Flavour and Collider Signals from a Singly Charged Scalar

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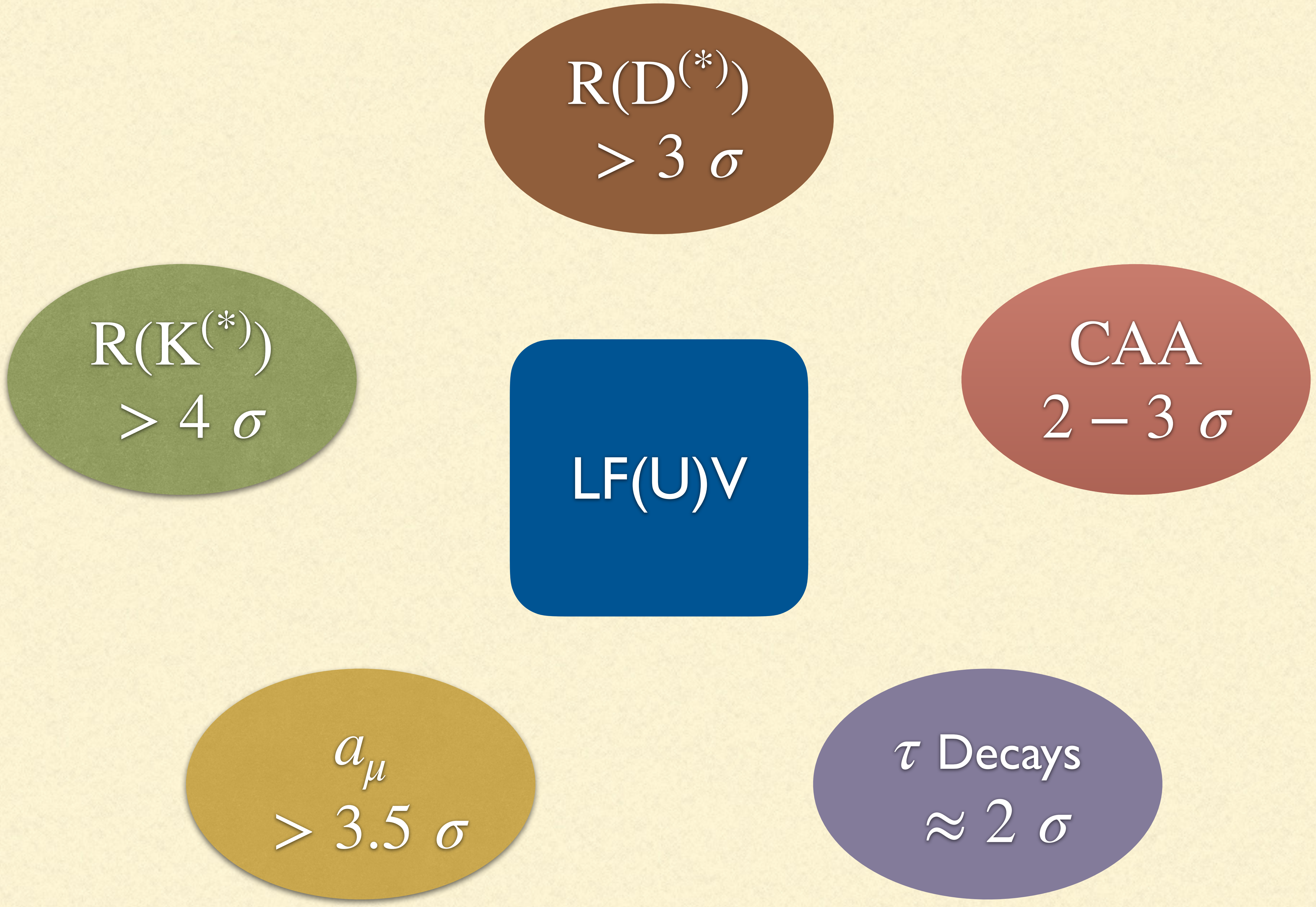
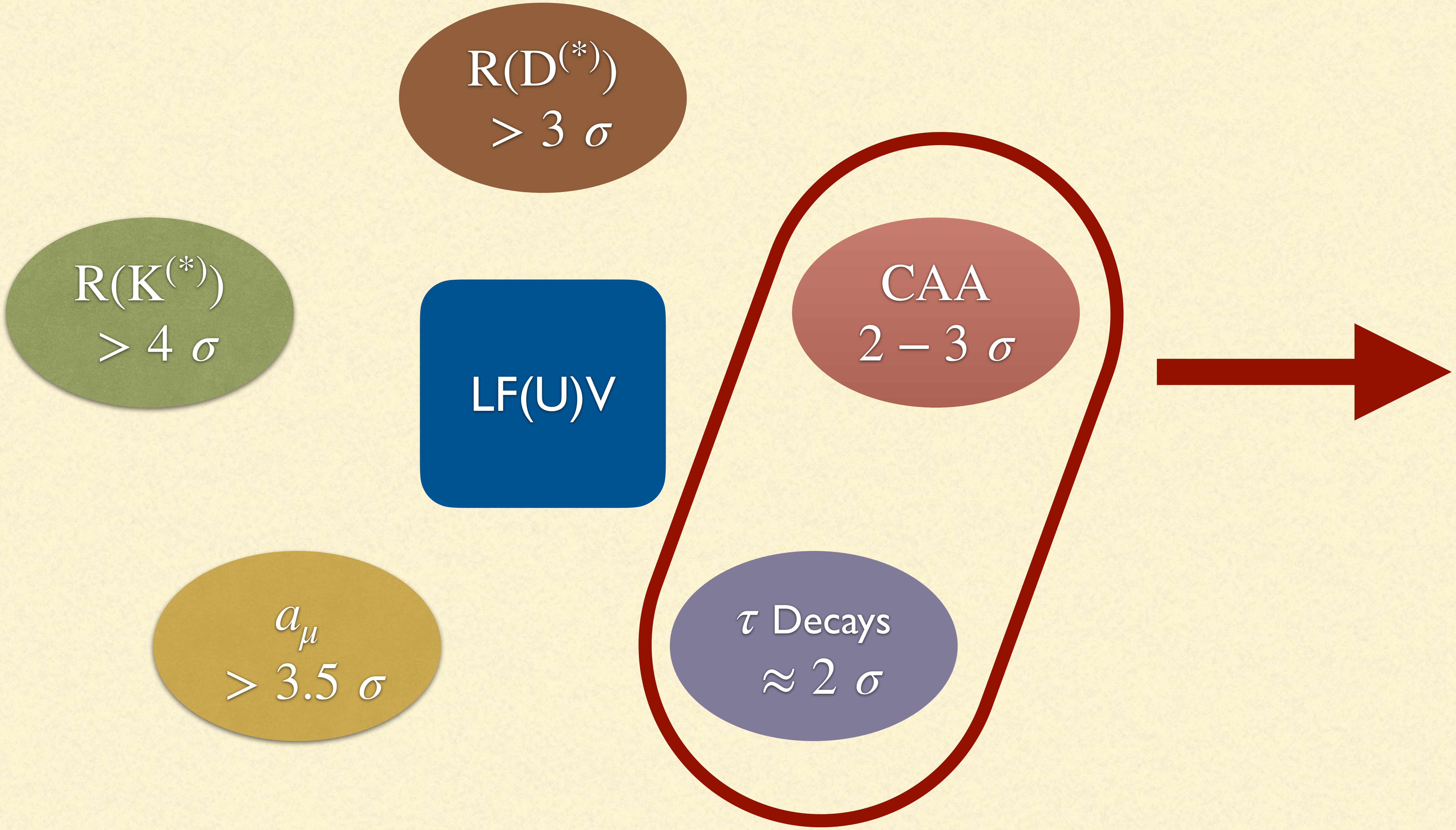
A.Crivellin, F.Kirk, C.A.M., L.Panizzi arXiv: 2012.09845

