Charmless B decays and (non)factorization

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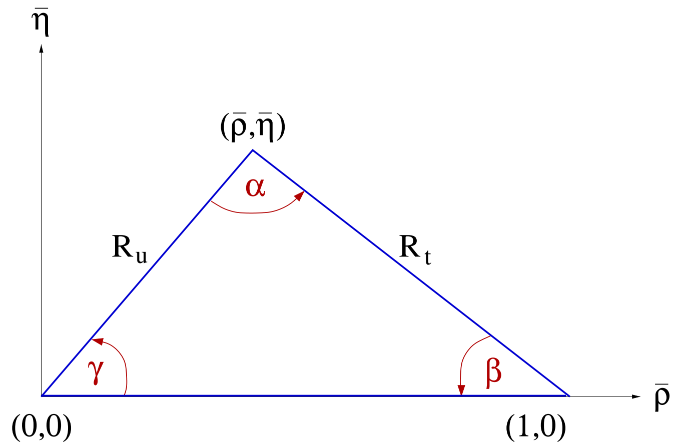
- B-decays $\longrightarrow$ stringent test of the flavour dynamics of SM & of the CKM mechanism of CP-violation
- charmless B-decays $\longrightarrow$ the most sensitive to New Physics
- testing of SM by overconstraining the CKM matrix parameters

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = \sin\theta_c = 0.22$$

- standard, non-squashed unitarity triangle (from 6 possible):

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



$$R_u = R_b = \left|\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right| \; ; \; R_t = \left|\frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}}\right|$$

$$\bar\rho = \rho(1-\tfrac{1}{2}\lambda^2) \; ; \; \bar\eta = \eta(1-\tfrac{1}{2}\lambda^2)$$

CP-asymmetry in B-decays to certain CP-eigenstate final state:

$$a_{CP} = \frac{\Gamma[\overline{B^0}(t)\to\bar f] - \Gamma[B^0(t)\to f]}{\Gamma[\overline{B^0}(t)\to\bar f] + \Gamma[B^0(t)\to f]} = a^{mix}_{CP}\sin(\Delta m t) + a^{dir}_{CP}\cos(\Delta m t)$$

a^{mix}_{CP} - $B^0 - \overline{B^0}$ mixing

a^{dir}_{CP} - from different CP-viol. weak phases and CP-conserv. strong phases:

$$A(B\to f) \quad = \quad \langle f|\mathcal{H}_{weak}|B\rangle = \sum_k e^{i\Phi_k}|A_k|e^{\delta_k} \qquad \Phi = \text{weak phase;}$$

$$\overline{A}(\overline{B}\to \bar f) \quad = \quad \langle \bar f|\mathcal{H}_{weak}|\overline{B}\rangle = \sum_k e^{-i\Phi_k}|A_k|e^{\delta_k} \qquad \delta = \text{strong phase}$$

$\Rightarrow$ if $\left|\frac{\overline{A}}{A}\right| \neq 1 \Rightarrow$ CP VIOLATION

▷ CURRENT EXPERIMENTAL STATUS FOR $B \to K$ DECAYS:

$$a_{CP}^{mix}(\text{from } B \to J/\psi K_s) = \sin \Phi_{mix} = \sin 2\beta = 0.726 \pm 0.037$$

$$a_{K^-\pi^+}^{dir} = \frac{\Gamma[\overline{B} \to K^-\pi^+] - \Gamma[B \to K^+\pi^-]}{\Gamma[\overline{B} \to K^-\pi^+] + \Gamma[B \to K^+\pi^-]} = -0.109 \pm 0.019$$

- "superweak" B-models are therefore excluded
- an indication for large stronge phases
- measurements of $B \to K\pi$ branching ratios are not consistent with theory
  (BR of color-suppressed $\overline{B^0} \to K^-\pi^+$ mode is comparable with
  $\text{BR}(B^- \to K^-\pi^0)$ mode)

