Measuring the CKM γ angle with $B^0 \to DK^{*0}$ decay at LHCb

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The γ angle of the CKM theory

- Quark mixing:

  mass eigenstates ≠ interaction eigenstates

  → Cabibbo-Kobayashi-Maskawa matrix (CKM)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix

- 3 x 3 matrix → can be parametrised by three real parameters and a complex phase

  Usually: Wolfenstein parametrisation

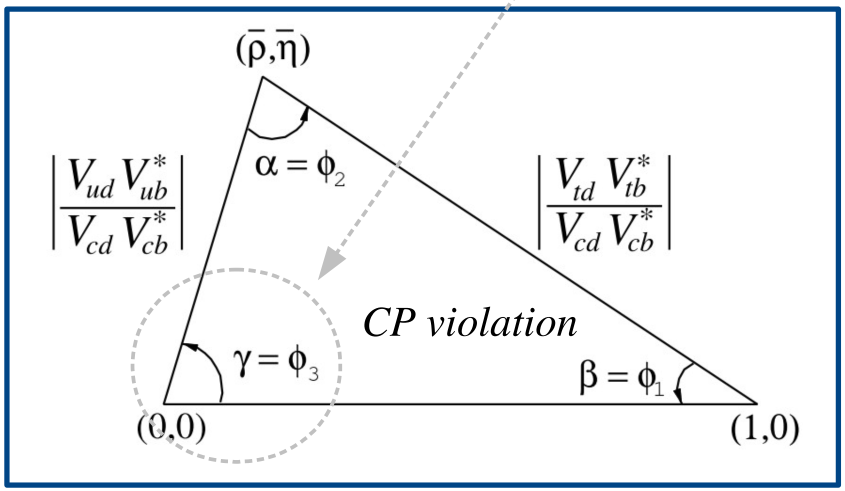
$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Rotation matrix → unitarity

$$V V^* = I$$

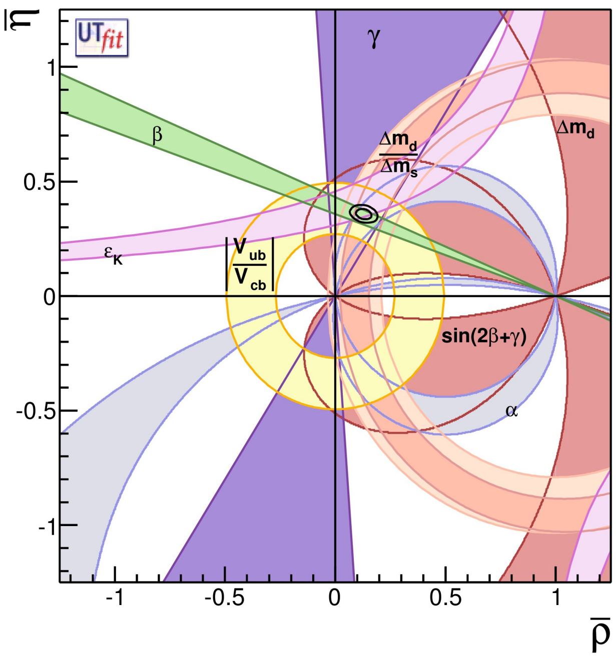
$$\underbrace{V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0}$$

The γ angle



CKM Unitary Triangle

State of the art

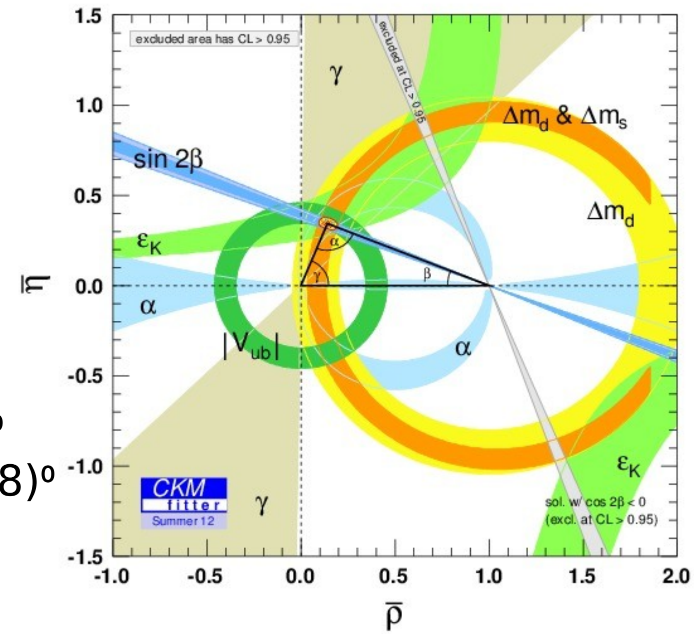


<u>UTfit</u>:

α = (88.7 ± 3.1)º
β = (21.95 ± 0.87)º
γ = (69.2 ± 3.2)º

<u>CKM fitter</u>:

α = (90.5 ± 4.3)º
β = (21.73 ± 0.78)º
γ = (67.7 ± 4.3)º



- Unitary Triangle well constrained from *B* factories, Tevatron and LHC results.
- Global fits combine all results in order to determine the different CKM parameters.
  - γ is the one known with the largest uncertainty.

