The Standard Model confronts CP Violation in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$

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JHEP 1205, 140 (2012) [arXiv:1203.3131 [hep-ph]]

1. Introduction
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3. Unitarity and FSI phases
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1. Introduction

- In the charm sector, CP is conserved to good approximation due to the dominance of the first two generations.

$$\underset{O(\lambda)}{V_{cd}^* V_{ud}} + \underset{O(\lambda)}{V_{cs}^* V_{us}} + \underset{O(\lambda^5)}{V_{cb}^* V_{ub}} = 0$$

- LHCb and CDF reported evidences of direct CPV in $D^0 \to \pi^+\pi^-, K^+K^-$:

$$\Delta A_{\rm CP} \equiv A_{\rm CP}(K^+K^-) - A_{\rm CP}(\pi^+\pi^-)$$
$$= \begin{cases} [-0.82 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{sys.})]\ \% & \text{LHCb} \\ [-0.62 \pm 0.21\,(\text{stat.}) \pm 0.10\,(\text{sys.})]\ \% & \text{CDF} \end{cases}$$

$$A_{\rm CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})} \approx a_{\rm CP}^{\rm dir}(f) + \frac{\langle t \rangle_f}{\tau_{D^0}} a_{\rm CP}^{\rm ind}$$

which is much larger than the naive expectation

$$O\left({\rm Im}\left[\frac{V_{cb}^* V_{ub}}{V_{cd}^* V_{ud}}\right] \frac{\alpha_s}{\pi}\right) \sim O(10^{-4})$$

Our strategy

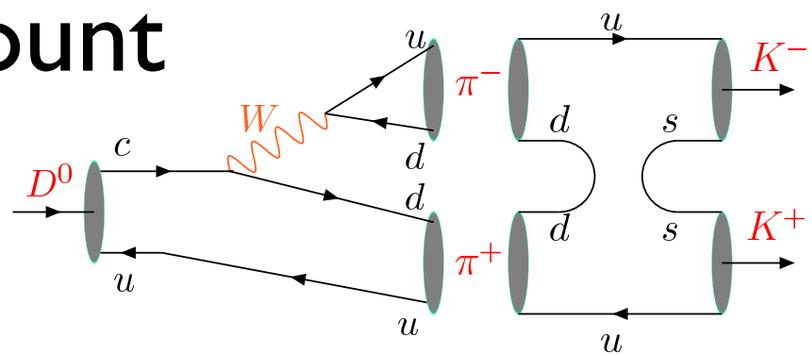
- Factorization methods are not so reliable, since $1/m_c$ corrections are expected to be large and the relevant energy scale is lower than the scale where a perturbative method is applicable well.

  ⇨ We do not use factorization.

- $SU(3)_F$ breaking effects are sizable.

  ⇨ We use only the isospin decomposition.

- Rescatterings are taken into account with unitarity and data on πN scattering near the D mass scale.



- We estimate the size of penguin from the observed CPV.

2. Isospin decomposition

$V_{cd}^* V_{ud}$ is real.

$$A(D^+ \to \pi^+\pi^0) = \frac{\sqrt{3}}{2}\mathcal{A}_2^\pi\,,$$

$$A(D^0 \to \pi^+\pi^-) = \frac{1}{\sqrt{6}}\mathcal{A}_2^\pi - \frac{1}{\sqrt{3}}\left(\mathcal{A}_0^\pi + i\,r_{\rm CKM}\mathcal{B}_0^\pi\right),$$

$$A(D^0 \to \pi^0\pi^0) = \sqrt{\frac{2}{3}}\mathcal{A}_2^\pi + \frac{1}{\sqrt{3}}\left(\mathcal{A}_0^\pi + i\,r_{\rm CKM}\mathcal{B}_0^\pi\right),$$

$$A(D^+ \to K^+\overline{K}^0) = \frac{\mathcal{A}_{13}^K}{2} + \left(\mathcal{A}_{11}^K + i\,r_{\rm CKM}\mathcal{B}_{11}^K\right),$$

$$A(D^0 \to K^+K^-) = \frac{-\mathcal{A}_{13}^K + \left(\mathcal{A}_{11}^K + i\,r_{\rm CKM}\mathcal{B}_{11}^K\right) - \left(\mathcal{A}_0^K + i\,r_{\rm CKM}\mathcal{B}_0^K\right)}{2},$$

$$A(D^0 \to K^0\overline{K}^0) = \frac{-\mathcal{A}_{13}^K + \left(\mathcal{A}_{11}^K + i\,r_{\rm CKM}\mathcal{B}_{11}^K\right) + \left(\mathcal{A}_0^K + i\,r_{\rm CKM}\mathcal{B}_0^K\right)}{2}.$$

$$r_{\rm CKM} = {\rm Im}\left(\frac{V_{cb}^* V_{ub}}{V_{cd}^* V_{ud}}\right) \sim 6.4\times 10^{-4}$$

$\mathcal{A}$: CP-even

$\mathcal{B}$: CP-odd

- $\mathcal{A}_0^{\pi(K)}$: $I = 0$ $\pi\pi(KK)$, $\Delta I = 1/2$
- $\mathcal{A}_2^\pi$: $I = 2$ $\pi\pi$, $\Delta I = 3/2$
- $\mathcal{A}_{11}^K$: $I = 1$ KK, $\Delta I = 1/2$
- $\mathcal{A}_{13}^K$: $I = 1$ KK, $\Delta I = 3/2$

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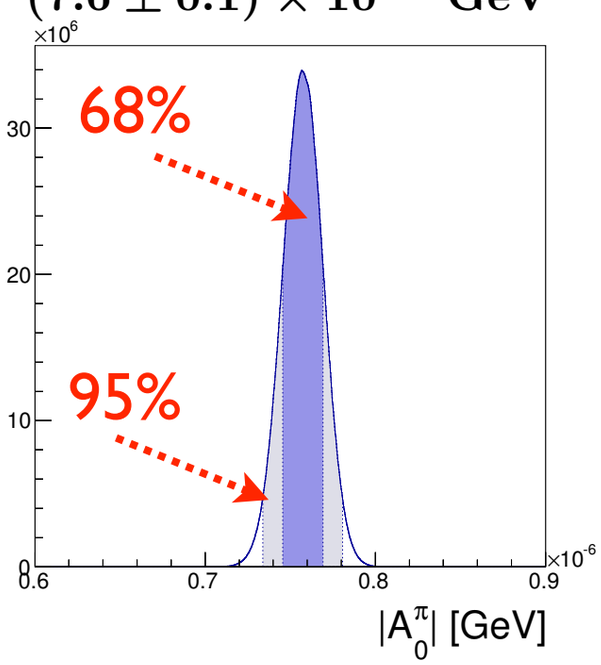
Br's and CP-even amplitudes

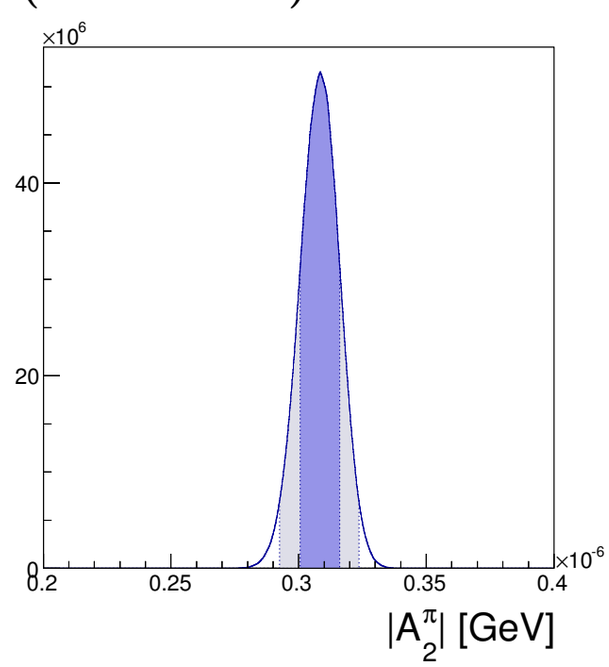
- Br's are governed by $\mathcal{A}$'s.
- No $\Delta I = 1/2$ like enhancement.
- The last one should vanish in the SU(3) limit.
- Large strong phase.

