CP-Asymmetries in Semileptonic Decays

How to Exploit Direct and Indirect CP-asymmetries in rare B-decays

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Based on works with S. Descotes-Genon, S. Fajfer, J.F. Kamenik, N. Kosnik and K. K. Vos
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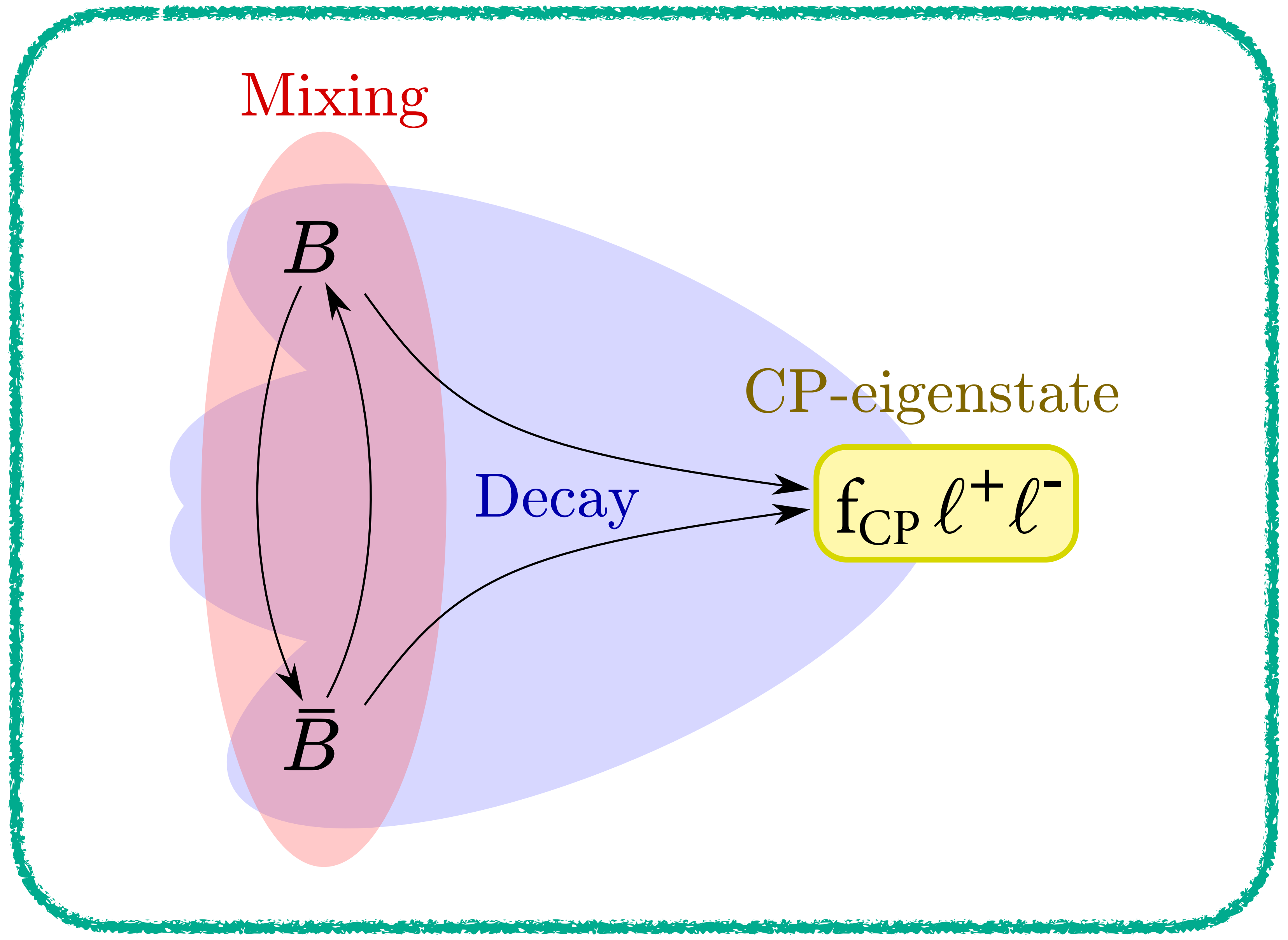
CSIC Consejo Superior de Investigaciones Científicas

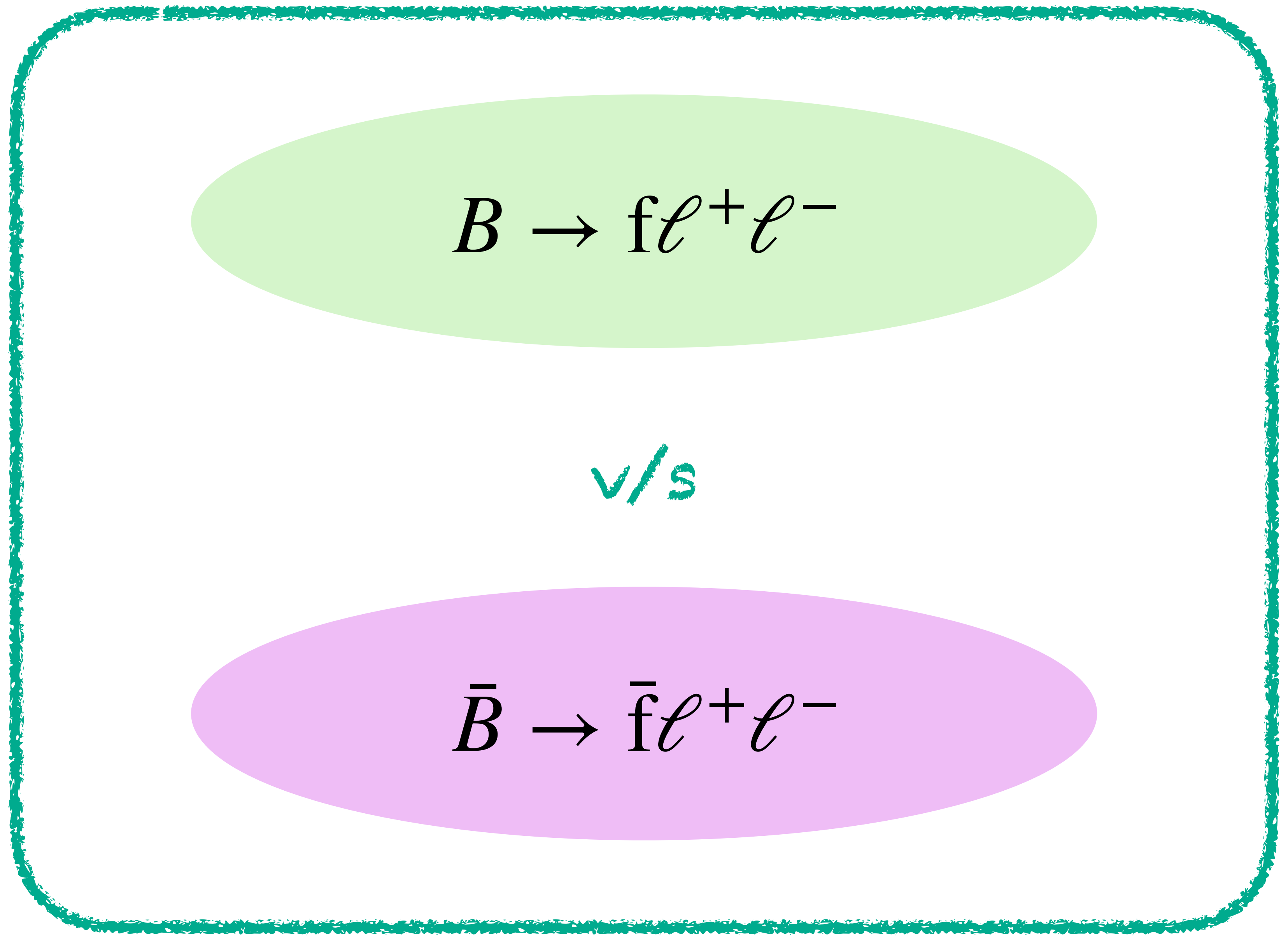
CP-Asymmetries:

What can they tell us about deviations in $b \to s\ell\ell$?

