Hadronic B decays and CPV

Ying Li

Yantai University

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Motivation

- Why study hadronic B decays
- CP Violation
- 2-body B decays
- 3-body B decays
- Summary

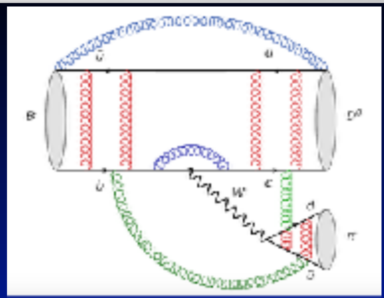
Why study B decays

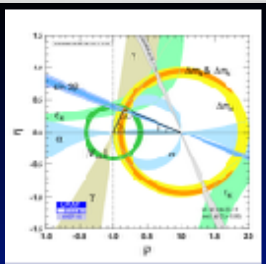
Baryon Asymmetry in the Universe:
A violation of the CP symmetry - which causes matter and anti-matter to evolve differently with time - seems to be necessary to explain the existence of matter in the Universe.
CP violation has so far only been found in hadron decays, which are experimentally investigated at LHCb and NA62 (CERN), SuperBelle (Japan),…

Indirect Search for BSM Physics:
To find hints for Physics beyond the Standard Model we can either use brute force (= higher energies) or more subtle strategies like high precision measurements.
New contributions to an observable f are identified via:

$$f^{\mathrm{SM}} + f^{\mathrm{NP}} = f^{\mathrm{Exp}}$$

Understanding QCD:
Hadron decays are strongly affected by QCD (strong interactions) effects, which tend to overshadow the interesting fundamental decay dynamics. Theory tools like effective theories, Heavy Quark Expansion, HQET, SCET ,…enable a control over QCD-effects and they are used in other fields like Collider Physics, Higgs Physics, DM searches…





Standard Model parameters:
Hadron decays depend strongly on Standard Model parameters like quark masses and CKM couplings (which are the only known source of CP violation in the SM). A precise knowledge of these parameters is needed for all branches of particle physics.

CP Violation and CKM

Mass Eigenstates $\neq$ Weak Eigenstates $\Rightarrow$ Quark Mixing

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

CKM Matrix

Complex matrix described by 4 independent real parameters

Wolfenstein parametrization:

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

phase

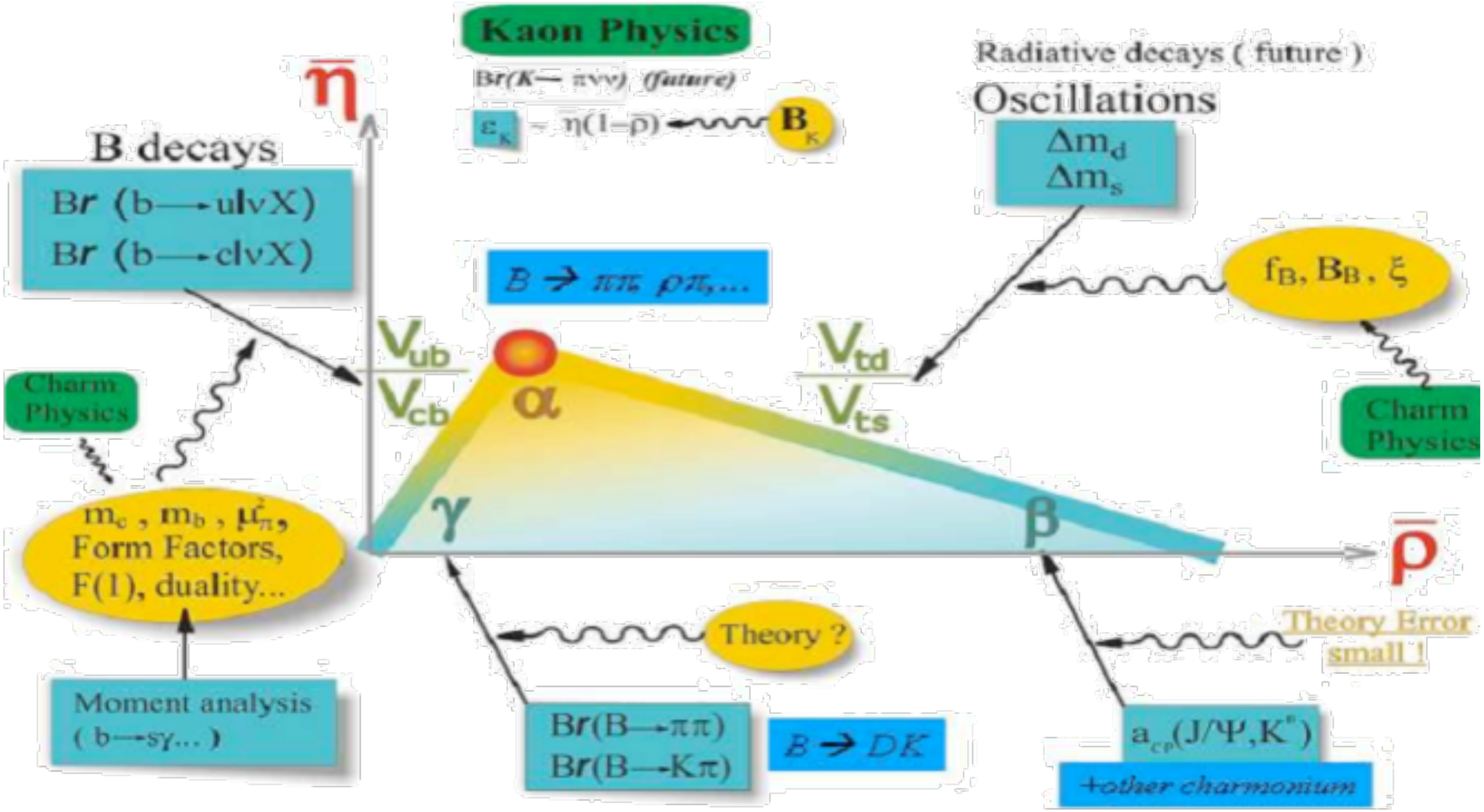
CP Violation:

$$J = \mathrm{Im}\left(V_{ik} V_{jk}^{*} V_{j\ell} V_{i\ell}^{*} \right) \neq 0$$