Large ~~SU(3)~~

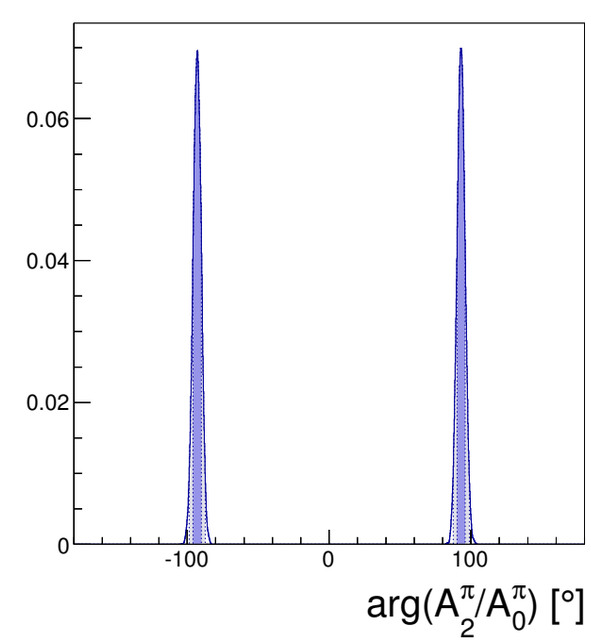
$(7.6 \pm 0.1) \times 10^{-7}$ GeV



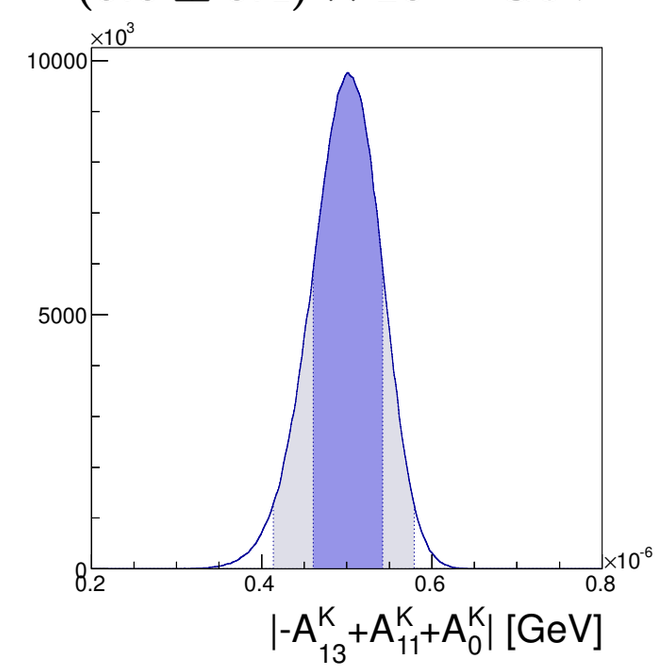
$(3.08 \pm 0.08) \times 10^{-7}$ GeV



$(\pm 93 \pm 3)^\circ$



$(5.0 \pm 0.4) \times 10^{-7}$ GeV



RG invariant parameterization

Buras, Silvestrini (2000)

$$\lambda_d \equiv V_{cd}^* V_{ud}$$

$$\mathcal{A}_2^\pi = -\sqrt{\frac{2}{3}}\,\lambda_d\,[E_1(\pi) + E_2(\pi)]\,,$$

$$\mathcal{A}_0^\pi = \frac{1}{\sqrt{3}}\,\lambda_d\,\left[2E_1(\pi) - E_2(\pi) + 3A_2(\pi) - 3P_1^{\rm GIM}(\pi) - 3P_3^{\rm GIM}(\pi)\right],$$

$$\mathcal{B}_0^\pi = -\sqrt{3}\,\lambda_d\,[P_1(\pi) + P_3(\pi)]\,,$$

$$\mathcal{A}_{13}^K = -\frac{2}{3}\,\lambda_d\,[A_1(K) + A_2(q,s,q,K)]\,,$$

$$\mathcal{A}_{11}^K = \lambda_d\left[E_1(K) - \frac{2}{3}A_1(K) + \frac{1}{3}A_2(q,s,q,K) + P_1^{\rm GIM}(K)\right],$$

$$\mathcal{B}_{11}^K = \lambda_d\,[E_1(K) + P_1(K)]\,,$$

$$\mathcal{A}_0^K = -\lambda_d\left[E_1(K) - A_2(q,s,q,K) + 2A_2(s,q,s,K) + P_1^{\rm GIM}(K) + 2P_3^{\rm GIM}(K)\right],$$

$$\mathcal{B}_0^K = -\lambda_d\,[E_1(K) + 2A_2(s,q,s,K) + P_1(K) + 2P_3(K)]\,,$$

$$E_1,\ A_1 \sim O(1)\,,$$

$$E_2,\ A_2,\ P_1,\ P_1^{\rm GIM} \sim O(1/N)\,,$$

$$P_3,\ P_3^{\rm GIM} \sim O(1/N^2)\,.$$

Significant subleading contributions

- From the fit to the BRs, we find that subleading topologies are of the same order of leading ones:

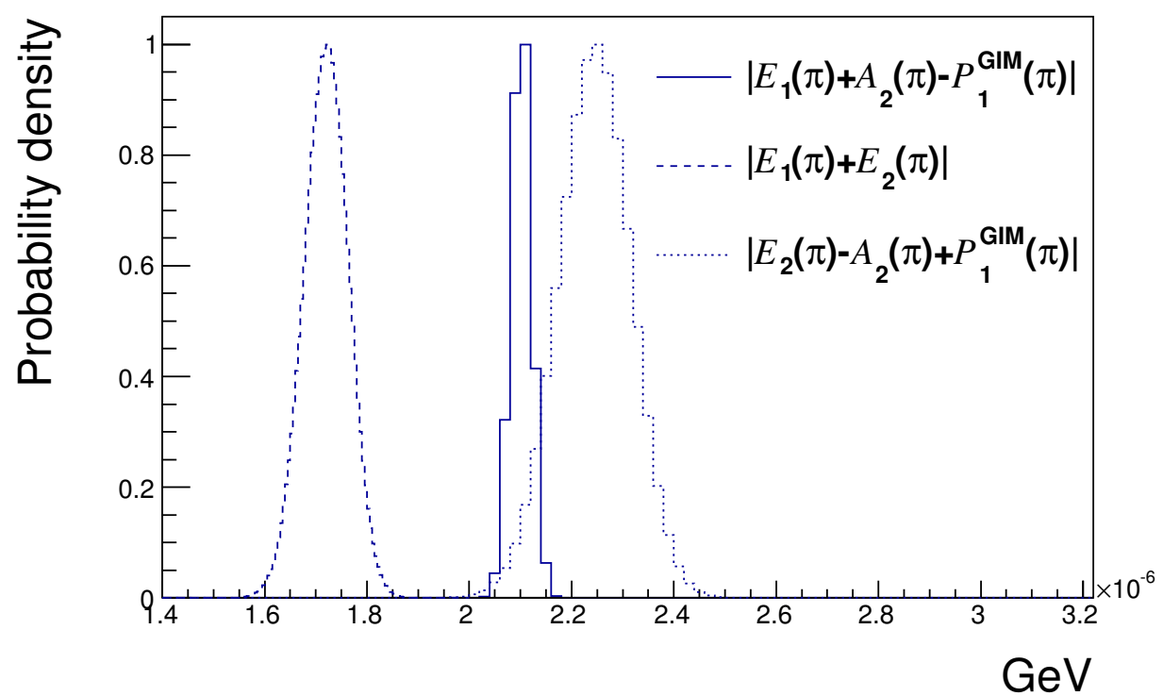
$$E_1(\pi) + E_2(\pi) = (1.72 \pm 0.04)\, e^{i\delta}$$

$$E_1(\pi) + A_2(\pi) - P_1^{\mathrm{GIM}}(\pi) = (2.10 \pm 0.02)\, e^{i(\delta \pm (71 \pm 3)^\circ)}$$

$$E_2(\pi) - A_2(\pi) + P_1^{\mathrm{GIM}}(\pi) = (2.25 \pm 0.07)\, e^{i(\delta \mp (62 \pm 2)^\circ)}$$

in units of 10^{-6} GeV

Leading amplitude



3. Unitarity and FSI phases

- Generalized Watson's theorem

$$S = \left(\begin{array}{c|ccc} D \to D & D \to \pi\pi & D \to K\bar{K} & \cdots \\ \hline \pi\pi \to D & \pi\pi \to \pi\pi & \pi\pi \to K\bar{K} & \cdots \\ K\bar{K} \to D & K\bar{K} \to \pi\pi & K\bar{K} \to K\bar{K} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{array}\right) \equiv \begin{pmatrix} 1 & -i(T)^T \\ -i\,\mathrm{CP}(T) & S_S \end{pmatrix}$$