Indirect



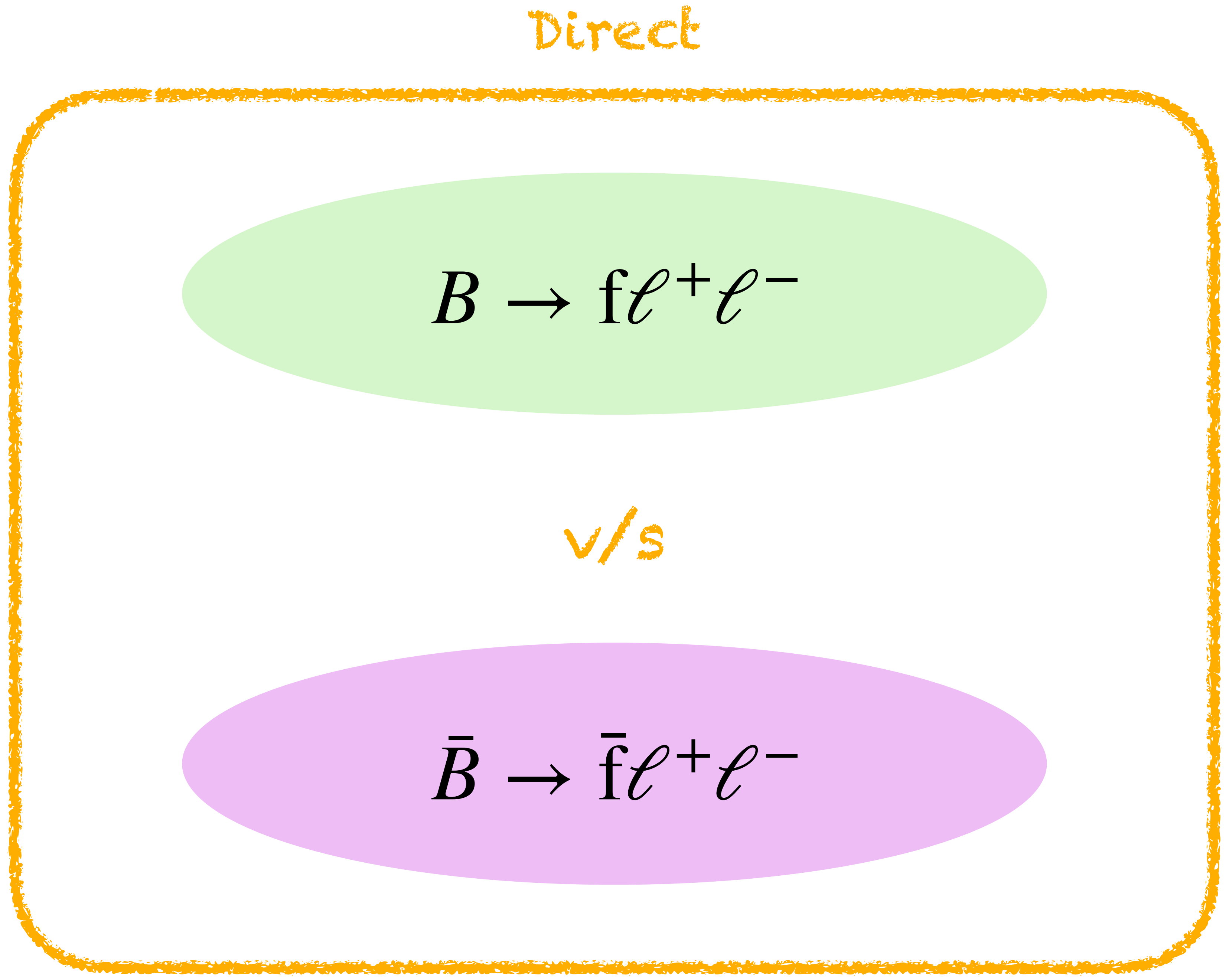
Direct

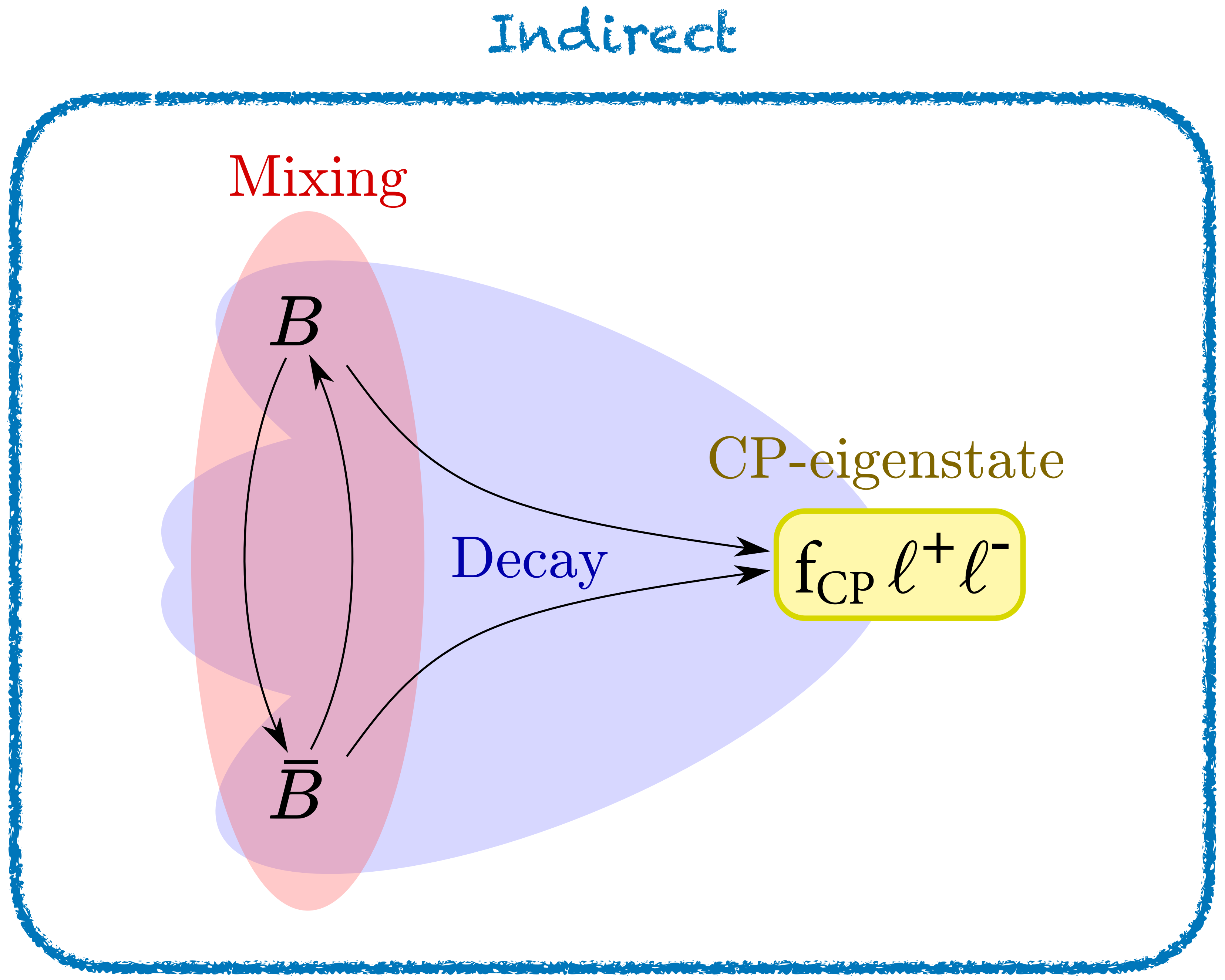


Direct vs Indirect CP-Asymmetries

- Difference between differential decay width of a mode and its CP-conjugate
- Can be "easily" measured in self tagging modes $(f \neq \bar{f})$
- They probe interference between CP-even and CP-odd phases

$$\mathscr{A}^{\text{dir}}_{CP} \equiv \frac{d\Gamma - d\bar{\Gamma}}{d\Gamma + d\bar{\Gamma}}$$





- Effect of mixing and decay interference
- They only appear in non-self tagging modes (experimentally challenging)
- Require a time-dependent analysis and a tagged B
- They probe interference between CP-even and mixing phases

$b \to s(d)\ell\ell$ Effective Hamiltonian

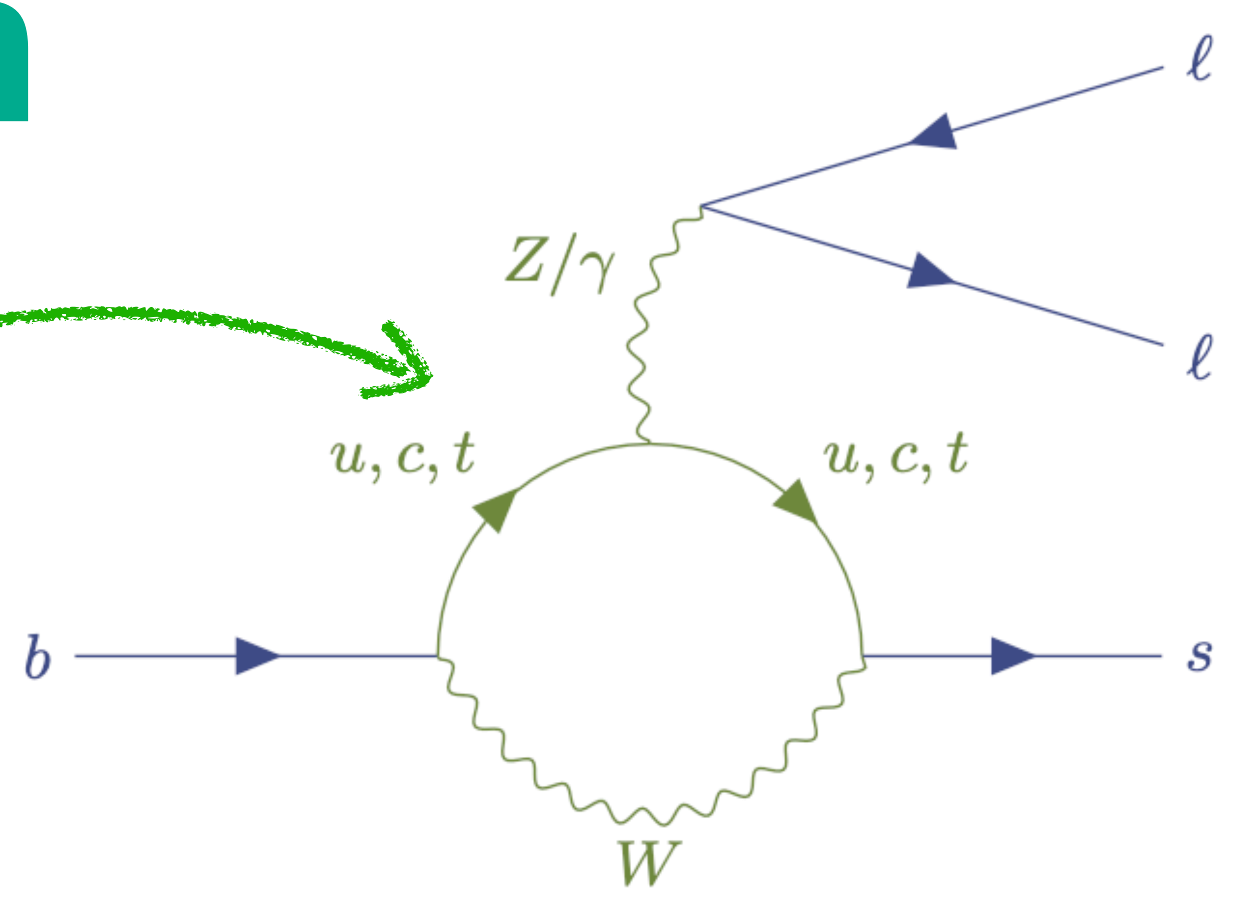
Local operator effective theory at scales below the electroweak scale

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left(\sum_{i=3}^{10} \mathcal{C}_i \mathcal{O}_i + \sum_{q=u,c} \frac{V_{qb}V_{qs}^*}{V_{tb}V_{ts}^*} \sum_{i=1,2} \mathcal{C}_i \mathcal{O}_i \right)$$

Short Distance

Long Distance

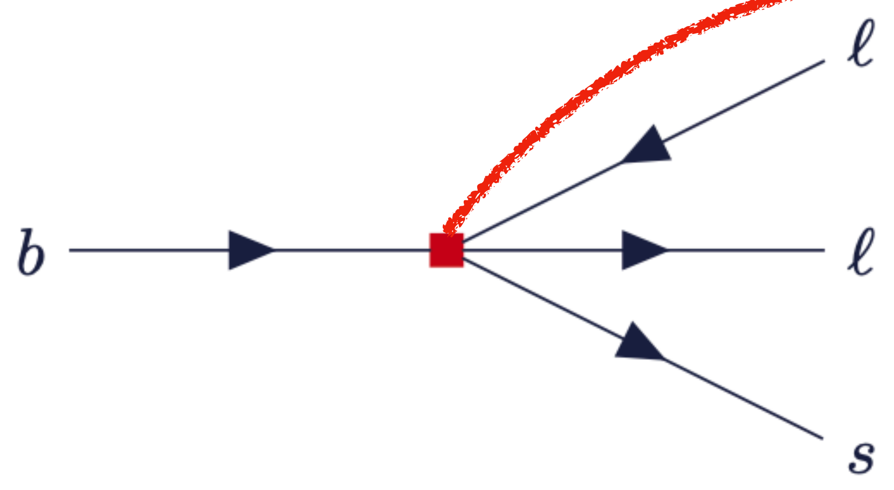
$$\mathcal{C}_i = \mathcal{C}_i^{NP} + \mathcal{C}_i^{SM}$$



