Studying radiative charm meson decays at the LHCb experiment

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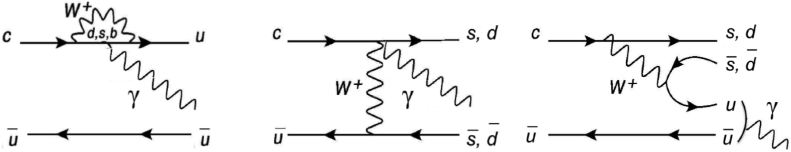
Outline

1. Motivation for studying $D^0 \to V\gamma$ decays
2. Challenges of radiative decays in LHCb
3. Analysis strategy
4. Discriminating variables
5. Preliminary results and Outlook

Disclaimer: this analysis is in progress, all results shown there are preliminary and very much unofficial.

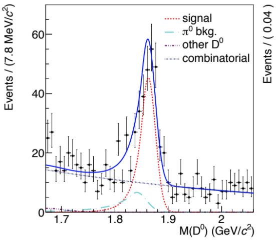
Motivation

Example diagrams contributing to $D^0 \to V\gamma$ - SM penguin, tree level, long-distance effect:



- Suppressed in the Standard Model - $BR(10^{-5} - 10^{-4})$
- Could be sensitive to BSM physics in the loops
- Observables sensitive to NP: the CP asymmetry between D^0 and $\bar{D}^0$ and photon polarization
- Need good experimental precision!

Previous results in radiative charm



Distributions of invariant mass (left) and helicity angle of ϕ(right) for the $D^0 \to (\phi\gamma)$ decay

Previously observed by Belle collaboration[1]:

- $D^0 \to \phi\gamma$: $A_{CP} = -0.094 \pm 0.066 \pm 0.001$; $BR = 2.76 \pm 0.19 \pm 0.10 \times 10^{-5}$;
- $D^0 \to \rho\gamma$: $A_{CP} = 0.056 \pm 0.152 \pm 0.006$; $BR = 1.77 \pm 0.3 \pm 0.07 \times 10^{-5}$;
- $D^0 \to K^*\gamma$: $A_{CP} = -0.003 \pm 0.02$, $BR = 4.66 \pm 0.21 \pm 0.21 \times 10^{-4}$;

Experimental challenges: soft photons, peaking background

- Our photons are relatively soft: $p^T \sim 1 GeV$:
  - Large combinatorial background
  - Trigger efficiency $\epsilon < 10^{-4}$
- Calorimeter resolution of energy/invariant mass is limited
  - Much worse resolution for final states containing neutral particles compared to charged tracks only
-
  - $BR(D^0 \to V\pi^0) \sim 10^{-3} \rightarrowtail$ radiative channels dominated by an *irreducible peaking background*
  - 'Merged' π^0 - two γ reconstructed as a single photon cluster
  - 'Resolved' π^0 - two γ clusters reconstructed, but one is missed
- For the measurement of A_{CP}, nusiance asymmetries have to be taken into account.

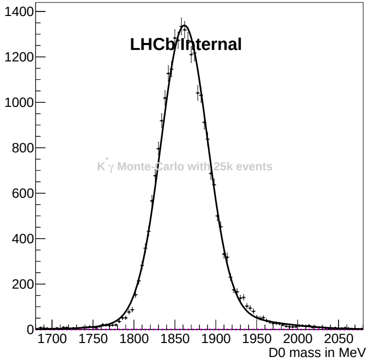
Analysis strategy: overview

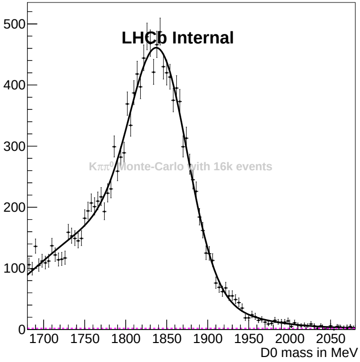
- Experimental data: 2 fb^{-1} of LHCb data collected in Run 1, with additional 3.5 fb^{-1} from the Run 2.
- Decay chain:
  - $\boldsymbol{D^{*+} \to (D^0 \to V\gamma)\pi^+_{soft}; D^{*-} \to (\bar{D}^0 \to V\gamma)\pi^-_{soft} \,|\, V = \rho, \phi, K^*}$
  - $\boldsymbol{\phi \to KK}$
  - $\boldsymbol{\rho \to \pi\pi}$
  - $\boldsymbol{K^* \to K^-\pi^+}$