$$T = \mathcal{A} + i\mathcal{B}$$

Unitarity ⇨

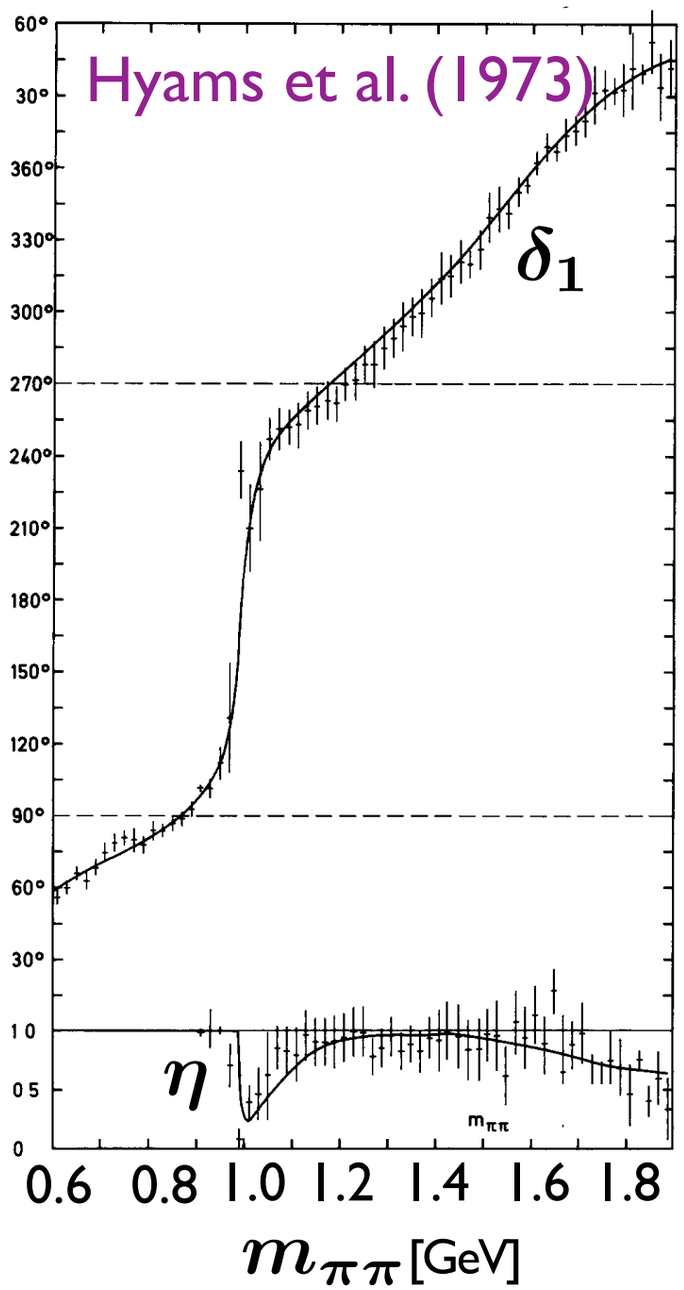
$$\mathcal{A} = S_S\,(\mathcal{A})^*$$ ← CP-even amp.

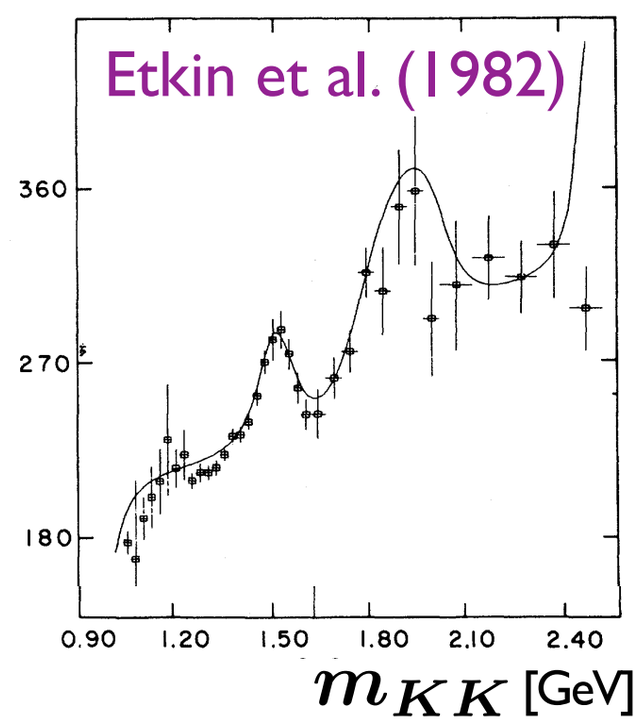
$$\mathcal{B} = S_S\,(\mathcal{B})^*$$ ← CP-odd amp.

- Since exp data on the scatterings at m_D are ambiguous, we consider the two scenarios for the I=0 amplitudes:
  - Two-channel unitarity
  - Three-channel unitarity (where KK is almost decoupled.)

Experimental data for I=0 amplitudes

- I=0 S-wave phase and inelasticity parameter are extracted from the πN scattering data.





$$\delta_1 = (40 \pm 10)^\circ$$

$$\pi\pi \to \pi\pi$$

$$\delta_1 + \delta_2 = (360 \pm 60)^\circ$$

$$\pi\pi \to KK$$

$$\eta = 0.95 \pm 0.05$$

I=1 and I=2 amplitudes

- No available data for the I=1 KK scattering around the D mass scale.
- The data for the I=2 $\pi\pi$ scattering shows a sizable inelaticity at the D mass scale.

Durusoy et al. (1973)

We do not impose unitarity relations.

4. Analysis of direct CP asymmetries

- We impose an upper bound on the size of CPV contributions as follows:

$$|\mathcal{B}_0^\pi| < \kappa\,|\mathcal{A}_0^\pi|$$
$$|\mathcal{B}_0^K - \mathcal{A}_0^K| < \kappa\,|\mathcal{A}_0^K|$$
$$|\mathcal{B}_{11}^K - (\mathcal{A}_{11}^K - \mathcal{A}_{13}^K)| < \kappa\,|\mathcal{A}_{11}^K - \mathcal{A}_{13}^K|$$

parameterizes the size of the subleading (penguin) amplitudes

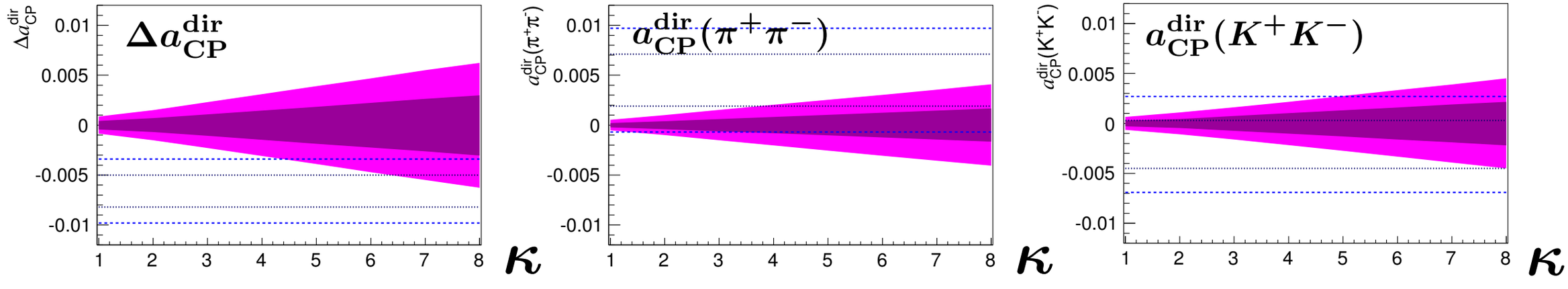
$$|P_1(\pi)| \leq \kappa \left| \frac{2}{3} E_1(\pi) - \frac{1}{3} E_2(\pi) + A_2(\pi) - P_1^{\rm GIM}(\pi) \right|$$

$$|P_1(K) - P_1^{\rm GIM}(K) + A_2(q,s,q,K)|$$
$$\leq \kappa\,|E_1(K) - A_2(q,s,q,K) + 2A_2(s,q,s,K) + P_1^{\rm GIM}(K)|$$

$$|P_1(K) - P_1^{\rm GIM}(K) - A_2(q,s,q,K)|$$
$$\leq \kappa\,|E_1(K) + A_2(q,s,q,K) + P_1^{\rm GIM}(K)|$$

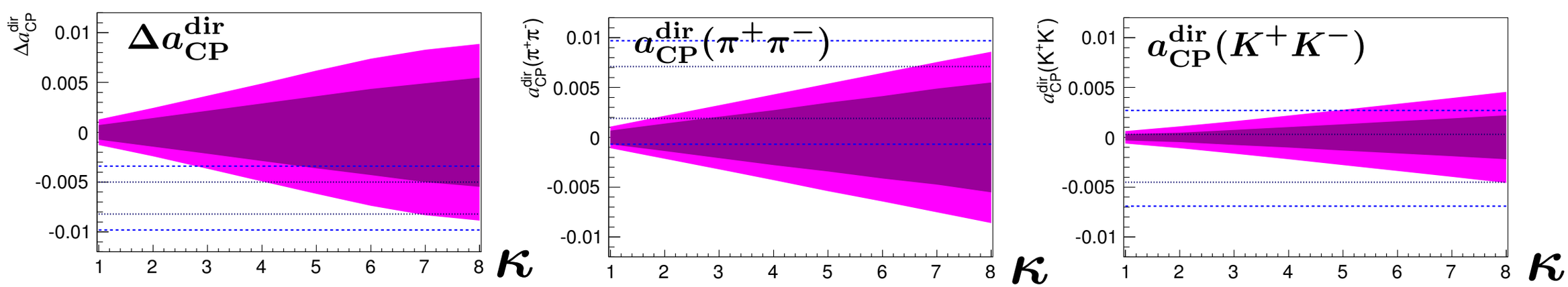
Predictions (CP asym's are not included in the fits.)

- Two-channel scenario:



The prediction does not reach the central value of the data within 2σ even for $\kappa = 8$.