γ^{BaBar} = (69 ± 17)º
γ^{Belle} = (68 ± 15)º
γ^{LHCb} = (71.1 ± 16.7)º

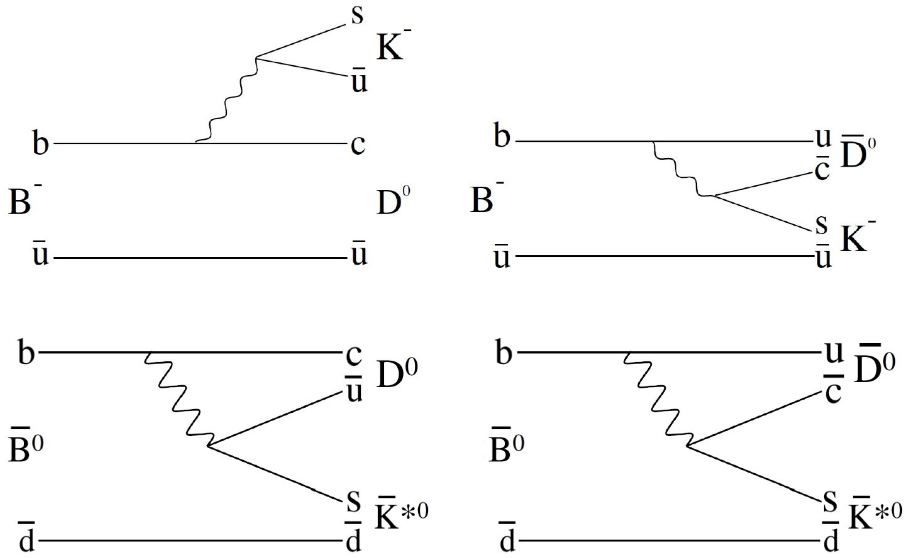
Large uncertainties in the γ direct measurements compared with the global fits. Need to measure γ precisely to check the Unitary Triangle consistency.

Measuring γ at the tree level

- From the Unitary Triangle:

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

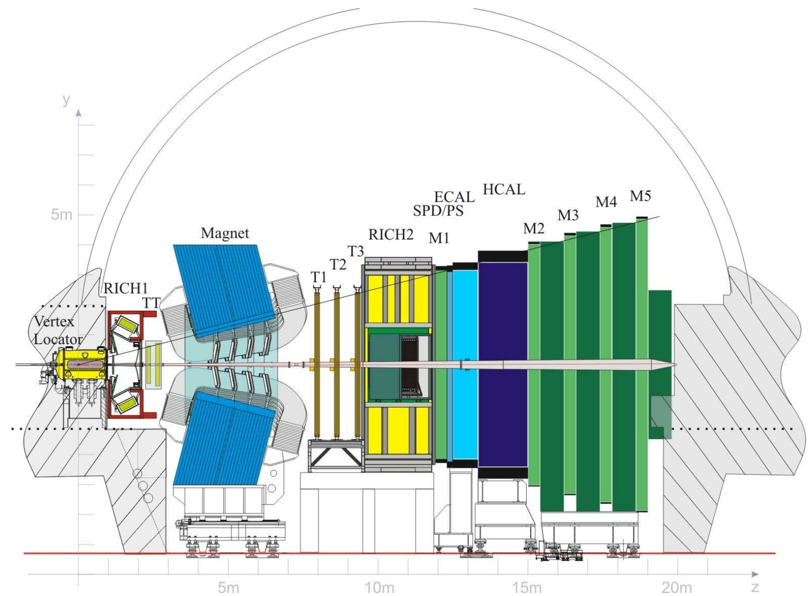
- With tree diagrams, γ is measured from decays involving the interference of a $b \to u$ (V_{ub}) transition and a $b \to c$ (V_{bc}) transition.
  - No physics beyond the Standard Model contributions (no loops).
  - Typically decays of the type $B^{\pm,0} \to DK^{\pm,*0}$.



- When the same final state is accessible for both D^0 and $\overline{D}^0$, the interference can be studied.
  - Access to γ from the measurement of *CP* observables (asymmetries between $B^{0,+}$ and $\overline{B}^{0,-}$ signal yields).

$B \to DK$ decays at LHCb

- LHCb detector well suited for the study of heavy flavoured hadronic decays, thanks to:
  - Geometry, $2 < \eta < 5$.
  - Vertex locator:
    - Precise reconstruction of primary and secondary vertices (resolution = 45 fs for $B_s \to J/\psi\, \varphi$ and for $B_s \to D_s\, \pi$).
  - RICHs particle identification detectors:
    - Excellent $K - \pi$ separation (K identification efficiency = 95 % with 5 % of π misidentification).
  - LHC collision energy:
    - All type of B hadrons produced ($B^{\pm}$, B^0, B_s^0, b-baryons, $B_c^{\pm}$).
    - Big boost, long-lived particles fly over long distances.
      - Easy secondary vertex separation.
  - Hadronic trigger (HCAL+ECAL):
    - Able to select B decays to open charm purely hadronic final states.

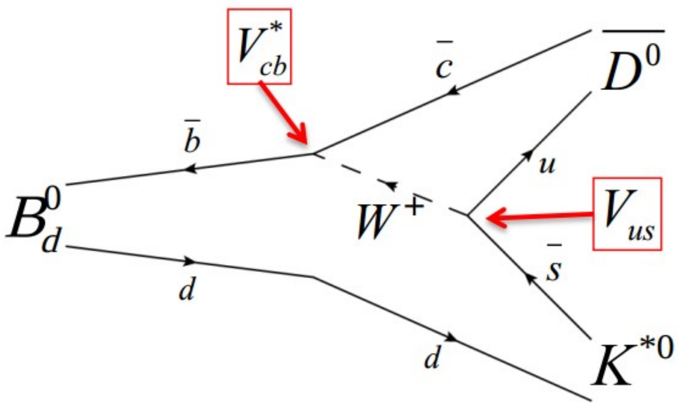


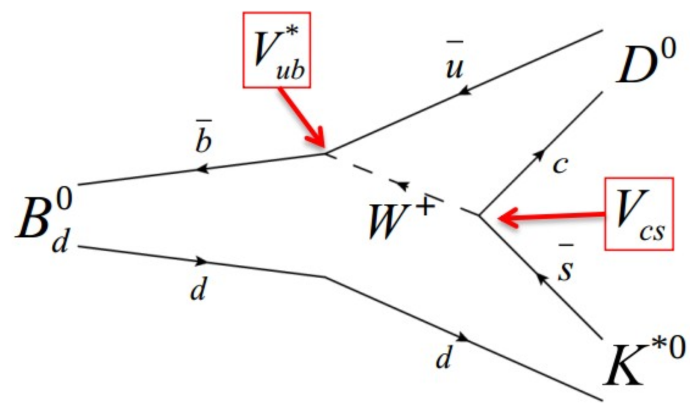
More information in
S. T'jampens talk of yesterday

