PQCD approach to hadronic B decays

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PQCD picture

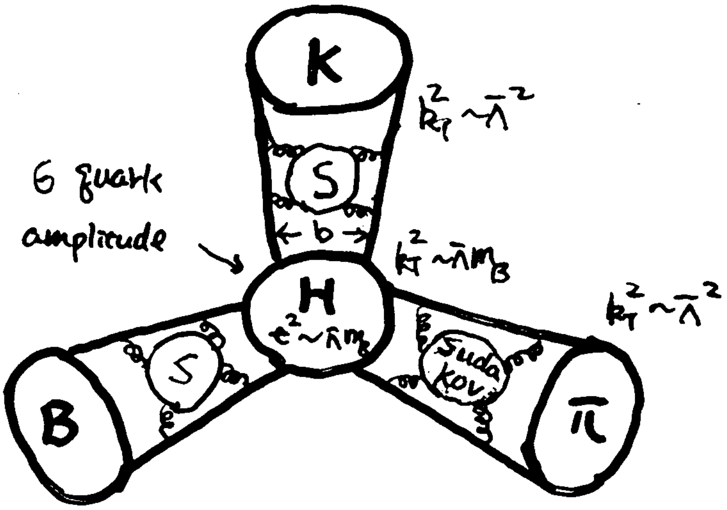
Br and $\not{CP}$ of $B \to PP$, VP, VV (charmless)

$B \to D^0\pi^0$ and $\pi^+\pi^0$

Three-body hadronic decays

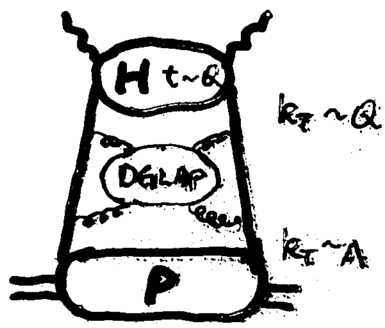
Conclusion

PQCD picture



$\bar{\Lambda} = m_B - m_b$

DIS



Sudakov ⇔ double log   **DGLAP ⇔ single log**

no real gluons during hard decay   has real gluons

⇒ small color dipole is preferred (color singlet)

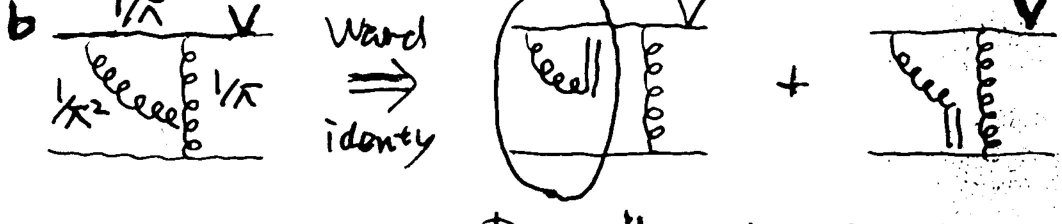
⇒ Sudakov effect (no end-point singularity)

importance of $t^2 \sim \bar{\Lambda} m_B$

- **power behavior of $F^{B\pi}$**

$$F^{B\pi} \propto \frac{f_B f_\pi}{t^2} \quad f_B \sim \frac{\bar{\Lambda}^{3/2}}{m_B^{1/2}} \quad \left(\frac{\bar{\Lambda}}{m_B}\right)^{3/2} \Leftrightarrow \textbf{HQET}$$

- **gauge invariance of Φ_B** (nonlocal matrix element)



Φ_B || Wilson line

- **dynamical enhancement of penguin**

$$C_{4,6}(\bar{\Lambda} m_B) \sim 1.5\, C_{4,6}(m_B)$$

inputs

- $\phi_\pi, \phi_K, \phi_\rho, \phi_{K^*}, \phi_\omega, \phi_\phi, \cdots$ **light meson DA**

known from QCD sum rules

Gaugenbauer ↓

$$\phi_\pi(x) = \frac{f_\pi}{2\sqrt{6}}\, x(1-x)\left[1 + a_2 C_2^{1/2}(1-2x) + a_4 C_4^{1/2}(1-2x)\right]$$

$a_2 = 0.44 \pm 30\%$ $\qquad$ $a_4 = 0.09 \pm 30\%$

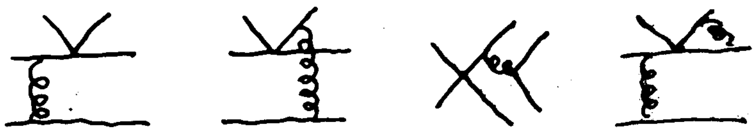
- ϕ_B is unknown **choose quark model**

$$\phi_B(x,b) = \frac{f_B}{2\sqrt{6}} N_B\, x^2(1-x)^2\, e^{-\frac{1}{2}\left(\frac{x m_B}{\omega_B}\right)^2} e^{-\frac{1}{2}(\omega_B b)^2}$$

