9th International Workshop on the Unitarity Triangle (CKM2016)

TIFR, Mumbai, 1/12/2016

Measurements of Mixing and Indirect CPV in multi-body Charm decays at LHCb

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on behalf the LHCb Collaboration

Outline

- Mixing and Indirect CP Violation in Charm decays
- Mixing and Coherence Factor in $D^0 \to K^{\mp}\pi^{\pm}\pi^{-}\pi^{+}$
- Mixing in $D^0 \to K^0_S\pi^+\pi^-$
- LHCb Prospects for Run2

Mixing in Charm Decays

Mixing of Neutral Mesons

- **Pure Quantum Mechanics effect**

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

- **By labelling the mass eigenstates**

$$\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D}^0\right\rangle$$

- **The mixing parameters can be defined**

$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta M}{\Gamma} \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}$$

Mixing in Charm Decays

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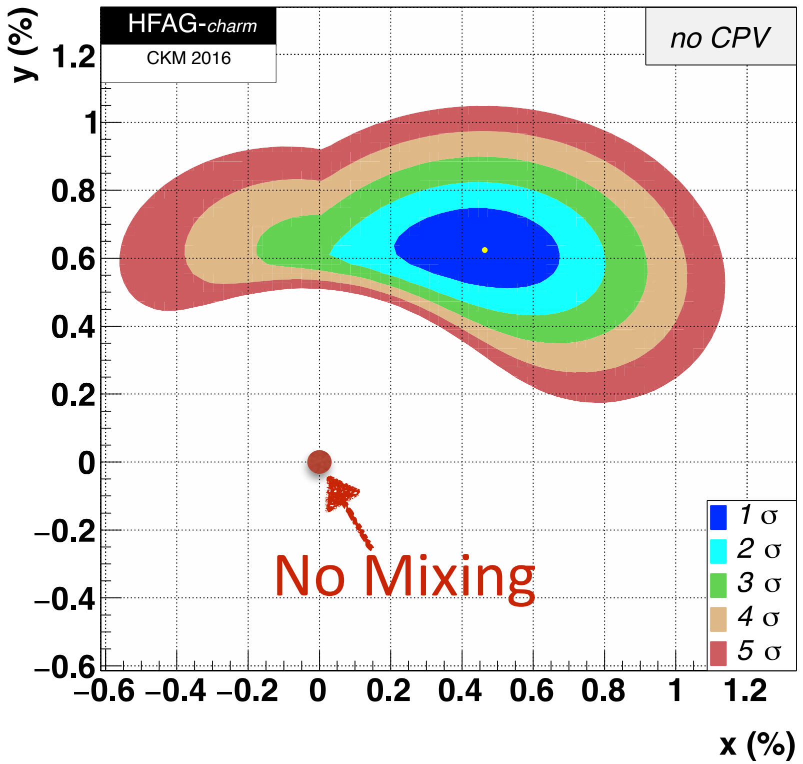
- Established!



Mixing and Indirect CPV in Charm Decays

CPV and Mixing

- CPV can arise from mixing

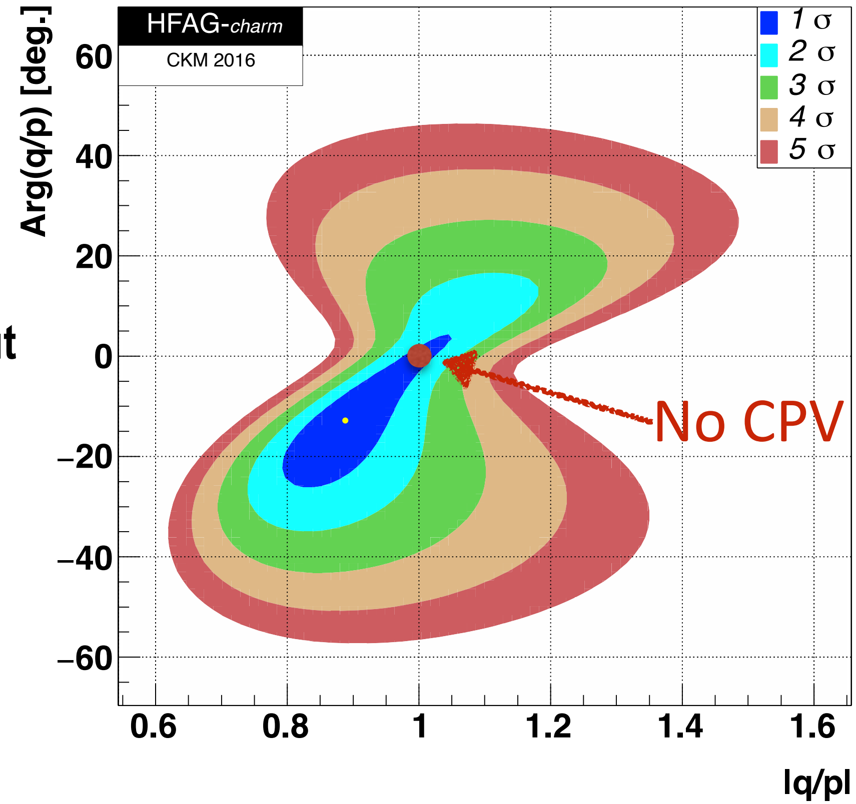
$$\left|\frac{q}{p}\right| \neq 1$$

- or from interference of decay with and without mixing $D^0 \to f; D^0 \to \overline{D}^0 \to f$

