The role of neutral kaons in precision measurements of *CP* violation in the charm sector

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on behalf of the LHCb collaboration

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CP violation in the charm sector

2019: first and unique observation of CPV in the charm sector

- pp collisions data collected by the LHCb detector (Run 2, 6 fb^{-1})
- Measured $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$:

$$\boxed{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}} \Longrightarrow \Delta A_{CP} \neq 0 \text{ @ } 5\sigma \quad [1]$$

$$\text{with } A_{CP}(D \to f) \equiv \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}$$

- Result still debated in the community: compatible with the SM?

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Currently: looking for CPV in other $D^0, D^+, D_s^+, \Lambda_c$ channels

- LHCb is collecting new large data samples

→ achievement of **high precision** $\mathcal{O}(10^{-4})$, and even less, in many processes:

need to control any bias source up to 10^{-4}

Nuisance asymmetries: detector-induced bias

Ingredient for CP asymmetry in $D \to f$:
number of **reconstructed** decays of the particle and the anti-particle

$$A_{raw}(D \to f) \equiv \frac{N(D \to f) - N(\bar{D} \to \bar{f})}{N(D \to f) + N(\bar{D} \to \bar{f})}$$

$A_{raw}(D \to f)$ influenced by charge-asymmetric effects in the detector

$$A_{raw}(D \to f) \approx \underbrace{A_P(D)}_{\mathcal{O}(10^{-2})} + \underbrace{A_{CP}(D \to f)}_{\mathcal{O}(10^{-3}-10^{-4})} + \underbrace{A_D(f)}_{\mathcal{O}(10^{-2})}$$

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Example: LHCb measurement of $A_{CP}(D^+ \to \phi\pi^+)$ [2]

Channel of interest: $\underbrace{D^+}_{A_P(D^+)} \to \underbrace{\phi}_{A_D(\not\phi, K_S^0)} \; \underbrace{\pi^+}_{A_D(\pi^+)}$

Calibration channel: $\overbrace{D^+} \to \overbrace{K_S^0} \; \overbrace{\pi^+}$

Our work:

Improve the precision of $A_D(K^0_\mathrm{S})$ in preparation of measurements with Upgrade I (and beyond) samples

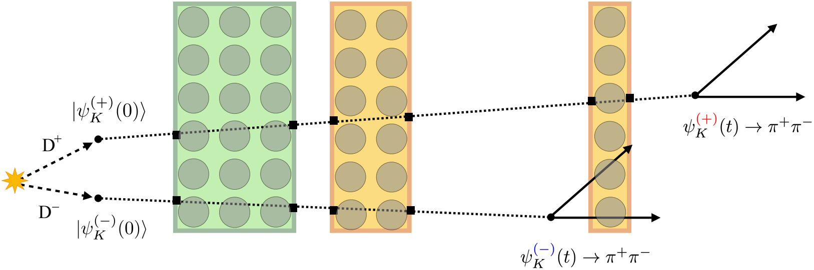
Several precision measurements use calibration channels with a **neutral kaon** in the final state:

$$D^+ \to K^0_\mathrm{S}\pi^+ \ , \ D^+_s \to K^0_\mathrm{S}K^+ \ , \ D^0 \to K^0_\mathrm{S}\pi^+\pi^-, \ ...$$

$$\Downarrow$$

Need for precise, robust, and data-driven models for $A_D(K^0_\mathrm{S})$ in charm CP violation measurements

Time-dependent neutral kaon asymmetry

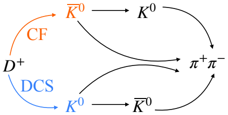


Time-dependent neutral kaon asymmetry

1. CP **violation in mixing**: $\mathscr{P}(K^0(t) \to \overline{K}^0) \neq \mathscr{P}(\overline{K}^0(t) \to K^0)$
2. **Different interaction with nucleons**: $\sigma(K^0) \neq \sigma(\overline{K}^0)$
3. **New effect: Initial state of the neutral kaon in charm decays** [3]

→ D^+/D^0 can produce both a $\overline{K}^0$ and a K^0:

- Cabibbo-Favoured (**CF**) decay: $c \to s\bar{d}u$
- Doubly Cabibbo-Suppressed (**DCS**) decay: $c \to d\bar{s}u$



