Asymmetries in polarised cLFV decays

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Based on work to appear soon in collaboration with

J. Kriewald and A. M. Teixeira

Introduction: lepton flavours

In the SM: neutrinos are (strictly) massless by construction

$\Rightarrow$ Accidental symmetries: conservation of lepton flavour and total lepton number

$\Rightarrow$ Lepton flavour universality mostly preserved (only broken by Yukawas)

$\Rightarrow$ Lepton EDMs are tiny (4-loop from δ_{CKM})

But: Neutrinos oscillate $\Rightarrow$ neutral lepton flavour is violated, neutrinos are **massive**!

$\rightarrow$ charged lepton flavour is also violated? New sources of **CP violation**?

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Trivially extend **SM**, accomodate $\nu_\alpha \leftrightarrow \nu_\beta$ with 3 ν_R ($\Rightarrow$ Dirac masses, $\mathbf{SM}_{m_\nu}$)

$\Rightarrow$ cLFV possible, but not observable: BR$(\mu \rightarrow e\gamma) \sim 10^{-54}$ (EDM at 2 loops but tiny)

$\Rightarrow$ lepton number conservation “put by hand”, naturality issues $Y_\nu \simeq 10^{-16}$

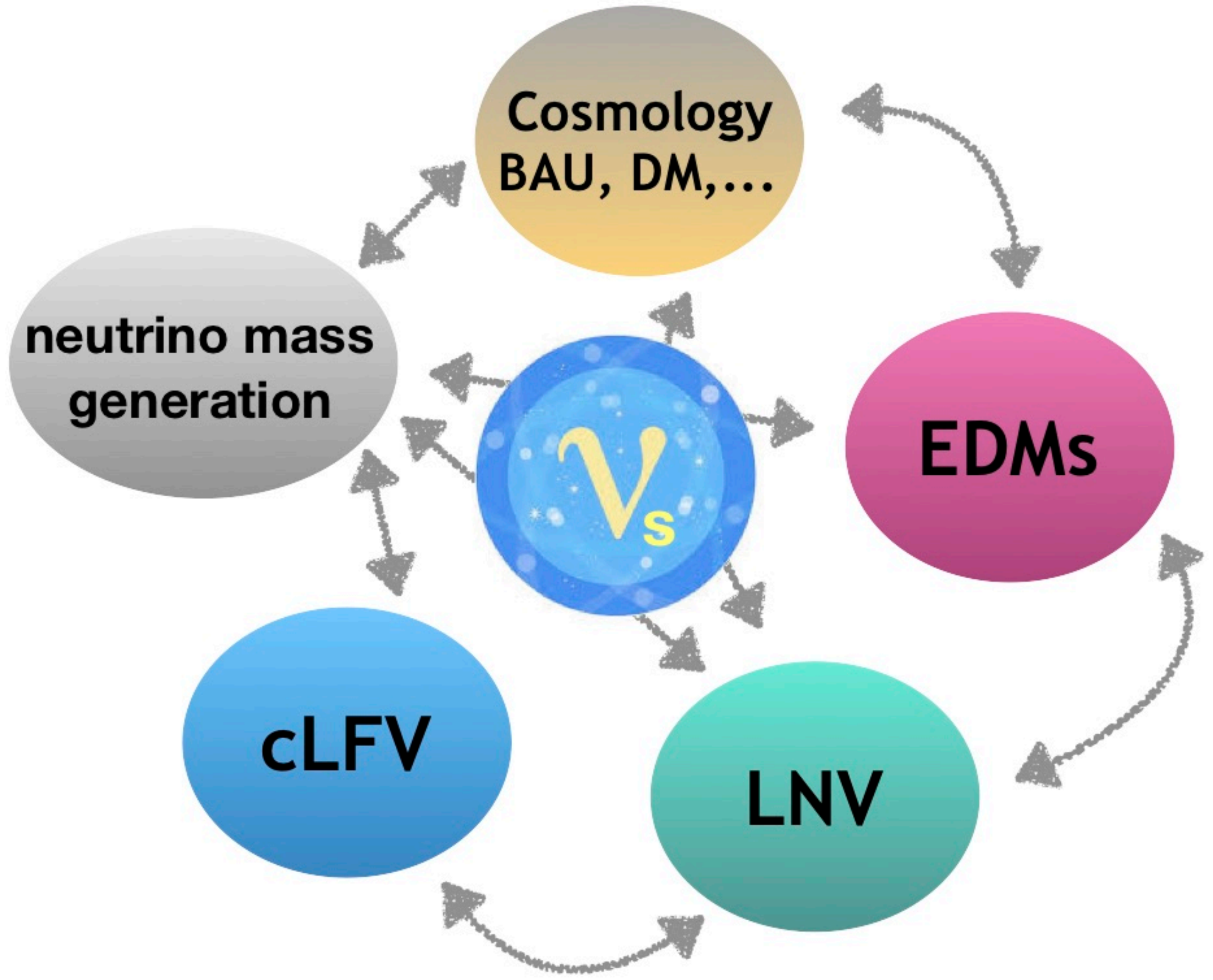
$\Rightarrow$ Any cLFV signal points towards non-trivial **SM** extensions…

(possibly in association to m_ν generation)

Strong arguments in favour of New Physics involving (neutral) leptons!

Extended lepton sectors and/or **New states** coupling to **leptons** (exotic fermions, scalars, vectors...) ⟹ **Neutrino** oscillations, **Baryon asymmetry** of the Universe, Viable **dark matter** candidate (?)

- **Majorana sterile fermions - a very appealing hypothesis, motivated by extensive theoretical and observational arguments**



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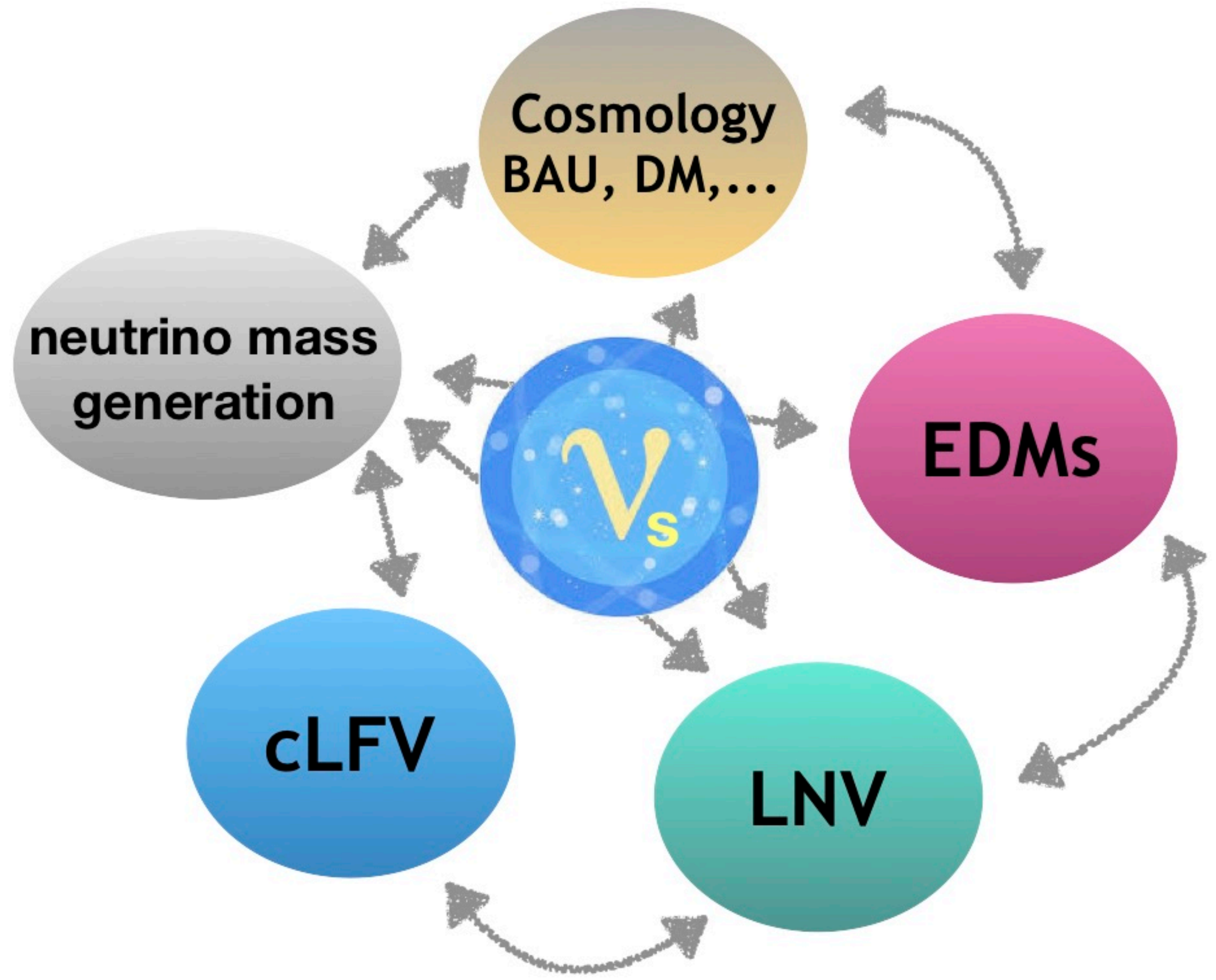


Potentially **very "visible NP portal":** extensive imprints from ***colliders*** to ***low-energy*** experiments, from ***flavour*** dedicated, to ***CPV*** searches, …

Exp. signals within current & future sensitivities

⇒ **Focus** on **sterile neutrinos** as sources of **flavour violation** in the lepton sector, **lepton number violation** and **CP violation** (Dirac and Majorana)

Simple “3+2” SM extension

Numerous well motivated models feature **heavy neutral leptons** (HNL)…

Make no assumption on the origin of m_ν, assume 2 (heavy) Majorana neutrinos $N_{4,5}$ present

⇒ From a **unitary** left-handed lepton mixing $\mathcal{U}_{PMNS}$ to a **non unitary** $\tilde{\mathcal{U}}_{PMNS}$, and $\mathcal{U}_{\alpha i}$, an **active-sterile** mixing rectangular matrix

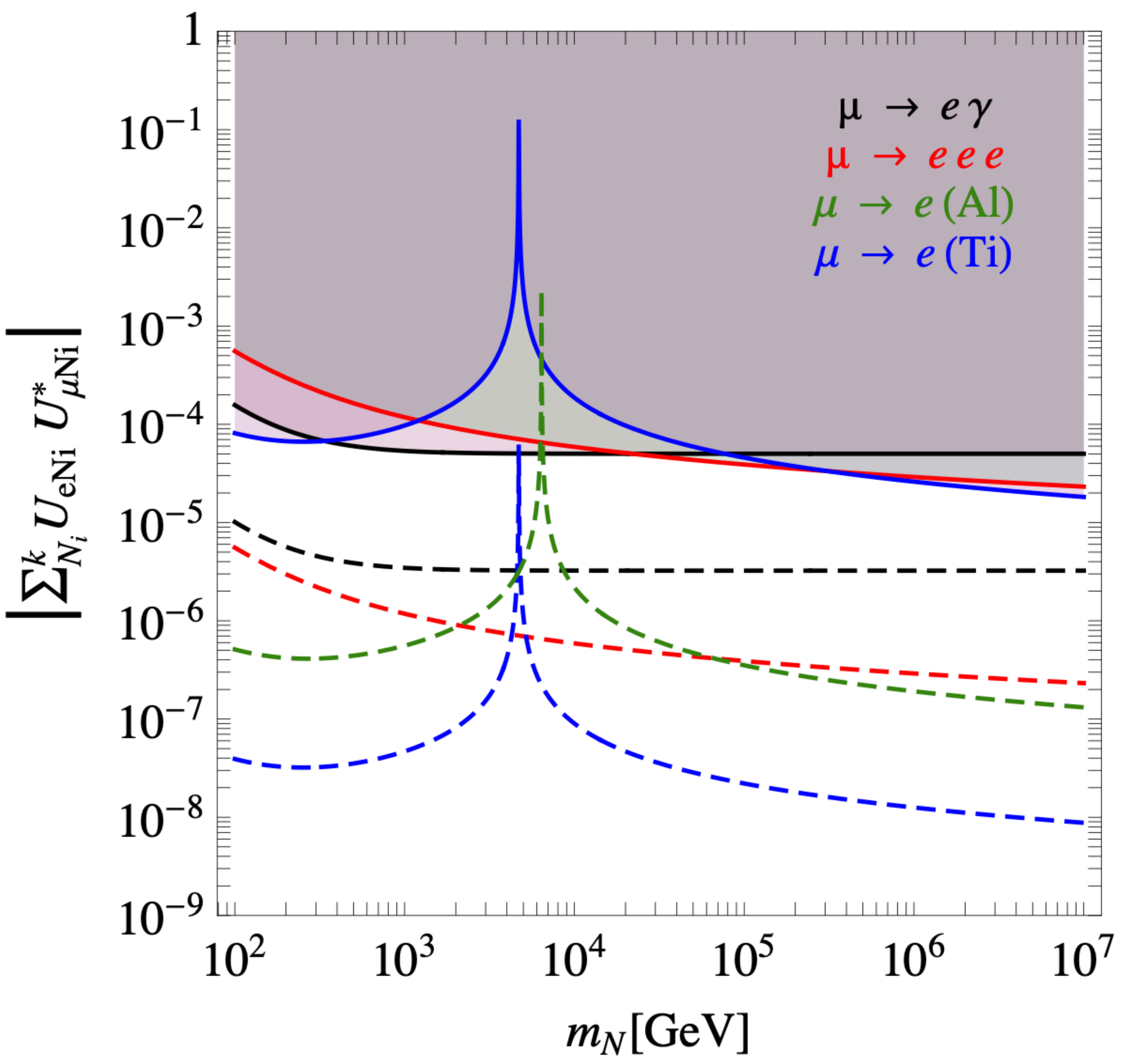
$$\mathcal{U}_{3\times3} = \begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \mathcal{U}_{e3} \\ \mathcal{U}_{\mu1} & \mathcal{U}_{\mu2} & \mathcal{U}_{\mu3} \\ \mathcal{U}_{\tau1} & \mathcal{U}_{\tau2} & \mathcal{U}_{\tau3} \end{pmatrix} \Longrightarrow \mathcal{U}_{5\times5} = \begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \mathcal{U}_{e3} & \mathcal{U}_{e4} & \mathcal{U}_{e5} \\ \mathcal{U}_{\mu1} & \mathcal{U}_{\mu2} & \mathcal{U}_{\mu3} & \mathcal{U}_{\mu4} & \mathcal{U}_{\mu5} \\ \mathcal{U}_{\tau1} & \mathcal{U}_{\tau2} & \mathcal{U}_{\tau3} & \mathcal{U}_{\tau4} & \mathcal{U}_{\tau5} \\ \mathcal{U}_{N_11} & \mathcal{U}_{N_12} & \mathcal{U}_{N_13} & \mathcal{U}_{N_14} & \mathcal{U}_{N_15} \\ \mathcal{U}_{N_21} & \mathcal{U}_{N_23} & \mathcal{U}_{N_23} & \mathcal{U}_{N_24} & \mathcal{U}_{N_25} \end{pmatrix}$$

$$\mathcal{U}_{5\times5} = R_{45}R_{35}R_{25}R_{15}R_{34}R_{24}R_{14}R_{23}R_{13}R_{21} \times \mathrm{diag}(1, e^{i\varphi_2}, e^{i\varphi_3}, e^{i\varphi_4}, e^{i\varphi_5})$$

⇒ Physical neutrino spectrum comprises **5 states** (3 light, 2 heavy)

Mixing parametrised via **10 mixing angles** θ_{ij}, **6 Dirac** $\delta_{\alpha j}$ and **4 Majorana phases** φ_j

Simple “3+2” SM extension



Alonso, Dehn, Gavela, Hambye [1209.2679]

$$\mathcal{U} = \begin{pmatrix} \mathcal{U}_{\nu\nu} & \mathcal{U}_{\nu N} \\ \mathcal{U}_{N\nu} & \mathcal{U}_{NN} \end{pmatrix} \qquad \mathcal{U}_{\nu\nu} \approx (1-\varepsilon)\, \mathcal{U}_{\text{PMNS}}$$

