Model-independent determination of the CKM angle γ in $B^{\pm} \to (K^+K^-\pi^+\pi^-)_D h^{\pm}$ decays

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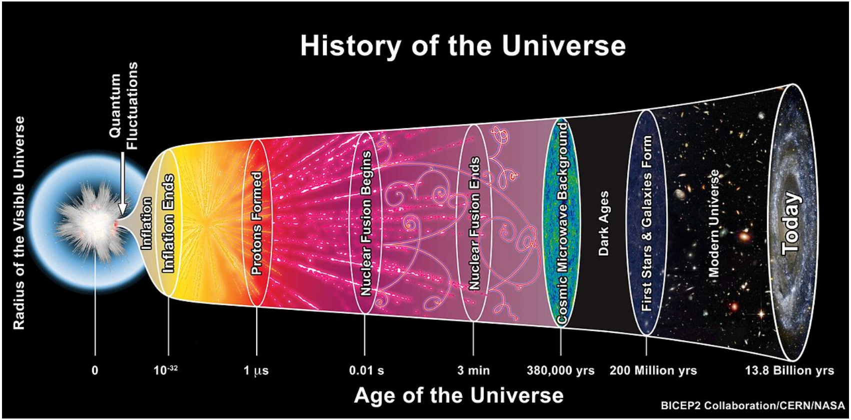
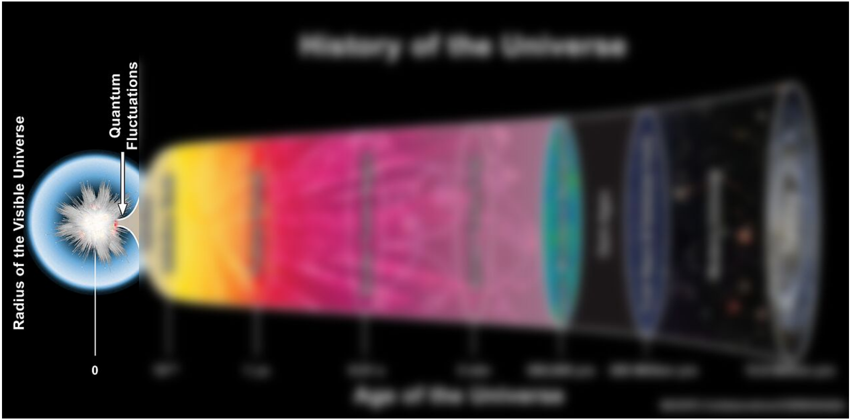
Introduction to CP violation

Big Bang and matter-antimatter asymmetry



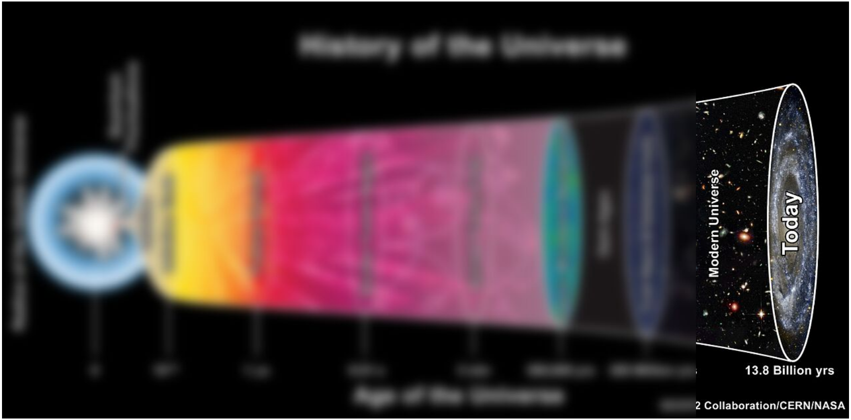
Where is the antimatter in the universe?

