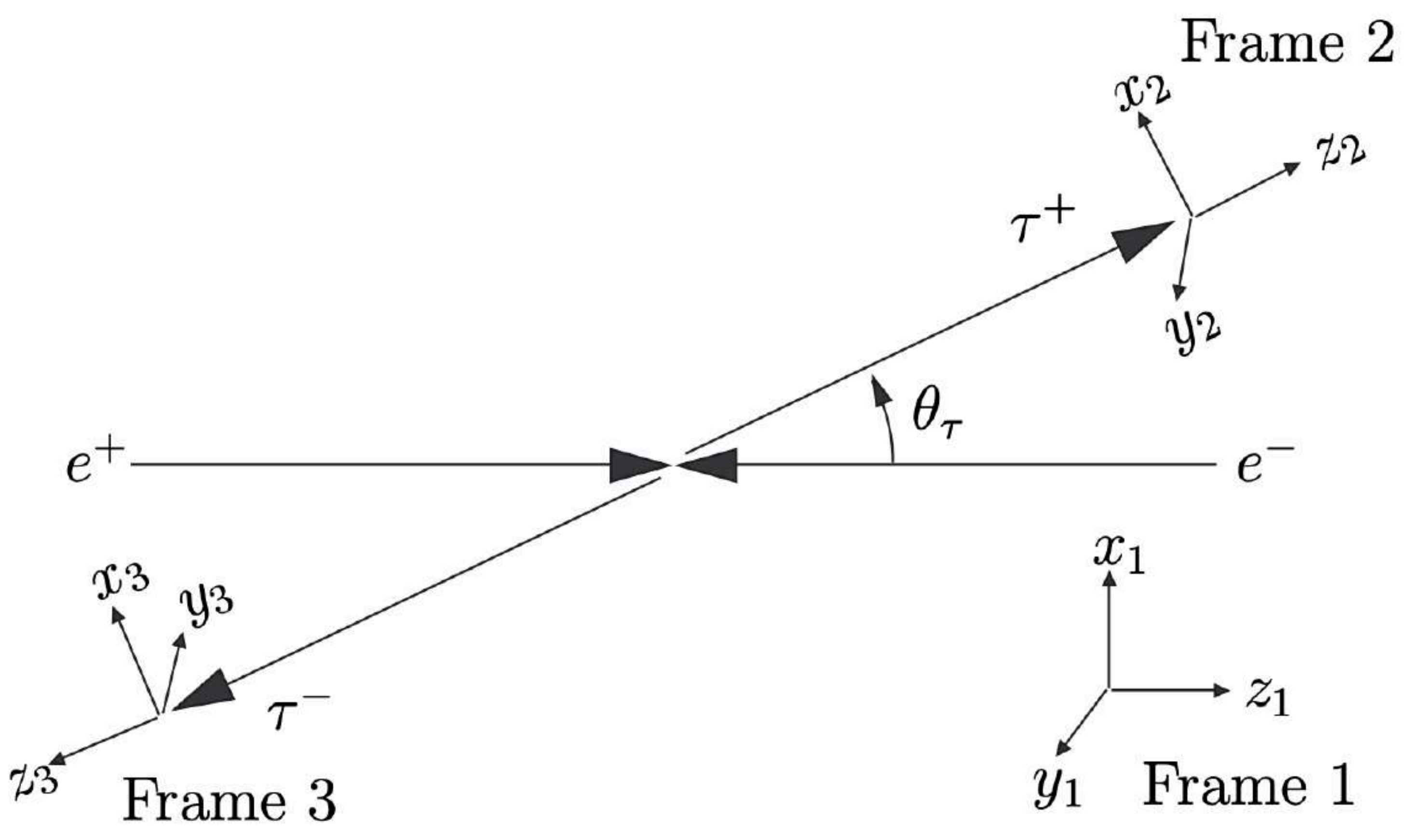

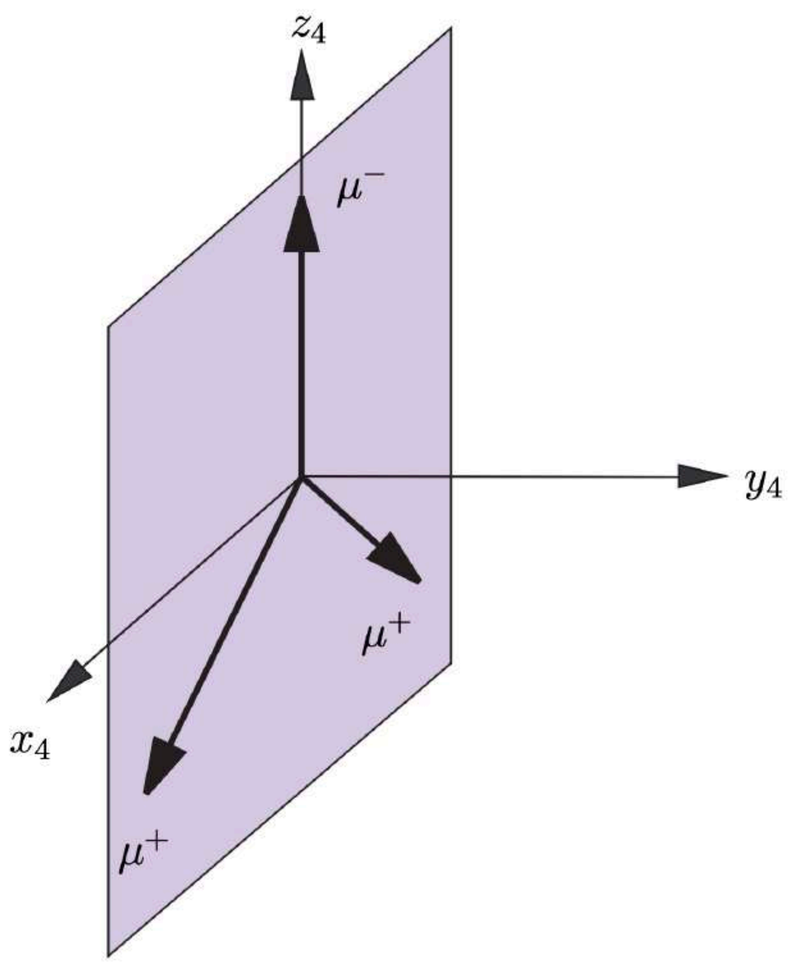

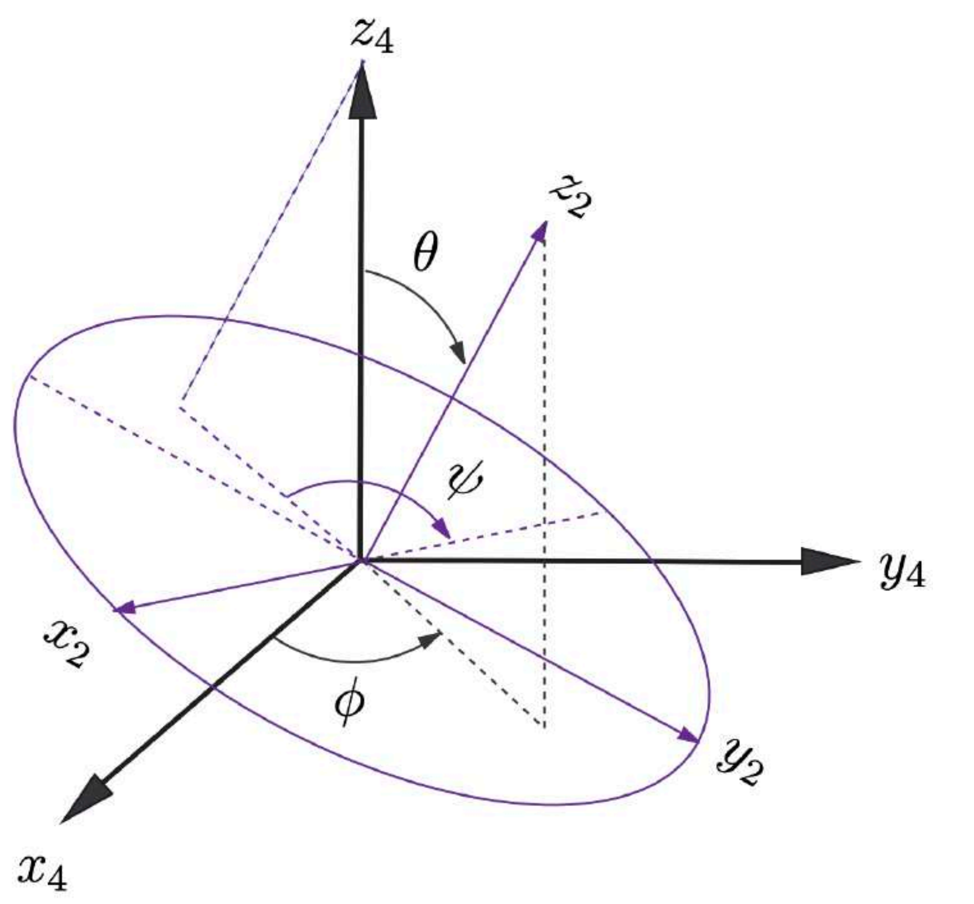

$$d\sigma\left(e^+e^- \to \tau^+\tau^- \to \mu^+\mu^+\mu^- + \pi^-\nu\right)$$

$$= \sigma\left(e^+e^- \to \tau^+\tau^-\right) B\left(\tau^- \to \pi^-\nu\right)\left(\frac{m_\tau^5 G_F^2}{128\pi^4}/\Gamma\right)\frac{d\cos\theta_\pi}{2}dx_1 dx_2 d\cos\theta d\phi$$

$$\times\left[X - \frac{s-2m_\tau^2}{s+2m_\tau^2}\{Y\cos\theta + Z\sin\theta\cos\phi + W\sin\theta\sin\phi\}\cos\theta_\pi\right]$$