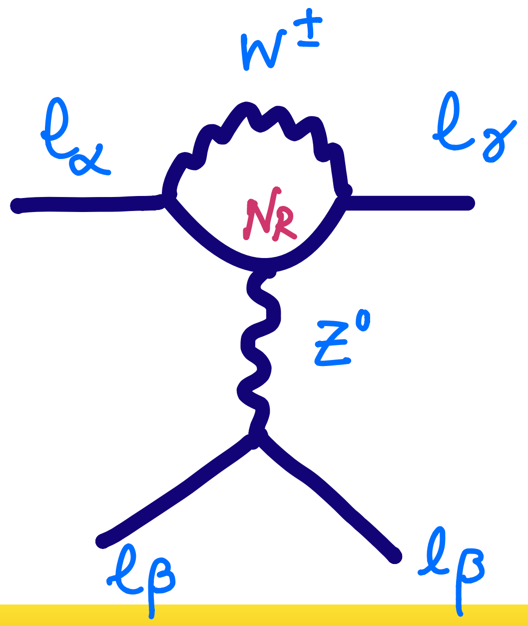
“Heavy-light” mixing given by (for $\cos\theta_{\alpha 4,5} \approx 1$):

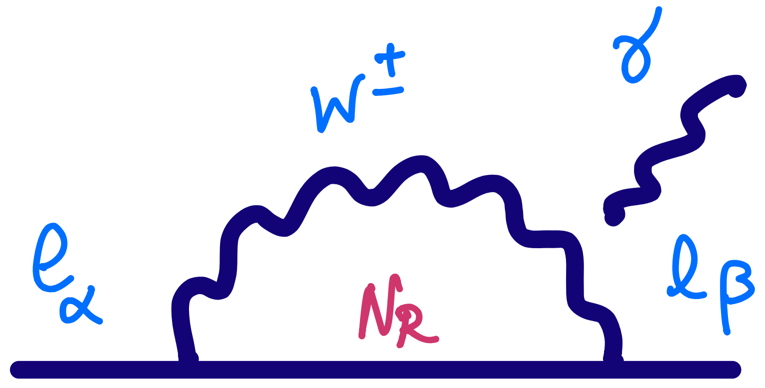
$$\mathcal{U}_{\alpha i} \approx \begin{pmatrix} \sin\theta_{14} e^{-i(\delta_{14}-\varphi_4)} & \sin\theta_{15} e^{-i(\delta_{15}-\varphi_5)} \\ \sin\theta_{24} e^{-i(\delta_{24}-\varphi_4)} & \sin\theta_{25} e^{-i(\delta_{25}-\varphi_5)} \\ \sin\theta_{34} e^{-i(\delta_{34}-\varphi_4)} & \sin\theta_{35} e^{-i(\delta_{35}-\varphi_5)} \end{pmatrix}$$

Heavy states do not decouple

$\Rightarrow$ modified neutral and charged leptonic currents

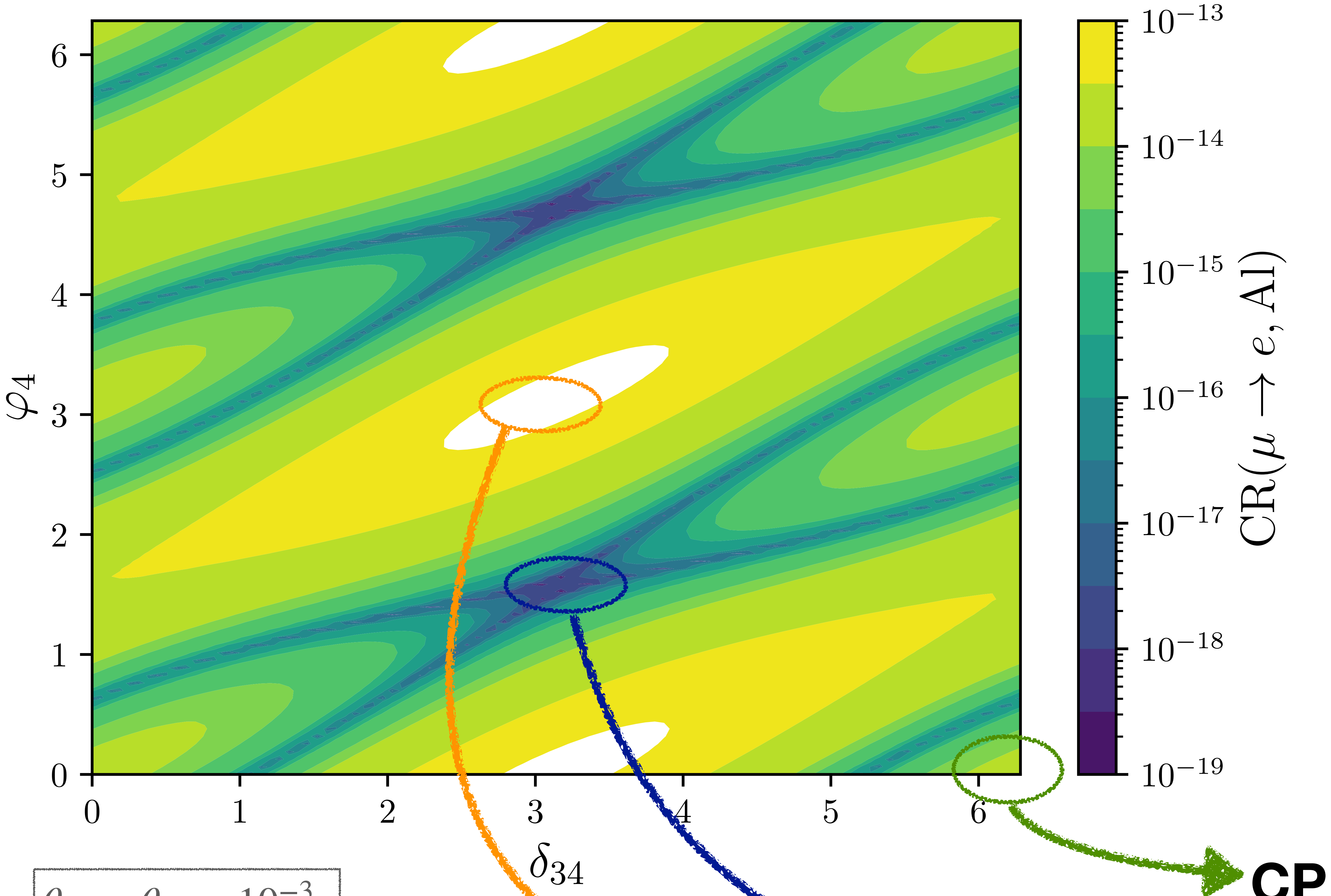
Rich phenomenology at **high intensities and at colliders**





Simplified approach: $\sin\theta_{\alpha 4} = \sin\theta_{\alpha 5}$ fixed ; $m_4 = m_5 = 1$ TeV ; (fix all parameters but 2 phases)

Abada, Kriewald, Teixeira [2107.06313]



$\theta_{e4} = \theta_{e5} = 10^{-3}$
$\theta_{\mu 4} = \theta_{\mu 5} = 0.01$
$\theta_{\tau 4} = \theta_{\tau 5} = 0.1$

→ **Interference effects**

Both destructive *AND* constructive!

Joint effect of **Dirac** ($\boldsymbol{\delta_{34}}$) and

Majorana ($\boldsymbol{\varphi_4}$) **CPV phases**

⇒ **From beyond experimental sensitivity**…

to **within near future reach...**

and even **already excluded!**

CP conserving

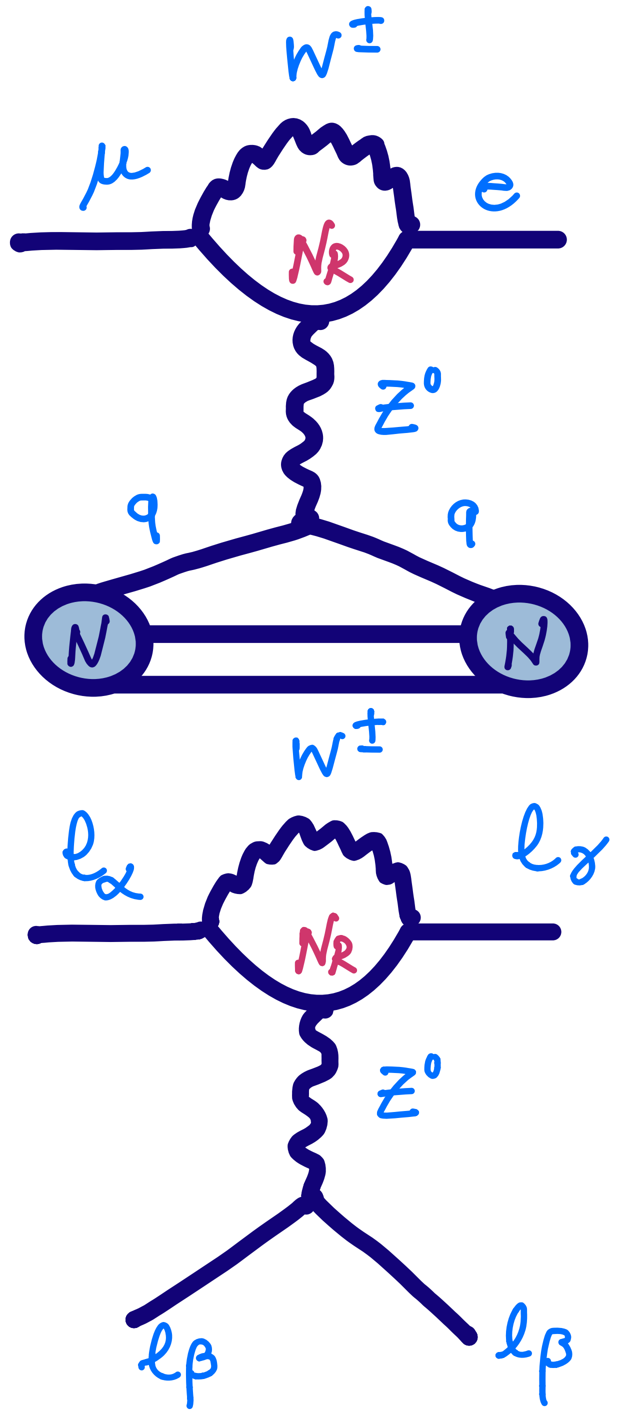
CPV (**max destructive** interference)

CPV (**max constructive** interference)

Peculiar cLFV patterns… what if CPV & cLFV?

cLFV signatures: ratios of observables to **identify mediators** & constrain their **masses!**

But - CP violating phases do matter! *And impact naïve expectations…*



Observables dominated by **common topology**

$\mu - e$ **conversion in nuclei**

3-body muon decays ($\mu \to 3e$)

Z-penguin dominance

$m_4 = m_5 = 1$ TeV

- CP conserving

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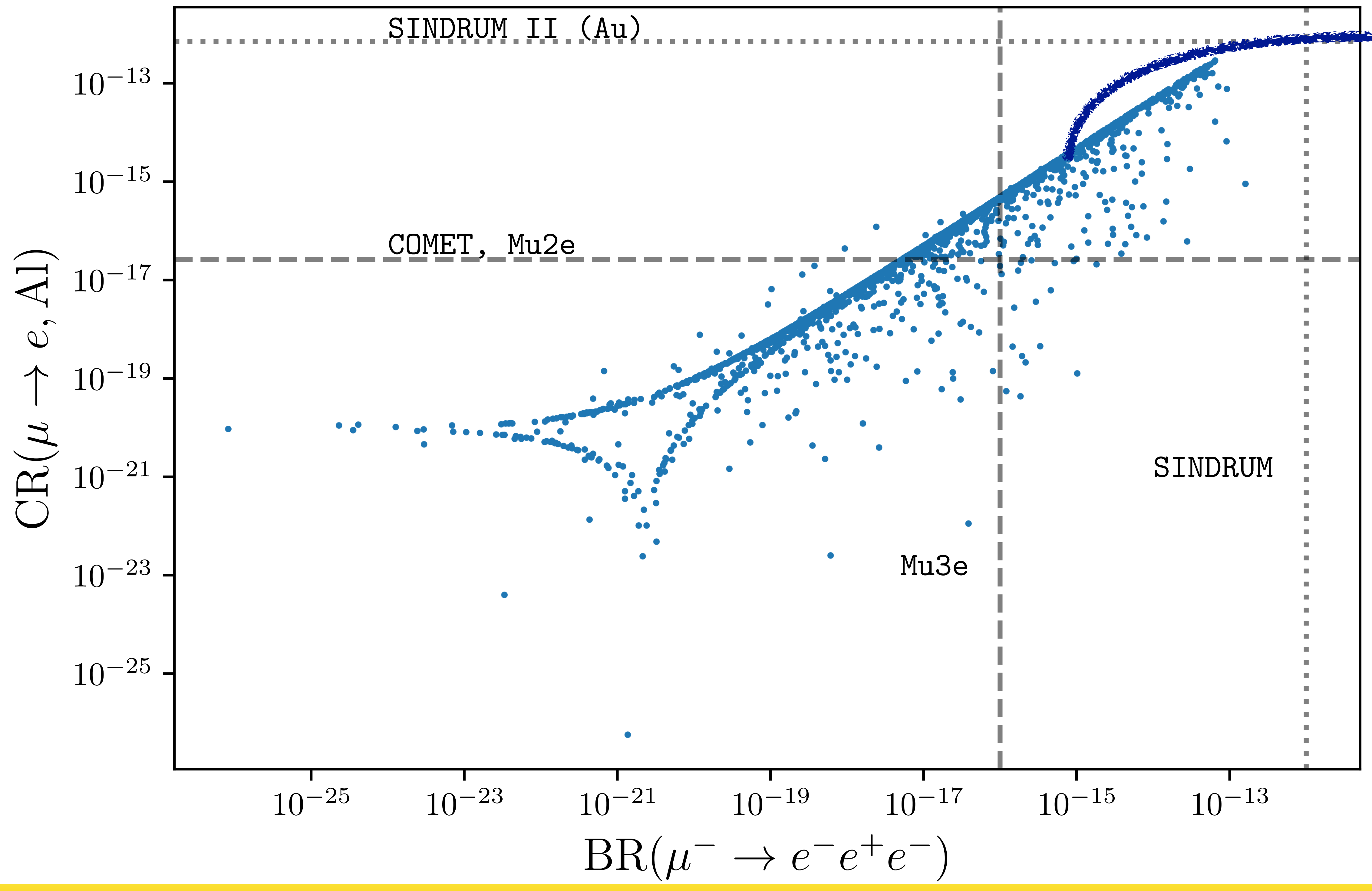

Strong correlation
(CP conserving)

Observation *of* $\mu \to 3e$
$\Rightarrow$ *observation of*
$\mu - e$ **conversion**

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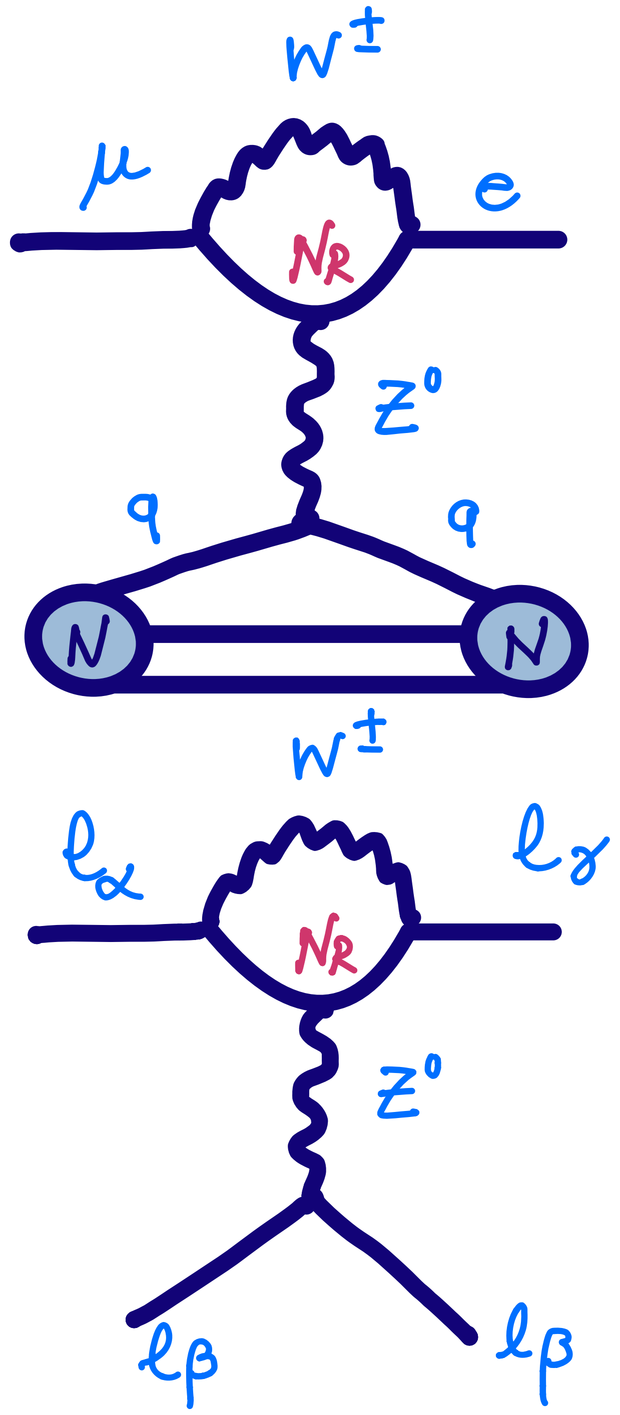