▷ SIGNS FOR CP-VIOLATION IN THE B-DECAYS TO π's:

$$a_{\pi^+\pi^-}^{mix} = \begin{array}{ll} -0.30 \pm 0.17 & \text{BaBar} \\ -1.00 \pm 0.22 & \text{BELLE} \end{array} \quad \to \alpha$$

$$a_{\pi^+\pi^-}^{dir} = \begin{array}{ll} -0.09 \pm 0.15 & \text{BaBar} \\ -0.54 \pm 0.17 & \text{BELLE} \end{array} \quad \to \gamma$$

- CP-asymmetry : weak phase from a phase in CKM matrix & strong phases from CP-conserving strong amplitude:

$$|A|e^{i\delta} \sim \langle \bar{f}|\mathcal{H}_{weak}|\bar{B}\rangle = \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \underbrace{\langle \bar{f}|\mathcal{O}_k(\mu)|\bar{B}\rangle}_{\text{non-pert. QCD}}$$

- how to calculate hadronic matrix elements $\langle \bar{f}|\mathcal{O}_\mu|\bar{B}\rangle$?

$$\mathcal{H}_{weak} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb}V_{pd}^* \left\{ C_1(\mu)\mathcal{O}_1^p + C_2(\mu)\mathcal{O}_2^p + \sum_{i=3,..,10} C_i(\mu)\mathcal{O}_i + C_{7\gamma}\mathcal{O}_{7\gamma} + C_{8g}\mathcal{O}_{8g} \right\}$$

$$\text{i.e.} \quad \langle \pi\pi|\mathcal{O}_1|B\rangle = \underbrace{\langle \pi|\bar{d}\Gamma_\mu u|0\rangle \langle \pi|\bar{u}\Gamma^\mu b|B\rangle}_{'naive'\ factorization} \left[1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda_{QCD}/m_b)\right]$$

$$= i m_b^2 f_\pi F^+_{B\to\pi}(m_\pi^2) \left[1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\Lambda_{QCD}/m_b)\right]$$

- Is it enough to keep only leading terms in $1/m_b$, i.e how large are $O(\Lambda_{QCD}/m_b)$ corrections ?

MODELS FOR CALCULATING MATRIX ELEMENTS:

- ▷ QCD FACTORIZATION APPROACH (Beneke, Buchalla, Neubert, Sachrajda '99)
  - factorization of hadronic matrix elements in the $m_b \to \infty$ limit (does not apply for $B \to \mathrm{light} + D$ decays)
  - only $\mathcal{O}(\alpha_s)$ corrections are calculable
- ▷ PQCD APPROACH (Keum, Sanda, Li '01)
  - $\langle \pi\pi | \mathcal{O}_i | B \rangle$ is calculated perturbatively, by implementing the Sudakov suppression of non-factorizing long-distance contributions
- ▷ SCET(soft-collinear eff. theory) (Bauer, Fleming, Luke, Stewart '01)
  - nonperturbative effects are included in form of matrix elements of certain operators
- ▷ LIGHT-CONE SUM RULE METHOD (Khodjamirian '01)
  - $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\Lambda/m_b)$ corrections calculable

$$\text{i.e.}\quad \langle \pi\pi | \mathcal{O}_1 | B \rangle = \langle \pi | \bar{d}\Gamma_\mu u | 0 \rangle \langle \pi | \bar{u}\Gamma^\mu b | B \rangle \left[1 + O(\alpha_s) + O(\Lambda_{QCD}/m_b) \right]$$

$$= \underbrace{\underbrace{i m_b^2 f_\pi F^+_{B\to\pi}(m_\pi^2)}_{\text{naive factorization}} \left[1 + O(\alpha_s) + O(\Lambda_{QCD}/m_b) \right]}_{\text{QCD factorization}}$$

▷ there are strong indications that QCD FACTORIZATION model (applied by CKM fits) fails to fit the data $\Rightarrow$ large nonfactorizable $\mathcal{O}(\Lambda_{QCD}/m_b)$ contributions:

▽ "charming penguin" (= 'LD charmed loops', '$D-\overline{D}$ rescattering') contributions (Ciuchini et al. '01)
- long-distance large $O(\Lambda/m_b)$ contributions and large strong phases

$$\frac{P^{charm}}{A^{TOT}} = (0.11 \pm 0.05)e^{i(-0.2\pm0.9)}$$
$$\frac{P^{GIM}}{A^{TOT}} = (0.43 \pm 0.14)e^{i(-0.2\pm0.7)}$$