$B^0 \to D\,K^{*0}$ analysis at LHCb

$B^0 \to D K^{*0}$ introduction

- Sensitivity to the CKM weak phase γ:





  - Both decays are colour suppressed → larger ratio of amplitudes between the two diagrams, enhanced interference (compared to $B^{\pm} \to DK^{\pm}$, which is the "usual" mode for measuring γ).
  - Small branching fractions.
  - $K^{*0} \to K^+ \pi^-$ → self-tagged decay, the flavour of the B known from the sign of the K from the K^{*0} in the final state.
  - Different methods to extract γ depending on the D decay mode:
    - GLW (Gronau, London, Wyler): $D \to K^+ K^-$ (CP eigenstates).
    - ADS (Atwood, Dunietz, Soni): suppressed $D \to K^- \pi^+$ (flavour specific final state).
    - GGSZ (Giri, Grossman, Soffer, Zupan): $D \to$ multi-body decay.

Analysis overview

- $B^0 \to D K^{*0}$, $D \to K^+ K^-$ (signal channel), $D \to K^+ \pi^-$ (favoured, normalisation channel)
- GLW analysis, sensitive to the γ angle.
- Cut-based analysis using 1 fb^{-1} of 2011 data.
- Measurement of CP asymmetries and ratios built from the partial widths of $B^0 \to D K^{*0}$, and its conjugate $\overline{B}^0 \to D \overline{K}^{*0}$ decay.
  - Which depend on γ.
  - Together with
    - the ratios of amplitudes $r_{B0,D}$,
    - strong phases $\delta_{B0,D}$ and the
    - K^{*0} coherence factor κ.

$$\mathcal{A}_d^{KK} = \frac{\Gamma(\overline{B}^0 \to [K^+K^-]_D\overline{K}^{*0}) - \Gamma(B^0 \to [K^+K^-]_D K^{*0})}{\Gamma(\overline{B}^0 \to [K^+K^-]_D\overline{K}^{*0}) + \Gamma(B^0 \to [K^+K^-]_D K^{*0})} = \frac{\pm 2\kappa r_{B^0} \sin\delta_{B^0} \sin\gamma}{1 + r_{B^0}^2 \pm 2\kappa r_{B^0} \cos\delta_{B^0} \cos\gamma},$$

$$\mathcal{R}_d^{KK} = \frac{\Gamma(\overline{B}^0 \to [K^+K^-]_D\overline{K}^{*0}) + \Gamma(B^0 \to [K^+K^-]_D K^{*0})}{\Gamma(\overline{B}^0 \to [K^-\pi^+]_D\overline{K}^{*0}) + \Gamma(B^0 \to [K^+\pi^-]_D K^{*0})} = \frac{1 + r_{B^0} \pm 2\kappa r_{B^0} \cos\delta_{B^0} \cos\gamma}{1 + r_{B^0}^2 r_D^2 \pm 2\kappa r_{B^0} r_D \cos(\delta_{B^0} + \delta_D) \cos\gamma}$$

$$\mathcal{A}_s^{KK} = \frac{\Gamma(B_s^0 \to [K^+K^-]_D\overline{K}^{*0}) - \Gamma(\overline{B}_s^0 \to [K^+K^-]_D K^{*0})}{\Gamma(B_s^0 \to [K^+K^-]_D\overline{K}^{*0} + \Gamma(\overline{B}_s^0 \to [K^+K^-]_D K^{*0})},$$

$$\mathcal{A}^{\text{fav}} = \frac{\Gamma(\overline{B}^0 \to [K^-\pi^+]_D\overline{K}^{*0}) - \Gamma(B^0 \to [K^+\pi^-]_D K^{*0})}{\Gamma(\overline{B}^0 \to [K^-\pi^+]_D\overline{K}^{*0}) + \Gamma(B^0 \to [K^+\pi^-]_D K^{*0})}.$$

Selection

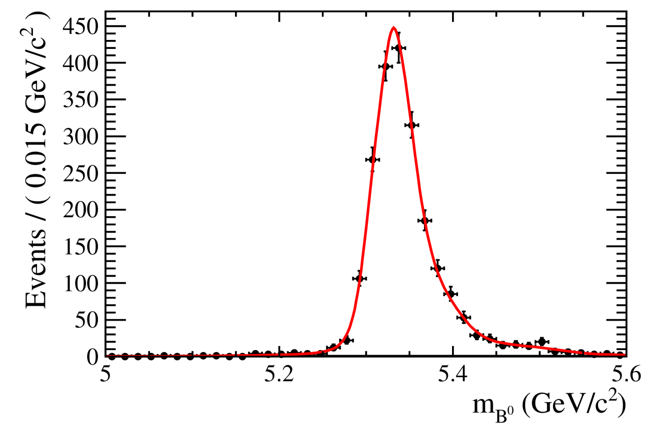
Meson	Variable	Cut value
D^0	$p_T(K^\pm, \pi^\pm)$	> 400 MeV$/c$
	$\mathrm{DLL}_{K\pi}(K^\pm)$	> 0
	$\mathrm{DLL}_{K\pi}(\pi^\pm)$	< 4
	Vertex χ^2/ndf	< 5
	Min IPχ^2	> 4
	Flight distance significance	> 2.5
	$\lvert M(K\pi) - M(D^0)\rvert$	< 20 MeV$/c^2$
K^{*0}	$p_T(K^\pm, \pi^\pm)$	> 300 MeV$/c$
	$\mathrm{DLL}_{K\pi}(K^\pm)$	> 3
	$\mathrm{DLL}_{K\pi}(\pi^\pm)$	< 3
	$\mathrm{DLL}_{pK}(K^\pm)$	< 10
	Min IPχ^2	> 25
	$\lvert M(K\pi) - M(K^{*0})\rvert$	< 50 MeV$/c^2$
B	Vertex χ^2/ndf	< 4
	Min IPχ^2	< 9
	$\cos(\theta_{\mathrm{dira}})$	> 0.99995
	$\sum_{\mathrm{tracks}} \sqrt{\mathrm{IP}\chi^2}$	> 32
	$\lvert\cos\theta^*\rvert$	> 0.4
	$\lvert M(K\pi\pi) - M(D^+)\rvert$	> 15 MeV$/c^2$
	$\lvert M(KK\pi) - M(D_s^+)\rvert$	> 15 MeV$/c^2$