$$\arg(\lambda_f) + \arg(\lambda_{\bar{f}}) \neq 0$$

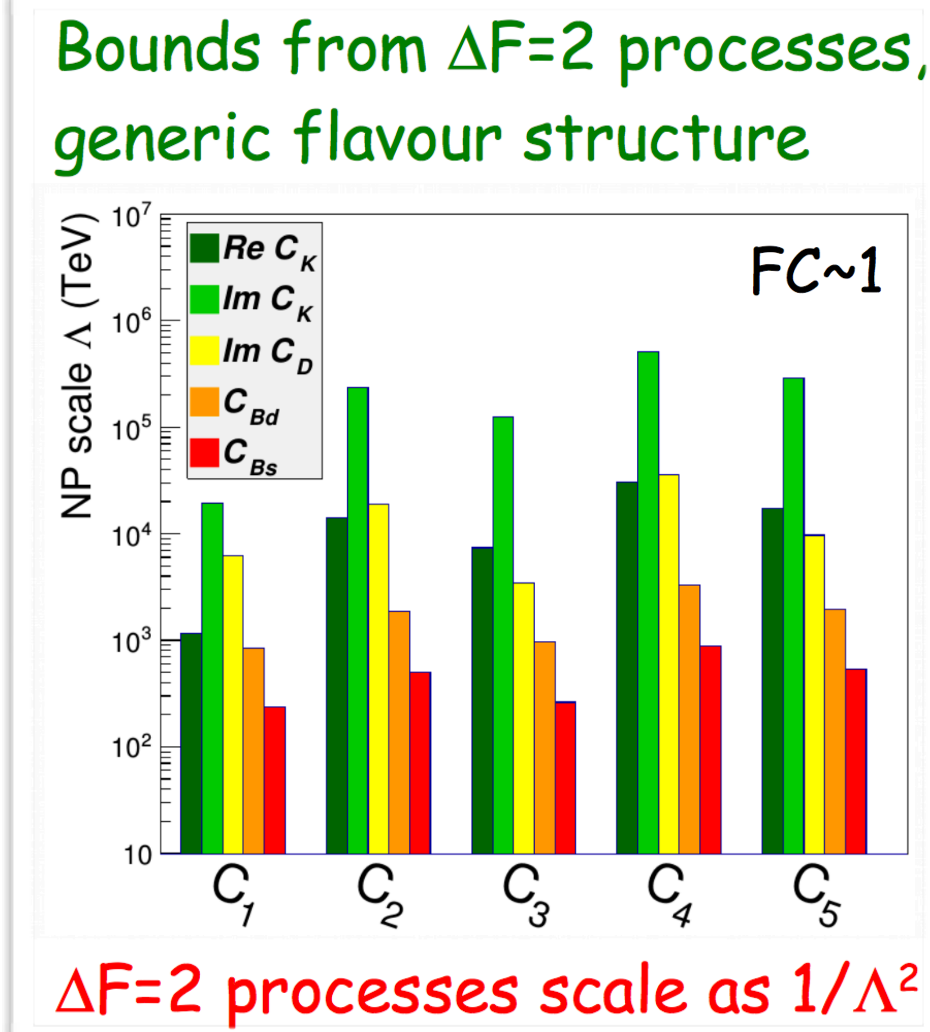
$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- Still consistent with no CPV



A Portal for BSM Physics

UTFit Collaboration, 2016



Indirect Searches

- **Charm mixing sets the second stringent bounds on NP from ΔF=2 processes**
- **Not as much powerful on other models (NMFV), but still worth considering**

Up-sector

- **Charm probes up-sector quark mixing**
  Alternative path to NP
- **Very small SM expectations**

Multi-Body Decays

Cons

- **Lower efficiency than two-body**
- **Long-range dynamics more difficult to predict**
- **May need understanding the resonant structure of the decay**

Pros

- **Large number of intermediate states**
  offer many possible interference patters
- **More observables exploiting the underlying resonant structure**
- **Useful for γ measurement using $B \to D^0 K$**

Phys. Rev. Lett. 116, 241801 (2016)

$D^0 \to K\pi\pi\pi$
Mixing and Coherence Factor

$D^0 \to K\pi\pi\pi$ - Mixing and Coherence Factor

WS/RS Ratio

- Exploits mixing by measuring the time-dependent ratio of $D^0 \to K^+\pi^-\pi^+\pi^-$ (WS) decays to $D^0 \to K^-\pi^+\pi^+\pi^-$ (RS) decays (assuming CP symmetry)

$$R(t) \approx \left(r_D^{K3\pi}\right)^2 - r_D^{K3\pi} R_D^{K3\pi} y'_{K3\pi} \frac{t}{\tau} + \frac{x^2+y^2}{4}\left(\frac{t}{\tau}\right)^2$$

$r_D^{K3\pi}$ phase space averaged ratio of DCS/CF amplitudes

$R_D^{K3\pi}$ coherence factor: $R_D^{K3\pi} e^{-i\delta_D^{K3\pi}} \equiv \langle \cos\delta \rangle + i \langle \sin\delta \rangle$

$y'_{K3\pi}$ interference term: $y'_{K3\pi} \equiv y \cos\delta_D^{K3\pi} - x \sin\delta_D^{K3\pi}$

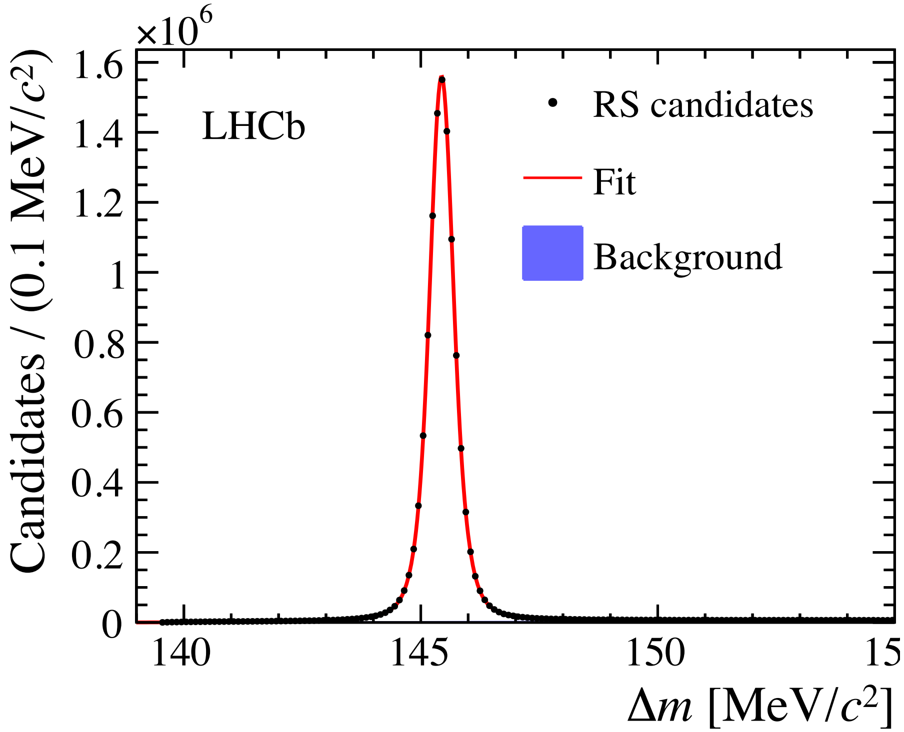
All the three parameters are needed for measuring γ with $B \to D^0(K\pi\pi\pi)K$

