

Theory of γ from tree decays

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Partially based on

Brod, Zupan, JHEP 1401 (2014) 051

Brod, Phys.Lett. B743 (2015) 56-60

Brod, Lenz, Tetlalmatzi-Xolocotzi, Wiebusch, Phys.Rev. D92 (2015) 033002



“Introduzione”

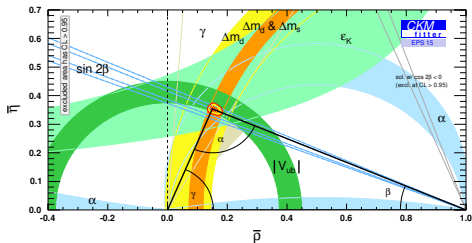
Definition of γ

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- The fundamental equation: $\gamma \equiv \phi_3$

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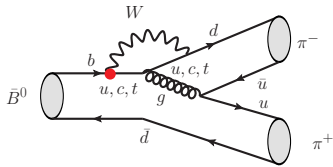
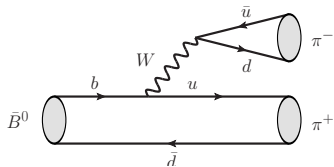
- The fundamental equation (extended version):

$$\gamma \equiv \phi_3 \equiv \arg(-V_{ud} V_{ub}^* / V_{cd} V_{cb}^*)$$

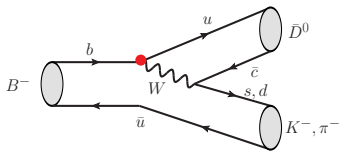
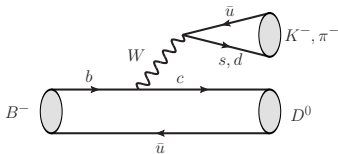
- Determination from $B \rightarrow DK$ theoretically extremely clean
 - Fit hadronic parameters from data

Motivation: Tree vs. Loop

- From $B \rightarrow \pi\pi$ determine $\alpha = \pi - \beta - \gamma$ [Gronau, London 1990]
- Use $B \rightarrow \pi\pi$ and $B_s \rightarrow KK$ to extract γ [Fleischer 1999]



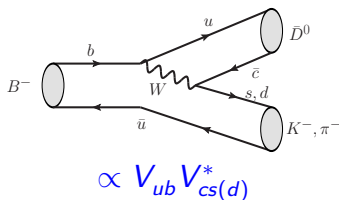
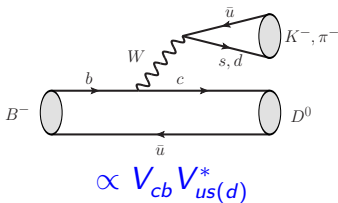
- Compare to γ from tree-level $B \rightarrow DK$ [Bigi, Sanda 1981]



Outline

- γ from tree decays
- Theory uncertainty
- New-physics contributions?

γ from tree decays – general idea



- $b \rightarrow c\bar{u}s(d), b \rightarrow u\bar{c}s(d)$
- no penguin contribution
- interference from common D^0, \bar{D}^0 final states

$$r_B^{Dh} e^{i(\delta_B - \gamma)} = \frac{A(B^- \rightarrow \bar{D}^0 h^-)}{A(B^- \rightarrow D^0 h^-)}$$

Several choices for final state f in D decay

- CP eigenstates (e.g. $D \rightarrow K^+K^- , \pi^+\pi^- ; K_S\pi^0$)

[Gronau, London 1990, Gronau, Wyler 1991]

- Flavor states (e.g. $D \rightarrow \pi^-K^+ , \pi^+K^-$) [Atwood, Dunietz, Soni 1997]

- Many-body final states (e.g. $D \rightarrow K_S K^+ K^- , K_S \pi^+ \pi^-$)

[Giri, Grossman, Soffer, Zupan 2003; Poluektov 2004]

- Many variants:

- Use $D^* \rightarrow D\pi^0 , D\gamma$ [Bondar, Gershon 2004]

- Many-body B final states

[Aleksan, Petersen, Soffer 2002; Gershon 2008; Gershon, Poluektov 2009]

- Neutral B_D, B_S [Aleksan, Dunietz, Kayser 1992; Kayser, London 2000; Atwood, Soni 2003;

Fleischer 2003; Gronau et al. 2004]

- ...