  We can tag the flavour of D^0 from the charge of the (soft) pion.
  $\boldsymbol{\Delta M \equiv M(D^{*+}) - M(D^0)}$is a good discriminator vs. mis-tagging.
- Reconstruction - 2 charged tracks + photon-like object + soft pion.
-
  - Soft photons removed: $p^T > 2\ GeV$.
  - Resolved π^0 vetoed; $\epsilon \approx 50\%$
  - Merged π^0s are discriminated with a Multivariate Classifier based on ECAL variables. $\epsilon_{sig} \approx 85\%$, $1 - \epsilon_{\pi^0} \approx 64\%$

Discriminating variables - $M(D^0)$

Invariant mass of $\boldsymbol{D^0}$ for $\boldsymbol{D^0 \to K^*\gamma}$ (left) and $\boldsymbol{D^0 \to K\pi\pi^0}$ (right) taken from the simulation of 2012 data.

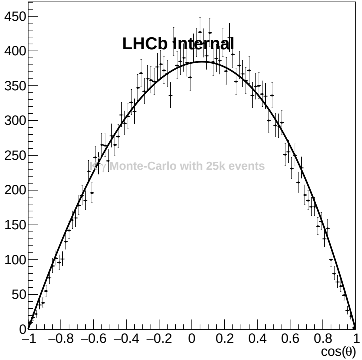


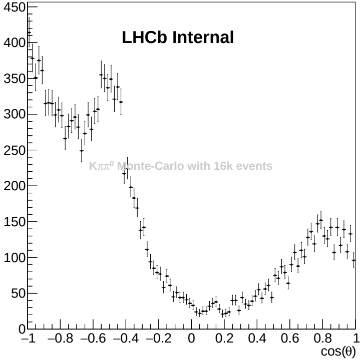


- Resolution for the signal channel: **35 *MeV***; For $\pi^{\mathbf{0}}$: $\approx$ **50 *MeV***

Discriminating variables - cosine of helicity angle θ

Helicity angle of the K^* from $D^0 \to K^*\gamma$ Monte-Carlo (left), and for $K\pi\pi^0$ (right):

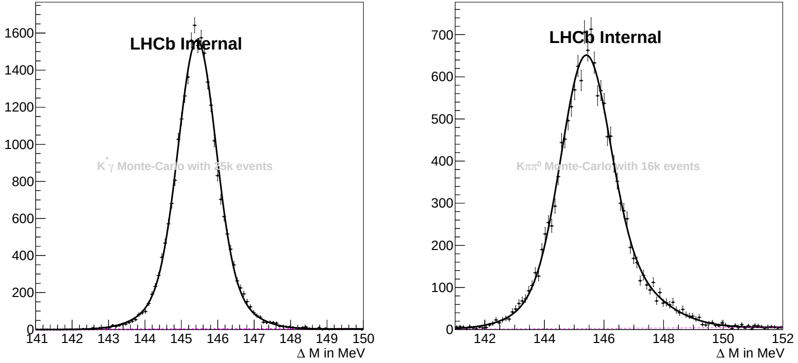




- Signal channel follows $\mathbf{1 - cos^2(\theta)}$ shape; dominant peaking background is $\boldsymbol{cos^2(\theta)}$-like.