$D^0 \to K\pi\pi\pi$ - Run1 Analysis

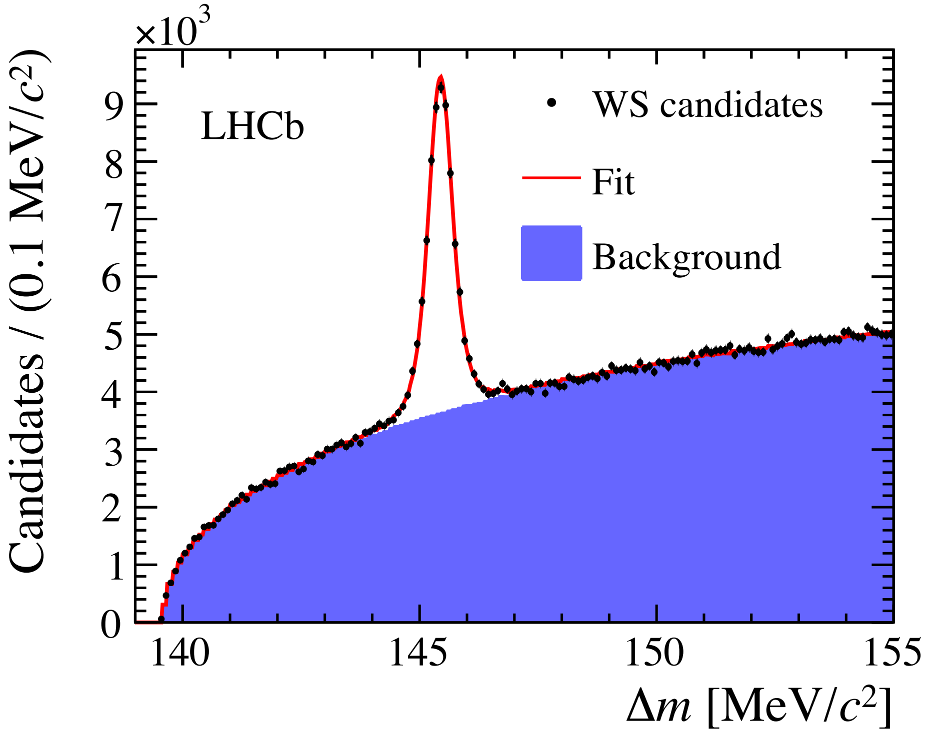
Phys. Rev. Lett. 116, 241801 (2016)

Dataset

- Prompt $D^{*+} \to D^0\pi^+$ decays
- Run1: $3fb^{-1}$ at 7 and 8 TeV



$N_{RS}=11.4x10^6$



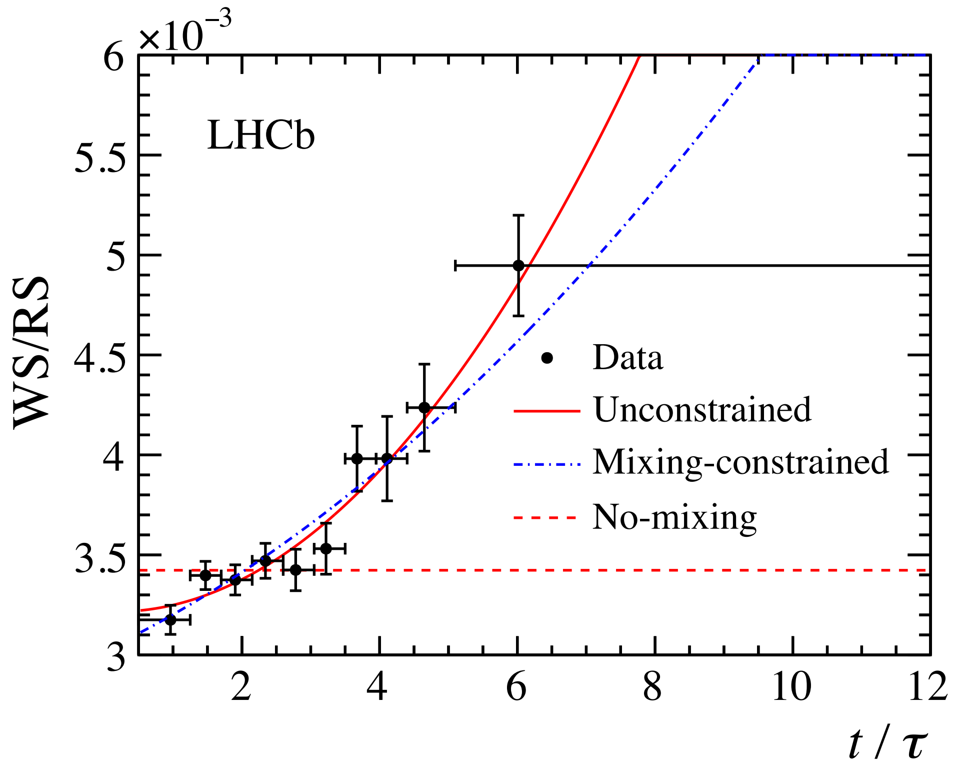
$N_{WS}=42.5x10^3$

$D^0 \to K\pi\pi\pi$ - Run1 Analysis

Phys. Rev. Lett. 116, 241801 (2016)