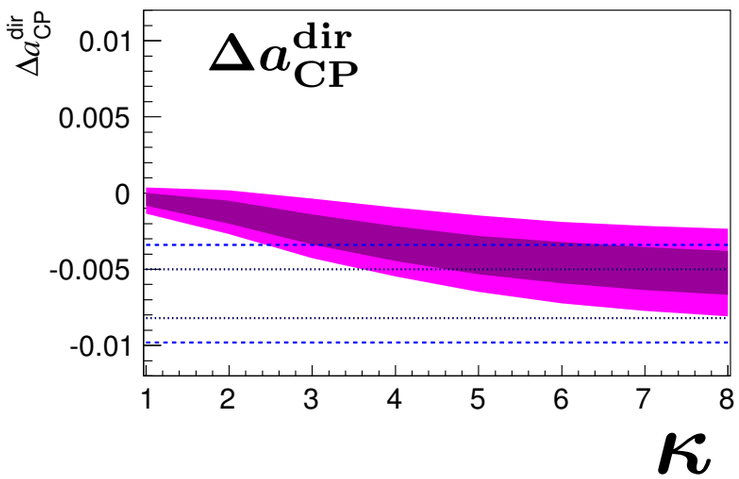
- Three-channel scenario (the most general case is similar):

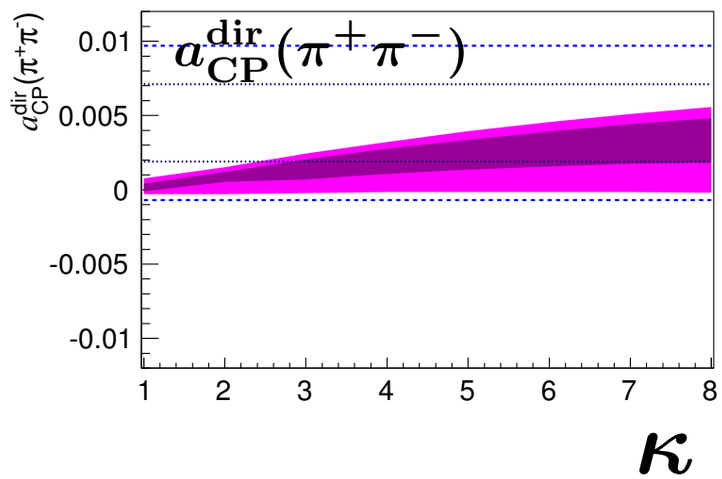


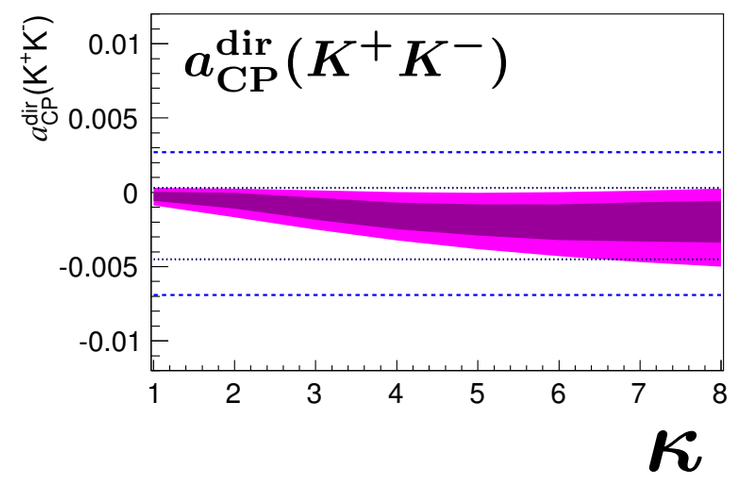
The prediction reaches the central value at the 2σ level for $\kappa \gtrsim 5$.

Fits (CP asym's are included in the fits.)

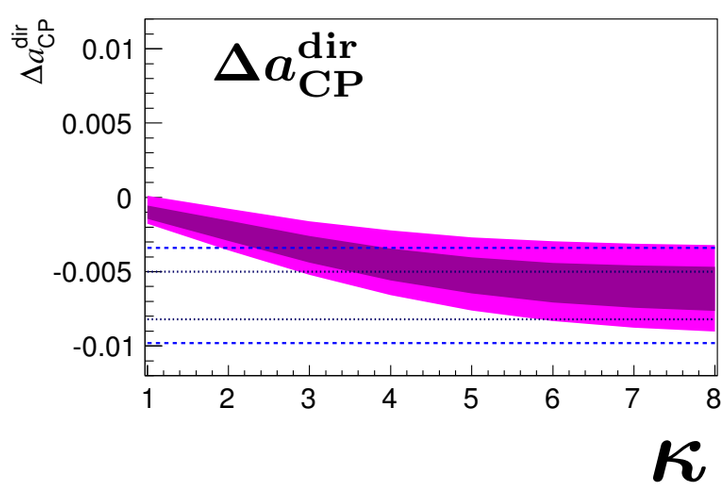
- Two-channel scenario:

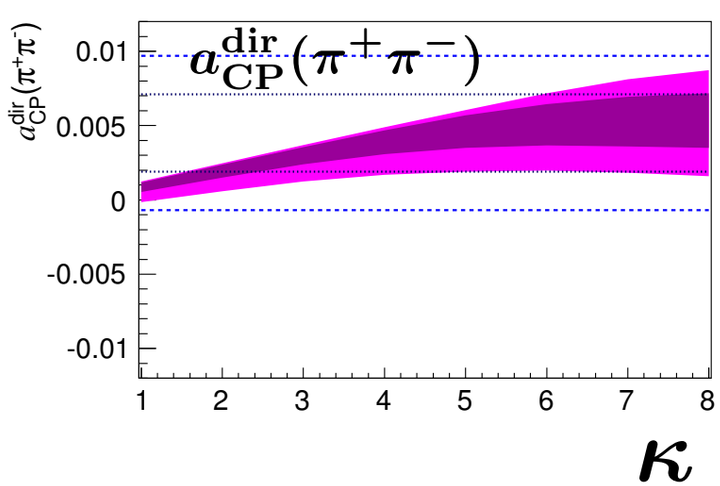


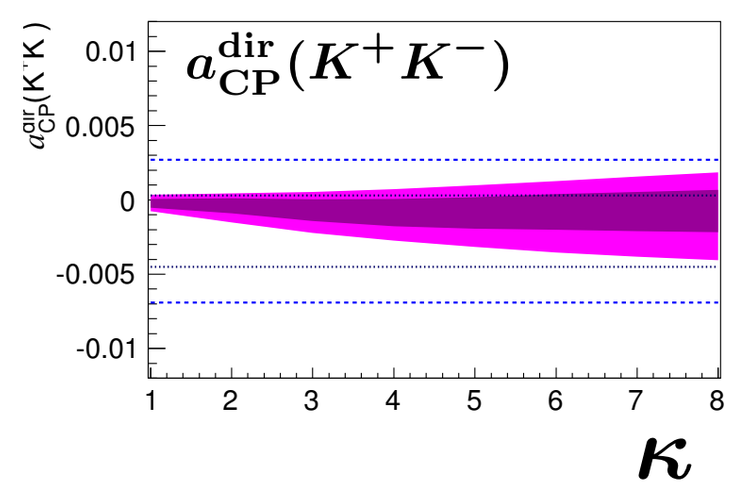




- Three-channel scenario:







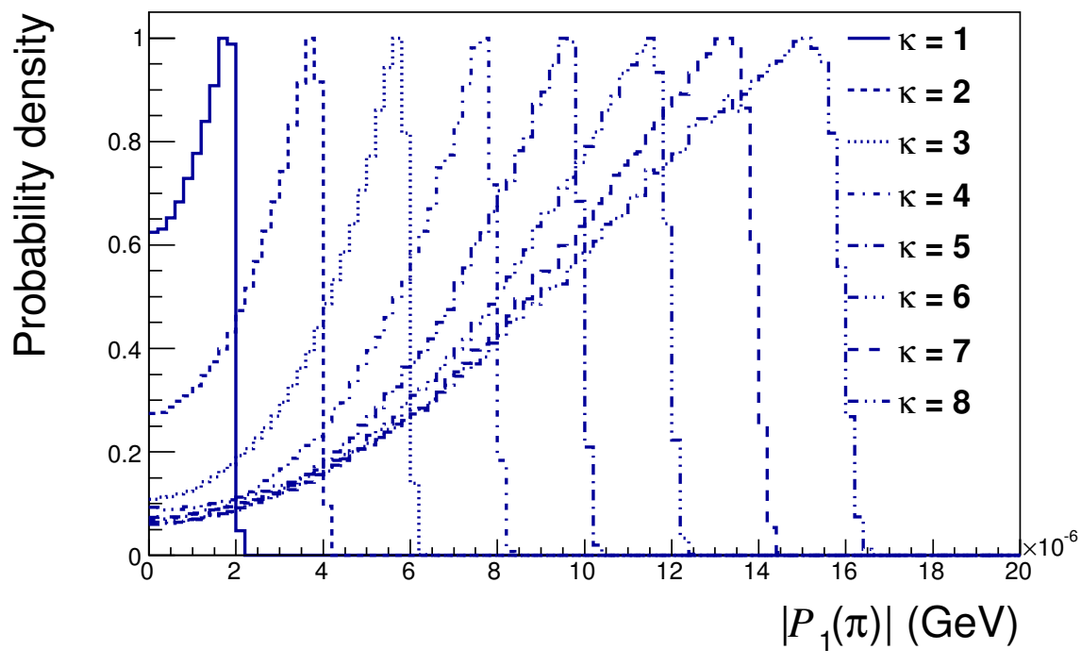
How large is penguin?