Violation of Lepton Flavour Universality



Violation of Lepton Flavour Universality



Data Require a Constructive NP effect in:

$$\mu \to e\nu\nu \ \& \ \tau \to \mu\nu\nu$$

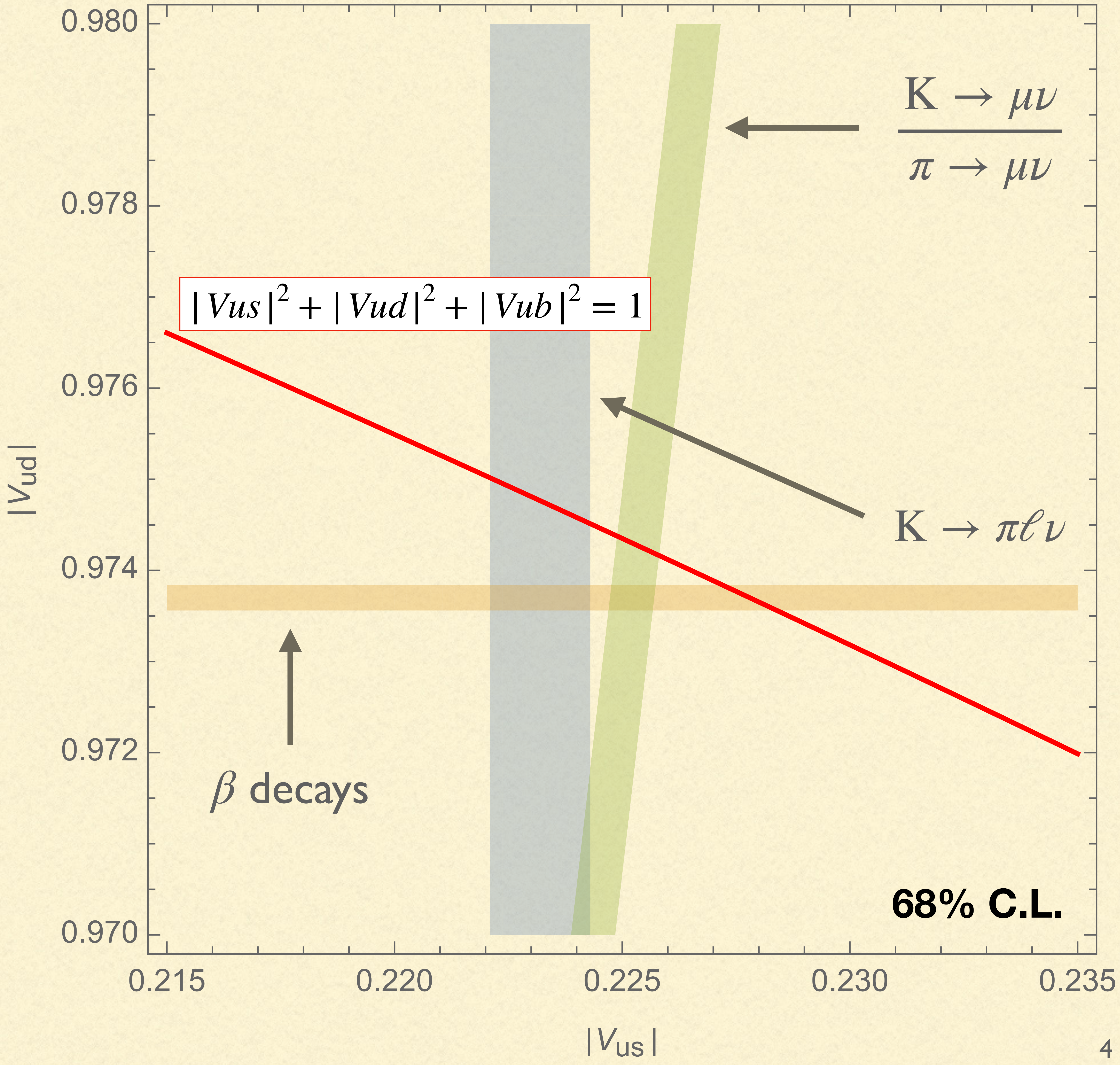
Cabibbo Angle Anomaly

PDG 2020

$$|V_{us}|^2 + |V_{ud}|^2 + |V_{ub}|^2 = 0.9985(5)$$

$$\left|\frac{V_{ud}}{V_{us}}\right|^2 \sim 20$$

≈ 0.0037, negligible



Cabibbo Angle Anomaly

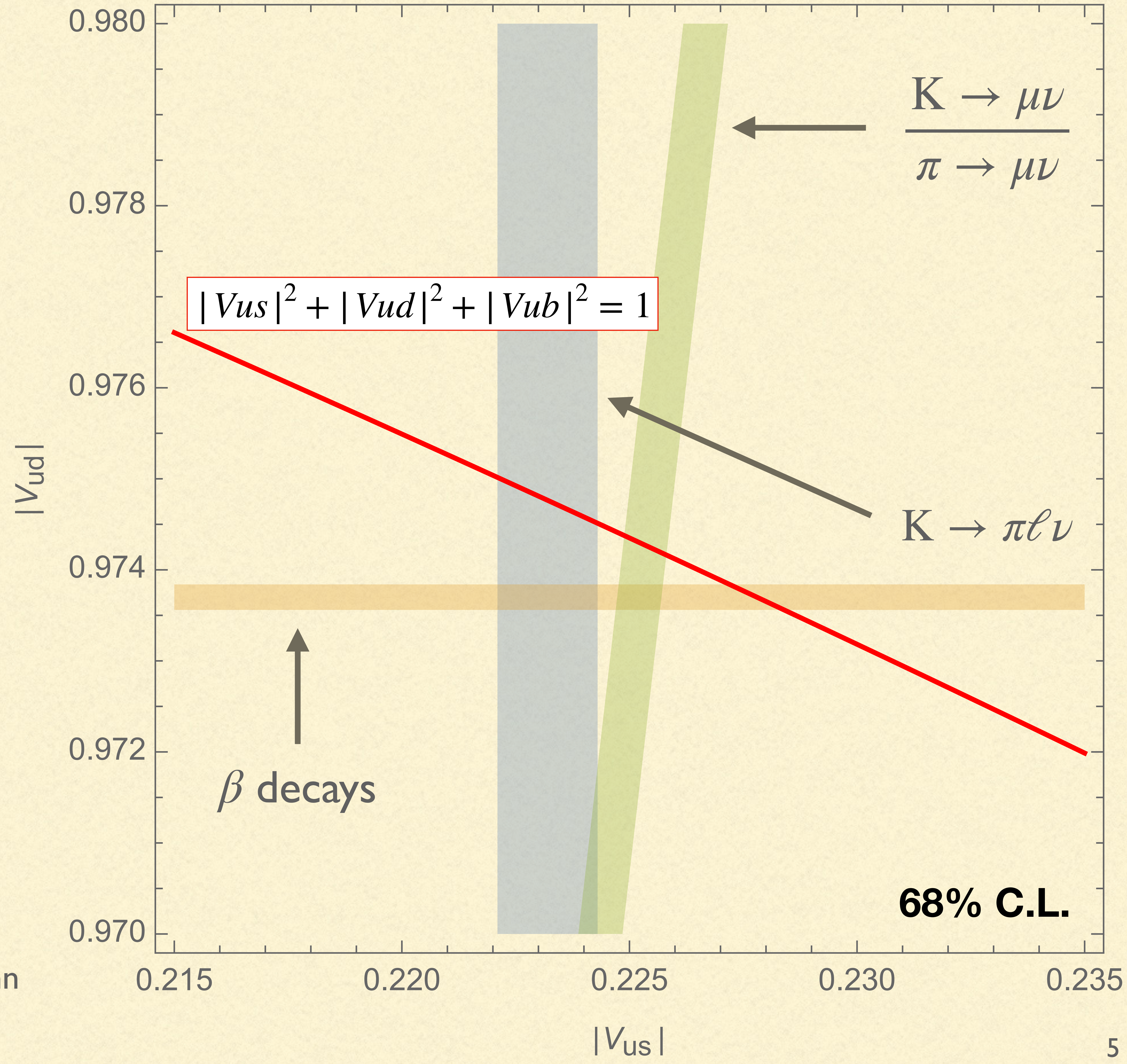
PDG 2020

$$|V_{us}|^2 + |V_{ud}|^2 + |V_{ub}|^2 = 0.9985(5)$$

$$\left|\frac{V_{ud}}{V_{us}}\right| \sim 20 \qquad \approx 0.0037\text{, negligible}$$

?

$$|V_{us}|^2 + |V_{ud}|^2(1-\varepsilon)^2 + |V_{ub}|^2 = 0.9985(5)$$



Note: there is also a (less significant) deficit in the first column of the CKM unitarity relation. This further strengthen the idea of a modification in V_{ud} from β decays.