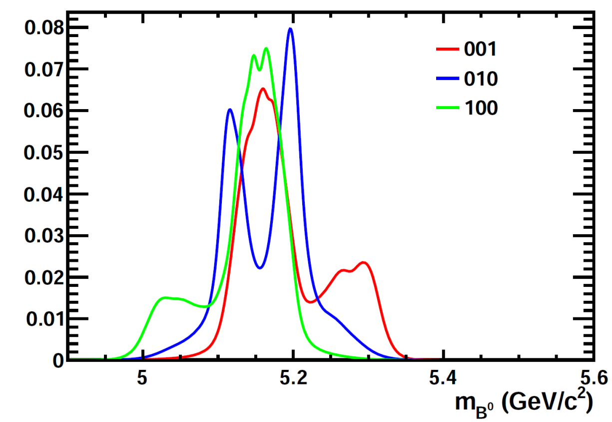
- Topology:
  - B vertex.
  - Displaced D vertex.
  - K and π from K^{*0} coming from the B vertex (wide resonance).
- Cut-based selection: kinematics, vertex quality, particle identification ($\mathrm{DLL}_{K\text{-}\pi}$).
- Background from charmless decays (such as $B^0 \to K^+ K^- K^{*0}$, etc.) removed by D meson flight distance significance cut.
- $B^0 \to D_{(s)}^{+/-} h^{-/+}$ (same particles in the final state) and $\Lambda_b^0 \to \overline{D}^0 p h^-$ (proton mis-id) contributions vetoed ($h = K, \pi$).

Mass fit philosophy

- **B^0 and $\overline{B}_s^0$ signals.**
  - Double gaussians.
  - Shape fixed from simulation samples, resolution free.
  - Same resolutions for the B^0 and $\overline{B}_s^0$ peak, $M(B_s^0)$-$M(B^0)$ fixed to PDG value.
- **Cross-feed from $B^0 \to D\,\rho^0(\pi^+\pi^-)$.**
  - One of the π from the ρ^0 is misidentified for a K.
  - Shape extracted from simulation.
- **Low mass background from partially reconstructed $B_{(s)}^0 \to D^* K^{*0}$.**
  - $D^{*0} \to D^0\,\pi^0/\gamma$, if π^0/γ not reconstructed.
  - Three possible helicity amplitudes.
  - Shapes reproduced from simulation.
- **Combinatorial background.**
  - Exponential shape.
  - Slope free, same value for both D modes.
  - B^0 and $\overline{B}^0$ yields forced to be the same in each mode.