Ratios Fit

- The WS/RS ratio measured in 10 decay time bins in [0.5,12.0]τ_D
- $R = \sqrt{N_{WS}^{D^0} N_{WS}^{\bar{D}^0} / N_{RS}^{D^0} N_{RS}^{\bar{D}^0}}$ to cancel production or $\pi_s^\pm$ detection asymmetries
- Uncertainties in the plot include systematics
  - double mis-id ($K^+\pi^- \to K^-\pi^+$)
  - $D^0 \to K^+\pi^-K^0_S$
  - contribution from secondary decays (bin-by-bin)
  - trigger efficiency
- A few hypotheses are tested
  - Mixing
  - No Mixing (excluded at 8.2σ)
  - WA Mixing (compatible at 1.8σ)



Fit Type χ^2/ndf (p-value)	Parameter	Fit result	Correlation coefficient $r_D^{K3\pi}$	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$\frac{1}{4}(x^2+y^2)$
Unconstrained	$r_D^{K3\pi}$	$(5.67 \pm 0.12) \times 10^{-2}$	1	0.91	0.80
7.8/7 (0.35)	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$(0.3 \pm 1.8) \times 10^{-3}$		1	0.94
	$\frac{1}{4}(x^2+y^2)$	$(4.8 \pm 1.8) \times 10^{-5}$			1

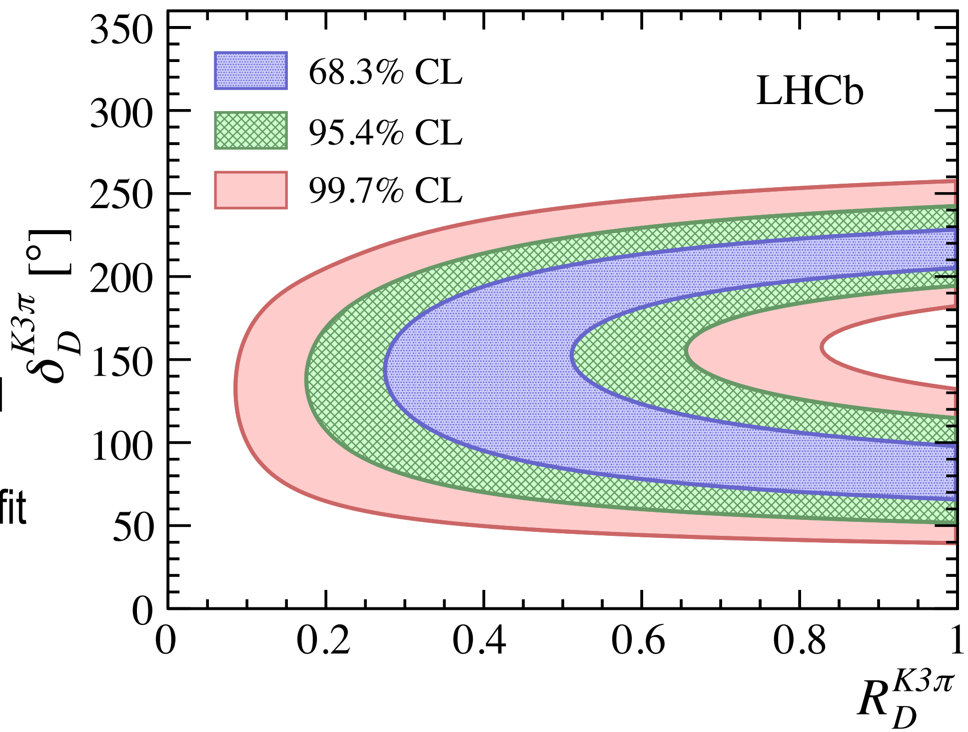
$D^0 \to K\pi\pi\pi$ - Coherence Factor

Phys. Rev. Lett. 116, 241801 (2016)

The Constrained Fit

- **Allows to determine a line of solutions in the ($\delta_D^{K3\pi}$, $R_D^{K3\pi}$) plane**
  Uncertainties on $r_D^{K3\pi}$ and $R_D^{K3\pi} y'_{K3\pi}$ are greatly reduced
- **Improves constraints previously produced by CLEO-c**
  But a combination would require a combined fit
- **Will increase the sensitivity to γ in $B \to D^0(K\pi\pi\pi)K$**

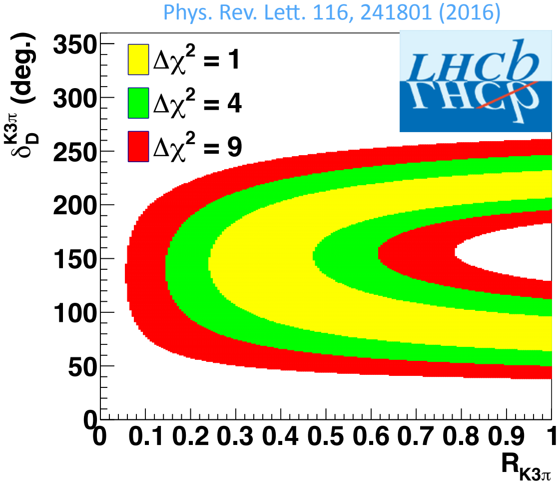
oss: $y'_{K3\pi} \equiv y \cos \delta_D^{K3\pi} - x \sin \delta_D^{K3\pi}$

