LHCb Sensitivity to γ with $B^0 \rightarrow D^0 K^*$ decay

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Physics at LHC

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Outline

- The Physics
  - the weak phase γ
  - extraction of γ with $B^0 \to D^0 K^*$ Decays
- Event Selection at LHCb
- Annual Event Yields and Backgrounds
- Sensitivity to γ
  - Toy Monte Carlo
  - Joint Probability Density Function
- Summary

The weak phase γ

The unitarity of CKM matrix gives nine relations

Two of them are relevant for B physics:

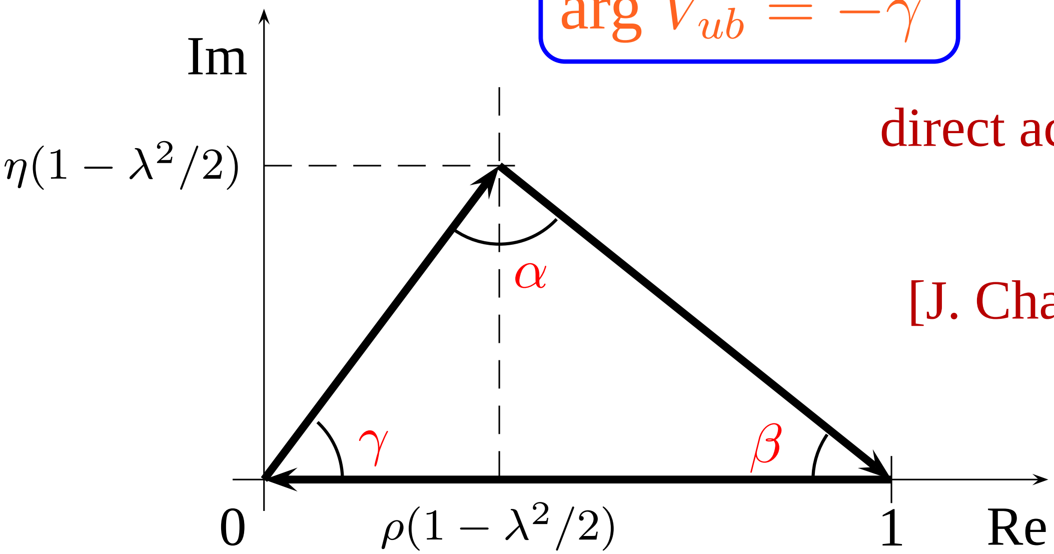
$V_{cd}V_{cb}^* + V_{td}V_{tb}^* + V_{ud}V_{ub}^* = 0$

$V_{ts}V_{us}^* + V_{td}V_{ud}^* + V_{tb}V_{ub}^* = 0$

Using Wolfenstein parametrization

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

$\arg V_{ub} = -\gamma$



There is no
direct accurate measurement of γ yet

from CKM fitters
[J. Charles *et al.* hep-ph/0406186]
$50° < \gamma < 72°$

Extraction of γ

- The strategy is to use $D^0\overline{D}^0$mixing [M. Gronau and D. Wyler]
- The modes of interest are $B^0 \rightarrow D_1 K^{*0}$ and $\overline{B}^0 \rightarrow D_1 \overline{K}^{*0}$ [Dunietz]

  $D_1 = \frac{1}{\sqrt{2}}(D^0 + \overline{D}^0)$
- $K^{*0} \rightarrow K^+\pi^-$ occurs 2/3 of the time
- sign of K tags the B^0 flavour - Self tagging mode

  no need for time-dependent measurements!
- $D_1 \rightarrow \pi^+\pi^-, K^+K^-$ even CP eigenstates
- CP violation in the D system is supposed to be negligible
- New physics in $D^0\overline{D}^0$mixing could affect the value of γ!

Extraction of γ

$$\mathcal{A}(\mathrm{B}^0 \to \mathrm{D}_1 \mathrm{K}^{*0})$$
$$= \frac{1}{\sqrt{2}}[\mathcal{A}(\mathrm{B}^0 \to \bar{\mathrm{D}}^0 \mathrm{K}^{*0}) + \mathcal{A}(\mathrm{B}^0 \to \mathrm{D}^0 \mathrm{K}^{*0})]$$
$$= \frac{1}{\sqrt{2}}[|A_1| + |A_2| \mathrm{e}^{i(\delta+\gamma)}]$$
$$\equiv \frac{1}{\sqrt{2}} A_3$$