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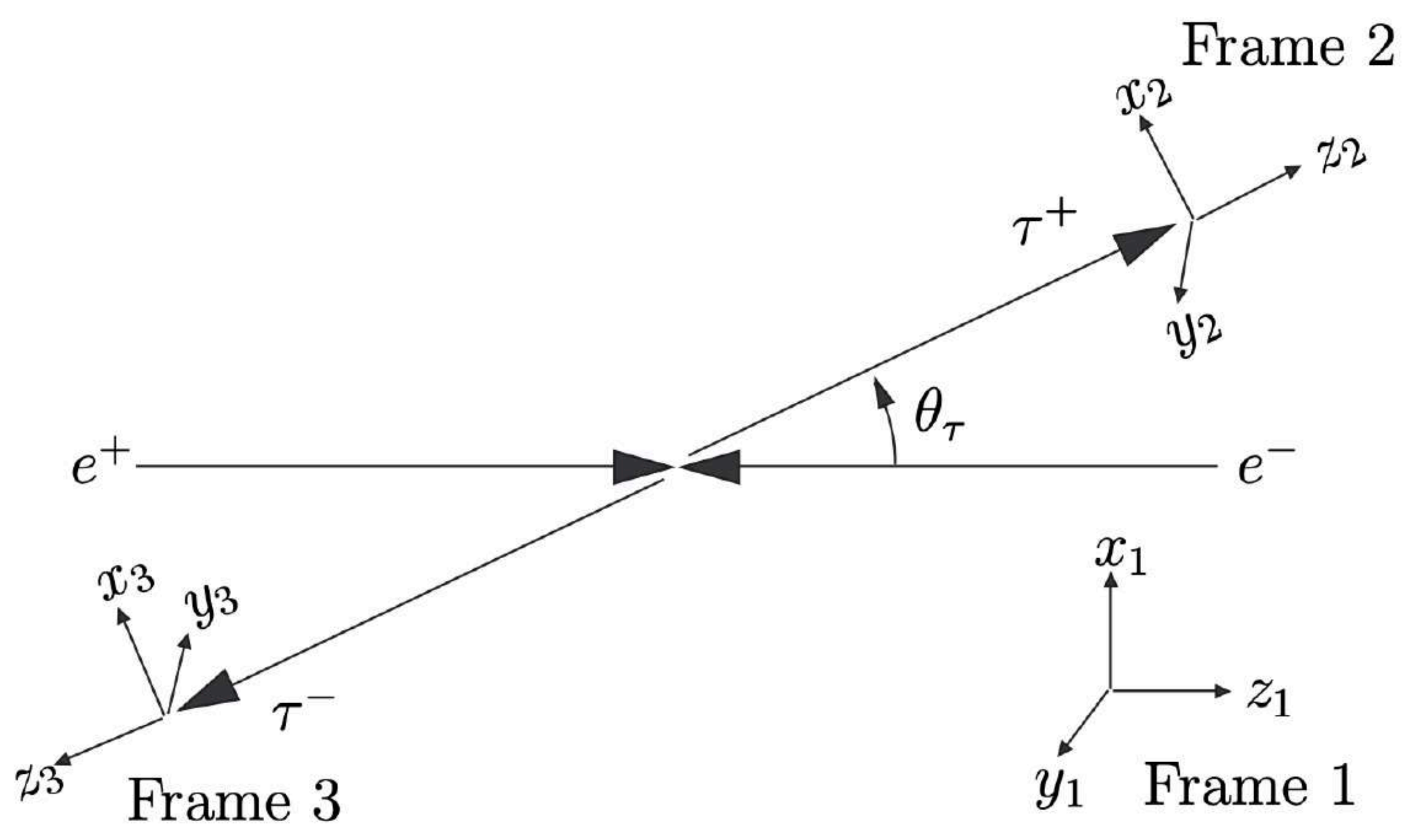

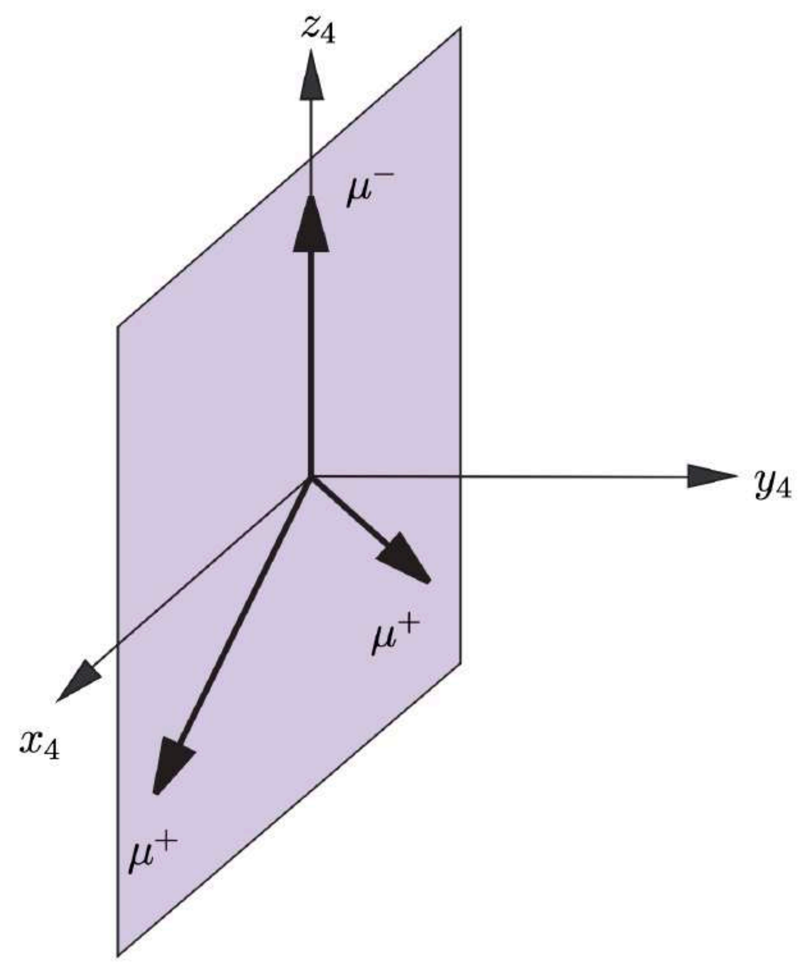

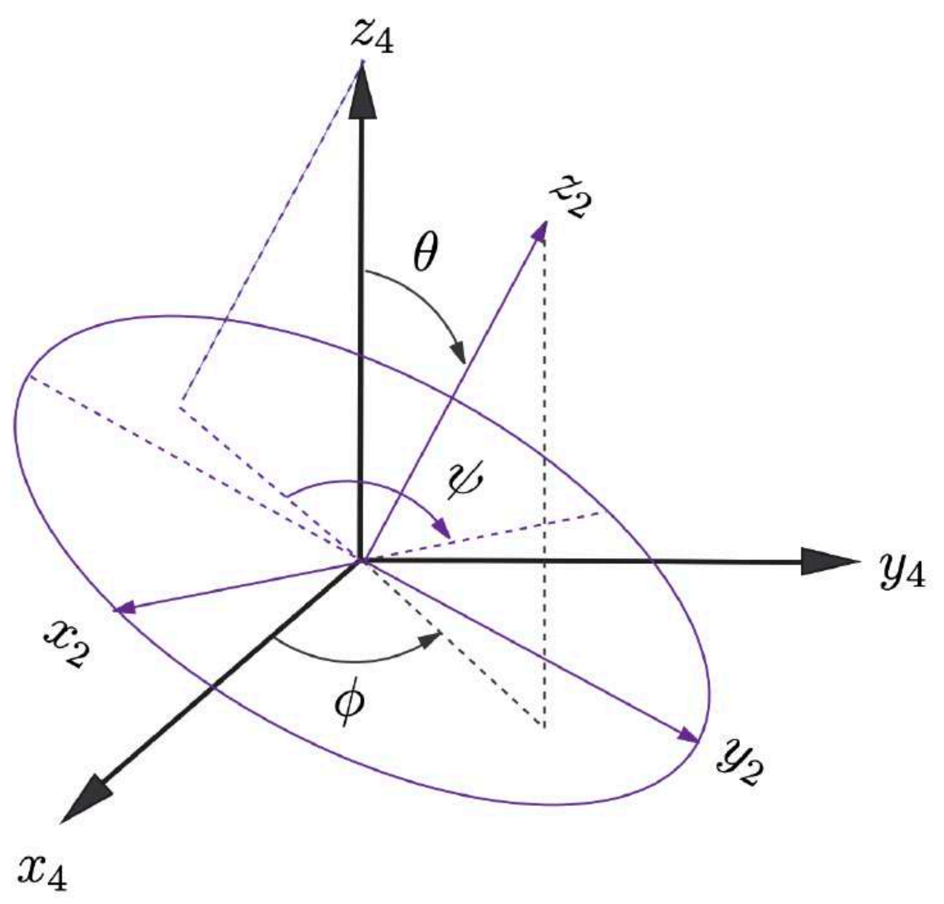

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Can distinguish $C_{V,LX}, C_{V,LX}, C_{S,R}$ **from** $C_{V,RX}, C_{V,RX}, C_{S,L}$ **but not scalars from vectors**

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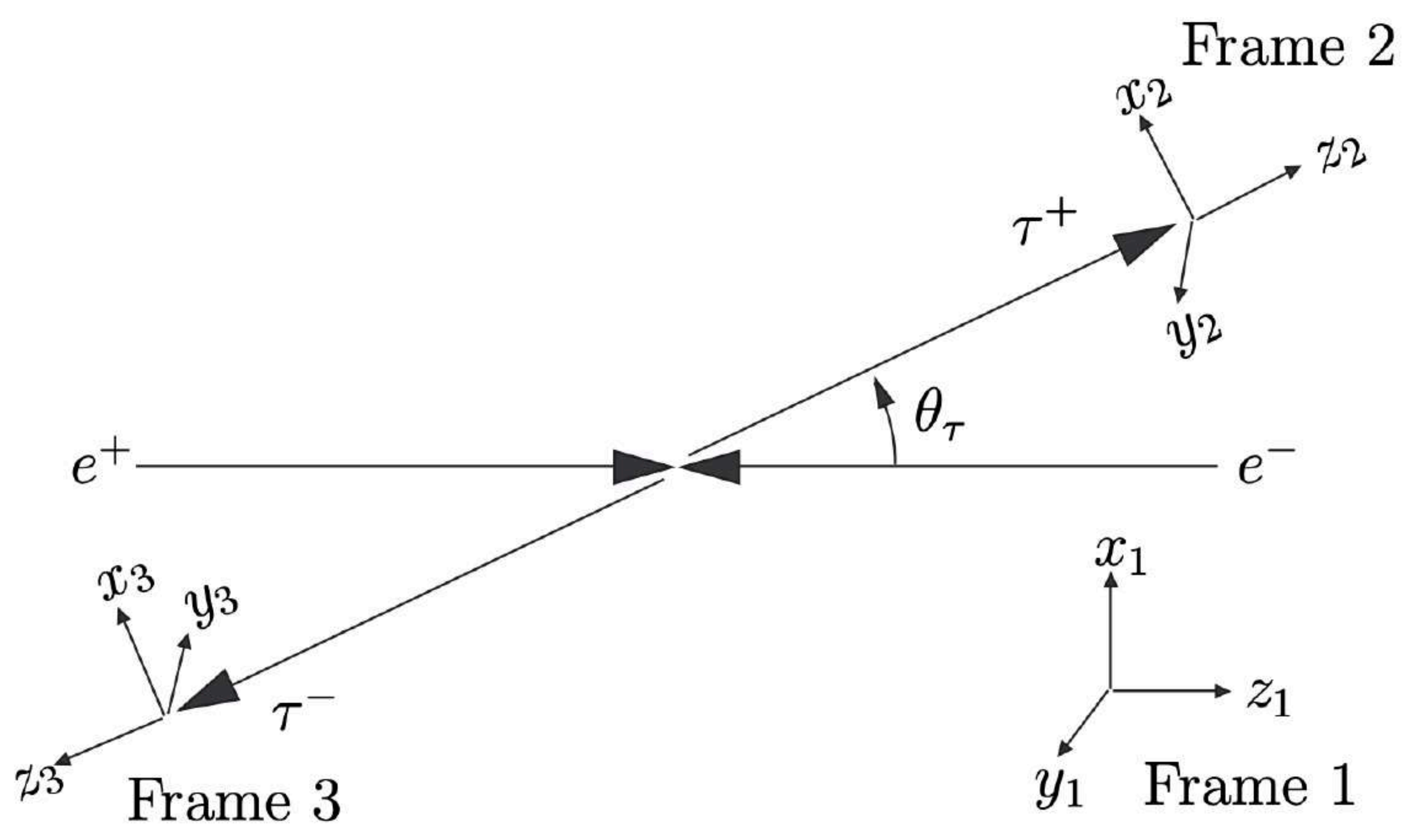