Discriminating variables - ΔM

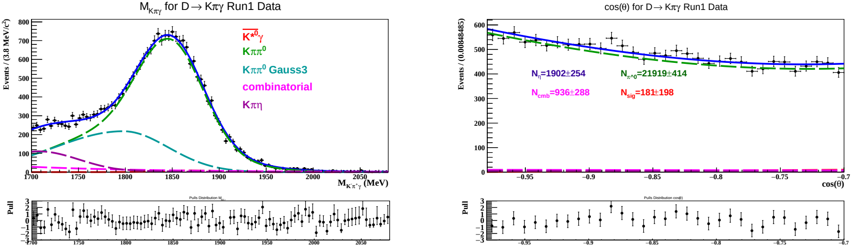
Left - $\boldsymbol{\Delta M}$ from the $\boldsymbol{D^0} \rightarrow \boldsymbol{K}^*\gamma$ Monte-Carlo, right - for $\boldsymbol{D^0} \rightarrow \boldsymbol{K}\pi\pi^0$



- Resolution of $\boldsymbol{\Delta M}$ is much less affected by neutral particle reconstruction, $\boldsymbol{\sigma(\Delta M)_\gamma < 1\ MeV}$, $\boldsymbol{\sigma(\Delta M)_{\pi^0} \approx 1\ MeV}$

Fit to calibration data for $D^0 \to ((K^* \to K^-\pi^+)\gamma)$

- Calibration sample: $cos(\theta) < -0.7$; signal heavily suppressed.
- Needed in order to control for possible data-MC differences .

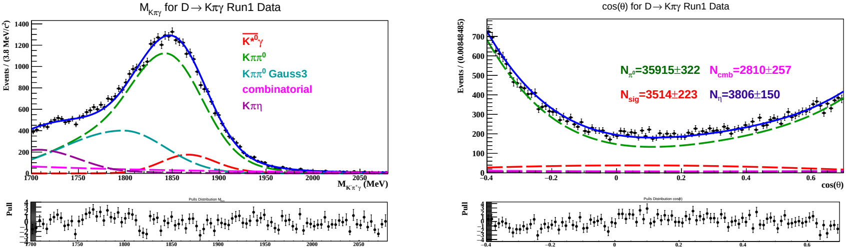


Invariant mass of D^0 (left) and helicity angle of the K^* meson (right) for 2012 data.

- In the signal-enhanced region, we take peaking background shapes from this fit rather than straight from Monte-Carlo.

Preliminary fit for $D^0 \to ((K^* \to K^-\pi^+)\gamma)$

- Signal enhanced region: $-0.4 < \cos(\theta) < 0.7$

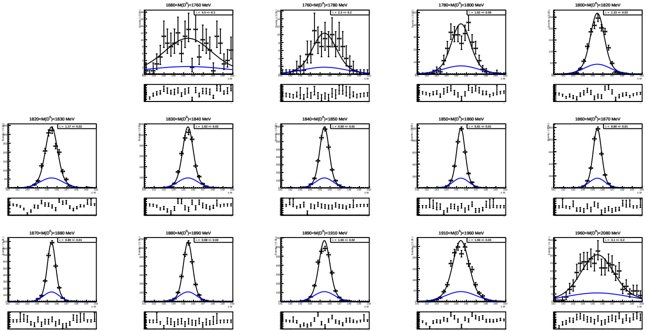


Invariant mass of $K\pi\gamma$ (left) and helicity angle of the K^* meson (right) for 2012 data.

- In principle, this fit can be split by D^0 flavour to obtain CP asymmetries.
- ...But one component is missing:

Complication for multidimensional fit - $corr(\Delta M, M(D^0))$

- By definition, $\Delta M = M(D^{*+})$ - $M(D^0)$ and $M(D^0)$ are not independent! $\sigma_{\Delta M} = \sigma_{\Delta M}(M)$.

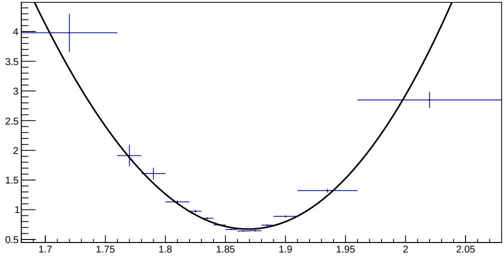


Fits to the ΔM observable in bins of $M(D^0)$, from lowest (top left) to highest (bottom right), using 2012 simulation. Real data shows similar dependence.

- Conditional PDFs: $P = [F^1(\Delta M|M) \times F^2(M)] \times G(\cos(\theta))$

Functional dependence $\sigma_{\Delta M}(M)$

- ΔM resolution best around $M(D^0)$ peak, worsens with distance from the nominal mass.