simulation $B^0 \to D\,\rho^0(\pi^+\pi^-)$

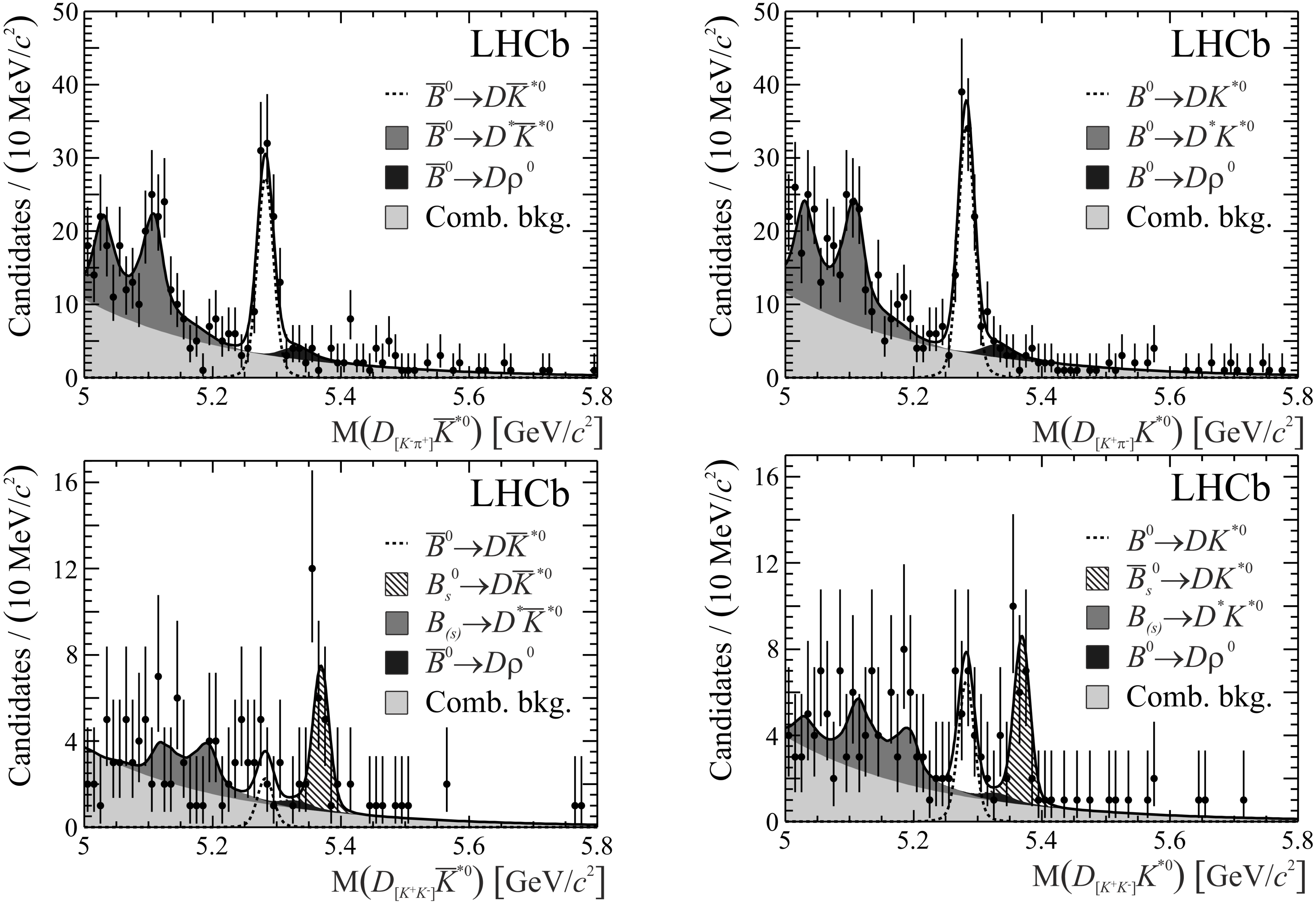




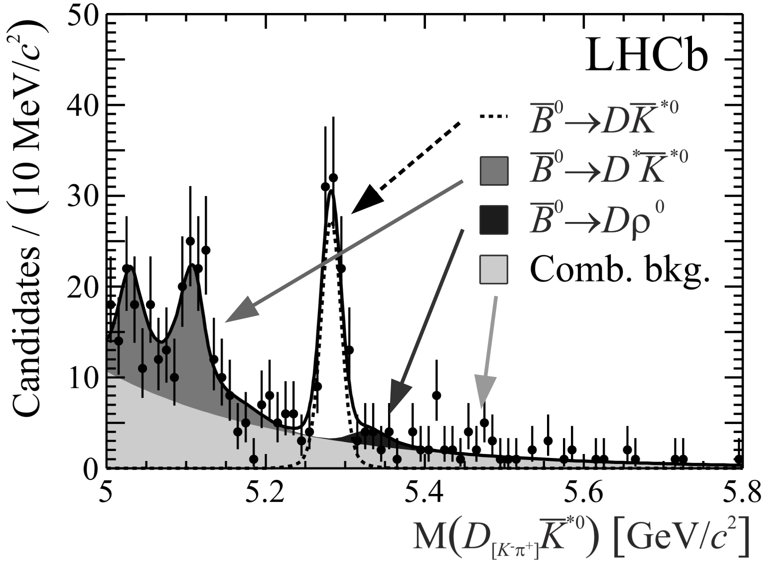
simulation $\overline{B}_s^0 \to D^* K^{*0}$

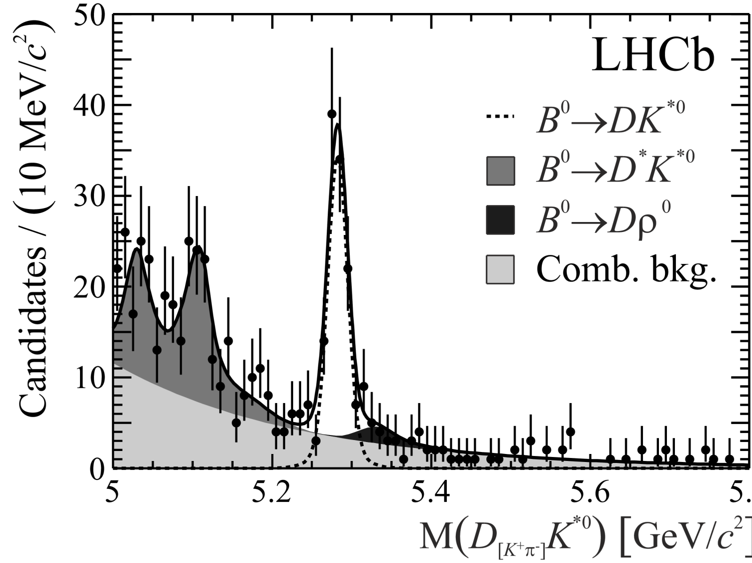
$(D^* \to D\,\gamma) + (D^* \to D\,\pi^0)$

Results


LHCb
$\overline{B}^0 \to D\overline{K}^{*0}$
$\overline{B}^0 \to D^*\overline{K}^{*0}$
$\overline{B}^0 \to D\rho^0$
Comb. bkg.
Candidates / (10 MeV/c^2)
$M(D_{[K^-\pi^+]}\overline{K}^{*0})$ [GeV/c^2]
LHCb
$B^0 \to DK^{*0}$
$B^0 \to D^*K^{*0}$
$B^0 \to D\rho^0$
Comb. bkg.
Candidates / (10 MeV/c^2)
$M(D_{[K^+\pi^-]}K^{*0})$ [GeV/c^2]
LHCb
$\overline{B}^0 \to D\overline{K}^{*0}$
$B_s^0 \to D\overline{K}^{*0}$
$B_{(s)} \to D^*\overline{K}^{*0}$
$\overline{B}^0 \to D\rho^0$
Comb. bkg.
Candidates / (10 MeV/c^2)
$M(D_{[K^+K^-]}\overline{K}^{*0})$ [GeV/c^2]
LHCb
$B^0 \to DK^{*0}$
$\overline{B}_s^0 \to DK^{*0}$
$B_{(s)} \to D^*K^{*0}$
$B^0 \to D\rho^0$
Comb. bkg.
Candidates / (10 MeV/c^2)
$M(D_{[K^+K^-]}K^{*0})$ [GeV/c^2]

$B^0 \to D K^{*0}$, $D^0 \to K^+ \pi^-$ (normalisation mode)