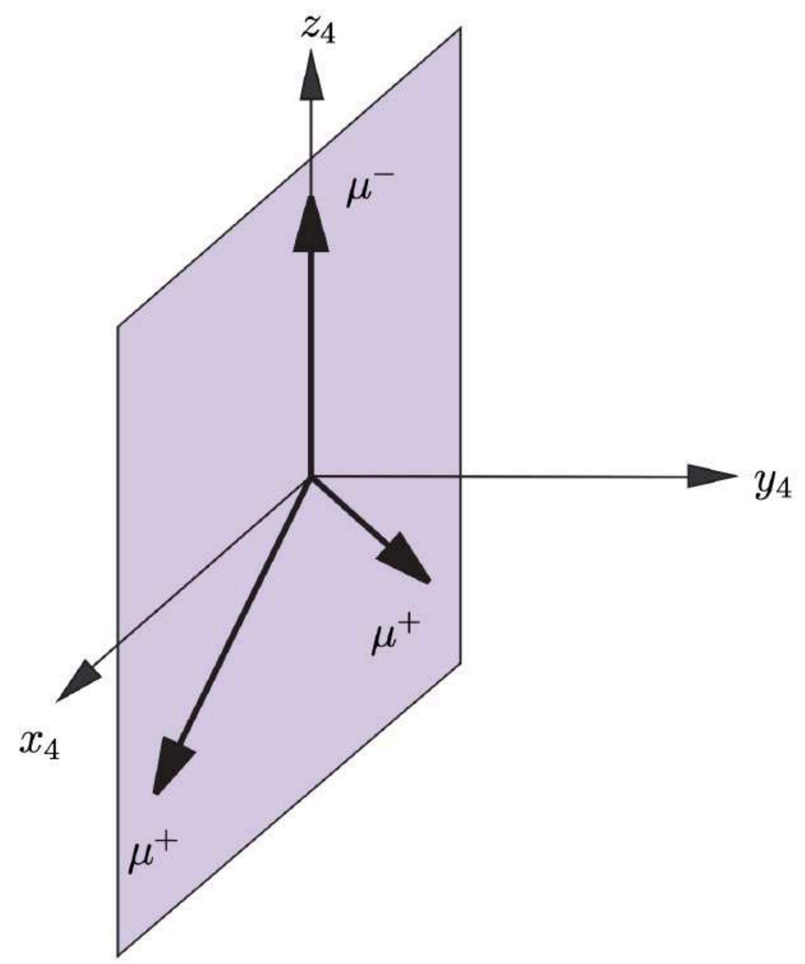

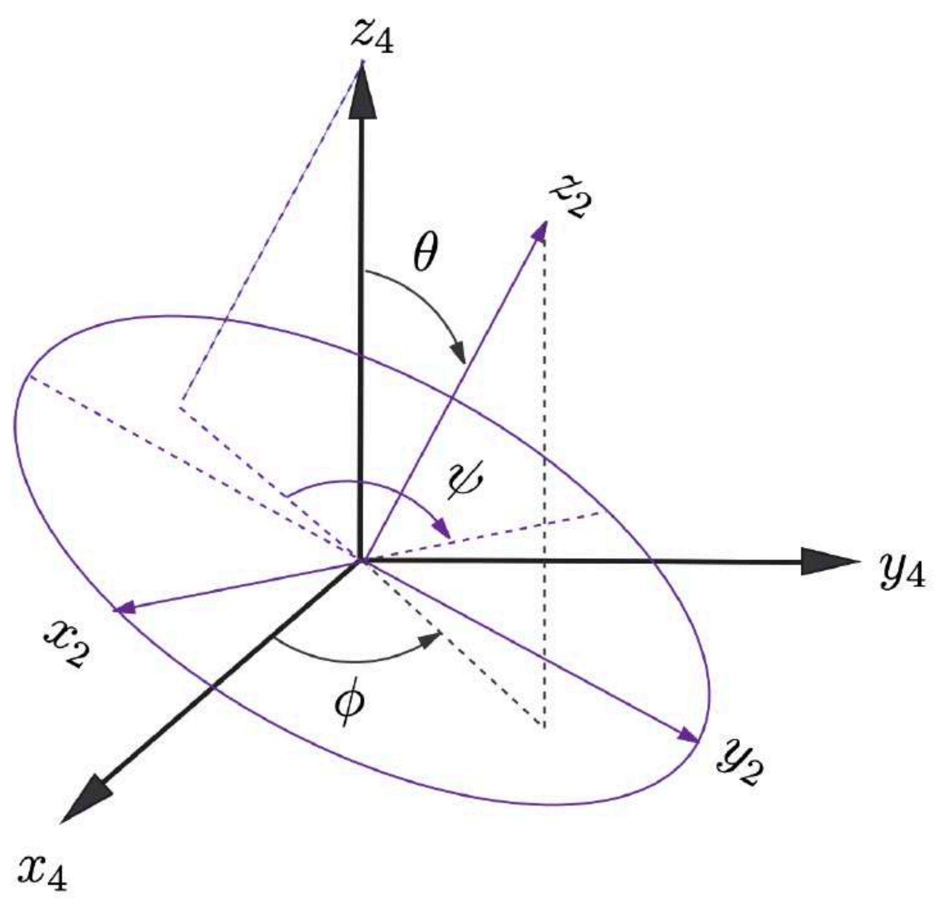

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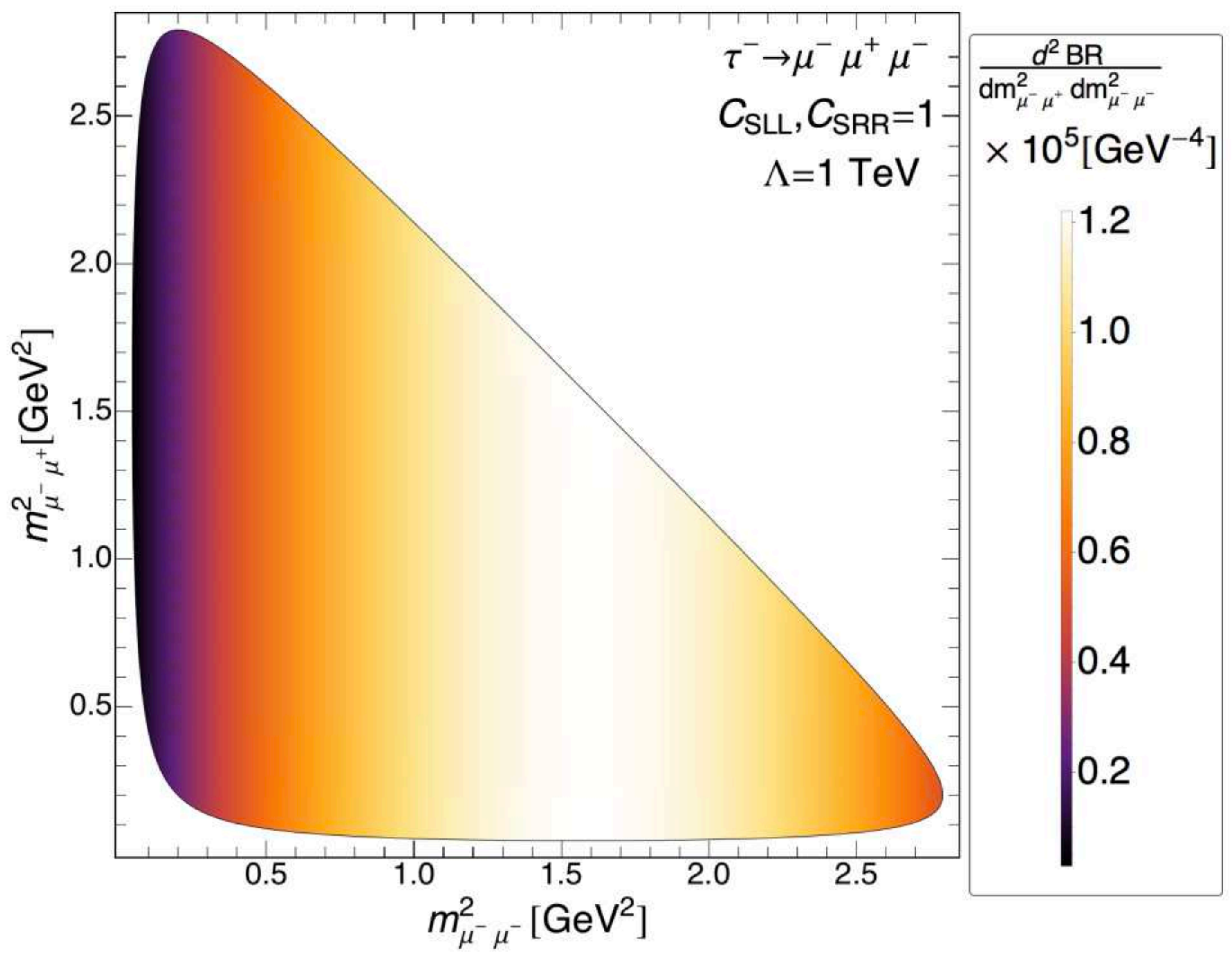
T asymmetry related to CP violation in LFV decay (phase between dipoles and vectors)