$\omega_B = 0.40 \pm 0.04$ determined from $F^{B\pi}(0) = 0.30 \pm 0.03$

- $m_0 = \dfrac{m^2_{\pi(K)}}{m_u + m_{d(s)}} = 1.4 \pm 0.4$ GeV

calculable

- **Wilson coefficients C**
- **hard part H**  + ...
- **Sudakov factor S**  + ...

formula

$\qquad\qquad 1/b \to t \qquad\qquad t \to M_W$

$$A \propto \int [dx][db]\, \Phi(x,b)\, S(x,t,b)\, H(x,t)\, C(t)$$

hard scale t determined by vanishing $O(\alpha_s^2)$ corrections

$t = \alpha\, x\, m_B \geq 1/b$ $\qquad$ α : $O(1)$ constant , $1/b$: factorization scale

$x\, m_B$: virtuality of internal particles

Quatity	CLEO	PQCD	BBNS
$\frac{Br(\pi^+\pi^-)}{Br(\pi^\pm K^\mp)}$	0.25 ± 0.10	$0.30 - 0.69$	$0.5 - 1.9$
$\frac{Br(\pi^\pm K^\mp)}{2Br(\pi^0 K^0)}$	0.59 ± 0.27	$0.78 - 1.05$	$0.9 - 1.4$
$\frac{2\ Br(\pi^0 K^\pm)}{Br(\pi^\pm K^0)}$	1.27 ± 0.47	$0.77 - 1.60$	$0.9 - 1.3$
$\frac{\tau(B^+)}{\tau(B^0)} \frac{Br(\pi^\mp K^\pm)}{Br(\pi^\pm K^0)}$	1.00 ± 0.30	$0.70 - 1.45$	$0.6 - 1.0$

Table 13: Ratios of CP-averaged rates in $B \to K\pi, \pi\pi$ decays with $\phi_3 = 80^0$, $R_b = 0.38$. Here we adopted $m_0^\pi = 1.3$ GeV and $m_0^K = 1.7$ GeV.

ponguin is dynamical enhanced.

$Br(\pi K)$ increase

$\frac{Br(\pi\pi)}{Br(\pi K)}$ is lower

chiral enhancement ($m_0 \sim 3$ GeV) in BBNS ?

use $B \to \phi K$ to test PQCD and QCDF (Chen, Keum, Li, Mishima)

$m_0 \to m_\phi \sim 1$ GeV, no chiral enhancement

$Br(B \to \phi K) \sim 10 \times 10^{-6}$, PQCD may be correct

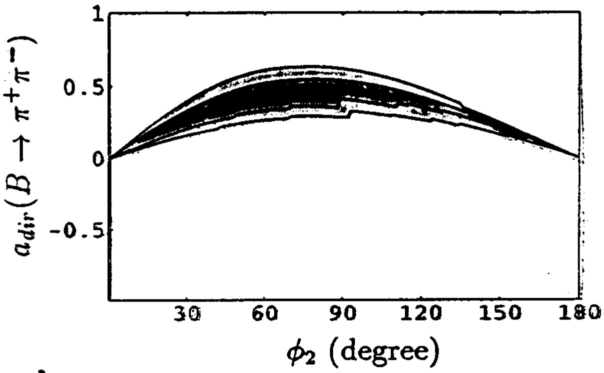
$Br(B \to \phi K) \sim 4 \times 10^{-6}$, QCDF may be correct

(Cheng et al., He et al.)

leading strong phases come from annihilation

we predict $A_{cp}(K\pi) < 0$, $A_{cp}(\pi^+\pi^-) > 0$ $|A_{cp}(K\pi)| < |A_{cp}(\pi\pi)|$

+ subleading (vertex corr. charm penguin)



Belle: $+0.94^{+0.25}_{-0.31} \pm 0.09$

BaBar: $+0.02 \pm 0.29 \pm 0.07$

$|A_{cp}|$ decreases (see Brodsky, Gardner)

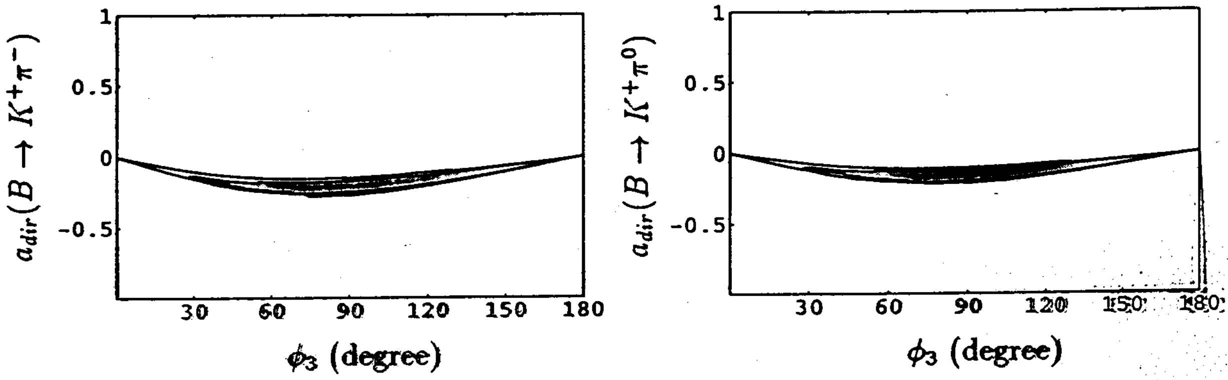
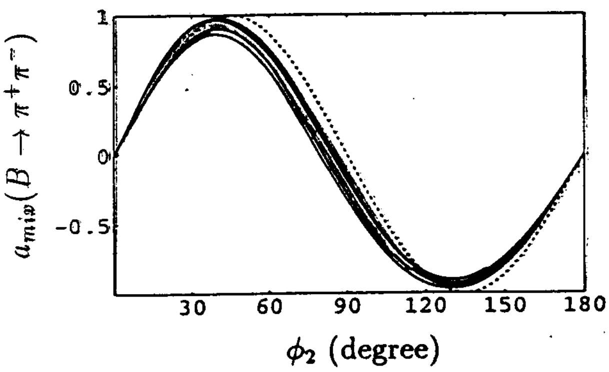