Big Bang and matter-antimatter asymmetry



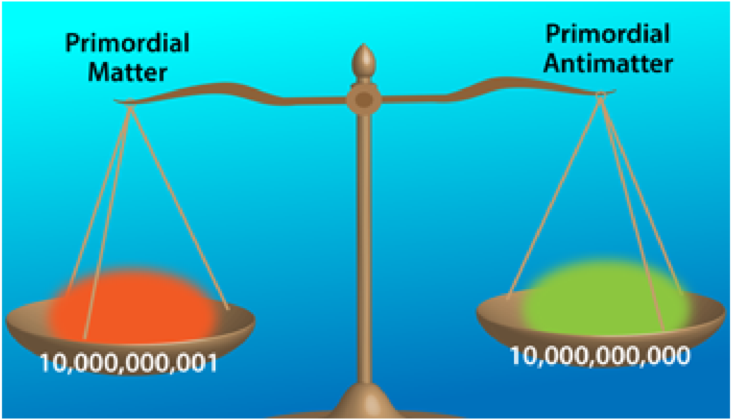
Initially equal amounts of matter and antimatter...

Big Bang and matter-antimatter asymmetry



... but today we only see matter!

Big Bang and matter-antimatter asymmetry



APS/Alan Stonebraker

The difference is very small...

Big Bang and matter-antimatter asymmetry

Quantum Diaries: Why B physics? Why not A Physics?

... but the effects we observe today are obviously huge!
How can we explain this?

CP violation

The Nobel Prize in Physics 1980

Photo from the Nobel Foundation archive.
James Watson Cronin
Prize share: 1/2

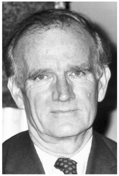


Photo from the Nobel Foundation archive.
Val Logsdon Fitch
Prize share: 1/2

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch "for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"

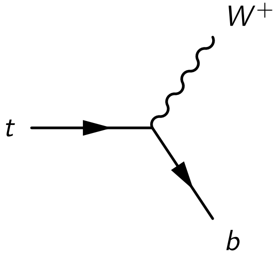
- *CP* violation discovery in 1964
- Phys. Rev. Lett. **13**, 138
- Observed $K_L^0 \to \pi^+\pi^-$
- Since, *CP* violation has also been observed in the B, B_s and D systems

Can Standard Model CPV explain the matter-antimatter asymmetry?
Or, could it be physics beyond the SM?

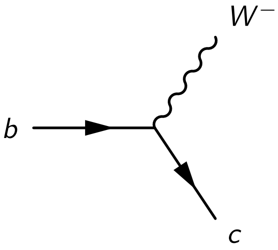
The CKM matrix and the Unitary Triangle

In SM, the charged current $W^{\pm}$ interactions couple (left-handed) up- and down-type quarks, given by

$$\frac{-g}{\sqrt{2}}\begin{bmatrix}\bar{u}_L & \bar{c}_L & \bar{t}_L\end{bmatrix}\gamma^{\mu}W_{\mu}V_{\mathrm{CKM}}\begin{bmatrix}d_L\\ s_L\\ b_L\end{bmatrix}+\mathrm{h.c.}$$



(a) $t \to bW^+$



(b) $b \to cW^-$

The CKM matrix and the Unitary Triangle

The Cabbibo-Kobayashi-Maskawa matrix V_{CKM},

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

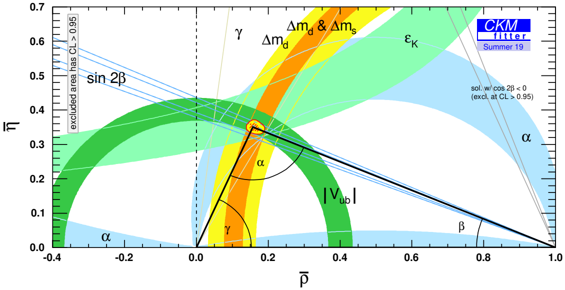
must be a unitary matrix: $V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = I \implies$

$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

Represent this constraint as a triangle in the complex plane: Unitary Triangle

The CKM matrix and the Unitary Triangle

- CPV in SM is described by the Unitary Triangle, with angles α, β, γ
- The angle $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is very important:
    1. Negligible theoretical uncertainties: Ideal SM benchmark
    2. Accessible at tree level: Indirectly probe New Physics that enter loops
    3. Compare with α, β measurements: Is the Unitary Triangle a triangle?

