Extraction of the CKM phase γ from charmless two-body B meson decays

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Based on work collaborated with Cai-Dian Lü (arXiv:1910.03160)

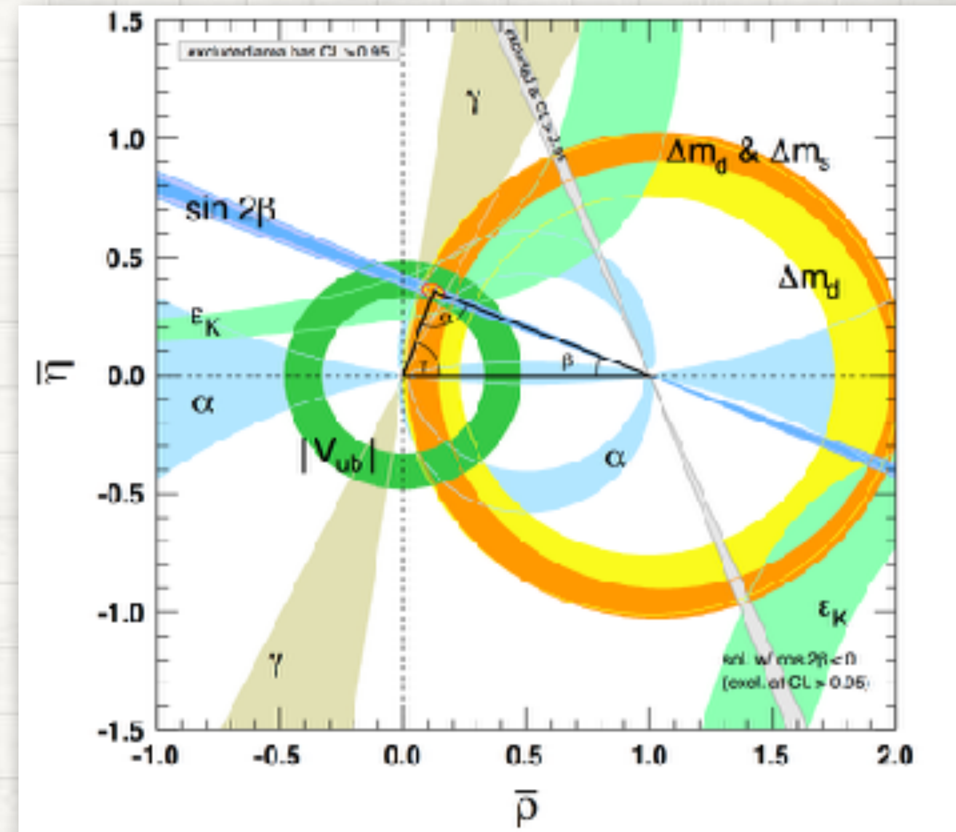
OUTLINE

- Introduction
- **F**actorization-**A**ssisted **T**opological-amplitude approach
- Extraction of the CKM phase γ in FAT approach
- Summary

Introduction

- Measure CKM parameters:
  - **SM:** V_{CKM} is unitary
  - **SM+NP:** V_{CKM} may not be unitary

  ➡ thus to test the closure of the unitarity triangle



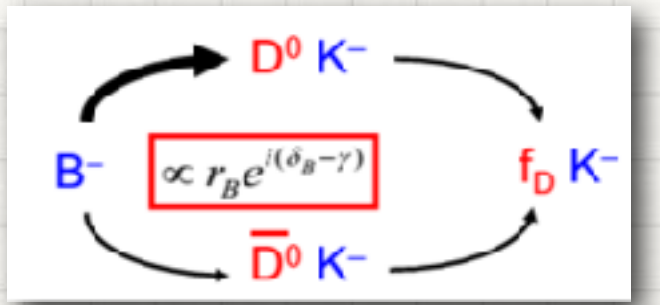
- $\alpha\,,\beta$ quite precise ; still room for γ
  - $\alpha\,,\beta$: mixing- induced CP violation of a single mode

$$A_{CP}(t,f)=\eta_f\sin(2\phi_D-2\phi_M)\sin(\Delta Mt) \qquad B^0\to J/\psi\,K_s\,,B^0\to\pi\pi\,,\rho\pi\,,\rho\rho$$

  - γ : might be to use B_s^0 decay $B_s^0\to\rho\,K_S$

be strongly diluted by the large $B_s^0-\bar{B}_s^0$ mixing

- Standard γ extraction : two-body charmed
  - $B^{\pm} \to DK^{\pm}, B^{\pm} \to D\pi^{\pm},$
  - $D \to 2P, 3P, ...$



- Interference: intermediate states D^0 and $\bar{D}^0$ mesons

- Standard γ extraction methods:
  - GLW (Gronau-London-Wyler) D decays to CP-eigenstates
  - ADS (Atwood-Danietz-Soni) doubly Cabibbo suppressed decays
  - GGSZ (Giri-Grossman-Sofer-Zupan) three-body D decays to self-conjugate modes

- The world average values $\sim 5^{\circ}$
  - HFLAV $\gamma = (71.1^{+4.6}_{-5.3})^{\circ}$ CKMfitter $\gamma = (73.5^{+4.2}_{-5.1})^{\circ}$ Utfit $\gamma = (70.0 \pm 4.2)^{\circ}$
  - Theoretically clean tree +higher order EW $\delta\gamma \lesssim \mathcal{O}(10^{-7})$
  - Experiment : statistically limited, small ratio of amplitude

❖ γ extraction : two-body charmless

- tree +penguin

- The problem: how to **calculate or extract** the different strong phases…
- Large branch rations ($\mathcal{O}(10^{-5} - 10^{-6})$), CP asymmetry
- The problem: how to **extract** the different strong phases…

Observables ≥ Unknown parameters

Flavor SU(3) symmetry/ U-spin flavor symmetry

U-spin pair: $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$

- R. Fleischer, Phys. Lett. B 459, 306 (1999) .

5 observables: $\mathcal{B}_d\,, \mathcal{B}_s\,, A^d_{CP}\,, A^s_{CP}\,, 2A^{in}_{CP}$

4 unknown: $\gamma\,, |a_1|\,, |a_2|\,, \delta$

γ is limited by the theoretical uncertainties from the flavor SU(3) breaking effects or U-spin-breaking corrections.

γ extraction from two-body charmless in FAT

- Factorization-assisted topological-amplitude approach

It is model-independent

I. Topological diagrams:

➡ parameterize all the contributions in charmless B decays by topological diagrams, fitted from the experimental measurements instead of perturbative QCD calculation.