4-quark operators contribute through loops:

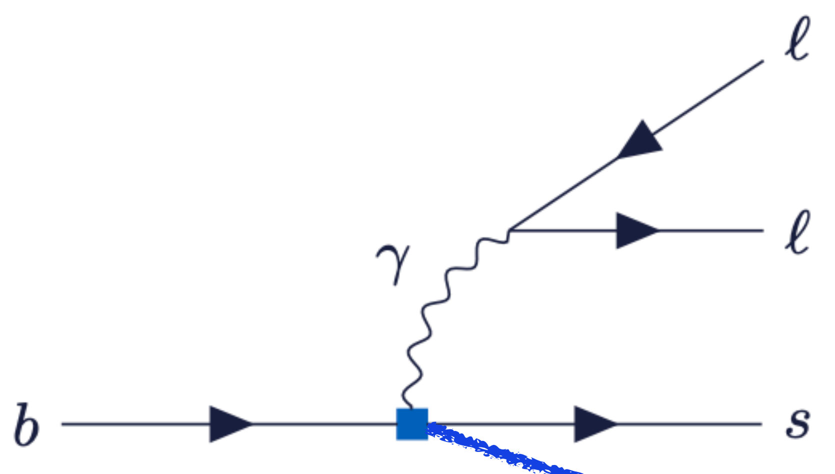
$$\mathcal{O}_1^q = (\bar{s}\gamma_\mu P_L T^a q)(\bar{q}\gamma^\mu P_L T^a b)$$

$$\mathcal{O}_2^q = (\bar{s}\gamma_\mu P_L q)(\bar{q}\gamma^\mu P_L b)\,, \quad \cdots$$



$$\mathcal{O}_{9^{(\prime)}} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10^{(\prime)}} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



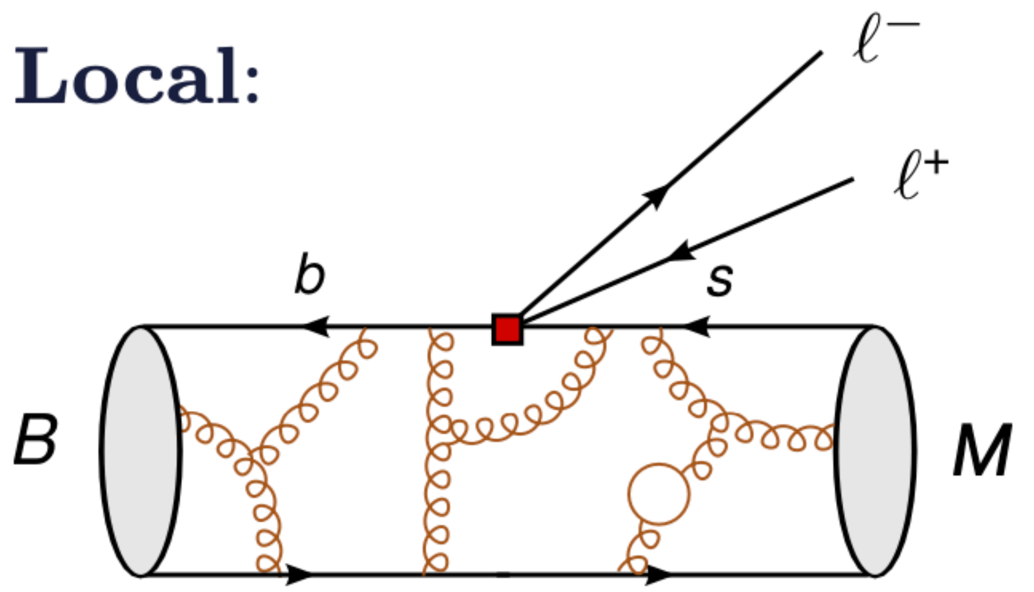
$$\mathcal{O}_{7^{(\prime)}} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

$b \to d\ell\ell$ is described with a similar framework

Theory of $B \to M\ell\ell$ decays

$$\mathcal{M}(B \to M\ell\ell) = \langle M\ell\ell|\mathcal{H}_{\text{eff}}|B\rangle = \mathcal{N}\Big[\left(\mathcal{A}_V^\mu + \mathcal{H}^\mu\right)\bar{u}_\ell\gamma_\mu v_\ell + \mathcal{A}_A^\mu\,\bar{u}_\ell\gamma_\mu\gamma_5 v_\ell\Big]$$

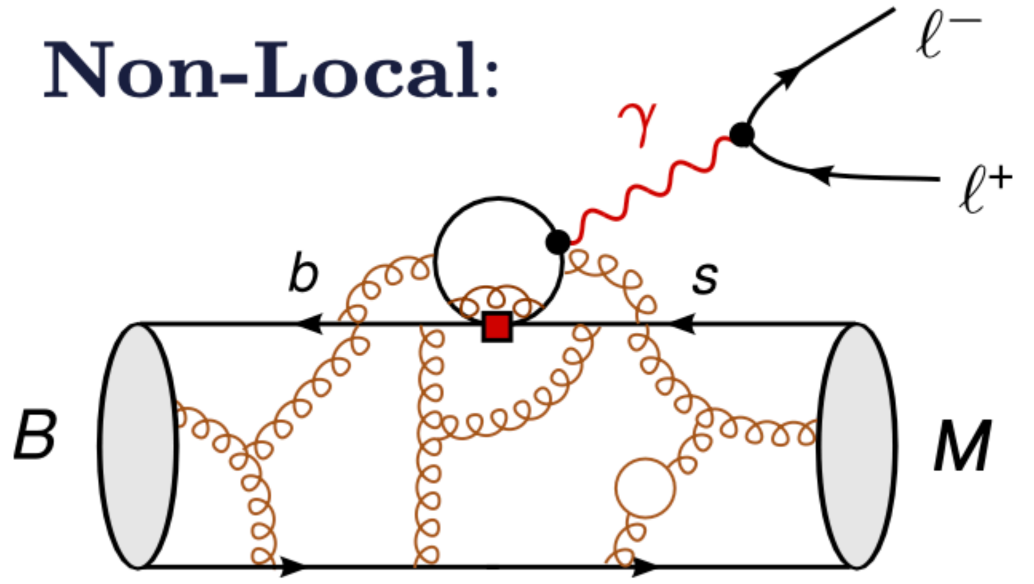
Local:



$$\mathcal{A}_V^\mu = -\frac{2im_b}{q^2}\,\mathcal{C}_7\langle M|\bar{s}\,\sigma^{\mu\nu}q_\nu\,P_R\,b|B\rangle + \mathcal{C}_9\langle M|\bar{s}\,\gamma^\mu\,P_L\,b|B\rangle + (P_L \leftrightarrow P_R, \mathcal{C}_i \to \mathcal{C}_i')$$

$$\mathcal{A}_A^\mu = \mathcal{C}_{10}\langle M|\bar{s}\,\gamma^\mu\,P_L\,b|B\rangle + (P_L \leftrightarrow P_R, \mathcal{C}_i \to \mathcal{C}_i')$$

Non-Local:



$$\mathcal{H}^\mu = \frac{-16i\pi^2}{q^2}\sum_{i=1,\ldots,6,8}\mathcal{C}_i\int dx^4 e^{iq\cdot x}\langle M|T\{j^\mu_{\text{em}}(x), \mathcal{O}_i(0)\}|B\rangle\,, \qquad j^\mu_{\text{em}} = \sum_q Q_q\,\bar{q}\gamma^\mu q$$

Wilson coefficients $\mathscr{C}_i = \mathscr{C}_i^{\text{SM}} + \mathscr{C}_i^{\text{NP}}$

- perturbative, short-distance physics (q^2 independent), well-known in SM, parameterise heavy NP

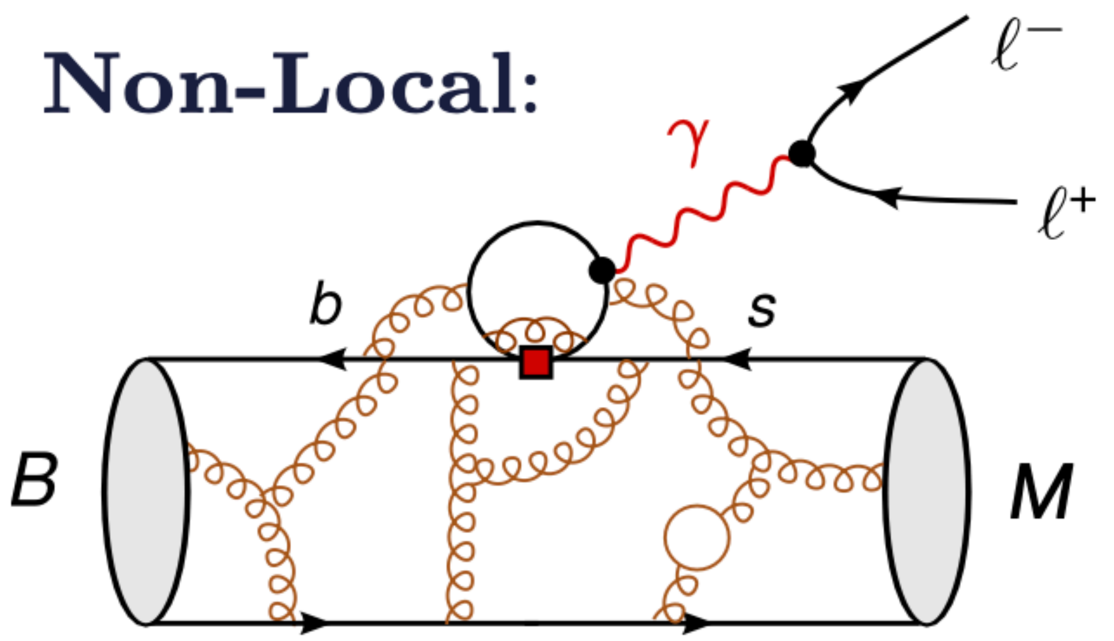
Local and non-local hadronic matrix elements

- non-perturbative, long-distance physics (q^2 dependent), depends on external states, main source of uncertainty

Theory of $B \to M\ell\ell$ decays

$$\tilde{\lambda}_q^{(s)} \equiv \frac{V_{qb}V_{qs}^*}{V_{tb}V_{ts}^*}$$

Non-Local:



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Non-local contributions mimic $\mathscr{C}_9$ can be absorbed in an effective q^2 and mode dependent $\mathscr{C}_9$

$$\mathscr{C}_9^{\rm eff}(q^2) = \mathscr{C}_9 - \tilde{\lambda}_c^{(s)} Y_{c\bar{c}}(q^2) - \tilde{\lambda}_u^{(s)} Y_{u\bar{u}}(q^2)$$

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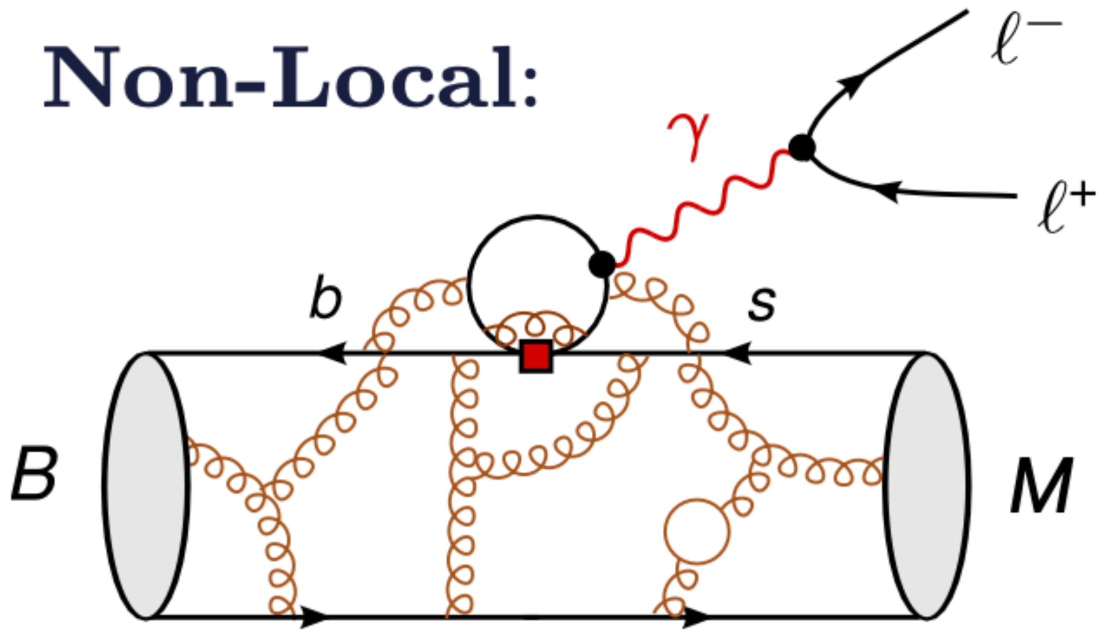

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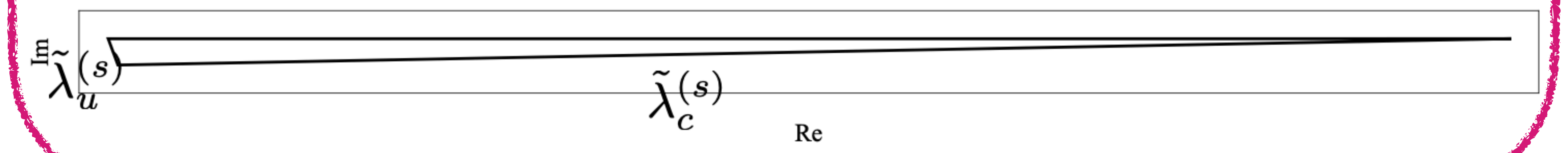
$c\bar{c}$ loop
Large effect in both b->sll and b->dll rates

$u\bar{u}$ loop
Supressed in b->sll rate due to CKM structure

Complex $Y_{c\bar{c}}(q^2)$ and $Y_{u\bar{u}}(q^2)$ even below $c\bar{c}$ threshold due to cuts in q^2 and $(q+k)^2$

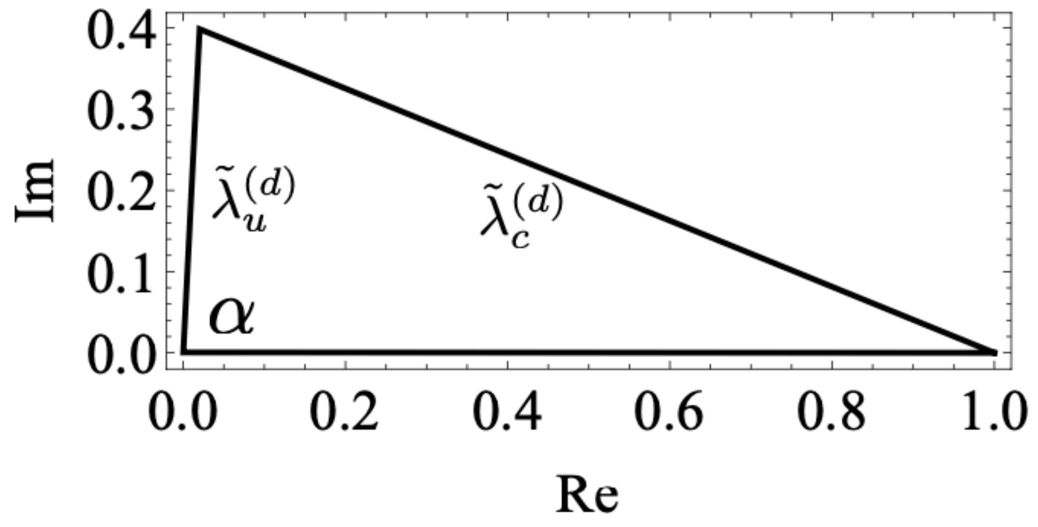
b->sll

$$\tilde{\lambda}_c^{(s)} = -1 + \lambda^2(\rho - i\eta)$$
$$\tilde{\lambda}_u^{(s)} = -\lambda^2(\rho - i\eta)$$



b->dll

$$\tilde{\lambda}_c^{(d)} = \frac{\rho - 1 + i\eta}{(1-\rho)^2 + \eta^2} \approx 0.4\,i - 1$$
$$\tilde{\lambda}_u^{(d)} = \frac{\rho(1-\rho) - \eta^2 - i\eta}{(1-\rho)^2 + \eta^2} \approx -0.4\,i$$



Direct Asymmetry: $B \to P\ell\ell$

$$\frac{(d\Gamma_K + d\bar{\Gamma}_K)/2}{dq^2} = \mathcal{N}_K \left(f_+^{(K)}\right)^2 \left[\mathcal{C}_{10}^2 + \left(\mathcal{C}_9 + \tilde{f}_T^{(K)}\mathcal{C}_7\right)^2 + 2\left(\mathcal{C}_9 + \tilde{f}_T^{(K)}\mathcal{C}_7\right)\mathrm{Re}Y_{c\bar{c}} + \mathcal{O}(\lambda^2, |Y_{c\bar{c}}^2|)\right]$$

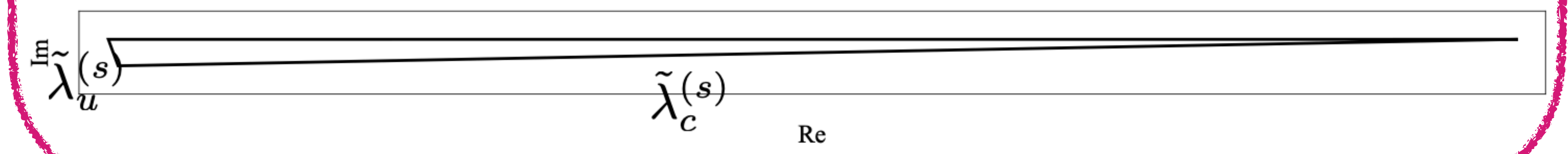
$$\frac{d\Gamma_K - d\bar{\Gamma}_K}{dq^2} = 4\mathcal{N}_K \left(f_+^{(K)}\right)^2 \eta\lambda^2 \left[1 + \mathcal{O}(\lambda^2)\right]\left[\left(\mathcal{C}_9 + \tilde{f}_T^{(K)}\mathcal{C}_7\right)\mathrm{Im}(Y_{u\bar{u}} - Y_{c\bar{c}}) - \mathrm{Im}(Y_{c\bar{c}}Y_{u\bar{u}}^*)\right]$$

Both $c\bar{c}$ and $u\bar{u}$ contribute to CP-odd rate

b->sll

$$\tilde{\lambda}_c^{(s)} = -1 + \lambda^2(\rho - i\eta)$$

$$\tilde{\lambda}_u^{(s)} = -\lambda^2(\rho - i\eta)$$



$$\mathrm{Im}\tilde{\lambda}_c^{(s)} = -\,\mathrm{Im}\tilde{\lambda}_u^{(s)} = \eta\lambda^2$$

$$\mathcal{N}_P = \frac{G_F^2\alpha^2|\lambda_t^{(q')}|^2}{3\cdot 512\pi^5 m_B^3}\lambda_P^{3/2}(q^2) \qquad \tilde{f}_T^{(P)} \equiv \frac{2f_T^{(P)}(q^2)(m_b + m_{q'})}{f_+^{(P)}(q^2)(m_B + m_P)}$$

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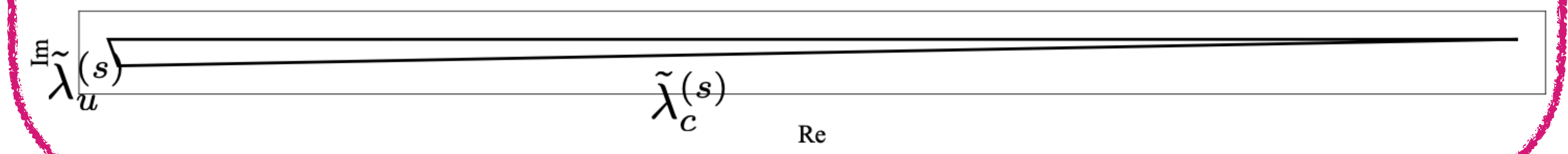