$N(\overline{B}^0) = 94 \pm 11$
$N(B^0) = 108\,^{+12}_{-11}$

Favoured, control mode
No *CP* asymmetry expected

$$\mathcal{A}_d^{\mathrm{fav}} = -0.08 \pm 0.08\ (\mathrm{stat}) \pm 0.01\ (\mathrm{syst})$$

$B^0 \to D K^{*0}$, $D^0 \to K^+ K^-$ (signal mode)

$$\mathcal{A}_d^{KK} = -0.45 \pm 0.23 \text{ (stat)} \pm 0.02 \text{ (syst)}$$

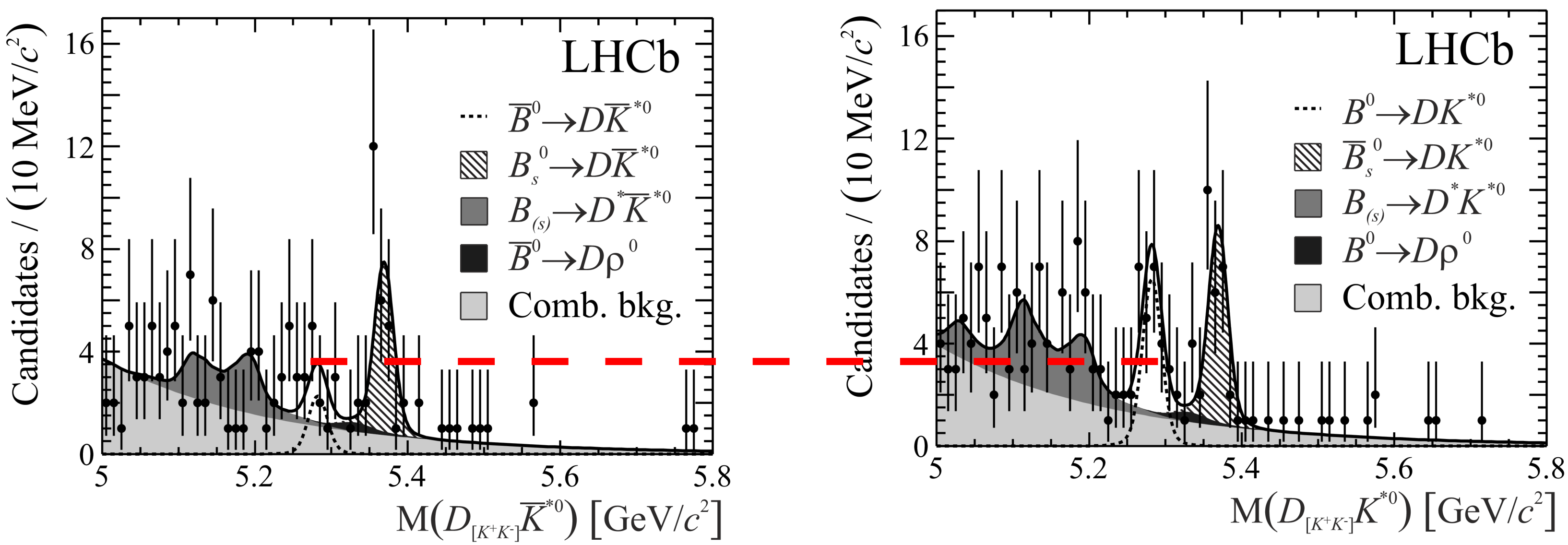
$$\mathcal{A}_s^{KK} = 0.04 \pm 0.16 \text{ (stat)} \pm 0.01 \text{ (syst)}$$

$$\mathcal{R}_d^{KK} = 1.36 \, {}^{+0.37}_{-0.32} \text{ (stat)} \pm 0.07 \text{ (syst)}$$

5.1 σ B^0 signal ($B^0 + \overline{B}^0$)

$N(\overline{B}^0)$ = 8 ± 4
$N(B^0) = 24\,^{+6}_{-5}$
$N(B_s^0) = 23\,^{+6}_{-5}$
$N(\overline{B}_s^0) = 24\,^{+6}_{-5}$

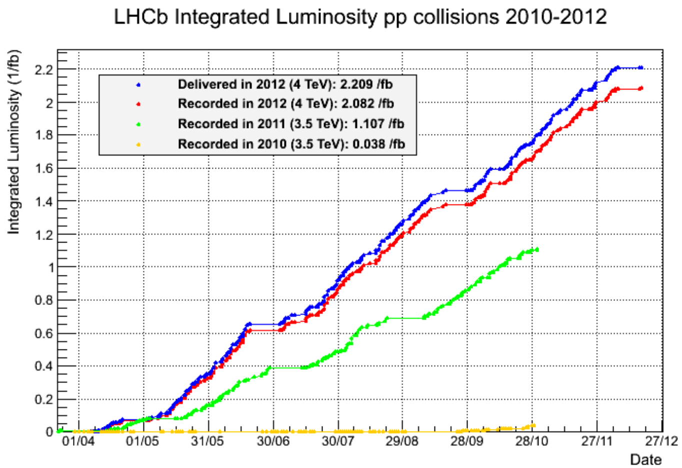
1st measurement in the $B^0 \to [K^+K^-]_D K^{*0}$ system



Conclusion

- LHCb well suited for the study of heavy flavoured hadronic decays.
- Measuring γ precisely is one of the main goals of its physics program.
- Result published on the CP asymmetries of the $B^0 \to D K^{*0}$ decay mode:

  LHCb collaboration, R. Aaij et al., *Measurement of CP observables in* $B^0 \to D K^{*0}$ *with* $D \to K^+ K^-$, JHEP **1303** (2013) 067, arXiv:1212.5205.
- Total dataset is 3 fb^{-1}.
  - 2 fb^{-1} of data collected by LHCb in 2012.
  - Plans:
    - Update this analysis with the complete data set.
    - Add new modes sensitive to γ.
      - GLW $D \to \pi^+\pi^-$.
      - ADS *suppressed* $D \to K^-\pi^+$.