→ CF-DCS interference with mixing: CPV source

Use-case to study this new interference effect: $D^+ \to K^0_S\pi^+$

$$\frac{\mathscr{A}(D^+ \to K^0\pi^+)}{\mathscr{A}(D^+ \to \overline{K}^0\pi^+)} \simeq r_\pi\, e^{i\delta_\pi} \quad \xrightarrow{FAT^1 \text{ prediction [3]}} \quad \begin{cases} r_\pi &= -0.073 \pm 0.004 \\ \delta_\pi &= -1.39 \pm 0.05 \end{cases}$$

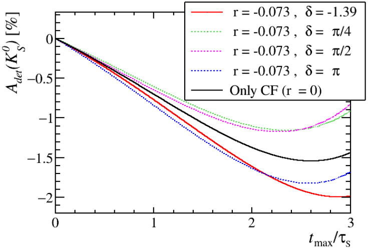
[1] Factorisation-Assisted Topological amplitudes method

Model for neutral kaon detection asymmetry in $D^+ \to K^0_S \pi^+$

$$A_D(K^0_S, t) \equiv \frac{\Gamma\left[\psi_K^{(+)}(t) \to \pi^+\pi^-\right] - \Gamma\left[\psi_K^{(-)}(t) \to \pi^+\pi^-\right]}{\Gamma\left[\psi_K^{(+)}(t) \to \pi^+\pi^-\right] + \Gamma\left[\psi_K^{(-)}(t) \to \pi^+\pi^-\right]}$$

Ingredients to compute the asymmetry

- K^0_S momentum and decay time (data)
- LHCb material map (from simulation at the moment. To be calibrated with data in future measurements).
- the initial state composition (r_π, δ_π)

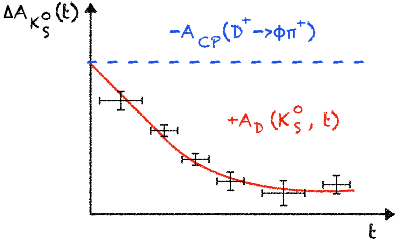


Measurement of $A_D(K^0_S)$ in $D^+ \to K^0_S\pi^+$ decays

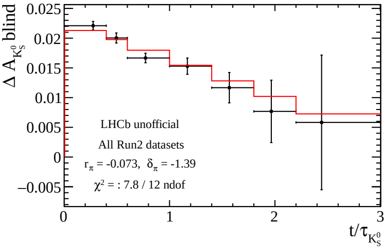
Goal: measure the time dependence of $A_D(K^0_S, t)$ from data
Calibration channel to remove $A_P(D^+)$ and $A_D(\pi^+)$: $D^+ \to \phi\pi^+$

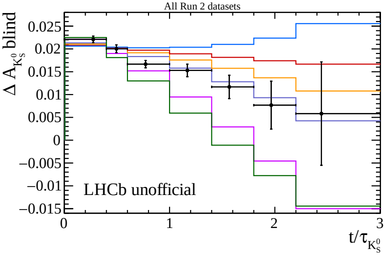
$$\mathbf{\Delta A_{K^0_S}(t)} \equiv A_{raw}(D^+ \to K^0_S(t)\pi^+) - A_{raw}(D^+ \to \phi\pi^+)$$
$$= \boxed{A_D(K^0_S, t)} - \boxed{A_{CP}(D^+ \to \phi\pi^+)}$$

1. time-dependent shape $\Rightarrow$ r_π and δ_π
   $\to$ $A_{CP}(D^+ \to \phi\pi^+)$ is constant
2. constant offset $\Rightarrow$ $A_{CP}(D^+ \to \phi\pi^+)$
   $\to$ $A_D(K^0_S, t = 0) = 0$



Preliminary results with Run 2 data (5.4 fb^{-1})





- $A_D(K^0_{\rm S}, t)$ describes well the time-dependent shape
  - $\rightarrow$ measurement of r_π, δ_π soon: **first time** in a hadronic environment
  - $\rightarrow$ LHCb material map in simulation is very accurate for Run 2 needs
- Measurement of $A_{CP}(D^+ \rightarrow \phi\pi^+)$ from the best-fit offset
  - $\rightarrow$ stat. and syst. uncertainties $\sim 4 \times 10^{-4}$
- **Application**: measurement of $A_{CP}(D^0 \rightarrow K^+K^-)$ with $D^0 \rightarrow K^0_{\rm S}\pi^+\pi^-$

Thanks for your attention!