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b->dll

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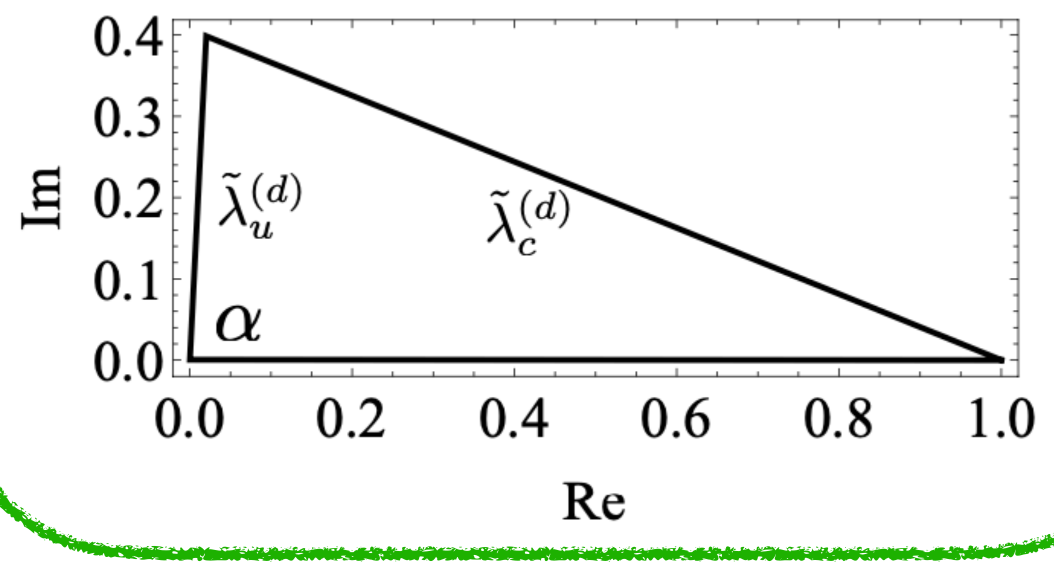

accidental cancellation in the real part of $\tilde{\lambda}_u^{(d)}$ due to the smallness of $\xi \equiv \rho(1-\rho) - \eta^2 = -0.022$

$$\frac{(d\Gamma_\pi + d\bar{\Gamma}_\pi)/2}{dq^2} = \mathcal{N}_\pi \left(f_+^{(\pi)}\right)^2 \left[\mathcal{C}_{10}^2 + (\mathcal{C}_9 + \tilde{f}_T^{(\pi)}\mathcal{C}_7)^2 + 2(\mathcal{C}_9 + \tilde{f}_T^{(\pi)}\mathcal{C}_7)\mathrm{Re}Y_{c\bar{c}}^\pi + |Y_{c\bar{c}}^\pi|^2 + (\mathrm{Im}\tilde{\lambda}_u^{(d)})^2|Y_{u\bar{u}}^\pi - Y_{c\bar{c}}^\pi|^2 + \mathcal{O}(\xi)\right]$$

$$\frac{d\Gamma_\pi - d\bar{\Gamma}_\pi}{dq^2} = 4\mathcal{N}_\pi \left(f_+^{(\pi)}\right)^2 \frac{(-\eta)\left[1 + \mathcal{O}(\lambda^2)\right]}{(1-\rho)^2 + \eta^2}\left[\left(\mathcal{C}_9 + \tilde{f}_T^{(\pi)}\mathcal{C}_7\right)\mathrm{Im}(Y_{u\bar{u}}^\pi - Y_{c\bar{c}}^\pi) - \mathrm{Im}(Y_{c\bar{c}}^\pi(Y_{u\bar{u}}^\pi)^*)\right]$$

Direct Asymmetry: $B \to P\ell\ell$

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Both $c\bar{c}$ and $u\bar{u}$ contribute to

$$= \eta\lambda^2$$

CP-odd rates have the same structure
up to U-spin breaking!
(non Trivial due to CKM)

$$\tilde{f}_T^{(P)} = \frac{2f_T^{(P)}(q^2)(m_b + m_{q'})}{f_+^{(P)}(q^2)(m_B + m_P)}$$

b->dll

$$\tilde{\lambda}_c^{(d)} = \frac{\rho - 1 + i\eta}{(1-\rho)^2 + \eta^2} \approx 0.4\,i - 1$$

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accidental cancellatio
due to the smallness o

$$\frac{(d\Gamma_\pi + d\bar{\Gamma}_\pi)/2}{dq^2} = \mathcal{N}_\pi \left(f_+^{(\pi)}\right)^2 \left[\mathcal{C}_{10}^2 + (\mathcal{C}_9 + \tilde{f}_T^{(\pi)}\mathcal{C}_7)^2 + 2(\mathcal{C}_9 + \tilde{f}_T^{(\pi)}\mathcal{C}_7)\mathrm{Re}Y_{c\bar{c}}^\pi + |Y_{c\bar{c}}^\pi|^2 + (\mathrm{Im}\tilde{\lambda}_u^{(d)})^2|Y_{u\bar{u}}^\pi - Y_{c\bar{c}}^\pi|^2 + \mathcal{O}(\xi)\right]$$

$$\frac{d\Gamma_\pi - d\bar{\Gamma}_\pi}{dq^2} = 4\mathcal{N}_\pi \left(f_+^{(\pi)}\right)^2 \frac{(-\eta)\left[1 + \mathcal{O}(\lambda^2)\right]}{(1-\rho)^2 + \eta^2}\left[\left(\mathcal{C}_9 + \tilde{f}_T^{(\pi)}\mathcal{C}_7\right)\mathrm{Im}(Y_{u\bar{u}}^\pi - Y_{c\bar{c}}^\pi) - \mathrm{Im}(Y_{c\bar{c}}^\pi(Y_{u\bar{u}}^\pi)^*)\right]$$

U-spin Ratio of CP-odd rates

$$\mathcal{N}_P = \frac{G_F^2 \alpha^2 |\lambda_t^{(q')}|^2}{3 \cdot 512 \pi^5 m_B^3} \lambda_P^{3/2}(q^2) \,,$$

$$R^{\mathrm{CP}}_{K/\pi} \equiv - \frac{(d\Gamma_K - d\bar{\Gamma}_K)/dq^2}{(d\Gamma_\pi - d\bar{\Gamma}_\pi)/dq^2}$$

$$\frac{d\Gamma_K - d\Gamma_K}{dq^2} = 4\mathcal{N}_K \left(f_+^{(K)}\right)^2 \eta\lambda^2 \left[1 + \mathcal{O}(\lambda^2)\right] \left[\left(\mathscr{C}_9 + \tilde{f}_T^{(K)} \mathscr{C}_7\right) \mathrm{Im}(Y_{u\bar{u}} - Y_{c\bar{c}}) - \mathrm{Im}(Y_{c\bar{c}} Y^*_{u\bar{u}})\right]$$

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$$R_{K/\pi}^{\mathrm{CP}} \equiv -\frac{(d\Gamma_K - d\bar{\Gamma}_K)/dq^2}{(d\Gamma_\pi - d\bar{\Gamma}_\pi)/dq^2}$$

Expanding on U-spin breaking

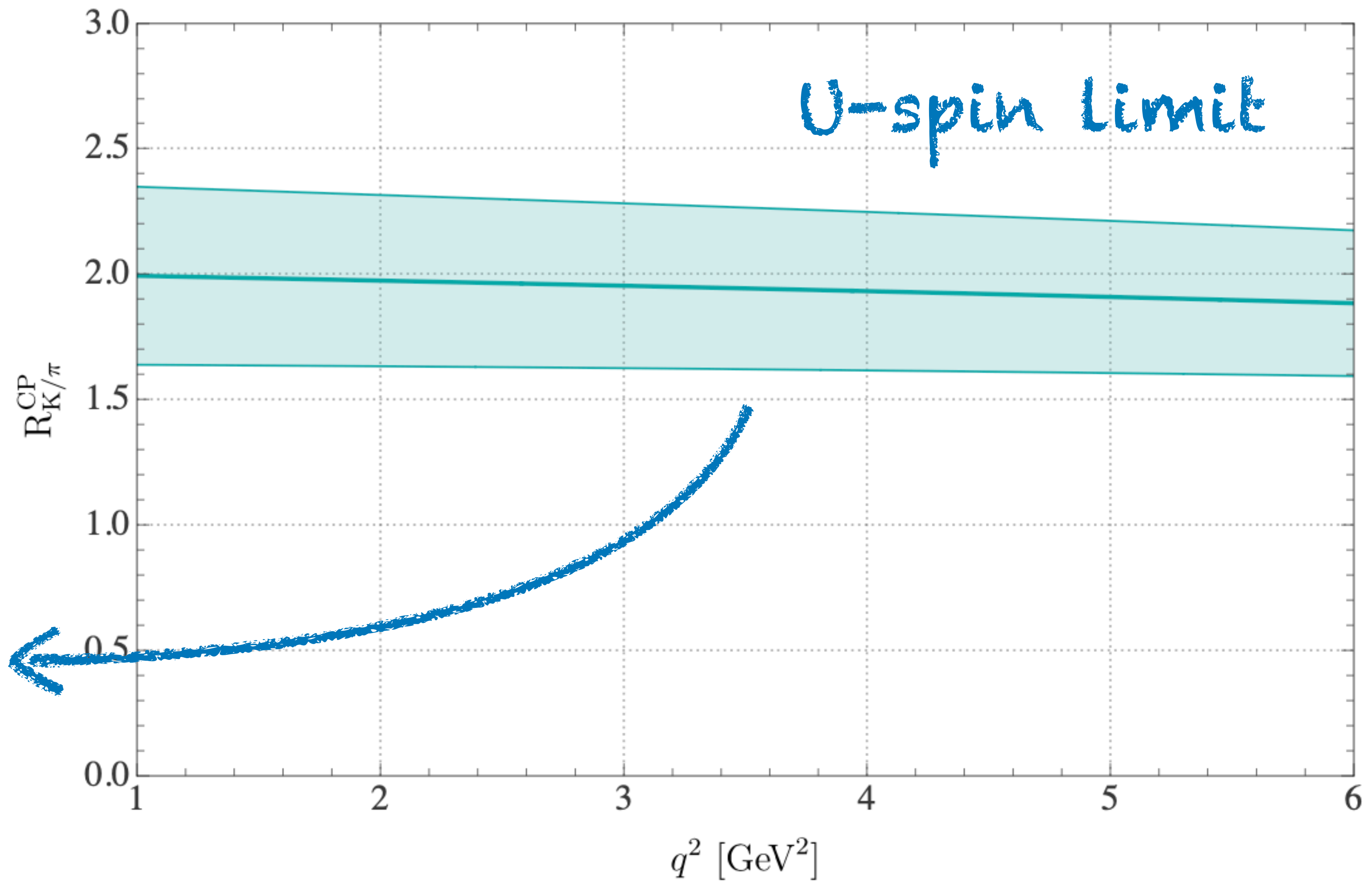
$$R_{K/\pi}^{\mathrm{CP}}|_{\mathrm{SM}} = \left(\frac{\lambda_K}{\lambda_\pi}\right)^{3/2}\left(\frac{f_+^{(K)}}{f_+^{(\pi)}}\right)^2\left[1 - \frac{\mathcal{C}_7^{\mathrm{SM}}(\tilde{f}_T^{(\pi)} - \tilde{f}_T^{(K)})}{\mathcal{C}_9^{\mathrm{SM}} + \mathcal{C}_7^{\mathrm{SM}}\tilde{f}_T^{(K)}} - \epsilon_{uc} + \mathcal{O}(\Delta_U^2)\right]$$

$$\mathrm{Im}\left(Y_{u\bar{u}}^\pi - Y_{c\bar{c}}^\pi\right) = (1+\epsilon_{uc})\,\mathrm{Im}\left(Y_{u\bar{u}}^K - Y_{c\bar{c}}^K\right)$$