(P^{GIM} includes also annihilation and corrections to emission topology)

▽ chirally-enhanced corrections could be large (nonfactor. hard-scattering corr.)

$$r_\chi^\pi = \frac{2m_\pi^2}{m_b(m_u+m_d)} = \mathcal{O}(1) \qquad !$$

▽ annihilation could be large

in QCD factorization model both effects are divergent and therefore parametrized:

$$X_{H,A} = (1 + \rho_{H,A} e^{i\Phi_{H,A}}) \log \frac{m_B}{\Lambda_h} \qquad \Lambda_h = 0.5\text{GeV}$$

$\rho_{H,A}$ and $\Phi_{H,A}$ parameters are determined from exp. data on BR's and a^s_{CP}

$\Rightarrow$ large theoretical uncertainties are introduced

▷ let us address this questions by LCSR method

$$F_\nu^{(\mathcal{O})}(p,q,k) = \int d^4x e^{-i(p-q)x} \int d^4y e^{i(p-k)y} \langle 0|T\{j_{\nu,5}^{(\pi)}(y)\mathcal{O}_i(0)j_5^{(B)}(x)\}|\pi(q)\rangle$$

- interpolating currents for a pion and a B meson:

$$j_{\nu,5}^{(\pi)} = \overline{u}\gamma_\nu\gamma_5 d \qquad\qquad j_5^{(B)} = m_b\overline{b}i\gamma_5 d$$

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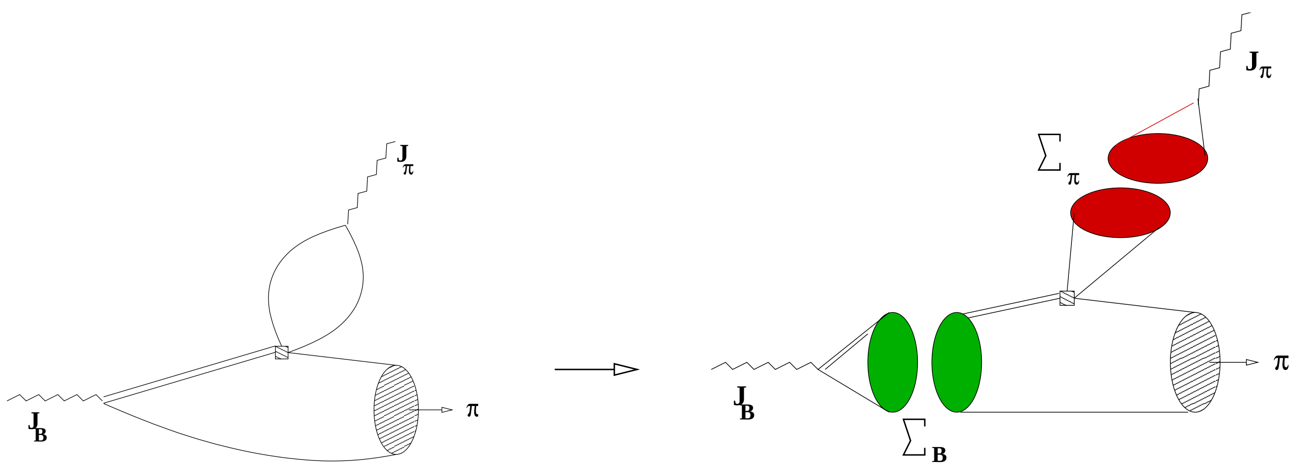
$$j_{\nu,5}^{(\pi)} = \bar{u}\gamma_\nu\gamma_5 d \qquad\qquad j_5^{(B)} = m_b \bar{b} i\gamma_5 d$$