[1] R. Aaij et al. “Observation of CP violation in charm decays”. In: *Phys. Rev. Lett.* (2019). DOI: 10.1103/PhysRevLett.122.211803.

[2] R. Aaij et al. “Search for CP Violation in $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0 K^+$, and $D^+ \to \phi\pi^+$ Decays”. In: *Phys. Rev. Lett.* (2019). DOI: 10.1103/PhysRevLett.122.191803.

[3] Di Wang, Fu-Sheng Yu, and Hsiang-nan Li. “CP Asymmetries in Charm Decays into Neutral Kaons”. In: *Phys. Rev. Lett.* (2017). DOI: 10.1103/PhysRevLett.119.181802.

[4] R. Aaij et al. “Measurement of CP asymmetry in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays”. In: *Journal of High Energy Physics* (2014). DOI: 10.1007/jhep07(2014)041.

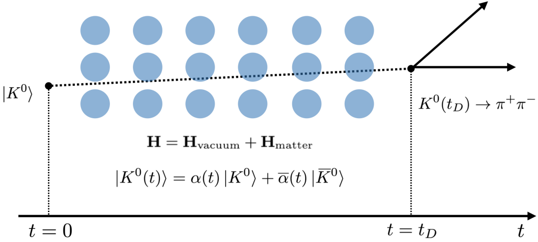
[5] Di Wang et al. “$K_S^0 - K_L^0$ asymmetries in D-meson decays”. In: *Phys. Rev. D* (2017). DOI: 10.1103/PhysRevD.95.073007.

BACKUP SLIDES

Time evolution of neutral kaons in matter

- Initial state: $|\psi_K(0)\rangle = |K^0\rangle$ or $|\overline{K}^0\rangle$
- Neutral kaon travels inside matter: $\mathbf{H} = \mathbf{H}_{\text{vacuum}} + \mathbf{H}_{\text{matter}}$
    - $\mathbf{H}_{\text{vacuum}}$: $K^0 - \overline{K}^0$ mixing
    - $\mathbf{H}_{\text{matter}}$: interaction with nucleons

→ final state: superposition $|\psi_K(t)\rangle = \alpha(t)\,|K^0\rangle + \overline{\alpha}(t)\,|\overline{K}^0\rangle$



$$\overbrace{\begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}}^{\mathbf{H}_{\text{vacuum}}}$$

$$\overbrace{\begin{pmatrix} \chi_{K^0} & 0 \\ 0 & \chi_{\overline{K}^0} \end{pmatrix}}^{\mathbf{H}_{\text{matter}}}$$

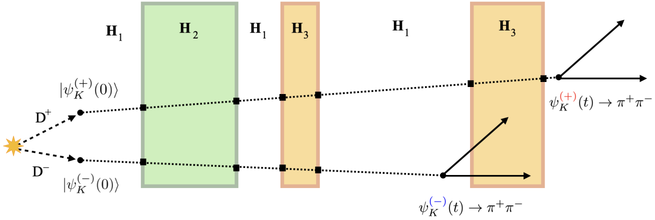
Modelling the the neutral kaon detection asymmetry

Computed for each K^0_S candidate at its measured decay time

- consider p and t of each K^0_S candidate (data sample dependent)
- analytical model for the time evolution of each K^0_S

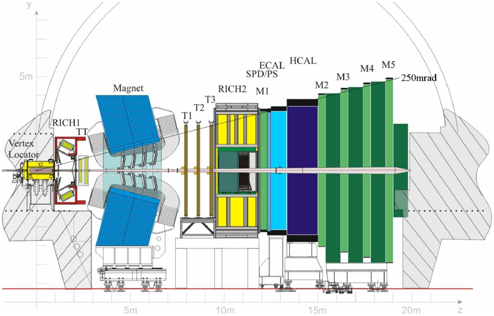
→ initial state defined by a given (r_π, δ_π) pair