Only depends on U-Spin Breaking of hadronic non-local contributions

How big is U-spin breaking?

$$\left|\frac{Y_{c\bar{c}}^{(K)}}{Y_{c\bar{c}}^{(\pi)}}\right|_{q^2=m_{J/\psi}^2} = \left|\frac{\lambda_c^{(d)}}{\lambda_c^{(s)}}\right|\sqrt{\frac{|\mathbf{k}_\pi|}{|\mathbf{k}_K|}\frac{\Gamma(B^+\to J/\psi K^+)}{\Gamma(B^+\to J/\psi\pi^+)}} = 1.2$$



Error domain by Form factors due to lack of correlations

U-spin Ratio of CP-odd rates

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$$R_{K/\pi}^{\mathrm{CP}} \equiv -\frac{(d\Gamma_K - d\bar{\Gamma}_K)/dq^2}{(d\Gamma_\pi - d\bar{\Gamma}_\pi)/dq^2}$$

Expanding on U-spin breaking

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$$\mathrm{Im}\left(Y_{u\bar{u}}^\pi - Y_{c\bar{c}}^\pi\right) = (1 + \epsilon_{uc})\,\mathrm{Im}\left(Y_{u\bar{u}}^K - Y_{c\bar{c}}^K\right)$$

How big is U-spin breaking?

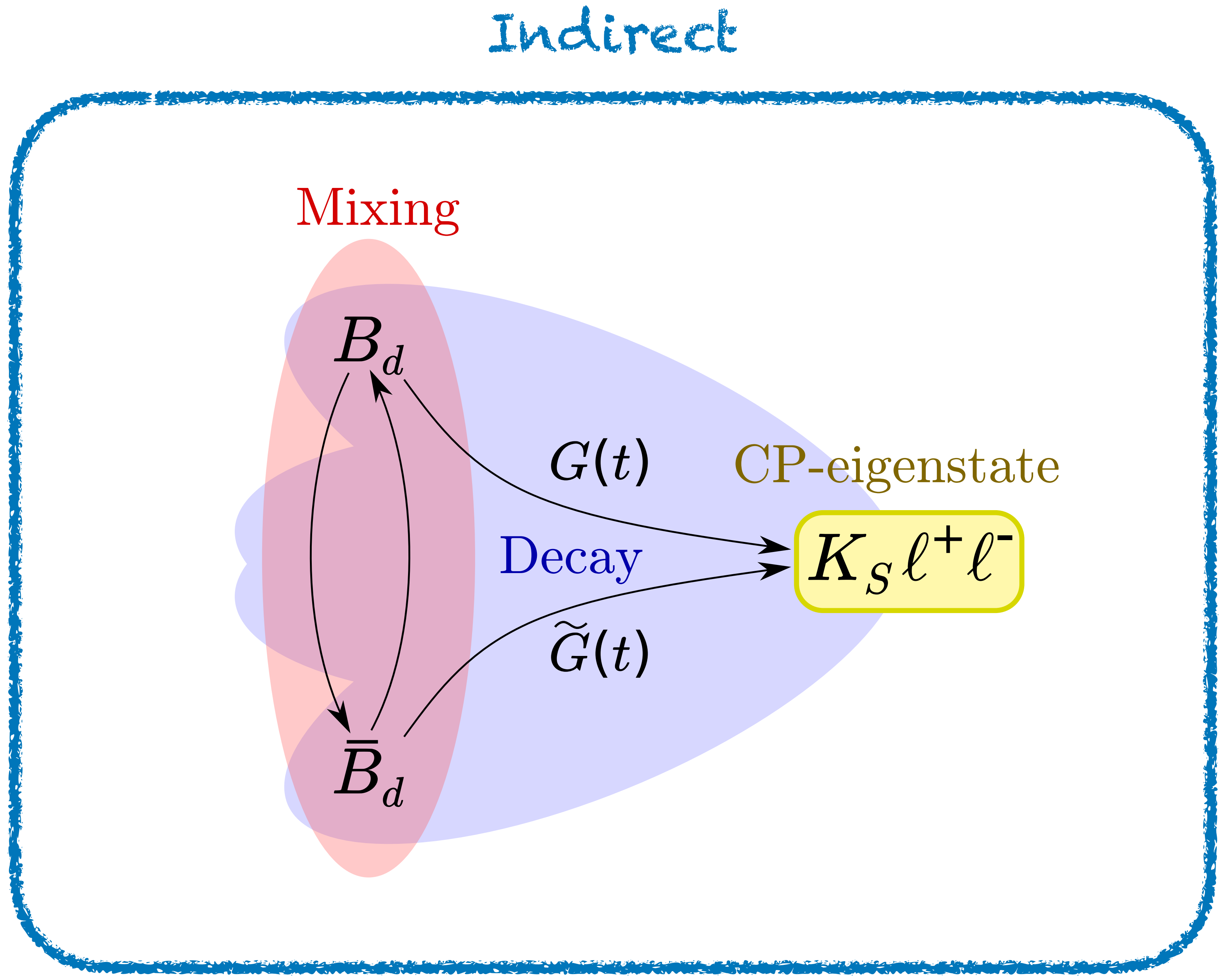
$$\left|\frac{Y_{c\bar{c}}^{(K)}}{Y_{c\bar{c}}^{(\pi)}}\right|_{q^2 = m_{J/\psi}^2} = \left|\frac{\lambda_c^{(d)}}{\lambda_c^{(s)}}\right| \sqrt{\frac{|\mathbf{k}_\pi|}{|\mathbf{k}_K|}\frac{\Gamma(B^+ \to J/\psi K^+)}{\Gamma(B^+ \to J/\psi \pi^+)}} = 1.2$$

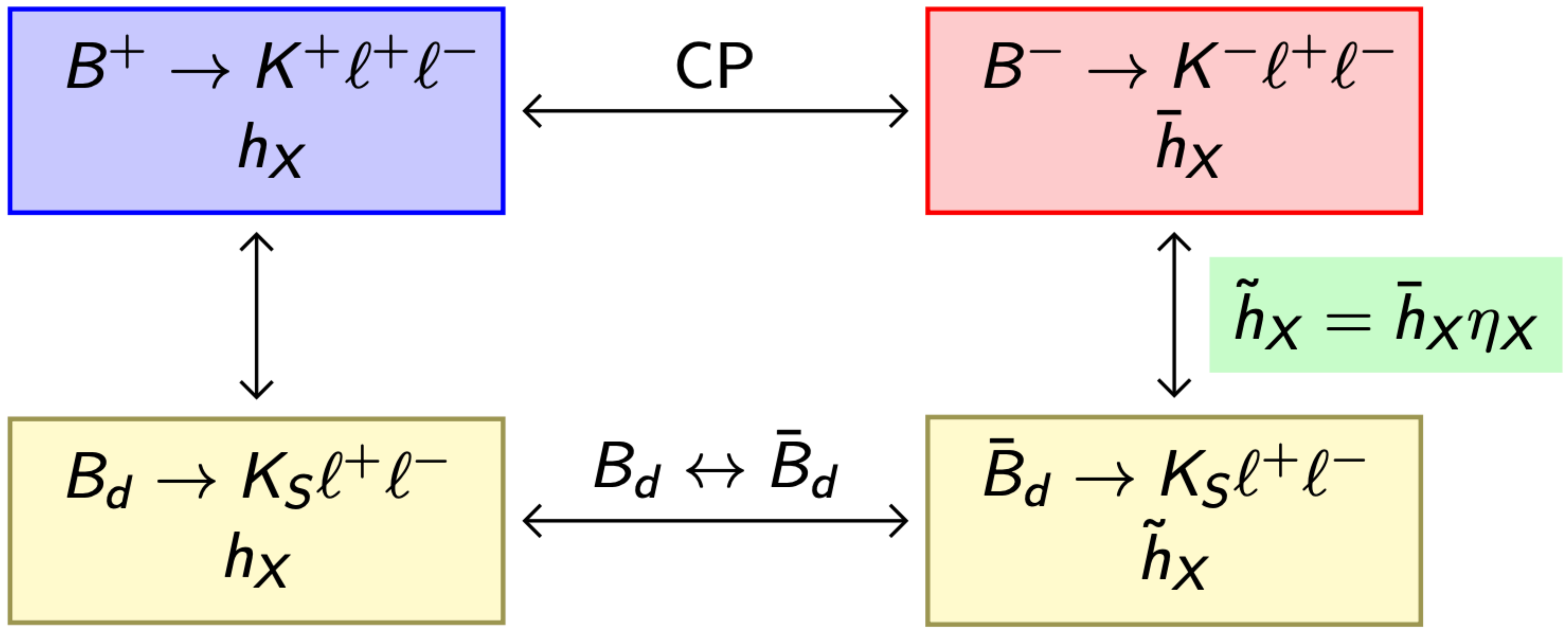
CP-conserving NP in $B \to K\ell\ell$

$$R_{K/\pi}^{\mathrm{CP}}|_{\mathrm{NP}} = \left(\frac{\lambda_K}{\lambda_\pi}\right)^{3/2}\left(\frac{f_+^{(K)}}{f_+^{(\pi)}}\right)^2 \left[1 - \frac{\mathcal{C}_7^{\mathrm{SM}}(\tilde{f}_T^{(\pi)} - \tilde{f}_T^{(K)})}{\mathcal{C}_9^{\mathrm{SM}} + \mathcal{C}_7^{\mathrm{SM}}\tilde{f}_T^{(K)}} - \epsilon_{uc} + \mathcal{O}(\Delta_U^2)\right] \times \left(1 + \frac{\delta\mathcal{C}_9^{(s)} + \delta\mathcal{C}_7^{(s)}\tilde{f}_T^{(K)}}{\mathcal{C}_9^{\mathrm{SM}} + \mathcal{C}_7^{\mathrm{SM}}\tilde{f}_T^{(K)}}\right)$$

Ratio probes CP-conserving contribution in orthogonal direction to CP-average (wrt hadronic contributions)

Indirect Asymmetry: How do you describe it?





h_X: Transversity amplitudes η_X: CP-parity associated to h_X

$$\eta_{V,A,P,T_t} = -1 \quad \text{and} \quad \eta_{S,T} = 1 \quad \Longrightarrow \quad \tilde{h}_X^{SM} = -\bar{h}_X^{SM}$$