$$\mathcal{A}(\bar{\mathrm{B}}^0 \to \mathrm{D}_1 \bar{\mathrm{K}}^{*0})$$
$$= \frac{1}{\sqrt{2}}[\mathcal{A}(\bar{\mathrm{B}}^0 \to \mathrm{D}^0 \bar{\mathrm{K}}^{*0}) + \mathcal{A}(\bar{\mathrm{B}}^0 \to \bar{\mathrm{D}}^0 \bar{\mathrm{K}}^{*0})]$$
$$= \frac{1}{\sqrt{2}}[|A_1| + |A_2| \mathrm{e}^{i(\delta-\gamma)}]$$
$$\equiv \frac{1}{\sqrt{2}} A_4.$$

$$\Gamma(\mathrm{B}^0 \to \mathrm{D}_1 \mathrm{K}^{*0}) \neq \Gamma(\overline{\mathrm{B}}^0 \to \mathrm{D}_1 \overline{\mathrm{K}}^{*0})$$
$$\Gamma(\mathrm{B}^0 \to \overline{\mathrm{D}}^0 \mathrm{K}^{*0}) = \Gamma(\overline{\mathrm{B}}^0 \to \mathrm{D}^0 \overline{\mathrm{K}}^{*0})$$
$$\Gamma(\mathrm{B}^0 \to \mathrm{D}^0 \mathrm{K}^{*}) = \Gamma(\overline{\mathrm{B}}^0 \to \overline{\mathrm{D}^0} \overline{\mathrm{K}}^{*0})$$

Extraction of γ

$$\mathcal{A}(\mathrm{B}^0 \to \mathrm{D}_1\mathrm{K}^{*0}) = \frac{1}{\sqrt{2}}[\mathcal{A}(\mathrm{B}^0 \to \bar{\mathrm{D}}^0\mathrm{K}^{*0}) + \mathcal{A}(\mathrm{B}^0 \to \mathrm{D}^0\mathrm{K}^{*0})]$$

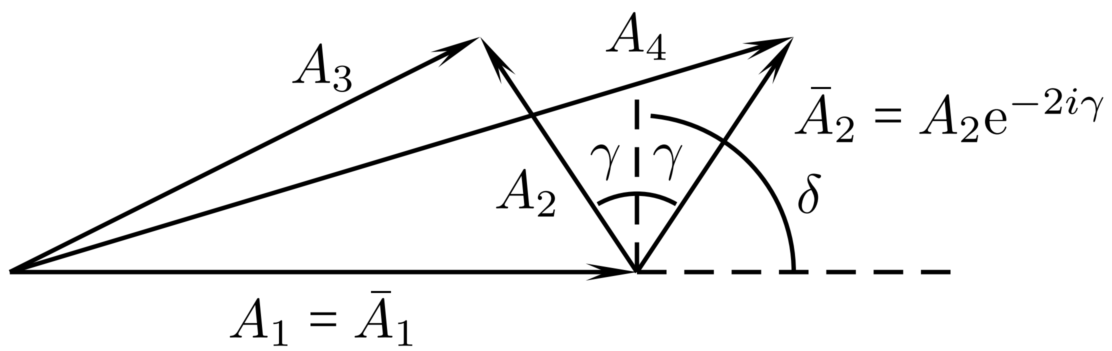
$$A_3 = |A_1| + |A_2|\mathrm{e}^{i(\delta+\gamma)}$$

$$\mathcal{A}(\bar{\mathrm{B}}^0 \to \mathrm{D}_1\bar{\mathrm{K}}^{*0}) = \frac{1}{\sqrt{2}}[\mathcal{A}(\bar{\mathrm{B}}^0 \to \mathrm{D}^0\bar{\mathrm{K}}^{*0}) + \mathcal{A}(\bar{\mathrm{B}}^0 \to \bar{\mathrm{D}}^0\bar{\mathrm{K}}^{*0})]$$

$$A_4 = |A_1| + |A_2|\mathrm{e}^{i(\delta-\gamma)}$$

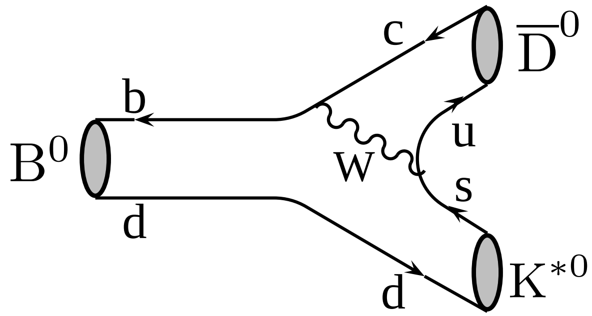
$$\cos(\delta+\gamma) = \frac{A_3^2 - A_1^2 - A_2^2}{2A_1A_2}$$