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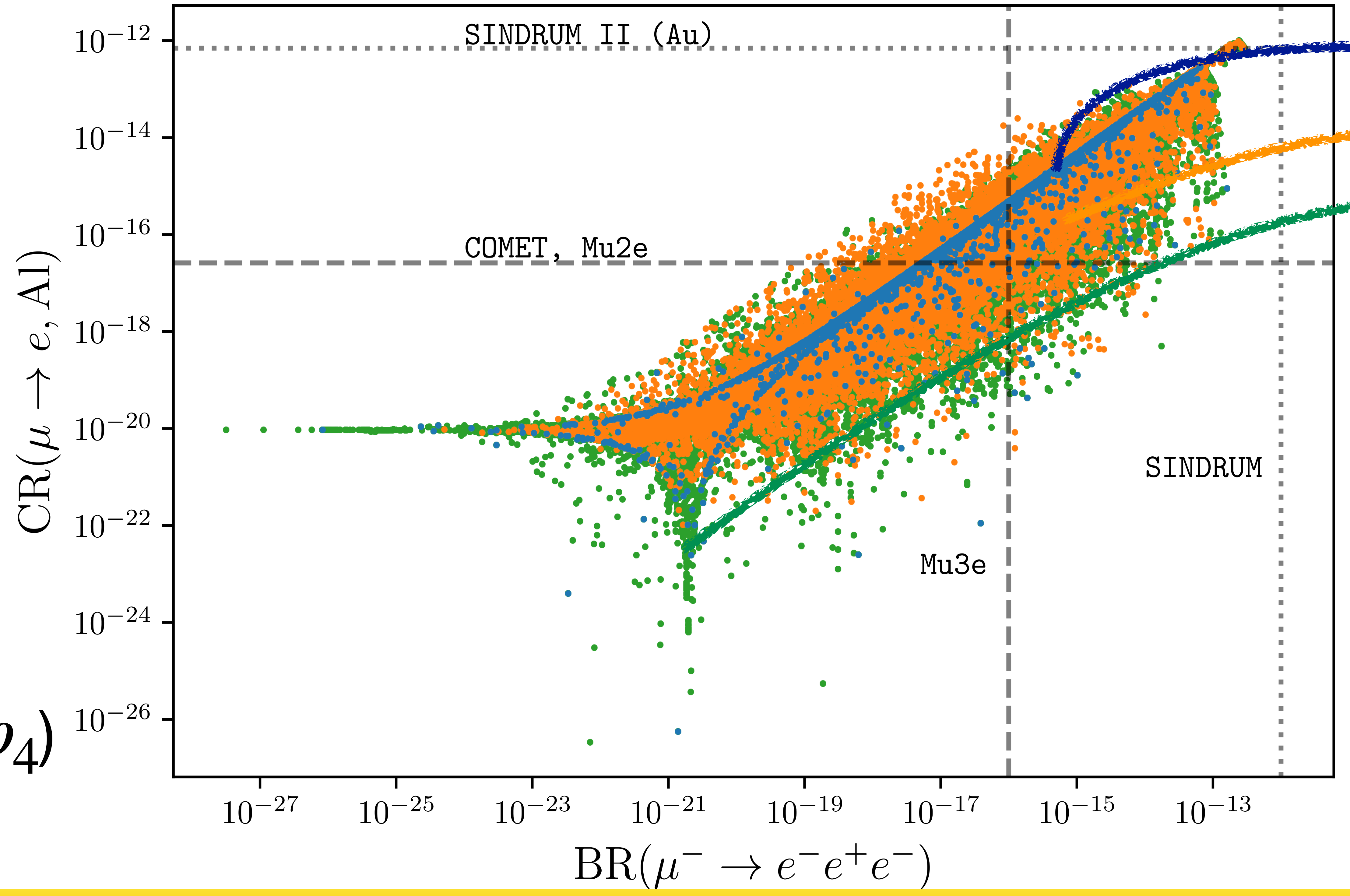
$m_4 = m_5 = 1$ TeV

- CP conserving
- CPV phases (random $\delta_{\alpha 4}, \varphi_4$)
- CPV phases (grid $n\pi/4$)

Abada, Kriewald, Teixeira [2107.06313]

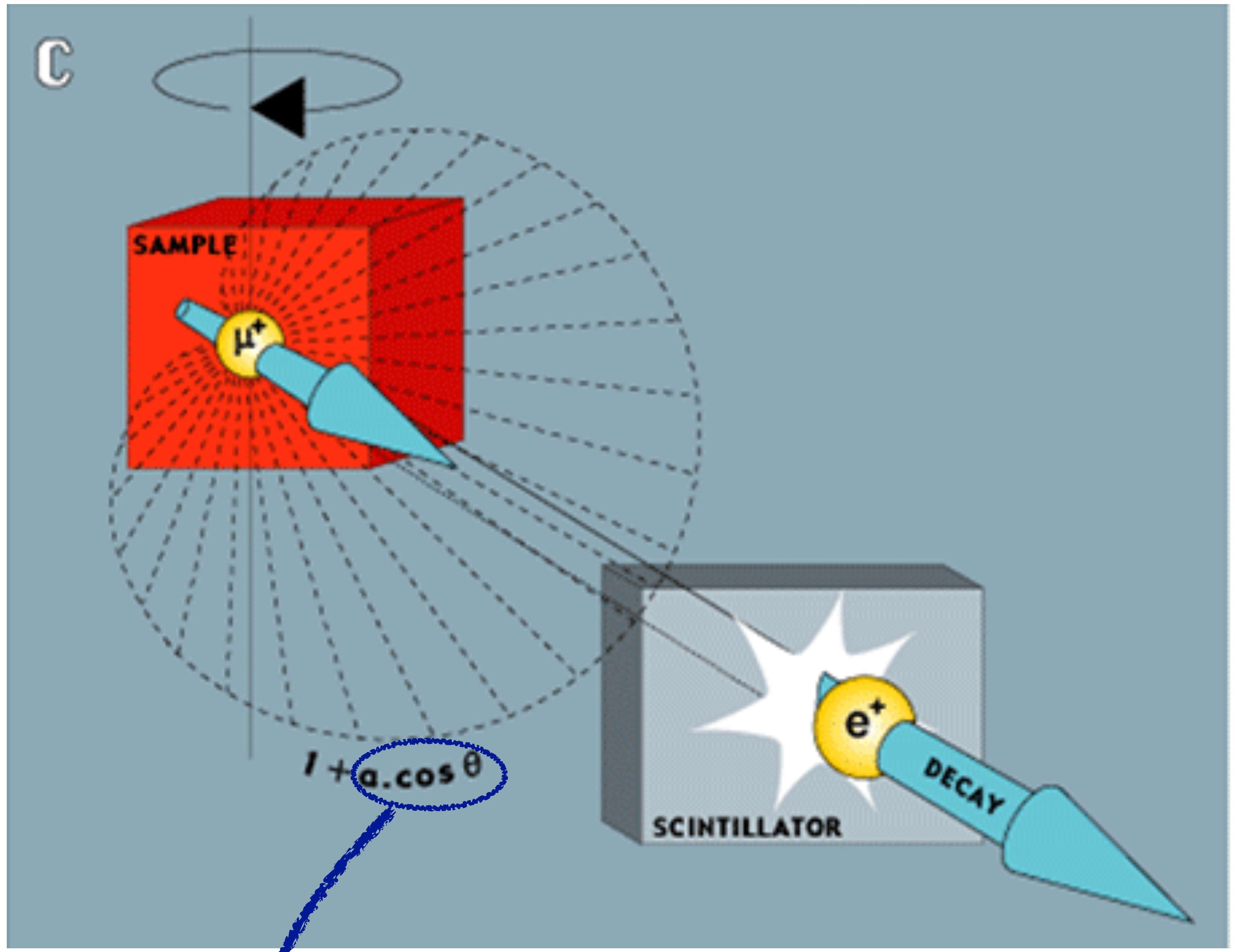


Strong correlation
(CP conserving)

Loss of correlation!
(CP violating)

Observation of $\mu \to 3e$
$\not\Rightarrow$ *observation of*
$\mu - e$ **conversion**

Polarised beams in experiments



P asymmetry

Experiments such as Mu3e, Belle II and SCTF aim at producing **polarised muons and taus** at high polarisation rates

$\Rightarrow$ **New set of observables** to explore CPV phases

Our goal: study this new set of observables for the leptonic cLFV 3-body decays of muons and taus.

(i)	(ii-a)	(ii-b)
$\tau^+/\mu^+ \to 3\ell_\alpha$	$\tau^+ \to \ell_\alpha^+ \ell_\beta^+ \ell_\beta^-$	$\tau^+ \to \ell_\alpha^+ \ell_\alpha^+ \ell_\beta^-$

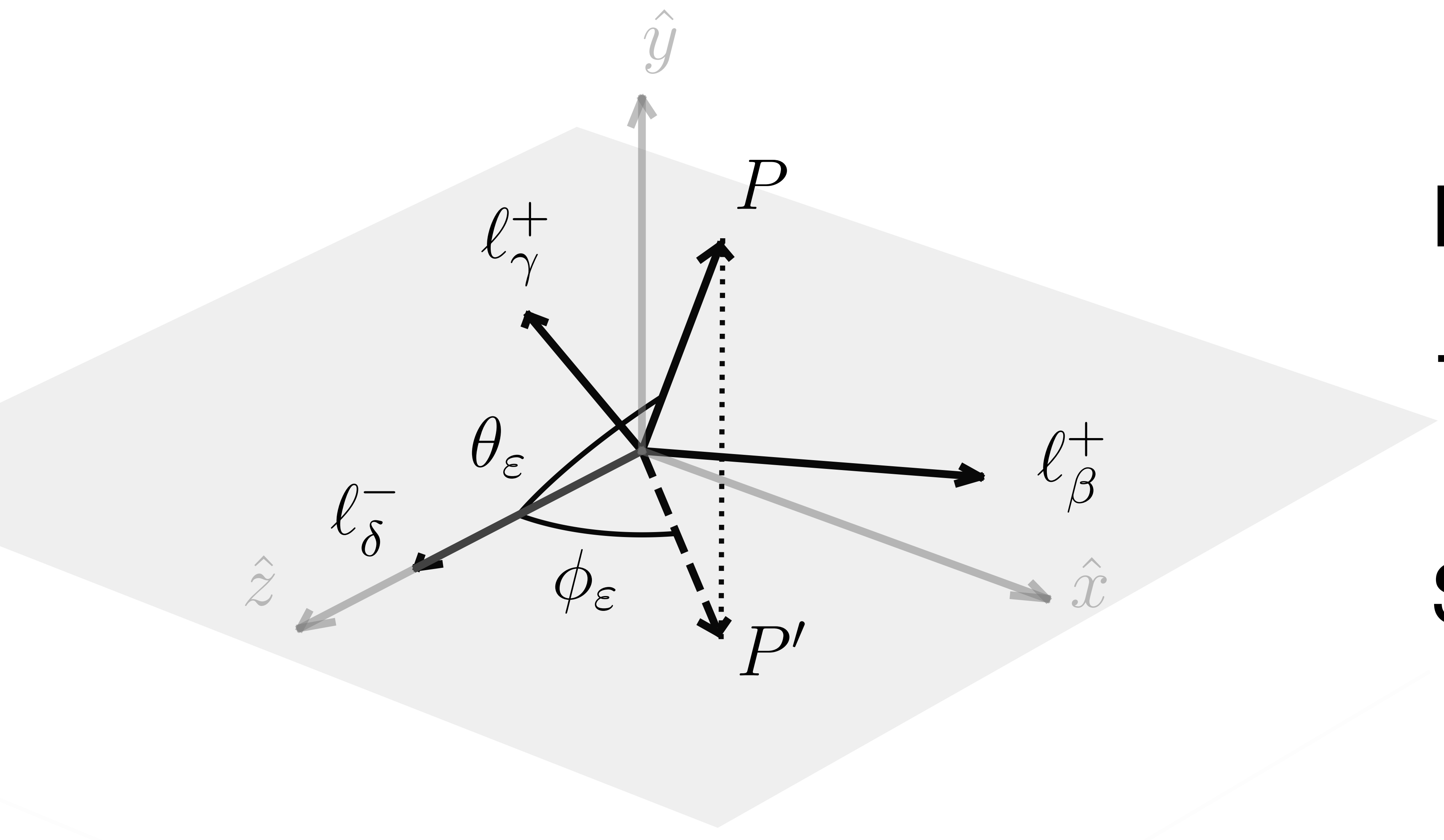
Bolton, Petcov [2204.03468]

Redigolo, Tammaro, Tesi [2408.00847]

But what is this new set of observables?

Polarised leptonic 3-body decays

Goto, Okada, Yamamoto [1012.4385]



Two angles (θ_ε ,ϕ_ε): defined from the **polarisation vector** of decaying particle and **4-momenta** of final states

$\rightarrow$ **3 asymmetries: P, P' and T !**

However ϕ_ε **ill-defined** for indistinguishable final states $\beta = \gamma$…

$\rightarrow$ Distinguish them by their energies, “slicing” phase space

Such “slicing” can also be done for distinguishable states $\beta \neq \gamma$

$\Rightarrow$ **New set of asymmetries**: “Forward-Backward”:

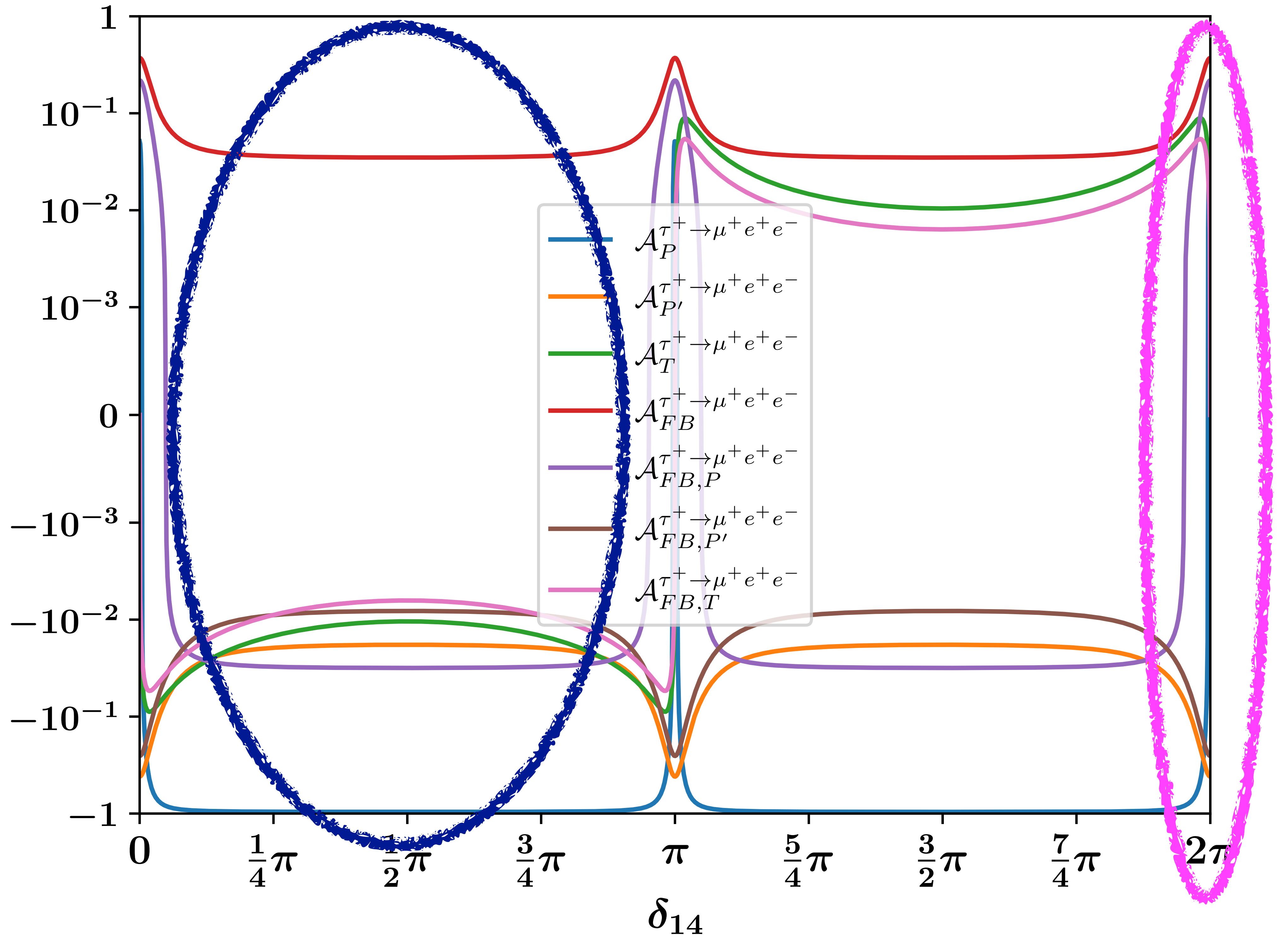
$\{\mathscr{A}^{FB}, \mathscr{A}_P^{FB}, \mathscr{A}_{P'}^{FB}, \mathscr{A}_T^{FB}\}$