FIG. 3. Direct CP asymmetry for $B \to \pi\pi$, $K\pi$ decay modes. The central value of KM factors [19,20] gives the darker shaded regions, and the lighter shaded regions include the error of KM factors. $a_{dir}(\pi^+\pi^0)$ is almost zero for any ϕ_2. $a_{dir}(K^0\pi^+)$ is almost zero for any ϕ_3. $a_{dir}(K^0\pi^0)$ becomes maximum at $\phi_3 = 90°$, $a_{dir}(K^0\pi^0) = -0.04$.



(Sanda, Ukai)

FIG. 4. Mixing induced CP asymmetry for $B \to \pi^+\pi^-$. The difference from the dotted line($\sin 2\phi_2$) shows sizeable penguin pollution.

BaBar

consistent with PQCD

Mode	Signal yield	$\mathcal{B}$ (10^{-6})
$\pi^+\pi^-$ [6]	41 ± 10	$4.1 \pm 1.0 \pm 0.7$
$K^+\pi^-$	169 ± 17	$16.7 \pm 1.6 \pm 1.3$
K^+K^-	$8.2^{+7.8}_{-6.4}$	< 2.5 (90% C.L.)
$\pi^+\pi^0$	37 ± 14	< 9.6 (90% C.L.)
$K^+\pi^0$	75 ± 14	$10.8^{+2.1}_{-1.9} \pm 1.0$
$K^0\pi^+$	59^{+11}_{-10}	$18.2^{+3.3}_{-3.0} \pm 2.0$
$\overline{K}^0K^+$	$-4.1^{+4.5}_{-3.8}$	< 2.4 (90% C.L.)
$K^0\pi^0$	$17.9^{+6.8}_{-5.8}$	$8.2^{+3.1}_{-2.7} \pm 1.2$
$K^0\overline{K}^0$ [7]	$3.4^{+3.4}_{-2.4}$	< 7.3 (90% C.L.)
ϕK^+ [8]	$31.4^{+6.7}_{-5.9}$	$7.7^{+1.6}_{-1.4} \pm 0.8$
ϕK^0	$10.8^{+4.1}_{-3.3}$	$8.1^{+3.1}_{-2.5} \pm 0.8$
ϕK^{*+}	—	$9.7^{+4.2}_{-3.4} \pm 1.7$
$\phi K^{*+}_{K^+\pi^0}$	$7.1^{+4.3}_{-3.4}$	$12.8^{+7.7}_{-6.1} \pm 3.2$
$\phi K^{*+}_{K^0\pi^+}$	$4.4^{+2.7}_{-2.0}$	$8.0^{+5.0}_{-3.7} \pm 1.3$
ϕK^{*0}	$20.8^{+5.9}_{-5.1}$	$8.7^{+2.5}_{-2.1} \pm 1.1$
$\phi\pi^+$	$0.9^{+2.1}_{-0.9}$	< 1.4 (90% C.L.)
ωK^+ [9]	$6.4^{+5.6}_{-4.4}$	< 4 (90% C.L.)
ωK^0	$8.1^{+4.6}_{-3.6}$	< 13 (90% C.L.)
$\omega\pi^+$	$27.6^{+8.8}_{-7.7}$	$6.6^{+2.1}_{-1.8} \pm 0.7$
$\omega\pi^0$	$-0.9^{+5.0}_{-3.2}$	< 3 (90% C.L.)
ηK^{*0} [10]	20.5 ± 6.0	$19.8^{+6.5}_{-5.6} \pm 1.7$
ηK^{*+}	14.3 ± 6.6	< 33.9 (90% C.L.)
$\eta' K^+$ [9]	—	$70 \pm 8 \pm 5$
$\eta'_{\eta\pi\pi}K^+$	$49.5^{+8.1}_{-7.3}$	63^{+10}_{-9}
$\eta'_{\eta\gamma}K^+$	$87.6^{+13.4}_{-12.5}$	80^{+12}_{-11}
$\eta' K^0$	—	$42^{+13}_{-11} \pm 4$
$\eta'_{\eta\pi\pi}K^0$	$6.3^{+3.3}_{-2.5}$	28^{+15}_{-11}
$\eta'_{\eta\gamma}K^0$	$20.8^{+7.4}_{-6.5}$	61^{+22}_{-19}
$\eta'\pi^+$	—	< 12 (90% C.L.)
$\eta'_{\eta\pi\pi}\pi^+$	$5.7^{+3.8}_{-2.8}$	$7.1^{+4.8}_{-3.5}$
$\eta'_{\eta\gamma}\pi^+$	$-0.9^{+7.8}_{-6.2}$	$-0.7^{+6.7}_{-5.3}$
$a_0^{\pm}\pi^{\mp}$ [12]	$18.1^{+8.7}_{-7.4}$	< 11.5 (90% C.L.)
$\rho^{\pm}\pi^{\mp}$ [13]	89 ± 16	$28.9 \pm 5.4 \pm 4.3$
$\rho^0\pi^0$	6.1 ± 5.8	< 10.6 (90% C.L.)
$K^{*0}\pi^+$ [14]	34.8 ± 7.6	$15.5 \pm 3.4 \pm 1.5$