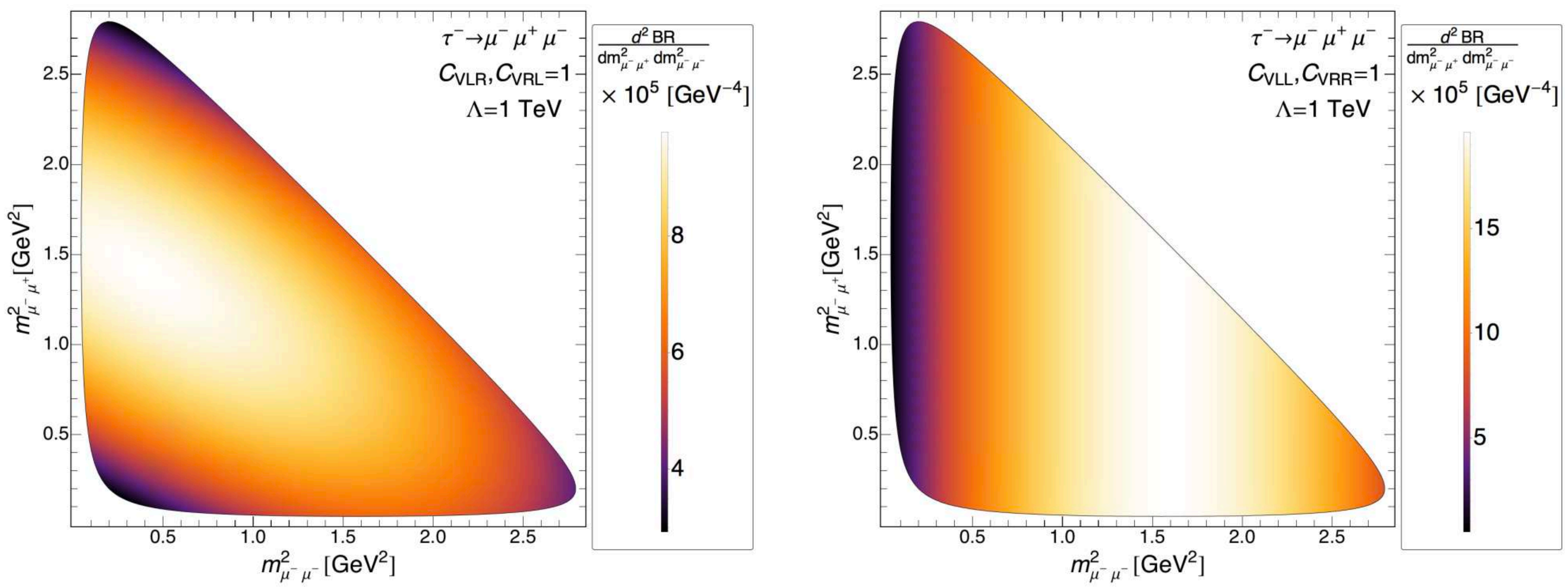
Three body decay: Dalitz plots

Celis, Passemar, Cirigliano 1403.5781

- Dalitz plots could also assist in distinguishing operators



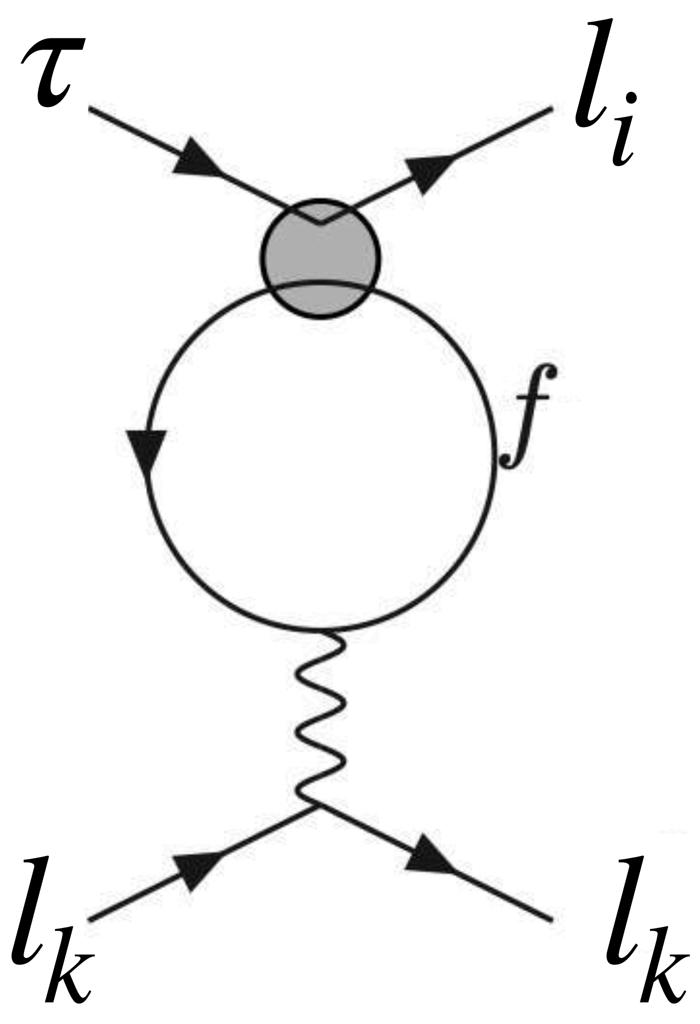
Scalars



Vectors

Leptonic three body decay: one-loop RGEs

- QED penguin can mix any $\tau \to l$ vector with the $\Delta F = 1$ four-lepton vector involved in the tree-level process, leading to a sensitivity to all vectors for NP scales $\Lambda \sim \text{few TeV}$ and $\mathcal{O}(1)$ coefficients



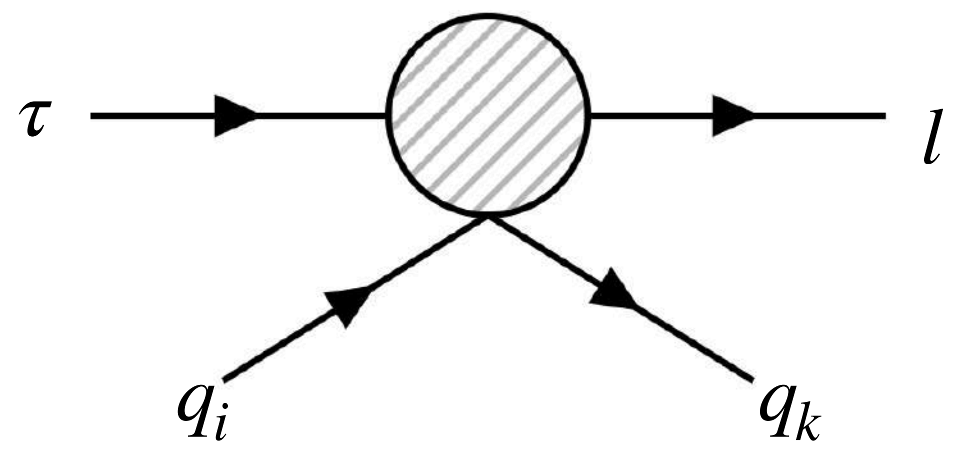
$$C_{V,XY}^{l_i \tau l_k l_k} \sim q_f \frac{\alpha}{\pi} \log\left(\frac{\Lambda}{m_\tau}\right) C_{V,XZ}^{l_i \tau f f}$$

Outline

- Leptonic decays ($\tau \to l_i\gamma$, $\tau \to l_i\bar{l}_k l_k$, $\tau \to \bar{l}_i l_k l_k$)
- Semi-leptonic decays (ex: $\tau \to \pi l_i$)
- Other processes
- Conclusion

Semi-leptonic τ LFV decays

- Various decay channels probing LFV interactions between τ flavoured currents and quarks



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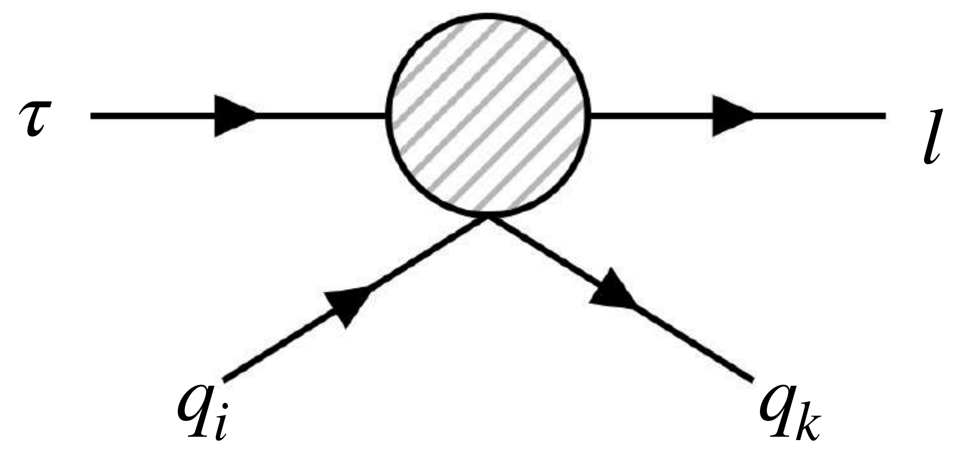

- $\tau \to lP$ where $P = \pi^0, \eta, \eta', K$

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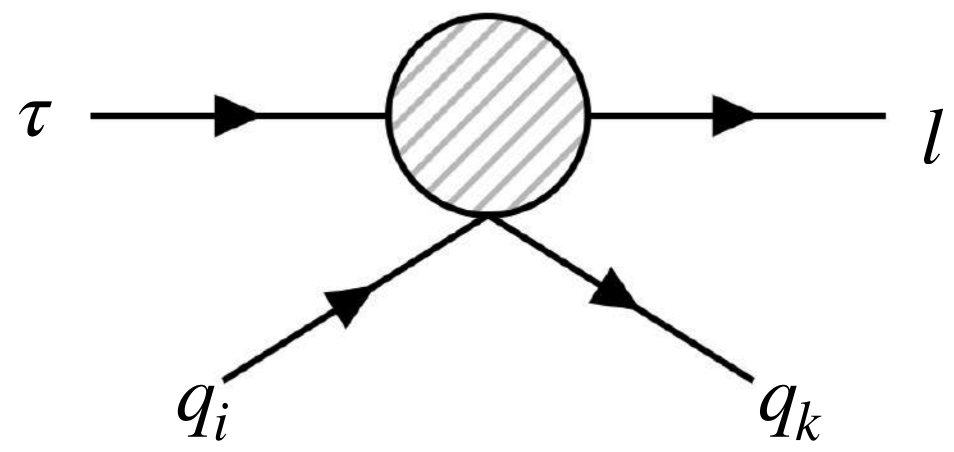