II. The amplitude of topological diagram:

➡ Flavor SU(3) breaking effects is introduced, assuming that the hadronic decay amplitudes are factorizable, characterized by different decay constants (f) and form factors (F).

$$A \sim \gamma \boxed{\chi\, e^{i\phi}} f\, F$$

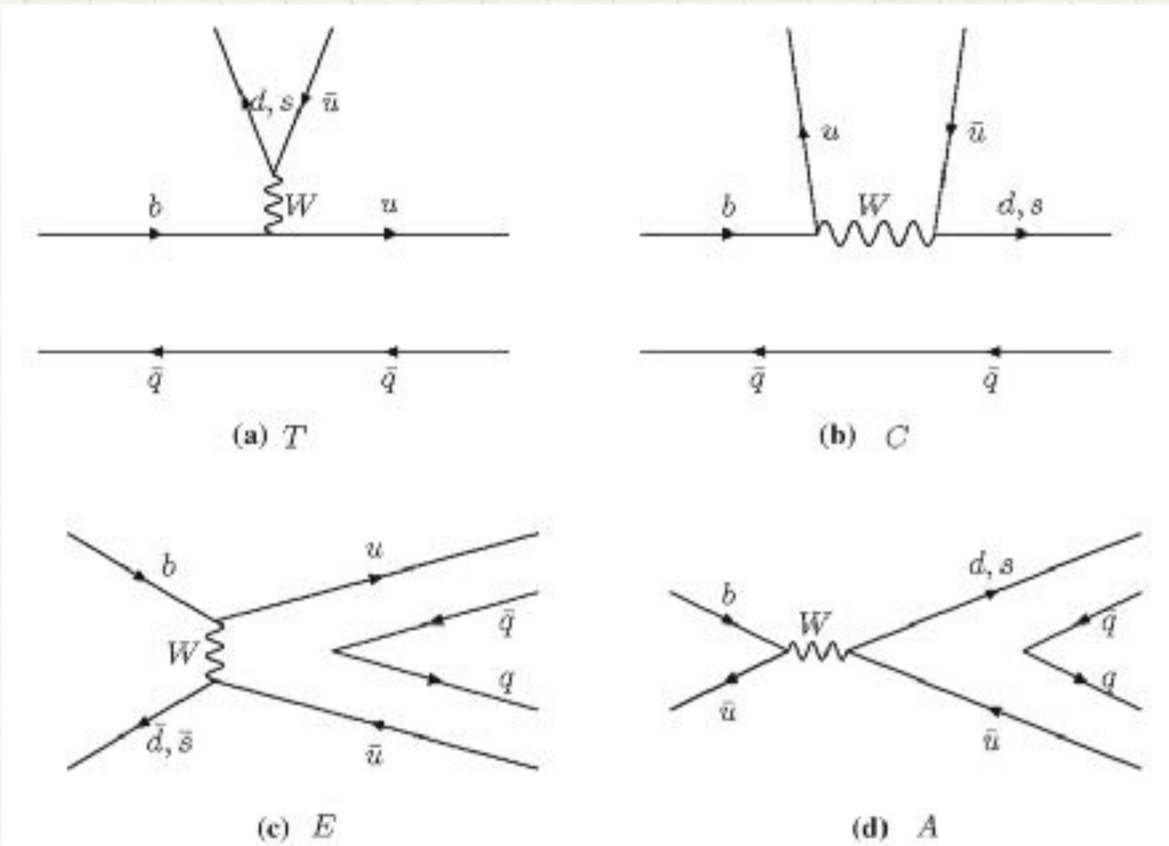
universal

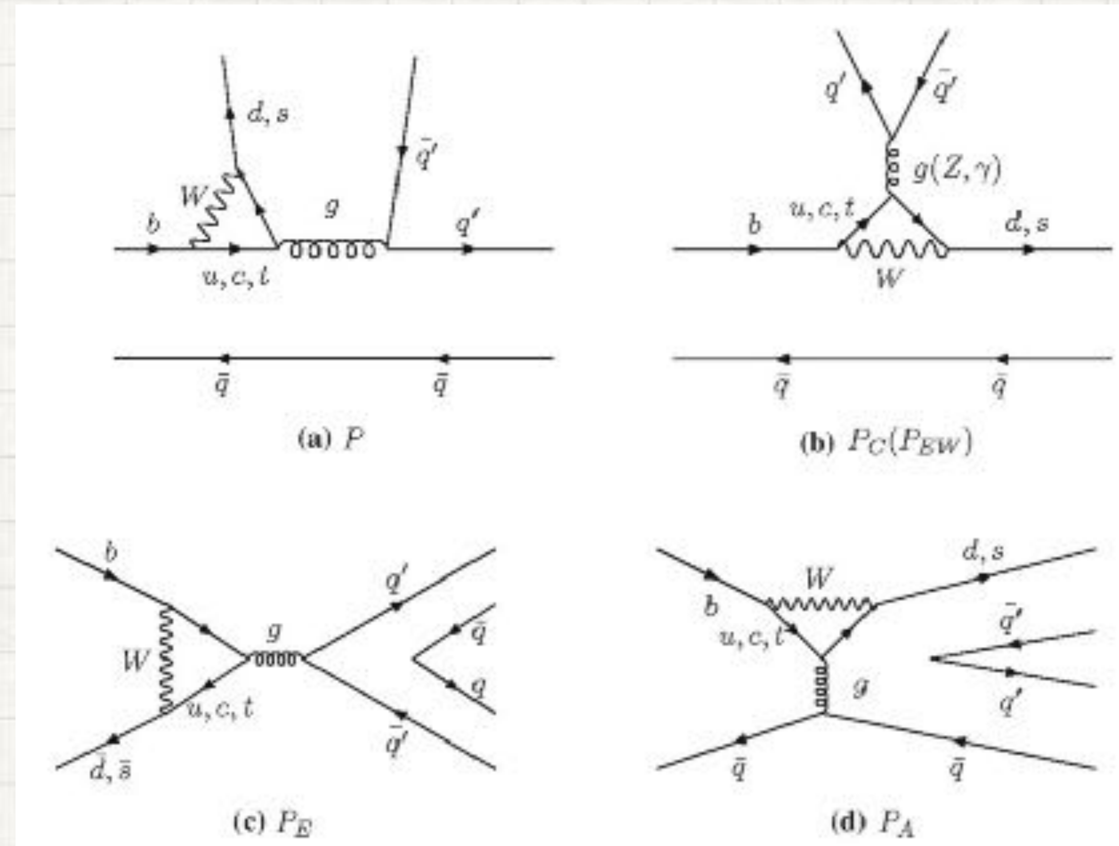
Number of parameter is reduced

III. Global Fit for γ together with hadronic parameters $\chi\,,\phi$

➡ All $B_{u\,,d} \to PP\,,PV$ decays from the current experimental data

Two-body charmless B decay $B \to PP, PV, VP$ in FAT

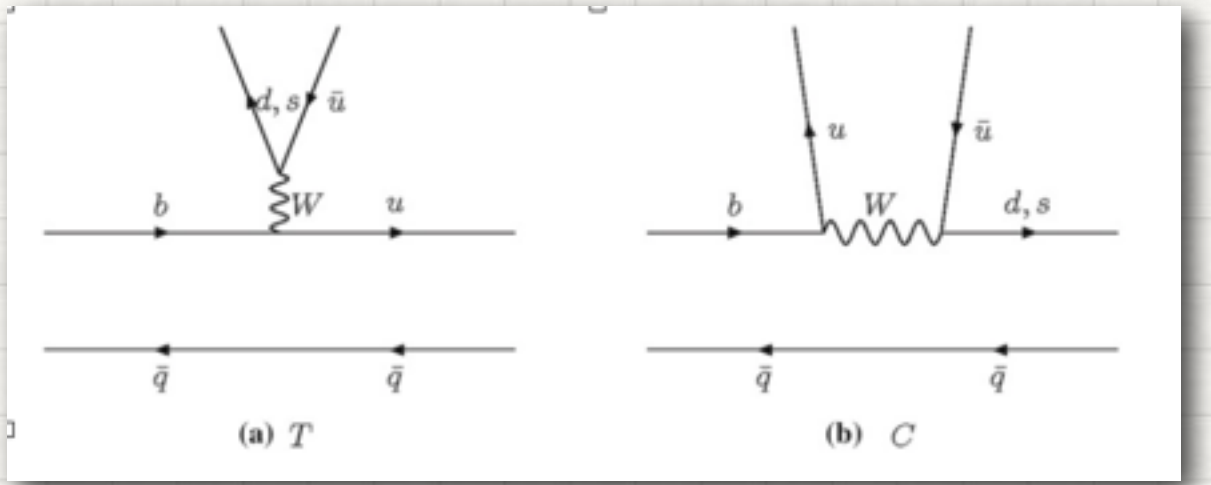




I. Topological diagrams:

Distinct by weak interaction and flavor flows with all strong interaction encoded, including non-perturbative ones.