In total: **7 asymmetries** for distinguishable final states and **3** for indistinguishable

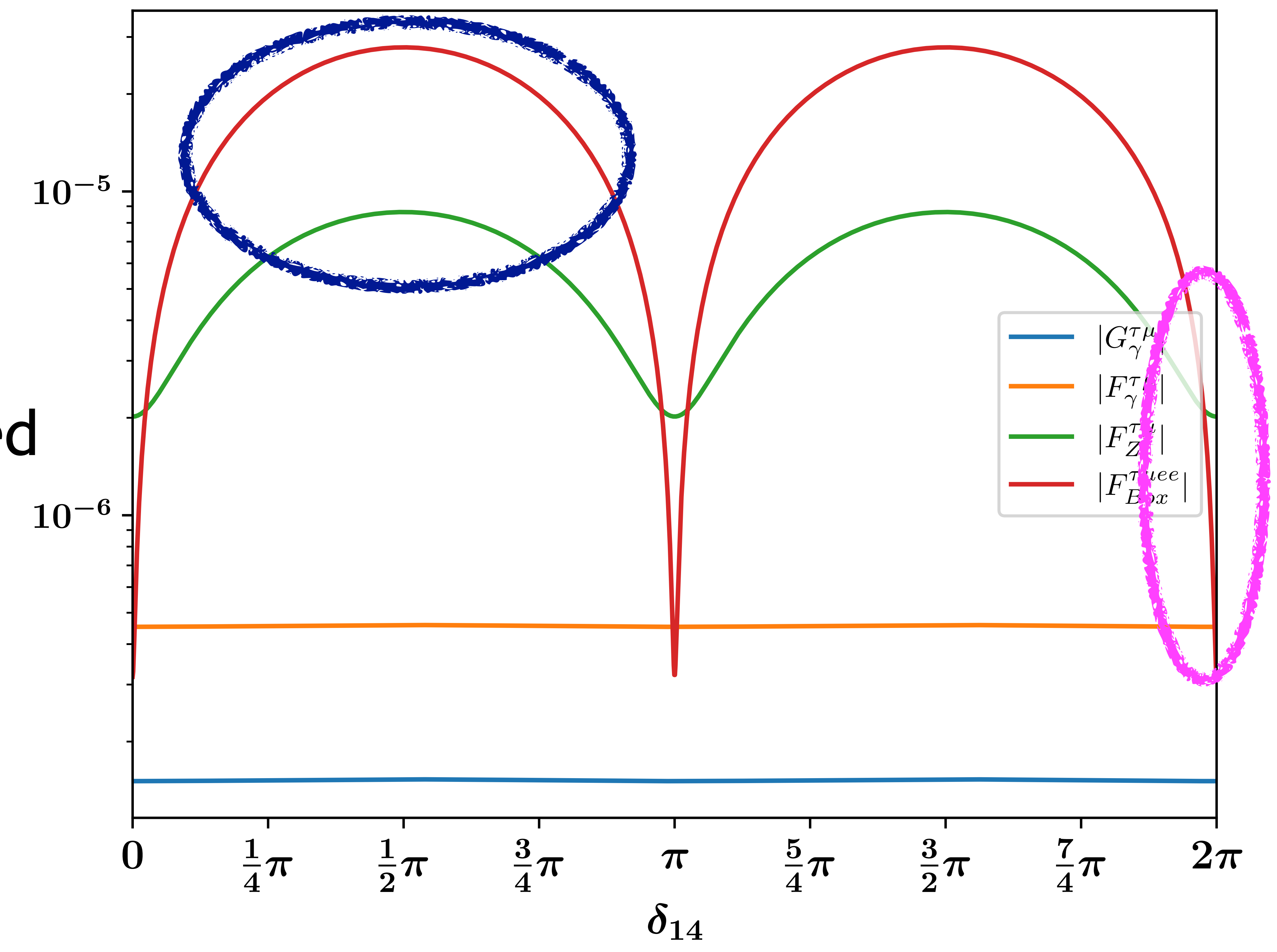
Role of CPV phases on asymmetries: $\tau^+ \to \ell_\alpha^+ \ell_\beta^+ \ell_\beta^-$

Simplified approach $\tau^+ \to \ell_\alpha^+ \ell_\beta^+ \ell_\beta^-$ asymmetries:

start with a CP conserving benchmark and only vary one CPV phase (δ_{14})



- Box dominated
- Z dominated

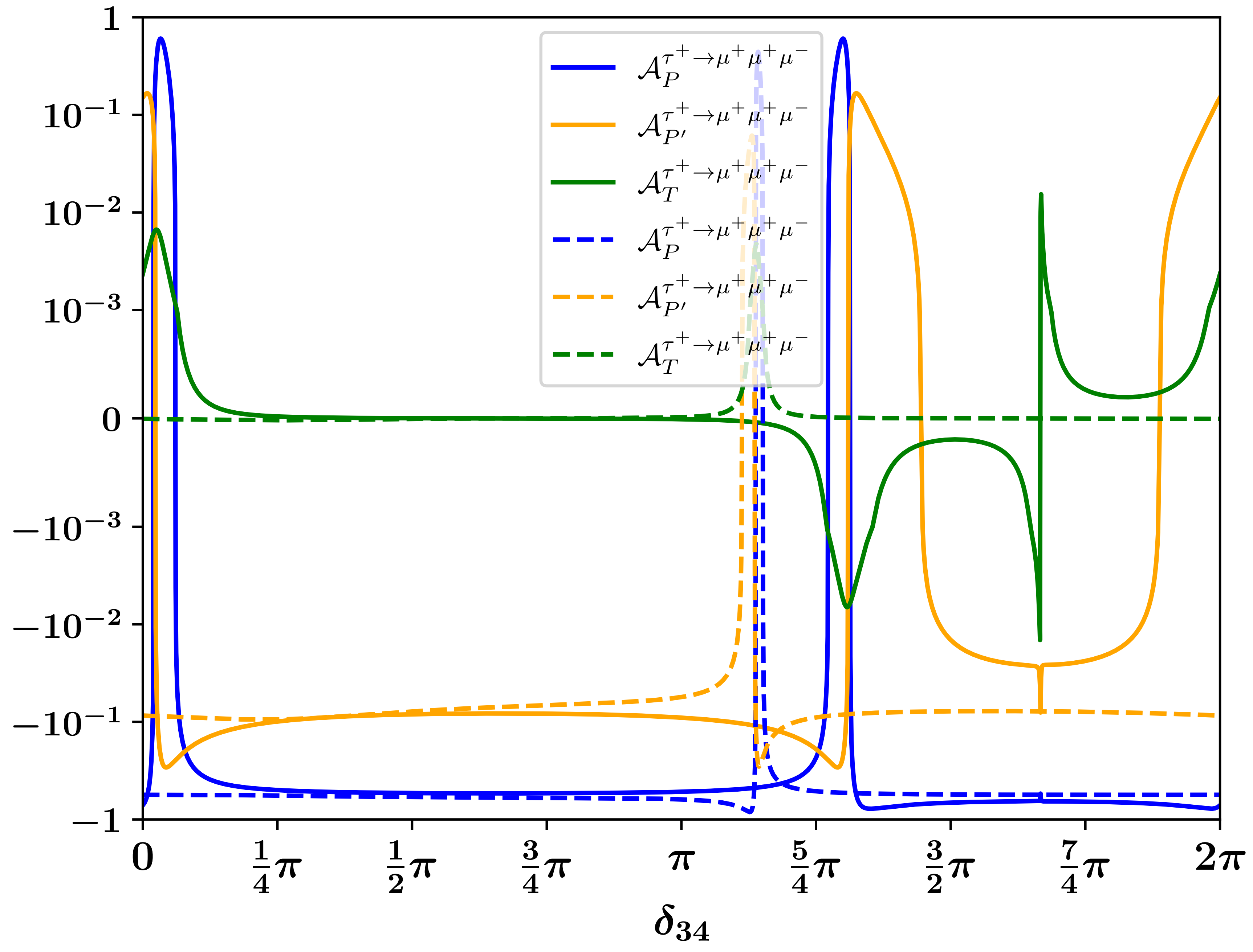


$\boxed{\text{CPV phases can change operator dominance} \to \textbf{large impact to the asymmetries!}}$

Role of CPV phases on asymmetries: $\ell_\alpha^+ \to 3\ell_\beta^+$

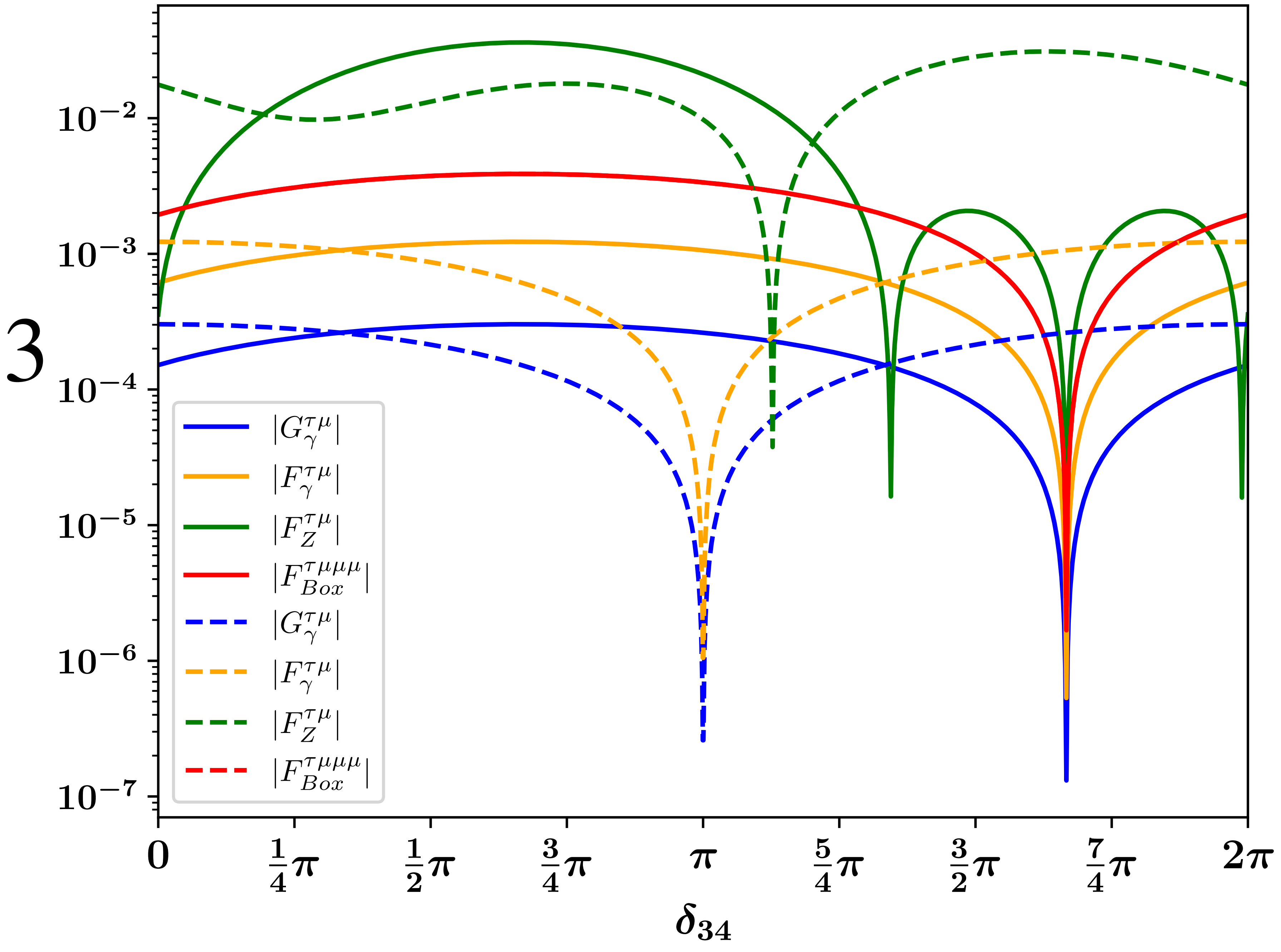
Simplified approach on $\ell_\alpha^+ \to 3\ell_\beta^+$ asymmetries:

start with a benchmark with 1 (2) CPV phase and only vary one other CPV phase (δ_{34})