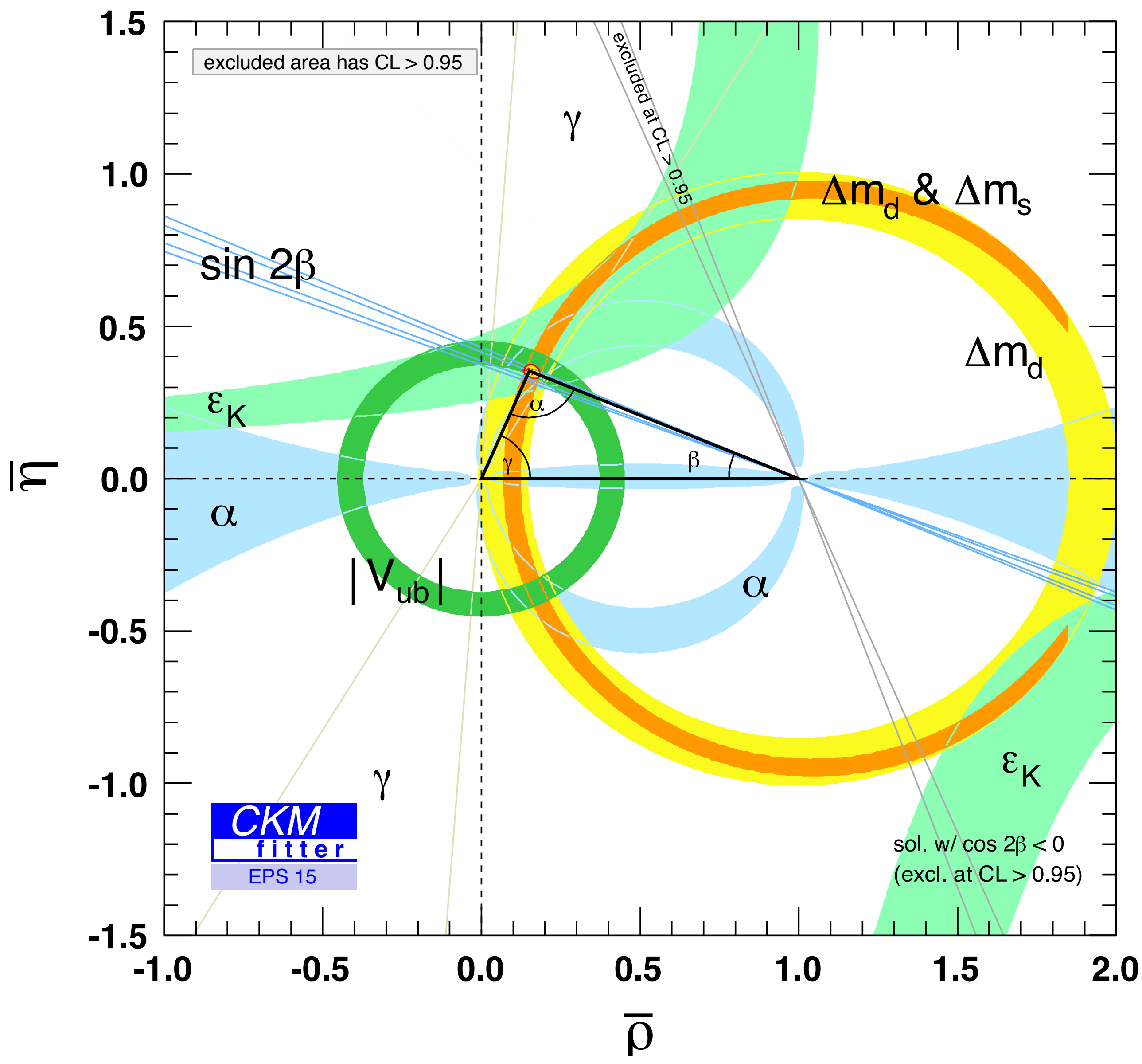
$$J \approx A^2\lambda^6\eta$$

$\eta = 0 \Rightarrow$ no CPV from SM

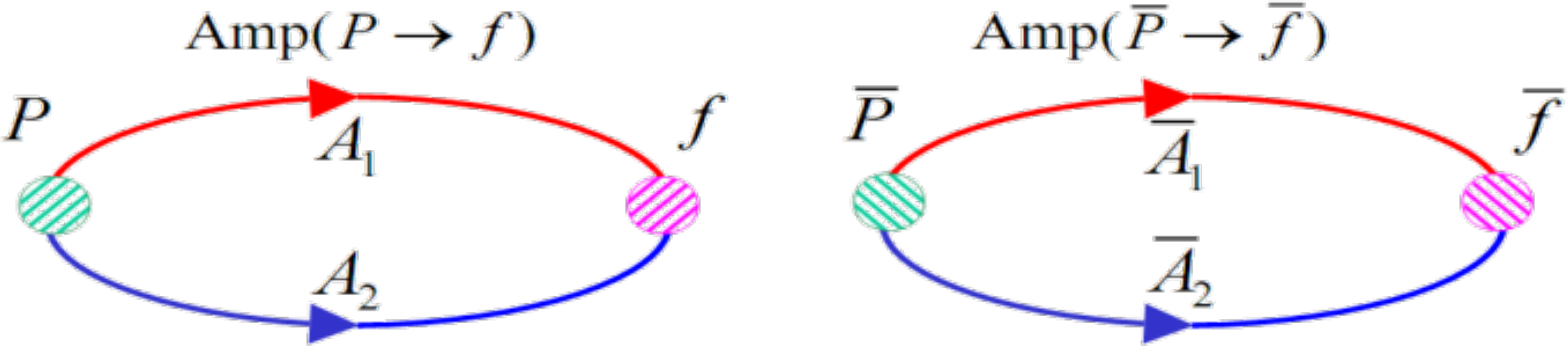
CP Violation and CKM



CP Violation and CKM

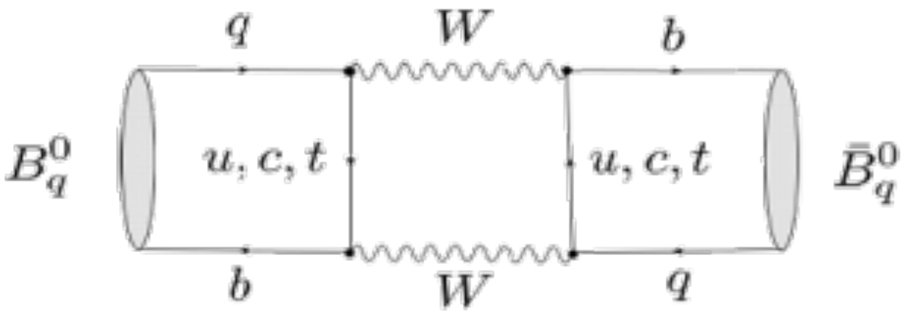


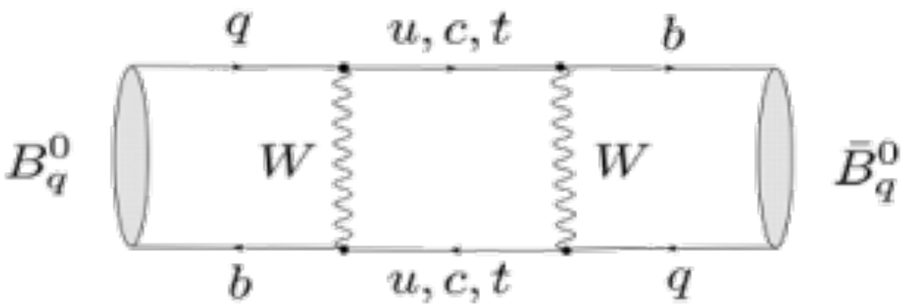
Direction CP Violation



$$A_{CP}^{dir} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{2r \sin \Delta\phi \sin \Delta\delta}{1 + r^2 + 2r \cos \Delta\phi \cos \Delta\delta}$$

CP Violation in Oscillation

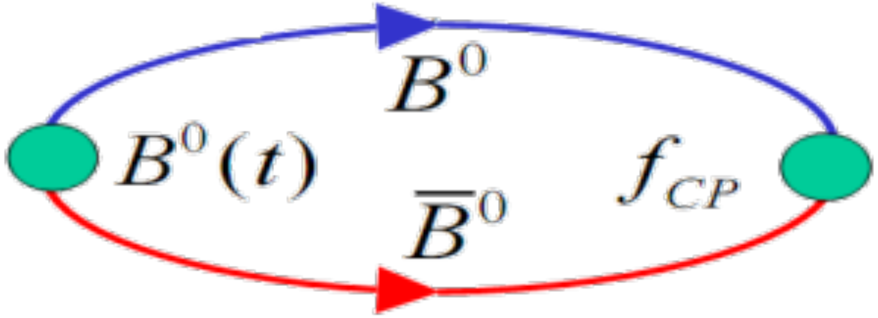


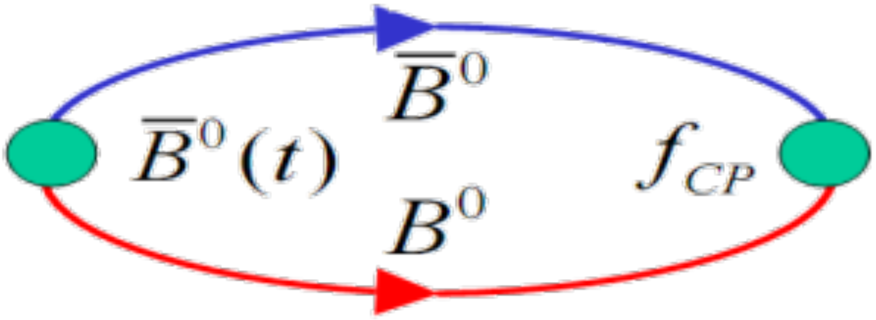


$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}.$$

$$\mathcal{A}_{CP} = \frac{1 - |p/q|^4}{1 + |p/q|^4}$$

Mixing CP Violation





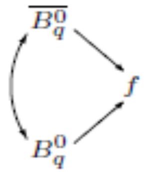
$$\frac{\Gamma(B_q^0(t)\to f)-\Gamma(\overline{B_q^0}(t)\to \overline{f})}{\Gamma(B_q^0(t)\to f)+\Gamma(\overline{B_q^0}(t)\to \overline{f})} = \left[\frac{\mathcal{A}_{\rm CP}^{\rm dir}\cos(\Delta M_q t)+\mathcal{A}_{\rm CP}^{\rm mix}\sin(\Delta M_q t)}{\cosh(\Delta\Gamma_q t/2)-\mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_q t/2)}\right]$$

$$\mathcal{A}_{\rm CP}^{\rm dir} = \frac{1-|\xi_f^{(q)}|^2}{1+|\xi_f^{(q)}|^2} = \underbrace{\frac{|A(B_q^0\to f)|^2-|A(\overline{B_q^0}\to \overline{f})|^2}{|A(B_q^0\to f)|^2+|A(\overline{B_q^0}\to \overline{f})|^2}}_{\text{“direct” CP violation}}$$

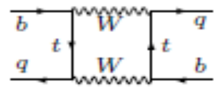
$$\mathcal{A}_{\rm CP}^{\rm mix} = \frac{2\,\mathrm{Im}\,\xi_f^{(q)}}{1+|\xi_f^{(q)}|^2} \quad \Rightarrow \quad \boxed{\text{“mixing-induced” CP violation}}$$

$$\mathcal{A}_{\Delta\Gamma} = \frac{2\,\mathrm{Re}\,\xi_f^{(q)}}{1+|\xi_f^{(q)}|^2} \quad \Rightarrow \quad \boxed{\text{not independent from } \mathcal{A}_{\rm CP}^{\rm dir} \text{ and } \mathcal{A}_{\rm CP}^{\rm mix}}$$

$$\xi_f^{(q)} \sim e^{-i\phi_q}\left[\frac{A(\overline{B_q^0}\to f)}{A(B_q^0\to f)}\right]$$



$$\phi_q \overset{\rm SM}{=} 2\arg(V_{tq}^* V_{tb}) = \begin{cases} +2\beta & (q=d) \\ -2\delta\gamma\ (=-2\lambda^2\eta) & (q=s) \end{cases}$$



Hierarchy of Scales

$$\underbrace{\Lambda_{\rm NP} \sim 10^{(0\ldots?)}\,\text{TeV} \gg \Lambda_{\rm EW} \sim 10^{-1}\,\text{TeV}}_{\text{(very) short distances}} \ggg \underbrace{\Lambda_{\rm QCD} \sim 10^{-4}\,\text{TeV}}_{\text{long distances}}$$

- Powerful theoretical concepts/techniques:

  $\rightarrow$ "Effective Field Theories"

  – Heavy degrees of freedom (NP particles, top, Z, W) are "integrated out" from appearing explicitly: $\rightarrow$ *short-distance loop functions.*

  – Calculation of *perturbative QCD corrections*.

  – *Renormalization group* allows the summation of large $\log(\mu_{\rm SD}/\mu_{\rm LD})$.

- Applied to the SM and various NP scenarios, such as the following:

  – MSSM, UED, WED, LH, LHT, Z' models, ...

Low-energy Effective Hamiltonian

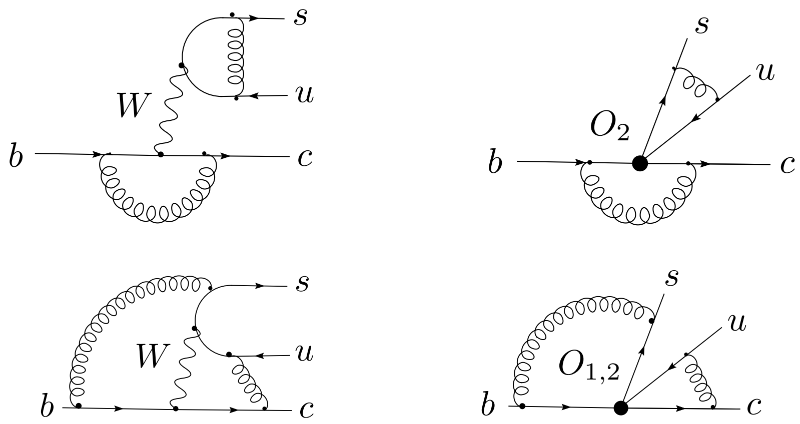
- Separation of short-distance from long-distance contributions (OPE):

$$\langle \bar{f}|\mathcal{H}_{\text{eff}}|\bar{B}\rangle = \frac{G_{\text{F}}}{\sqrt{2}} \sum_j \lambda^j_{\text{CKM}} \sum_k C_k(\mu)\, \langle \bar{f}|Q^j_k(\mu)|\bar{B}\rangle$$

[G_{F}: Fermi's constant, λ^j_{CKM}: CKM factors, μ: renormalization scale]

- Short-distance physics: [Buras *et al.*; Martinelli *et al.* ('90s); ...]