II. The amplitude of topological diagram:



- Color-favored tree emission diagram $\mathcal{T}$

It is proved factorization to all order of α_s expansion in QCDF, PQCD and SCET.

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

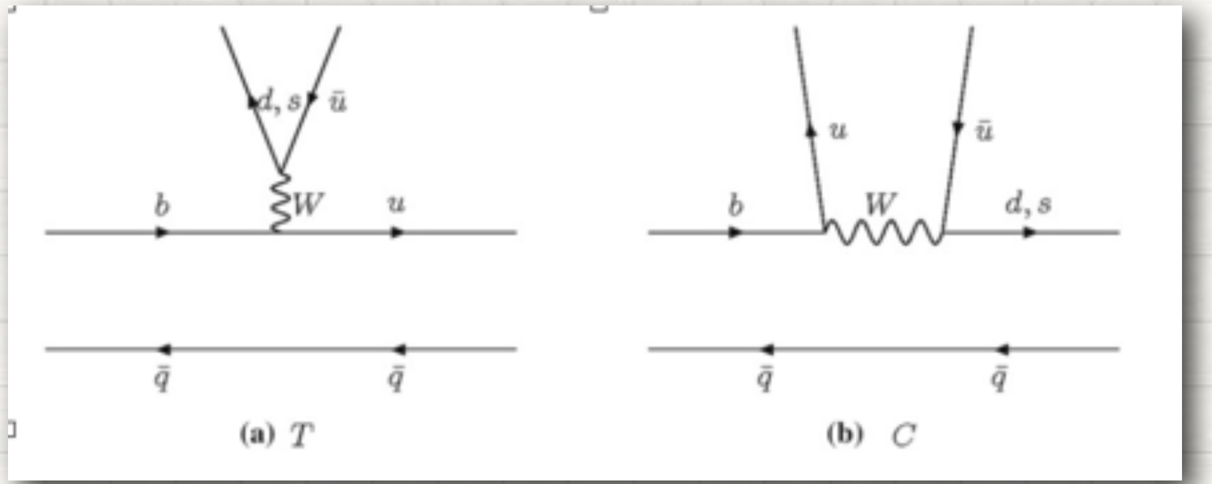
$$T^{VP} = \sqrt{2}G_F V_{ub}V_{uq'}\,a_1(\mu)f_P m_V A_0^{B-V}(m_P^2)(\varepsilon_V^* \cdot p_B),$$

$$T^{PV} = \sqrt{2}G_F V_{ub}V_{uq'}\,a_1(\mu)f_V m_V F_1^{B-P}(m_V^2)(\varepsilon_V^* \cdot p_B),$$

Effective Wilson coefficient

decay constants and form factors

characterize the SU(3)breaking effects.



- Color-suppressed tree emission diagram C

Inspired by Glauber phase for the pseudo-scalar meson emission diagram.

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

$$C^{VP} = \sqrt{2}G_F V_{ub}V^*_{uq'}\chi^C e^{i\phi^C} f_P m_V A_0^{B-V}(m_P^2)(\varepsilon_V^* \cdot p_B),$$

emitted pseudo-scalar

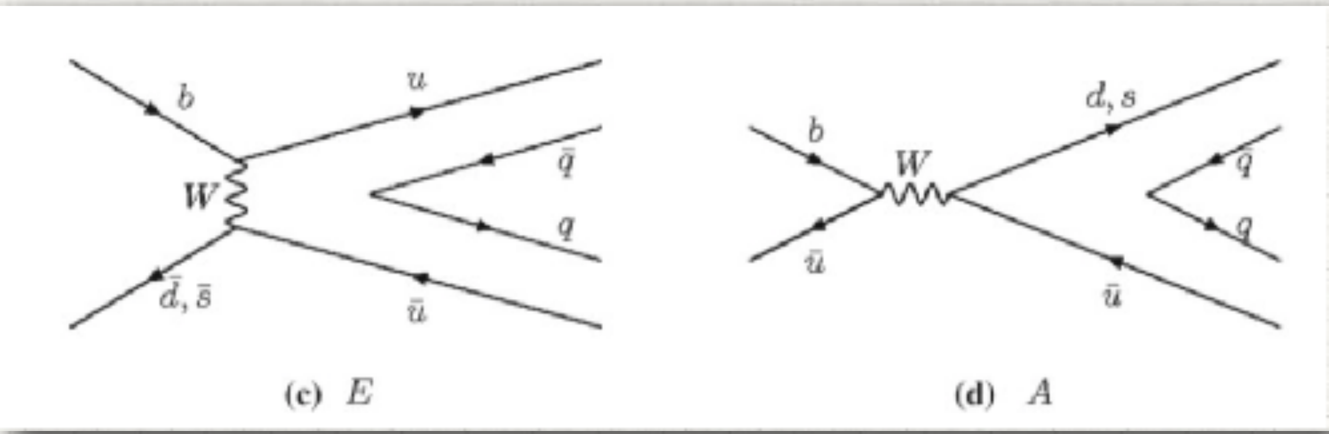
$$C^{PV} = \sqrt{2}G_F V_{ub}V^*_{uq'}\chi^{C'} e^{i\phi^{C'}} f_V m_V F_1^{B-P}(m_V^2)(\varepsilon_V^* \cdot p_B),$$

emitted Vector

Unknown gamma

Unknown Parameters for magnitude and strong phase

Input Parameters



- The annihilation type diagrams $\mathcal{E}$ and $\mathcal{A}$

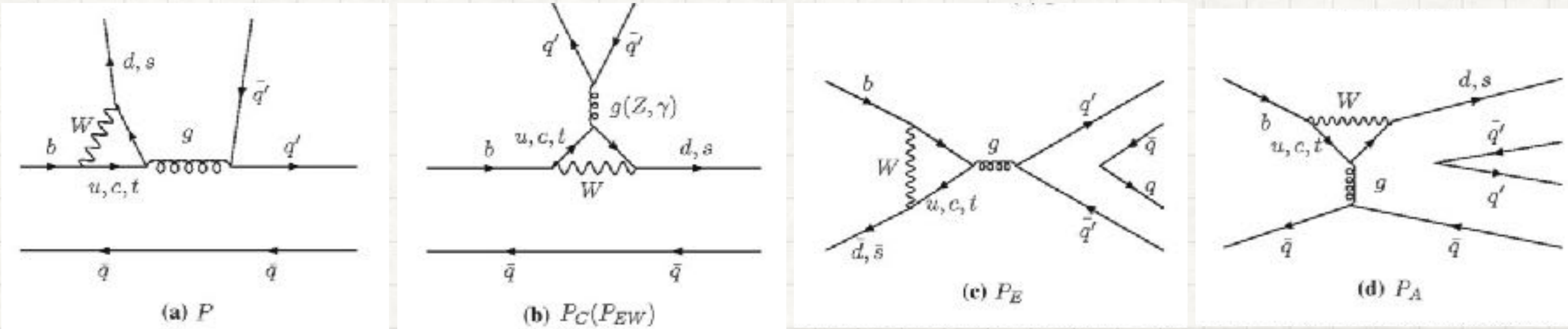
non-factorization and is expected smaller than emission diagram due to helicity suppression.

$$E^{P_1P_2} = i\frac{G_F}{\sqrt{2}}V_{ub}V^*_{uq'}\chi^E e^{i\phi^E} f_B m_B^2 (\frac{f_{p_1}f_{p_2}}{f_\pi^2}),$$

$$E^{PV,VP} = \sqrt{2}G_F V_{ub}V^*_{uq'}\chi^E e^{i\phi^E} f_B m_V (\frac{f_P f_V}{f_\pi^2})(\varepsilon^*_V \cdot p_B),$$

- As discussed in conventional topological diagram approach, $\mathcal{A}$ contribution is negligible.