— $\varphi_4 = 2\pi/3$, $\delta_{24} = 2\pi/3$

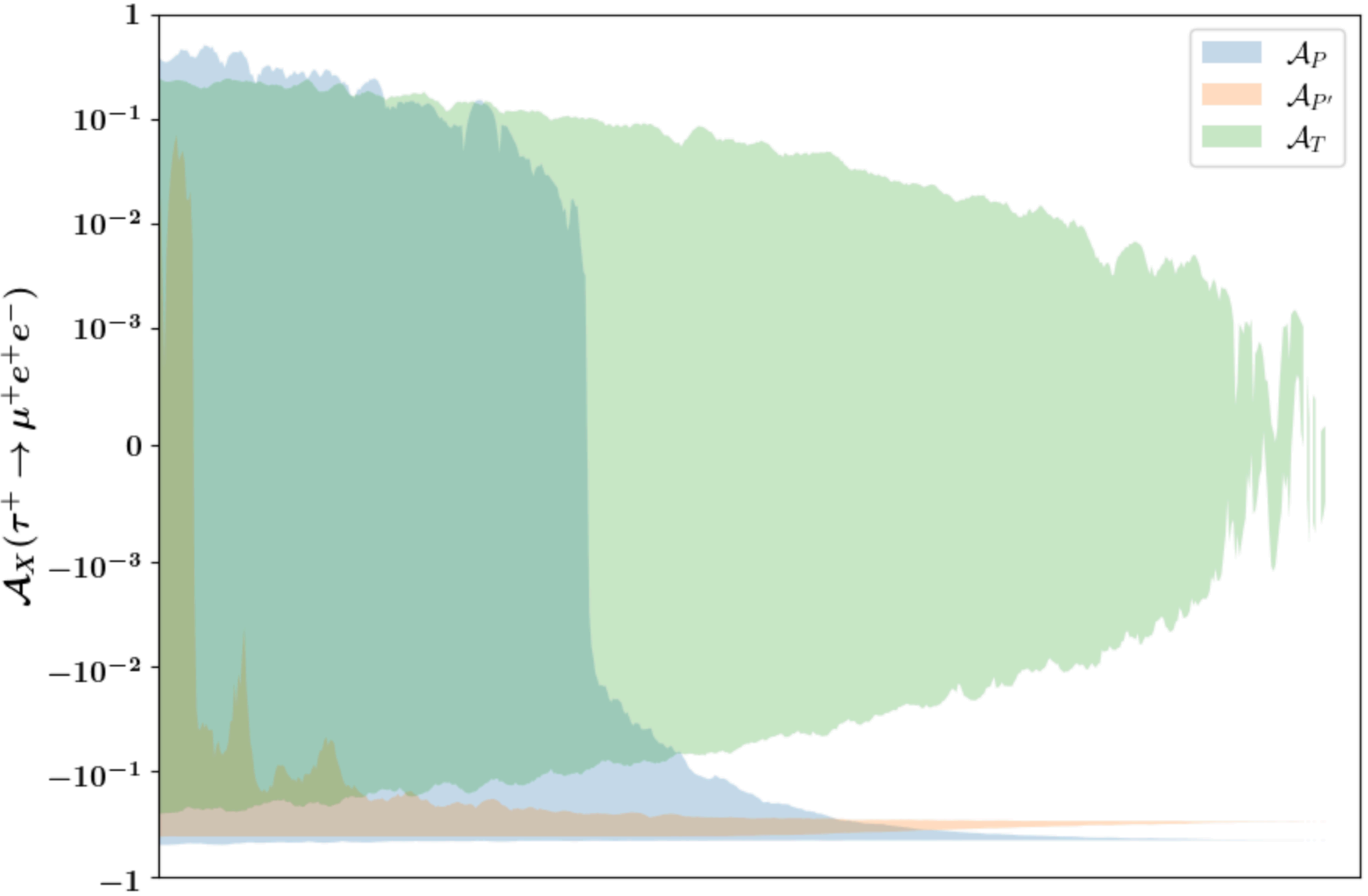
- - - $\varphi_4 = 2\pi/3$

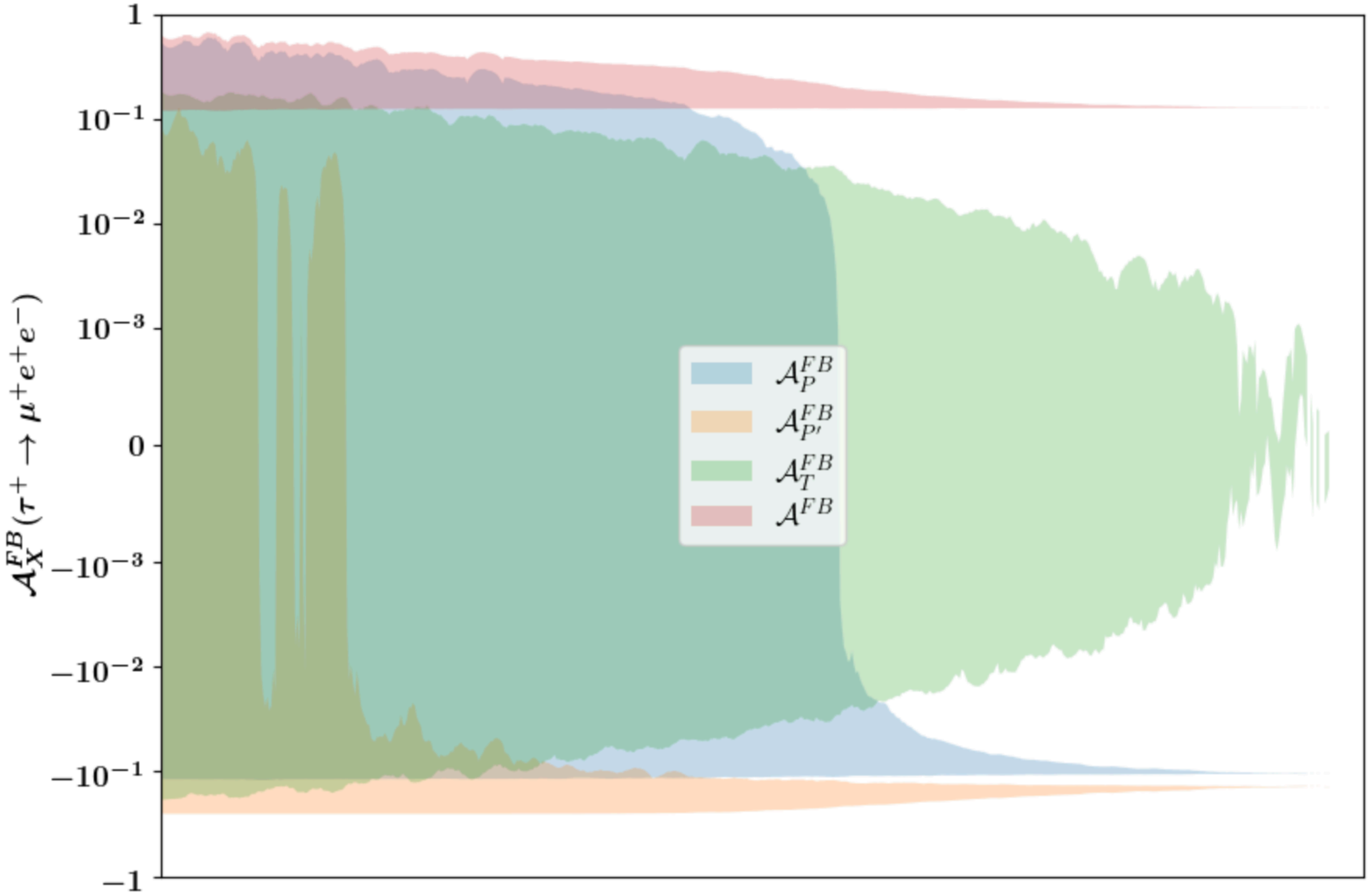


Adding more CPV phases drastically **changes phenomenology**…

Phases have a **strong impact** on cLFV analyses

Now scanning over all parameters keeping only "phenomenologically viable points"

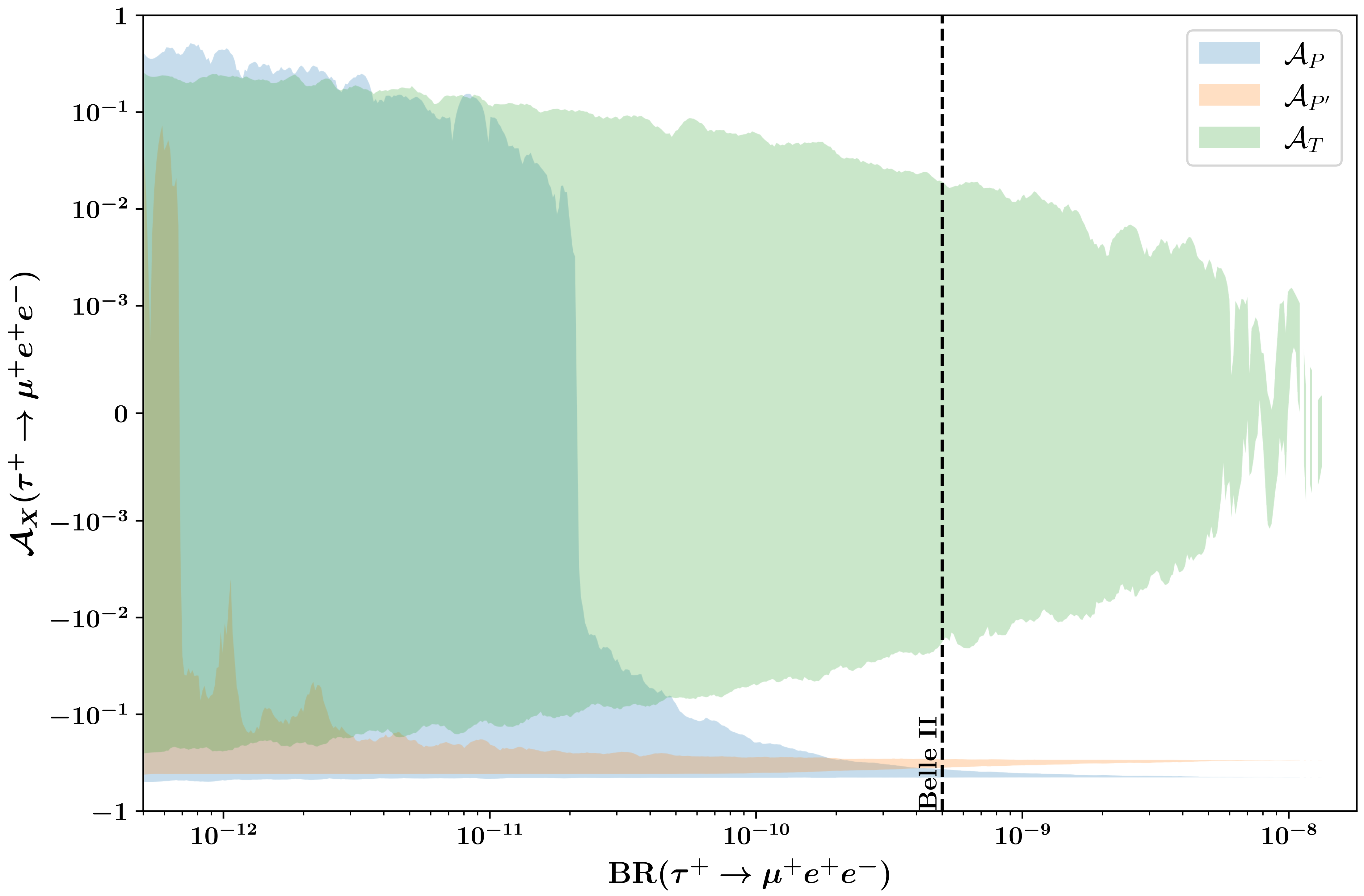


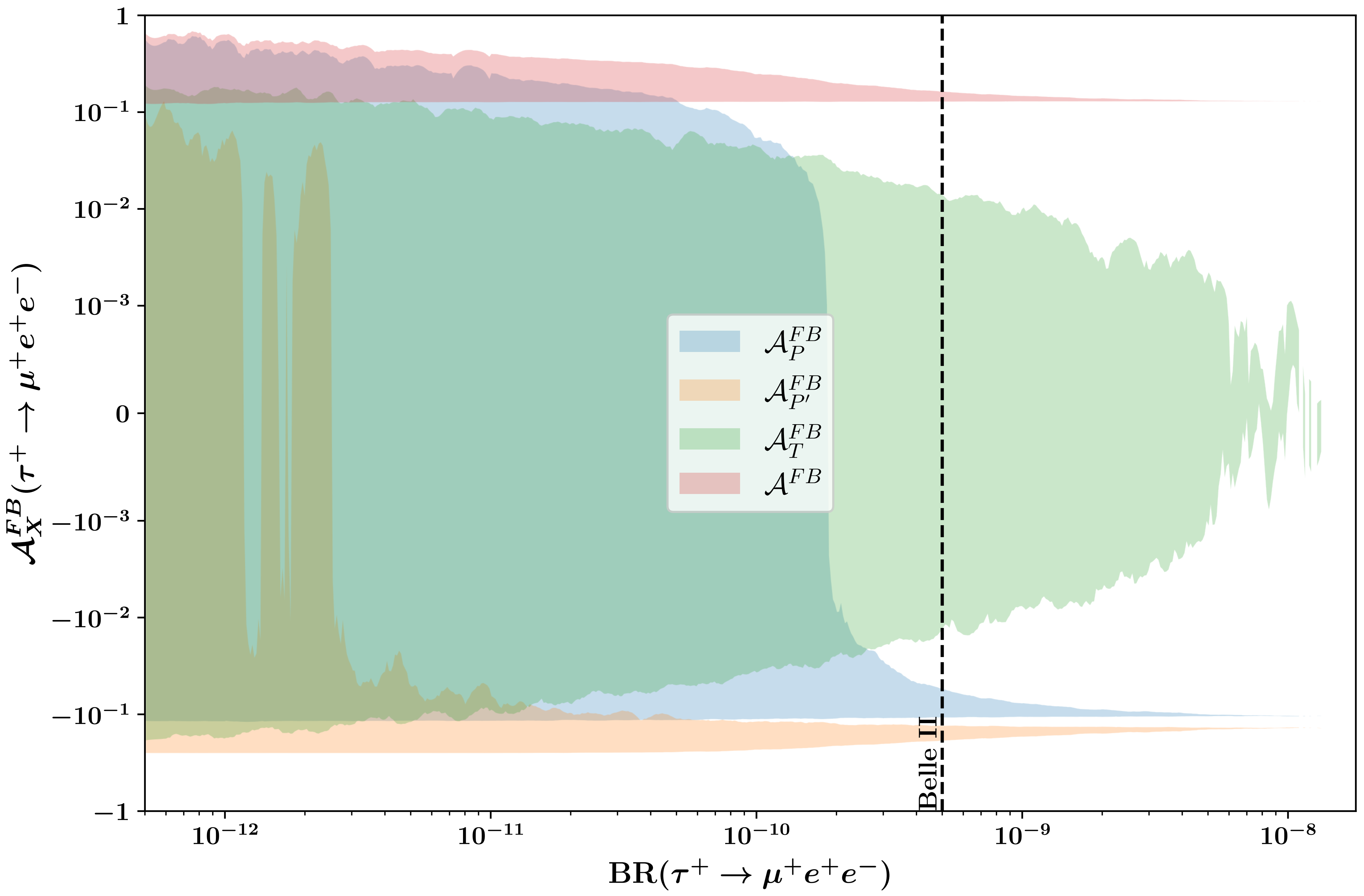


Vast regimes expected for $\mathscr{A}_X^{(FB)}$, with large asymmetries potentially reachable!

But what about detectability?

Asymmetries in tau decays



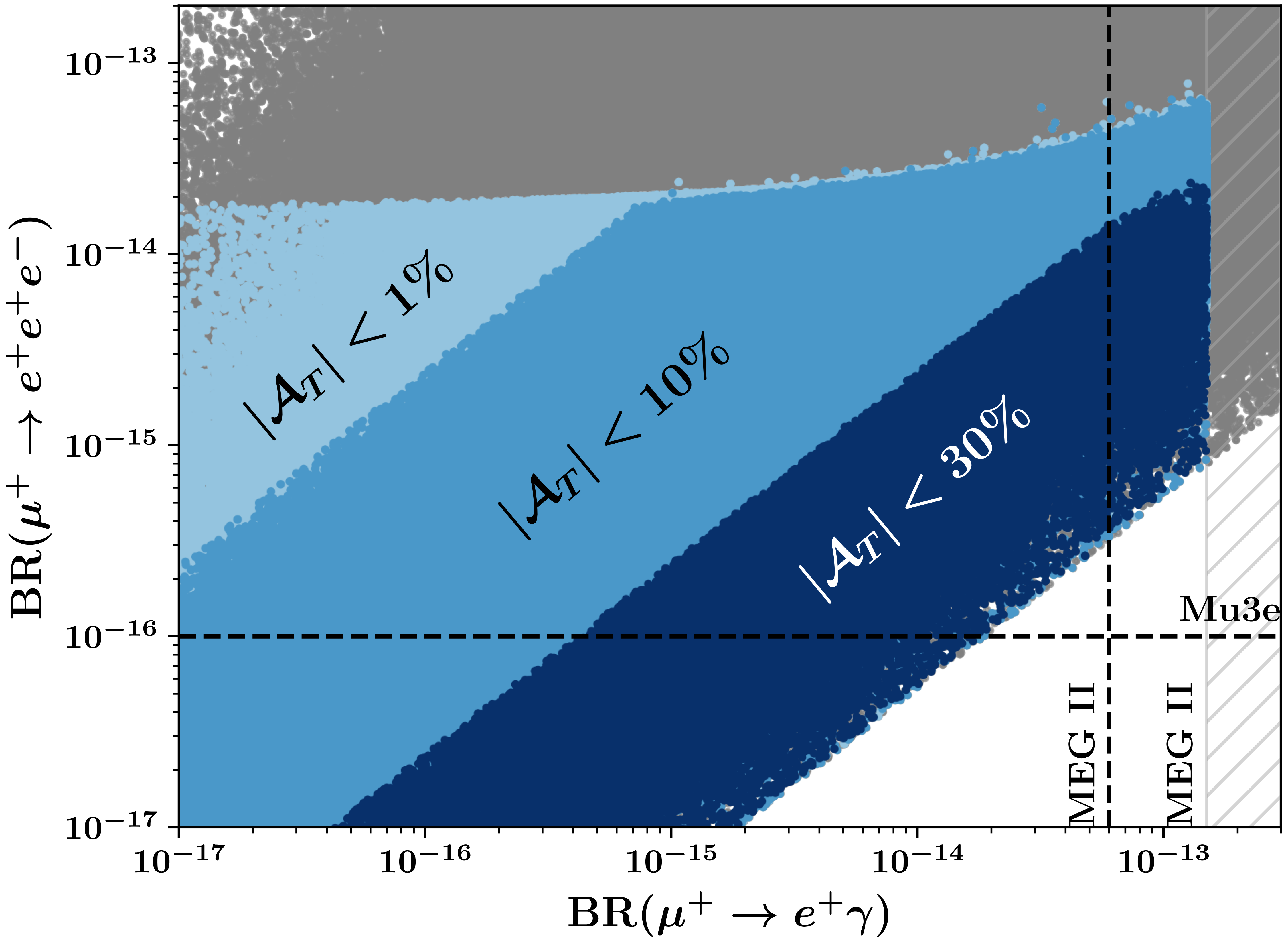


With current future sensitivity, only a **narrow region** for which asymmetries can be studied…

$\Rightarrow$ **Clear prediction** for values of asymmetries in $\tau^+ \to \ell_\alpha^+ \ell_\beta^+ \ell_\beta^-$ decays if measured by Belle II!