$$|P_1(\pi)| \leq \kappa \left| \frac{2}{3} E_1(\pi) - \frac{1}{3} E_2(\pi) + A_2(\pi) - P_1^{\mathrm{GIM}}(\pi) \right|$$

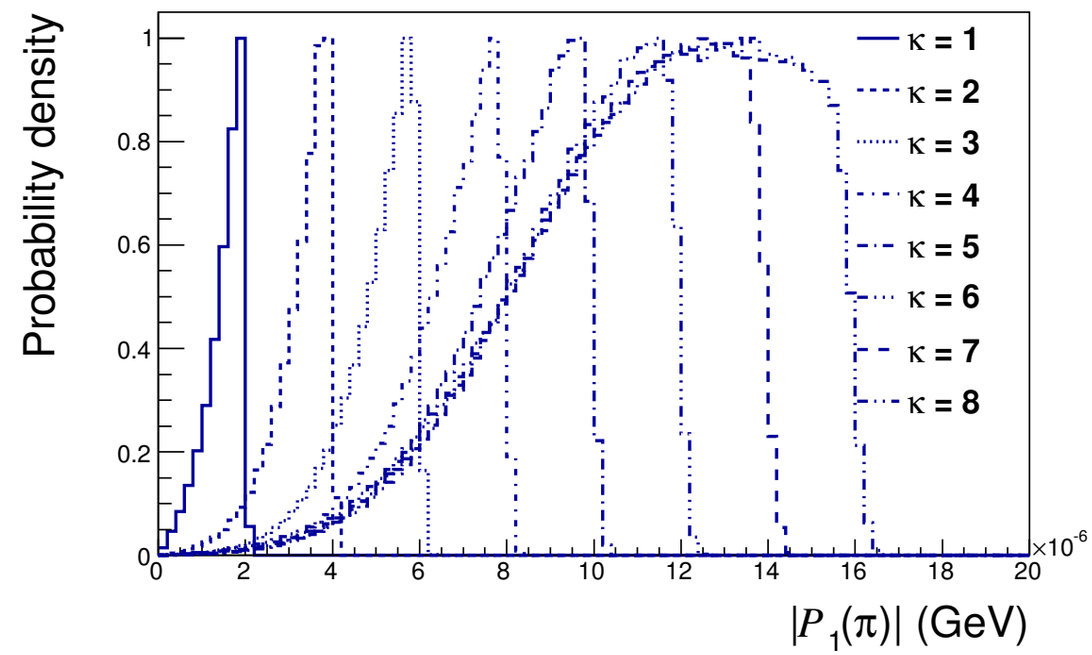
$P_1 \sim P_s - P_b$

$P_1^{\mathrm{GIM}} \sim P_s - P_d$

Two-channel



Three-channel



- In the three-channel scenario, the central value of the data corresponds to $|P_1| \sim 13 \times 10^{-6}$ GeV, about 6 times larger than the other RGI param's.

5. Conclusions

- We have studied $\Delta a_{\rm CP}^{\rm dir}$ phenomenologically, based on isospin decomposition with partial information on rescatterings from the πN scattering data.
- We have confirmed large nonfactorizable cont's, large SU(3) breaking and large strong phases.
- Unfortunately, the FSIs are not able to be fully determined from the πN scattering data.
- Penguin must be enhanced by a factor of 6 (or larger), which is well beyond theoretical expectations.
- Improving the experimental accuracy could lead to an indirect signal of NP.

Backup

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CPV in SCS D^0 decays

- In the case of D^0 decays, the time-integrated CP asymmetry may be written as a sum of direct and indirect asymmetries:

$$A_{\rm CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})} \approx a_{\rm CP}^{\rm dir}(f) + a_{\rm CP}^{\rm ind} \int_0^\infty dt \, \frac{t}{\tau_{D^0}} \, D_f(t)$$

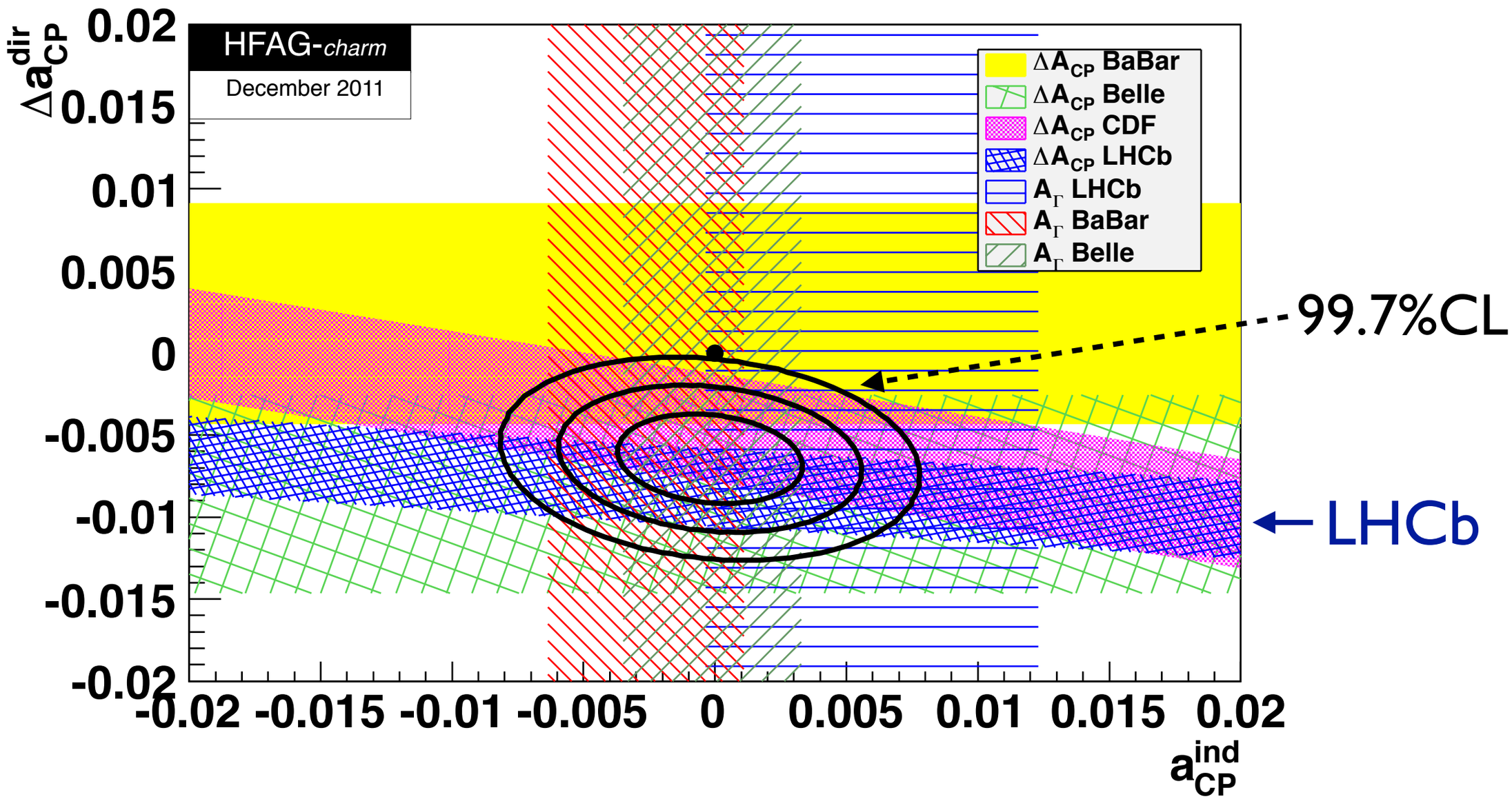
$$= a_{\rm CP}^{\rm dir}(f) + \frac{\langle t \rangle_f}{\tau_{D^0}} \, a_{\rm CP}^{\rm ind}$$

Distribution of proper decay time

- The effects from indirect CPV cancel to a large extent by taking the difference

$$\Delta A_{\rm CP} \equiv A_{\rm CP}(K^+K^-) - A_{\rm CP}(\pi^+\pi^-)$$
$$= a_{\rm CP}^{\rm dir}(K^+K^-) - a_{\rm CP}^{\rm dir}(\pi^+\pi^-) + \frac{\Delta\langle t \rangle}{\tau_{D^0}} \, a_{\rm CP}^{\rm ind}$$

First evidence of CPV in SCS D decays



$$a_{\rm CP}^{\rm ind} = (-0.019 \pm 0.232)\% \qquad \Delta a_{\rm CP}^{\rm dir} = (-0.645 \pm 0.180)\%$$

Isospin decomposition

Effective Hamiltonian:

$$H_{\rm eff} = H_{3/2}\left|\frac{3}{2},\,\frac{1}{2}\right\rangle + H_{1/2}\left|\frac{1}{2},\,\frac{1}{2}\right\rangle$$