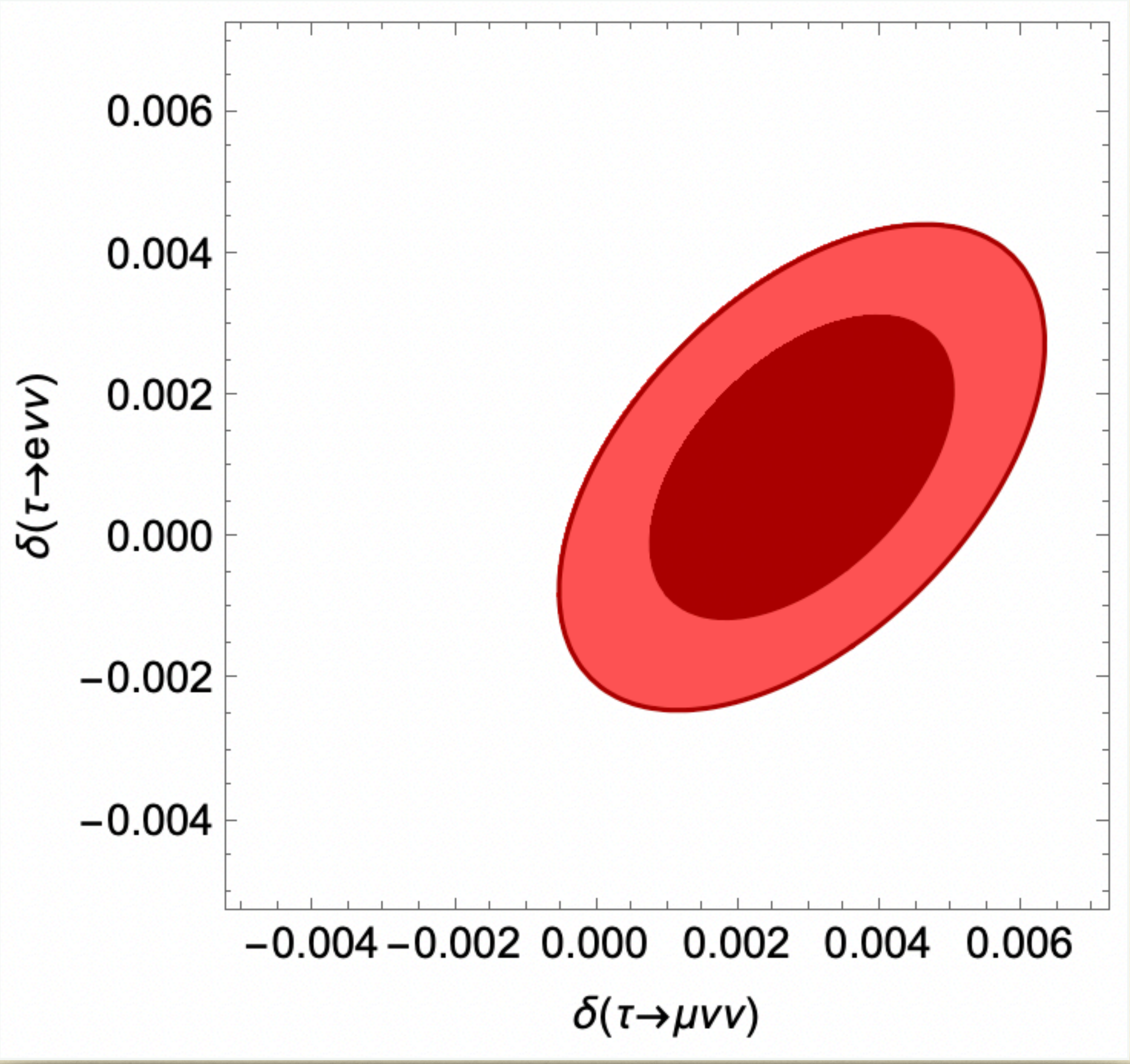
τ Decays

$$\left.\frac{\mathscr{A}(\tau \to \mu\nu\bar{\nu})}{\mathscr{A}(\mu \to e\nu\bar{\nu})}\right|_{EXP} = 1.0029(14)$$

$$\left.\frac{\mathscr{A}(\tau \to \mu\nu\bar{\nu})}{\mathscr{A}(\tau \to e\nu\bar{\nu})}\right|_{EXP} = 1.0018(14)$$

$$\left.\frac{\mathscr{A}(\tau \to e\nu\bar{\nu})}{\mathscr{A}(\mu \to e\nu\bar{\nu})}\right|_{EXP} = 1.0010(14)$$

$\mu \to e\nu\nu$ shows explicitly the connection with CAA



The Singly Charged Scalar

$$\mathscr{L} = \mathscr{L}_{SM} - \left(\frac{\lambda_{ij}}{2} \bar{L}^c_{a,i} \varepsilon_{ab} L_{b,j} \phi^+ + h.c. \right)$$

$$\lambda_{12}(\bar{e}^c \nu_\mu - \bar{\nu}^c_e \mu)\phi^+ + \dots$$

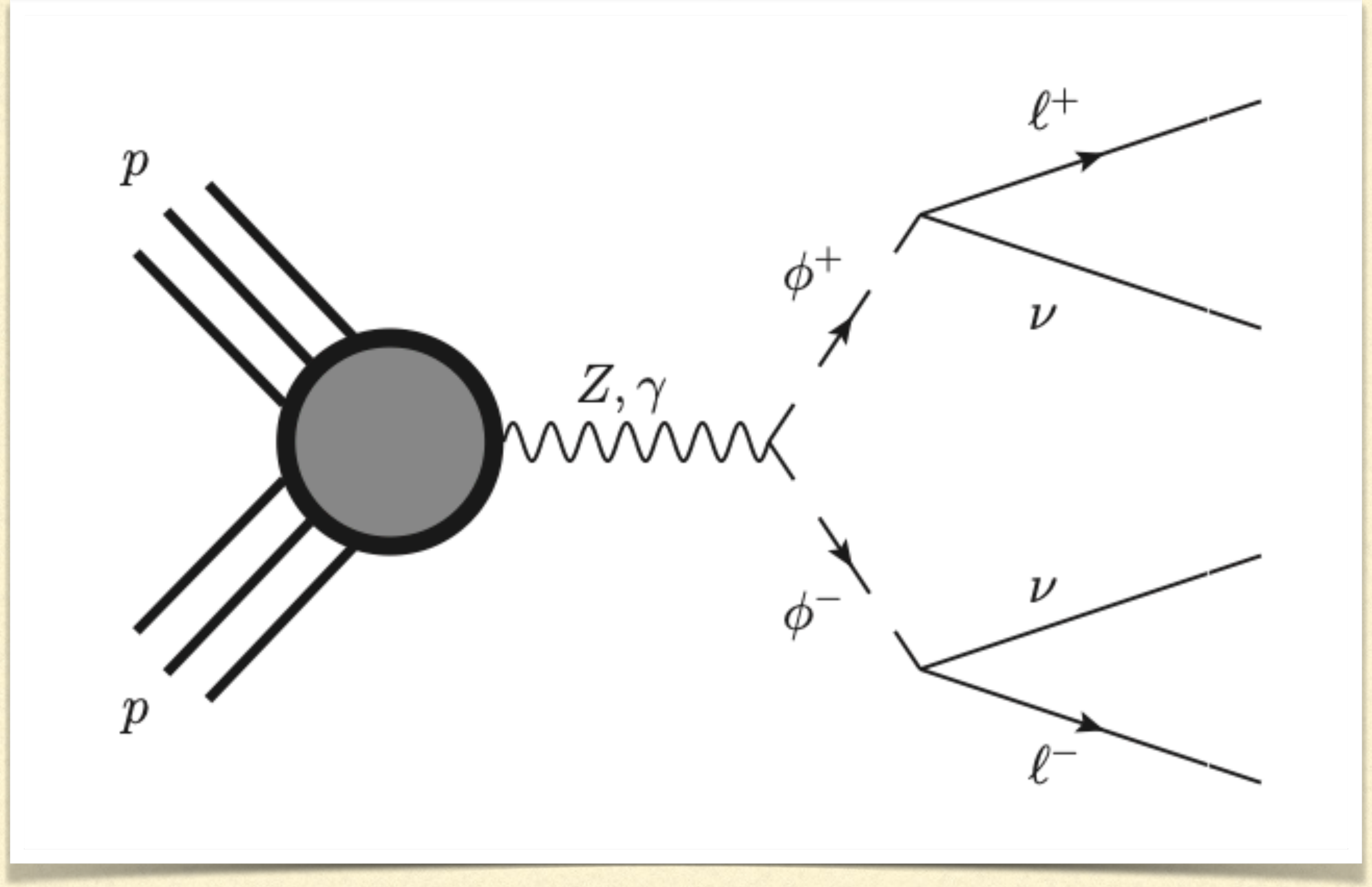
- $Y = +1, \quad \mathrm{SU(2)_L}$ singlet, $\quad Q = +1$
- Cannot couple to quarks

Automatically violates Lepton Flavour

- Couplings are <u>anti-symmetric</u> in flavour space $\Longrightarrow$ **only 3 free couplings!**