This simple extension is **easily falsifiable** if $\mathrm{BR}(\tau^+ \to \ell_\alpha^+ \ell_\beta^+ \ell_\beta^-) \geq 5 \times 10^{-10}$

T Asymmetry in muon decays



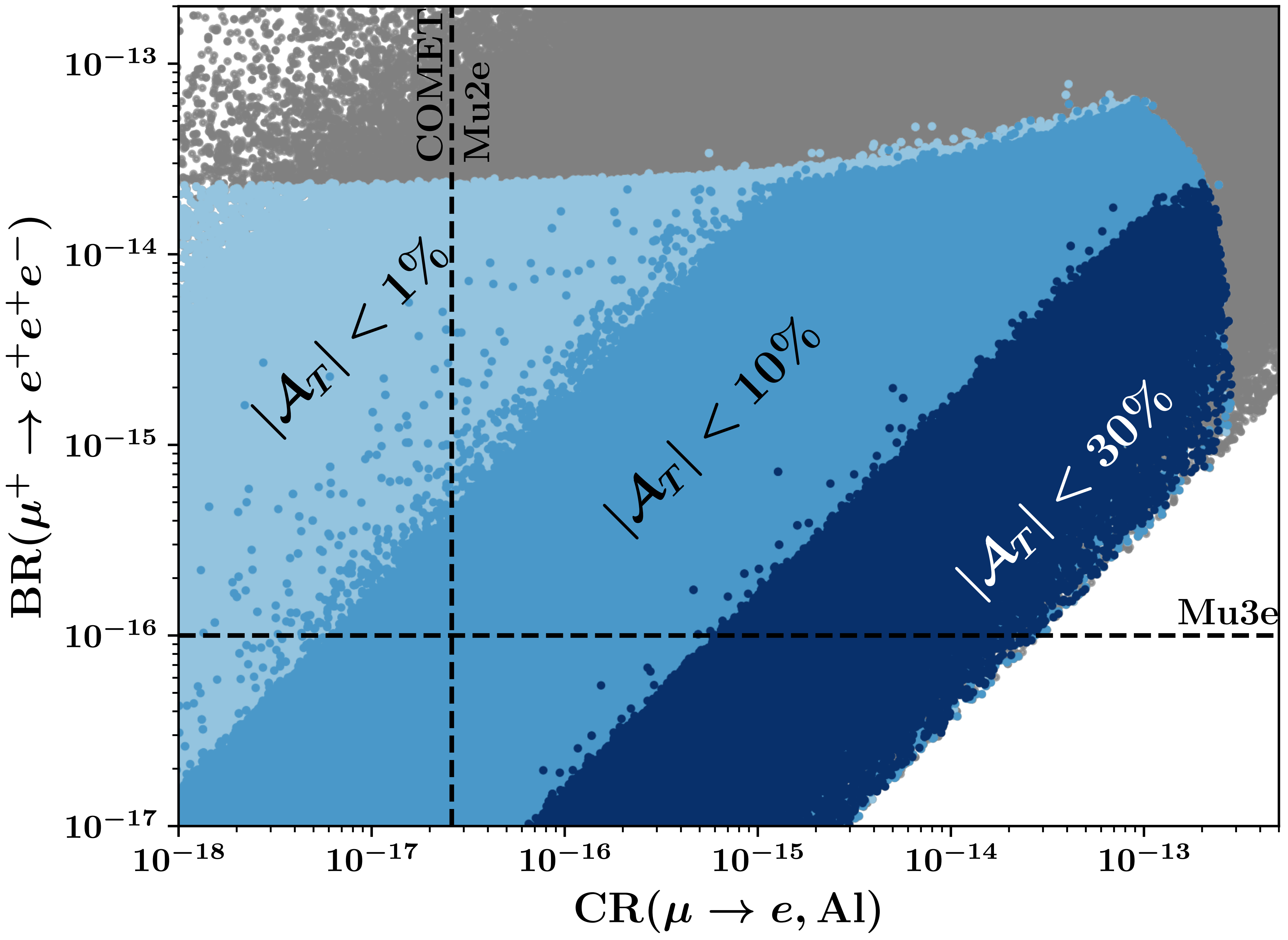
CPV phases lead to a **loss of correlation** between μ decays…

If large T **asymmetry** in association with $\mu^+ \to e^+e^+e^-$,

⇒ **narrow down** the allowed values for BR($\mu^+ \to e^+\gamma$)!

Unfortunately, **measurement** of $\mu^+ \to e^+e^+e^-$ and its asymmetries **does not imply measurement** of $\mu^+ \to e^+\gamma$…

T Asymmetry in muon decays



CPV phases lead to a **loss of correlation** between μ decays…

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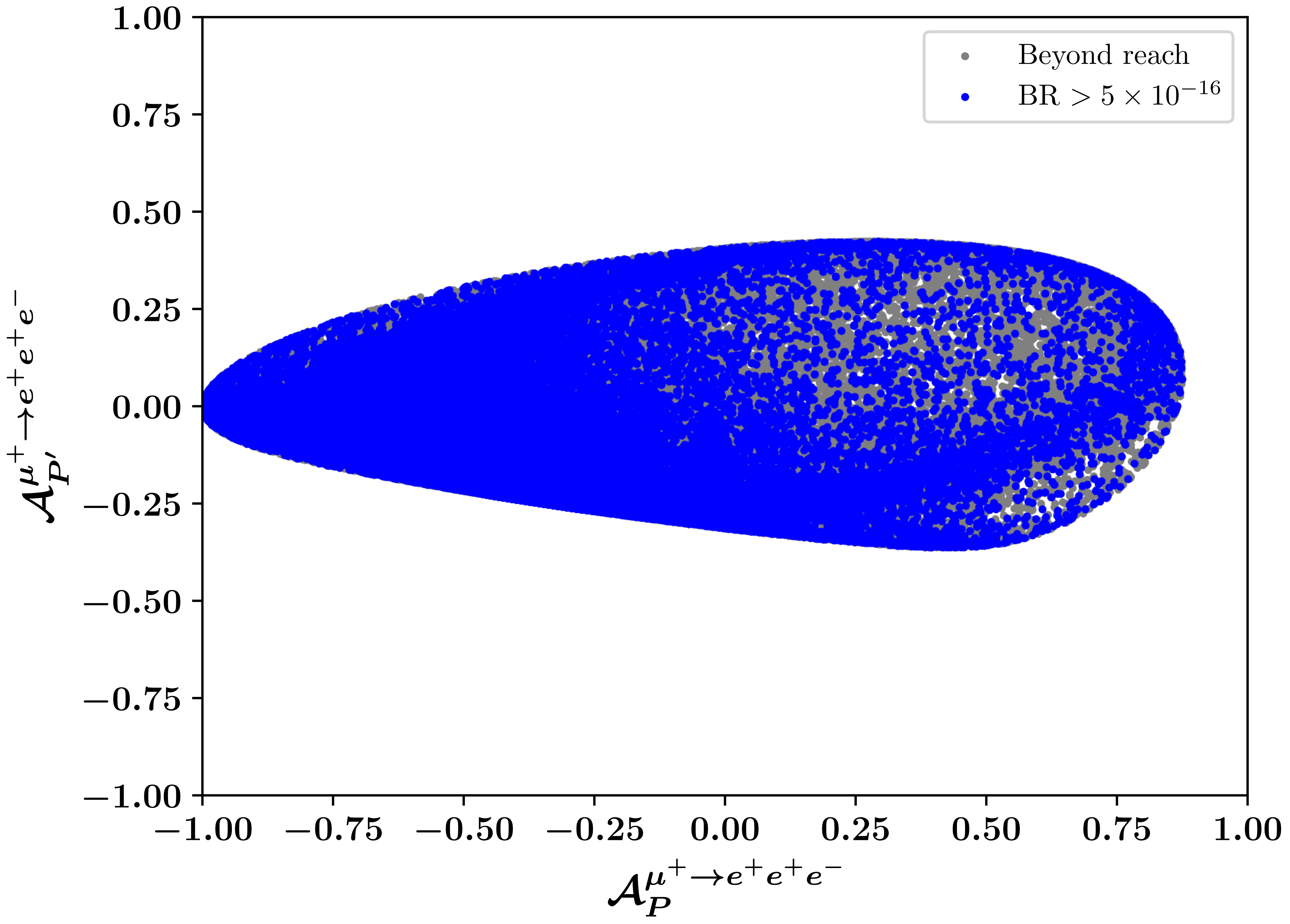
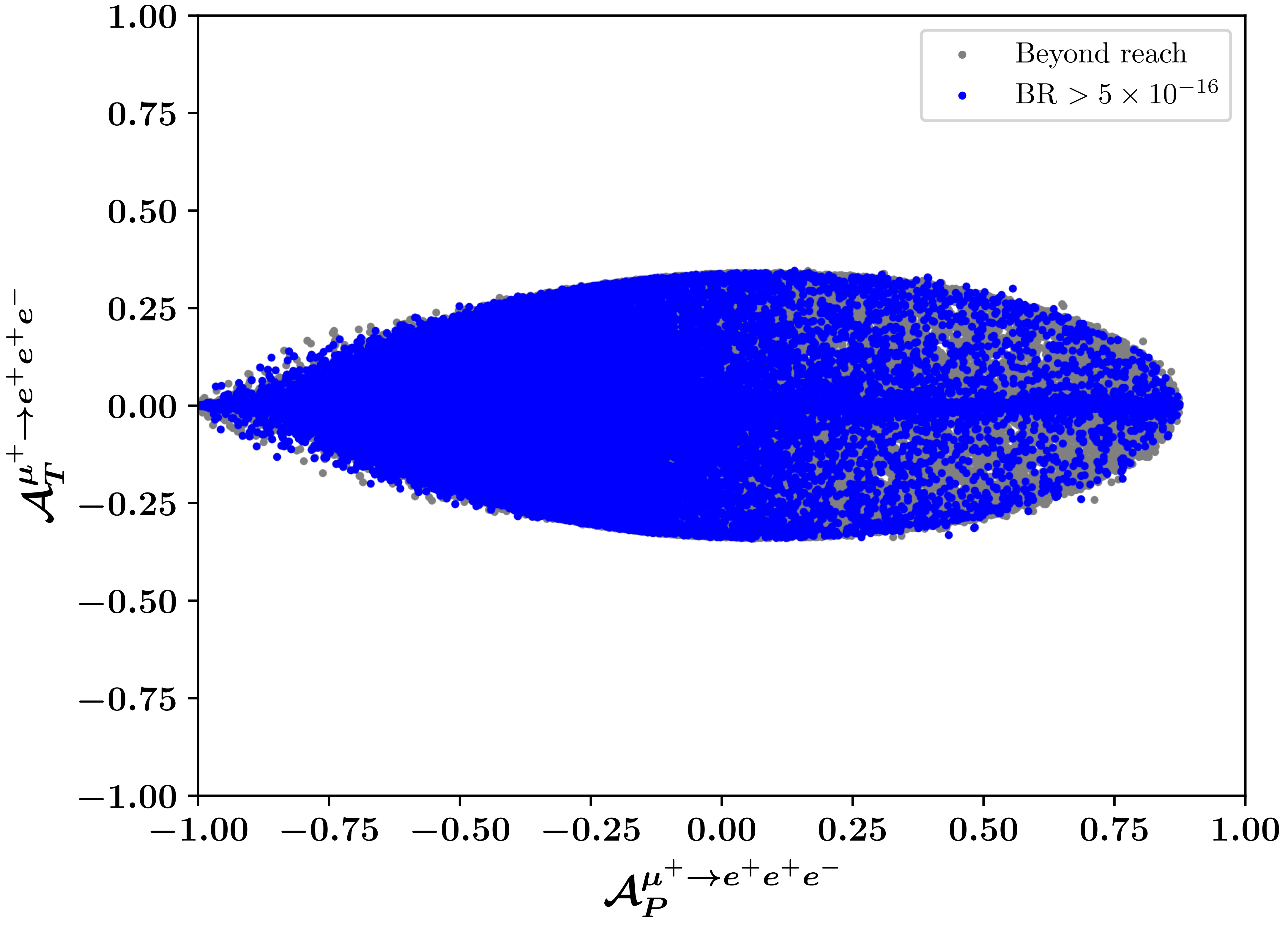
⇒ **narrow down** the allowed values for CR($\mu \to e$, Al)!

Measurement of $\mu^+ \to e^+e^+e^-$ decay with T **asymmetry** $\gtrsim 10\ \%$ would **imply measurement** by COMET and Mu2e!

Muon decay asymmetries: allowed regions

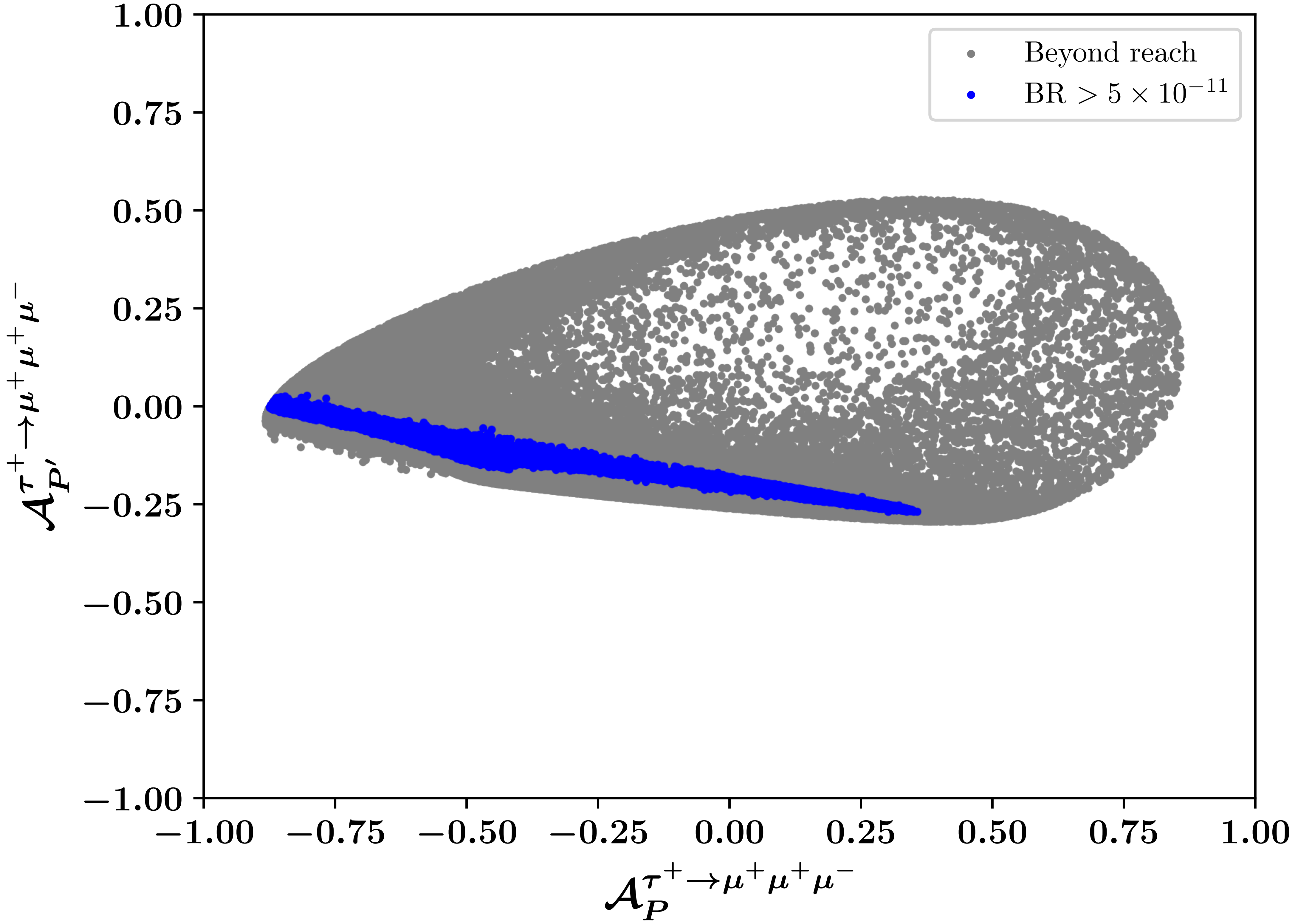


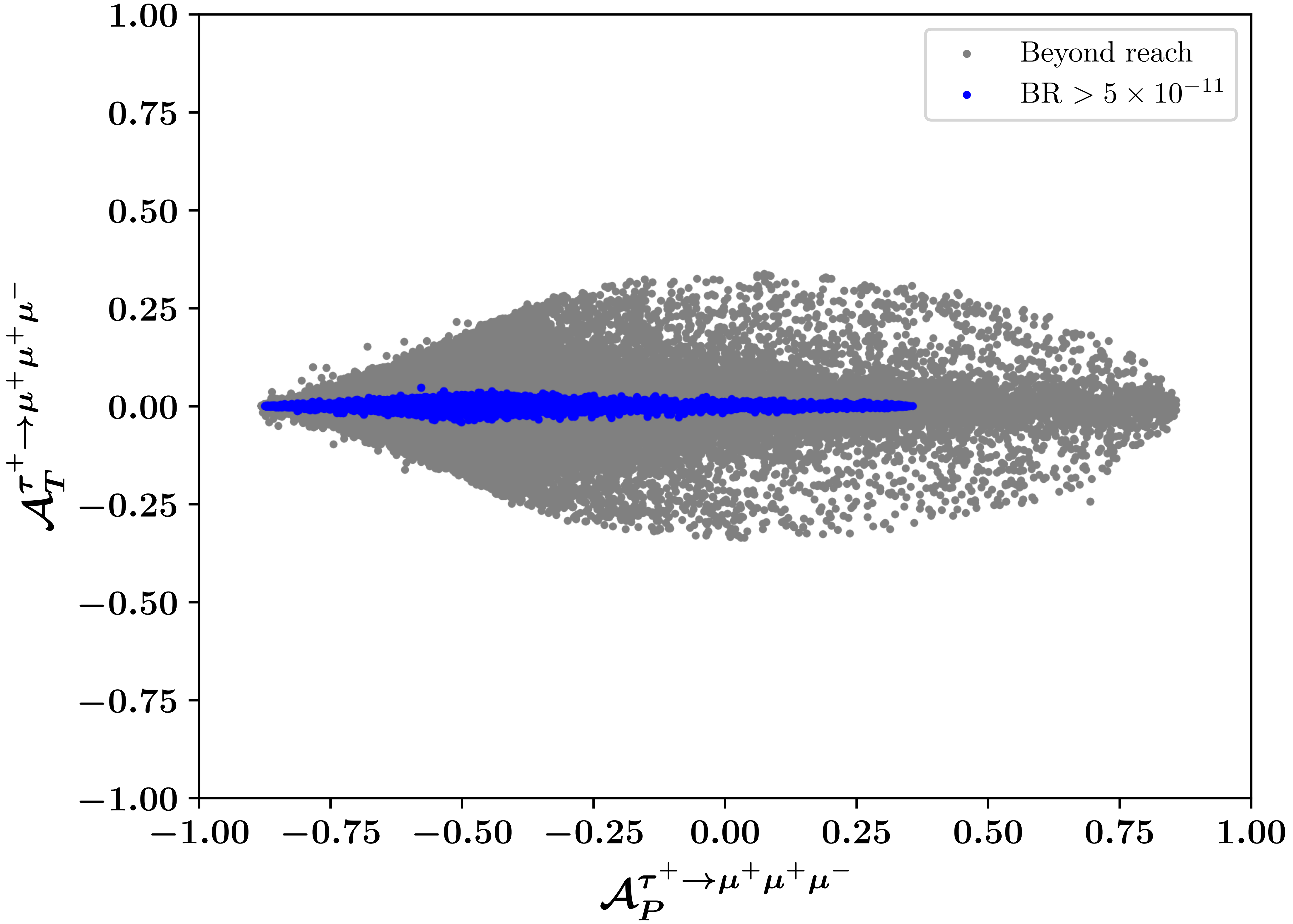


Well defined boundaries for region accessible by asymmetries, all within reach of future Mu3e sensitivity