- $\tau \to lP$ where $P = \pi^0, \eta, \eta', K$

- $\tau \to lV$ where $V = \rho, \omega, K^*, \phi$

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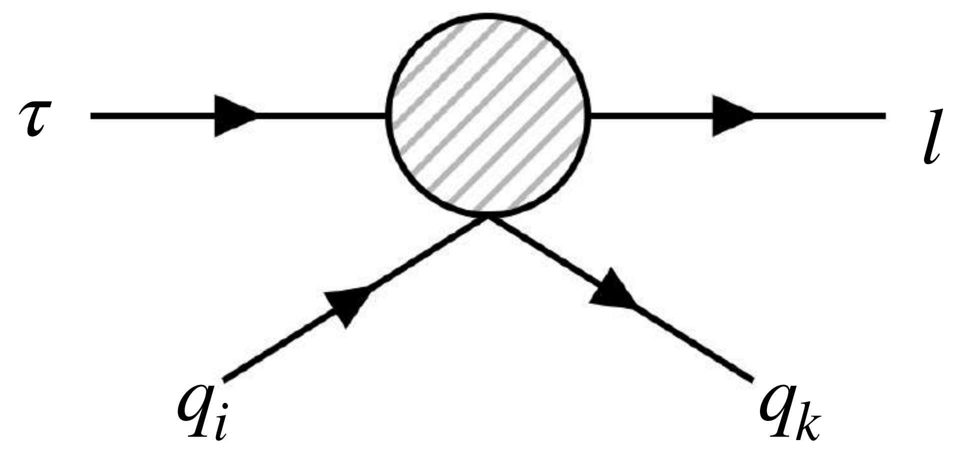

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- $\tau \to l\pi\pi,\ lKK,\ lK\pi\ldots$

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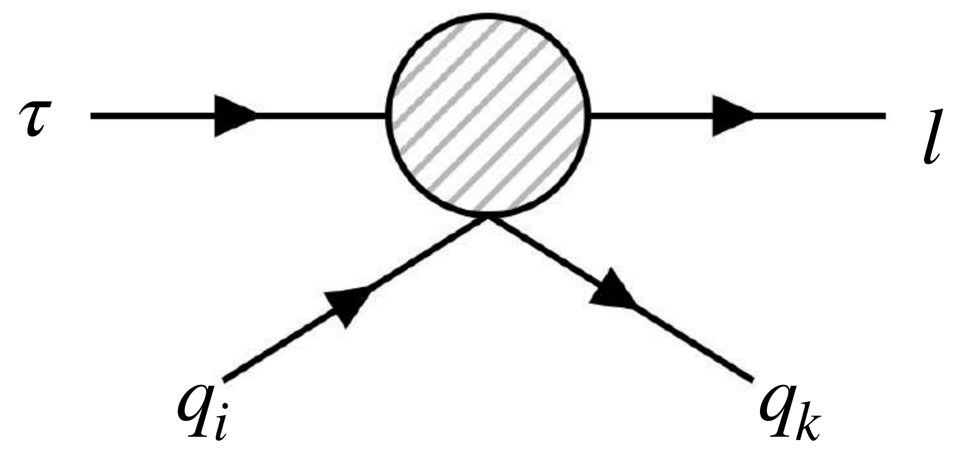

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For a recent EFT analysis see Plakias, Sumensari 2312.14070

Semi-leptonic τ LFV decays

Black et al. hep-ph/0206056

Davidson 2010.00317

- Rate predictions depend on the hadronic matrix elements

$$\left\langle 0 \left| 1/2 \left(\bar{u}\gamma^\alpha\gamma_5 u - \bar{d}\gamma^\alpha\gamma_5 d\right) \right| \pi^0(P) \right\rangle = iP^\alpha f_\pi$$

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$$\frac{Br\left(\tau \to l\pi_0\right)}{Br(\tau \to l\bar{\nu}\nu)} = \frac{3\pi^2 f_\pi^2}{m_\tau^2}\frac{v^4}{\Lambda^4}\left| C^{l\tau uu}_{V,XR} - C^{l\tau uu}_{V,XL} - C^{l\tau dd}_{V,XR} + C^{l\tau dd}_{V,XL} \right|^2$$

$$+24\pi^2\left(\frac{m_{\pi_0}}{m_\tau}\right)^4\left(\frac{f_\pi}{m_u + m_d}\right)^2\frac{v^4}{\Lambda^4}\left| C^{l\tau uu}_{S,XR} - C^{l\tau uu}_{S,XL} - C^{l\tau dd}_{S,XR} + C^{l\tau dd}_{S,XL} \right|^2$$

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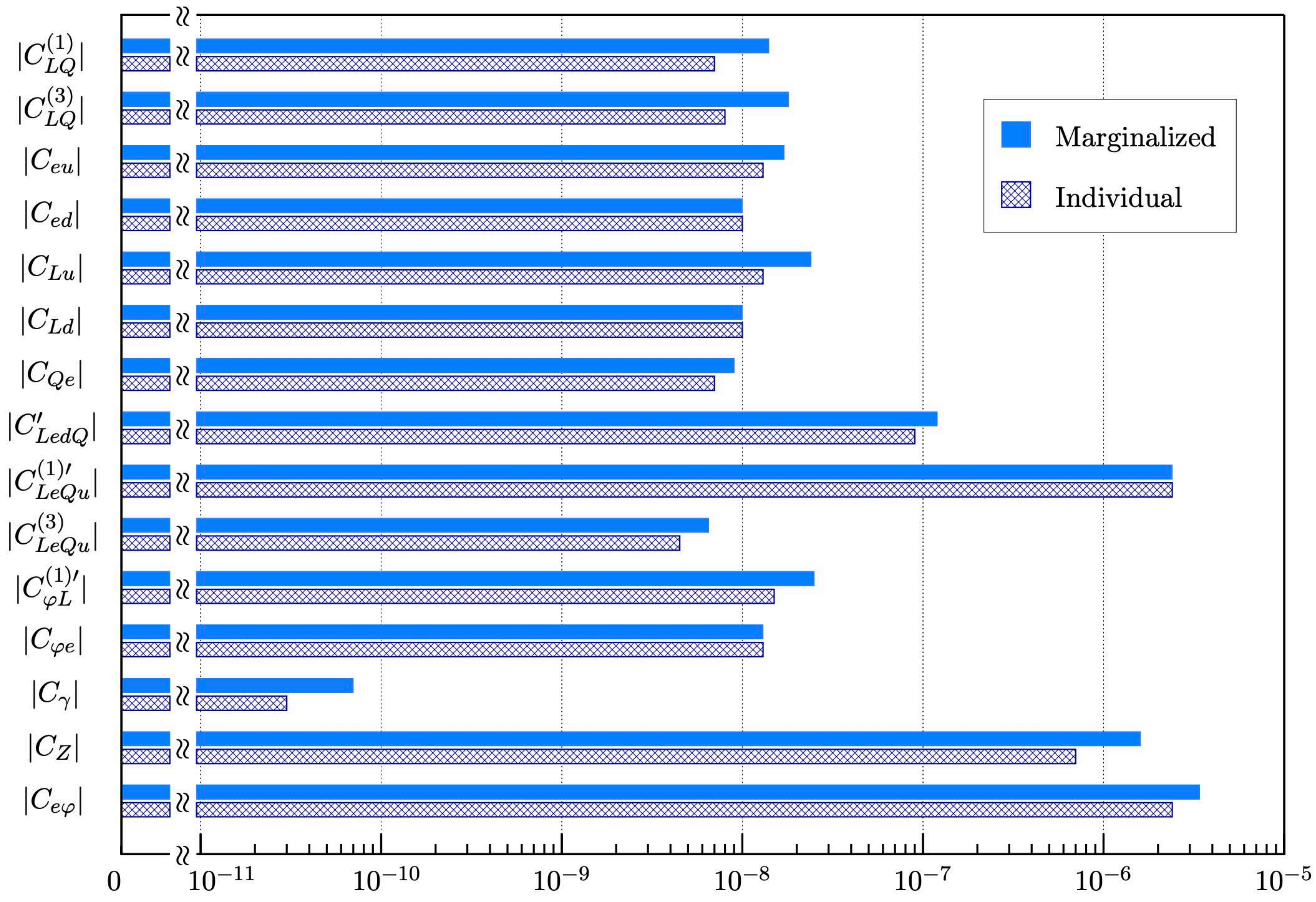
- Sensitive to all vector that can mix with the axial current at one-loop, and also marginally to tensors that can mix with the pseudoscalar current. QCD running is relevant to get numbers right!

Semi-leptonic τ LFV decays

Husek, Monsalvez, Portoles 2009.10428

- New Physics scale probed by τ LFV decays (dimension six SMEFT operators)



Differential distributions to distinguish operators

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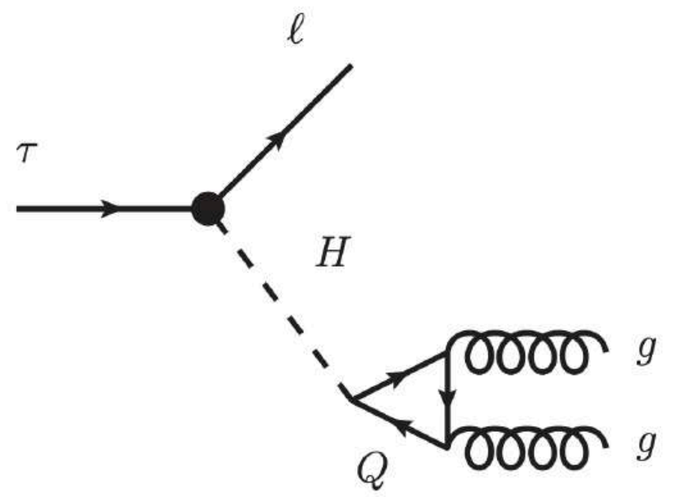