- $B^0 \to D K^{*0}$ does not bring constraints to γ yet, but with the new LHCb data it becomes a promising channel.

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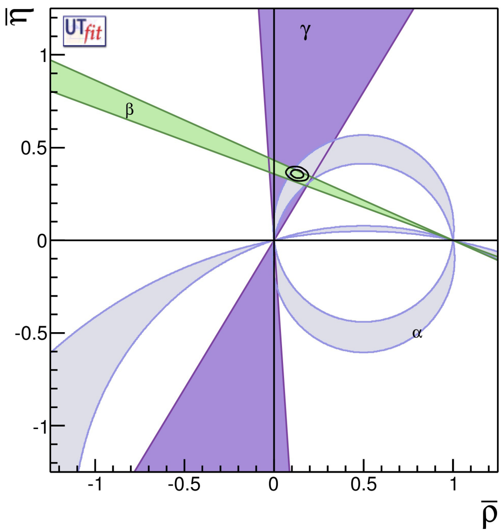
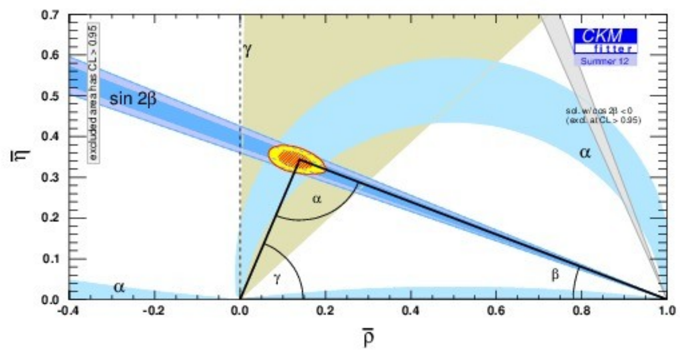
Back up

The γ angle status





Global fits

$\gamma^{UTfit} = (69.2 \pm 3.2)^o$

$\gamma^{CKMfitter} = (67.7 \pm 4.3)^o$

- Focusing on the angles:
  - γ is the one known with the largest uncertainty.

$\gamma^{BaBar} = (69 \pm 17)^o$

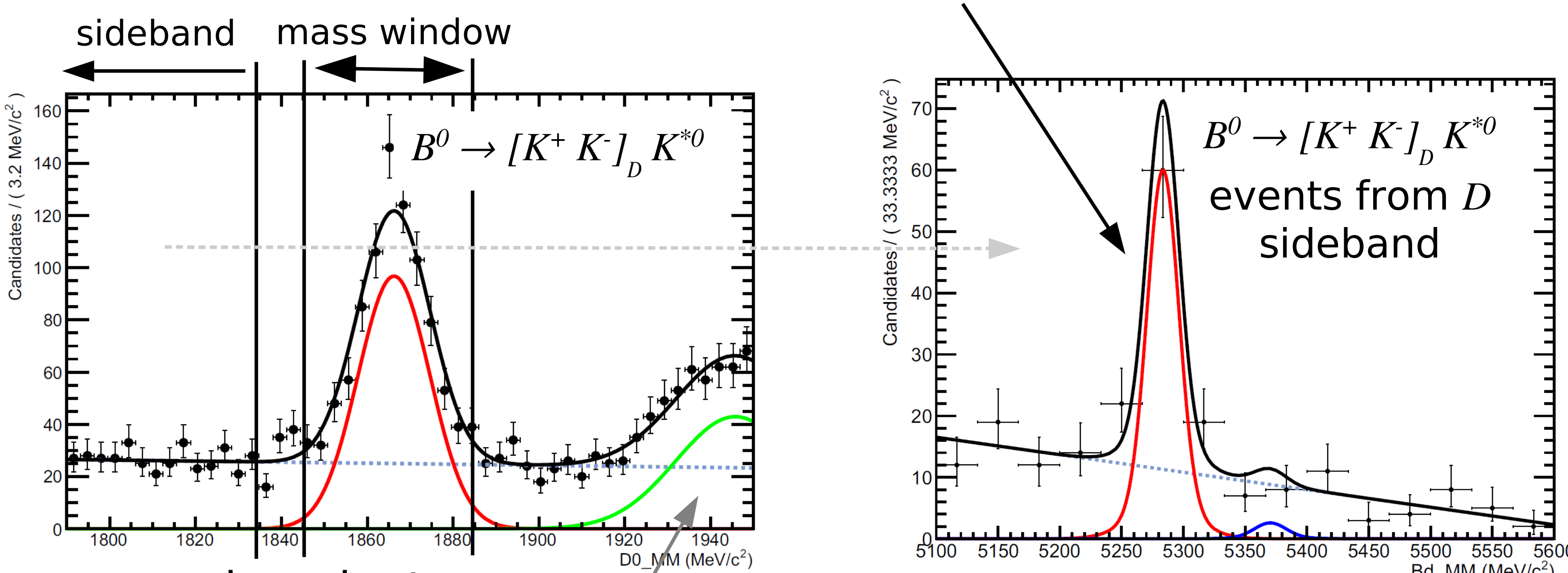
$\gamma^{Belle} = (68 \pm 15)^o$

$\gamma^{LHCb} = (71.1 \pm 16.7)^o$

Large uncertainties in the direct measurements compared with the global fits. Need to measure γ precisely to check the Unitary Triangle consistency.

Charmless background: a closer look

- From $B^0 \to K^+ K^- K^{*0}(K^+ \pi^-)$ decays.
- The case when the four final state particles come from the B vertex.
  - Instead of having a D displaced vertex.
- Estimate it from the D mass distributions sidebands.
  - Look for peaks at the B invariant mass coming from these events.