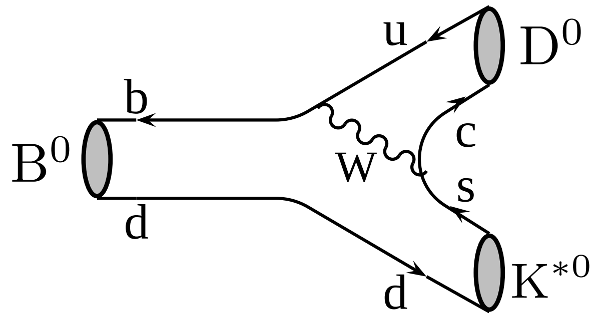
$$\cos(\delta-\gamma) = \frac{A_4^2 - A_1^2 - A_2^2}{2A_1A_2}$$



B^0 versus B^+

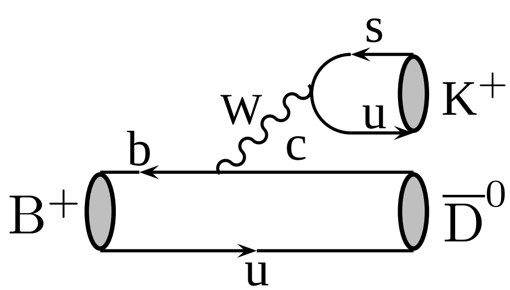
$B^0 \rightarrow D^0K^*$

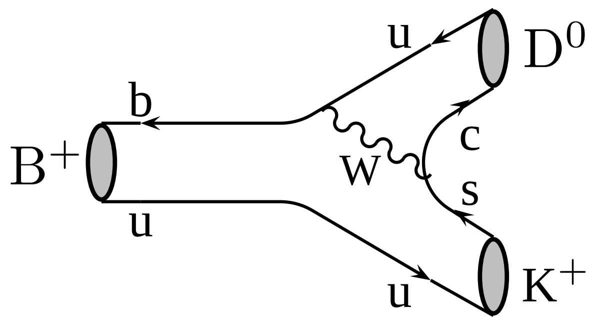




$$\frac{\|A(B^0 \rightarrow D^0 K^{*0})\|}{\|A(B^0 \rightarrow \bar{D}^0 K^{*0})\|} \approx O(\tfrac{1}{2})$$

$B^+ \rightarrow D^0K^+$





$$\frac{\|A(B^+ \rightarrow D^0 K^+)\|}{\|A(B^+ \rightarrow \bar{D}^0 K^+)\|} \approx O(\tfrac{1}{10})$$

Simulation

- pp @ $\sqrt{s} = 14$TeV – Pythia 6.2.
  Includes pileup and spill over with L = 2×10^{32}cm^{-2}s^{-1}
- decay of unstable particles – QQ package
- interaction with detector – Geant 3
- reoptimized LHCb geometry and material described in detail

$50\mathrm{k}\ \mathrm{B}^0 \to \overline{\mathrm{D}}^0(\mathrm{K}\pi)\mathrm{K}^{*0}$

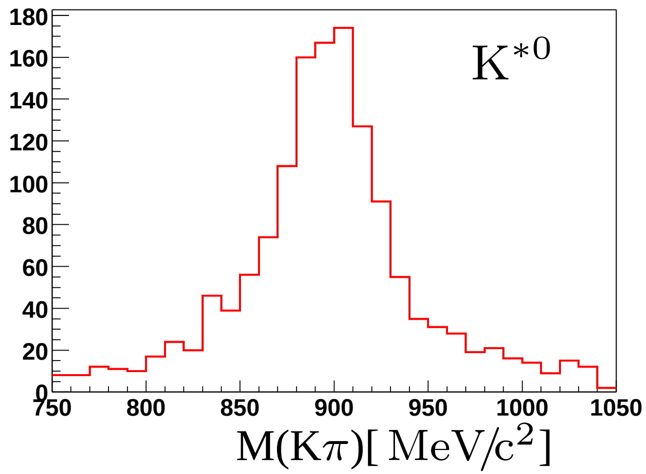
$50\mathrm{k}\ \mathrm{B}^0 \to \mathrm{D}^0(\mathrm{KK})\mathrm{K}^{*0}$

$30\mathrm{k}\ \mathrm{B}^0 \to \mathrm{D}^0(\pi\pi)\mathrm{K}^{*0}$

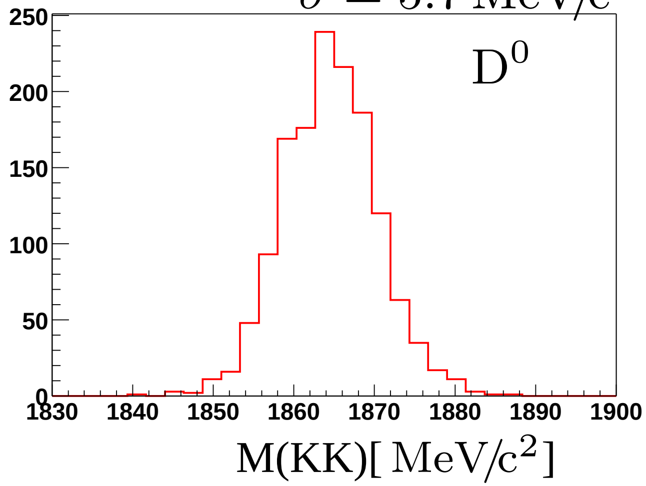
$10\mathrm{M}\ \ \text{inclusive}\ \ \mathrm{b}\overline{\mathrm{b}}$