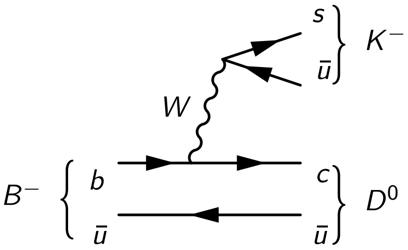


CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005)

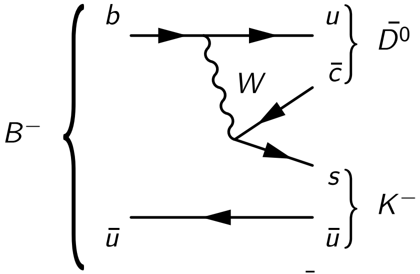
How to measure γ?

Sensitivity through interference

Measure γ through interference effects in $B^{\pm} \to DK^{\pm}$



Favoured $B^- \to D^0 K^-$



Suppressed $B^- \to \bar{D}^0 K^-$

- Superposition of D^0 and $\bar{D}^0$
- $b \to u\bar{c}s$ and $b \to c\bar{u}s$ interference $\to$ Sensitivity to γ

$$\mathcal{A}(B^-) \propto \mathcal{A}(D^0) + r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$$
$$\mathcal{A}(B^+) \propto \mathcal{A}(\bar{D}^0) + r_B e^{i(\delta_B + \gamma)} \mathcal{A}(D^0)$$

- The magnitude of interference effects governed by $r_B \approx 0.1$

D decays to a CP eigenstate

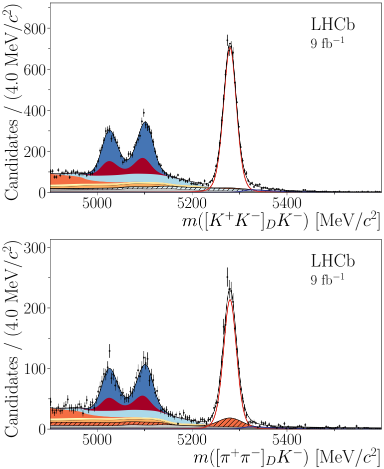
A well known strategy is to consider D decays to a CP eigenstate

For CP eigenstates, $\mathcal{A}(D^0) = \mathcal{A}(\bar{D}^0)$

$$\begin{tikzcd}
 & D^0K^- \arrow[dr, bend left, "\mathcal{A}_{D^0}"] & \\
B^- \arrow[ur, bend left, "\mathcal{A}_B"] \arrow[dr, bend right, "\mathcal{A}_B r_B e^{i(\delta_B - \gamma)}"'] & & DK^- \\
 & \bar{D}^0K^- \arrow[ur, bend right, "\mathcal{A}_{D^0}"'] &
\end{tikzcd}$$

$$|\mathcal{A}(B^-)|^2 \propto |\mathcal{A}(D^0)|^2 \left(1 + r_B^2 + 2r_B\cos(\delta_B - \gamma)\right)$$

D decays to a CP eigenstate



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In $B^\pm \to [h^+h^-]_D K^\pm$, we see large CPV effects!

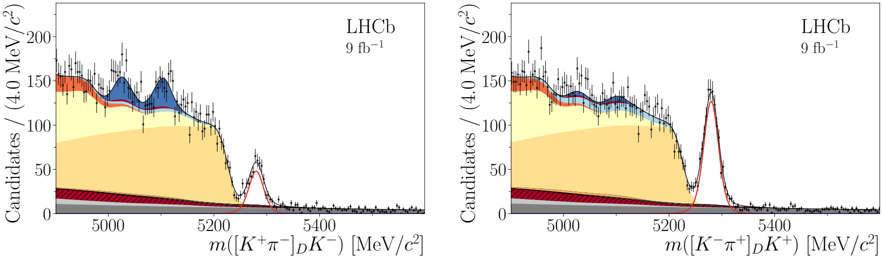
Doubly Suppressed Cabbibo D decays

Can we enhance the interference effects?