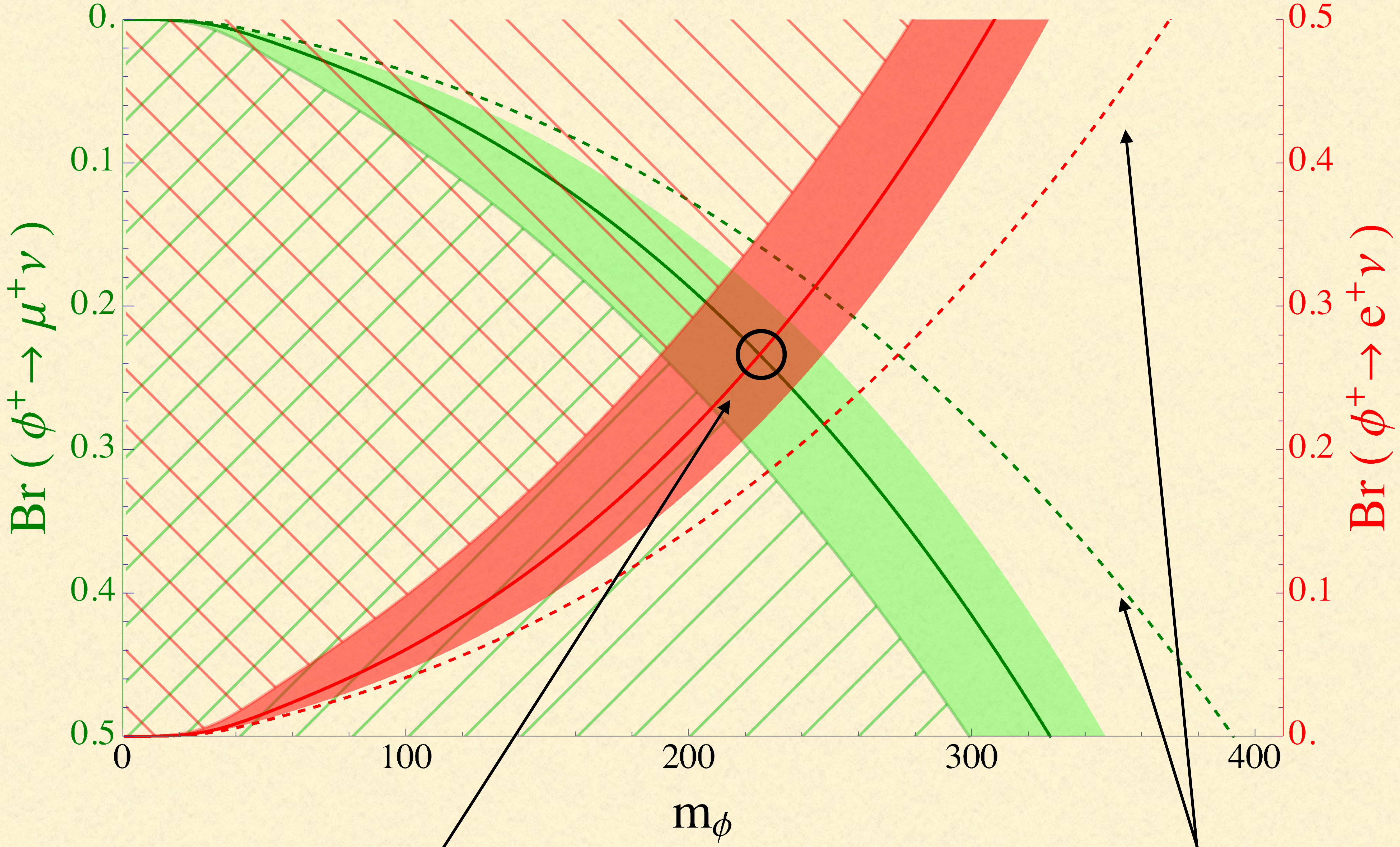
Note: $\lambda H^\dagger H \phi^+ \phi^-$ contributes to the mass m_ϕ and has only a significant impact on $h \to \gamma\gamma$

LHC Searches



Drell-Yan Pair production

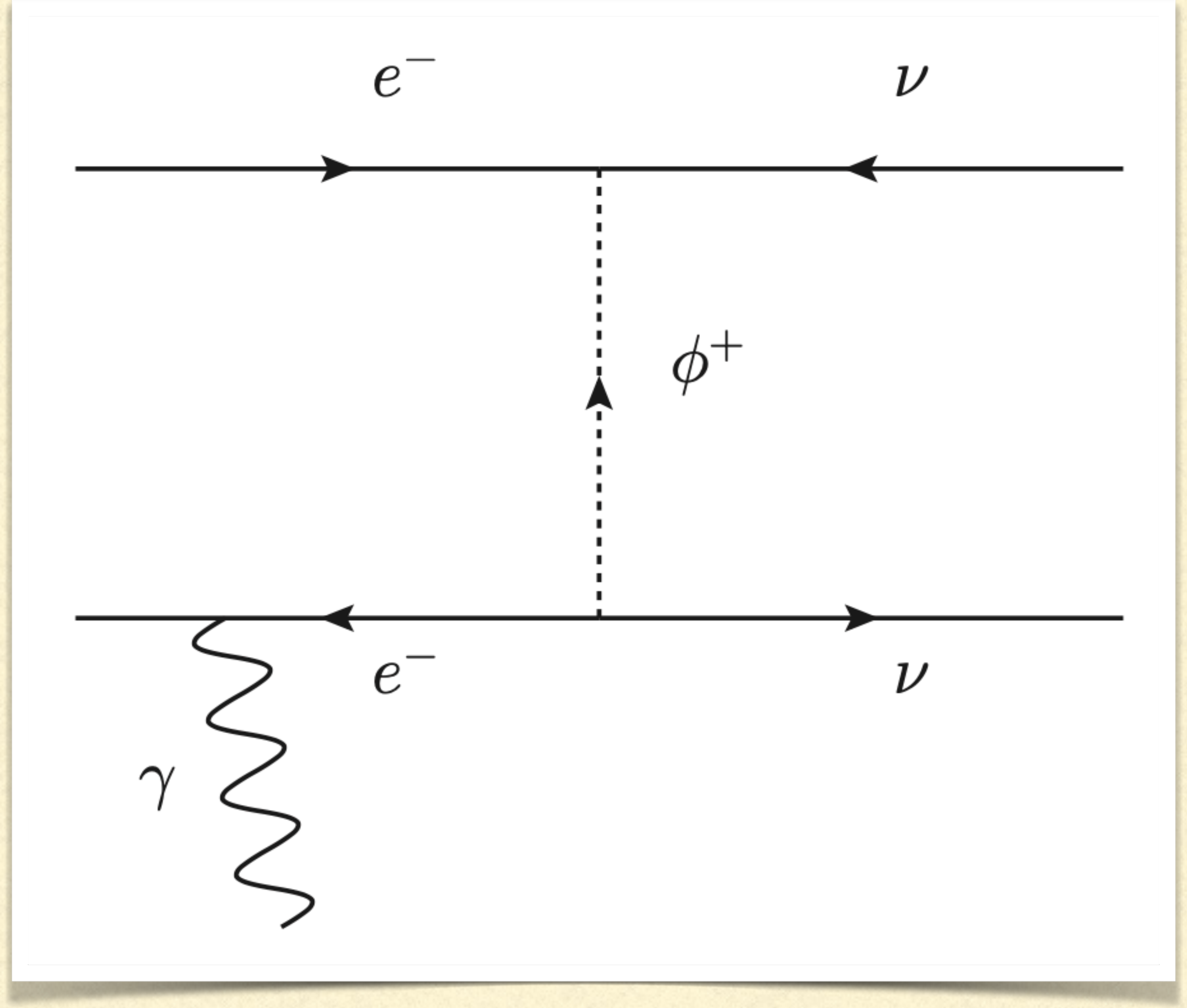
Recast of ATLAS searches for sleptons at 139 fb^{-1} arXiv:1908.08215 [hep-ex]



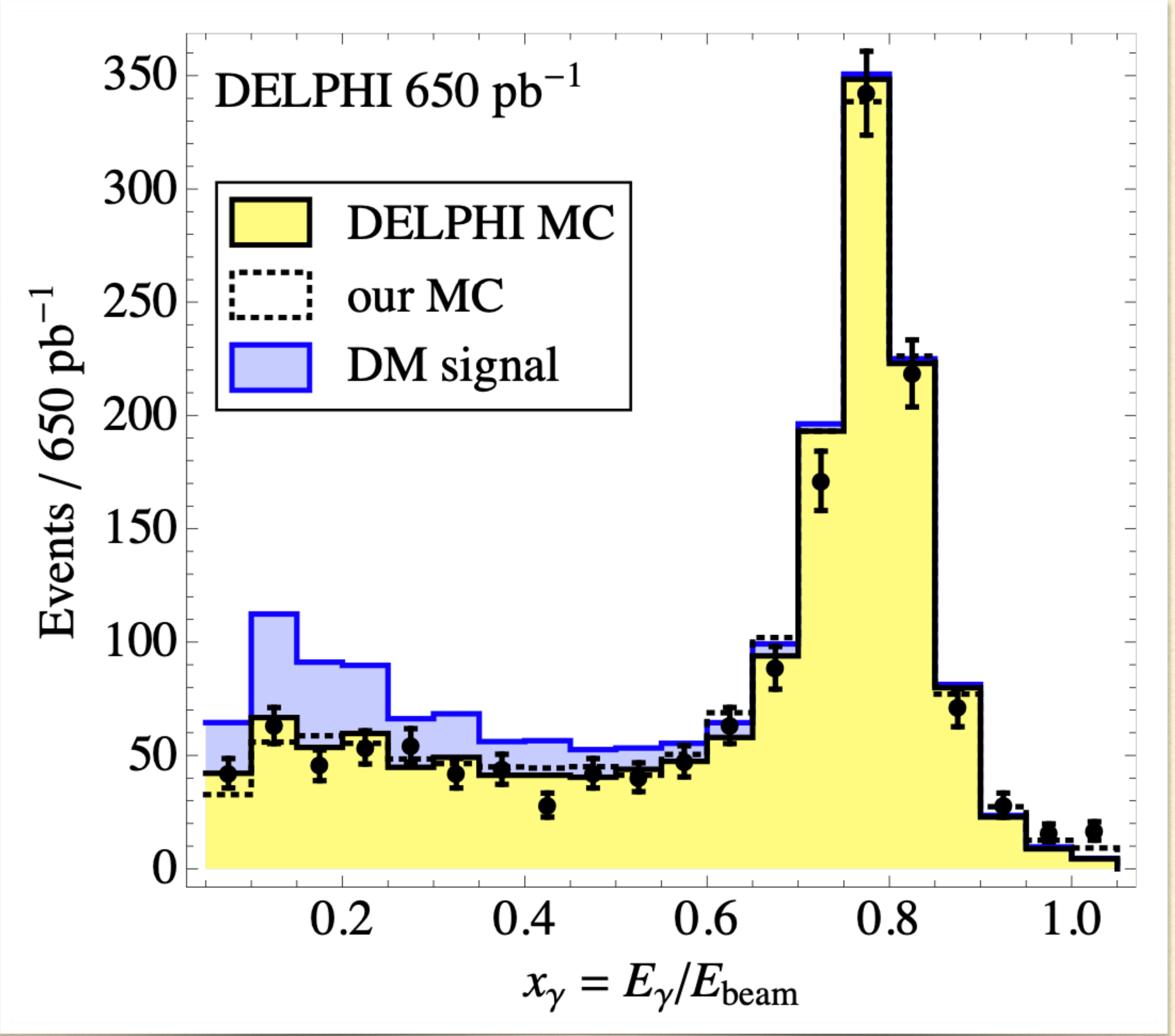
Model Independent limit due to the anti-symmetry of the couplings