  $\rightarrow$ Wilson coefficients $C_k(\mu)$ $\rightarrow$ *perturbative* quantities $\rightarrow$ known!

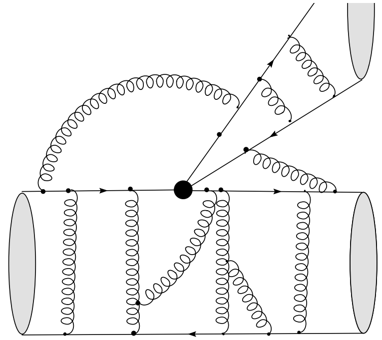


- Long-distance physics:

  $\rightarrow$ matrix elements $\langle \bar{f}|Q^j_k(\mu)|\bar{B}\rangle$ $\rightarrow$ *non-perturbative* $\rightarrow$ "unknown" !?

Theoretical Framework of Hadronic B decays

$$|A_j|e^{i\delta_j} \propto \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \boxed{\langle \overline{f}|Q_k^j(\mu)|\overline{B}\rangle}$$



- QCD factorization (QCDF):

  Beneke, Buchalla, Neubert & Sachrajda (99–01); Beneke & Jäger (05); ... Bell, Bobeth, ..

- Perturbative Hard-Scattering (PQCD) Approach:

  Li & Yu ('95); Cheng, Li & Yang ('99); Keum, Li & Sanda ('00); ...

- Soft Collinear Effective Theory (SCET):

  Bauer, Pirjol & Stewart (2001); Bauer, Grinstein, Pirjol & Stewart (2003); ...

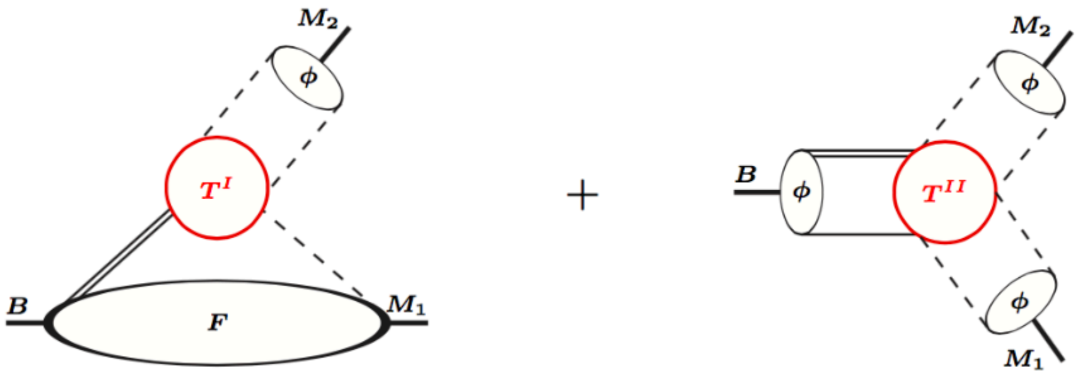
- QCD sum rules:

  Khodjamirian (2001); Khodjamirian, Mannel & Melic (2003); ...

$\Rightarrow$ Lots of (technical) progress, still a theoretical challenge

QCD Factorization

$$\langle M_1 M_2|\mathcal{O}|B\rangle = F^{BM_1}\int du\, T^I(u)\phi_{M_2}(u) + \int d\omega\, du\, dv\, T^{II}(\omega,u,v)\phi_B(\omega)\phi_{M_1}(u)\phi_{M_2}(v)$$



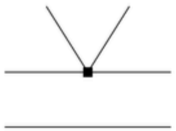
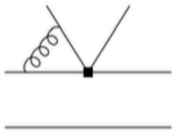
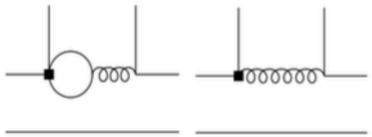
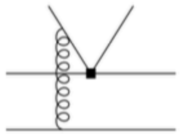
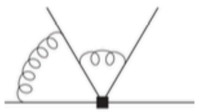
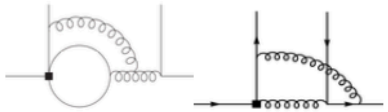
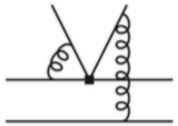
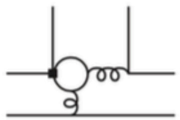
- Vertex corrections: $T^I(u) = 1 + \mathcal{O}(\alpha_s)$
- Spectator scattering: $T^{II}(\omega, u, v) = \mathcal{O}(\alpha_s)$ – (power suppressed if M_1 is heavy)
- Strong phases are perturbative $[\mathcal{O}(\alpha_s)]$ or power suppressed $[\mathcal{O}(\Lambda/m_b)]$.

QCD Factorization

Two hard-scattering kernels for each operator insertion: T^{I} (vertex), T^{II} (spectator)

$$\langle M_1 M_2 | \mathcal{O}_i | B \rangle \simeq F^{BM_1} T_i^{I} \otimes \phi_{M_2} + T_i^{II} \otimes \phi_B \otimes \phi_{M_1} \otimes \phi_{M_2}$$

and two classes of topological amplitudes: "Tree", "Penguin".

	T^{I}, tree	T^{I}, penguin	T^{II}, tree	T^{II}, penguin
LO: $\mathcal{O}(1)$				
NLO: $\mathcal{O}(\alpha_s)$ BBNS '99-'04				
NNLO: $\mathcal{O}(\alpha_s^2)$	 Bell '07,'09 Beneke, Huber, Li '09	 Kim, Yoon '11, Bell Beneke, Huber, Li '15	 Beneke, Jager '05 Kivel '06, Pilipp '07	 Beneke, Jager '06 Jain, Rothstein, Stewart '07

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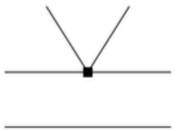
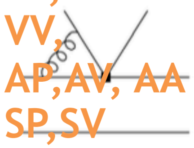
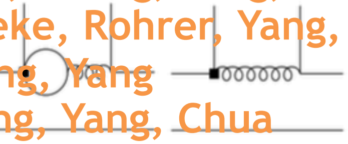
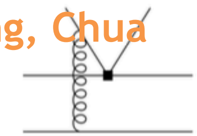
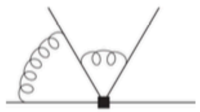
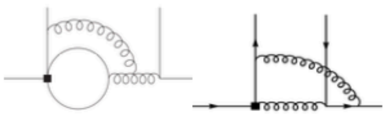
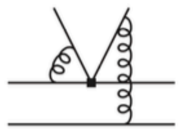
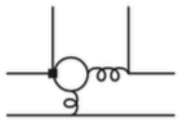
LO: $\mathcal{O}(1)$				
NLO: $\mathcal{O}(\alpha_s)$ BBNS '99-'04	 PP, PV VV, AP,AV, AA SP,SV TP, TV	 BBNS, Cheng, Yang, Chua Beneke, Rohrer, Yang, Cheng, Chua Cheng, Yang Cheng, Yang, Chua Cheng, Yang		
NNLO: $\mathcal{O}(\alpha_s^2)$	 Bell '07,'09 Beneke, Huber, Li '09	 Kim, Yoon '11, Bell Beneke, Huber, Li '15	 Beneke, Jager '05 Kivel '06, Pilipp '07	 Beneke, Jager '06 Jain, Rothstein, Stewart '07

QCD Factorization

$$T \equiv a_1(\pi\pi) = 1.009 + [0.023 + 0.010i]_{\rm NLO} + [0.026 + 0.028i]_{\rm NNLO}$$
$$- \left[\frac{r_{\rm sp}}{0.485}\right] \left\{[0.015]_{\rm LOsp} + [0.037 + 0.029i]_{\rm NLOsp} + [0.009]_{\rm tw3}\right\}$$
$$= 1.00 + 0.01i \quad \rightarrow \quad 0.93 - 0.02i \quad (\text{if } 2 \times r_{\rm sp})$$

$$C \equiv a_2(\pi\pi) = 0.220 - [0.179 + 0.077i]_{\rm NLO} - [0.031 + 0.050i]_{\rm NNLO}$$
$$+ \left[\frac{r_{\rm sp}}{0.485}\right] \left\{[0.123]_{\rm LOsp} + [0.053 + 0.054i]_{\rm NLOsp} + [0.072]_{\rm tw3}\right\}$$
$$= 0.26 - 0.07i \quad \rightarrow \quad 0.51 - 0.02i \quad (\text{if } 2 \times r_{\rm sp})$$

	Theory I	Theory II	Experiment
$B^- \to \pi^- \pi^0$	$5.43\,^{+0.06}_{-0.06}\,^{+1.45}_{-0.84}$ (⋆)	$5.82\,^{+0.07}_{-0.06}\,^{+1.42}_{-1.35}$ (⋆)	$5.59^{+0.41}_{-0.40}$
$\bar{B}^0_d \to \pi^+ \pi^-$	$7.37\,^{+0.86}_{-0.69}\,^{+1.22}_{-0.97}$ (⋆)	$5.70\,^{+0.70}_{-0.55}\,^{+1.16}_{-0.97}$ (⋆)	5.16 ± 0.22
$\bar{B}^0_d \to \pi^0 \pi^0$	$0.33\,^{+0.11}_{-0.08}\,^{+0.42}_{-0.17}$	$0.63\,^{+0.12}_{-0.10}\,^{+0.64}_{-0.42}$	1.55 ± 0.19
		BELLE CKM 14:	0.90 ± 0.16