(Melic)

(Chen)

gluon content ?

(Kou, Sanda)

consistent

(Lu, Yang)

consistent

Mode	A_{CP}
$K^*\gamma$ [3]	$-0.044 \pm 0.076 \pm 0.012$
$K^+\pi^-$ [15]	$-0.07 \pm 0.08 \pm 0.04$
$K^+\pi^0$ [6]	$0.00 \pm 0.18 \pm 0.04$
$K^0\pi^+$ [6]	$-0.21 \pm 0.18 \pm 0.03$
ϕK^+ [8]	$-0.05 \pm 0.20 \pm 0.03$
ϕK^{*+} [8]	$-0.43^{+0.36}_{-0.30} \pm 0.06$
ϕK^{*0} [8]	$0.00 \pm 0.27 \pm 0.03$
$\omega\pi^+$ [16]	$-0.01^{+0.29}_{-0.31} \pm 0.03$
$\eta' K^+$ [16]	$-0.11 \pm 0.11 \pm 0.02$
$\rho^{\pm}\pi^{\mp}$ [13]	$-0.04 \pm 0.18 \pm 0.02$

Belle

Results of $B \to K\pi, \pi\pi$

in PQCD

mode	signal yield	Σ	$\mathcal{B}(10^{-5})$	
• $K^+\pi^-$	218 ± 18	16.4	$2.18 \pm 0.18 \pm 0.15$	1.55 ± 0.30
$K^+\pi^0$	58 ± 11	6.3	$1.25 \pm 0.24 \pm 0.12$	
$K^0\pi^+$	66 ± 10	8.2	$1.88 \pm 0.30 \pm 0.15$	
$K^0\pi^0$	19 ± 8	2.7	$0.77 \pm 0.32 \pm 0.16$	
$\pi^+\pi^-$	51 ± 11	5.4	$0.51 \pm 0.11 \pm 0.04$	
• $\pi^+\pi^0$	36 ± 11	3.5	$0.70 \pm 0.22 \pm 0.08$	0.37 ± 0.15
$\pi^0\pi^0$	12 ± 6	2.2	< 0.56	
K^+K^-	0 ± 2	0	< 0.05	
K^+K^0	0 ± 2	0	< 0.38	
K^0K^0	1 ± 3	0	< 1.3	
• ωK^-			$0.99^{+0.27}_{-0.24} \pm 0.1$	~ 0.32

$$2\mathcal{B}(K^+\pi^0)/\mathcal{B}(K^0\pi^+) = 1.33 \pm 0.33 \pm 0.14$$

$$\mathcal{B}(K^+\pi^-)/2\mathcal{B}(K^0\pi^0) = 1.43 \pm 0.60 \pm 0.28$$

$$\tau_+/\tau_0\mathcal{B}(K^+\pi^-)/\mathcal{B}(K^0\pi^+) = 1.27 \pm 0.23 \pm 0.09 \pm 0.04$$

$$\mathcal{B}(\pi^+\pi^-)/\mathcal{B}(K^+\pi^-) = 0.24 \pm 0.06 \pm 0.02$$

• $$\tau_+/\tau_0\mathcal{B}(\pi^+\pi^-)/2\mathcal{B}(\pi^+\pi^0) = 0.40 \pm 0.15 \pm 0.05 \pm 0.01$$

$$\tau_+/\tau_0\mathcal{B}(\pi^0\pi^0)/\mathcal{B}(\pi^+\pi^0) < 0.77 \ (90\% \text{ C.L.})$$

mode	N($\bar{B}$)	N(B)	$\mathcal{A}_{cp}$	90% C.L.	
$K^+\pi^-$	103 ± 12	115 ± 14	$-0.06 \pm 0.08 \pm 0.01$	-0.20:0.09	
$K^+\pi^0$	28 ± 8	30 ± 8	$-0.04 \pm 0.19 \pm 0.03$	-0.39:0.30	
• $K_S^0\pi^+$	49 ± 8	18 ± 6	$0.46 \pm 0.15 \pm 0.02$	0.18:0.73	~ 0
$\pi^+\pi^0$	24 ± 8	13 ± 7	$0.31 \pm 0.31 \pm 0.05$	-0.25:0.89	