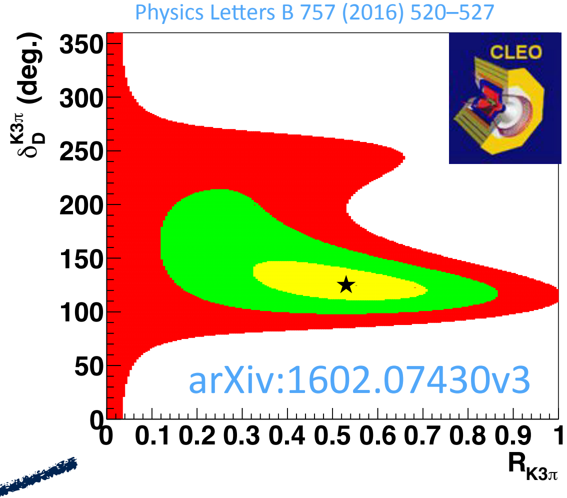


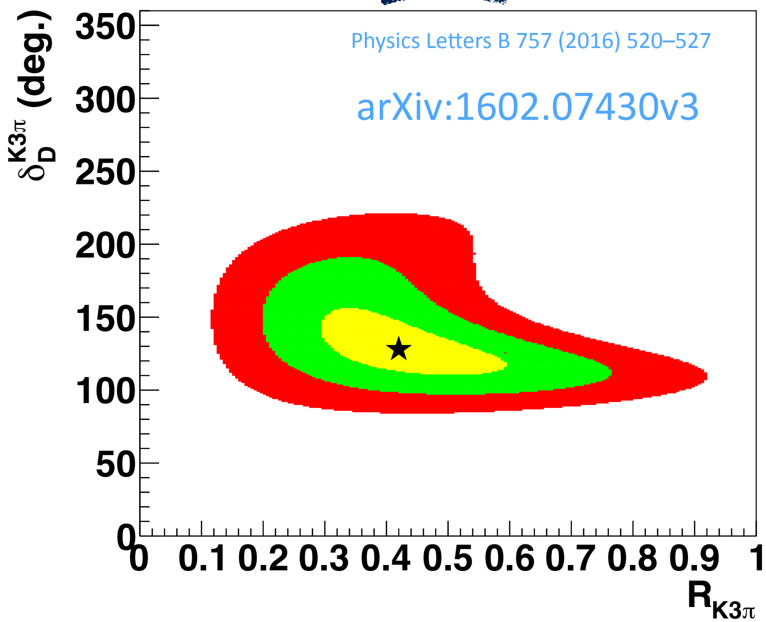
			$r_D^{K3\pi}$	$R_D^{K3\pi} \cdot y'_{K3\pi}$	x	y
Mixing-constrained	$r_D^{K3\pi}$	$(5.50 \pm 0.07) \times 10^{-2}$	1	0.83	0.17	0.10
11.2/8 (0.19)	$R_D^{K3\pi} \cdot y'_{K3\pi}$	$(-3.0 \pm 0.7) \times 10^{-3}$		1	0.34	0.20
	x	$(4.1 \pm 1.7) \times 10^{-3}$			1	-0.40
	y	$(6.7 \pm 0.8) \times 10^{-3}$				1

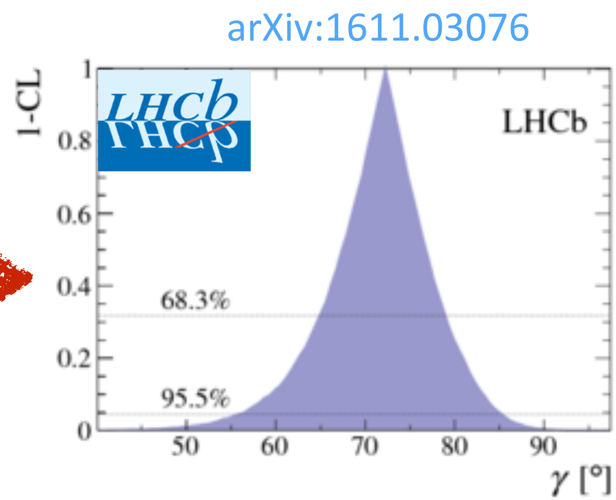
Combination with CLEO-c

Physics Letters B 757 (2016) 520–527









JHEP 03 (2016) 033

$D^0 \rightarrow K^0_S \pi^+ \pi^-$ Mixing

Mixing and CPV in $D^0 \to K^0_S \pi^+ \pi^-$

Phys. Rev. D 72 (2005) 012001

A Golden Mode for Mixing and CPV

- **Both CF and DCS components are present in the same final state**
- **It gives direct access to all the mixing parameters**
  x, y, q/p, arg(q/p)
- **Thanks to the various contributions in the Dalitz plot, whose time dependance is modified by mixing parameters**

All that Glitters is not Gold…

- **Amplitude structure**
- **Time dependance of the Amplitude structure**
  Time-dependent Dalitz-plot Analysis
- **Presence of varying strong phases across the DP need to be treated with care**
  It is fixed in two-body decays
- **A time-dependent amplitude analysis approach has been pioneered by CLEO and later followed by BaBar and Belle**
- **At LHCb this approach is more challenging**
  Run1 trigger has decay-time dependent selections → need to model that bias
  (Things should be better in Run2…)

$D^0 \to K^0_S\pi^+\pi^-$ - Model Independent Approach (I)

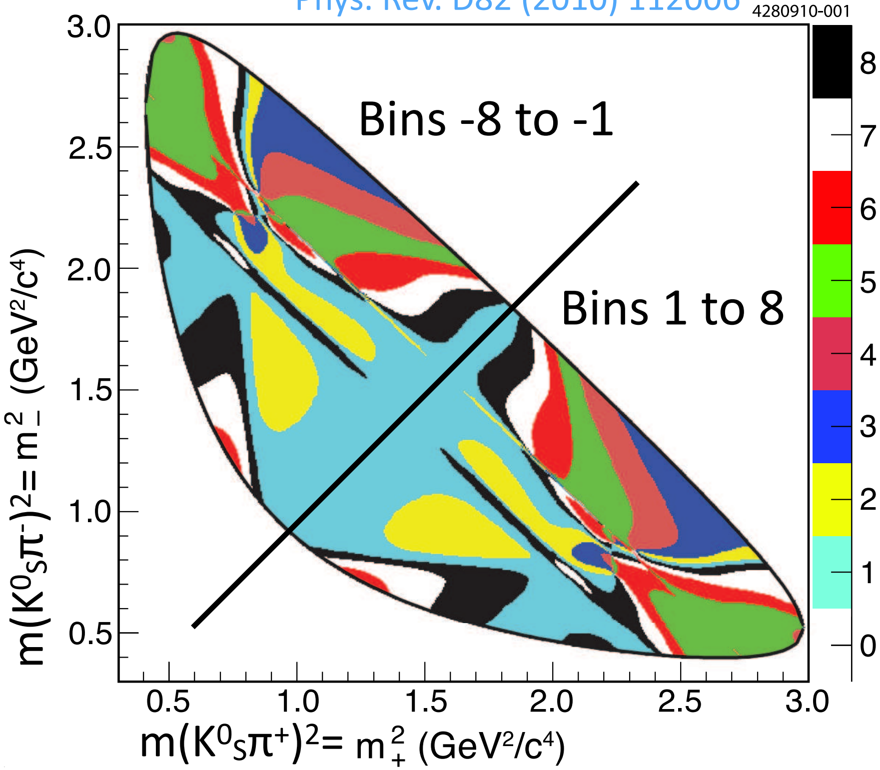
External Input

- In reality one does not need to know perfectly the Amplitude structure
- Just how the strong phases vary along the Dalitz plot
- External input can be used