- Have $\sim n_D n_B$ measurements, $\sim n_D + n_B$ unknowns

Why measure γ ?

- Important SM input parameter
- Theoretically very clean
 - Hadronic parameters can be fitted from data
- In the (far) future can be used to search for NP at high scales
- \Rightarrow what is the uncertainty?

The devil is in the detail



“Fuga del diavolo”

Precision in γ

- Direct CP violation in D decays

[E.g. Martone, Zupan 2012; Wang 2012; Bhattacharya et al. 2013; Bondar et al. 2013]

- $\delta\gamma = \mathcal{O}(r_f/r_B)$
 - $r_B(DK) = \mathcal{O}(10\%)$, $\delta\gamma = \mathcal{O}(\text{few } \%)$
 - $r_B(D\pi) = \mathcal{O}(0.5\%)$, $\delta\gamma = \mathcal{O}(1)$

- Can still “solve the system”

- (Shift symmetry: Need one CPC D decay mode)

- $D - \bar{D}$, $K - \bar{K}$, $B_{(s)} - \bar{B}_{(s)}$ mixing

[E.g. Grossman et al. 2005, Bondar et al. 2010; Rama 2014; Gronau et al. 2007; Grossman et al. 2013]

- Shift of $\lesssim 3^\circ$
- Can be included exactly if mixing is precisely measured!

So, why a theory talk?



“Silentium!”

What are we actually measuring?

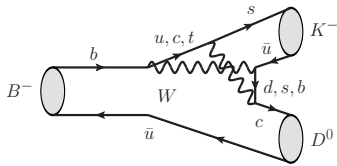
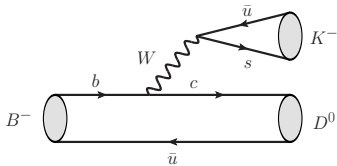
- When is the phase extracted in $B \rightarrow Dh$ not γ ?
 - Subleading terms in Wolfenstein expansion
[Grossman, Savastio 2013, Brod 2014]
 - Electroweak corrections
[Brod, Zupan 2013; Brod 2014]
 - Tree-level new physics
[Brod, Lenz, Tetlalmatzi-Xolocotzi, Wiebusch 2014]

Subleading weak phases

- Extracting γ from $B \rightarrow DK$ involves the ratio
 - $V_{cd} V_{cs} / (V_{ud} V_{us}) = -1 + \lambda^4 A^2 (1 - (\rho + i\eta)) + \mathcal{O}(\lambda^6)$
- Extracting γ from $B \rightarrow D\pi$ involves the ratio
 - $V_{cd}^2 / V_{ud}^2 = \lambda^2 [1 - \lambda^4 A^2 (1 - 2(\rho + i\eta))] + \mathcal{O}(\lambda^6)$
- The $\mathcal{O}(\lambda^4 \approx 2.6 \times 10^{-3})$ uncertainty can be removed by independent measurements of $\arg[V_{cd} V_{cs} / (V_{ud} V_{us})]$, $\arg[V_{cd} / V_{ud}]$

Irreducible theory uncertainty

- QED radiative corrections \rightarrow CP conserving
- Electroweak corrections
 - No effect from Z exchange
 - No effect from vertex corrections
 - **Box diagrams can change CKM structure**



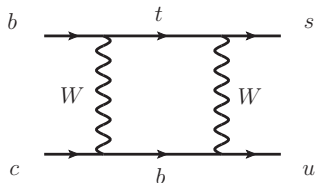
$B \rightarrow DK$



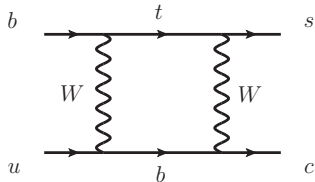
“Scherzo”