Preliminary

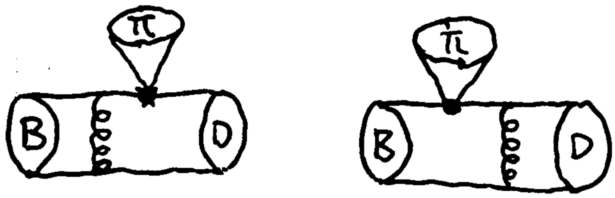
- No clear evidence for partial rate asymmetries

(Kurimoto, Li, Lu)

$B \to D\pi$ ($|a_2|/a_1$)

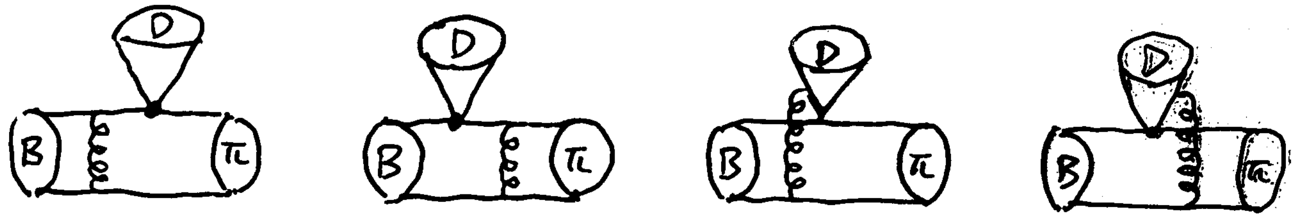
$$\phi_D(x) = \frac{f_D}{2\sqrt{6}} x(1-x)[1+0.3(1-2x)]$$

a_1:



dominate

a_2:

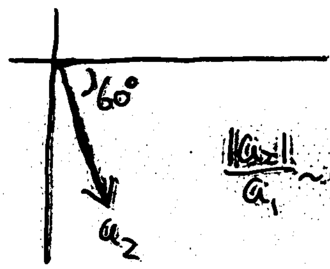


small Wilson coeff. no soft cancellation

$\mathcal{B}(B^- \to D^0\pi^-) \propto |a_1+a_2|^2 \sim 1.5$

$\mathcal{B}(B^0 \to D^+\pi^-) \propto |a_1|^2 \sim 1$

$\mathcal{B}(B^0 \to D^0\pi^0) \propto |a_2|^2/2 \sim 0.13/2$



$\frac{|a_2|}{a_1} \sim 0.36$

$$\begin{array}{ccccc} & B\to D\pi & & B\to\pi\pi \\ \text{fact : nonfact} = & 1 : \frac{m_D}{m_B} & \xrightarrow{m_D \to m_\pi} & 1 : \frac{\bar{\Lambda}}{m_B} \\ & \| & & \\ & 0.3 & & \end{array}$$

	PQCD (10^{-3})	Exp (10^{-3})	
$B(D^0\pi^-)$	~4.8	5.3 ± 0.5	
$B(D^+\pi^-)$	~3.0	3.0 ± 0.4	
$B(D^0\pi^0)$	~0.2 (preliminary)	0.3 ± 0.1	(Belle)
		0.27 ± 0.05	(CLEO)

$$r = \frac{B(\pi^+\pi^-)}{2B(\pi^+\pi^0)} \sim 0.4 \quad \text{(Belle)}$$

is difficult to understand

a_2 is small in $B \to \pi\pi$

the Wilson coefficient $C_1 + \frac{C_2}{N_c}$ vanishes

nonfactorizable contributions cancel

PQCD prefers $r = \frac{|a_1|^2}{2|a_1+a_2|^2/2} \lesssim 1$

if data persist, PQCD can not explain r

$\Rightarrow$ something new

final state interaction can lower r (Hou et al)

but the upper bound of $B(B\to K^+K^-)$ puts a strong

constraint on FSI

if Belle's bound is taken, $B(B\to K^+K^-) < 5\times 10^{-7}$
$\lesssim 1\times 10^{-7}$ in PQCD

FSI is not sufficient to explain r

BaBar's result ?