Initial states:

$$|D^+\rangle = |1/2, 1/2\rangle\,, \qquad |D^0\rangle = |1/2, -1/2\rangle$$

Final states:

$$|\pi^+\pi^0\rangle = |2,\,1\rangle\,, \quad |\pi^+\pi^-\rangle = \frac{1}{\sqrt{3}}\,|2,\,0\rangle + \sqrt{\frac{2}{3}}\,|0,\,0\rangle\,, \quad |\pi^0\pi^0\rangle = \sqrt{\frac{2}{3}}\,|2,\,0\rangle - \frac{1}{\sqrt{3}}\,|0,\,0\rangle\,,$$

$$\left|K^+\overline{K}^0\right\rangle = |1,\,1\rangle\,, \quad |K^+K^-\rangle = \frac{1}{\sqrt{2}}\big(\,|1,\,0\rangle + |0,\,0\rangle\,\big)\,, \quad \left|K^0\overline{K}^0\right\rangle = \frac{1}{\sqrt{2}}\big(\,|1,\,0\rangle - |0,\,0\rangle\,\big)$$

$$\pi\pi \;:\quad I = 0, 2$$

$$KK \;:\quad I = 0, 1$$

Isospin decomposition

- The decay amplitudes are written in terms of reduced matrix elements:

$$A(D^+ \to \pi^+\pi^0) = \frac{\sqrt{3}}{2}\langle 2||H_{3/2}||1/2\rangle\,,$$
$$A(D^0 \to \pi^+\pi^-) = \frac{1}{\sqrt{6}}\langle 2||H_{3/2}||1/2\rangle + \frac{1}{\sqrt{3}}\langle 0||H_{1/2}||1/2\rangle\,,$$
$$A(D^0 \to \pi^0\pi^0) = \sqrt{\frac{2}{3}}\langle 2||H_{3/2}||1/2\rangle - \frac{1}{\sqrt{3}}\langle 0||H_{1/2}||1/2\rangle\,,$$
$$A(D^+ \to K^+\overline{K}^0) = -\frac{1}{2}\langle 1||H_{3/2}||1/2\rangle + \langle 1||H_{1/2}||1/2\rangle\,,$$
$$A(D^0 \to K^+K^-) = \frac{1}{2}\langle 1||H_{3/2}||1/2\rangle + \frac{1}{2}\langle 1||H_{1/2}||1/2\rangle + \frac{1}{2}\langle 0||H_{1/2}||1/2\rangle\,,$$
$$A(D^0 \to K^0\overline{K}^0) = \frac{1}{2}\langle 1||H_{3/2}||1/2\rangle + \frac{1}{2}\langle 1||H_{1/2}||1/2\rangle - \frac{1}{2}\langle 0||H_{1/2}||1/2\rangle\,.$$

Generalized Watson's theorem

$$S_S = \begin{pmatrix} \eta\, e^{2i\delta_\pi} & i\sqrt{1-\eta^2}\, e^{i(\delta_\pi+\delta_K)} \\ i\sqrt{1-\eta^2}\, e^{i(\delta_\pi+\delta_K)} & \eta\, e^{2i\delta_K} \end{pmatrix}$$

$$\Rightarrow \begin{cases} \cos(\arg(\mathcal{A}_0^K) - \delta_K) = \left|\dfrac{\mathcal{A}_0^\pi}{\mathcal{A}_0^K}\right| \sqrt{\dfrac{1+\eta}{1-\eta}}\, \sin(\arg(\mathcal{A}_0^\pi) - \delta_\pi)\,, \\ \sin(\arg(\mathcal{A}_0^K) - \delta_K) = \left|\dfrac{\mathcal{A}_0^\pi}{\mathcal{A}_0^K}\right| \sqrt{\dfrac{1-\eta}{1+\eta}}\, \cos(\arg(\mathcal{A}_0^\pi) - \delta_\pi)\,, \end{cases}$$

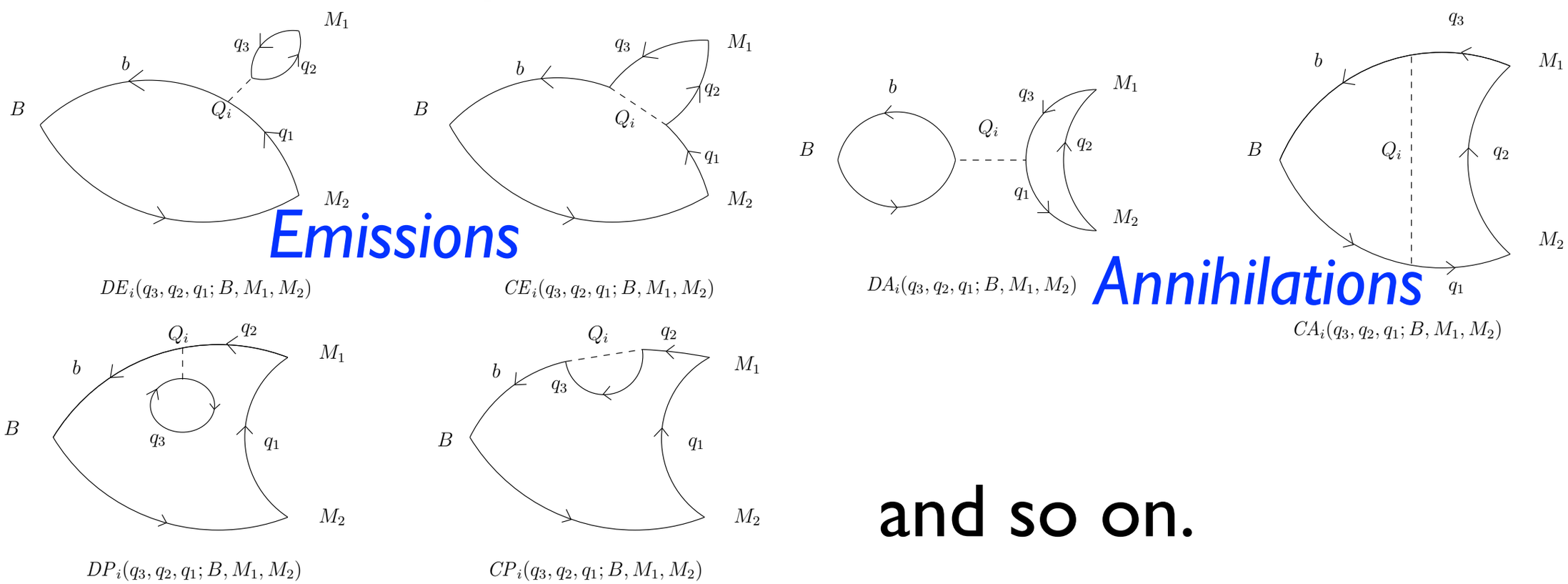
where $\dfrac{1-\eta}{1+\eta} \leq \left|\dfrac{\mathcal{A}_0^K}{\mathcal{A}_0^\pi}\right|^2 \leq \dfrac{1+\eta}{1-\eta}$ has to be satisfied,

and analogous formulae for the CP-odd amp's.

RG invariant parameterization Buras, Silvestrini (2000)

- Buras and Silvestrini introduced an RG invariant parameterization of two-body non-leptonic B-decay amplitudes based on the OPE in Heff and on Wick contractions.

1. Consider all possible contractions:



and so on.

RG invariant parameterization Buras, Silvestrini (2000)

- Buras and Silvestrini introduced an RG invariant parameterization of two-body non-leptonic B-decay amplitudes based on the OPE in Heff and on Wick contractions.

2. Construct the effective amplitudes which are independent of renormalization scale and scheme:

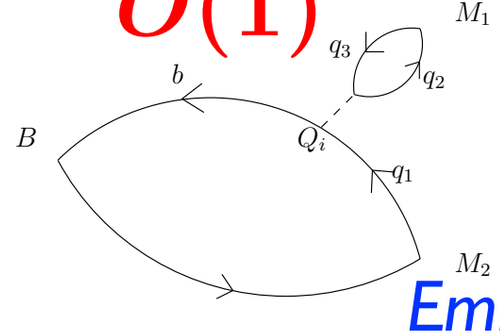
$$E_1 = C_1\, DE_1 + C_2\, CE_2\,, \qquad E_2 = C_2\, DE_2 + C_1\, CE_1\,,$$
$$A_1 = C_1\, DA_1 + C_2\, CA_2\,, \qquad A_2 = C_2\, DA_2 + C_1\, CA_1\,,$$
$$P_1 = C_1\, CP_1 + C_2\, DP_2 + \cdots\,, \qquad P_3 = C_1\, CPA_1 + C_2\, DPA_2 + \cdots\,,$$
$$P_1^{\rm GIM} = C_1\big[CP_1(s) - CP_1(d)\big] + C_2\big[DP_2(s) - DP_2(d)\big]\,,$$
$$P_3^{\rm GIM} = C_1\big[CPA_1(s) - CPA_1(d)\big] + C_2\big[DPA_2(s) - DPA_2(d)\big]\,.$$