QCD Factorization

$$a_4^u(\pi\bar{K})/10^{-2} = -2.87 - [0.09+0.09i]_{V_1} + [0.49-1.32i]_{P_1} - [0.32+0.71i]_{P_2} + \left[\frac{r_{sp}}{0.434}\right]\left\{[0.13]_{LO} + [0.14+0.12i]_{HV} - [0.01-0.05i]_{HP} + [0.07]_{tw3}\right\}$$
$$= (-2.46^{+0.49}_{-0.24}) + (-1.94^{+0.32}_{-0.20})i$$

$$r_{sp} = \frac{9 f_{M_1} \hat{f}_B}{m_b f_+^{B\pi}(0)\lambda_B}$$

$$a_4^c(\pi\bar{K})/10^{-2} = -2.87 - [0.09+0.09i]_{V_1} + [0.05-0.62i]_{P_1} - [0.77+0.50i]_{P_2} + \left[\frac{r_{sp}}{0.434}\right]\left\{[0.13]_{LO} + [0.14+0.12i]_{HV} + [0.01+0.03i]_{HP} + [0.07]_{tw3}\right\}$$
$$= (-3.34^{+0.43}_{-0.27}) + (-1.05^{+0.45}_{-0.36})i$$

f	NLO	NNLO	NNLO + LD	Exp
$\pi^-\bar{K}^0$	$0.71^{+0.13+0.21}_{-0.14-0.19}$	$0.77^{+0.14+0.23}_{-0.15-0.22}$	$0.10^{+0.02+1.24}_{-0.02-0.27}$	-1.7 ± 1.6
π^0K^-	$9.42^{+1.77+1.87}_{-1.76-1.88}$	$10.18^{+1.91+2.03}_{-1.90-2.62}$	$-1.17^{+0.22+20.00}_{-0.22-\ 6.62}$	4.0 ± 2.1
π^+K^-	$7.25^{+1.36+2.13}_{-1.36-2.58}$	$8.08^{+1.52+2.52}_{-1.51-2.65}$	$-3.23^{+0.61+19.17}_{-0.61-\ 3.36}$	-8.2 ± 0.6
$\pi^0\bar{K}^0$	$-4.27^{+0.83+1.48}_{-0.77-2.23}$	$-4.33^{+0.84+3.29}_{-0.78-2.32}$	$-1.41^{+0.27+5.54}_{-0.25-6.10}$	1 ± 10
$\delta(\pi\bar{K})$	$2.17^{+0.40+1.39}_{-0.40-0.74}$	$2.10^{+0.39+1.40}_{-0.39-2.86}$	$2.07^{+0.39+2.76}_{-0.39-4.55}$	12.2 ± 2.2
$\Delta(\pi\bar{K})$	$-1.15^{+0.21+0.55}_{-0.22-0.84}$	$-0.88^{+0.16+1.31}_{-0.17-0.91}$	$-0.48^{+0.09+1.09}_{-0.09-1.15}$	-14 ± 11

QCD Factorization

Main limitation of QCDF approach, e.g. weak annihilation

$$\sim \int d\omega\, du\, dv\; T(\omega, u, v)\; \phi_B(\omega)\; \phi_{M_1}(v)\; \phi_{M_2}(u) \quad ?$$

- convolutions diverge at endpoints $\Rightarrow$ non-factorisation in SCET-2
- currently modelled with arbitrary soft rescattering phase

Pure annihilation decays

$$10^6\,\mathrm{Br}(B_d \to K^+K^-) = 0.13 \pm 0.05 \qquad (\Delta D = 1, \text{exchange topology})$$

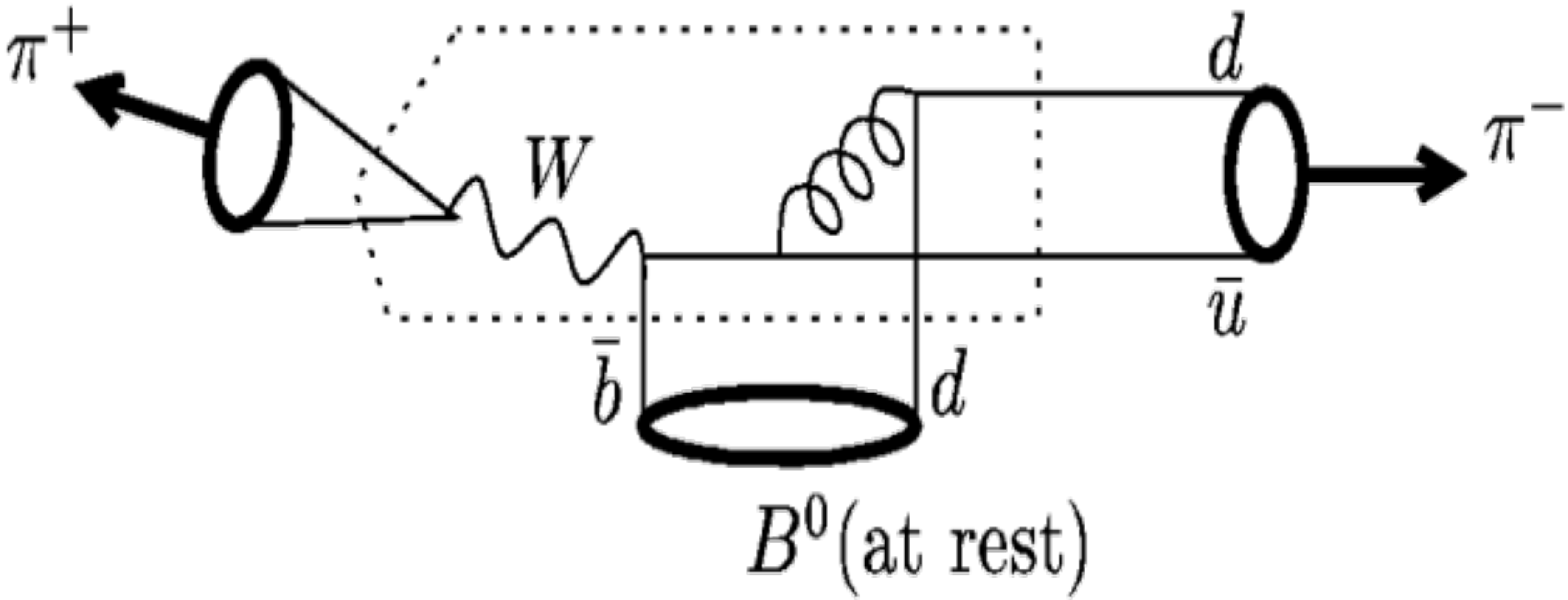
$$10^6\,\mathrm{Br}(B_s \to \pi^+\pi^-) = 0.76 \pm 0.13 \qquad (\Delta S = 1, \text{penguin annihilation})$$

$\Rightarrow$ extract weak annihilation amplitudes from data [Wang, Zhu 13; Bobeth, Gorbahn, Vickers 14; Chang, Sun, Yang, Li 14]

▷ Or use "clean" combinations, *e.g.* $\Delta = T - P$ in penguin mediated decays

Perturbative QCD Approach

Li, Lu, Sanda, Kuem, Yang



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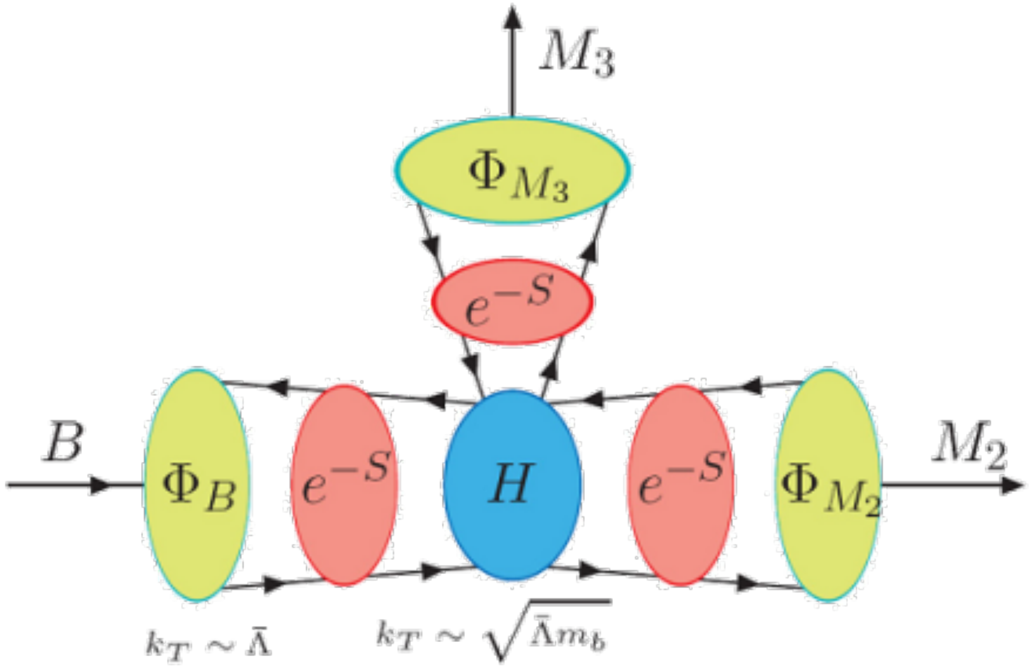
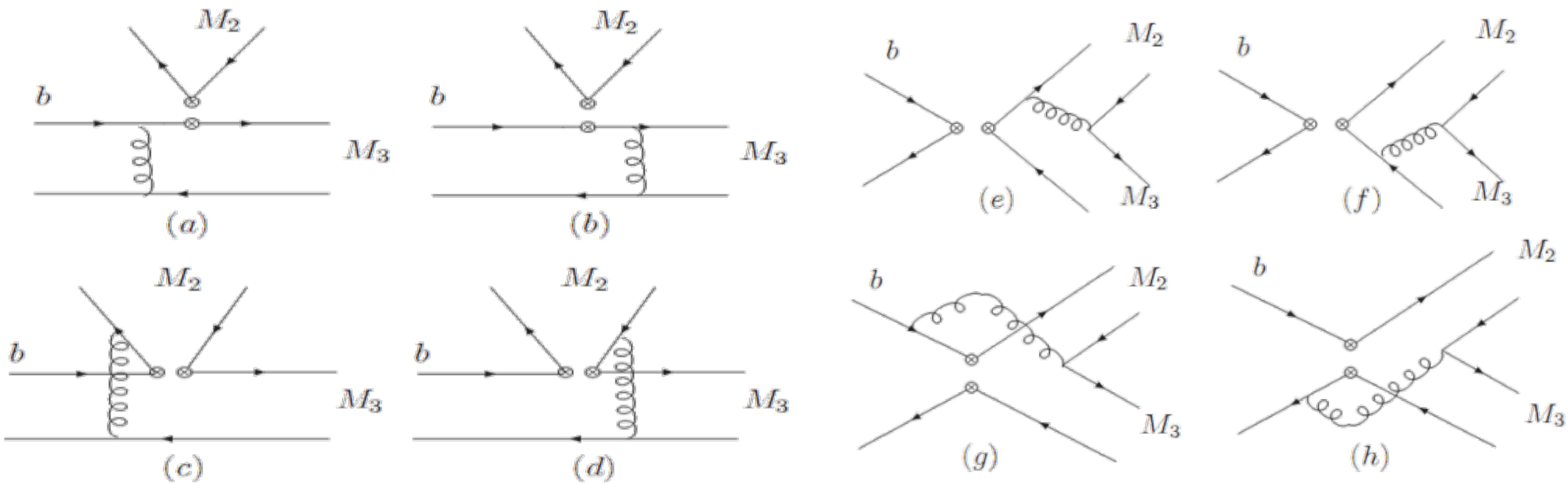