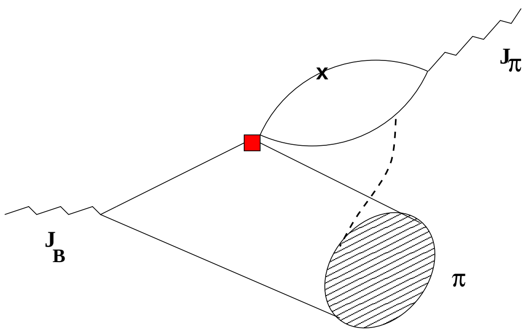
$$\sum_B \sum_\pi \frac{\langle 0|j_{\nu,5}^{(\pi)}|\pi\rangle\langle\pi|\langle\pi|\mathcal{O}_i(0)|B\rangle\langle B|j_5^{(B)}|0\rangle}{(m_\pi^2-(p-k)^2)(m_b^2-(p-q)^2)} = \int ds \int ds' \frac{\mathrm{Im}_{s'}\mathrm{Im}_s F_{QCD}(s,s')}{(s-(p-k)^2)(s'-(p-q)^2)}$$



quark-hadron duality $\rightarrow \langle\pi\pi|\mathcal{O}|B\rangle$

▷ NONFACTORIZABLE $O(\Lambda/m_b)$ corrections from $\mathcal{O}_2 = \frac{1}{N_c}\mathcal{O}_1 + 2\,\tilde{\mathcal{O}}_1$ operator

color-octet operator $\tilde{\mathcal{O}}_1 = (\bar{d}\Gamma_\mu \frac{\lambda^a}{2} u)(\bar{u}\Gamma^\mu \frac{\lambda^a}{2} b)$



(Khodjamirian '01)

- defined in terms of twist-3 and twist-4 distribution amplitudes:

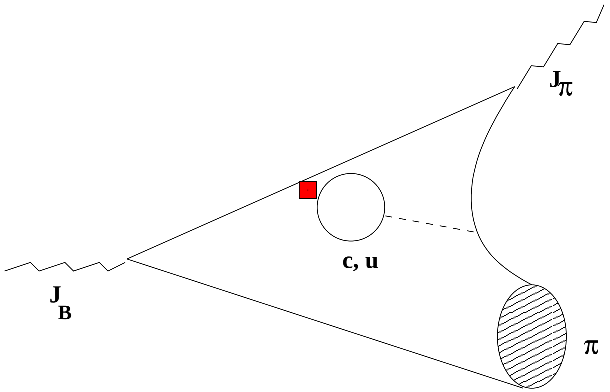
$$\langle \pi | \bar{u} \sigma_{\mu\nu} \gamma_5 G_{\alpha\beta}\, d | 0 \rangle \sim \phi_{3\pi}(...) \qquad twist - 3\; w.f.$$

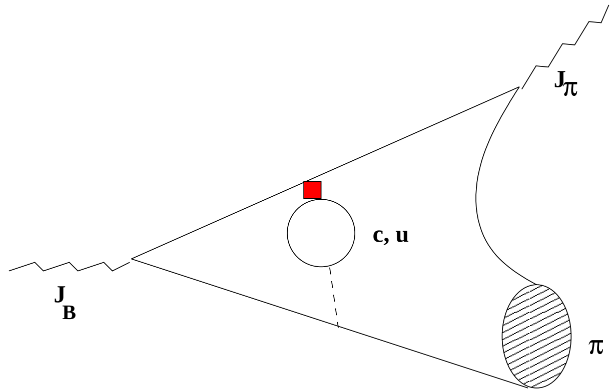
$$\langle \pi | \bar{u} \gamma^\mu \tilde{G}_{\alpha\beta}\, d | 0 \rangle \sim (...)\tilde{\phi}_{||} + (...)\tilde{\phi}_{\perp} \qquad twist - 4\; w.f.$$

$O(\Lambda/m_b)$ corrections are small, but they are of the same order as $O(\alpha_s)$
(corrections calculated in QCD factorization)

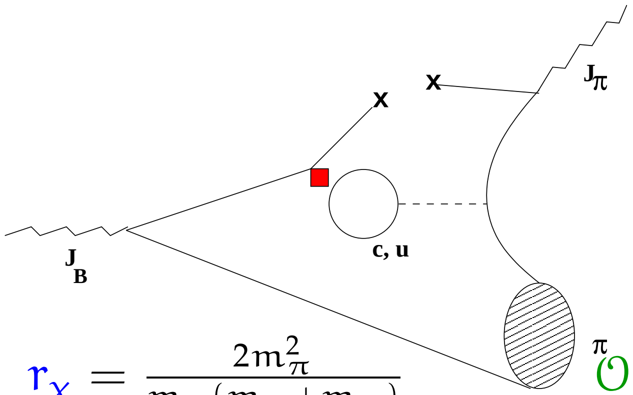
▷ PENGUIN LOOP CONTRIBUTIONS - $P^{u,c}_{loop}$ (Khodjamirian, Mannel, BM)