Yes! Use a Doubly Suppressed Cabbibo decay: $\mathcal{A}(D^0) = r_D e^{i\delta_D}\mathcal{A}(\bar{D}^0)$

$$\begin{tikzcd}
 & D^0 K^- \arrow[dr, bend left, "r_D e^{i\delta_D}\mathcal{A}_{\bar{D}^0}"] & \\
B^- \arrow[ur, bend left, "\mathcal{A}_B"] \arrow[dr, bend right, "\mathcal{A}_B r_B e^{i(\delta_B-\gamma)}"'] & & DK^- \\
 & \bar{D}^0 K^- \arrow[ur, bend right, "\mathcal{A}_{\bar{D}^0}"'] &
\end{tikzcd}$$

$$|\mathcal{A}(B^-)|^2 \propto |\mathcal{A}(D^0)|^2\left(r_D^2 + r_B^2 + 2r_B r_D\cos(\delta_B - \gamma + \delta_D)\right)$$



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$B^\pm \to [K^\mp\pi^\pm]_D K^\pm$ has lower statistics, but a spectacular asymmetry!

Additionally, the partially reconstructed background has an equal but opposite asymmetry

The $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$ decay mode

The $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$ decay mode

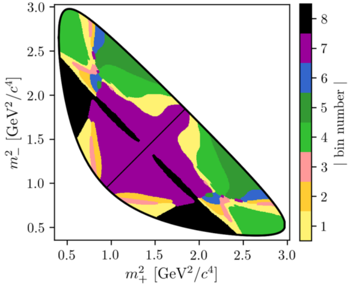
The mode $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$ has been proposed as a powerful channel for a measurement of γ

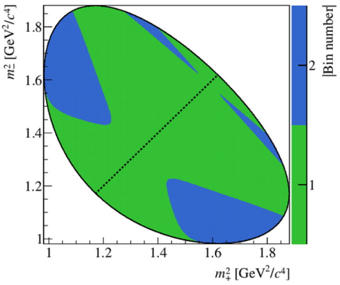
- First proposed by J. Rademacker and G. Wilkinson
  - Phys. Lett. **B647** (2007) 400
  - Amplitude model by FOCUS
  - Expected γ precision from amplitude fit with 1000 candidates: 14°
- State of the art amplitude analysis by LHCb:
  - JHEP **02** (2019) 126
  - Exploits the huge dataset of charm decays at LHCb
- $D \to K^+K^-\pi^+\pi^-$ has the best of both worlds:
  - Singly Suppressed Cabbibo decay: Larger branching fraction
  - Large interference effects in some regions of phase space

Binned γ analysis of the $D \to K^+K^-\pi^+\pi^-$ mode

Binned measurement of γ

- Final measurement will be model-independent
  - Poor binning reduces statistical sensitivity $\rightarrow$ No bias!
- Need strong phases of D decay $\rightarrow$ Measure at BESIII
- LHCb-PAPER-2020-019: $B^{\pm} \rightarrow Dh^{\pm}$, $D \rightarrow K_S^0 h^+ h^-$
  - Single most precise measurement: $\gamma = (68.7^{+5.2}_{-5.1})^{\circ}$





The BPGGSZ method

- $B^{\pm} \to Dh^{\pm}$ amplitude:

$$\mathcal{A}(B^-) = \mathcal{A}(D^0) + r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$$
$$\mathcal{A}(B^+) = \mathcal{A}(\bar{D}^0) + r_B e^{i(\delta_B + \gamma)} \mathcal{A}(D^0)$$

- $\mathcal{A}(D^0)$ and $\mathcal{A}(\bar{D}^0)$ depend on D phase space
- Strong-phase difference of D^0 and $\bar{D}^0$ decays inaccessible at LHCb
- Model-independent measurement: Integrate over bins of phase space