Box diagrams

- $b \rightarrow u\bar{c}s$:
 - tree level $\sim V_{ub} V_{cs}^*$
 - box diagram $\sim (V_{tb} V_{ts}^*)(V_{ub} V_{cb}^*)$
- same weak phase, no shift in γ



- $b \rightarrow c\bar{u}s$:
 - tree level $\sim V_{cb} V_{us}^*$
 - box diagram $\sim (V_{tb} V_{ts}^*)(V_{cb} V_{ub}^*)$
- different weak phase, induces $\delta\gamma$



The resulting shift $\delta\gamma^{DK}$

$$\delta\gamma^{DK} = \frac{\text{Im}\Delta C_1}{C_1 + C_2 r_A} + \frac{\text{Im}\Delta C_2}{C_1/r_A + C_2}$$

- Here,

$$r_A = \frac{\langle K^- D^0 | Q_2^{\bar{c}u} | B^- \rangle}{\langle K^- D^0 | Q_1^{\bar{c}u} | B^- \rangle} \approx \frac{f_D F_0^{B \rightarrow K}(0)}{f_K F_0^{B \rightarrow D}(0)} \approx 0.4$$

- and $Q_1^{\bar{c}u} = (\bar{c}b)_{V-A}(\bar{s}u)_{V-A}$, $Q_2^{\bar{c}u} = (\bar{s}b)_{V-A}(\bar{c}u)_{V-A}$.
- Full RG analysis (resumming leading QCD logs) yields

$$\delta\gamma^{DK} / \gamma \lesssim \mathcal{O}(10^{-7})$$

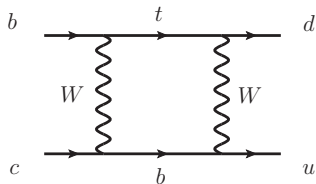
$$B \rightarrow D\pi$$



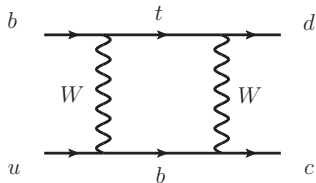
“Forte vivace”

Box diagrams

- $b \rightarrow u\bar{c}d$:
 - tree level $\sim V_{ub} V_{cd}^*$
 - box diagram $\sim (V_{tb} V_{td}^*)(V_{ub} V_{cb}^*)$
- different weak phase, induces $\delta\gamma$



- $b \rightarrow c\bar{u}d$:
 - tree level $\sim V_{cb} V_{ud}^*$
 - box diagram $\sim (V_{tb} V_{td}^*)(V_{cb} V_{ub}^*)$
- different weak phase, induces $\delta\gamma$
- CKM-suppressed by 10^{-2} – neglect!



The resulting shift $\delta\gamma^{D\pi}$

$$\delta\gamma^{D\pi} = -\frac{\text{Im}\Delta C_1}{C_1 + C_2 r_{A'}} - \frac{\text{Im}\Delta C_2}{C_1/r_{A'} + C_2}$$

- Here,

$$r_{A'} = \frac{\langle \pi^- D^0 | Q_2^{\bar{u}c} | B^- \rangle}{\langle \pi^- D^0 | Q_1^{\bar{u}c} | B^- \rangle} = ?? N_c = 3??$$

- **problematic** – note $C_1(m_b) = 1.10$, $C_2(m_b) = -0.24$
- For $r_{A'} \approx 4.6$ the denominator in $\delta\gamma^{D\pi}$ vanishes!

$$\delta\gamma^{D\pi}/\gamma \lesssim \mathcal{O}(10^{-4})$$

Tree-level New Physics?