K^{*0} and D^0 Pre-selection

- $K^{*0} \to K^{\pm}\pi^{\mp}$: opposite charged K,$\pi$ using standard LHCb PID
- $D^0 \to K^-\pi^+$, $\overline{D}^0 \to K^+\pi^-$, $D_1 \to K^+K^-$ and $D_1 \to \pi^+\pi^-$
- $\frac{IP_{K,\pi}}{\sigma}$, $\frac{IP_{K^{*0}}}{\sigma}$, $\frac{IP_{D^0}}{\sigma} > 1$
- χ^2 of the vertex fit < 30
- $P_T(D^0, K^{*0}) > 500$ MeV/c
- $|\Delta M_{K\pi}| < 150\,\mathrm{MeV/c^2}$
- $|\Delta M_{D^0}| < 60\,\mathrm{MeV/c^2}$
- χ^2 of the mass constrained vertex fit for $D^0 < 25$

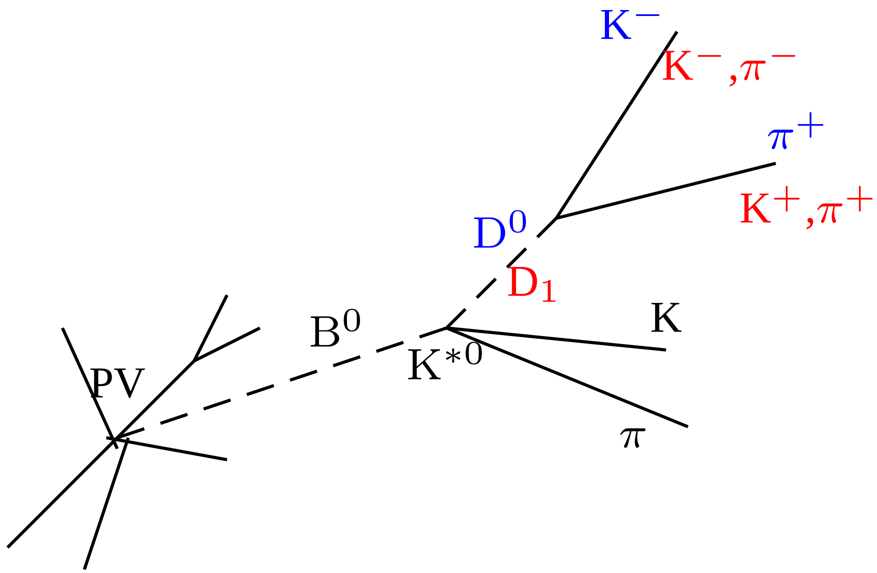


$\sigma = 5.7\,\mathrm{MeV/c^2}$

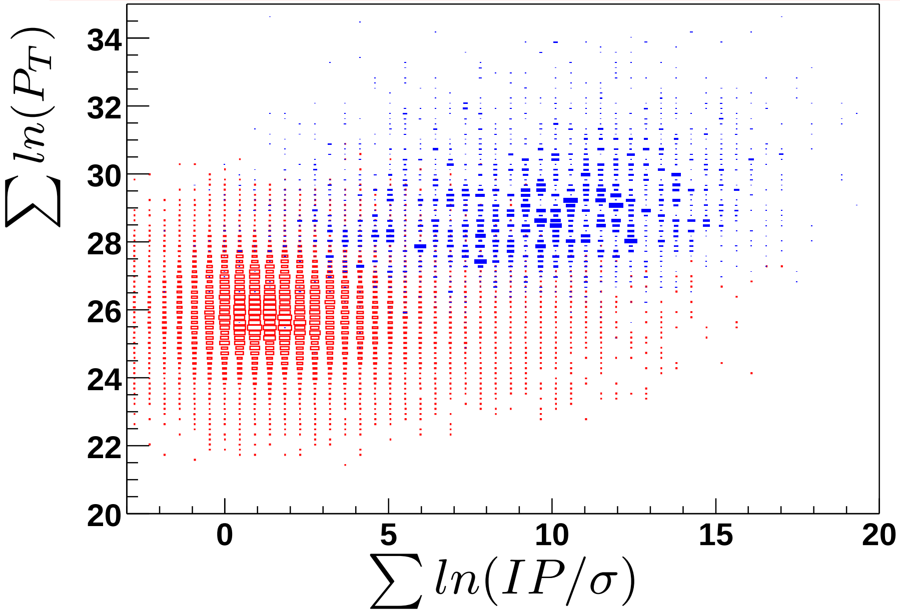


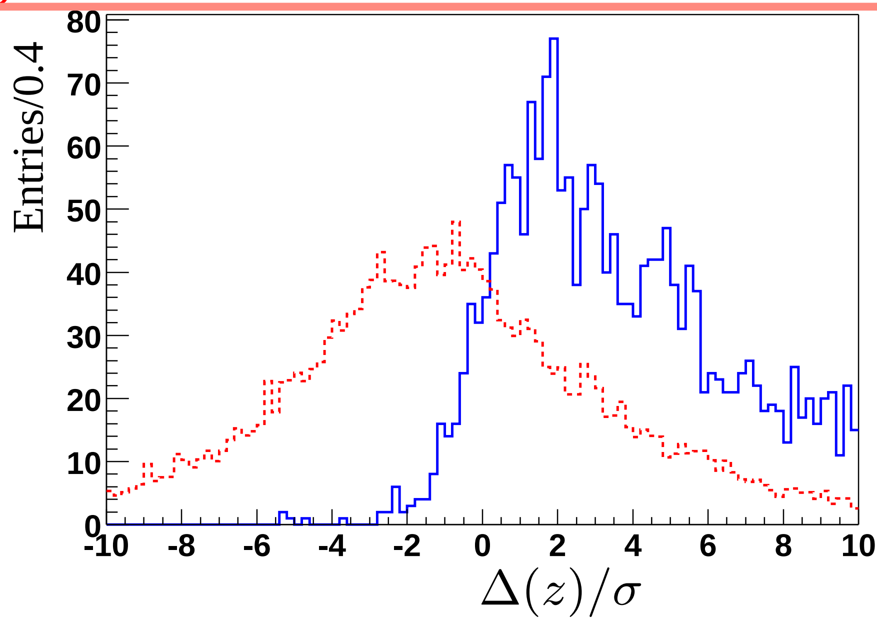
B^0 **Reconstruction**

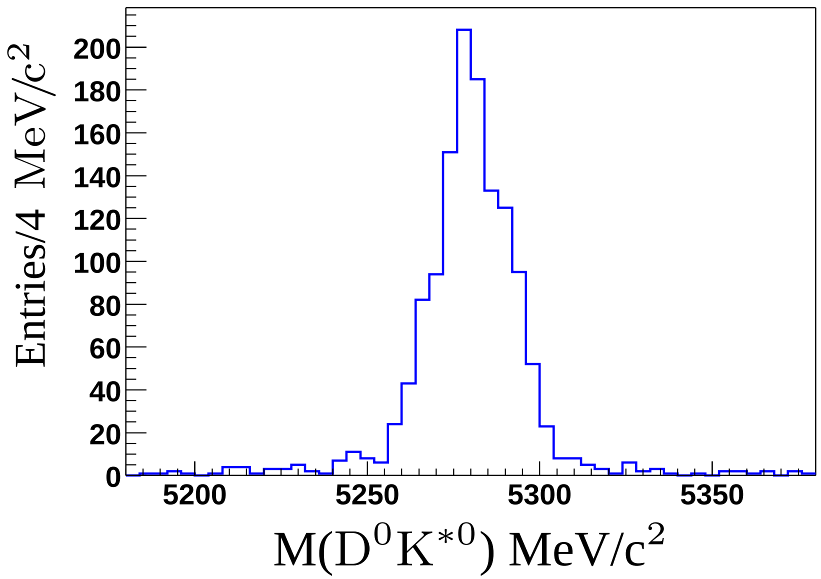
- 3 different sets of cuts values, one for each D^0 state.
- Combine K^{*0} and D^0 into a vertex with a χ^2 cut
- reconstructed mass $< \pm 25\,\mathrm{MeV/c}^2$ of true B^0 mass.
- Choose a primary vertex as the one which gives the smallest IP significance.



signal/background







$\sigma = 11$ MeV/c^2

Event Yield and B/S ratios

	$B^0 \to \overline{D}^0(K\pi)K^{*0}$	$B^0 \to D_1(KK)K^{*0}$	$B^0 \to D_1(\pi\pi)K^{*0}$
Generated events	49500	49000	30000
Selection $\epsilon(4\pi)$	0.93%	1.20%	1.06%
L0/L1 trigger $\epsilon(4\pi)$	0.31%	0.35%	0.41%
Annual yield (S)	3000	540	221
B/S (inclusive $b\bar{b}$)	[0.00, 0.58]	[0.00, 2.93]	[0.00, 8.51]

No events selected in the 10M $b\bar{b}$ sample
in an enlarged mass window of $\pm 500\,\mathrm{MeV/c^2}$

BR for D_1 modes depends on γ

AY and B/S for D_1 modes
assume $\gamma = 65°$ and $\delta = 0°$
[...] indicates 90% CL limits.