Event yield in bin i

$$N_i^- = h_{B^-}\left(F_i + (x_-^2 + y_-^2)\bar{F}_i + 2\sqrt{F_i\bar{F}_i}(x_- c_i + y_- s_i)\right)$$
$$N_{-i}^+ = h_{B^+}\left(F_i + (x_+^2 + y_+^2)\bar{F}_i + 2\sqrt{F_i\bar{F}_i}(x_+ c_i + y_+ s_i)\right)$$

The BPGGSZ method

Event yield in bin i

$N_i^- = h_{B^-}\left(F_i + (x_-^2 + y_-^2)\bar{F}_i + 2\sqrt{F_i\bar{F}_i}(x_- c_i + y_- s_i)\right)$
$N_{-i}^+ = h_{B^+}\left(F_i + (x_+^2 + y_+^2)\bar{F}_i + 2\sqrt{F_i\bar{F}_i}(x_+ c_i + y_+ s_i)\right)$

- CP observables:
  - $x_\pm^{DK} = r_B^{DK}\cos\left(\delta_B^{DK} \pm \gamma\right), \quad y_\pm^{DK} = r_B^{DK}\sin\left(\delta_B^{DK} \pm \gamma\right)$
  - $x_\xi^{D\pi} = \mathrm{Re}(\xi^{D\pi}),\ y_\xi^{D\pi} = \mathrm{Im}(\xi^{D\pi}) \qquad \left(\xi^{D\pi} = \frac{r_B^{D\pi}}{r_B^{DK}} e^{i(\delta_B^{D\pi} - \delta_B^{DK})}\right)$
- Fractional bin yield:
  - $F_i = \frac{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)|^2}{\sum_j \int_j \mathrm{d}\Phi |\mathcal{A}(D^0)|^2}$
  - Floated in the fit, mostly constrained by $B^\pm \to D\pi^\pm$
- Amplitude averaged strong phases can be obtained from BESIII:

$$c_i = \frac{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)||\mathcal{A}(\bar{D}^0)|\cos(\delta_D)}{\sqrt{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)|^2 \int_i \mathrm{d}\Phi \left|\mathcal{A}(\bar{D}^0)\right|^2}} \qquad s_i = \frac{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)||\mathcal{A}(\bar{D}^0)|\sin(\delta_D)}{\sqrt{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)|^2 \int_i \mathrm{d}\Phi \left|\mathcal{A}(\bar{D}^0)\right|^2}}$$

Binning scheme

Binning scheme requirements

A binning scheme must satisfy the following:

- Minimal dilution of strong phases when integrating over bins
- Enhance interference between $B^\pm \to D^0 h^\pm$ and $B^\pm \to \bar{D}^0 h^\pm$

How to bin a 5-dimensional phase space?

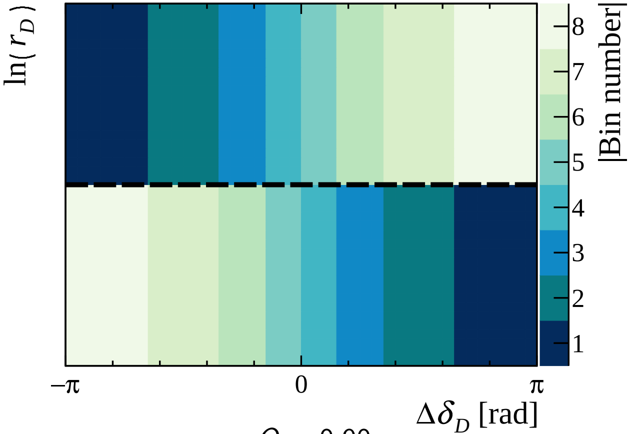
- Generate C++ code for LHCb amplitude model using AmpGen[1]
- For each $B^\pm$ candidate, calculate

$$\frac{\mathcal{A}(D^0)}{\mathcal{A}(\bar{D}^0)} = r_D e^{i\delta_D}$$

- Bin along δ_D and r_D, maximize Q-value to optimize

[1] AmpGen by Tim Evans

Binning scheme



$Q = 0.90$

Bins $i < 0$ on top, $i > 0$ below