$$\mathcal{A} \sim C(t)\Phi(x)H(t)\exp\left\{-s(s,p) - 2\int_{1/b}^{t} \frac{d\mu}{\mu}\gamma_q(\alpha_s(\mu))\right\}$$

Perturbative QCD Approach

Li, Lu, Sanda, Kuem, Yang



Perturbative QCD Approach

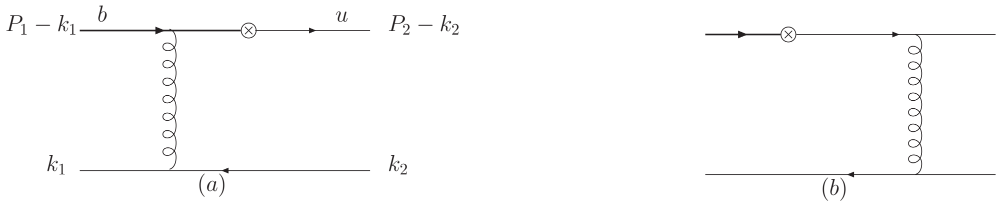
Mishima, Li

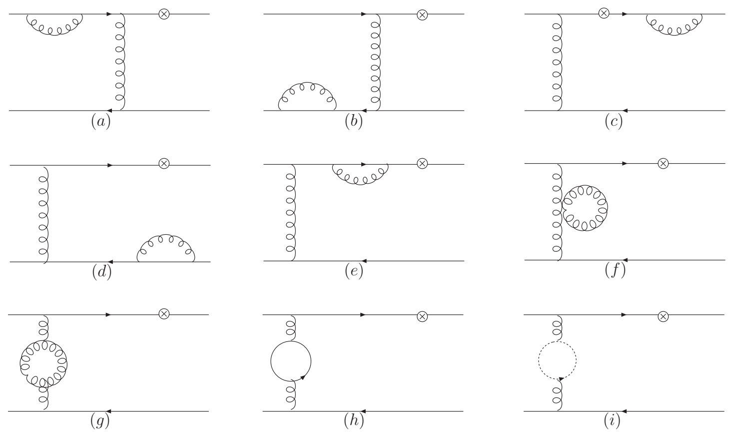
Mode	Data [1]	LO	LO_{NLOWC}	+VC	+QL	+MP	+NLO
$B^\pm \to \pi^\pm K^0$	24.1 ± 1.3	17.3	32.9	31.6	34.9	24.5	$24.9^{+13.9\,(+13.2)}_{-\;8.2\,(-\;8.2)}$
$B^\pm \to \pi^0 K^\pm$	12.1 ± 0.8	10.4	18.7	17.7	19.7	14.2	$14.2^{+10.2\,(+\;7.1)}_{-\;5.8\,(-\;4.3)}$
$B^0 \to \pi^\mp K^\pm$	18.9 ± 0.7	14.3	28.0	26.9	29.7	20.7	$21.1^{+15.7\,(+11.1)}_{-\;8.4\,(-\;6.6)}$
$B^0 \to \pi^0 K^0$	11.5 ± 1.0	5.7	12.2	11.9	13.0	8.8	$9.2^{+\;5.6\,(+\;5.1)}_{-\;3.3\,(-\;3.0)}$
$B^0 \to \pi^\mp \pi^\pm$	5.0 ± 0.4	7.1	6.8	6.6	6.9	6.7	$6.6^{+\;6.7\,(+\;2.7)}_{-\;3.8\,(-\;1.8)}$
$B^\pm \to \pi^\pm \pi^0$	5.5 ± 0.6	3.5	4.2	4.1	4.2	4.2	$4.1^{+\;3.5\,(+\;1.7)}_{-\;2.0\,(-\;1.2)}$
$B^0 \to \pi^0 \pi^0$	1.45 ± 0.29	0.12	0.28	0.37	0.29	0.21	$0.30^{+0.49\,(+0.12)}_{-0.21\,(-0.09)}$

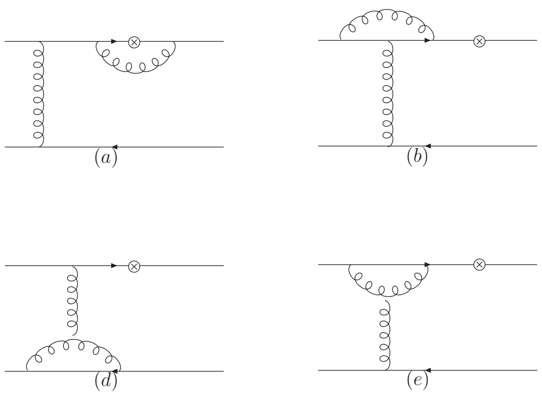
Mode	Data [1]	LO	LO_{NLOWC}	+VC	+QL	+MP	+NLO
$B^\pm \to \pi^\pm K^0$	-0.02 ± 0.04	-0.01	-0.01	-0.01	0.00	-0.01	$0.00 \pm 0.00\,(\pm 0.00)$
$B^\pm \to \pi^0 K^\pm$	0.04 ± 0.04	-0.08	-0.06	-0.01	-0.05	-0.08	$-0.01^{+0.03\,(+0.03)}_{-0.05\,(-0.05)}$
$B^0 \to \pi^\mp K^\pm$	-0.115 ± 0.018	-0.12	-0.08	-0.09	-0.06	-0.10	$-0.09^{+0.06\,(+0.04)}_{-0.08\,(-0.06)}$
$B^0 \to \pi^0 K^0$	—	-0.02	0.00	-0.07	0.00	0.00	$-0.07^{+0.03\,(+0.01)}_{-0.03\,(-0.01)}$
$B^0 \to \pi^\mp \pi^\pm$	0.37 ± 0.10	0.14	0.19	0.21	0.16	0.20	$0.18^{+0.20\,(+0.07)}_{-0.12\,(-0.06)}$
$B^\pm \to \pi^\pm \pi^0$	0.01 ± 0.06	0.00	0.00	0.00	0.00	0.00	$0.00 \pm 0.00\,(\pm 0.00)$
$B^0 \to \pi^0 \pi^0$	$0.28^{+0.40}_{-0.39}$	-0.04	-0.34	0.65	-0.41	-0.43	$0.63^{+0.35\,(+0.09)}_{-0.34\,(-0.15)}$

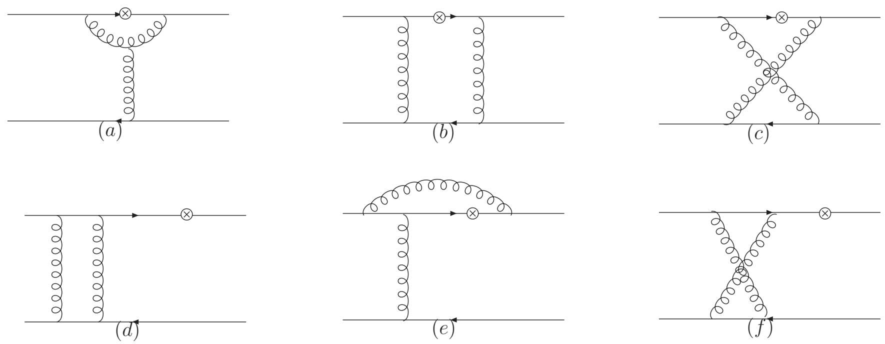
NLO Calculation

Xiao, Cheng,Lu, Li, Wang..