"hard contributions" (QCD factorization & LCSR):

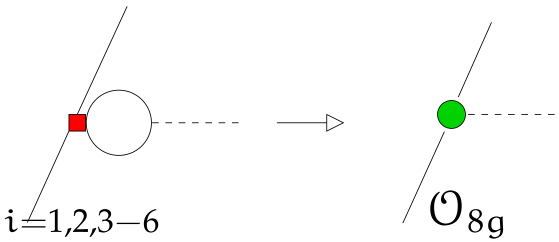




$\mathcal{O}(\alpha_s) + \mathcal{O}(\frac{\alpha_s}{m_b})$ $\mathcal{O}(\frac{\alpha_s}{m_b})$



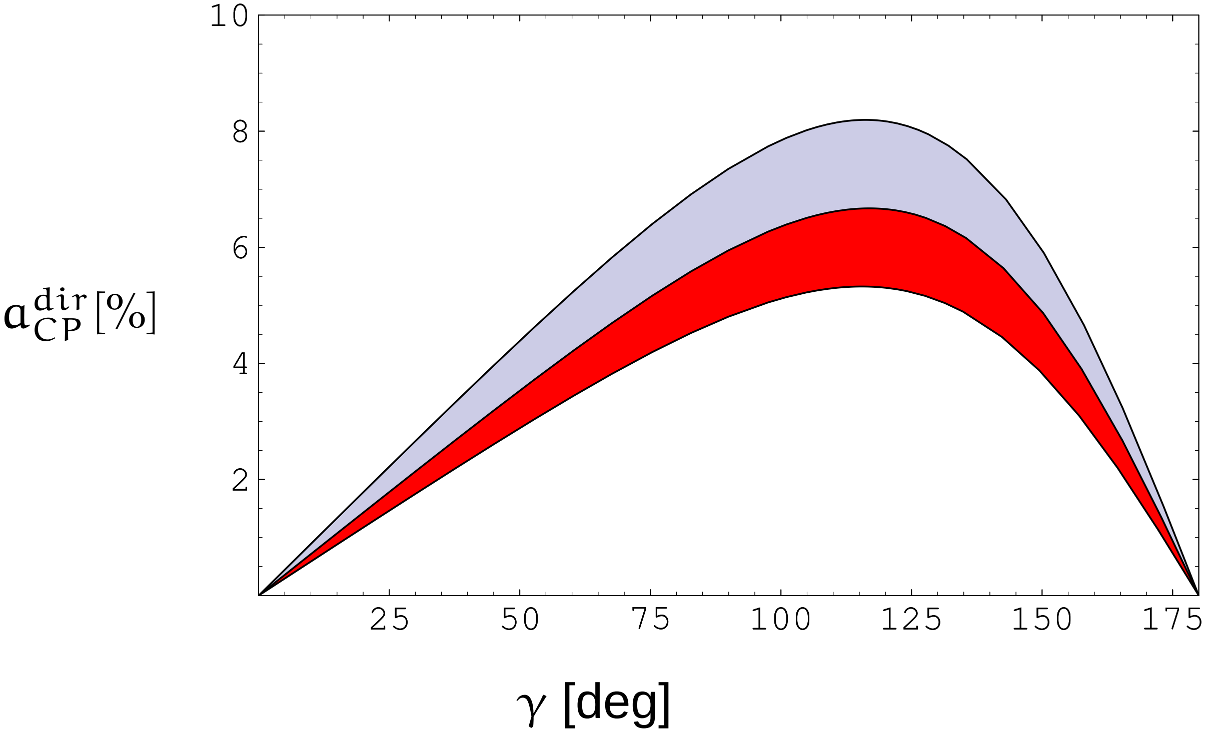
$r_\chi = \frac{2m_\pi^2}{m_b(m_u+m_d)}$ $\mathcal{O}(\alpha_s\, r_\chi) + \mathcal{O}(\alpha_s \frac{r_\chi}{m_b})$