Projected exclusion reach for a luminosity of 3/ab

Mono Photon Searches

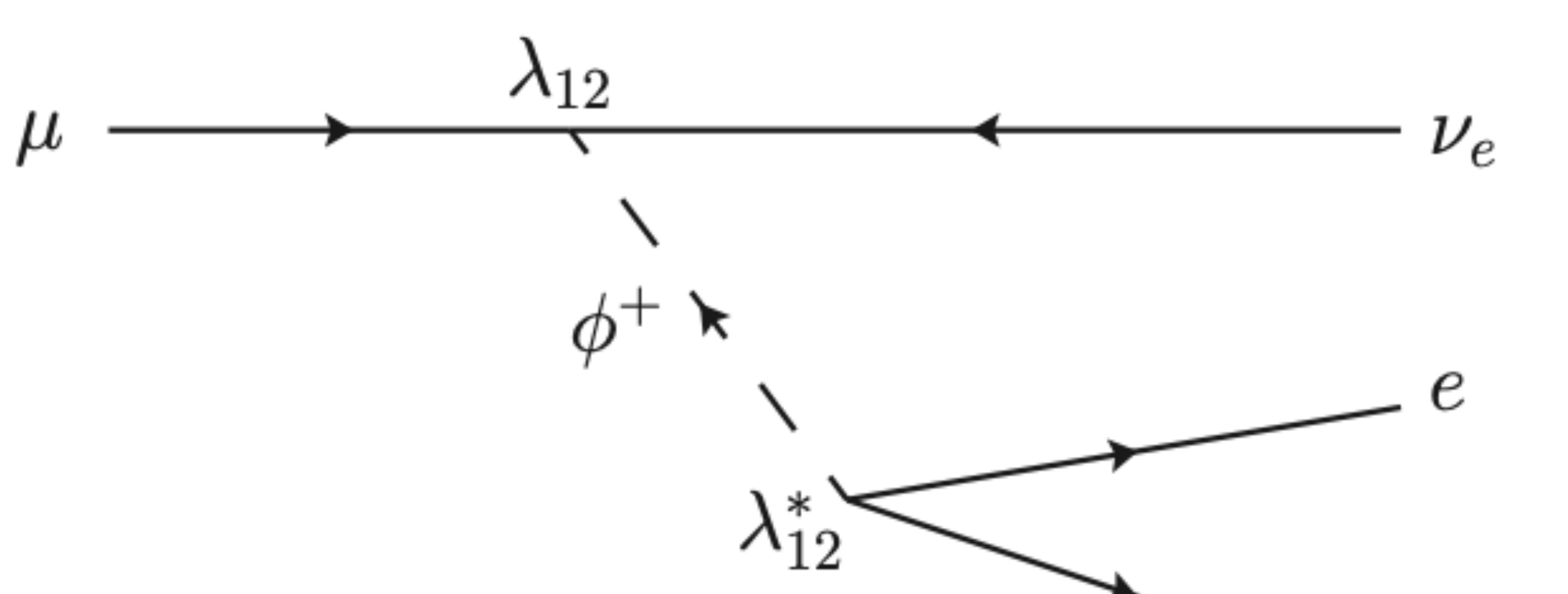


$$\frac{|\lambda_{12,13}|^2}{m_\phi^2} \lesssim \frac{1}{(175\ \mathrm{GeV})^2}$$



P. J.Fox, R.Harnik, J.Kopp,Y. Tsai arXiv:1103.0240

Lepton Decays



SIMILARLY FOR
$\tau \to \mu\nu\nu$ and $\tau \to e\nu\nu$

$$\delta(\ell_i \to \ell_j \nu\nu) = \frac{\mathscr{A}_{\rm NP}(\ell_i \to \ell_j \nu_i \bar{\nu}_j)}{\mathscr{A}_{\rm SM}(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} = \frac{|\lambda_{ij}|^2}{g_2^2} \frac{m_W^2}{m_\phi^2}$$