$BR_{vis}(B^0 \to \overline{D}^0(K^+\pi^-)K^{*0})$	$(1.2 \pm 0.3) \times 10^{-6}$
$BR_{vis}(B^0 \to D^0(KK)K^{*0})$	$(0.13 \pm 0.03) \times 10^{-6}$
$BR_{vis}(B^0 \to D^0(\pi^+\pi^-)K^{*0})$	$(0.046 \pm 0.012) \times 10^{-6}$

Calculation of Amplitudes

$$A_1 = A(\mathrm{B}^0 \to \overline{\mathrm{D}}^0\mathrm{K}^{*0}) = \bar{\mathrm{A}}_1$$
$$A_2 = A(\mathrm{B}^0 \to \mathrm{D}^0\mathrm{K}^{*}) = e^{i2\gamma}\bar{A}_2$$
$$A_3 = \sqrt{2}A(\mathrm{B}^0 \to \mathrm{D}_1\mathrm{K}^{*0}) = \mathrm{A}_1 + \mathrm{A}_2\mathrm{e}^{\mathrm{i}(\delta+\gamma)}$$
$$A_4 = \sqrt{2}A(\overline{\mathrm{B}}^0 \to \mathrm{D}_1\overline{\mathrm{K}}^{*0}) = \mathrm{A}_1 + \mathrm{A}_2\mathrm{e}^{\mathrm{i}(\delta-\gamma)}$$

- $A_1 = \sqrt{\frac{S_1}{BR_1 \times \epsilon_1}}$ $\quad \sigma(A_1) = \frac{1}{2}\sqrt{1 + B_1/S_1}\,\frac{A_1}{\sqrt{S_1}}$
- $A_2 = 0.147 A_1$ $\quad \sigma(A_2) = 0.147\sigma(A_1)$ [PDG 2003]
  ($\bar{\rho} = 0.162 \quad \bar{\eta} = 0.347$ [Battaglia *et al.* hep-ph/0304132])
- $A_3 = \sqrt{\frac{1}{2}[A_1^2 + A_2^2 + 2A_1A_2\cos(\delta+\gamma)]}$
  $A_4 = \sqrt{\frac{1}{2}[A_1^2 + A_2^2 + 2A_1A_2\cos(\delta-\gamma)]}$
  $S_{3,4} = A_{3,4}^2 \times BR_{3,4} \times \epsilon_{3,4}$
  $\sigma(A_{3,4}) = \frac{1}{2}\sqrt{1 + B_{3,4}/S_{3,4}}\,\frac{A_{3,4}}{\sqrt{S_{3,4}}}$

A_3 and A_4 are obtained with modes $\mathrm{B}^0 \to \mathrm{D}_1(\mathrm{K}^+\mathrm{K}^-)\mathrm{K}^{*0}$ and $\mathrm{B}^0 \to \mathrm{D}_1(\pi^+\pi^-)\mathrm{K}^{*0}$.

Fast Monte Carlo Approach

A Gaussian random number is added to each amplitude according to its respective uncertainty.