Three-body hadronic decays

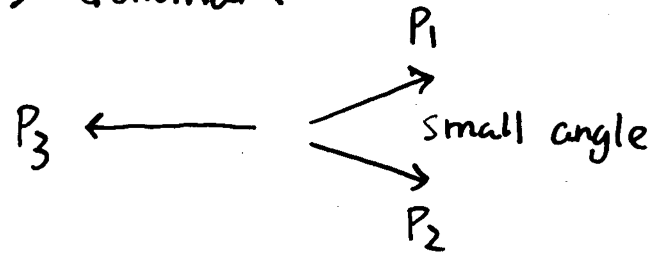
- **kinematics of $B \to P_1 P_2 P_3$**

all P's carry $O(m_B)$ momentum

$\Rightarrow$ power suppressed

one carries $O(\bar{\Lambda})$, two carry $O(m_B)$

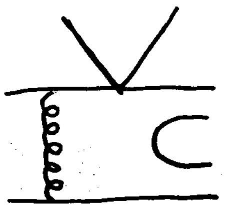
$\Rightarrow$ dominant



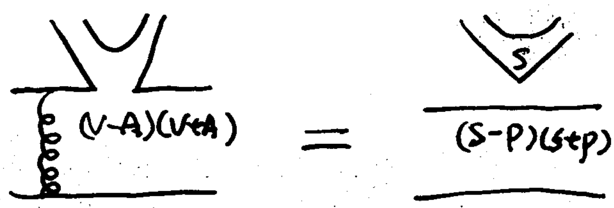
invariant mass of $P_1 + P_2$

$\sim O(\bar{\Lambda} m_B)$

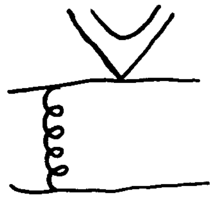
- **4 topologies**



$\mathrm{I} \propto \frac{1}{\bar{\Lambda} m_B} \frac{1}{\bar{\Lambda} m_B}$

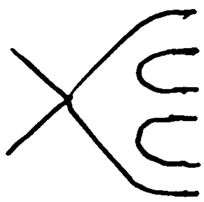


$\mathrm{II\,E} \propto \frac{1}{\bar{\Lambda} m_B} \frac{1}{\bar{\Lambda} m_B} \frac{m_0}{m_B}$



helicity suppression ↓

$\mathrm{II\,A} \propto \frac{1}{\bar{\Lambda} m_B} \frac{1}{\bar{\Lambda} m_B} \frac{\bar{\Lambda}}{m_B}$



$\mathrm{III} \propto \frac{1}{\bar{\Lambda} m_B} \frac{1}{m_B^2}$

$\mathrm{I} : \mathrm{II\,E} : \mathrm{II\,A} : \mathrm{III} = 1 : \frac{m_0}{m_B} : \frac{\bar{\Lambda}}{m_B} : \frac{\bar{\Lambda}}{m_B}$

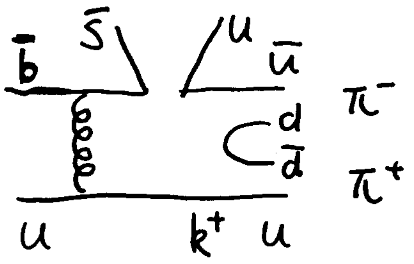
I dominates in the heavy quark limit.

IIE may be important for physical value of m_B

2π distribution amplitude (DA)

concentrate on leading topology I,

still too many diagrams $2\times 2\times 8 = 32$



2π system has the invariant mass $w^2 \sim O(\bar{\Lambda} m_B)$

$w^2 = (P_1+P_2)^2 \equiv P^2$

P_K in minus direction $(-\hat{z})$, 2π mainly in plus dir.

$P^+ \sim O(m_B)$, $\quad P^- \sim O(\bar{\Lambda})$, $\quad |\vec{P}_T| = |\vec{P}_{1T}| = |\vec{P}_{2T}| \sim O(\sqrt{\bar{\Lambda} m_B})$

$P^+ \gg |P_T| \gg P^-$ $\Leftrightarrow$ similar to the collinear configuration

$B \to \pi$ at fast recoil, $P_\pi^+ \sim O(m_B)$, $P_\pi^- \sim O(\frac{\bar{\Lambda}^2}{m_B})$, $|P_{\pi T}| \sim O(\bar{\Lambda})$

$P_\pi^2 \sim O(\bar{\Lambda}^2)$, $\quad P_\pi^+ \gg |\vec{P}_{\pi T}| \gg P_\pi^-$ $\Rightarrow$ pion DA

hint : can introduce 2π DA $\qquad$ twist-3 $\begin{cases} \sigma^{\mu\nu} \\ I \end{cases}$

$$\Phi_{2\pi}(z,\zeta,w^2) = \int \frac{dy^-}{2\pi} e^{-izP^+y^-} \langle \pi^+(P_1)\pi^-(P_2) | \bar{q}(y^-)\gamma^+ q(0) | 0 \rangle$$

parton momentum fraction $z = \frac{k^+}{P^+}$, $\quad \zeta = \frac{P_1^+}{P^+}$ (pion mtm fractio

all other kinematic variables

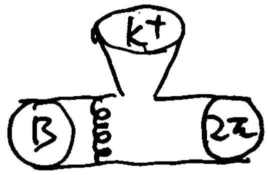
$$P^- = \frac{w^2}{2P^+}, \quad P_1^- = \frac{(1-\zeta)w^2}{2P^+}, \quad P_T^2 = \zeta(1-\zeta)w^2$$

$$P_2^+ = (1-\zeta)P^+, \quad P_2^- = \frac{\zeta w^2}{2P^+}$$

All four topologies can be calculated.