1-loop penguin diagram



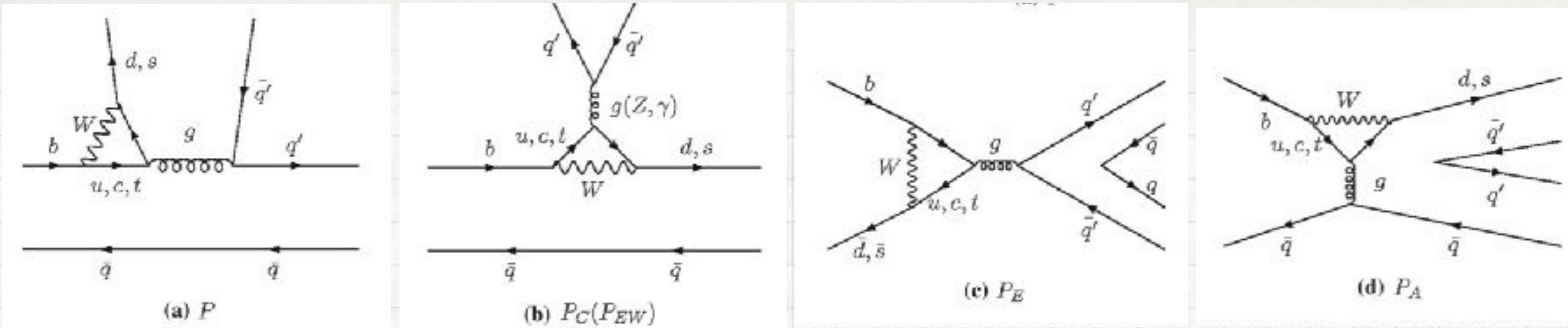
(a) P (b) $P_C(P_{EW})$ (c) P_E (d) P_A

- color-favored penguin emission diagram $\mathcal{P}$
  - The *leading contribution* from topology P diagram is similar to diagram T, which is proved factorization in various QCD-inspired approaches.
  - *"chiral enhanced" penguin contributions* need to be fitted.

$$P^{PP} = -i\frac{G_F}{\sqrt{2}} V_{tb} V_{tq'}^* \left[a_4(\mu) + \chi^P \mathrm{e}^{i\phi^P} r_\chi \right] f_{p_2} (m_B^2 - m_{p_1}^2) F_0^{BP_1}(m_{p_2}^2),$$

$$P^{VP} = -\sqrt{2} G_F V_{tb} V_{tq'}^* \left[a_4(\mu) - \chi^P \mathrm{e}^{i\phi^P} r_\chi \right] f_P m_V A_0^{B-V}(m_P^2)(\varepsilon_V^* \cdot p_B),$$

$$P^{PV} = -\sqrt{2} G_F V_{tb} V_{tq'}^* a_4(\mu) f_V m_V F_1^{B-P} m_V^2 (\varepsilon_V^* \cdot p_B),$$



(a) P (b) $P_C(P_{EW})$ (c) P_E (d) P_A

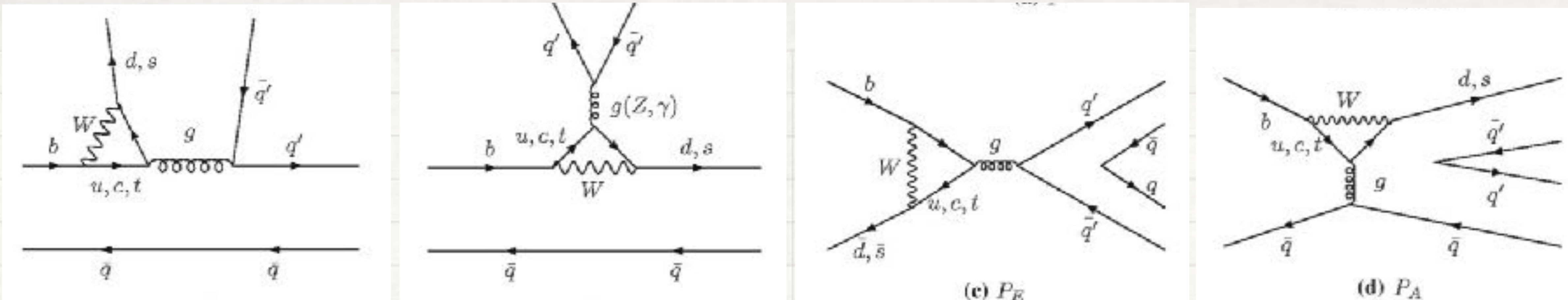
- Power correction to $\mathcal{P}$-penguin annihilation diagram $\mathcal{P}_{\mathcal{A}}$

$\mathcal{P}_{\mathcal{A}}$ is similar with P and the difference is only at QCD not EW.

$$P^{PP} = -i\frac{G_F}{\sqrt{2}}V_{tb}V^*_{tq'}\left[a_4(\mu) + \chi^P e^{i\phi^P} r_\chi\right] f_{p_2}(m_B^2 - m_{p_1}^2)F_0^{BP_1}(m_{p_2}^2),$$
$$P^{VP} = -\sqrt{2}G_F V_{tb}V^*_{tq'}\left[a_4(\mu) - \chi^P e^{i\phi^P} r_\chi\right] f_P m_V A_0^{B-V}(m_P^2)(\varepsilon_V^* \cdot p_B),$$
$$P^{PV} = -\sqrt{2}G_F V_{tb}V^*_{tq'} a_4(\mu) f_V m_V F_1^{B-P} m_V^2(\varepsilon_V^* \cdot p_B),$$

The contribution of $\mathcal{P}_{\mathcal{A}}$ can be included in $\chi^P e^{i\phi^P}$ except for $B \to PV$ where we need two more parameters

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



(a) P (b) $P_C(P_{EW})$ (c) P_E (d) P_A

P_E diagram is argued smaller than P_A diagram, which can be ignored reliably in decay modes not dominated by it, except