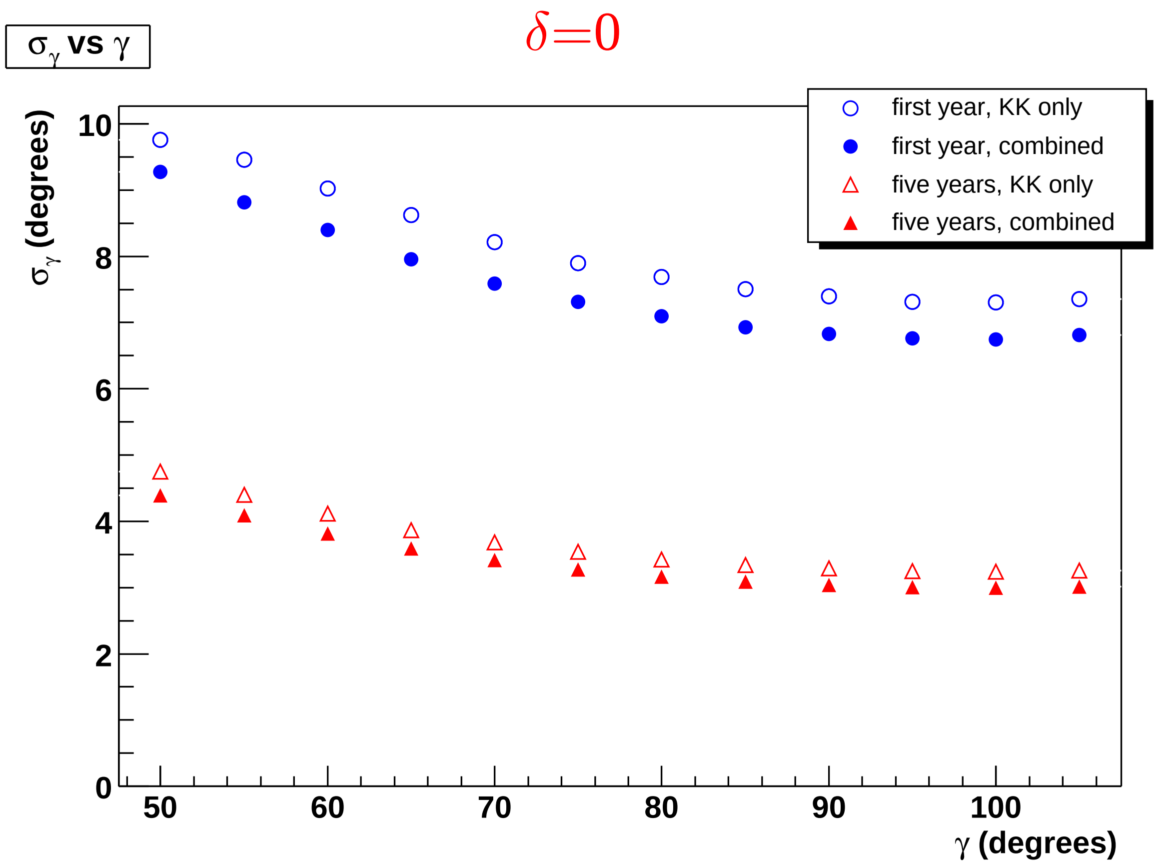
$$\gamma = \frac{1}{2}\{cos^{-1}(\frac{A_3^2-A_1^2-A_2^2}{2A_1A_2}) - cos^{-1}(\frac{A_4^2-A_1^2-A_2^2}{2A_1A_2})\}$$

A Gaussian fit is performed to the γ distribution.
Uncertainty obtained from the fit.

When $|cos(\gamma)| > 1$ the event is removed. This bias is

- small for the values of γ and δ in the intervals: $55^\circ < \gamma < 105^\circ$ and $-20^\circ < \delta < 20^\circ$.
- large for larger values of δ or when $\delta = \gamma$

Fast Monte Carlo Approach



Joint Probability Density Function Approach

The probability density function of γ and δ can be obtained from the combined χ^2 function of the four independent sides of the triangles.

$$\chi^2(A_1, A_2, A_3, A_4) = \sum_{i=1}^{4} \left(\frac{A_i - \bar{A}_i}{\sigma(\bar{A}_i)}\right)^2,$$

A_3 and A_4 can be expressed in terms of γ and δ

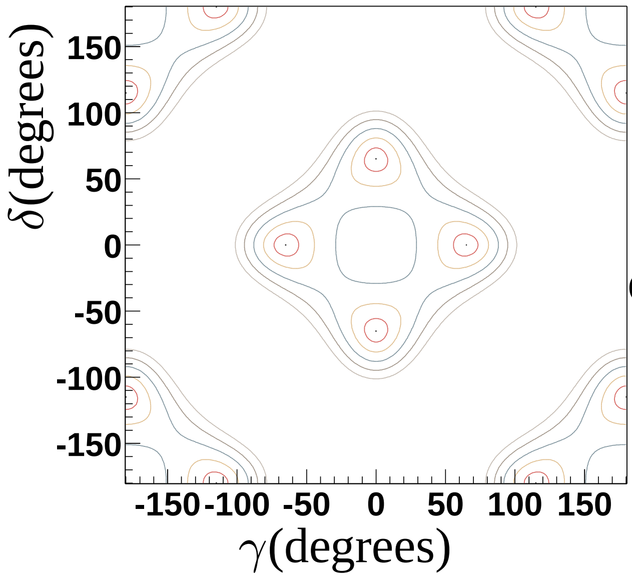
$$A_3^2 = A_1^2 + A_2^2 + 2A_1A_2cos(\delta + \gamma),$$

$$A_4^2 = A_1^2 + A_2^2 + 2A_1A_2cos(\delta - \gamma).$$

$$\mathcal{J}(\gamma, \delta) = F \int dA_1 \int dA_2 \mathrm{e}^{-\frac{1}{2}\chi^2(A_1, A_2, \gamma, \delta)}$$

integration performed in the interval $A_{1,2} - 7\sigma(A_{1,2})$ to $A_{1,2} + 7\sigma(A_{1,2})$