End-point singularity

with 2π DA, 3-body decays reduce to 2-body decays.



same number of diagrams

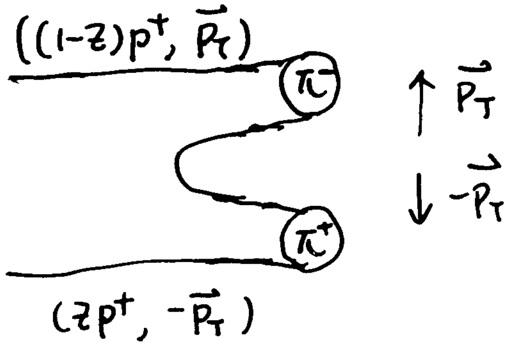
also the same end-point singularity

$$\int dx\,dz \frac{\phi_B(x)\,\Phi_{2\pi}(z,\zeta,w^2)}{x z^2 m_B^2} \quad \text{diverges like} \quad \int_0^1 \frac{dz}{z}$$

in 2-body decays, introduce parton k_T and Sudakov suppression (k_T distribution)

$$\frac{1}{x z^2 m_B^2} \rightarrow \frac{S(k_T)}{(xz m_B^2 + (k_{\pi T} - k_{3T})^2)(\cdots)} \quad \text{size of pion} \Leftrightarrow k_T^2$$

in 3-body decays, the invariant mass of the 2π system provides a natural smearing



$$\frac{1}{x z^2 m_B^4} \rightarrow \frac{1}{(x z m_B^2 + P_T^2)(z m_B^2 + P_T^2)}$$

size of 2π system $\Leftrightarrow$ $P_T^2 = \zeta(1-\zeta)w^2$

$$\Gamma \propto \int d\eta\, d\zeta \ \ln \zeta(1-\zeta)\eta \quad \text{finite !} \quad \eta = \frac{w^2}{m_B^2}$$

no end-point singularity in the leading contribution to 3-body decays

formalism applicable to the whole kinematic range

$0 < w^2 < m_B^2$

Dalitz plot (Belle)

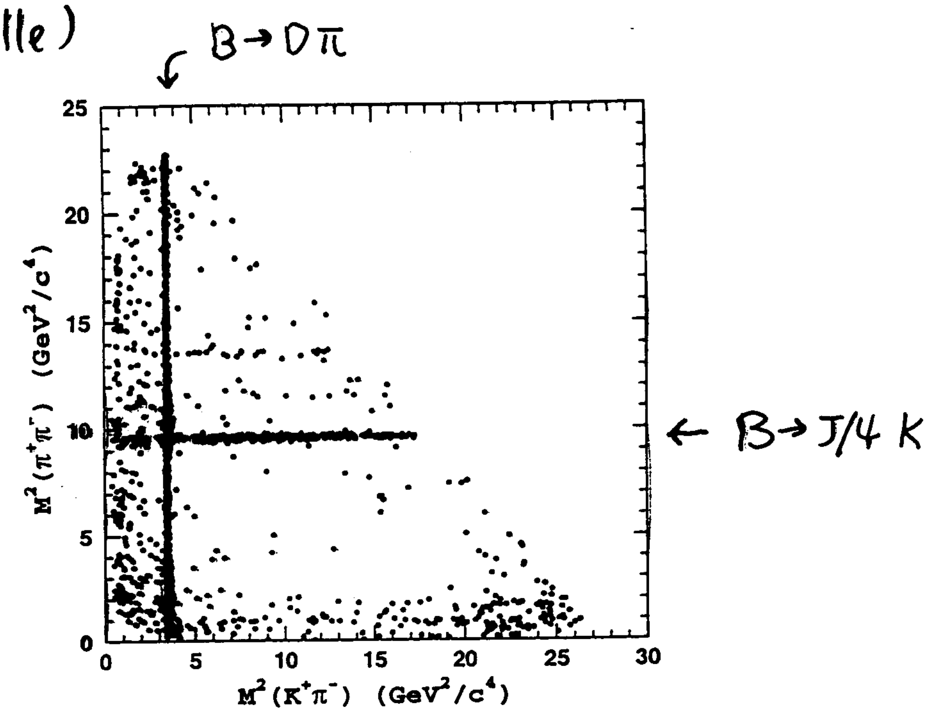


FIG. 1: The Dalitz plot for $B^+ \to K^+\pi^+\pi^-$ candidates from the B signal region.