Emissions, Annihilations, Penguin contractions, GIM penguins

1/N power counting

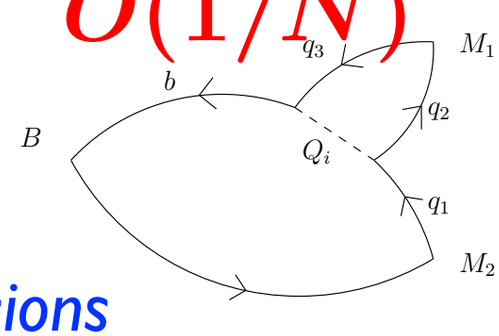
- Large-Nc classification:

$O(1)$



$DE_i(q_3, q_2, q_1; B, M_1, M_2)$

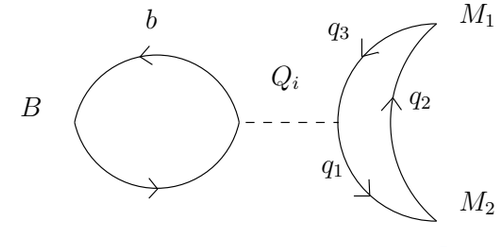
$O(1/N)$



$CE_i(q_3, q_2, q_1; B, M_1, M_2)$

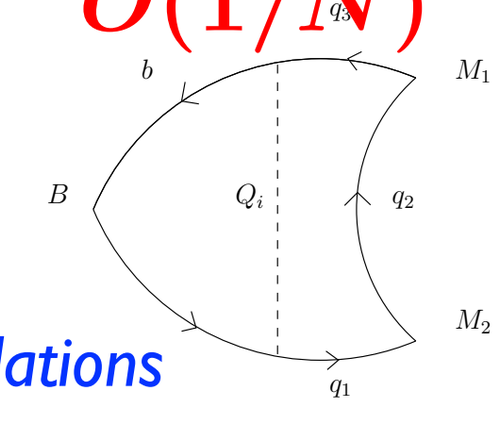
Emissions

$O(1)$



$DA_i(q_3, q_2, q_1; B, M_1, M_2)$

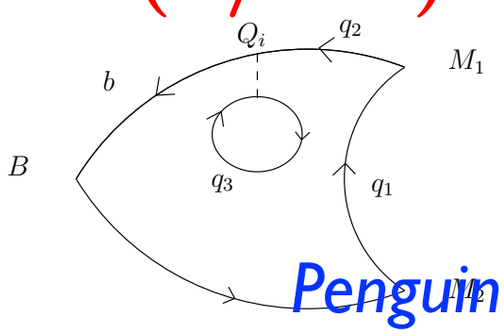
$O(1/N)$



$CA_i(q_3, q_2, q_1; B, M_1, M_2)$

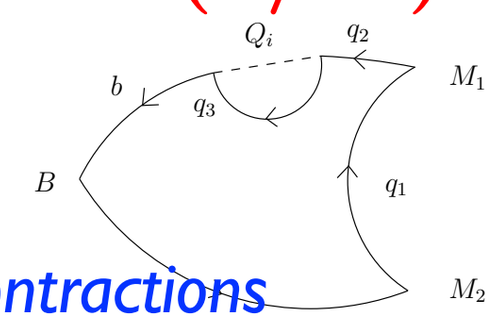
Annihilations

$O(1/N^2)$



$DP_i(q_3, q_2, q_1; B, M_1, M_2)$

$O(1/N)$



$CP_i(q_3, q_2, q_1; B, M_1, M_2)$

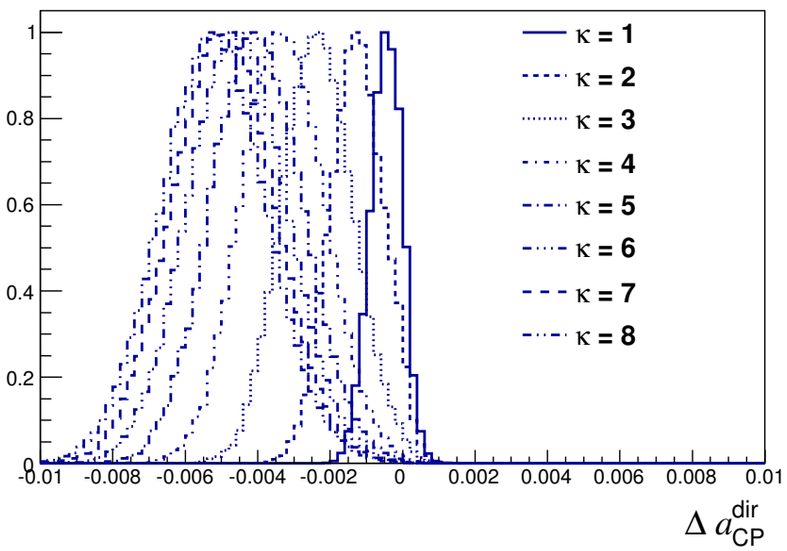
Penguin contractions

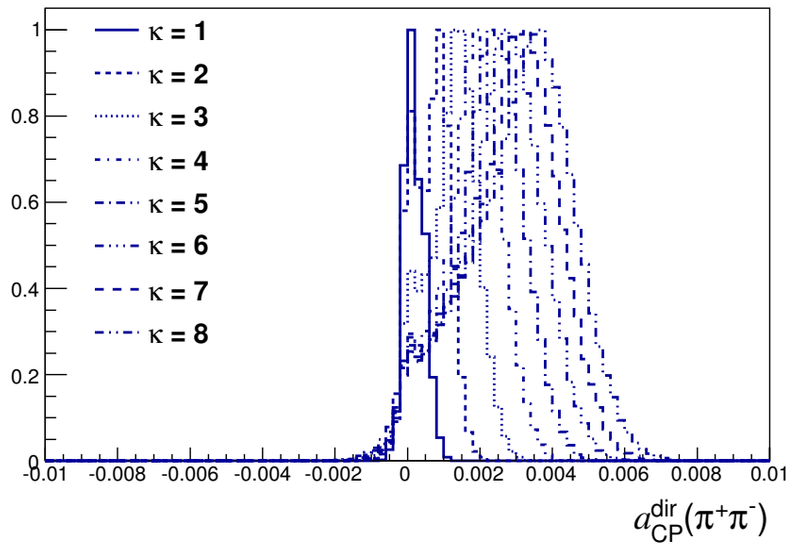
- Also, numerically, the Wilson coefficients obey

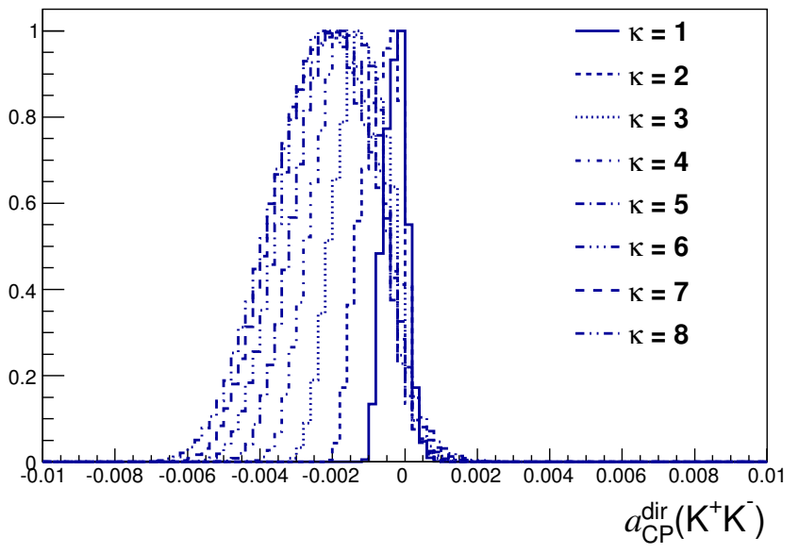
$$C_1 \sim O(1)\,, \quad C_2 \sim O(1/N)\,,$$

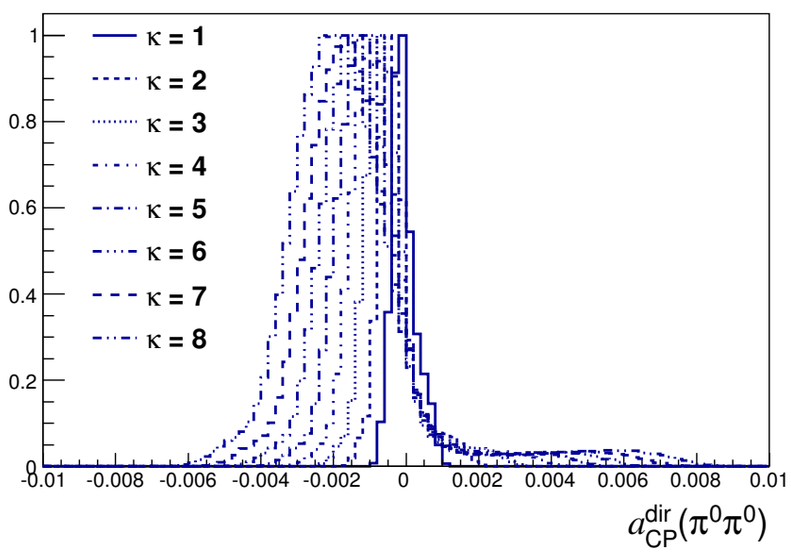
$$C_{4,6} \sim O(1/N^3)\,, \quad C_{3,5} \sim O(1/N^4)\,.$$

