Theory of γ/ϕ_3 from tree decays

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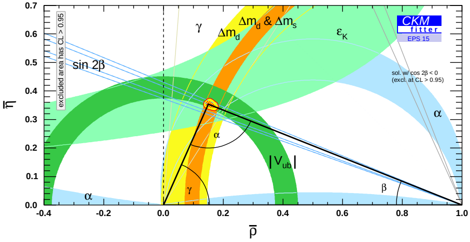
Partially based on
Brod, Zupan, JHEP 1401 (2014) 051
Brod, Phys.Lett. B743 (2015) 56-60

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

"Introduzione"

Definition of γ

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



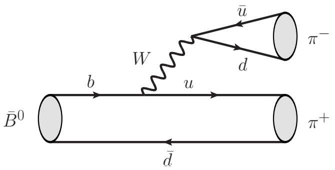
- The fundamental equation (extended version):

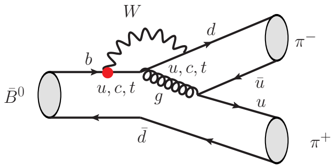
$$\gamma \equiv \phi_3 \equiv \arg(-V_{ud} V_{ub}^* / V_{cd} V_{cb}^*)$$

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

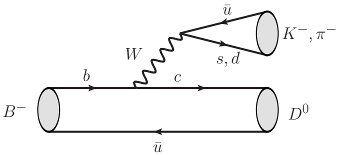
Motivation: Tree vs. Loop

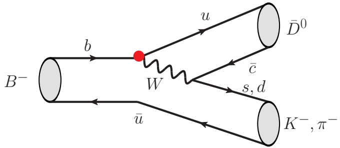
- From $B \to \pi\pi$ determine $\alpha = \pi - \beta - \gamma$ [Gronau, London 1990]
- Use $B \to \pi\pi$ and $B_s \to KK$ to extract γ [Fleischer 1999]





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

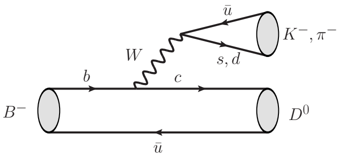




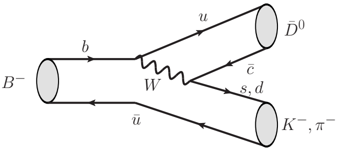
Outline

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

γ from tree decays – general idea



$\propto V_{cb} V^*_{us(d)}$



$\propto V_{ub} V^*_{cs(d)}$

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

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

Several choices for final state f in D decay

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

  [Gronau, London 1990, Gronau, Wyler 1991]
- Flavor states (e.g. $D \to \pi^-K^+, \pi^+K^-$) [Atwood, Dunietz, Soni 1997]
- Many-body final states (e.g. $D \to K_SK^+K^-, K_S\pi^+\pi^-$)

  [Giri, Grossman, Soffer, Zupan 2003; Poluektov 2004]
- Many variants:
  - Use $D^* \to D\pi^0, D\gamma$ [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]

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

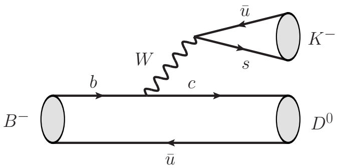
- When is the phase extracted in $B \to Dh$ not γ?
  - Subleading terms in Wolfenstein expansion
    [Grossman, Savastio 2013, Brod 2014]
  - Electroweak corrections
    [Brod, Zupan 2013; Brod 2014]
  - Tree-level new physics
    [Brod, Lenz, Tetlalmatzi-Xolocotzi, Wiebusch 2014]

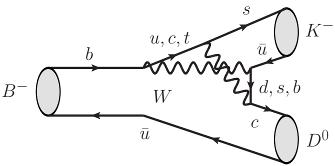
Subleading weak phases

- Extracting γ from $B \to DK$ 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 $B \to D\pi$ 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 $\to$ CP conserving
- Electroweak corrections
  - No effect from Z exchange
  - No effect from vertex corrections
  - Box diagrams can change CKM structure



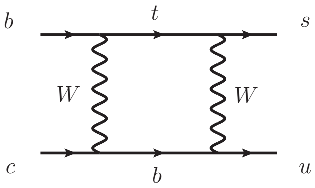


$B \to DK$

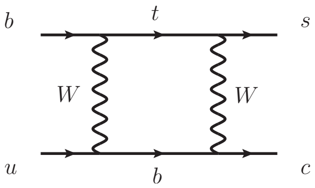
"Scherzo"

Box diagrams

- $b \to u\bar{c}s$:
  - 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



- $b \to c\bar{u}s$:
  - 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 $\delta\gamma^{DK}$

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

- Here,

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

- 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

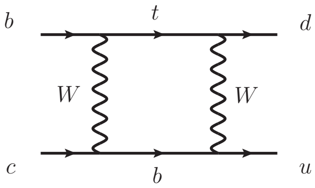
$$\boxed{\delta\gamma^{DK}/\gamma \lesssim \mathcal{O}(10^{-7})}$$

$B \to D\pi$

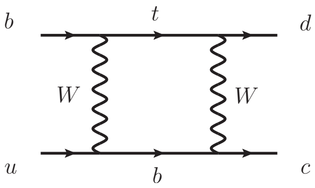
"Forte vivace"

Box diagrams

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



- $b \to c\bar{u}d$:
  - 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 $\delta\gamma^{D\pi}$

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

- 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!

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

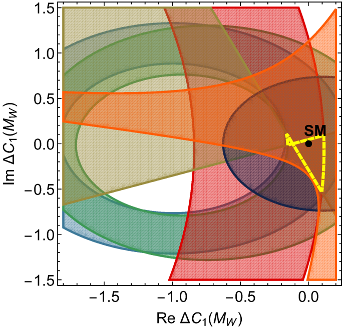
Tree-level New Physics?

"Fortissimo vivacissimo"

Tree-level New Physics?

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

- Sizeable contributions to $\mathrm{Im}\Delta C_1$, $\mathrm{Im}\Delta C_2$ are not excluded from data
- $\delta\gamma^{\mathrm{NP}} = \mathcal{O}(5^\circ)$ for generic $r_{A'}$
- However, unkown $r_{A'}$ makes contribution to γ hard to quantify



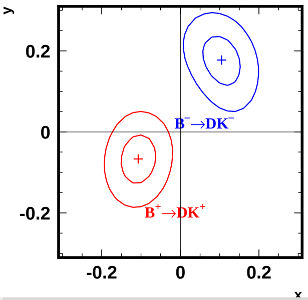
Tree-level New Physics?

- γ from $B \to DK$ has built-in test for NP in decay amplitude [J. Zupan, talk at LHCb Implications 2012]

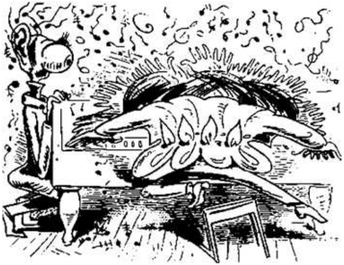
- Different r_B for B^+ and B^-:

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

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

Bravo Bravissimo

[Image credit: Wilhelm Busch]

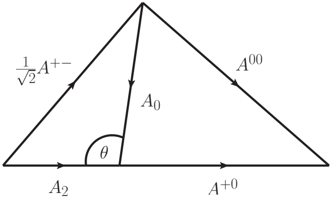
Backup

Tree vs. loop

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

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

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



- Determines $\sin 2\alpha$, $\alpha = \pi - \beta - \gamma$

- From $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$, using U spin, extract β and γ simultaneously [Fleischer 1999]