Necessarily constructive interference with SM

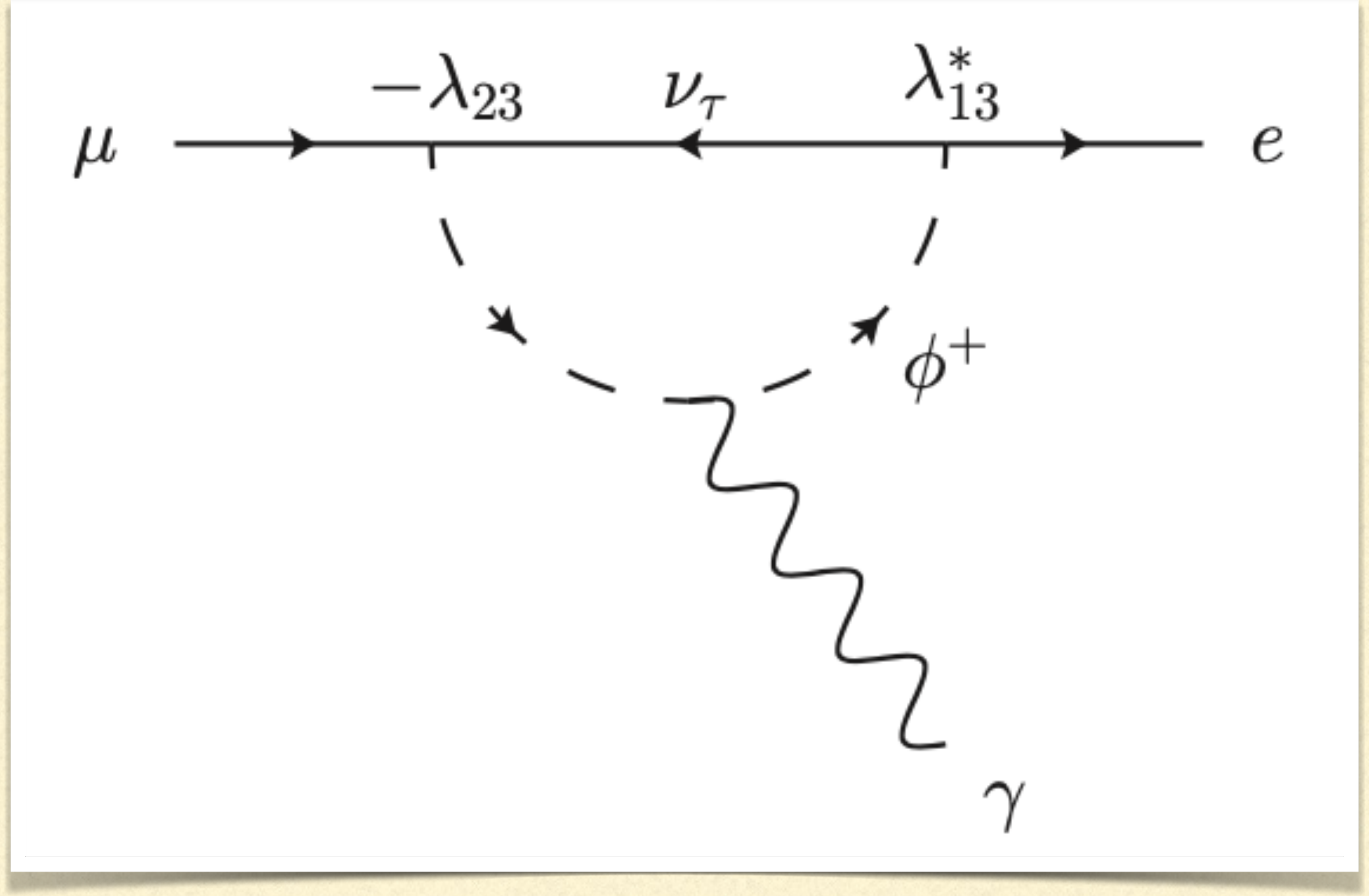
Modification of the Fermi Constant

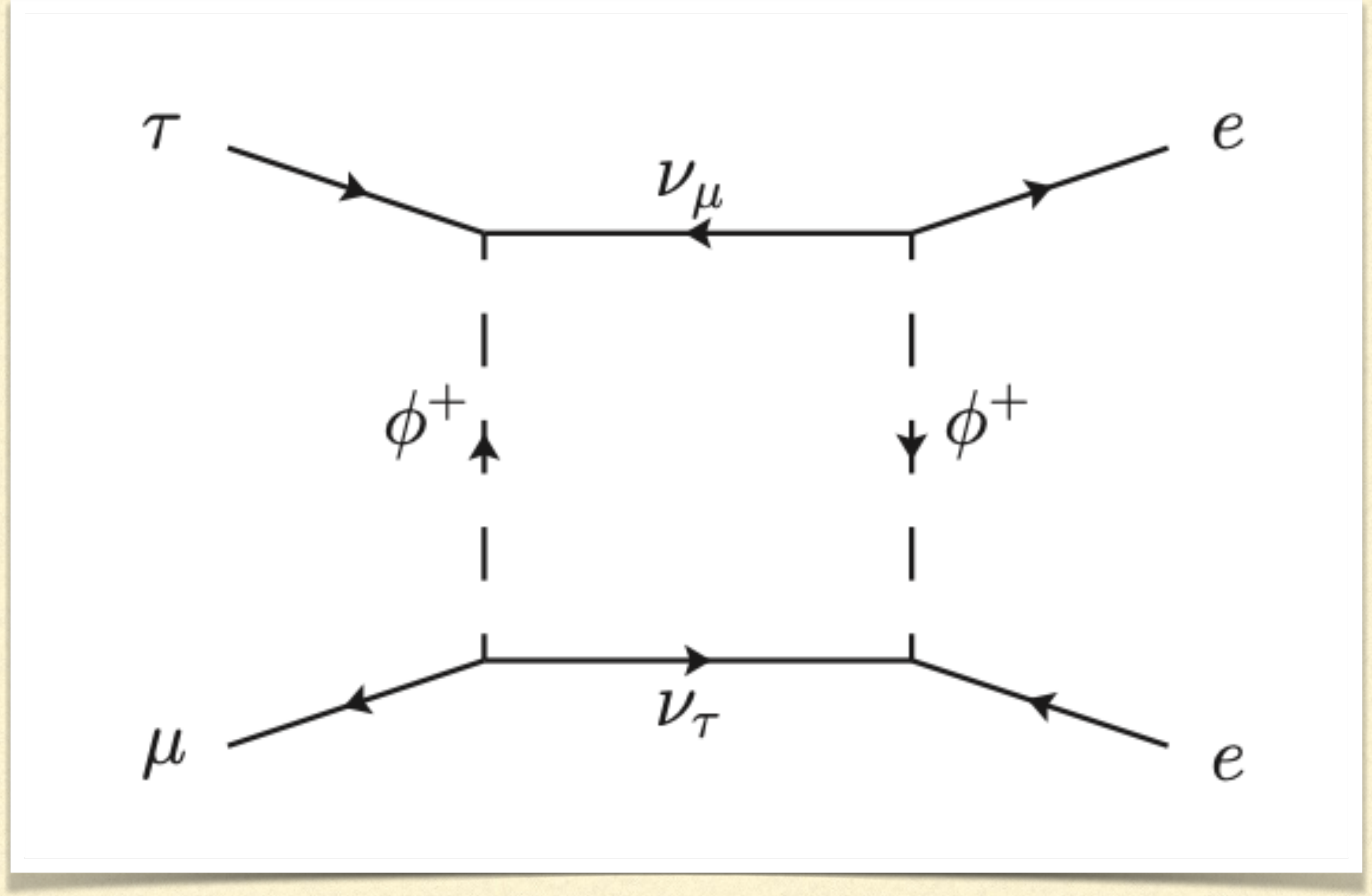
- EW observables
- V_{ud} from β decays:

$$V_{ud}^{\beta} = V_{ud}(1 - \varepsilon_{GF})$$

$$\boxed{\delta(\mu \to e\nu\nu) = 0.00065(15)}$$

Loop Effects





$\mathrm{Br}[\mu \to e\gamma] \le 4.2 \times 10^{-13}$

$\mathrm{Br}[\tau \to \mu\gamma] \le 4.4 \times 10^{-8}$

$\mathrm{Br}[\tau \to e\gamma] \le 3.3 \times 10^{-8}$

$\mathrm{Br}[\mu^- \to e^- e^+ e^-] \le 1.0 \times 10^{-12}$

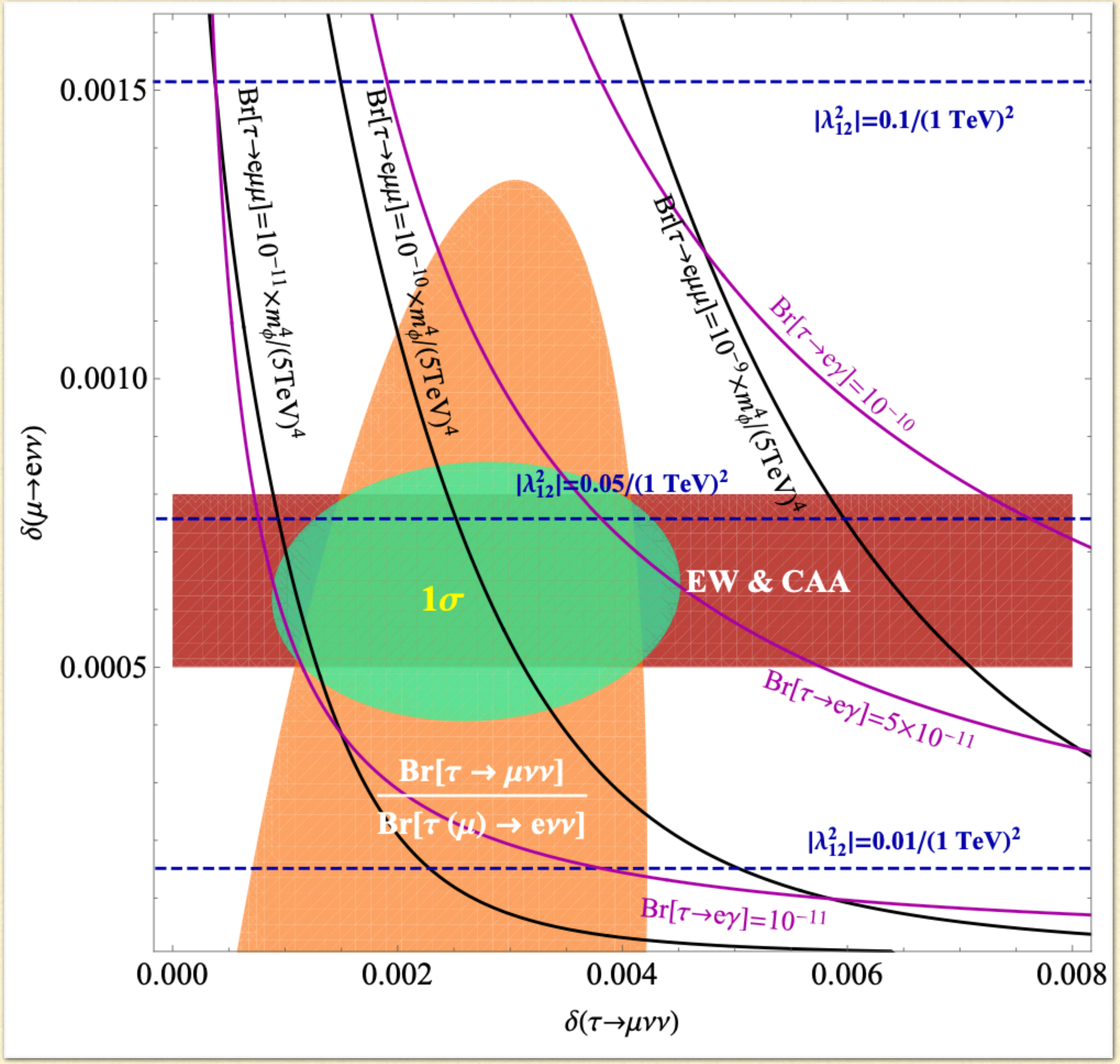
$\mathrm{Br}[\tau^- \to e^- e^+ e^-] \le 1.4 \times 10^{-8}$