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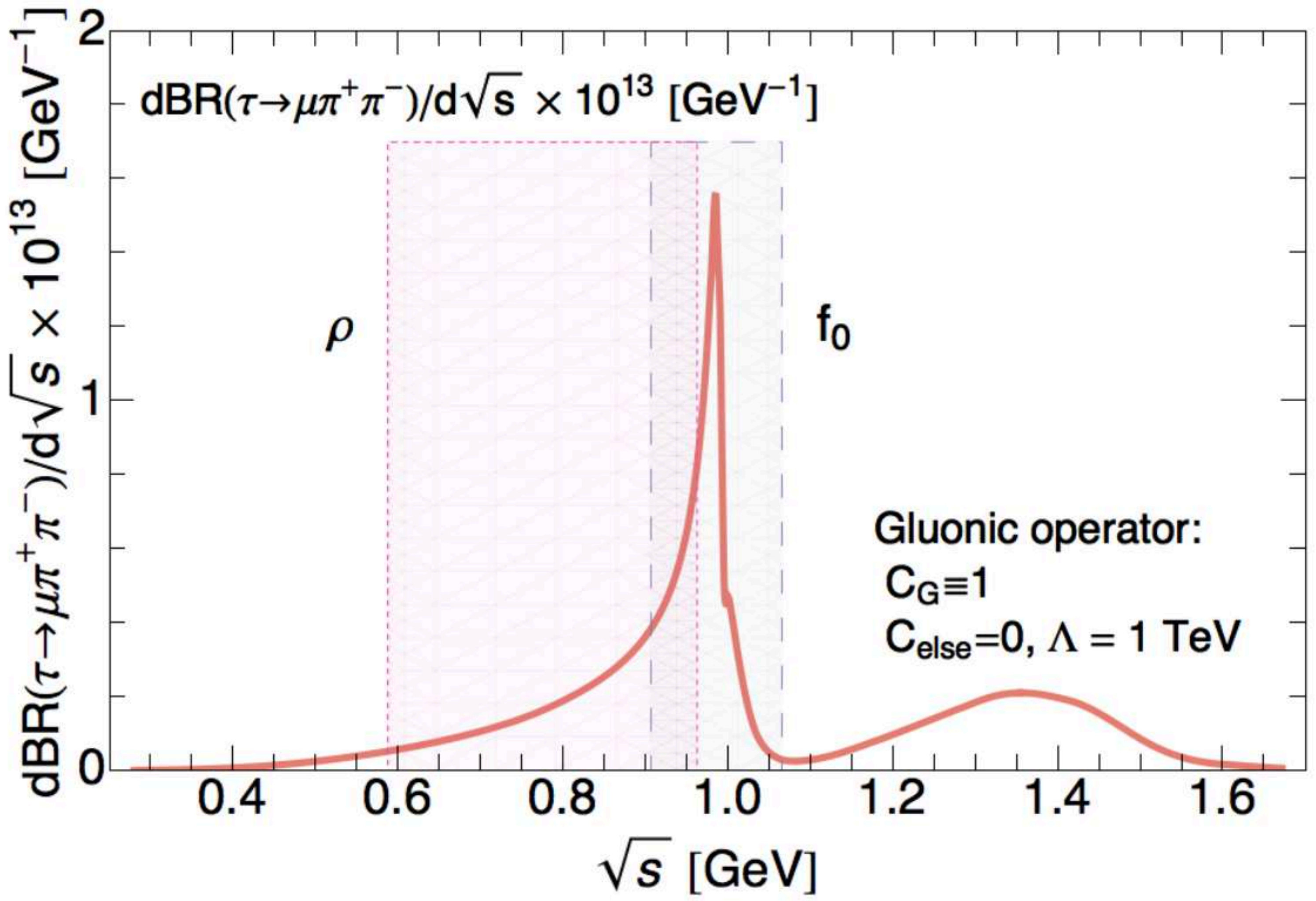

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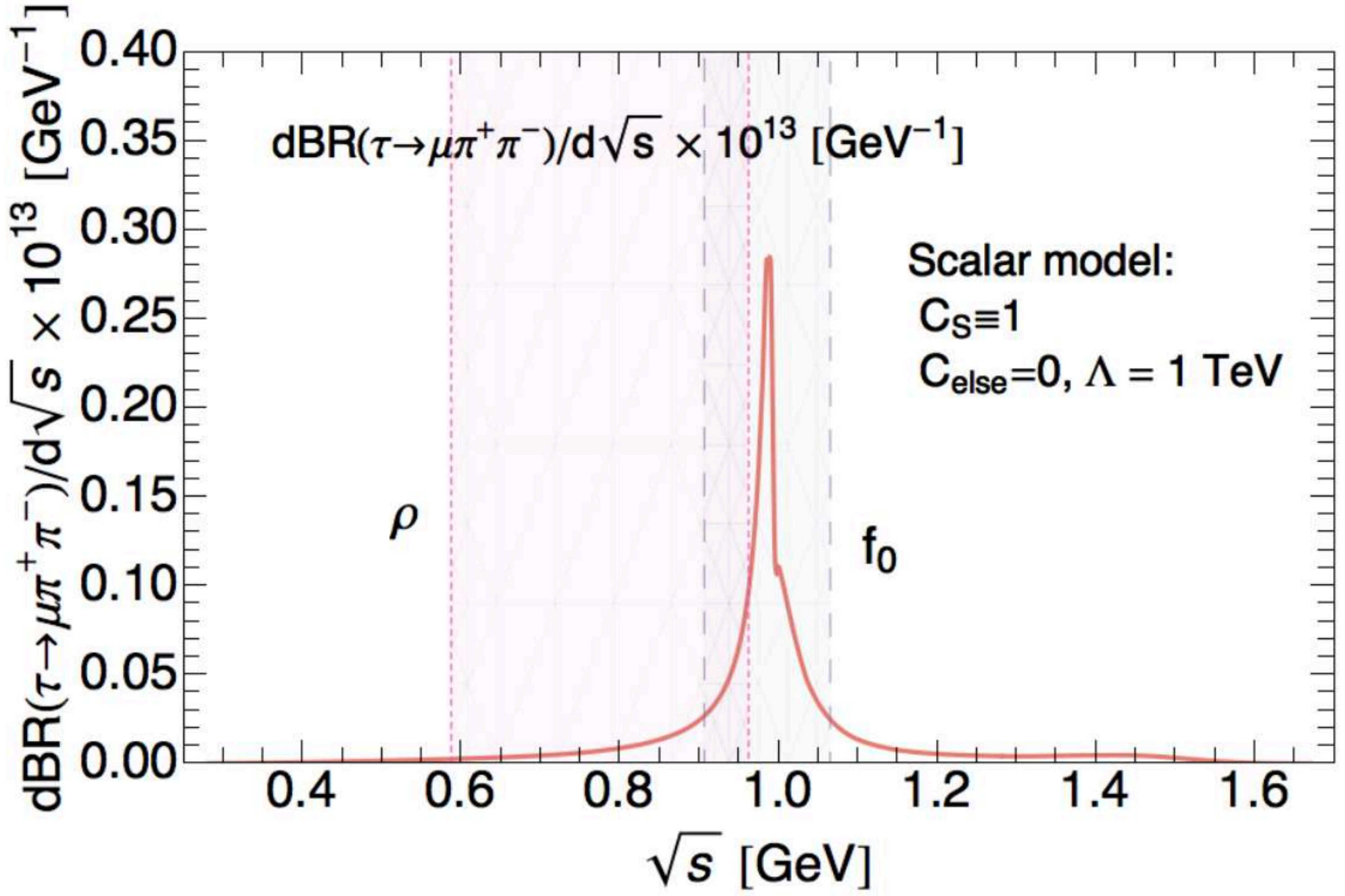

Celis, Passemar, Cirigliano 1403.5781

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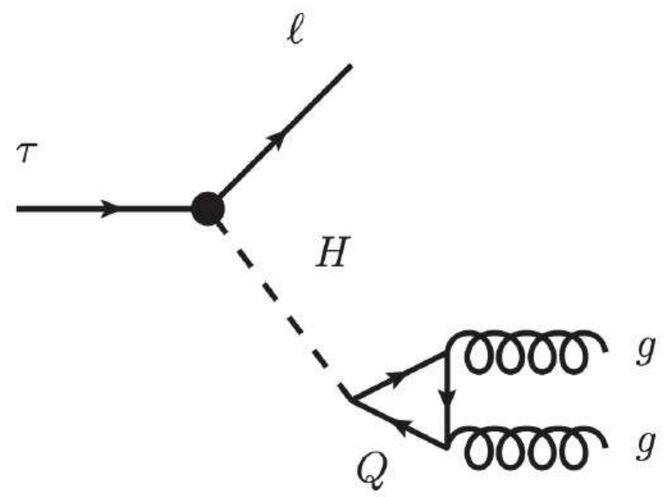

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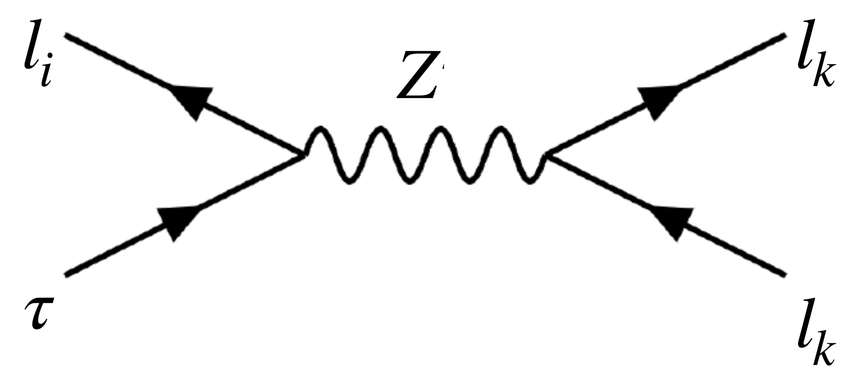
Complementarity: Z decays



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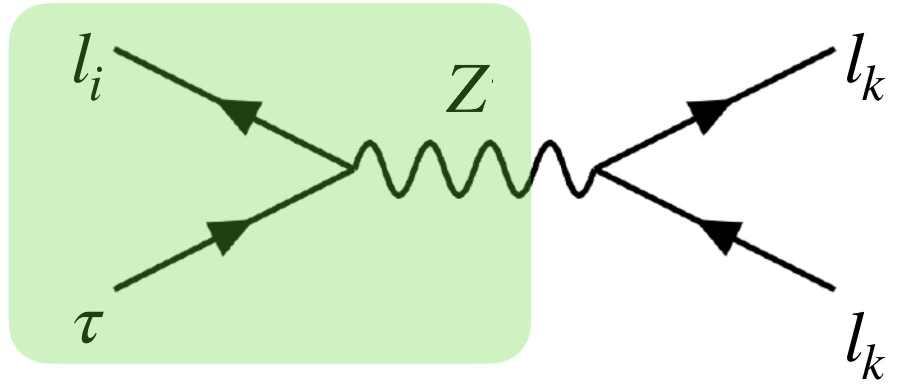

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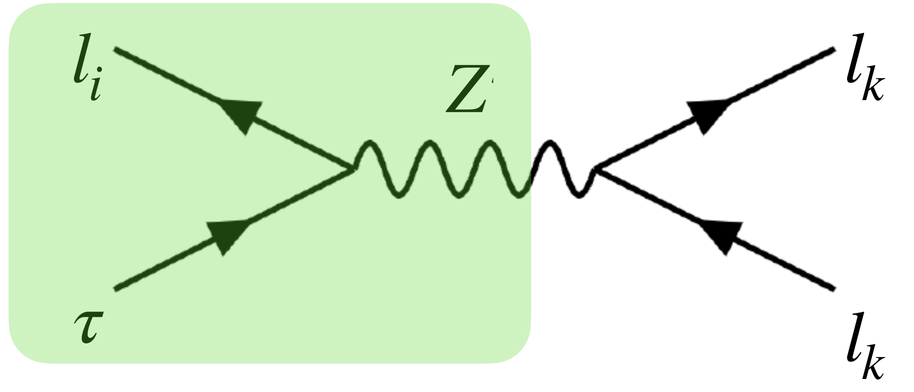

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$\mathrm{BR}(Z \to \tau e) < 5.0 \times 10^{-6}$