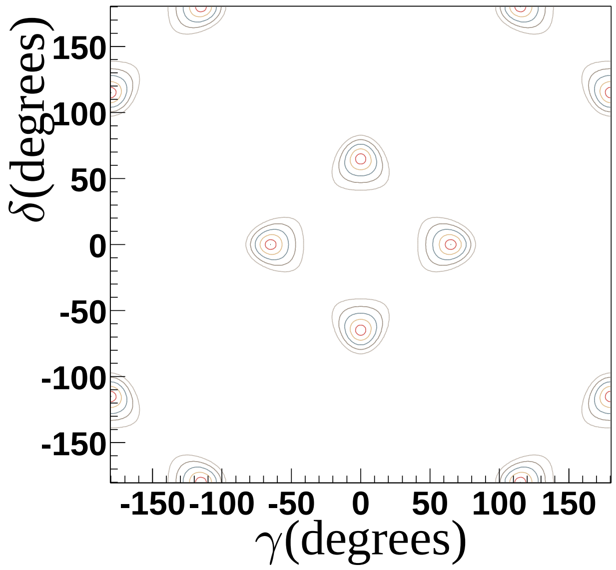
JPDF Results



$\gamma = 65°$

$\delta = 0°$

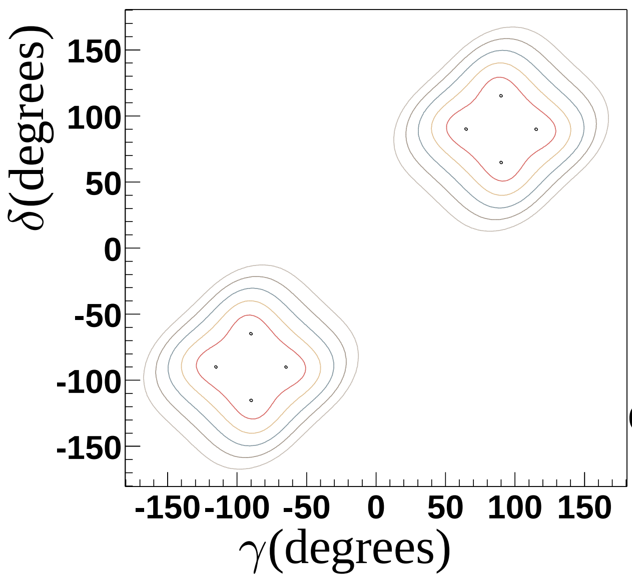
one year



$\gamma = 65°$

$\delta = 0°$

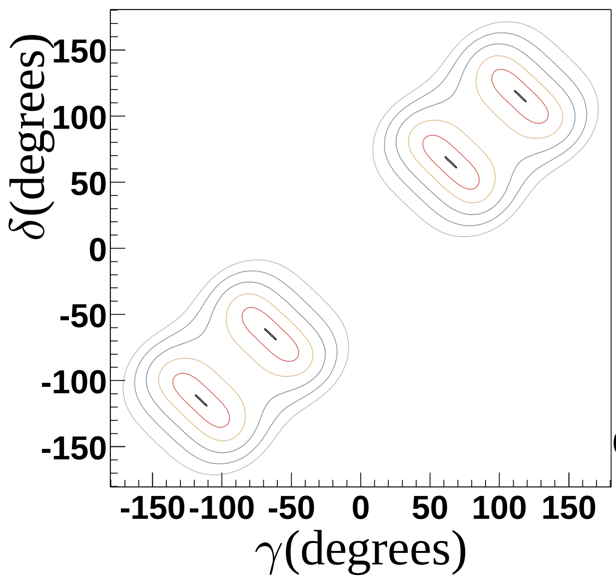
5 years



$\gamma = 65°$

$\delta = 90°$

one year



$\gamma = 65°$

$\delta = 65°$

one year

Summary

- We have presented a way of extracting γ using $D^0\ \overline{D}^0$ mixing with modes $B^0 \rightarrow D_1 K^{*0}$ and $\overline{B}^0 \rightarrow D_1 \overline{K}^{*0}$
- The D_1 has been reconstructed through (KK) and ($\pi\pi$) modes.
- LHCb can well reconstruct it with B^0 mass resolution of 11 $\mathrm{MeV/c^2}$
- An annual yield of $\approx$ 3000, 540 and 221 for $B^0 \rightarrow \overline{D}^0(K\pi)K^{*0}$, $B^0 \rightarrow D_1(KK)K^{*0}$ and $B^0 \rightarrow D_1(\pi\pi)K^{*0}$, respectively
- Two approaches have been used to measure the sensitivity.
- Both give compatible results in the range $55^\circ < \gamma < 105^\circ$ and $-20^\circ < \delta < 20^\circ$
- As an example, the uncertainty on γ is estimated to be of the order of 4° after 5 years of data taking for $\gamma = 65^\circ$ and $\delta = 0^\circ$.