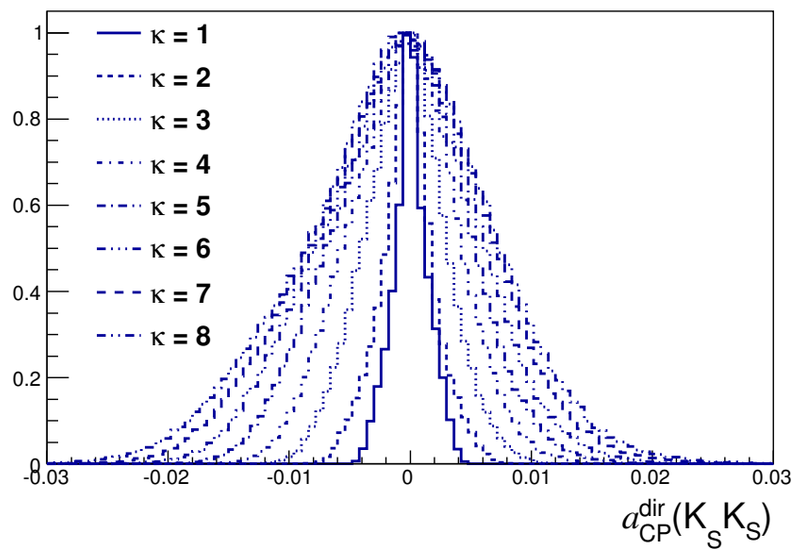
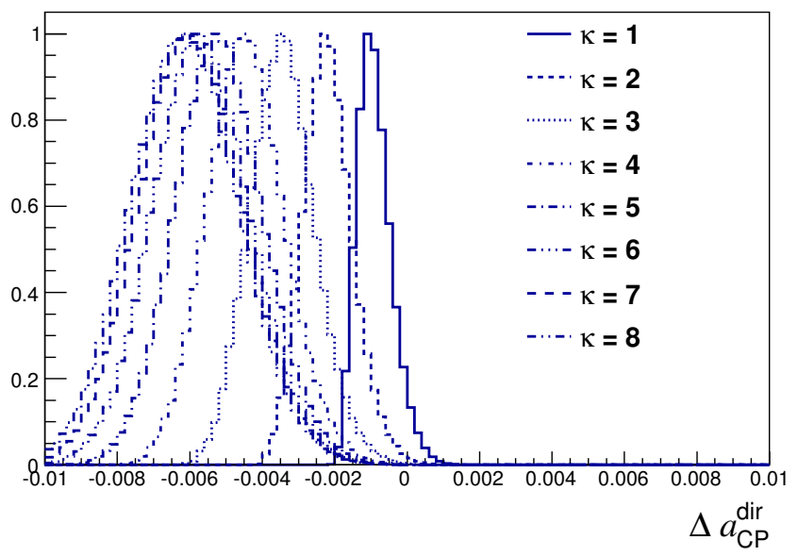
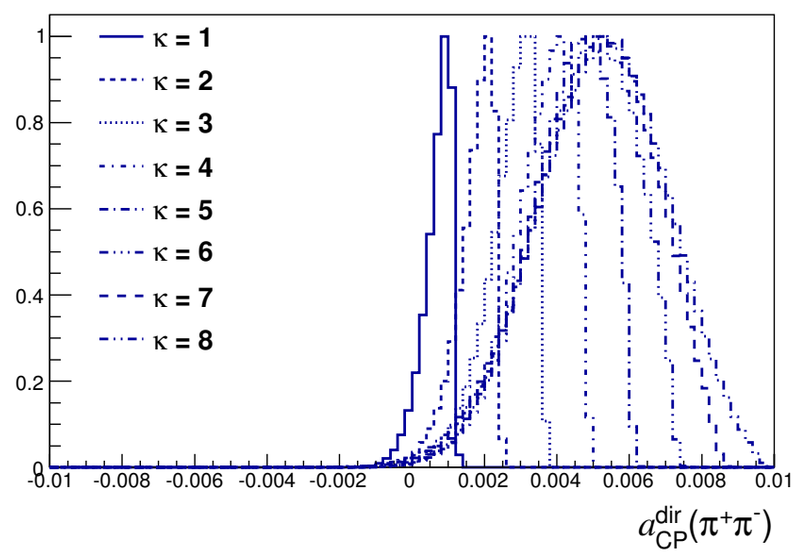
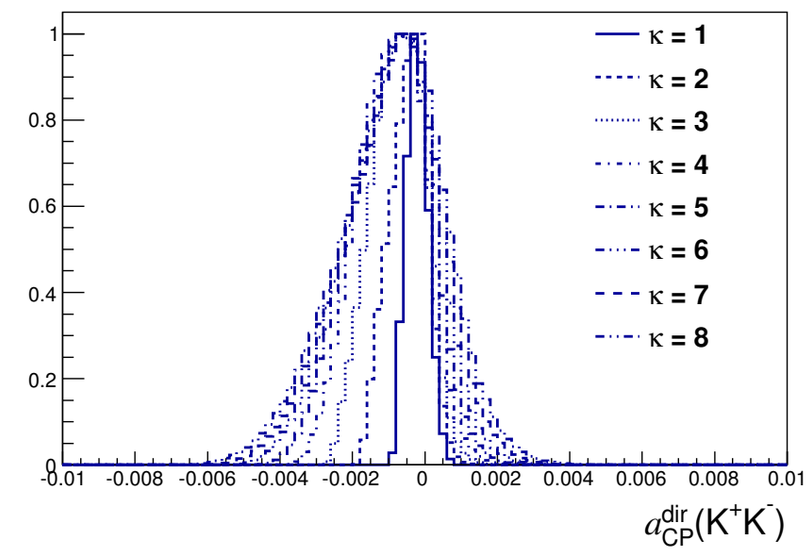
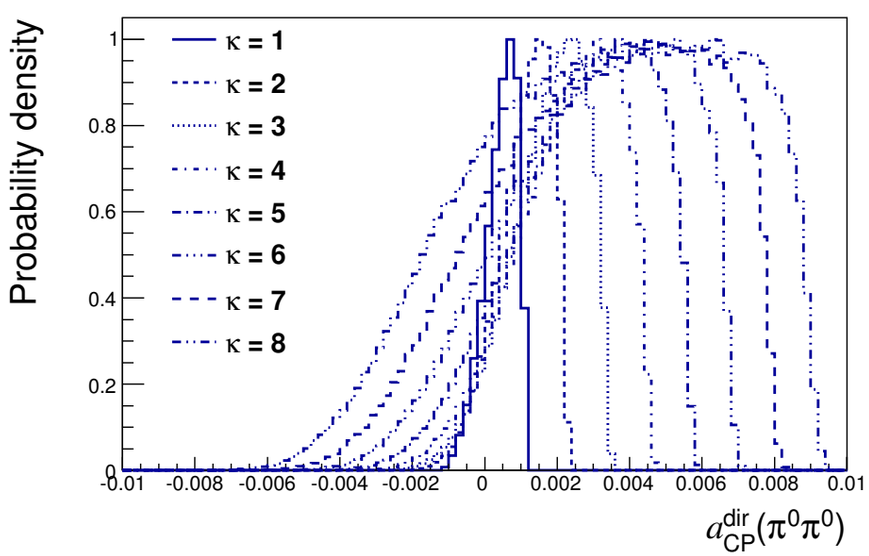
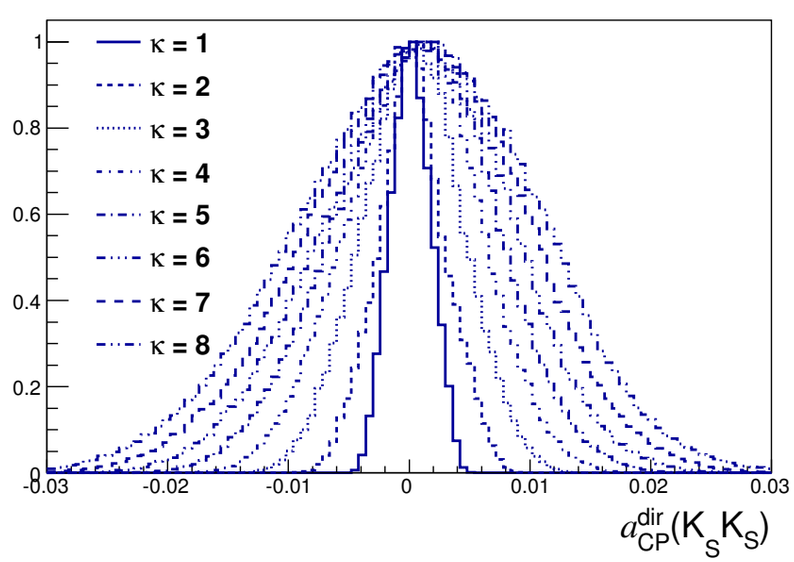
P.d.f.'s in the two-channel scenario











P.d.f.'s in the three-channel scenario