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LHC current bounds

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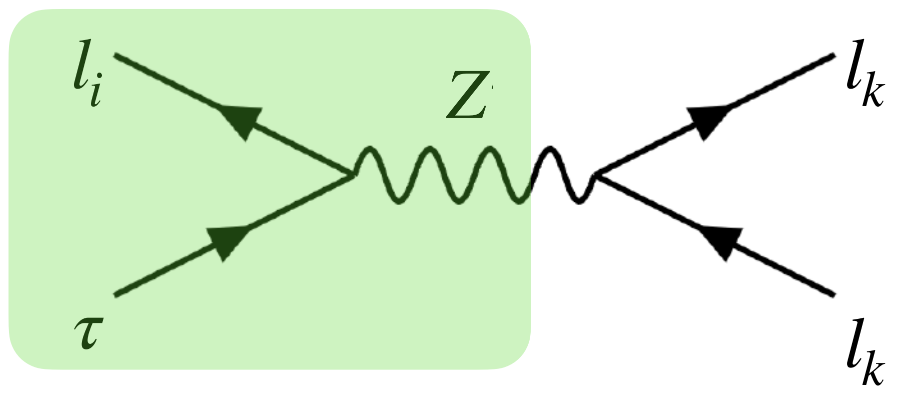

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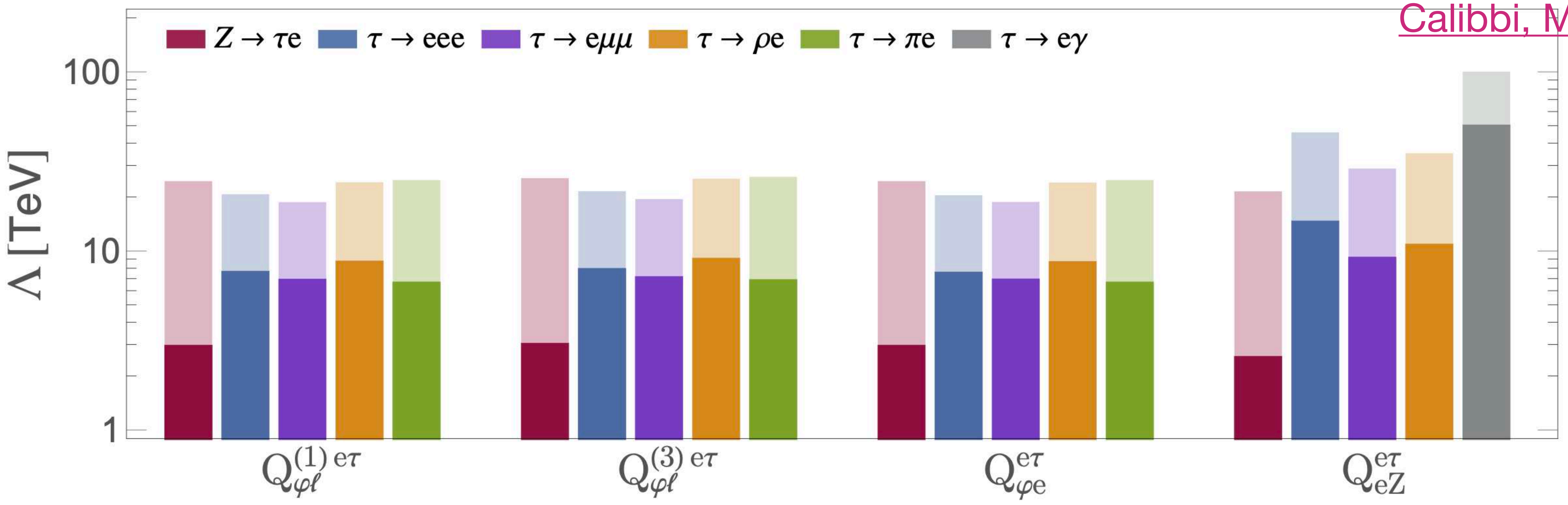
LHC current bounds

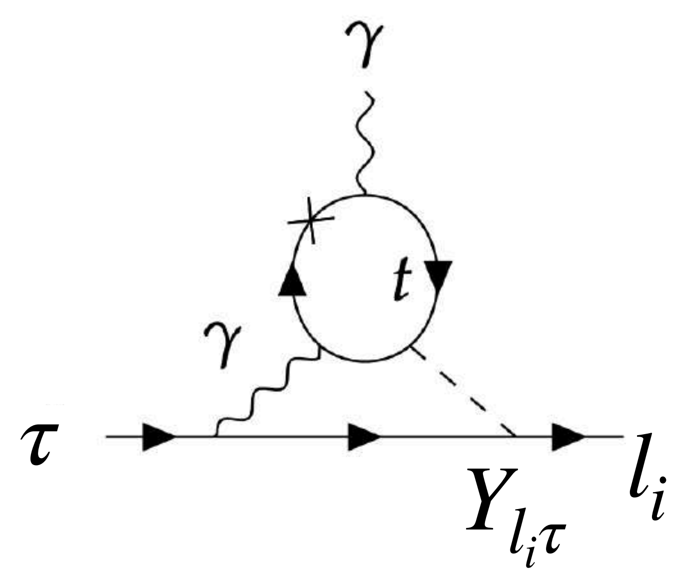
- Expect a huge number of Z at the FCC-ee = can compete/outperform the sensitivities of Belle-II for the LFV decays

Calibbi, Marcano, Roy 2107.10273

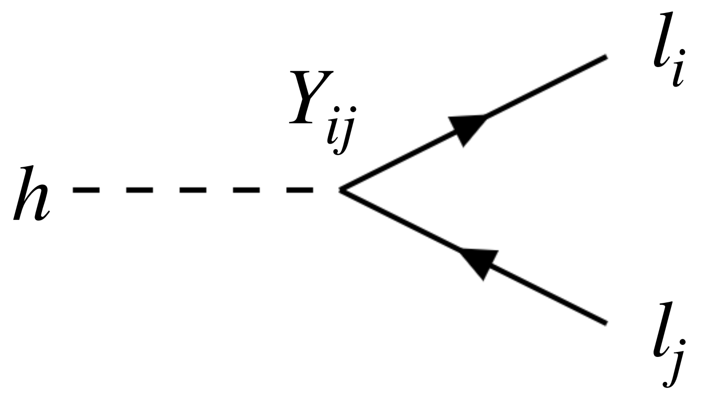


Similar for $\tau \to \mu$

Complementarity: Higgs decays



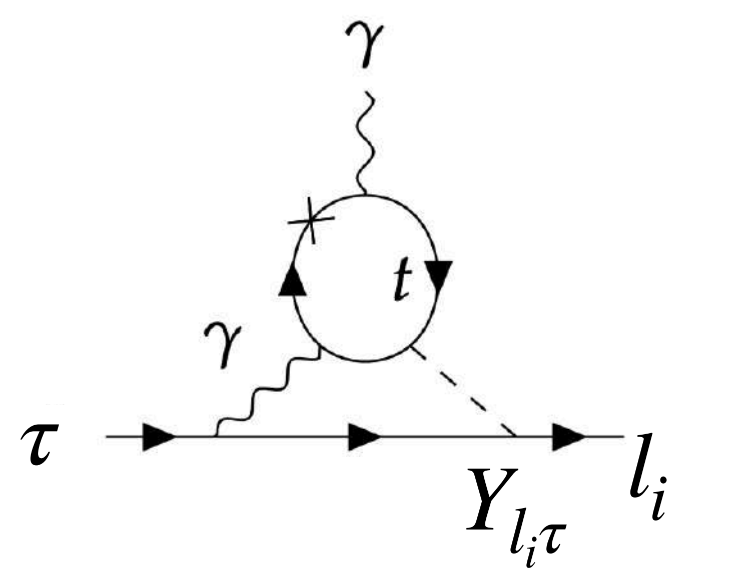
vs



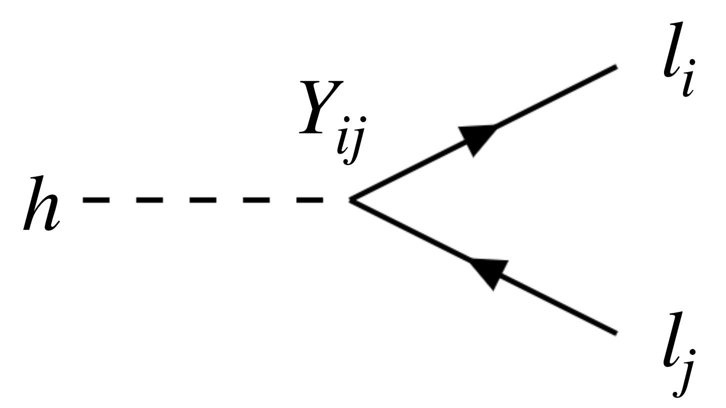
$$\mathrm{BR}(h \to \tau e) < 0.20\,\%$$
$$\mathrm{BR}(h \to \tau\mu) < 0.15\,\%$$

- If the τ decays happen via Higgs LFV couplings, they could be probed by $h \to \tau l_i$ searches

Complementarity: Higgs decays



vs



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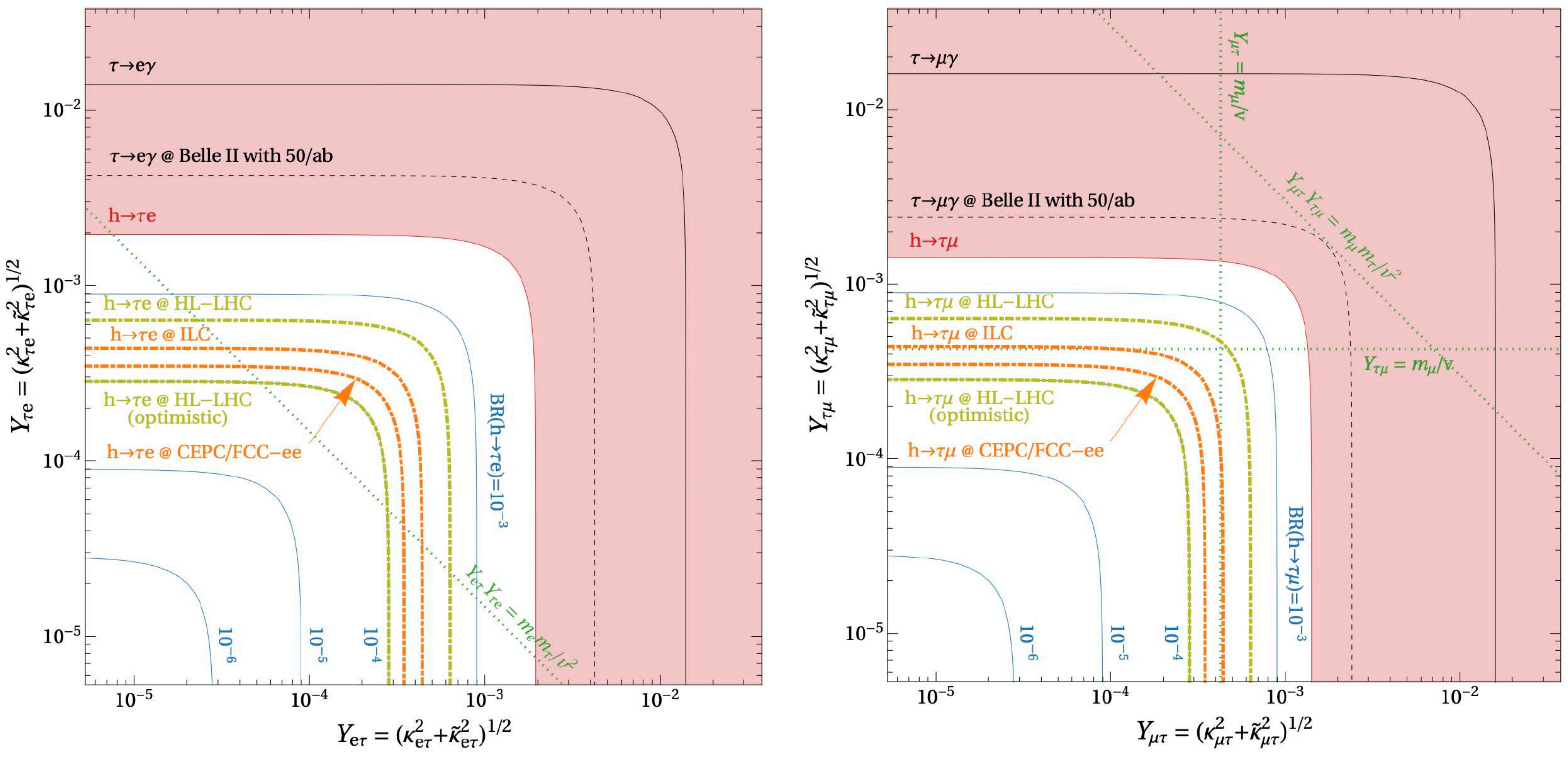