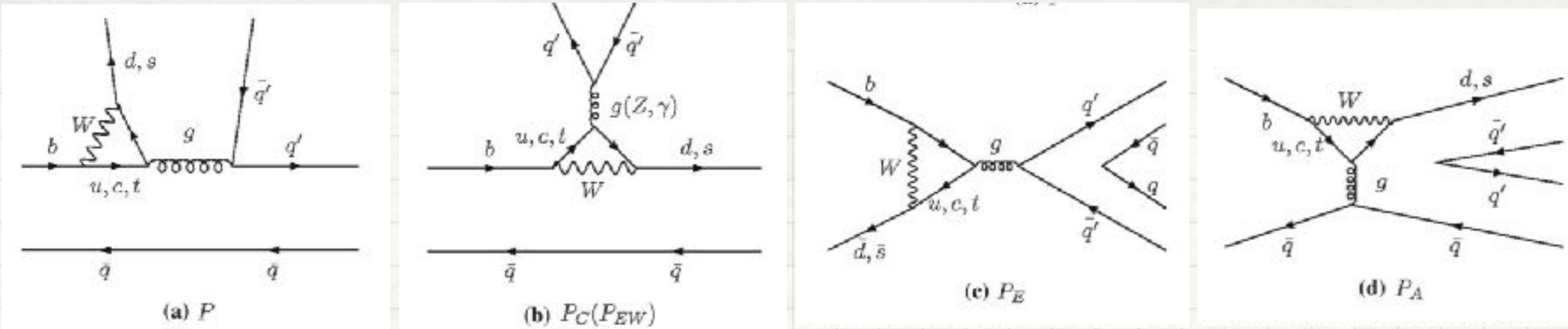
$$Br(B_s \to \pi^+\pi^-) = (0.76 \pm 0.19) \times 10^{-6}$$

The flavor-singlet QCD penguin diagram P_C only contribute to the isospin singlet mesons $\eta\,, \eta'\,, \omega\,, \phi$

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

$$P_C^{VP} = -\sqrt{2} G_F V_{tb} V_{tq'}^* \chi^{P_C} \mathrm{e}^{i\phi^{P_C}} f_P m_V A_0^{B-V}(m_P^2)(\varepsilon_V^* \cdot p_B)$$

$$P_C^{PV} = -\sqrt{2} G_F V_{tb} V_{tq'}^* \chi^{P'_C} \mathrm{e}^{i\phi^{P'_C}} f_V m_V F_1^{B-P}(m_V^2)(\varepsilon_V^* \cdot p_B),$$



(a) P (b) $P_C(P_{EW})$ (c) P_E (d) P_A

EW-penguin unnegligiblely contribute to the neutral isospin 1 meson emission decays.

P_EW is very similar to the T diagram Factorization

$$P_{EW}^{PP} = -i\frac{G_F}{\sqrt{2}} V_{tb} V_{tq'}^{*} e_q \frac{3}{2} a_9(\mu) f_{p_2} (m_B^2 - m_{p_1}^2) F_0^{BP_1}(m_{p_2}^2),$$

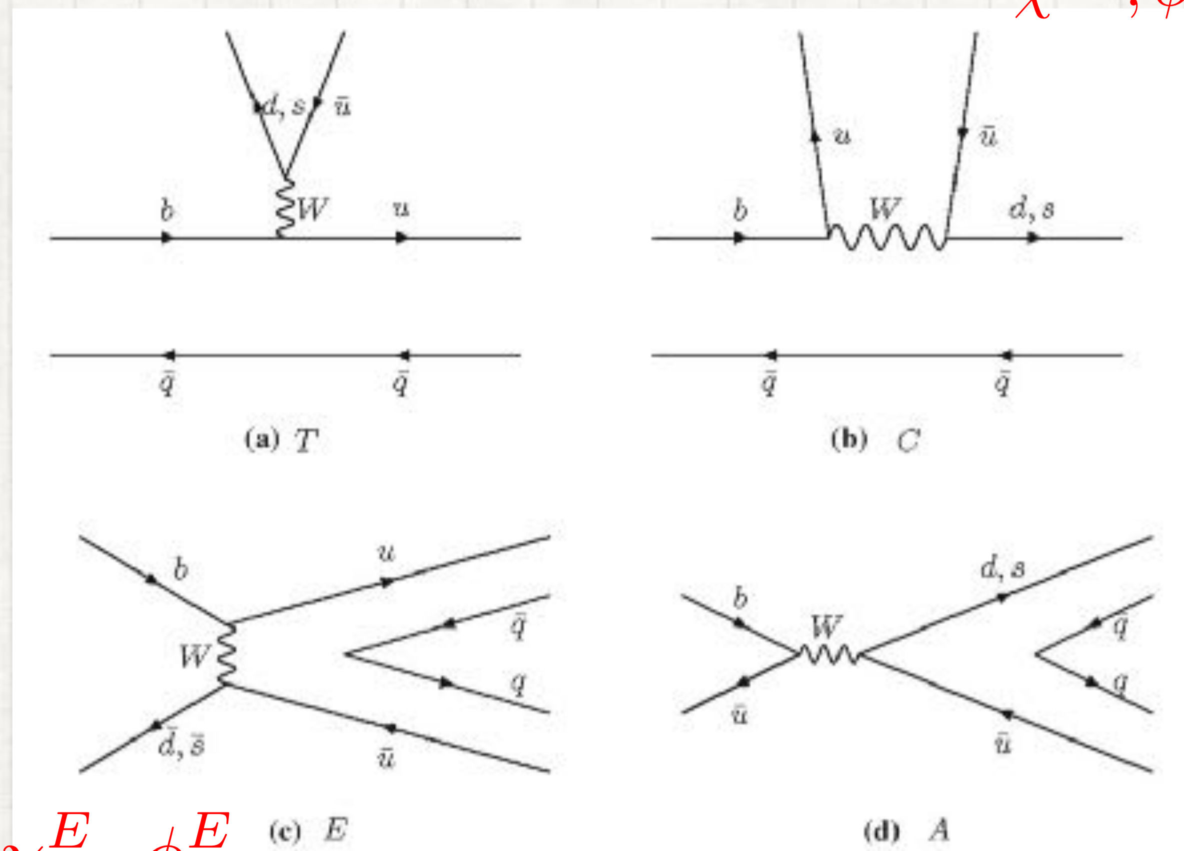
$$P_{EW}^{VP} = -\sqrt{2} G_F V_{tb} V_{tq'}^{*} e_q \frac{3}{2} a_9(\mu) f_P m_V A_0^{B-V}(m_P^2)(\varepsilon_V^{*} \cdot p_B),$$

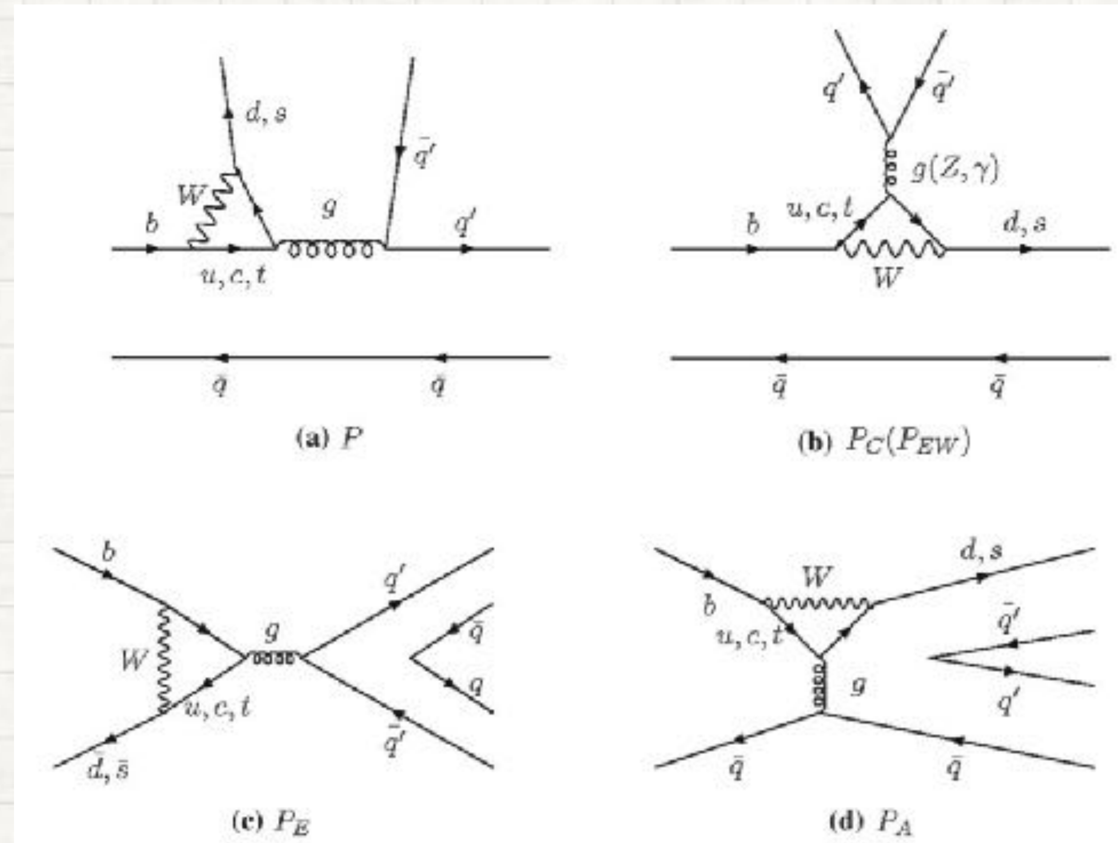
$$P_{EW}^{PV} = -\sqrt{2} G_F V_{tb} V_{tq'}^{*} e_q \frac{3}{2} a_9(\mu) f_V m_V F_1^{B-P}(m_V^2)(\varepsilon_V^{*} \cdot p_B),$$