$\mathrm{Br}[\tau^- \to e^- \mu^+ \mu^-] \le 1.6 \times 10^{-8}$

$\mathrm{Br}[\tau^- \to \mu^- e^+ e^-] \le 1.1 \times 10^{-8}$

$\mathrm{Br}[\tau^- \to \mu^- \mu^+ \mu^-] \le 1.1 \times 10^{-8}$

Phenomenology

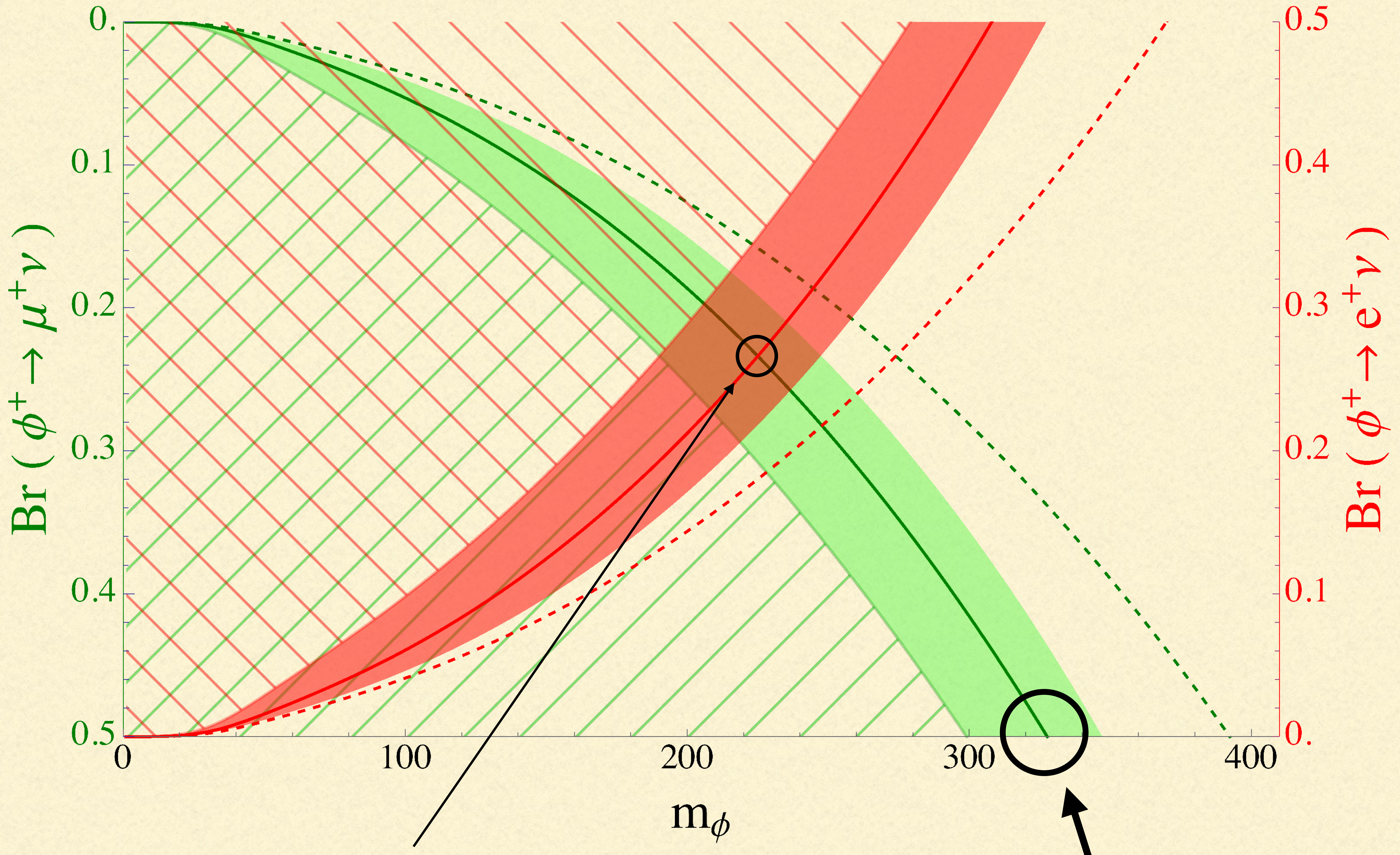


- λ_{13} must be vanishingly small in order to not violate bounds from $\mu \to e\gamma$.
- $\lambda_{13} \approx 0 \implies \text{Br}(\phi^+ \to \mu\nu) = 0.5$
  $\implies m_{\phi^+} \gtrsim 300\text{ GeV}$ (LHC)

What can be tested?

- $\text{Br}[\tau \to e\mu\mu]$ — BELLE II, FCC-ee
- $\dfrac{|\lambda_{12}|^2}{m_\phi^2}$ — ILC, CLIC, CEPC, FCC-ee

Recast of ATLAS searches for sleptons at $139\ \mathrm{fb}^{-1}$ arXiv:1908.08215 [hep-ex]



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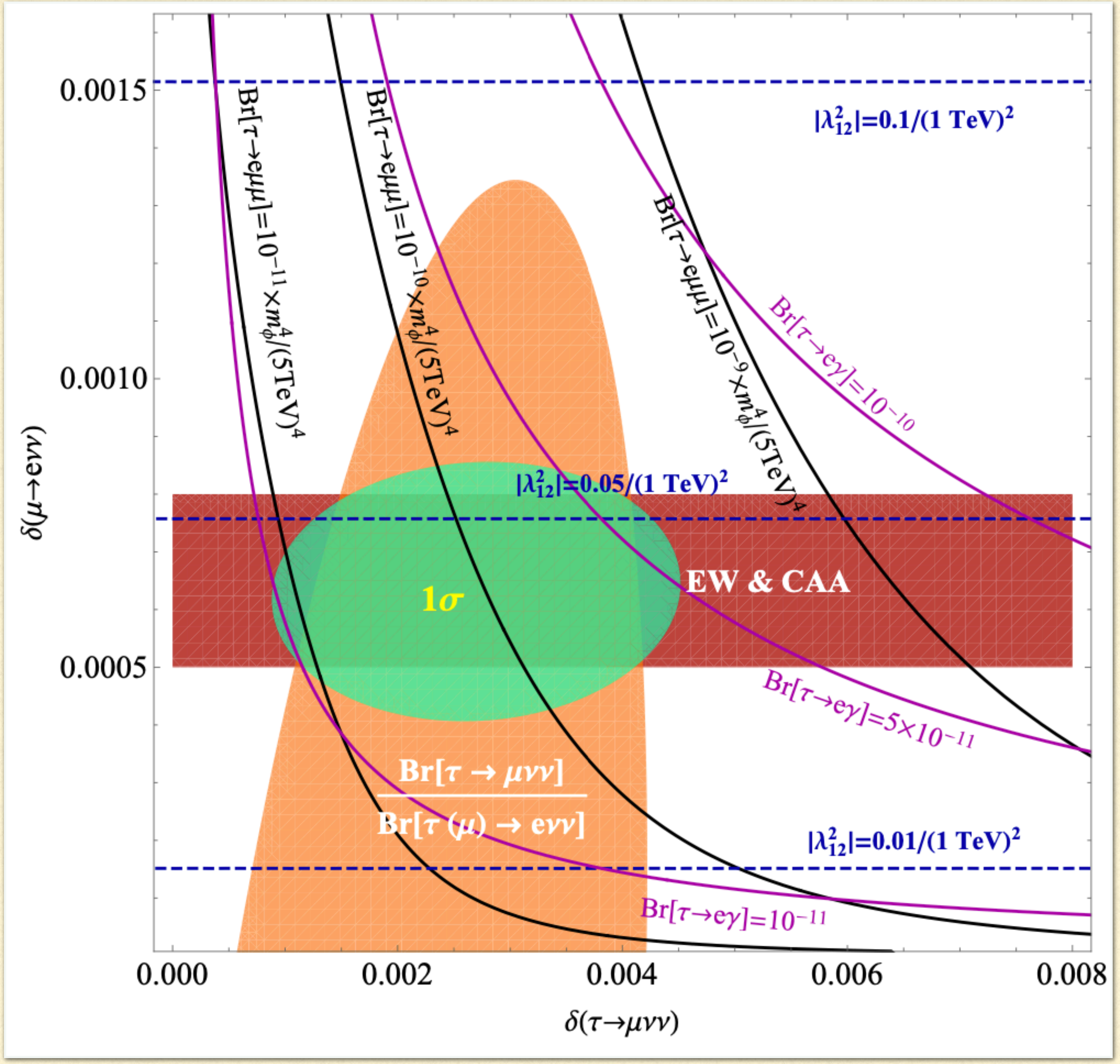