Phys. Rev. D78 (2008) 034023
Phys. Rev. D82 (2010) 112006

Strong Phases Measurement

- Quantum coherence of D^0-$\bar{D}^0$ needed to separate D^0 and $\bar{D}^0$ decays
- Assuming an amplitude model as a reference, the difference of strong phase between bin -i and i is measured



$D^0 \to K^0_S \pi^+ \pi^-$ - Model Independent Approach (II)

Formalism

- **Fraction of events in a bin**

$$T_i = \int_i |\mathcal{A}| dm^2_{12} dm^2_{13}$$

- **Interference terms**

$$c_i = \frac{1}{\sqrt{T_i T_{-i}}} \int_i |\mathcal{A}^*_{D^0}||\mathcal{A}_{\overline{D}^0}| \cos \Delta\delta_i dm^2_+ dm^2_-$$

$$s_i = \frac{1}{\sqrt{T_i T_{-i}}} \int_i |\mathcal{A}^*_{D^0}||\mathcal{A}_{\overline{D}^0}| \sin \Delta\delta_i dm^2_+ dm^2_-$$

- **Time-dependent decay rate**

$$\mathcal{P}_{D^0}(i;t) \approx e^{\Gamma t} \left(T_i - \Gamma t \sqrt{T_i T_{-i}} (y c_i + x s_i) \right)$$

$$\mathcal{P}_{\overline{D}^0}(i;t) \approx e^{\Gamma t} \left(T_{-i} - \Gamma t \sqrt{T_i T_{-i}} (y c_i - x s_i) \right)$$

x, y can be measured from the decay-time distribution of events in the DP bins

$D^0 \to K^0_S\pi^+\pi^-$ at LHCb: 2011 Analysis

JHEP 03 (2016) 033

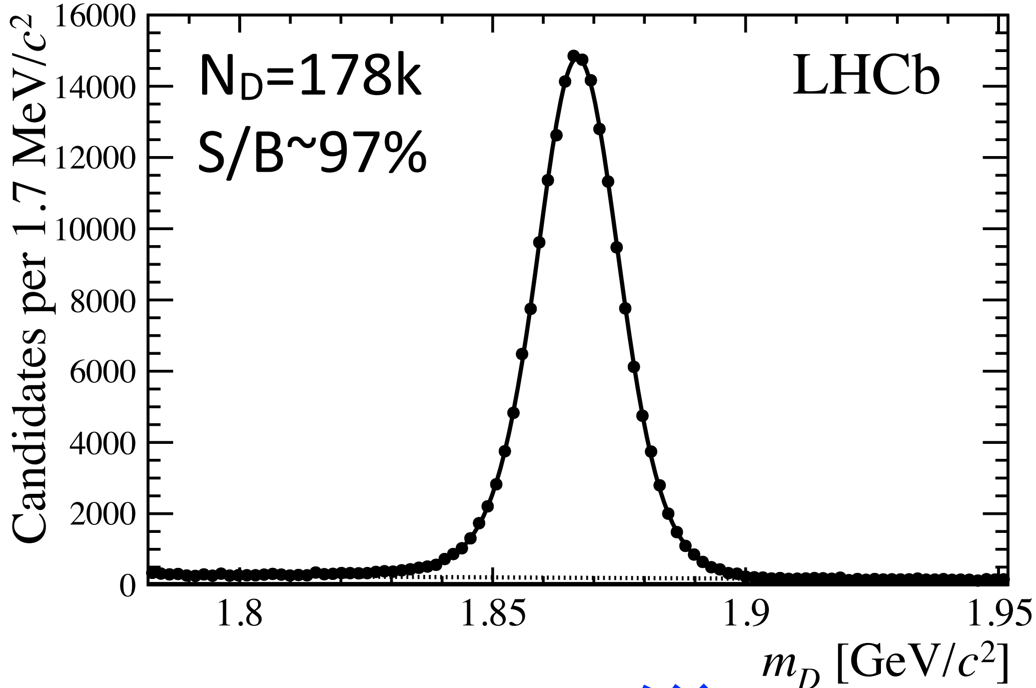
[1]JHEP 1204 (2012) 129

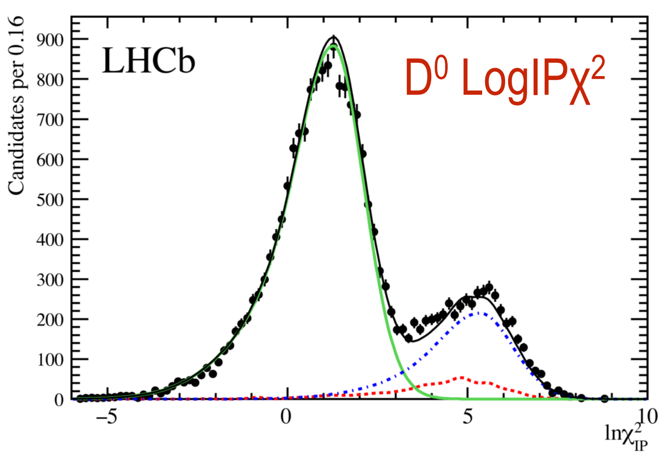
Dataset

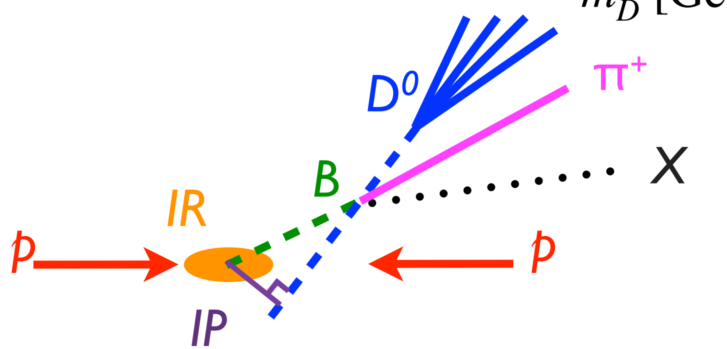
- **Prompt $D^{*+} \to D^0\pi^+$ decays**
- **2011 data: $1fb^{-1}$**