where $a_9(\mu)$ is the effective Wilson coefficient

- 15 unknown theoretical parameters in topological amplitudes

14 strong interaction parameters χ^{C}, ϕ^{C} $\chi^{C'}, \phi^{C'}$ χ^{P}, ϕ^{P} χ^{P_C}, ϕ^{P_C} $\chi^{P'_C}, \phi^{P'_C}$





χ^{E}, ϕ^{E} χ^{P_A}, ϕ^{P_A}

Weak CKM phase γ

$$V_{ub}\,V^*_{ud(s)}$$

$$V_{tb}\,V^*_{td(s)} = -(V_{ub}\,V^*_{ud(s)} + V_{cb}\,V^*_{cd(s)})$$

Except $V_{ub} \equiv |V_{ub}|\, e^{-i\gamma}$, all other CKM matrix elements are are approximately real numbers without electroweak phase.

- # Input parameters

CKM from PDG-2019

$$|V_{ud}| = 0.97420 \pm 0.00021\,, \quad |V_{us}| = 0.2243 \pm 0.0005\,, \quad |V_{ub}| = 0.00394 \pm 0.00036\,,$$
$$|V_{cd}| = 0.218 \pm 0.004\,, \quad |V_{cs}| = 0.997 \pm 0.017\,, \quad |V_{cb}| = 0.0422 \pm 0.0008\,.$$

Decay constants and Form factor

TABLE I: The decay constants of light pseudo-scalar mesons and vector mesons (in unit of MeV).

f_π	f_K	f_B	f_ρ	f_{K^*}	f_ω	f_ϕ
130.2 ± 1.7	155.6 ± 0.4	190.9 ± 4.1	213 ± 11	220 ± 11	192 ± 10	225 ± 11

TABLE II: The transition form factors of B meson decays at q^2=0 and dipole model parameters.

	$F_0^{B\to\pi}$	$F_0^{B\to K}$	$F_0^{B\to\eta_q}$	$F_1^{B\to\pi}$	$F_1^{B\to K}$	$F_1^{B\to\eta_q}$	$A_0^{B\to\rho}$	$A_0^{B\to\omega}$	$A_0^{B\to K^*}$
$F_i(0)$	0.28 ± 0.03	0.31 ± 0.03	0.21 ± 0.02	0.28 ± 0.03	0.31 ± 0.03	0.21 ± 0.02	0.36 ± 0.04	0.32 ± 0.03	0.39 ± 0.04
α_1	0.50	0.53	0.52	0.52	0.54	1.43	1.56	1.60	1.51
α_2	-0.13	-0.13	0	0.45	0.50	0.41	0.17	0.22	0.14

- The above various topological amplitudes appear in all processes of charmless B decay in the form of some linear combinations,

e.g. $$A_{\pi^-\pi^0} = \frac{1}{\sqrt{2}}(C + P + P_{EW})$$

Observables:

37

$$\mathcal{B}(B \to M_1 M_2) = \frac{\Gamma(B \to M_1 M_2) + \Gamma(\bar{B} \to \bar{M}_1 \bar{M}_2)}{2} \times \tau_B,$$

$$\mathcal{A}_{cp}(t) = \mathcal{S}_f \sin(\Delta m_B t) - \mathcal{C}_f \cos(\Delta m_B t),$$

11

$$\mathcal{C}_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2},$$

$$\mathcal{S}_f = \frac{2\mathrm{Im}(\lambda_f)}{1 + |\lambda_f|^2},$$

15 parameters

48 observables

→ Observables as the function of parameters → γ extracted with a fit

III. Global Fit for γ together with 14 hadronic parameters

- the best-fitted parameters as:

$$\gamma = (69.8 \pm 2.1)^\circ \qquad \text{with} \quad \chi^2/d.o.f = 1.4$$

transmitted from the experimental uncertainty

$$\begin{aligned}
\chi^C &= 0.41 \pm 0.06, & \phi^C &= -1.74 \pm 0.09, \\
\chi^{C'} &= 0.40 \pm 0.17, & \phi^{C'} &= 1.78 \pm 0.10, \\
\chi^E &= 0.06 \pm 0.006, & \phi^E &= 2.76 \pm 0.13, \\
\chi^P &= 0.09 \pm 0.003, & \phi^P &= 2.55 \pm 0.03 \\
\chi^{P_C} &= 0.045 \pm 0.003, & \phi^{P_C} &= 1.53 \pm 0.08, \\
\chi^{P'_C} &= 0.037 \pm 0.003, & \phi^{P'_C} &= 0.67 \pm 0.08, \\
\chi^{P_A} &= 0.006 \pm 0.0008, & \phi^{P_A} &= 1.49 \pm 0.09,
\end{aligned}$$

- The major source of theoretical uncertainties: $V_{ub}\,,V_{cb}\,,f\,,F$

$$\gamma = (69.8 \pm 2.1 \pm 0.9)^\circ$$

Summary

- We use FAT to extract gamma from charmless B decays
- We try to parametrize the decay amplitudes into different topological diagrams
- To improve the precision of the global fit, we factorize the corresponding decay constant and form factors to characterize the flavor SU(3) breaking effect.
- We extract the CKM weak angle γ using all the measured two body charmless $B \to PP, PV$ decays
- The determined value is $(69.8 \pm 2.1 \pm 0.9)^{\circ}$

As the LHCb upgrade, additional and the increasing precision of the collected data sets, especially the CP asymmetries introduced by mixing and decay of B^0 meson, are expected to improve constraints on the CKM CP-violating phase gamma.

Thank You

BACKUP

TABLE IV: Branching fractions ($\times 10^{-6}$) of various $\bar{B} \to PP$ decay modes. We also show the experimental data [22] and results from conventional flavor diagram approach [14] for comparison.