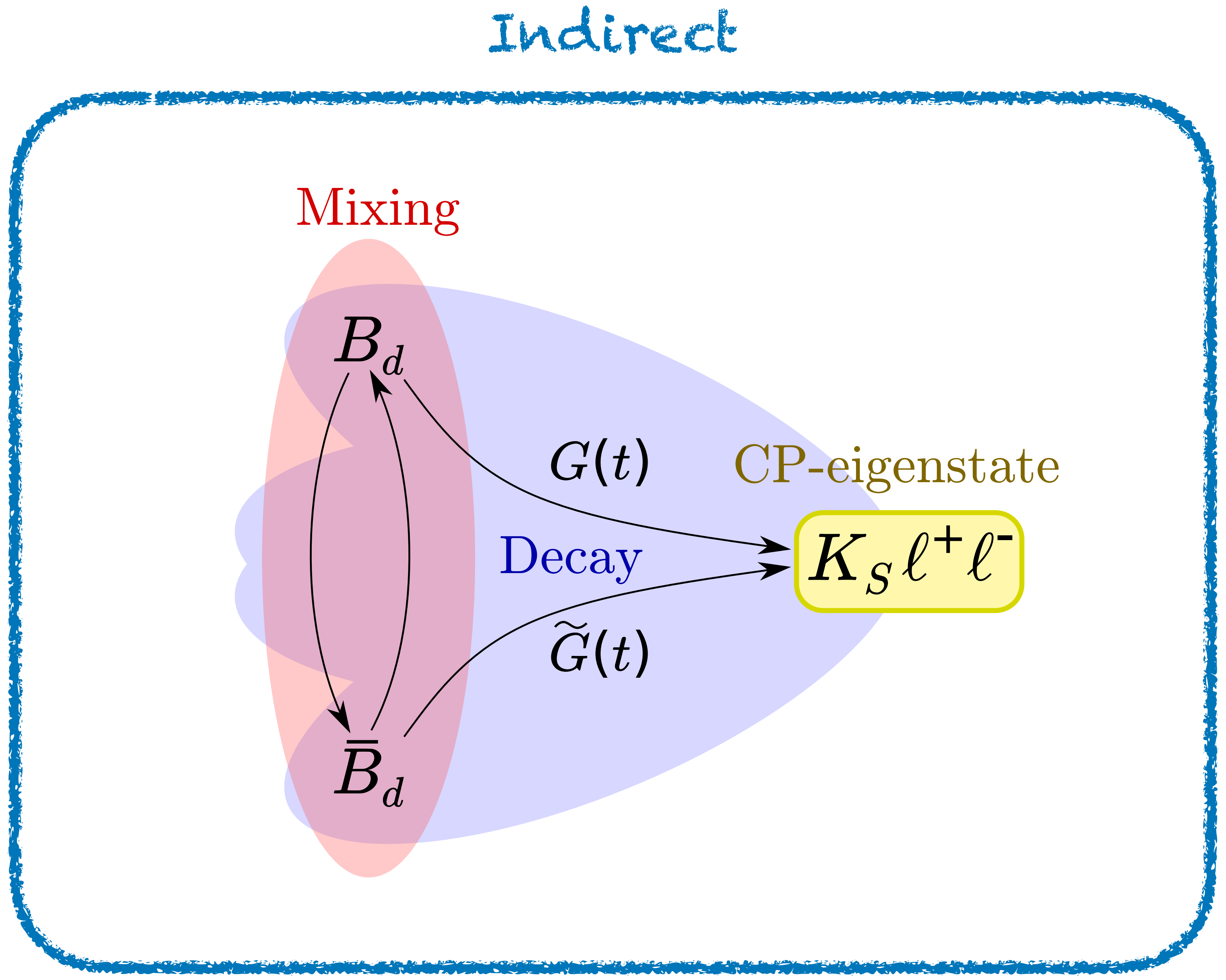
[Dunietz et al '01, Descotes-Genon et al '15]

$$G_2 = -\frac{4\beta_\ell^2}{3}\left(\left|h_V\right|^2 + \left|h_A\right|^2 - 2\left|h_T\right|^2 - 4\left|h_{T_t}\right|^2\right)$$

$$\bar{h}_A \propto (\mathscr{C}_{10} + \mathscr{C}_{10'}) f_+(q^2)$$

$$\frac{d^2\Gamma(B^+ \to K^+\ell^+\ell^-)}{dq^2\, d\cos\theta_\ell} = G_0(q^2) + G_1(q^2)\cos\theta_\ell + G_2(q^2)\frac{1}{2}(3\cos^2\theta_\ell - 1)$$

Indirect Asymmetry: How do you describe it?



CP-Average

Time-evolution of CP-average

Encodes the same information as si

$$G_i(t) + \tilde{G}_i(t) = e^{-\Gamma t}\left[(G_i + \tilde{G}_i)\cosh\left(\frac{\Delta\Gamma t}{2}\right) - h_i \sinh\left(\frac{\Delta\Gamma t}{2}\right)\right]$$

$$G_i(t) - \tilde{G}_i(t) = e^{-\Gamma t}\left[(G_i - \tilde{G}_i)\,\cos(\Delta m t) - s_i \sin(\Delta m t)\right]$$

Indirect CP-Asymmetry

Direct CP-Asymmetry

$$G_2 = -\frac{4\beta_\ell^2}{3}\left(\left|h_V\right|^2 + \left|h_A\right|^2 - 2\left|h_T\right|^2 - 4\left|h_{T_t}\right|^2\right)$$

$$\bar{h}_A \propto (\mathscr{C}_{10} + \mathscr{C}_{10'}) f_+(q^2)$$

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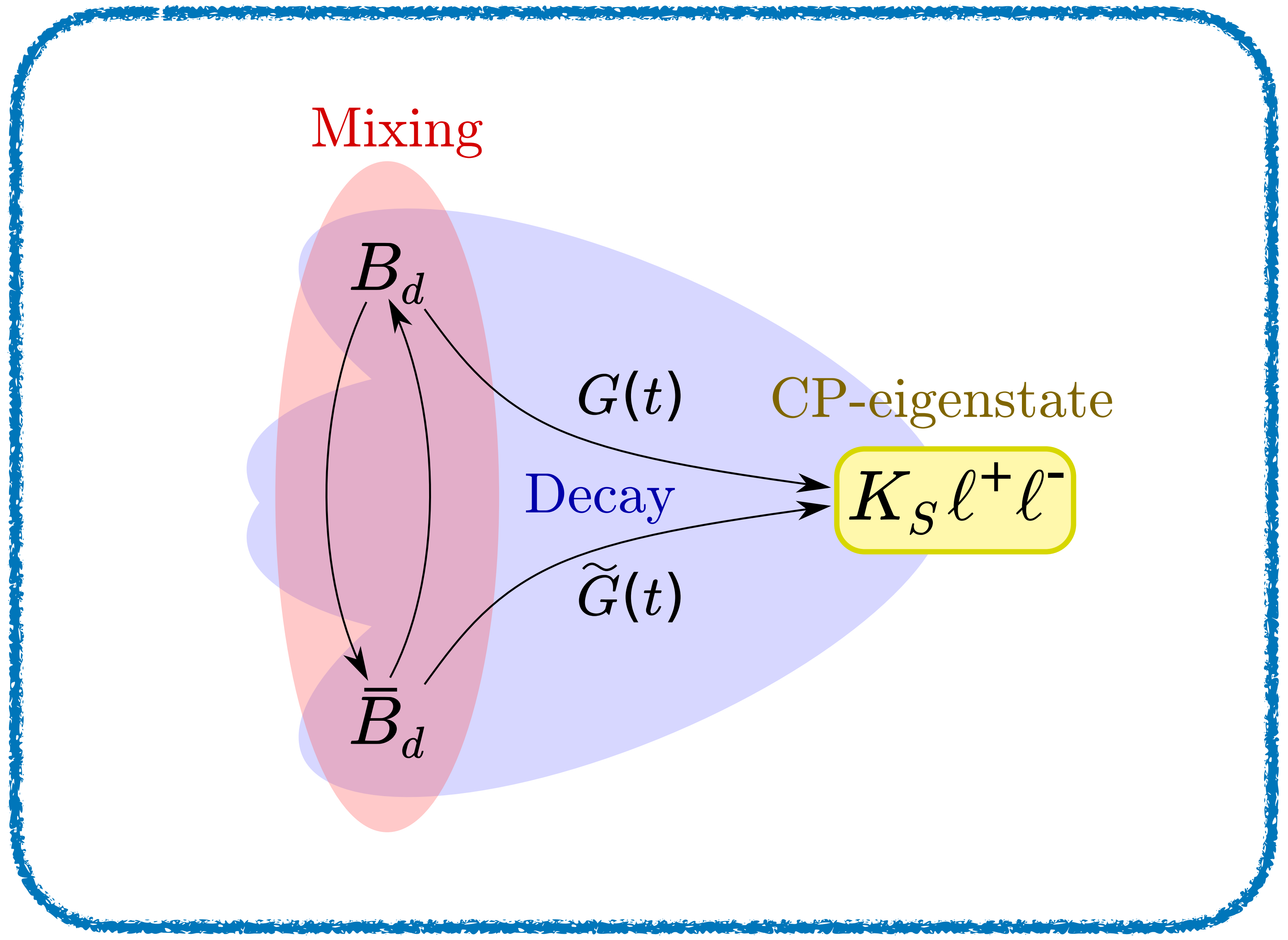
Indirect Asymmetry: What does it probe?