Challenges

- **Per-event decay-time acceptance**
  Data-driven (swimming[1])
- **Secondary ($B \to D^{*+}X$) candidates rejection**





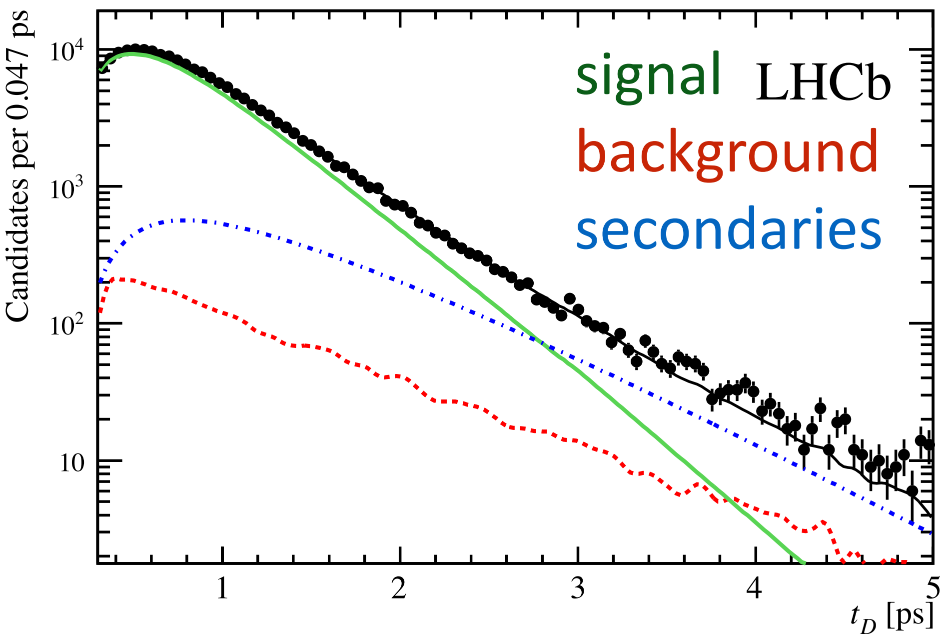


$D^0 \to K^0_S \pi^+ \pi^-$ at LHCb: 2011 Analysis

JHEP 03 (2016) 033

Analysis

- **The distributions of D^0 mass, D^0 LogIPχ^2 and D^0 decay time are fit separately in various steps and finally simultaneously to measure the mixing parameter**
- **Systematic uncertainties studying by measuring the impact on final result**
  - external input (T_i)
  - mass resolution
  - decay time resolution
  - combinatorial background
  - efficiency over PS
  - per-event decay time acceptance



$$x = (-0.86 \pm 0.53 \pm 0.17) \times 10^{-2},$$
$$y = (+0.03 \pm 0.46 \pm 0.13) \times 10^{-2}.$$

WA (HFAG2016)

x = (0.46±0.15)%

y = (0.62±0.08)%

Synergy with BESIII

External Inputs

- Quantum coherence of D^0-$\overline{D}^0$ mesons produced at c factories allows complementary measurements to LHCb
- A proposal is out describing where branching fraction and strong phases measurements could help (LHCb-PUB-2016-025)
- Focused on the determination of γ at LHCb, but applies also to mixing and CPV in Charm

LHCb-PUB-2016-025
October 11, 2016

Synergy of BESIII and LHCb physics programmes

LHCb Collaboration

LHCb Run2 Prospects

Much Larger Yields

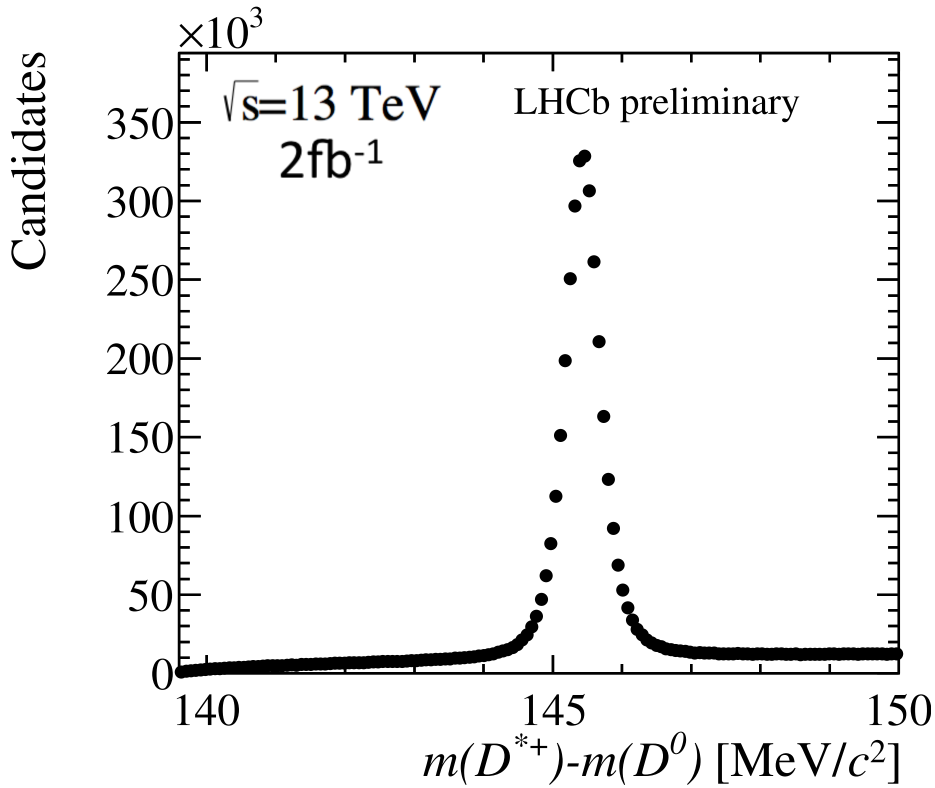
- **$c\bar{c}$ cross-section almost doubled**
- **Extensive work during LS1 on Charm triggers (Turbo)**
  Larger efficiency
  Improved acceptance
- **Online Alignment and Calibration**