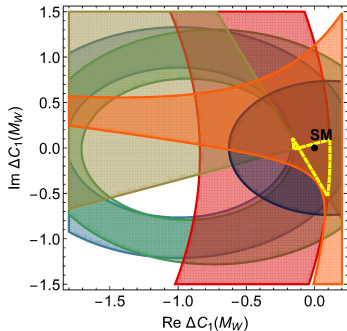


“Fortissimo vivacissimo”

Tree-level New Physics?

$$\delta\gamma \approx \frac{\text{Im}\Delta C_2 + r_{A'}\text{Im}\Delta C_1}{C_2 + r_{A'}C_1} - \frac{\text{Im}\Delta C_2 + r_A\text{Im}\Delta C_1}{C_2 + r_A C_1} \approx (r_{A'} - r_A) \frac{\text{Im}\Delta C_1}{C_2}$$

- Sizeable contributions to $\text{Im}\Delta C_1$, $\text{Im}\Delta C_2$ are **not excluded** from data
- $\delta\gamma^{\text{NP}} = \mathcal{O}(5^\circ)$ for generic $r_{A'}$
- However, **unknown** $r_{A'}$ makes contribution to γ **hard to quantify**
- \rightarrow Talk by G. Tetlalmatzi-Xolocotzi



Tree-level New Physics?

- γ from $B \rightarrow DK$ has built-in test for NP in decay amplitude

[J. Zupan, talk at LHCb Implications 2012]

- Different r_B for B^+ and B^- :

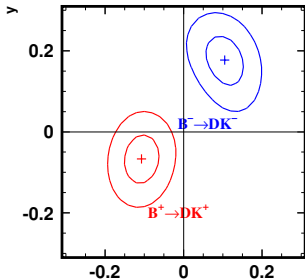
$$r_{B^+} \rightarrow |r_B e^{i(\delta_B + \gamma)} + r'_B e^{i(\delta'_B + \gamma')}|, \quad r_{B^-} \rightarrow |r_B e^{i(\delta_B - \gamma)} + r'_B e^{i(\delta'_B - \gamma')}|$$

- NP in $B \rightarrow DK$ amplitudes if

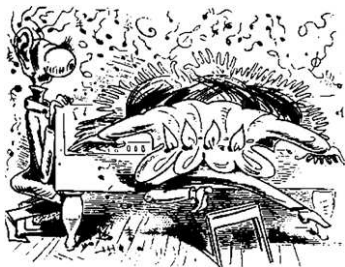
$$|r_{B^+}| \neq |r_{B^-}|$$

- $x_{\pm} = r_B \cos(\gamma \pm \delta_B)$,
 $y_{\pm} = \pm r_B \sin(\gamma \pm \delta_B)$

- E.g. measured by Belle [Belle 2008]



Finale Furioso



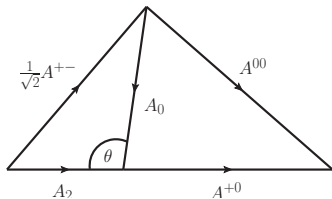
- γ from $B \rightarrow DK$ is theoretically extremely clean,
 - $\delta\gamma^{DK}/\gamma \lesssim \mathcal{O}(10^{-7})$
- γ from $B \rightarrow D\pi$ is most likely theoretically extremely clean,
 - $\delta\gamma^{D\pi}/\gamma \lesssim \mathcal{O}(10^{-4})$
- Sensitive test of NP

Backup

Tree vs. loop

- From $B \rightarrow \pi\pi$ [Gronau, London 1990]

$$\text{Im}\xi_{+-} = \text{Im} \left[e^{-2i(\beta+\gamma)} \frac{1 - \bar{A}_0/\bar{A}_2}{1 - A_0/A_2} \right]$$
$$\text{Im}\xi_{00} = \text{Im} \left[e^{-2i(\beta+\gamma)} \frac{1 + \bar{A}_0/2\bar{A}_2}{1 + A_0/2A_2} \right]$$



- Determines $\sin 2\alpha$, $\alpha = \pi - \beta - \gamma$
- From $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$, using U spin, extract β and γ simultaneously [Fleischer 1999]