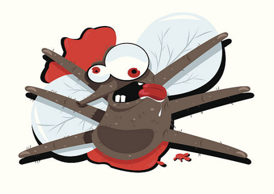


X axis - D^0 invariant mass in GeV; Y axis - $\frac{\sigma_{\Delta M}}{\sigma_0}$

- Similar (but slightly weaker) correlations observed for π^0 peaking background.
- Incorporating these dependences into the full 3D model for the data.

Outlook

- Radiative decays with LHCb are challenging for numerous reasons
  - Our group is currently finalizing Run 1 data. My focus is on $D^0 \to K^*\gamma$ channel, analysis of $D^0 \to \phi\gamma, D^0 \to \rho\gamma$ is in a similar stage.
- Signal yields in Run 1: $D^0 \to K^*\gamma \sim 3000$ events, $D^0 \to \phi\gamma \sim 300$ events
  - We're moving to Run 2 data that had to be reprocessed.
  - Some technical issues had to be resolved along the way:



Thank you for your attention!

Reference

1. Bell collaboration (T.Nanut et al.)"Observation of $D^0 \to \rho\gamma$ and Search for CP Violation in Radiative Charm Decays" Phys. Rev. Lett. 118, 051801 (2017)
2. C.S. Wu et al., Phys. Rev. 105 (1957) 1413
3. LHCb Collaboration (R. Aaij et al.), "Observation of CP Violation in Charm Decays", Phys. Rev. Lett. 122, 211803 (2019).

Backup

CP violation

$$V_{CKM} = \begin{bmatrix} 1-\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2 A\lambda^2 & \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1+O(\lambda^3) \end{bmatrix} + O(\lambda^4)$$

- One CP-violating phase in the SM (ρ,η in Wolfenstein parametrization)
- First observed in kaon system by C.S Wu in 1957[2]
- Studied in B-meson by b-factories (Belle and BaBaR), direct CP violation established in 2004.
- Observed in the charm sector by LHCb in 2019 [3]

$$A_{CP} = \frac{\Gamma_{D^0} - \Gamma_{\bar{D}^0}}{\Gamma_{D^0} + \Gamma_{\bar{D}^0}}$$

Experimental challenges - nuisance asymmetries

Measurement of A_{CP} is a counting experiment. But CP is not the only source of asymmetry:

$$\boldsymbol{A_{raw} = A_{CP} + A_{production} + A_{detection}}$$

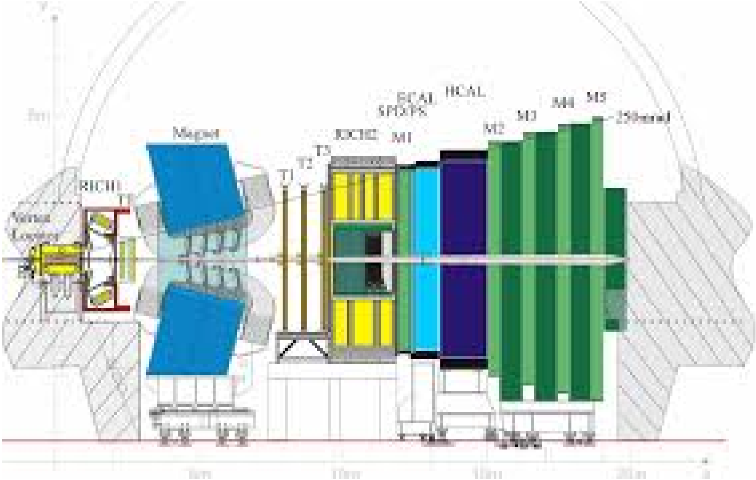
This is a general problem for all CP measurements.

- $\sigma(D^{*+}) \neq \sigma(D^{*-})$
- Detectors are made of matter - slightly different interactions for h^+ and h^-

Common solution:

$$\boldsymbol{\Delta A_{raw} = \Delta A_{CP} + (A^1_{prod.} - A^2_{prod.}) + (A^2_{det.} - A^2_{det.}) \approx \Delta A_{CP}}$$

LHCb detector (before Upgrade I)



Efficiency of a multivariate cut