$\mathcal{O}_{i=1,2,3-6}$ $\mathcal{O}_{8g}$

$$a_{CP}^{dir} = \frac{-2|R| \sin\gamma \sin(\delta_{P^c_{loop}} - \delta_{P^u_{loop}})}{1 - 2|R| \cos\gamma + |R|^2}$$

$$R \equiv -\frac{1}{R_b}\frac{P}{T}$$



the uppermost curve: $m_b \to \infty$ result

red region $\to$ LSCR result
(with uncertainties from LCSR included)

no additional uncert. included
(annihilation ? , $\delta(V_{ub}/V_{cb})$)

violet region: $\to 1/m_b$ corrections !

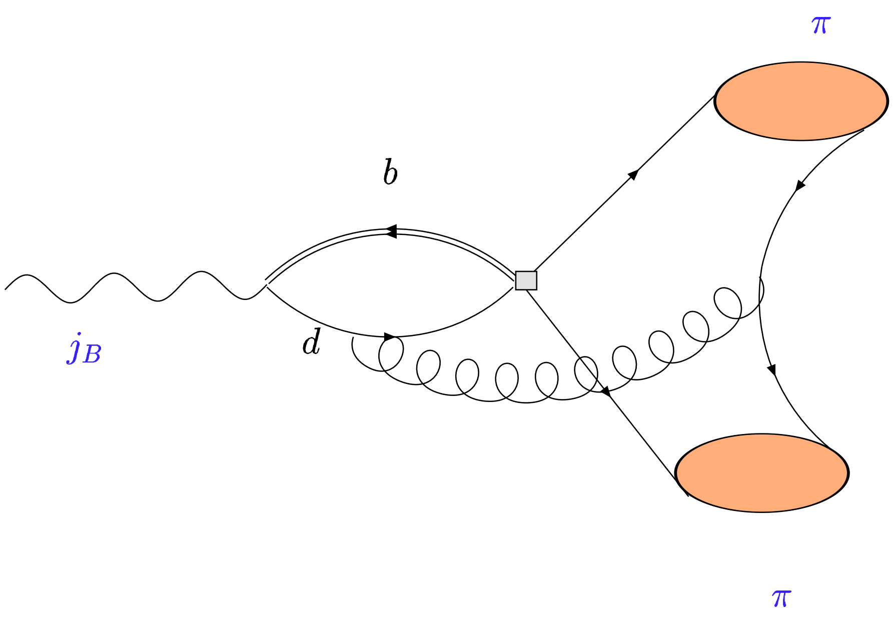
$$(a_{CP}^{dir})|_{m_b\to\infty, \gamma=80^\circ} = 6.25\%$$

$$(a_{CP}^{dir})|_{LCSR, \gamma=80^\circ} = 4 - 5\%$$

ANNIHILATION

(work in progress : Khodjamirian, Mannel, Melcher, BM)

- leading contribution:



- there is an imaginary phase (final state interaction)
- hopefully it would be able to explain large nonfactorizable contributions needed by experimental data

- ▷ we have focused on B-meson decays $B \to \pi\pi$ and $B \to K\pi$, which are particularly fertile testing ground for SM and CP-violation by CKM mechanism
- ▷ factorization is unable to reproduce observed BR's of $B \to \pi\pi$ and $B \to K\pi$ decays

  - $B \to \pi\pi$ data favour large nonfactorizable effects
  - $B \to \pi\pi$ data point to large a_{CP}^{mix} and a_{CP}^{dir} asymmetries
  - 'puzzling effects' in $B \to K\pi$ system need futher valorization before any conclusion about New Physics
- ▷ calculation of ANNIHILATION and other power-suppressed effects in charmless B-decays is extremely important
- ▷ the unsatisfactory theoretical understanding of nonfactorizable power-suppressed effects in charmless nonleptonic B-decays prevent indentification of New Physics effects
- ▷ new and/or more precise data from B-factories (Tevatron - run II, LHCb, BTeV, Super KEK) are needed to overconstrain the unitary triangle as much as possible