Indirect



CP-Average

Time-evolution of CP-average

Encodes the same information as si Re vs Im part

$$G_i(t) + \tilde{G}_i(t) = e^{-\Gamma t}\left[(G_i + \tilde{G}_i)\cosh\left(\frac{\Delta\Gamma t}{2}\right) - h_i \sinh\left(\frac{\Delta\Gamma t}{2}\right)\right]$$

$$G_i(t) - \tilde{G}_i(t) = e^{-\Gamma t}\left[(G_i - \tilde{G}_i)\ \cos(\Delta m t) - s_i \sin(\Delta m t)\right]$$

Indirect CP-Asymmetry

Direct CP-Asymmetry

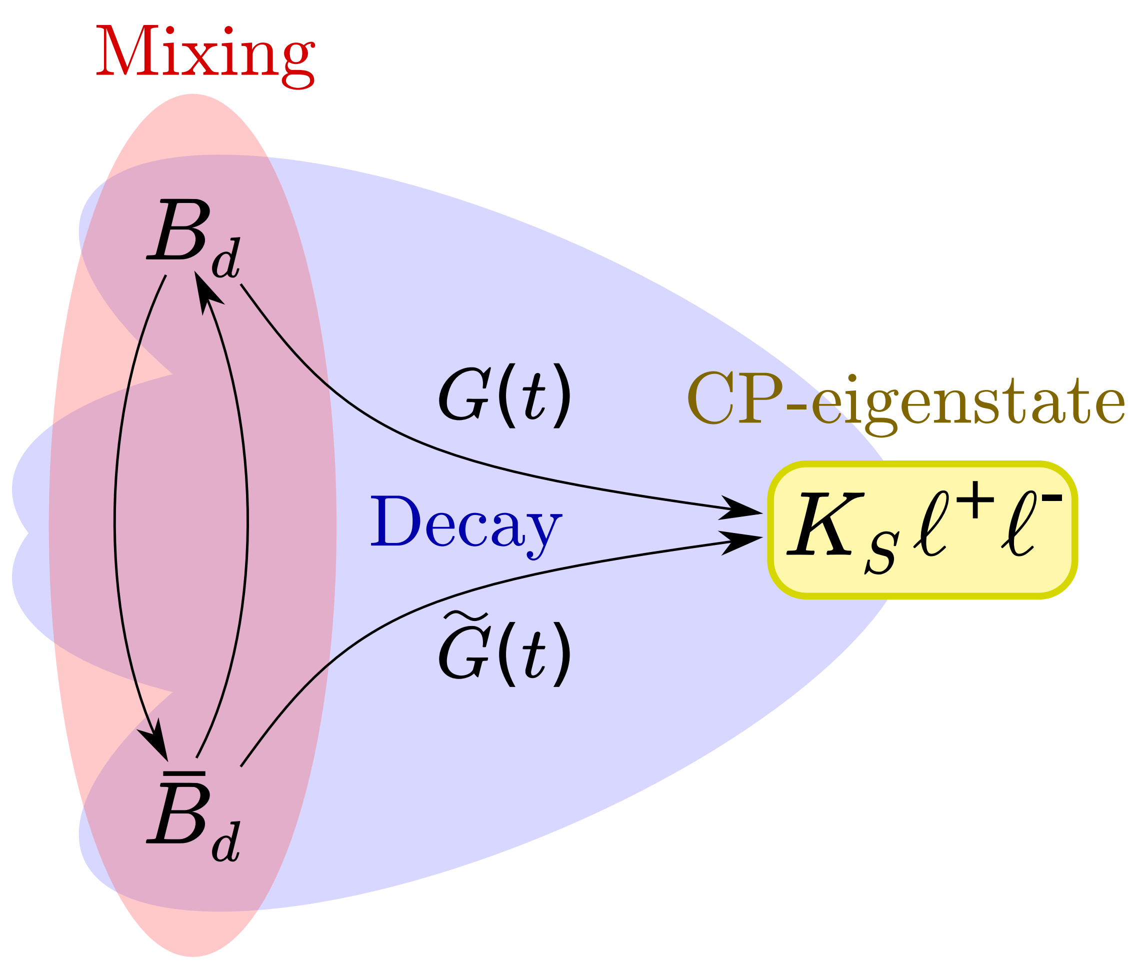
$$s_2 = -\frac{8\beta_\ell^2}{3}\mathrm{Im}\left[e^{i\phi}\left[\tilde{h}_V h_V^* + \tilde{h}_A h_A^* - 2\tilde{h}_T h_T^* - 4\tilde{h}_{T_t} h_{T_t}^*\right]\right]$$

Scalar/Tensor Currents

$$s_2 \simeq -2\sin\phi\left(G_2 - \frac{32}{3}\left|\bar{h}_{T_t}\right|^2\right)$$

Real Scalar and Tensor Currents due to their CP-parities (Substantially supressed)

Indirect Asymmetry: What does it probe?



CP-Average

Time-evolution of CP-average

Encodes the same information as si Re vs Im part

$$G_i(t) + \tilde{G}_i(t) = e^{-\Gamma t}\left[(G_i + \tilde{G}_i)\cosh\left(\frac{\Delta\Gamma t}{2}\right) - h_i \sinh\left(\frac{\Delta\Gamma t}{2}\right)\right]$$

$$G_i(t) - \tilde{G}_i(t) = e^{-\Gamma t}\left[(G_i - \tilde{G}_i)\cos(\Delta m t) - s_i \sin(\Delta m t)\right]$$

Direct CP-Asymmetry

Indirect CP-Asymmetry

$$s_2 = -\frac{8\beta_\ell^2}{3}\mathrm{Im}\left[e^{i\phi}\left[\tilde{h}_V h_V^* + \tilde{h}_A h_A^* - 2\tilde{h}_T h_T^* - 4\tilde{h}_{T_t} h_{T_t}^*\right]\right]$$

Complex NP

$$s_2 \simeq -2\sin(\phi - \phi_{NP})G_2$$

Interference between weak (CP-odd) phase and mixing phases

Clean Sensitive Probes of Complex NP!!!

Observable	SM	$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -1.12$	$\mathcal{C}_{9\mu}^{\mathrm{NP}} = -1.12 + i1.00$
σ_0	0.368(5)	0.368(5)	0.273(6)
σ_2	−0.359(5)	−0.359(5)	−0.266(6)

Conclusions and Future Prospects

- Cancellations due to CKM structure implies similar structure in B->Kll and B->πll CP-odd rates up to U-spin breaking.
- U-spin ratio of CP-odd rates is an indicator of validity of CKM mechanism. Provides orthogonal handle on CP-even New Physics.
- Estimate of U-spin breaking needed!

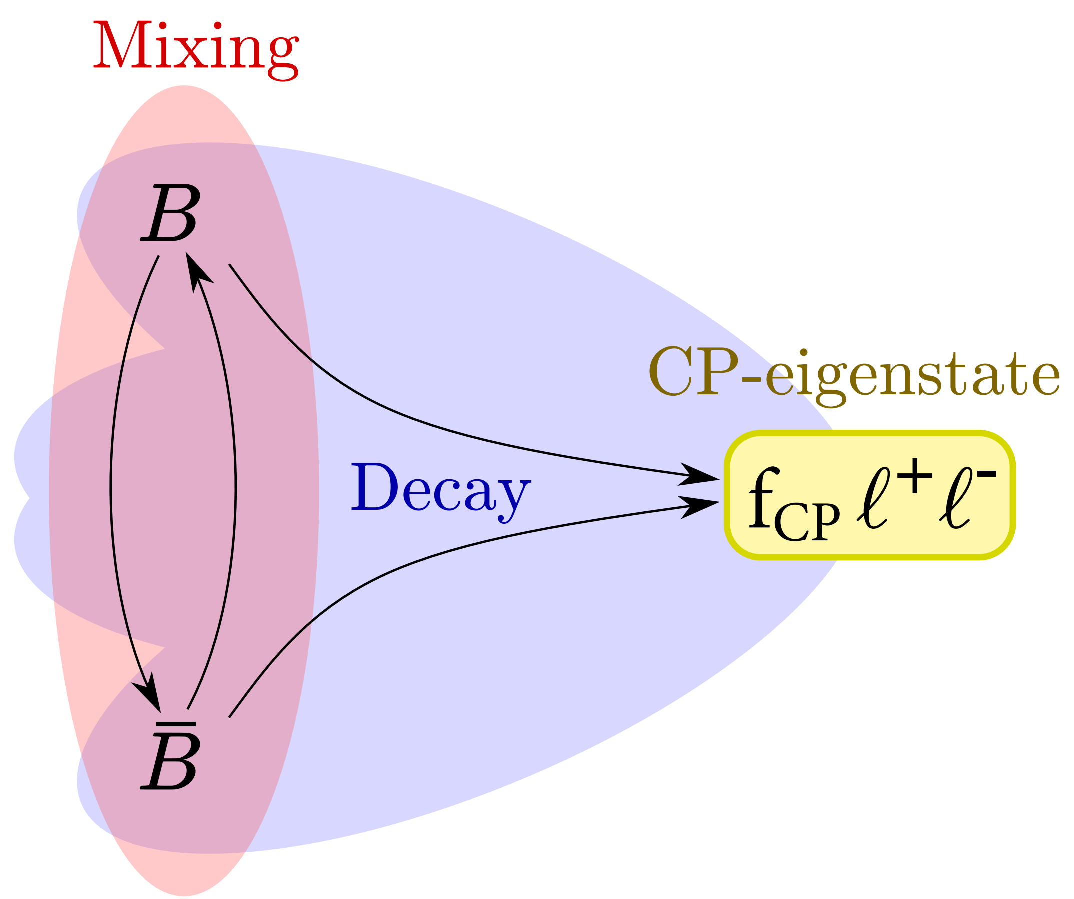
Direct

$B \to f\ell^+\ell^-$

V/S

$\bar{B} \to \bar{f}\ell^+\ell^-$

Indirect



- A Bd->KSll time dependent analysis can help to constrain NP complex phases in b->sll. LHCb, BelleII?
- Similar arguments can be made in the case of Bs decays.
- B->Vll decays are more complex but still strongly sensitive to CP-odd phase.

CP-Asymmetries in Semileptonic Decays

How to Exploit Direct and Indirect CP-asymmetries in rare B-decays

Martín Novoa-Brunet

Based on works with S. Descotes-Genon, S. Fajfer, J.F. Kamenik, N. Kosnik and K. K. Vos
arXiv:2008.08000 and arXiv: 2403.13056

IFIC Institut de Física Corpuscular
Vniversitat de València
CSIC Consejo Superior de Investigaciones Científicas

Back Up

Indirect Asymmetry: How to extract it?

In $B_d \to K_S \ell^+ \ell^-$: $y = \Delta\Gamma_{B_d}/2\Gamma$ very small ⇒ Only 3 observables (s_i) accessible

In B_s decays : $x = \Delta m_{B_s}/\Gamma$ large, $y = \Delta\Gamma_{B_s}/2\Gamma$ small (low sensitivity) ⇒ All observables accessible

No need for flavour tagging needed to access h_i (lower sensitivity due to small y and small mixing angle)

- Time integration different for hadronic machines (incoherent production) and B-factories (coherent production).
  - Incoherent: $t \in [0, \infty)$ ⇒time since b-quarks have been produced
  - Coherent: $t \in (-\infty, \infty)$ ⇒time difference between B and $\bar{B}$ decay
- Hadronic machines involve an additional term compared to the B-factories ($x = \delta m/\Gamma$ ⇒mixing parameter).

$$\langle G_i + \tilde{G}_i \rangle_{\text{Hadronic}} = \frac{1}{\Gamma}\left[\frac{1}{1-y^2} \times (G_i + \tilde{G}_i) - \frac{y}{1-y^2} \times h_i\right]$$

$$\langle G_i - \tilde{G}_i \rangle_{\text{B-factory}} = \frac{2}{\Gamma}\frac{1}{1+x^2}[G_i - \tilde{G}_i]$$