[Altmannshofer et al. 2205.10576]

Conclusion

- LFV is New Physics that must exist because we see it in neutrino oscillations, and could be just around the corner

- τ LFV is interesting because:

  A. If observed, the new interactions should be relatively large

  B. There are numerous processes that one can look for in τ decays because of the large phase space

- We can investigate τ LFV in the EFT framework by assuming heavy new states. Generally, experiments are sensitive to $\tau \to l_i$ Wilson coefficients if the New Physics scale is around $\Lambda \sim 10$ TeV

- The multitude of processes, together with Dalitz plots, angular and kinematical distributions, allow for a detailed knowledge of the EFT coefficients, with a promising potential to pinpoint particular models

- There is an interesting complementarity between high-energy probes that further restrict the space of possible UV realization

Back-up

SMEFT basis dimension six

$1: X^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D^\mu H\right)^*\left(H^\dagger D_\mu H\right)$

$5: \psi^2H^3 + \mathrm{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$

$4: X^2H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$
Q_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W^I_{\mu\nu}B^{\mu\nu}$

$6: \psi^2XH + \mathrm{h.c.}$	
Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$
Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$

$7: \psi^2H^2D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p\tau^I\gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p\tau^I\gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$	
Q_{ll}	$(\bar l_p\gamma^\mu l_r)(\bar l_s\gamma_\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma^\mu q_r)(\bar q_s\gamma_\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma^\mu\tau^I q_r)(\bar q_s\gamma_\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma^\mu l_r)(\bar q_s\gamma_\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma^\mu\tau^I l_r)(\bar q_s\gamma_\mu\tau^I q_t)$

$8: (\bar RR)(\bar RR)$	
Q_{ee}	$(\bar e_p\gamma^\mu e_r)(\bar e_s\gamma_\mu e_t)$
Q_{uu}	$(\bar u_p\gamma^\mu u_r)(\bar u_s\gamma_\mu u_t)$
Q_{dd}	$(\bar d_p\gamma^\mu d_r)(\bar d_s\gamma_\mu d_t)$
Q_{eu}	$(\bar e_p\gamma^\mu e_r)(\bar u_s\gamma_\mu u_t)$
Q_{ed}	$(\bar e_p\gamma^\mu e_r)(\bar d_s\gamma_\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar u_p\gamma^\mu u_r)(\bar d_s\gamma_\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar u_p\gamma^\mu T^A u_r)(\bar d_s\gamma_\mu T^A d_t)$

$8: (\bar LL)(\bar RR)$	
Q_{le}	$(\bar l_p\gamma^\mu l_r)(\bar e_s\gamma_\mu e_t)$
Q_{lu}	$(\bar l_p\gamma^\mu l_r)(\bar u_s\gamma_\mu u_t)$
Q_{ld}	$(\bar l_p\gamma^\mu l_r)(\bar d_s\gamma_\mu d_t)$
Q_{qe}	$(\bar q_p\gamma^\mu q_r)(\bar e_s\gamma_\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar q_p\gamma^\mu q_r)(\bar u_s\gamma_\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar q_p\gamma^\mu T^A q_r)(\bar u_s\gamma_\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar q_p\gamma^\mu q_r)(\bar d_s\gamma_\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar q_p\gamma^\mu T^A q_r)(\bar d_s\gamma_\mu T^A d_t)$

$8: (\bar LR)(\bar RL) + \mathrm{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$

$8: (\bar LR)(\bar LR) + \mathrm{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\epsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$

$8: (\not B) + \mathrm{h.c.}$	
Q_{duql}	$\epsilon_{\alpha\beta\gamma}\epsilon_{jk}(d_p^\alpha C u_r^\beta)(q_s^{j\gamma} C l_t^k)$
Q_{qque}	$\epsilon_{\alpha\beta\gamma}\epsilon_{jk}(q_p^{j\alpha} C q_r^{k\beta})(u_s^\gamma C e_t)$
Q_{qqql}	$\epsilon_{\alpha\beta\gamma}\epsilon_{mn}\epsilon_{jk}(q_p^{m\alpha} C q_r^{j\beta})(q_s^{k\gamma} C l_t^n)$
Q_{duue}	$\epsilon_{\alpha\beta\gamma}(d_p^\alpha C u_r^\beta)(u_s^\gamma C e_t)$

Should we expect large(r) $\tau \to l$?

- We know that $\mu \to e$ is very suppressed $Br(\mu \to e) \lesssim 10^{-13} \to 10^{-18}$

- If we see $\tau \to l$, then it should be orders of magnitude bigger than $\mu \to e$

- Perhaps large $\tau \to l$ is connected to the Flavour Puzzle and residual flavour symmetries at the low energy may favor τ LFV

Lepton Flavour Triality 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, $+1$, $+1$, $\Delta T = 0 \mod 3$

- But also new states that dominantly couple with third generation fermions may lead to larger LFV involving taus

Hadronic matrix elements

Husek, Monsalvez, Portoles 2009.10428

$$
\begin{aligned}
[\, i\,\overline{q}_i\,\gamma_5\,q_j \;\to\; P\,] \quad &\simeq \quad 2\,B_0\,F\,\Omega_P^{(1)}(ij) \,+\, 2\,\frac{B_0}{F}\,\frac{d_m^2}{M_P^2}\,m_K^2\,\Omega_P^{(2)}(ij)\,,\\
[\,\overline{q}_i\,\gamma_\mu\,\gamma_5\,q_j \;\to\; P\,] \quad &\simeq \quad -i\,2\,F\,\Omega_A^{(1)}(ij)\,p_\mu\,,\\
[\,\overline{q}_i\,\gamma_\mu\,q_j \;\to\; V\,] \quad &\simeq \quad -2\,F_V\,M_V\,\Omega_V^{(1)}(ij)\,\varepsilon_\mu\,,\\
[\,\overline{q}_i\,\sigma_{\mu\nu}\,q_j \;\to\; V\,] \quad &\simeq \quad i\,2\,\frac{T_V}{M_V}\,\Omega_T^{(1)}(ij)\,(\,p_\mu\,\varepsilon_\nu \,-\, p_\nu\,\varepsilon_\mu\,)\,,
\end{aligned}
$$

$$
\begin{aligned}
[\,\overline{q}_i\,q_j \;\to\; P_1\,P_2\,] \simeq\; & 2\,B_0\,\Omega_S^{(1)}(ij)\left[1+4\,\frac{L_5^{\rm SD}}{F^2}\,\left(s-m_1^2-m_2^2\right)\right] + \,2\,\frac{B_0}{F^2}\,\frac{d_m^2}{M_P^2}\,m_K^2\,\Omega_S^{(2)}(ij)\\
&+\frac{B_0}{F^2}\,c_m\sum_S\frac{\Omega_S^{(3)}(ij)}{s\,-\,M_S^2}\left[c_d\,\Omega_S^{(4)}\,\left(\,s\,-\,m_1^2\,-\,m_2^2\,\right)\,+\,2\,c_m\,m_K^2\,\Omega_S^{(5)}\right]\\
&+\frac{1}{3}\,\frac{B_0}{F^2}\,\gamma\sum_T\frac{\Omega_T^{(2)}(ij)}{M_T^4}\,\Big\{g_T\,\Omega_T^{(3)}\,\left[\,(m_1^2-m_2^2)^2\,+\,M_T^2\,(m_1^2+m_2^2)\right.\\
&\left.-\,s\,(M_T^2+s)\right]\,+\,2\,(2M_T^2+s)\,\left[\beta\,\Omega_T^{(4)}(m_1^2+m_2^2-s)\,-\,2\,\gamma\,m_K^2\,\Omega_T^{(5)}\right]\Big\}\,,\\
[\,\overline{q}_i\,\gamma_\mu\,q_j \;\to\; P_1\,P_2\,] \simeq\; & \left[2\,\Omega_V^{(2)}(ij)\,+\,\sqrt{2}\,\frac{F_V\,G_V}{F^2}\sum_V\frac{s}{M_V^2\,-\,s}\,\Omega_V^{(1)}(ij)\,\Omega_V^{(3)}\right](\,p_1\,-\,p_2\,)_\mu\\
&+\left[\sqrt{2}\,\frac{F_V\,G_V}{F^2}\,(m_2^2-m_1^2)\sum_V\frac{\Omega_V^{(1)}(ij)\,\Omega_V^{(3)}}{M_V^2\,-\,s}\right](\,p_1\,+\,p_2\,)_\mu\,,\\
[\,\overline{q}_i\,\sigma^{\mu\nu}\,q_j \;\to\; P_1\,P_2\,] \simeq\; & \frac{i}{F^2}\left[-\Lambda_2^{\rm SD}\,\Omega_T^{(6)}(ij)\,+\,2\,\sqrt{2}\,G_V\,T_V\sum_V\frac{\Omega_T^{(1)}(ij)\,\Omega_V^{(3)}}{M_V^2\,-\,s}\right](\,p_1^\mu\,p_2^\nu\,-\,p_1^\nu\,p_2^\mu\,)\,.
\end{aligned}
$$