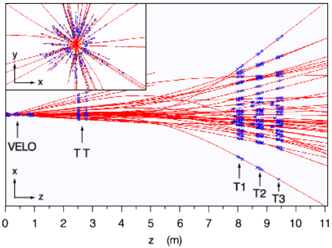
→ need a precise knowledge of the LHCb material map
(from the **Geant4** software-based simulation of the experiment)



Output: $\langle\, A_D(K^0_\mathrm{S}, t)\,\rangle$ in each decay-time bin for a given (r_π, δ_π) pair

LHCb Detector





Tracking: $\sigma_p/p \simeq 0.5\%$

- VELO $\sigma_{PV}^{xy} \sim 15\,\mu\text{m}$
- TT
- Dipole Magnet
- T Stations $T_{1,2,3}$

Particle Identification

- RICH1 e RICH2
- SPD/PS, ECAL
- HCAL
- 5 Muon Stations

Neutral kaons at LHCb

Reconstructed from $K^0_S \to \pi^+\pi^-$ decay

$K^0_S(LL)$: Long Tracks $\pi^\pm$

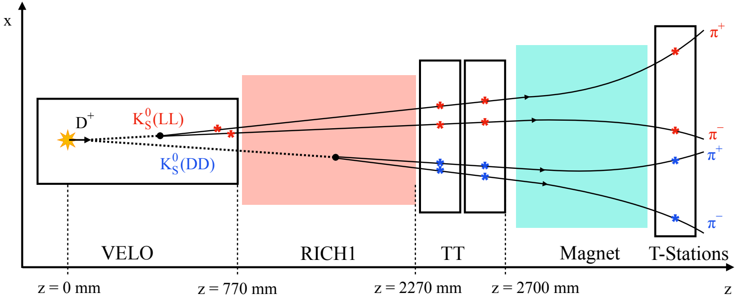
$\rightarrow DV_z \in [-100, 500]$ mm

$\rightarrow t < 0.4\,\tau_{K^0_S}$

$K^0_S(DD)$: Downstream Tracks $\pi^\pm$

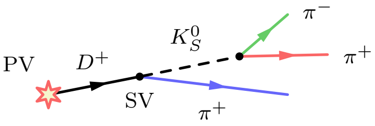
$\rightarrow DV_z \in [300, 2275]$ mm

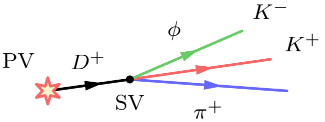
$\rightarrow t < 3\,\tau_{K^0_S}$

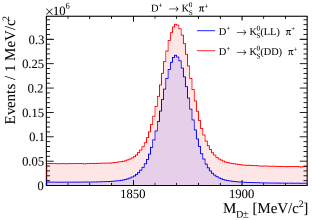


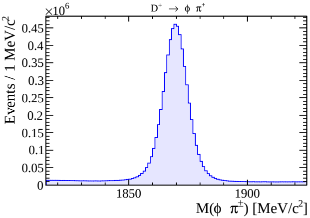
Abundant samples after trigger and offline selection:

50M $D^+ \to K^0_S\pi^+$ and **30M** $D^+ \to \phi\pi^+$









Selections optimised to minimise background and nuisance asymmetries

Time-dependent analysis in K_S^0 decay-time bins

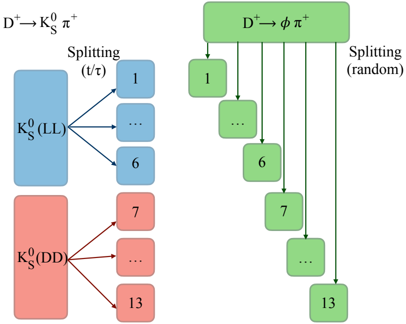
$D^+ \to \phi\pi^+$ used to precisely remove nuisance asymmetries in $D^+ \to K_S^0\pi^+$

- $D^+ \to K_S^0\pi^+$ candidates **split** into 13 independent sub-samples (bins)

→ as a function of K_S^0 decay time t/τ

- $D^+ \to \phi\pi^+$ candidates similarly **split** into 13 independent bins

→ cancel the nuisance asymmetries in each decay-time bin



- Equalisation of the kinematics of the D^+ and π^+ in each decay-time bin

Result of the kinematic weighting in the t/τ bins