Mode	Amplitudes	Exp	This work	Flavor diagram
$\pi^-\pi^0$	T, C, P_{EW}	$\star 5.5 \pm 0.4$	$5.08 \pm 0.39 \pm 1.02 \pm 0.02$	5.40 ± 0.79
$\pi^-\eta$	T, C, P, P_C, P_{EW}	$\star 4.02 \pm 0.27$	$4.13 \pm 0.25 \pm 0.64 \pm 0.01$	3.88 ± 0.39
$\pi^-\eta'$	T, C, P, P_C, P_{EW}	$\star 2.7 \pm 0.9$	$3.37 \pm 0.21 \pm 0.49 \pm 0.01$	5.59 ± 0.54
$\pi^+\pi^-$	$T, E, (P_E), P$	$\star 5.12 \pm 0.19$	$5.15 \pm 0.36 \pm 1.31 \pm 0.14$	5.17 ± 1.03
$\pi^0\pi^0$	$C, E, P, (P_E), P_{EW}$	$\star 1.91 \pm 0.22$	$1.94 \pm 0.30 \pm 0.28 \pm 0.05$	1.88 ± 0.42
$\pi^0\eta$	$C, E, P_C, (P_E), P_{EW}$	$4.3 + 1.8 - 1.7$	$0.86 \pm 0.08 \pm 0.08 \pm 0.04$	0.56 ± 0.03
$\pi^0\eta'$	$C, E, P_C, (P_E), P_{EW}$	1.2 ± 0.6	$0.87 \pm 0.08 \pm 0.10 \pm 0.03$	1.21 ± 0.16
$\eta\eta$	$C, E, P_C, (P_E), P_{EW}$	< 1.0	$0.44 \pm 0.09 \pm 0.08 \pm 0.005$	0.77 ± 0.12
$\eta\eta'$	$C, E, P_C, (P_E), P_{EW}$	< 1.2	$0.77 \pm 0.13 \pm 0.14 \pm 0.008$	1.99 ± 0.26
$\eta'\eta'$	$C, E, P_C, (P_E), P_{EW}$	< 1.7	$0.38 \pm 0.05 \pm 0.07 \pm 0.003$	1.60 ± 0.20
K^-K^0	P	$\star 1.31 \pm 0.17$	$1.32 \pm 0.04 \pm 0.26 \pm 0.01$	1.03 ± 0.02
$K^0\bar{K}^0$	P	$\star 1.21 \pm 0.16$	$1.23 \pm 0.03 \pm 0.25 \pm 0.01$	0.89 ± 0.11
$\pi^-\bar{K}^0$	P	$\star 23.7 \pm 0.8$	$23.2 \pm 0.6 \pm 4.6 \pm 0.2$	23.53 ± 0.42
π^0K^-	T, C, P, P_{EW}	$\star 12.9 \pm 0.5$	$12.8 \pm 0.32 \pm 2.35 \pm 0.10$	12.71 ± 1.05
ηK^-	T, C, P, P_C, P_{EW}	$\star 2.4 \pm 0.4$	$2.0 \pm 0.13 \pm 1.19 \pm 0.03$	1.93 ± 0.31
$\eta'K^-$	T, C, P, P_C, P_{EW}	$\star 70.6 \pm 2.5$	$70.1 \pm 4.7 \pm 11.3 \pm 0.22$	70.92 ± 8.54
π^+K^-	T, P	$\star 19.6 \pm 0.5$	$19.8 \pm 0.54 \pm 4.0 \pm 0.2$	20.2 ± 0.39
$\pi^0\bar{K}^0$	C, P, P_{EW}	$\star 9.9 \pm 0.5$	$8.96 \pm 0.26 \pm 1.96 \pm 0.09$	9.73 ± 0.82
$\eta\bar{K}^0$	C, P, P_C, P_{EW}	$\star 1.23 \pm 0.27$	$1.35 \pm 0.10 \pm 1.02 \pm 0.03$	1.49 ± 0.27
$\eta'\bar{K}^0$	C, P, P_C, P_{EW}	$\star 66 \pm 4$	$66.4 \pm 4.5 \pm 10.6 \pm 0.21$	66.51 ± 7.97