⇒ Expected future sensitivity of Mu3e offers a **good coverage** of the full range of asymmetries

Tau decays: allowed regions





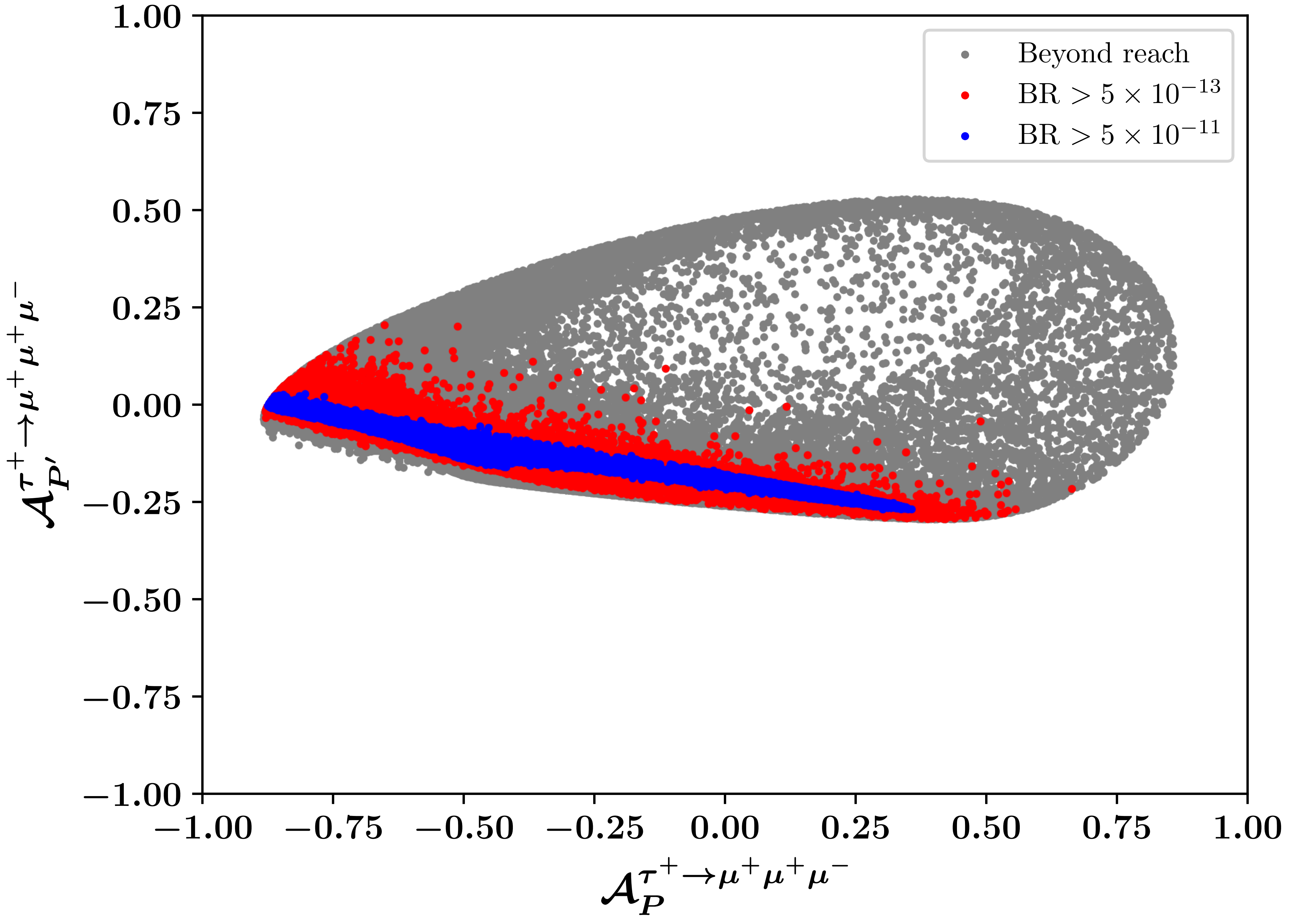
$\tau^+ \to \mu^+\mu^+\mu^-$ decay within future sensitivity

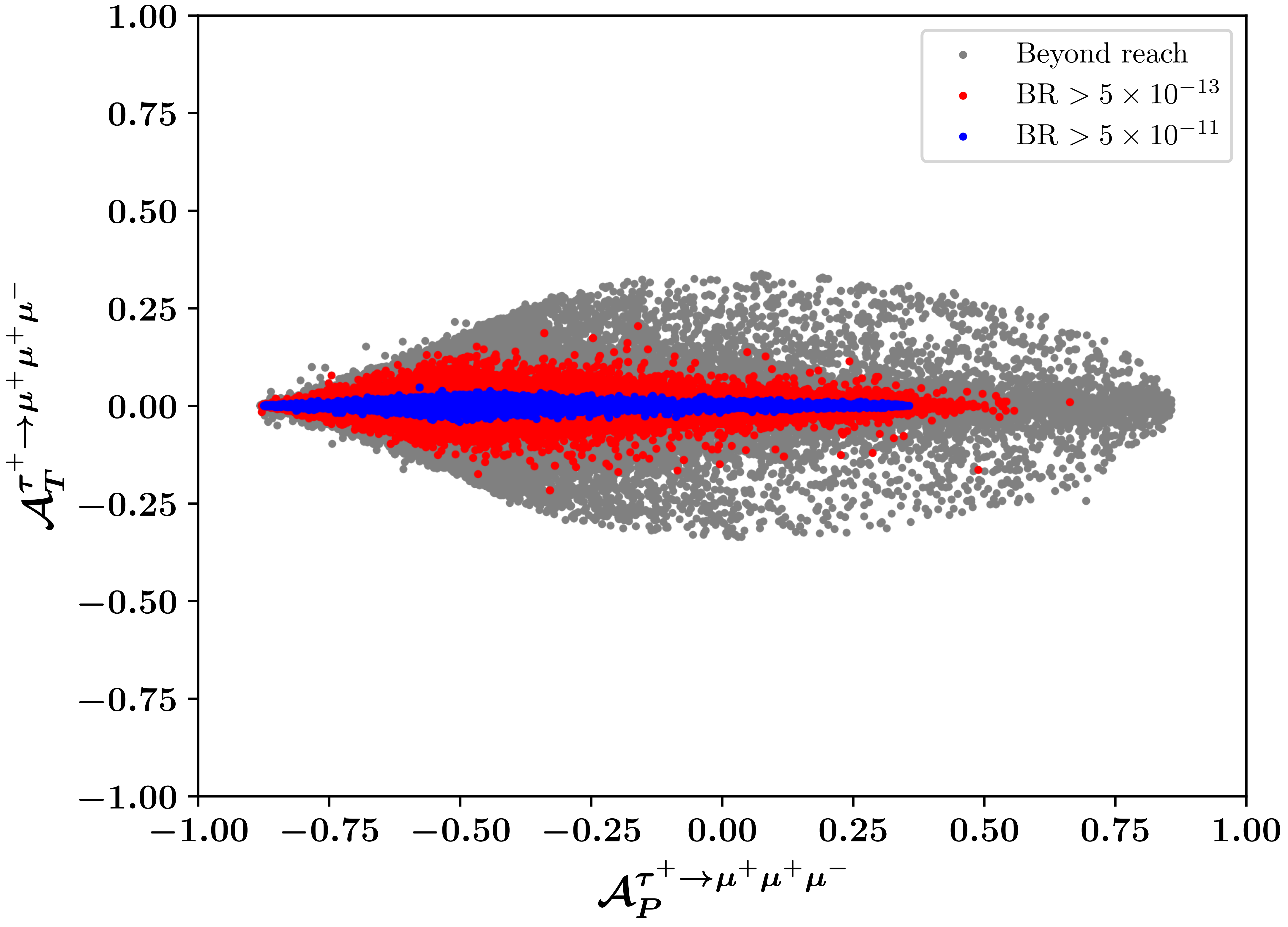
$\to$ **clear correlation** between asymmetries

Only small portion of the region accessible…

What if we are **more optimistic** on future sensitivity?

Tau decays: allowed regions





$\tau^+ \to \mu^+\mu^+\mu^-$ decay with improved future sensitivity

→ asymmetries **remain correlated**

But still **does not cover** the full allowed region!

Conclusions

→ **Thorough analysis** of asymmetries in 3 body cLFV leptonic decays for a **minimal extension** of the SM via **heavy neutral leptons**

Clear impact of CPV phases on cLFV decays

Prediction for values of asymmetries in $\tau^+ \to \ell_\alpha^+ \ell_\beta^+ \ell_\beta^-$ decay if measured in future experiments

T **asymmetry in** $\mu^+ \to e^+ e^+ e^-$ to **narrow down** allowed values of observable

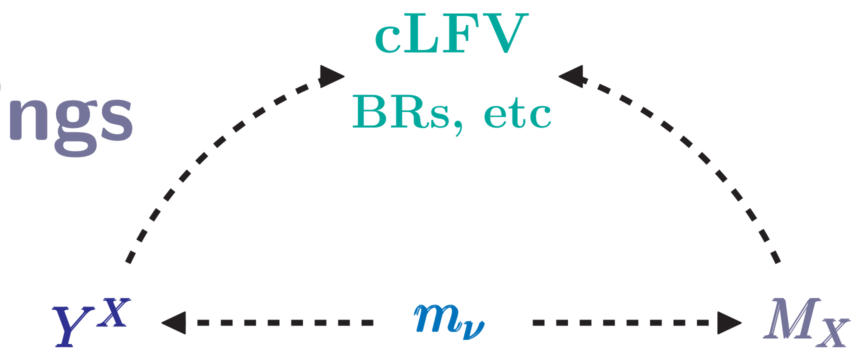
Asymmetries in $\tau^+ \to \mu^+ \mu^+ \mu^-$ decay also offer a way to **falsify the model**

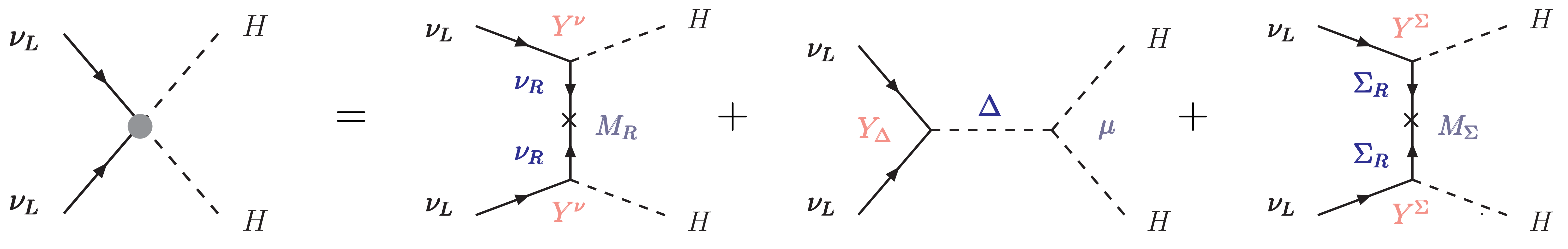
Asymmetries in τ 3 body cLFV decay as a **prime probe** for this minimal extension

Backup

Backup

★ **Seesaw mechanism:** explain **small ν masses** with **"natural" couplings** via **new dynamics** at **"heavy" scale**





$\frac{1}{\Lambda} L\,L\,H\,H$	ν_R (fermion singlet)	Δ (scalar triplet)	Σ_R (fermion triplet)
"Seesaw mechanism"	**Type I**	**Type II**	**Type III**

▶ **Observables:** depend on **powers of Y^ν** $\rightsquigarrow$ large rates $\Rightarrow$ sizable Y^ν and on the **mass of** the (virtual) **NP propagators**

▶ **Fermionic seesaws:** $Y^\nu \sim \mathcal{O}(1) \Rightarrow M_{\text{new}} \approx 10^{13-15}$ **GeV!**

Suppression of rates due to the **large mass of the mediators!**

▶ **Low scale seesaws:** **rich phenomenology** **at high-intensities!** (and also at LHC)

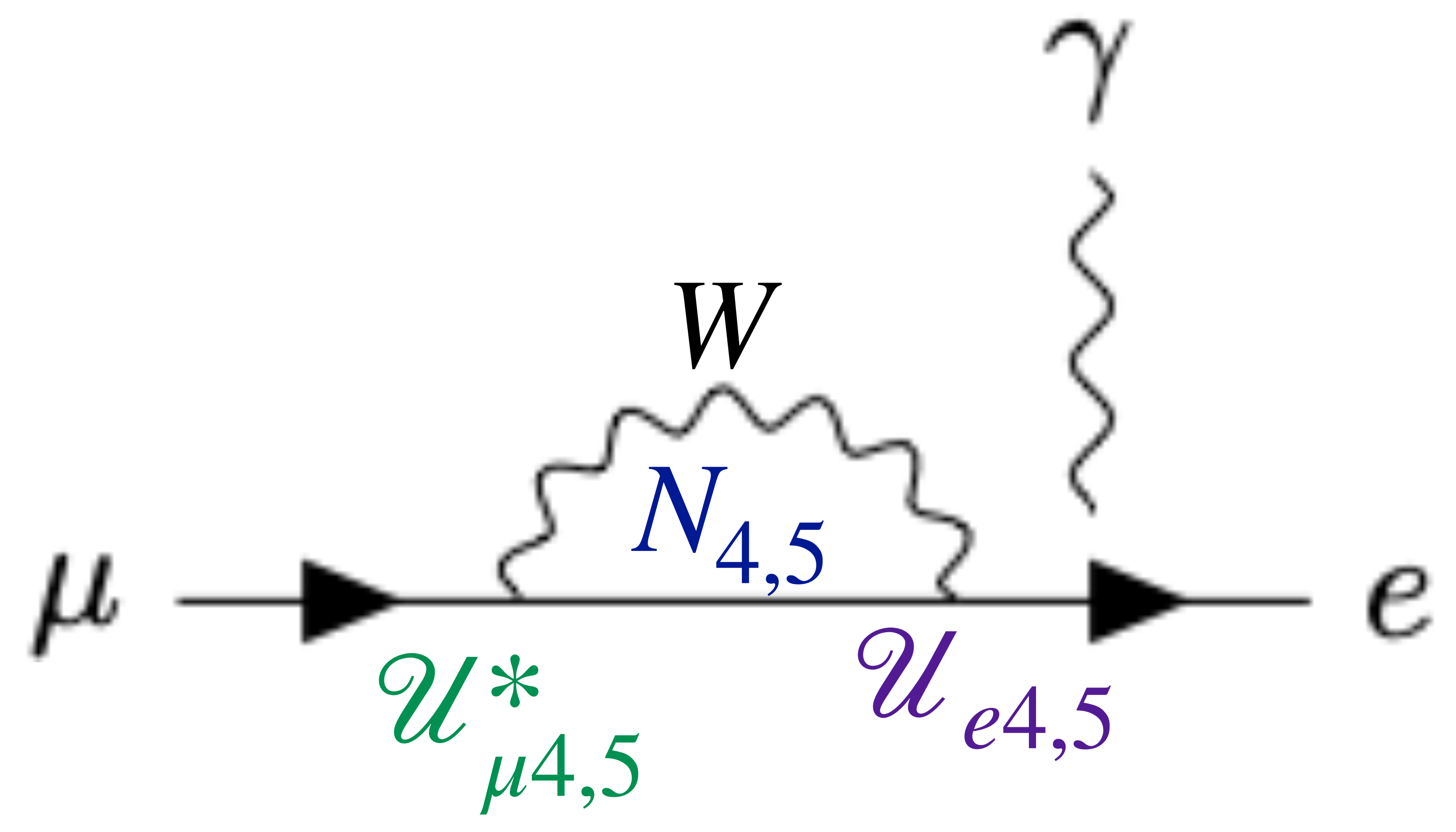
Backup

Example: $\mu \to e\gamma$

BR$(\mu \to e\gamma) \propto |G_\gamma^{\mu e}|^2$

cLFV form factor including mixing and loop function:

$$G_\gamma^{\mu e} = \sum_{i=4,5} \mathcal{U}_{ei}\mathcal{U}_{\mu i}^* G_\gamma\left(\frac{m_{N_i}^2}{m_W^2}\right)$$