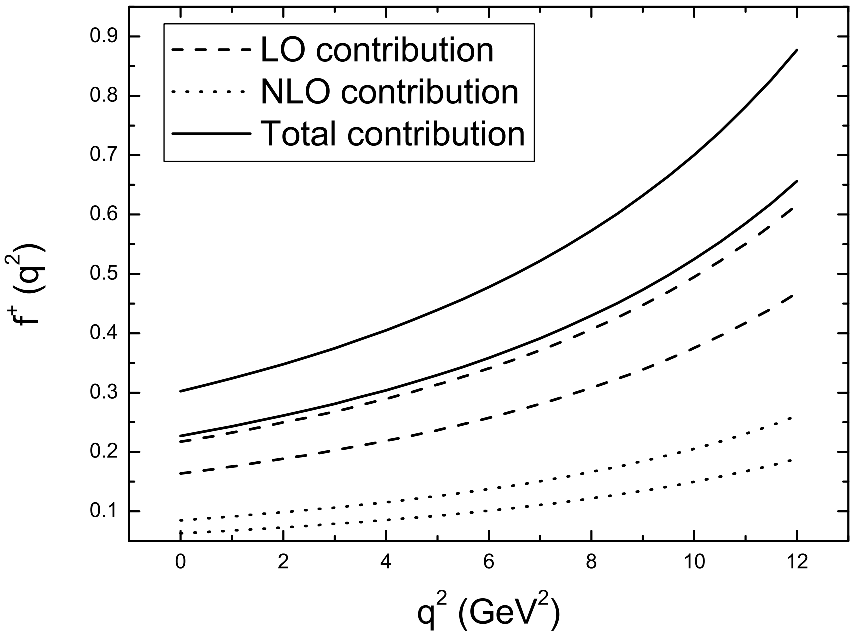


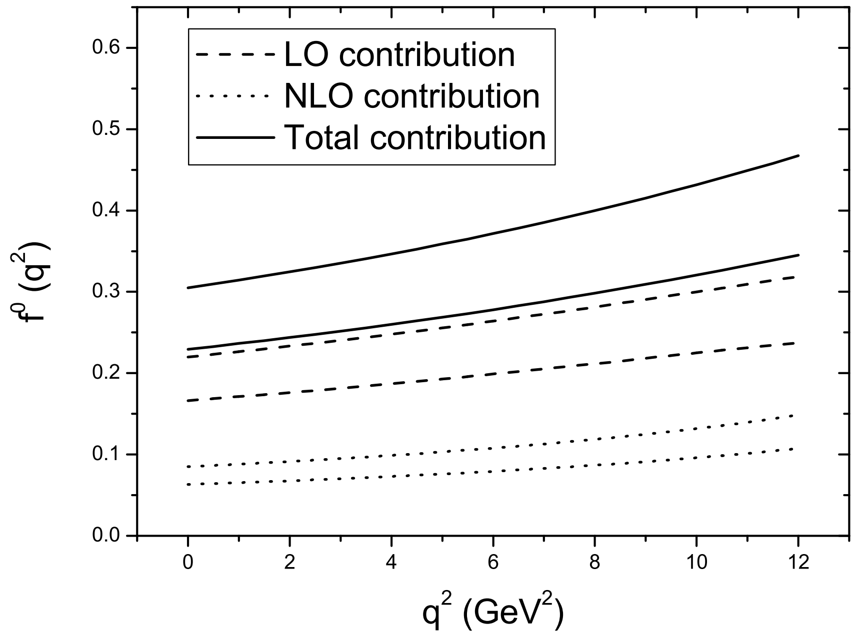




NLO Calculation

Wang, Shen, Cheng,Li,..

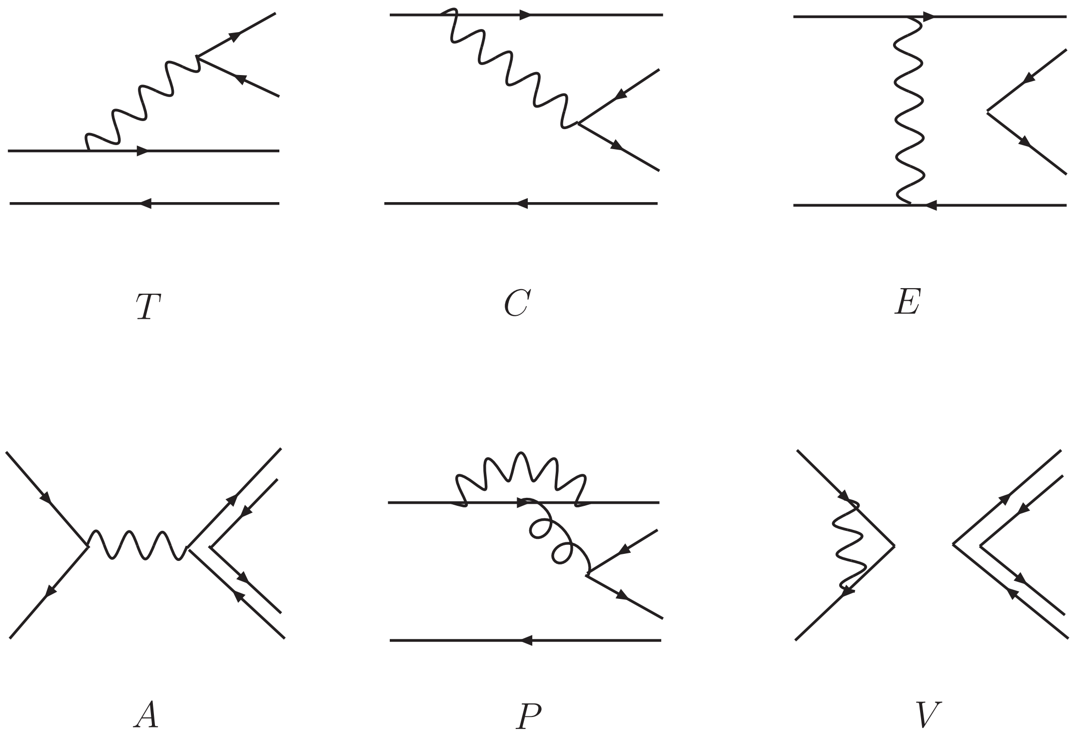




Channel	LO	NLO$_0$ [16]	NLO	QCDF[39]	Data
$Br(B^0 \to \pi^+\pi^-)$	6.87	7.67	$7.69^{+3.27}_{-2.67}$	8.9	5.11 ± 0.22
$Br(B^+ \to \pi^+\pi^0)$	3.54	4.27	$4.27^{+1.85}_{-1.47}$	6.0	$5.38^{+0.35}_{-0.34}$
$Br(B^0 \to \pi^0\pi^0)$	0.12	0.23	$0.24^{+0.09}_{-0.07}$	0.3	0.9 ± 0.12

Diagrammatic Approach

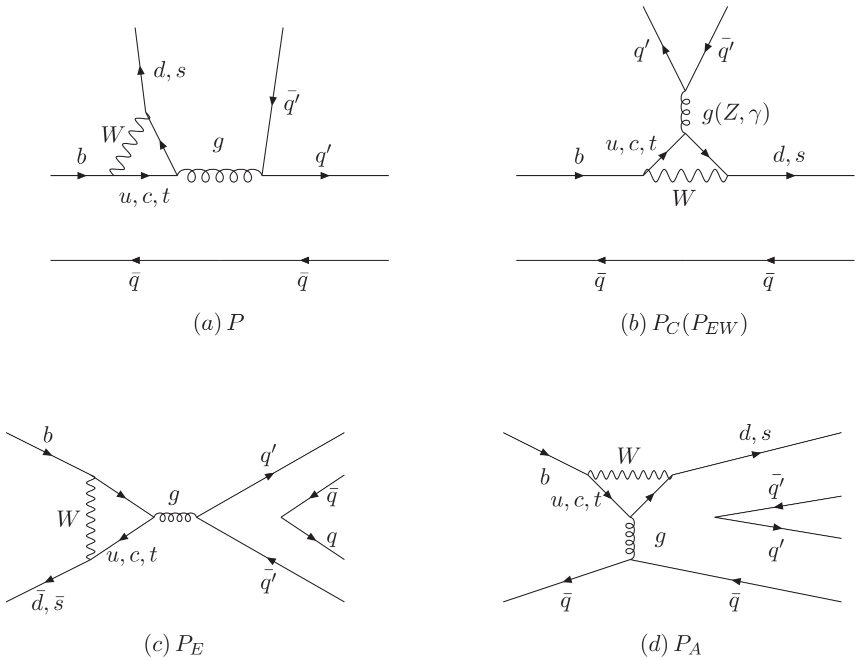
Cheng, Chiang



With SU(3) symmetry and data, the magnitude of each diagram can be fitted.

Diagrammatic Approach-FAT

Zhou, Yu, Lu, YL,...



$$T^{P_1P_2} = i\frac{G_F}{\sqrt{2}} V_{ub} V_{uq'} a_1(\mu) f_{p2} (m_B^2 - m_{p_1}^2) F_0^{BP_1}(m_{p_2}^2),$$

$$C^{P_1P_2} = i\frac{G_F}{\sqrt{2}} V_{ub} V_{uq'} \chi^C e^{i\phi^C} f_{p2} (m_B^2 - m_{p_1}^2) F_0^{BP_1}(m_{p_2}^2),$$

$$E^{P_1P_2} = i\frac{G_F}{\sqrt{2}} V_{ub} V_{uq'} \chi^E e^{i\phi^E} f_B m_B^2 (\frac{f_{p1} f_{p2}}{f_\pi^2}),$$

$$P^{PP} = -i\frac{G_F}{\sqrt{2}} V_{tb} V_{tq'}^* \left[a_4(\mu) + \chi^P e^{i\phi^P} r_\chi\right] f_{p2} (m_B^2 - m_{p1}^2) F_0^{BP_1}(m_{p2}^2),$$

$$P_C^{PP} = -i\frac{G_F}{\sqrt{2}} V_{tb} V_{tq'}^* \chi^{P_C} e^{i\phi^{P_C}} f_{p2} (m_B^2 - m_{p_1}^2) F_0^{BP_1}(m_{p_2}^2),$$

$$P_A^{PV} = -\sqrt{2} G_F V_{tb} V_{tq'}^* \chi^{P_A} e^{i\phi^{P_A}} f_B m_V (\frac{f_P f_V}{f_\pi^2})(\varepsilon_V^* \cdot p_B).$$