D invariant mass

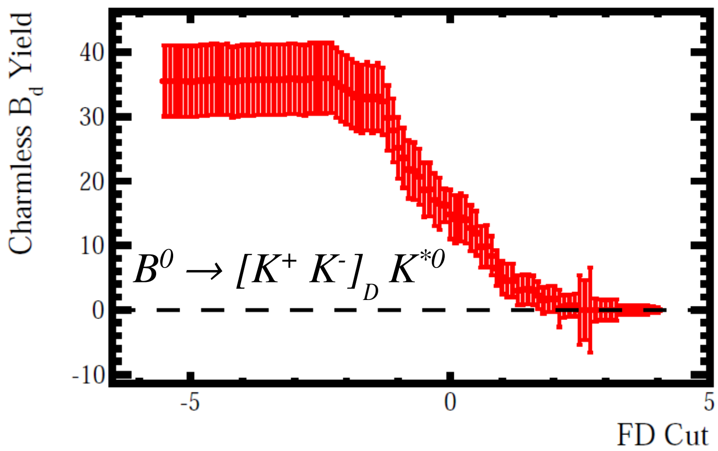
B invariant mass

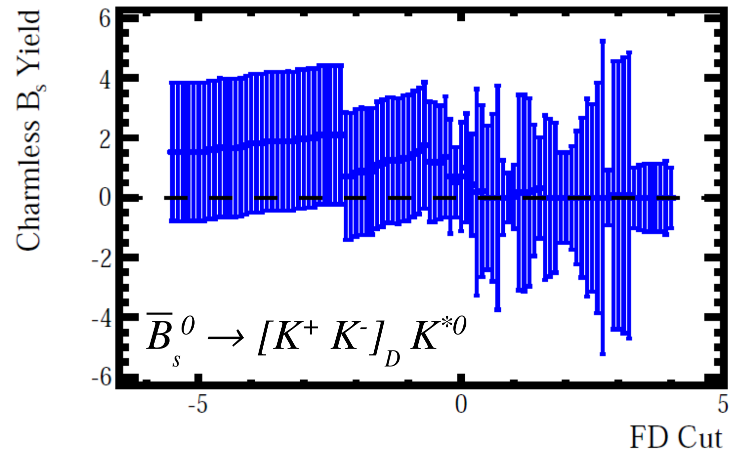
(This is $D \to K\pi$ mis-id as $D \to KK$. Negligible inside D mass window cut (± 20 MeV/c^2). OK)

Charmless background: a closer look

- Look for a D displaced vertex:
  - Apply a cut on the flight distance significance of the D meson.
    - And compute the number of events left from the D sidebands in the B mass distribution.

$$D_{FDsig} = \frac{z(D) - z(B)}{\sqrt{\sigma^2_{z(D)} + \sigma^2_{z(B)}}}$$

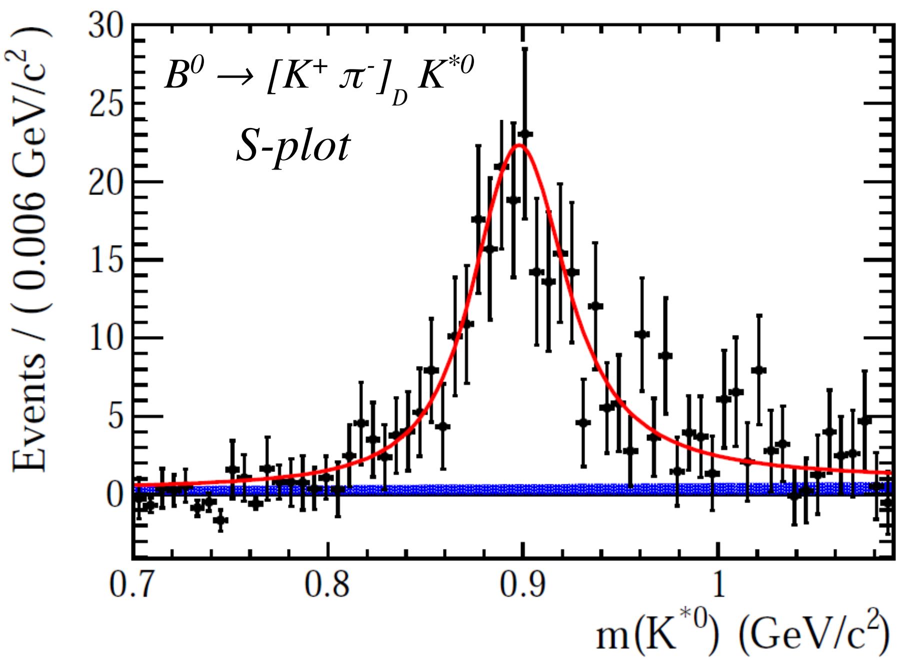




- A cut of $D_{FDsig} > 2.5$ removes this background.

Non-resonant K^{*0} background

- From $B^0 \to D K^+ \pi^-$ decays.
- Important to control for the γ extraction from this mode.
- Addressed by computing the background substracted distribution (s-Plot) of the K^{*0} invariant mass.
  - Signal in this plot is resonant, background is non-resonant.



Non-resonant background estimated to (4.8 ± 3.4) % in K^{*0} mass window.

Systematics

Source	$\mathcal{A}_d^{KK}$	$\mathcal{A}_d^{\text{fav}}$	$\mathcal{A}_s^{KK}$	$\mathcal{R}_d^{KK}$
Production asymmetry	0.005	0.006	–	0.003
PID efficiency	0.004	0.008	0.005	0.014
Trigger efficiency	0.004	0.001	0.005	0.022
Selection efficiency	–	–	–	0.040
Bias correction	0.004	–	0.001	0.013
Low-mass background	0.017	0.001	0.004	0.042
$B^0 \to D\rho^0$ cross-feed	0.001	–	0.002	0.008
Signal description	0.001	0.001	0.001	0.005
D branching fractions	–	–	–	0.022
Total	0.019	0.010	0.008	0.069