Assume $m_4 \approx m_5$ and $\sin\theta_{\alpha 4} \approx \sin\theta_{\alpha 5} \ll 1$:

$$|G_\gamma^{\mu e}|^2 \approx 4 s_{14}^2 s_{24}^2 \cos^2\left(\frac{\delta_{14} + \delta_{25} - \delta_{15} - \delta_{24}}{2}\right) G_\gamma\left(\frac{m_{N_i}^2}{m_W^2}\right)$$

$\Rightarrow$ Rate depends on Dirac phases, full cancellation for $\delta_{14} + \delta_{25} - \delta_{15} - \delta_{24} = \pi$

Other form factors more complicated, Z-penguin and boxes also depend on $\varphi_{4,5}$

Backup

Parameter space explored in numerical study

Observable	Current bound		Future sensitivity	
$\mathrm{BR}(\mu \to 3e)$	$< 1.0 \times 10^{-12}$	(SINDRUM)	$10^{-15(-16)}$	(Mu3e)
$\mathrm{BR}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$	(Belle)	5×10^{-10}	(Belle II)
$\mathrm{BR}(\tau \to 3\mu)$	$< 1.9 \times 10^{-8}$	(Belle II)	5×10^{-10}	(Belle II)
			5×10^{-11}	(FCC-ee)
$\mathrm{BR}(\tau^+ \to e^+\mu^+\mu^-)$	$< 2.7 \times 10^{-8}$	(Belle)	5×10^{-10}	(Belle II)
$\mathrm{BR}(\tau^+ \to \mu^+e^+e^-)$	$< 1.8 \times 10^{-8}$	(Belle)	5×10^{-10}	(Belle II)
$\mathrm{BR}(\tau^+ \to e^+e^+\mu^-)$	$< 1.5 \times 10^{-8}$	(Belle)	3×10^{-10}	(Belle II)
$\mathrm{BR}(\tau^+ \to \mu^+\mu^+e^-)$	$< 1.7 \times 10^{-8}$	(Belle)	4×10^{-10}	(Belle II)

$$
\begin{aligned}
&|\sin(\theta_{1\ 4,5})| \in [6.0 \times 10^{-5}, 6.0 \times 10^{-3}]\,,\\
&|\sin(\theta_{2\ 4,5})| \in [1.9 \times 10^{-4}, 0.036]\,,\\
&|\sin(\theta_{3\ 4,5})| \in [8.3 \times 10^{-4}, 0.13]\,,\\
&m_4 \in [10^3, 10^4]\ \mathrm{GeV}\,, \qquad \Delta m_{45} \in [10^{-2}, 5 \times 10^3]\ \mathrm{GeV}\\
&\delta_{\alpha i} \in [0, 2\pi]\,, \qquad \varphi_i \in [0, 2\pi]\,.
\end{aligned}
$$

Additional constraints from modified $\tilde{\mathcal{U}}_{PMNS}$ considered:

→ W mass and weak mixing angle

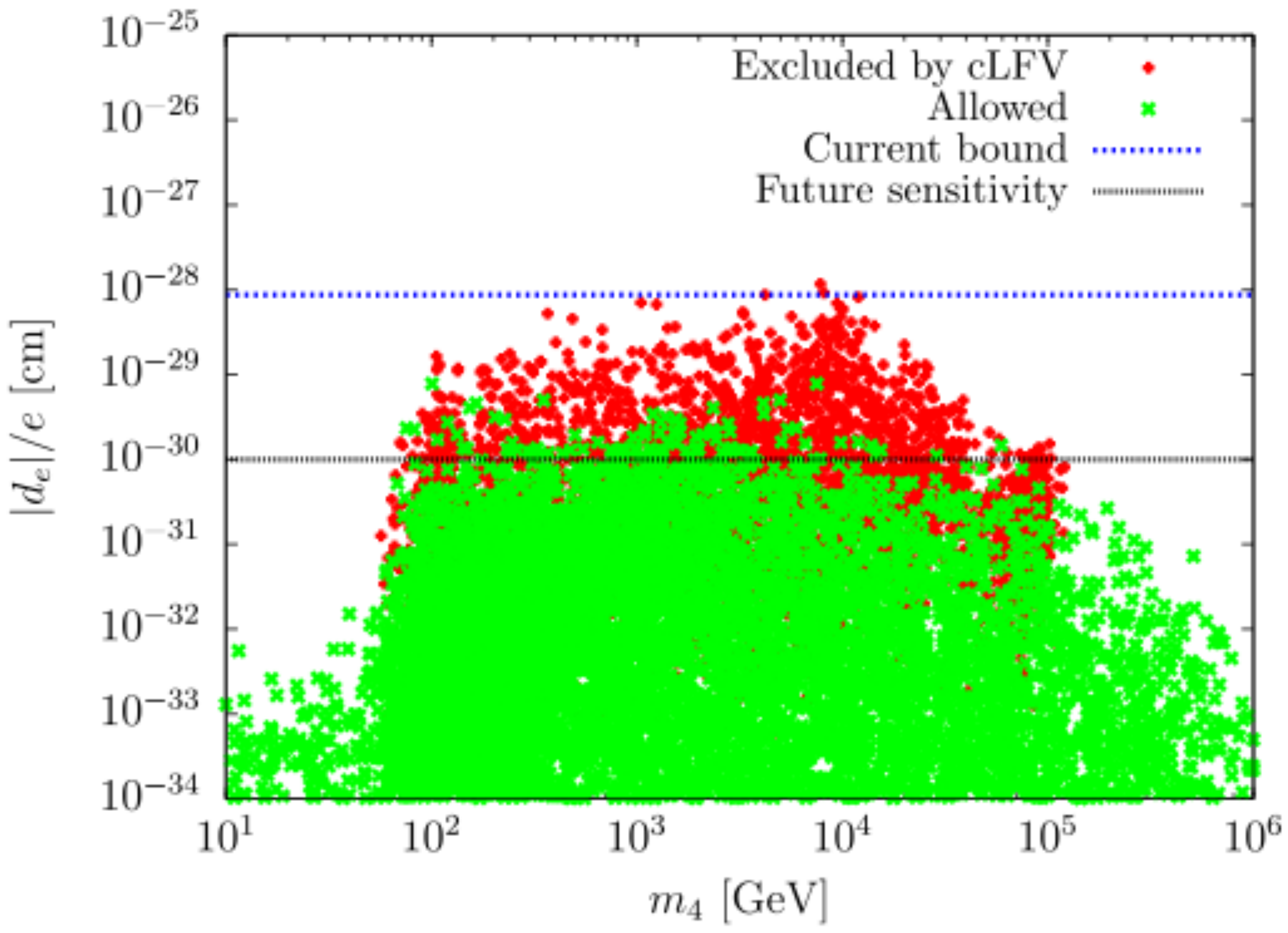
→ Z and weak decays

→ neutrinoless double beta decay

→ HNL decays

EDM

In the presence of CPV phases, possible contributions to electric dipole moments



Abada, Toma [1511.03265]

Electron EDM only within future reach if:

→ Sterile neutrinos are of Majorana nature

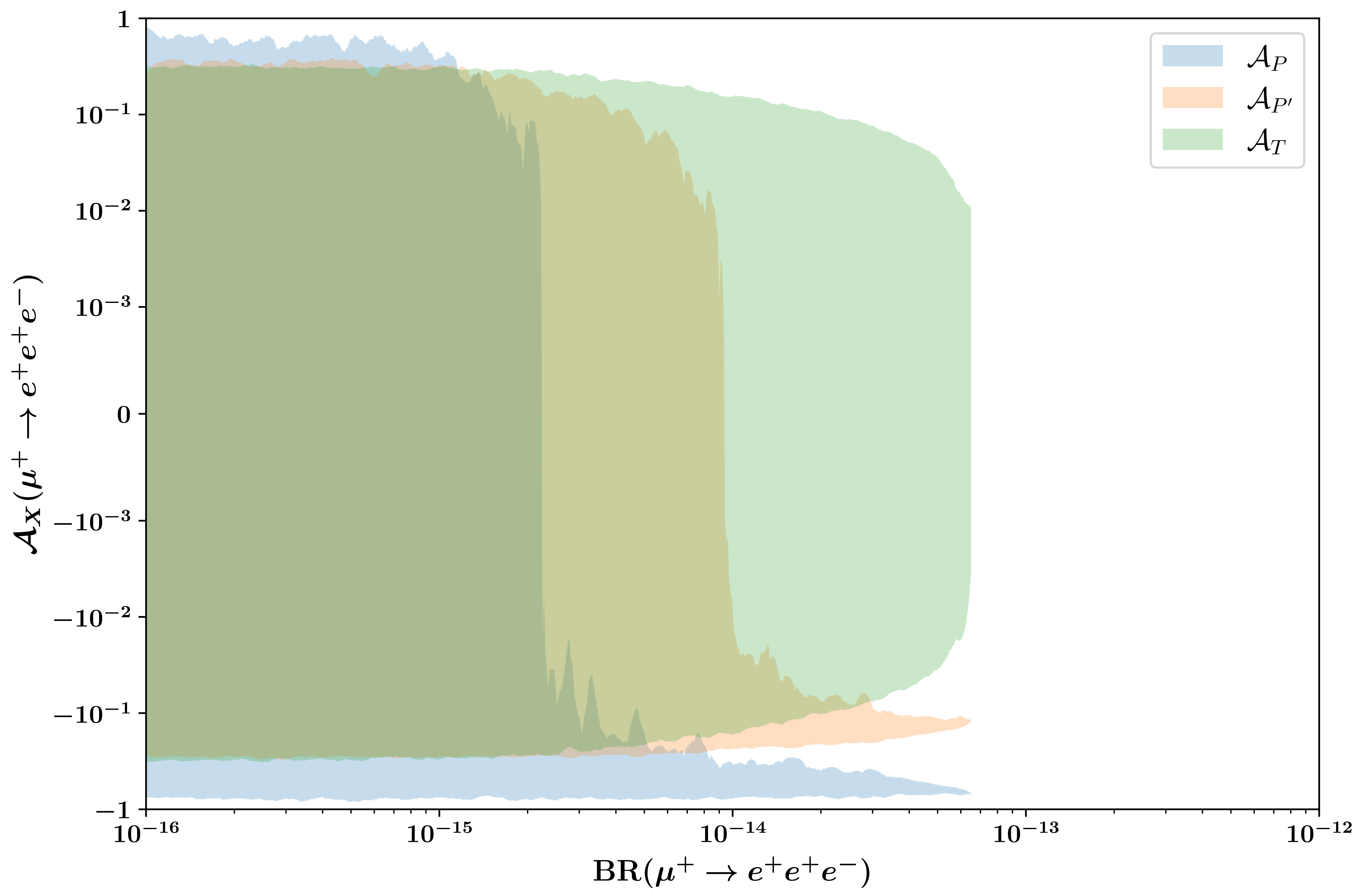
→ At least 2 HNL must be introduced

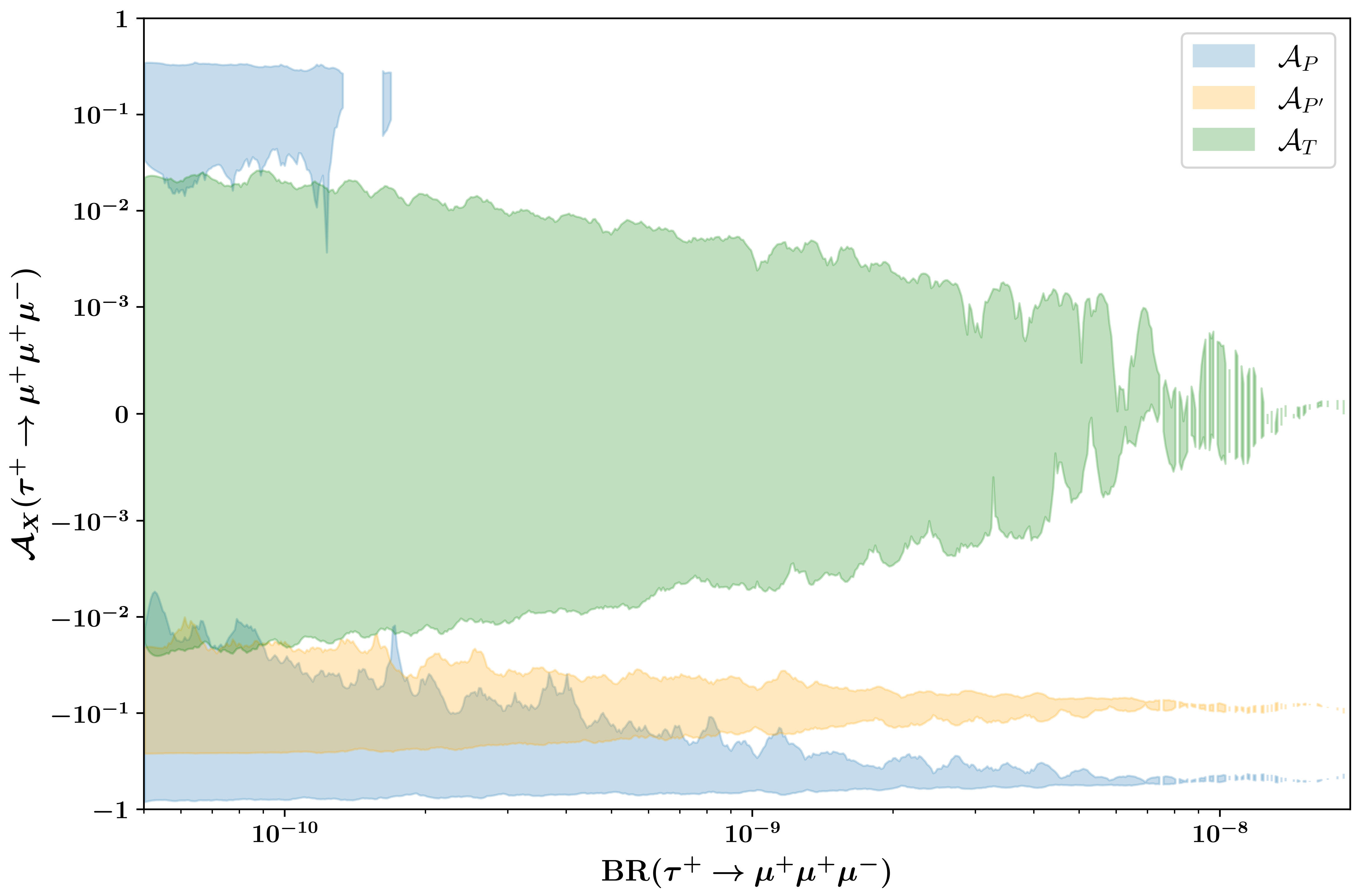
→ For the "3+2", 100 GeV $\lesssim M_{N_i} \lesssim$ 100 TeV

Tau and muon EDMs remain **several order of magnitude below future sensitivity.**

Backup

3 body decay asymmetries full scan





Backup

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IN2P3 Les deux infinis

$\tau^+ \to \ell_\alpha^+ \ell_\beta^+ \ell_\beta^-$ asymmetry space