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Conclusions

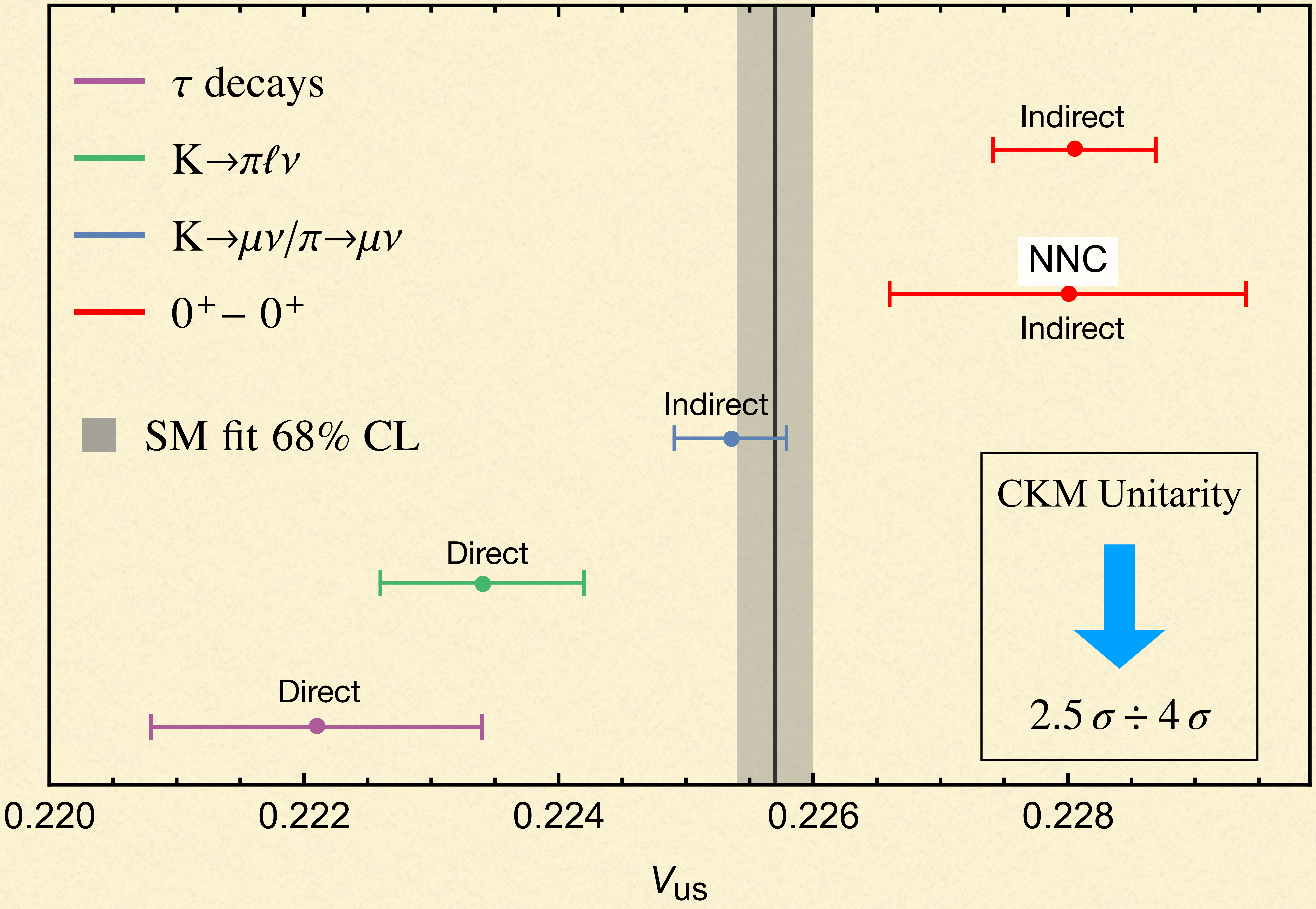
We study the phenomenology of a singly charged scalar:

- It has only 4 parameters: 3 free couplings + mass $\Longrightarrow$ it is very predictive;
- It violates LF(U) and gives a necessary positive contribution to $\ell \to \ell' \nu\nu$, as preferred by data;
- From collider searches we derive a coupling independent limit of $m_{\phi^+} \gtrsim 200$ GeV;
- Flavour data $(\lambda_{13} \sim 0)$ + Collider $\Longrightarrow$ $m_{\phi^+} \gtrsim 300$ GeV;
- We predict:

$$\mathrm{Br}[\tau \to e\gamma] \sim 10^{-11} \qquad \mathrm{Br}[\tau \to e\mu\mu] \sim 10^{-10} \frac{\mathrm{m}_{\phi^+}^4}{(5\mathrm{TeV})^4}$$

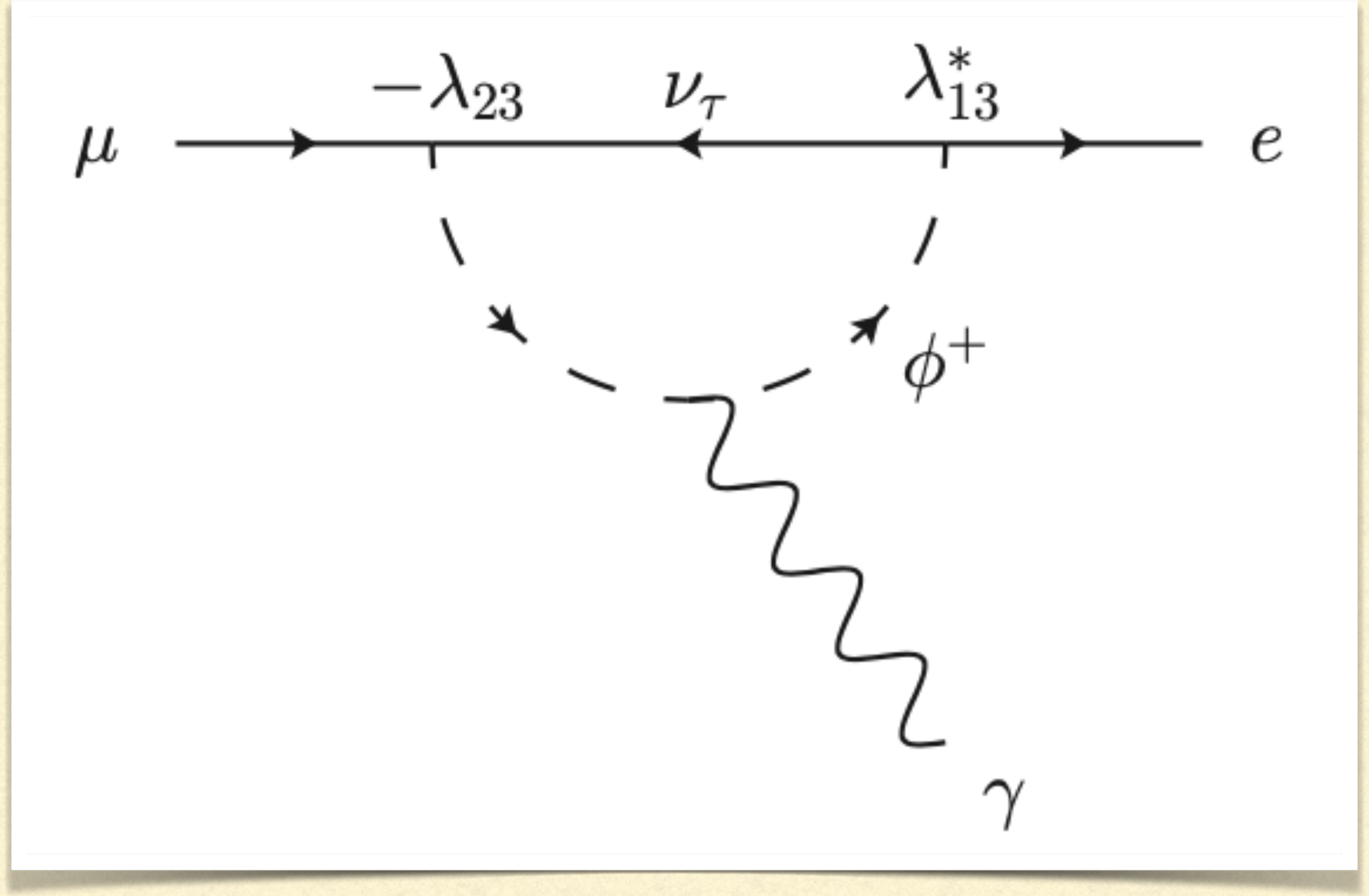
BACKUP SLIDES

CAA



τ decays
$K \to \pi \ell \nu$
$K \to \mu\nu / \pi \to \mu\nu$
$0^+ - 0^+$
SM fit 68% CL
Indirect
NNC
Indirect
Indirect
Direct
Direct
CKM Unitarity
$2.5\,\sigma \div 4\,\sigma$
0.220
0.222
0.224
0.226
0.228
V_{us}

$\mu \to e\gamma$



$\lambda_{13} \simeq 0$

required to be non zero by $\tau \to \mu\nu\nu$

$$\mathrm{Br}[\mu \to e\gamma] = \frac{m_\mu^3}{4\pi\,\Gamma_\mu} \left| \frac{e\,\lambda_{13}^*\,\lambda_{23}}{384\pi^2} \frac{m_\mu}{m_\phi^2} \right|^2 \leq 4.2 \times 10^{-13}$$

The other radiative lepton decays have weaker bounds:

$$\mathrm{Br}[\tau \to \mu\gamma] \leq 4.4 \times 10^{-8}$$

$$\mathrm{Br}[\tau \to e\gamma] \leq 3.3 \times 10^{-8}$$