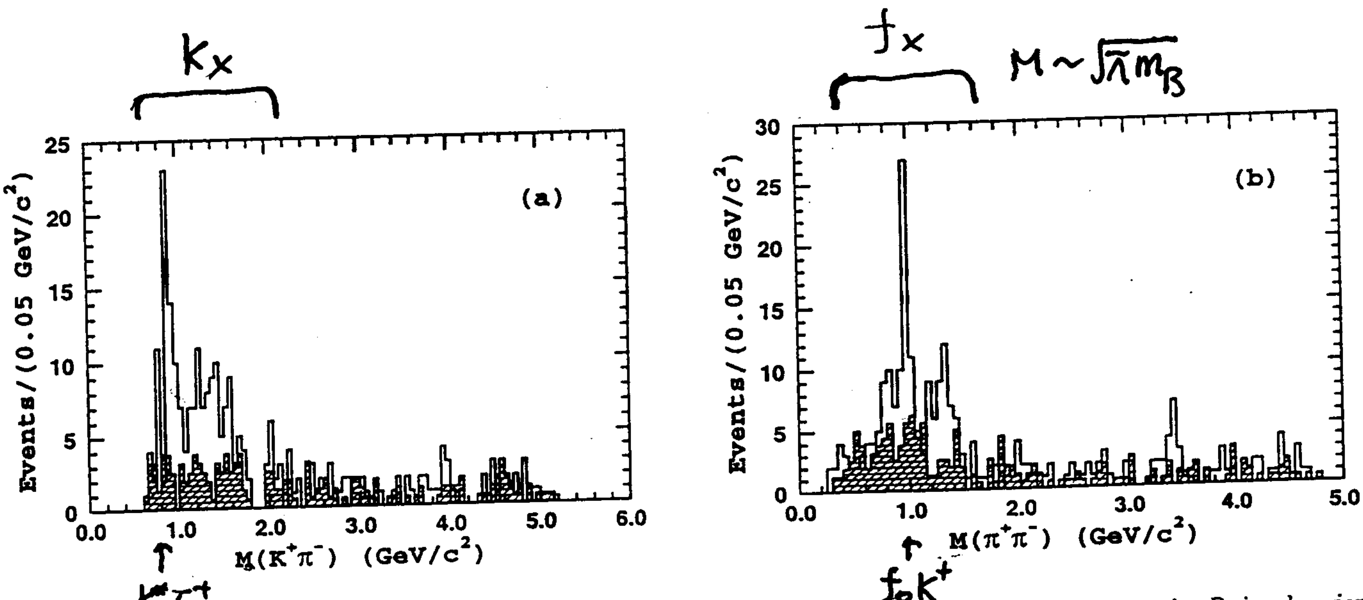


FIG. 3: The (a) $K^+\pi^-$ and (b) $\pi^+\pi^-$ invariant mass spectra for selected $B^+ \to K^+\pi^+\pi^-$ candidates in the B signal region (open histograms) and for background events in the ΔE sidebands (hatched histograms).

nonresonant contributions strongly overlap with the resonant $K_X\pi^+$ and $f_X K^+$ channels.

they have similar mass spectra

the rapid decrease of nonresonant contributions at large $M(K^+\pi^-, \pi^+\pi^-)$ is due to $1/m_B$ suppression

no clear evidence for $B \to K^+\sigma$

Preliminary Results (Brodsky, Chen, Li)

Belle: $Br(B^+ \to K^+ \pi^+ \pi^-) = (55.6 \pm 5.8 \pm 7.7) \times 10^{-6}$

$Br(B^+ \to K^+ K^+ K^-) = (35.3 \pm 3.7 \pm 4.5) \times 10^{-6}$

resonant through

$B^+ \to K_S^* \pi^+ \sim 12.9^{+2.8 +1.4 +2.3}_{-2.6 -1.4 -4.5}$

$B^+ \to K^+ f_0 \sim 9.6^{+2.5 +1.5 +3.4}_{-2.3 -1.5 -0.8}$

$B^+ \to K_X \pi^+ \sim 14.5^{+3.5 +1.8 +3.3}_{-3.3 -1.8 -6.5}$

$B^+ \to K^+ f_X \quad 11.1^{+3.4 +1.4 +7.2}_{-3.1 -1.4 -2.9}$

nonresonant contribution $3 \sim 10$

Dalitz plot of $B^+ \to K^+ K^+ K^-$ indicates stronger nonresonant contribution

Conclusion

- leading PQCD picture : $\Phi_B \otimes H \otimes \phi_{h_1} \otimes \phi_{h_2}$
- PQCD has the correct power behavior for form factors
- k_T factorization is gauge invariant (to appear)
- PQCD can explain most of data of Br and $C\!\!\!/ P\!\!\!/$
  penguin dynamical enhancement and annihilation
  play important roles
- PQCD predicts helicity amplitudes and phases among
  them in $B \to VV$ unambigiously ($B \to \phi K^*$ by Chen, Keum, Li)
- PQCD can explain $B \to D\pi$, $a_2/a_1 \sim 0.4\, e^{-i60^\circ}$
- $\dfrac{B(\pi^+\pi^-)}{2B(\pi^+\pi^0)}$ is tough, which violates power counting rules
- PQCD can be extended to three-body decays
- the formalism is simpler and has no end-point
  singularity
- nonresonant contribution can be calculated by
  introducing 2-meson distribution amplitudes
- need to investigate subleading contributions
  (Mishima, Sanda, to appear)