Mode	Amplitudes	Exp	This work	Flavor diagram
$\pi^-\rho^0$	T, C', P, P_A, P_{EW}	$\star 8.3 \pm 1.2$	$8.6 \pm 1.81 \pm 1.38 \pm 0.03$	7.59 ± 1.41
$\pi^-\omega$	$T, C', P, P'_C, P_A, P_{EW}$	$\star 6.9 \pm 0.5$	$6.78 \pm 1.46 \pm 1.09 \pm 0.02$	7.03 ± 1.42
$\pi^-\phi$	P'_C, P_{EW}	< 0.15	$0.28 \pm 0.004 \pm 0.055 \pm 0.003$	0.04 ± 0.02
$\pi^0\rho^-$	T, C, P, P_A, P_{EW}	$\star 10.9 \pm 1.4$	$12.9 \pm 0.73 \pm 2.30 \pm 0.12$	12.15 ± 2.52
$\eta\rho^-$	$T, C, P, P_C, P_A, P_{EW}$	7.0 ± 2.9	$8.16 \pm 0.48 \pm 1.43 \pm 0.07$	5.26 ± 1.19
$\eta'\rho^-$	$T, C, P, P_C, P_A, P_{EW}$	$\star 9.7 \pm 2.2$	$6.0 \pm 0.34 \pm 0.97 \pm 0.05$	5.66 ± 1.25
$\pi^+\rho^-$	$T, E, P, (P_E), P_A$	$\star 14.6 \pm 1.6$	$12.4 \pm 0.64 \pm 3.20 \pm 0.38$	15.20 ± 1.52
$\pi^-\rho^+$	$T, E, P, (P_E)$	$\star 8.4 \pm 1.1$	$6.04 \pm 0.47 \pm 1.70 \pm 0.25$	8.22 ± 1.06
$\pi^0\rho^0$	$C, C', E, P, P_A, (P_E), P_{EW}$	$\star 2 \pm 0.5$	$1.32 \pm 0.47 \pm 0.09 \pm 0.14$	2.24 ± 0.93
$\pi^0\omega$	$C, C', E, P, P_A, (P_E), P_{EW}$	< 0.5	$2.31 \pm 0.88 \pm 0.24 \pm 0.07$	1.02 ± 0.66
$\pi^0\phi$	P'_C, P_{EW}	< 0.15	$0.13 \pm 0.002 \pm 0.025 \pm 0.001$	0.02 ± 0.01
$\eta\rho^0$	$C, C', E, P, P_C, P'_C, P_A, (P_E), P_{EW}$	< 1.5	$4.41 \pm 1.15 \pm 0.39 \pm 0.17$	0.54 ± 0.32
$\eta\omega$	$C, C', E, P, P_C, P'_C, P_A, (P_E), P_{EW}$	$0.94^{+0.40}_{-0.31}$	$0.89 \pm 0.30 \pm 0.08 \pm 0.09$	1.12 ± 0.44
$\eta\phi$	P'_C, P_{EW}	< 0.5	$0.077 \pm 0.001 \pm 0.015 \pm 0.0008$	0.01 ± 0.01
$\eta'\rho^0$	$C, C', E, P, P_C, P'_C, (P_E), P_{EW}$	< 1.3	$3.19 \pm 0.77 \pm 0.29 \pm 0.12$	0.63 ± 0.33
$\eta'\omega$	$C, C', E, P, P_C, P'_C, (P_E), P_{EW}$	$1.0^{+0.5}_{-0.4}$	$0.95 \pm 0.21 \pm 0.05 \pm 0.06$	1.24 ± 0.47
$\eta'\phi$	P'_C, P_{EW}	< 0.5	$0.05 \pm 0.0008 \pm 0.01 \pm 0.0005$	0.01 ± 0.01
K^-K^{*0}	P, P_A	< 1.1	$0.59 \pm 0.06 \pm 0.10 \pm 0.01$	0.46 ± 0.03
K^0K^{*-}	P		$0.44 \pm 0.03 \pm 0.09 \pm 0.004$	0.31 ± 0.03
$K^0\bar{K}^{*0}$	P		$0.41 \pm 0.02 \pm 0.08 \pm 0.004$	0.29 ± 0.03
$\bar{K}^0K^{*0}$	P, P_A		$0.55 \pm 0.05 \pm 0.09 \pm 0.01$	0.43 ± 0.02
$\pi^-\bar{K}^{*0}$	P, P_A	$\star 10.1 \pm 0.9$	$10.0 \pm 0.95 \pm 1.78 \pm 0.15$	10.47 ± 0.60
π^0K^{*-}	T, C, P, P_A, P_{EW}	$\star 8.2 \pm 1.9$	$6.23 \pm 0.51 \pm 0.98 \pm 0.07$	9.79 ± 2.95
ηK^{*-}	$T, C, P, P_C, P_A, P_{EW}$	$\star 19.3 \pm 1.6$	$17.3 \pm 0.8 \pm 2.4 \pm 0.3$	16.57 ± 2.58
$\eta'K^{*-}$	$T, C, P, P_C, P_A, P_{EW}$	$4.8^{+1.8}_{-1.6}$	$3.31 \pm 0.44 \pm 0.38 \pm 0.13$	3.43 ± 1.43
$K^-\rho^0$	T, C', P, P_{EW}	$\star 3.7 \pm 0.5$	$3.97 \pm 0.25 \pm 0.80 \pm 0.04$	3.97 ± 0.90
$K^-\omega$	T, C', P, P'_C, P_{EW}	$\star 6.5 \pm 0.4$	$6.52 \pm 0.73 \pm 1.13 \pm 0.06$	6.43 ± 1.49
$K^-\phi$	P, P'_C, P_A, P_{EW}	$\star 8.8 \pm 0.7$	$8.38 \pm 1.21 \pm 0.69 \pm 0.50$	8.34 ± 1.31
$\bar{K}^0\rho^-$	P	$\star 8 \pm 1.5$	$7.74 \pm 0.47 \pm 1.55 \pm 0.07$	7.09 ± 0.77
π^+K^{*-}	T, P, P_A	$\star 8.4 \pm 0.8$	$8.40 \pm 0.77 \pm 1.46 \pm 0.14$	8.35 ± 0.50
$\pi^0\bar{K}^{*0}$	C, P, P_A, P_{EW}	$\star 3.3 \pm 0.6$	$3.35 \pm 0.36 \pm 0.65 \pm 0.08$	3.89 ± 1.98
$\eta\bar{K}^{*0}$	C, P, P_C, P_A, P_{EW}	$\star 15.9 \pm 1$	$16.6 \pm 0.7 \pm 2.3 \pm 0.3$	16.34 ± 2.48
$\eta'\bar{K}^{*0}$	$C, P, P_C, P'_C, P_A, P_{EW}$	$\star 2.8 \pm 0.6$	$3.0 \pm 0.5 \pm 0.3 \pm 0.1$	3.14 ± 1.24
$K^-\rho^+$	T, P	$\star 7 \pm 0.9$	$8.27 \pm 0.44 \pm 1.65 \pm 0.07$	8.28 ± 0.80
$\bar{K}^0\rho^0$	C', P, P_{EW}	$\star 4.7 \pm 0.4$	$4.59 \pm 0.34 \pm 0.79 \pm 0.04$	4.97 ± 1.14
$\bar{K}^0\omega$	C', P, P'_C, P_{EW}	$\star 4.8 \pm 0.6$	$4.80 \pm 0.61 \pm 0.95 \pm 0.05$	4.82 ± 1.26
$\bar{K}^0\phi$	P, P'_C, P_A, P_{EW}	$\star 7.3 \pm 0.7$	$7.77 \pm 1.12 \pm 0.64 \pm 0.46$	7.72 ± 1.21

TABLE VII: The direct CP asymmetries ($\mathcal{A}$) and mixing-induced CP asymmetries ($\mathcal{S}$) of $\bar{B} \to PP$ decays. We also show the results from conventional flavor diagram approach [14] for comparison.

Mode	$\mathcal{A}_{\exp}$	$\mathcal{A}_{this\ work}$	$\mathcal{A}_{Flavor\ diagram}$	$\mathcal{S}_{\exp}$	$\mathcal{S}_{this\ work}$	$\mathcal{S}_{Flavor\ diagram}$
$\pi^+\pi^-$	$\star 0.31 \pm 0.05$	0.31 ± 0.04	0.326 ± 0.081	$\star -0.67 \pm 0.06$	-0.60 ± 0.03	-0.717 ± 0.061
$\pi^0\pi^0$	0.43 ± 0.24	0.57 ± 0.06	0.611 ± 0.113		0.58 ± 0.06	0.454 ± 0.112
$\pi^0\eta$		-0.16 ± 0.16	0.566 ± 0.114		-0.98 ± 0.04	-0.098 ± 0.338
$\pi^0\eta^{'}$		0.39 ± 0.14	0.385 ± 0.114		-0.90 ± 0.07	0.142 ± 0.234
$\eta\eta$		-0.85 ± 0.06	-0.405 ± 0.129		0.33 ± 0.12	-0.796 ± 0.077
$\eta\eta^{'}$		-0.97 ± 0.04	-0.394 ± 0.117		-0.20 ± 0.15	-0.903 ± 0.049
$\eta^{'}\eta^{'}$		-0.87 ± 0.07	-0.122 ± 0.136		-0.46 ± 0.14	-0.964 ± 0.037
$\pi^0 K_s$	0.00 ± 0.13	-0.14 ± 0.03	-0.173 ± 0.019	$\star 0.58 \pm 0.17$	0.73 ± 0.01	0.754 ± 0.014
ηK_s		-0.30 ± 0.10	-0.301 ± 0.041		0.68 ± 0.04	0.592 ± 0.035
$\eta^{'} K_s$	0.06 ± 0.04	0.030 ± 0.004	0.022 ± 0.006	$\star 0.63 \pm 0.06$	0.69 ± 0.00	0.685 ± 0.004
$K^0\bar{K}^0$		-0.057 ± 0.002	0.017 ± 0.041	0.8 ± 0.5	0.099 ± 0.002	0
$\pi^-\pi^0$	0.03 ± 0.04	-0.026 ± 0.003	0.069 ± 0.027			
$\pi^-\eta$	-0.14 ± 0.07	-0.14 ± 0.07	-0.081 ± 0.074			
$\pi^-\eta^{'}$	0.06 ± 0.16	0.37 ± 0.07	0.374 ± 0.087			
$\pi^-\bar{K}^0$	-0.017 ± 0.016	0.0027 ± 0.0001	0			
$\pi^0 K^-$	0.037 ± 0.021	0.065 ± 0.024	0.047 ± 0.025			
ηK^-	$\star -0.37 \pm 0.08$	-0.22 ± 0.08	-0.426 ± 0.043			
$\eta^{'} K^-$	0.013 ± 0.017	-0.021 ± 0.007	-0.027 ± 0.008			
$K^- K^0$	-0.21 ± 0.14	-0.057 ± 0.002	0			
$\pi^+ K^-$	$\star -0.082 \pm 0.006$	-0.081 ± 0.005	-0.080 ± 0.011			