B—>DM
- 31 BF
- 4 dof

B—>PP,PV
- 37 BF+11CP
- 16 dof

B—>VV
- 18 BF+20 P+6 PHAS+2CP
- 10 dof

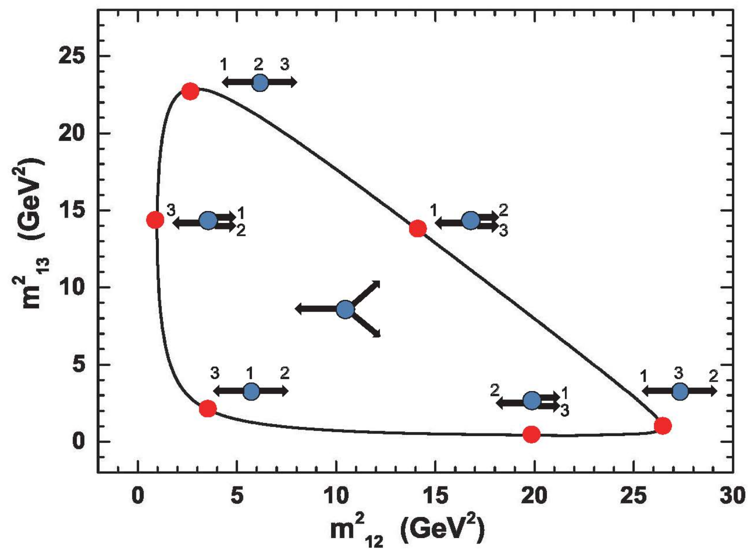
Diagrammatic Approach-FAT

Mode	Amplitudes	Exp	This work
$\pi^-\pi^0$	T, C, P_{EW}	$\star 5.5 \pm 0.4$	$5.08 \pm 0.39 \pm 1.02 \pm 0.02$
$\pi^-\eta$	T, C, P, P_C, P_{EW}	$\star 4.02 \pm 0.27$	$4.13 \pm 0.25 \pm 0.64 \pm 0.01$
$\pi^-\eta'$	T, C, P, P_C, P_{EW}	$\star 2.7 \pm 0.9$	$3.37 \pm 0.21 \pm 0.49 \pm 0.01$
$\pi^+\pi^-$	$T, E, (P_E), P$	$\star 5.12 \pm 0.19$	$5.15 \pm 0.36 \pm 1.31 \pm 0.14$
$\pi^0\pi^0$	$C, E, P, (P_E), P_E$	$\star 1.91 \pm 0.22$	$1.94 \pm 0.30 \pm 0.28 \pm 0.05$
$\pi^-\bar{K}^0$	P	$\star 23.7 \pm 0.8$	$23.2 \pm 0.6 \pm 4.6 \pm 0.2$
π^0K^-	T, C, P, P_{EW}	$\star 12.9 \pm 0.5$	$12.8 \pm 0.32 \pm 2.35 \pm 0.10$
ηK^-	T, C, P, P_C, P_{EW}	$\star 2.4 \pm 0.4$	$2.0 \pm 0.13 \pm 1.19 \pm 0.03$
$\eta' K^-$	T, C, P, P_C, P_{EW}	$\star 70.6 \pm 2.5$	$70.1 \pm 4.7 \pm 11.3 \pm 0.22$
π^+K^-	T, P	$\star 19.6 \pm 0.5$	$19.8 \pm 0.54 \pm 4.0 \pm 0.2$
$\pi^0\bar{K}^0$	C, P, P_{EW}	$\star 9.9 \pm 0.5$	$8.96 \pm 0.26 \pm 1.96 \pm 0.09$

Mode	$\mathcal{A}_{\text{exp}}$	$\mathcal{A}_{this\ work}$	$\mathcal{A}$
$\pi^+\pi^-$	$\star 0.31 \pm 0.05$	0.31 ± 0.04	
$\pi^0\pi^0$	0.43 ± 0.24	0.57 ± 0.06	
$\pi^0\eta$		-0.16 ± 0.16	
$\pi^0\eta'$		0.39 ± 0.14	
$\eta\eta$		-0.85 ± 0.06	
$\eta\eta'$		-0.97 ± 0.04	
$\eta'\eta'$		-0.87 ± 0.07	
π^0K_s	0.00 ± 0.13	-0.14 ± 0.03	
ηK_s		-0.30 ± 0.10	
$\eta' K_s$	0.06 ± 0.04	0.030 ± 0.004	
$K^0\bar{K}^0$		-0.057 ± 0.002	
$\pi^-\pi^0$	0.03 ± 0.04	-0.026 ± 0.003	
$\pi^-\eta$	-0.14 ± 0.07	-0.14 ± 0.07	
$\pi^-\eta'$	0.06 ± 0.16	0.37 ± 0.07	
$\pi^-\bar{K}^0$	-0.017 ± 0.016	0.0027 ± 0.0001	
π^0K^-	0.037 ± 0.021	0.065 ± 0.024	
ηK^-	$\star -0.37 \pm 0.08$	-0.22 ± 0.08	
$\eta' K^-$	0.013 ± 0.017	-0.021 ± 0.007	
K^-K^0	-0.21 ± 0.14	-0.057 ± 0.002	
π^+K^-	$\star -0.082 \pm 0.006$	-0.081 ± 0.005	

3-body Decays

- Data are results of entangled nonresonant and resonant contributions, and of different partial waves.
- Developing a reliable theoretical approach to 3-body hadronic B decays is important.
- Understand data and predict direct CP asymmetries of 3-body decay modes in localized regions of phase space
- Very challenging!

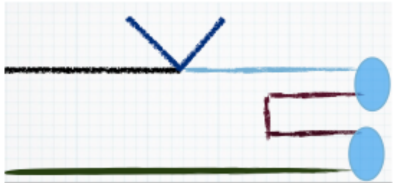


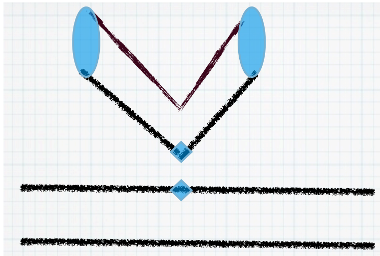
3-body Decays

- Factorization Approach Cheng, Chua, S. Fajfer, YLi,…
- PQCD Li, Chen, Wang, Wang, Lu, …
- QCD Factorization Krankl, Mannel, Virto,…
- Diagrammatic Approach combined SU(3) Gronau,London
- QCD Sum Rules Alexander Khodjamirian,…
- Others Feldman, Guo, He, Yang,…

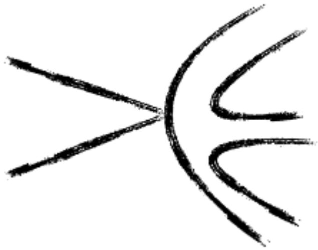
3-body Decays -Factorization

Cheng, Chua, Li,..

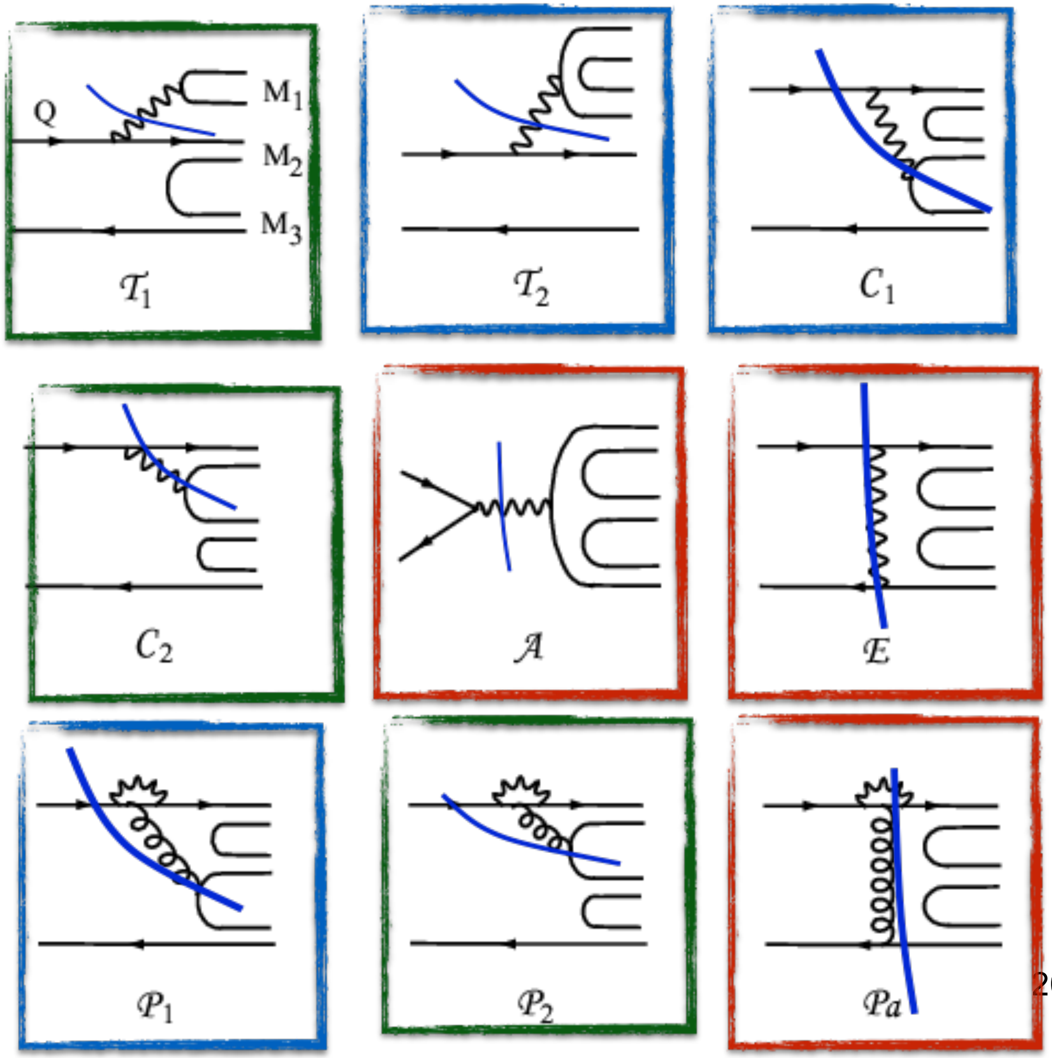




Transition Process



Annihilation Process



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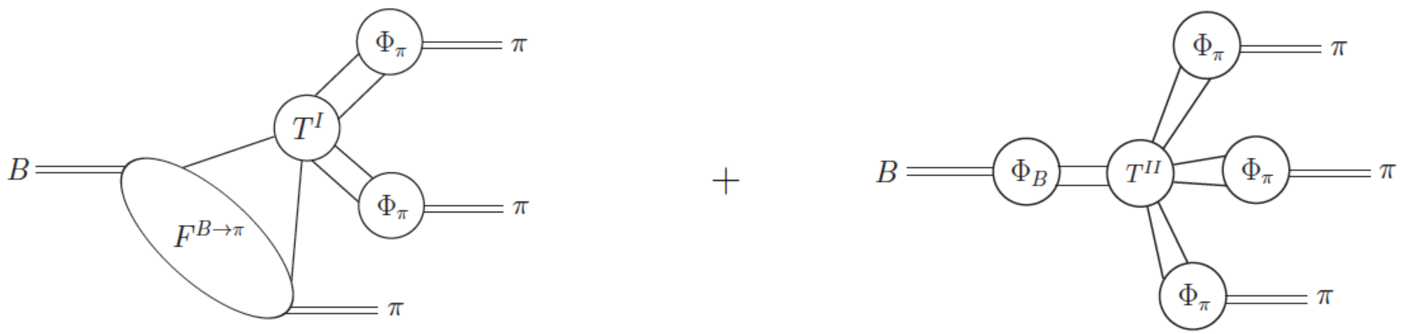
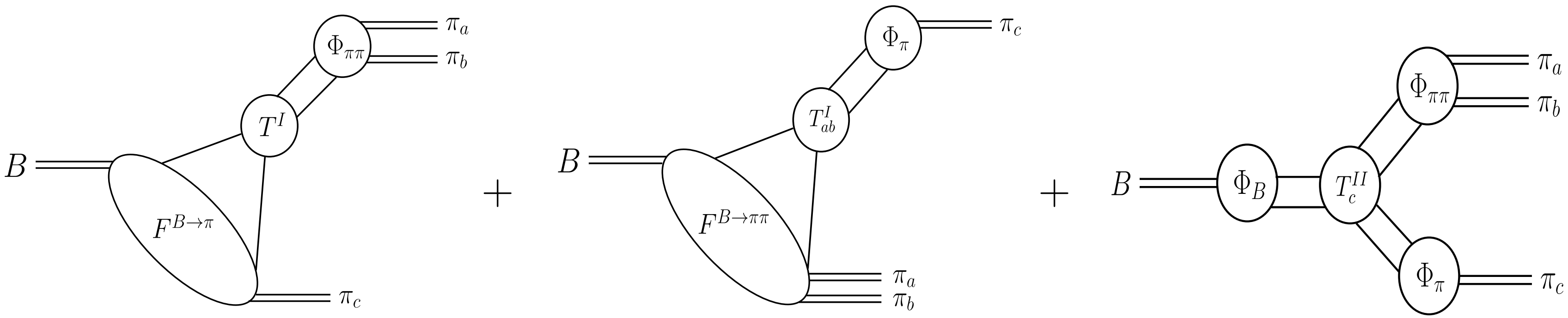
3-body Decays-QCDF

Krankle, Mannel,Virto,...



$$\langle \pi^+\pi^-\pi^+|\mathcal{O}_i|B^+\rangle_{s_{ij}\sim 1/3} = T_i^I \otimes F^{B\to\pi} \otimes \Phi_\pi \otimes \Phi_\pi + T_i^{II} \otimes \Phi_B \otimes \Phi_\pi \otimes \Phi_\pi \otimes \Phi_\pi \ ,$$



$$\langle \pi^a\pi^b\pi^c|\mathcal{O}_i|B\rangle_{s_{ab}\ll 1} = T_c^I \otimes F^{B\to\pi^c} \otimes \Phi_{\pi^a\pi^b} + T_{ab}^I \otimes F^{B\to\pi^a\pi^b} \otimes \Phi_{\pi^c}$$
$$+ T^{II} \otimes \Phi_B \otimes \Phi_{\pi^c} \otimes \Phi_{\pi^a\pi^b} \ .$$

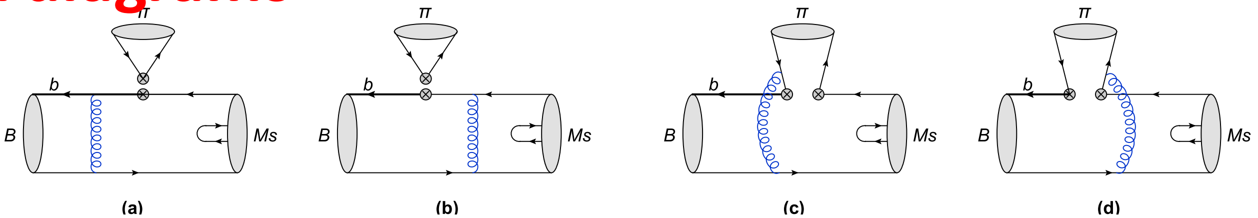
3-body Decays-PQCD

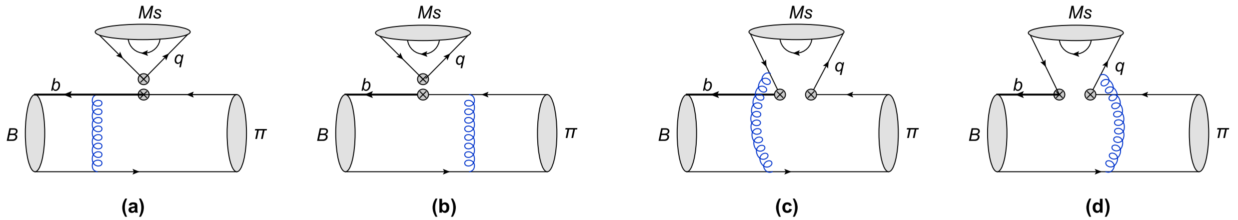
partial counting

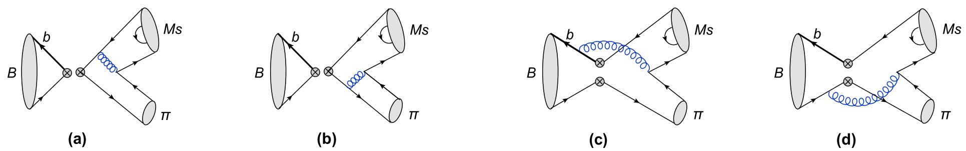
256 Feynman diagrams

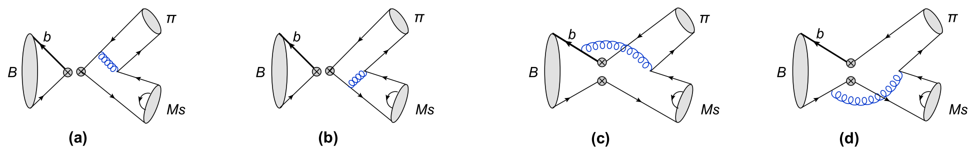
$$\mathcal{A} = \phi_B \otimes H \otimes \phi_{h_1 h_2} \otimes \phi_{h_3}$$

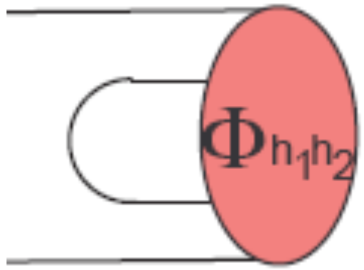
Xiao, Li, Li, ...











LI,Xiao,Wang,Lu,Li...

3-body Decays-PQCD

Xiao, Li, Li, ...

		Results	Data [98]
$K^+\pi^+\pi^-$	$\mathcal{B}\ (10^{-6})$	$3.42^{+0.78}_{-0.55}(\omega_B)^{+0.44}_{-0.39}(a_2^t)^{+0.39}_{-0.38}(m_0^K)^{+0.39}_{-0.32}(a_2^0)^{+0.29}_{-0.28}(a_2^s)$	3.7 ± 0.5
	$\mathcal{A}_{CP}$	$0.43^{+0.04}_{-0.05}(\omega_B) \pm 0.06(a_2^t) \pm 0.03(m_0^K) \pm 0.03(a_2^0) \pm 0.01(a_2^s)$	0.37 ± 0.10
$K^0\pi^+\pi^0$	$\mathcal{B}\ (10^{-6})$	$7.43^{+1.92}_{-1.31}(\omega_B)^{+1.65}_{-1.42}(a_2^t)^{+0.88}_{-0.91}(m_0^K)^{+0.60}_{-0.62}(a_2^0)^{+0.53}_{-0.47}(a_2^s)$	8.0 ± 1.5
	$\mathcal{A}_{CP}$	$0.15^{+0.02}_{-0.01}(\omega_B)^{+0.04}_{-0.05}(a_2^t) \pm 0.01(m_0^K)^{+0.01}_{-0.00}(a_2^0) \pm 0.00(a_2^s)$	-0.12 ± 0.17
$K^+\pi^-\pi^0$	$\mathcal{B}\ (10^{-6})$	$6.51^{+1.71}_{-1.12}(\omega_B)^{+0.58}_{-0.61}(a_2^t)^{+0.78}_{-0.77}(m_0^K)^{+0.67}_{-0.64}(a_2^0)^{+0.39}_{-0.47}(a_2^s)$	7.0 ± 0.9
	$\mathcal{A}_{CP}$	$0.31^{+0.00}_{-0.01}(\omega_B)^{+0.09}_{-0.08}(a_2^t)^{+0.03}_{-0.02}(m_0^K) \pm 0.01(a_2^0) \pm 0.02(a_2^s)$	0.20 ± 0.11
$K^0\pi^+\pi^-$	$\mathcal{B}\ (10^{-6})$	$3.76^{+1.09}_{-0.74}(\omega_B)^{+0.73}_{-0.60}(a_2^t)^{+0.52}_{-0.47}(m_0^K)^{+0.28}_{-0.25}(a_2^0)^{+0.26}_{-0.23}(a_2^s)$	4.7 ± 0.6
	$\mathcal{A}_{CP}$	$0.06^{+0.01}_{-0.02}(\omega_B)^{+0.00}_{-0.01}(a_2^t) \pm 0.00(m_0^K)^{+0.00}_{-0.01}(a_2^0) \pm 0.00(a_2^s)$	–

$$A_{CP}^{reg}(B^\pm \to \pi^\pm\pi^+\pi^-) = 0.52^{+0.12}_{-0.22}(\omega_B)^{+0.11}_{-0.09}(a_2^\pi)^{+0.03}_{-0.03}(m_0^\pi)$$

$$A_{CP}^{\text{region}}(\pi^+\pi^-\pi^-) = 0.584 \pm 0.082 \pm 0.027 \pm 0.007$$

Summary

- 2-body decays

    Power corrections

    NLO calculation of PQCD

    Determine the Wave function of Heavy meson

    New Physics effects

- 3-body decays

    Lots of data, great potential

    How to deal with resonance contribution

    2-meson LCDAs and B—>PP form factor

    Center region—>merge

Thanks for your attention!