Alternative Techniques

- **Amplitude analyses in Charm are gaining momentum**
- **Useful for measuring Mixing and CPV**

$D^0 \to K^0_S \pi^+ \pi^-$ Run2 Preview

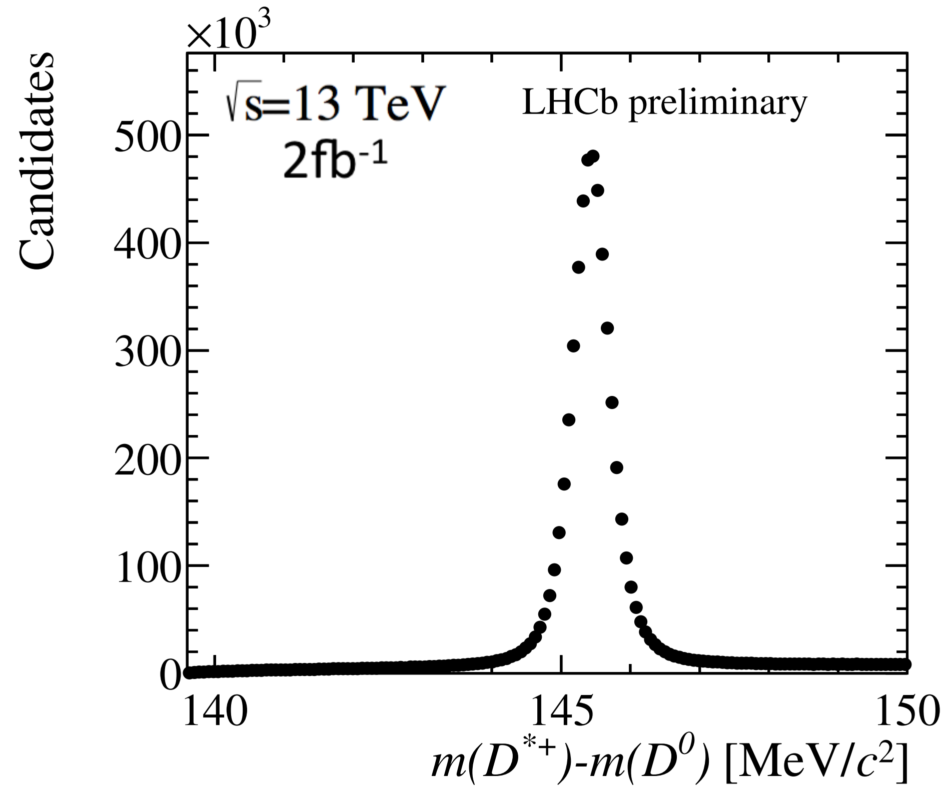
K^0_S vtx inside VELO



$N_D \approx 3.2 \times 10^6$ (1.6M/fb)

Run1: 0.3M/fb

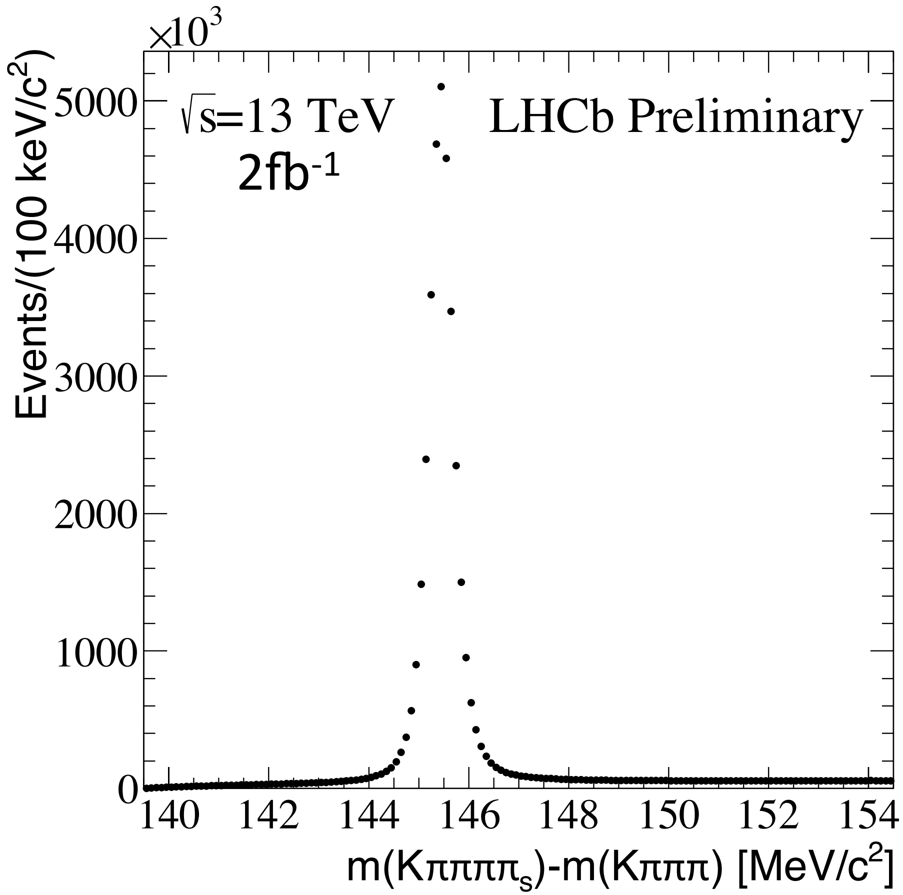
K^0_S vtx outside VELO



$N_D \approx 5.0 \times 10^6$ (2.5M/fb)

Run1: 0.4M/fb

$D^0 \to K\pi\pi\pi$ Run2 Preview



$N_D \approx 33\text{x}10^6$ (16M/fb)

Run1: 3.7M/fb

Summary

Just Started

- The study of Mixing and CPV in Charm multi-body decays at LHCb has just started
- Many more analysis are in the pipeline
- More experience with the detector will favour amplitude analyses

The Best is Yet to Come

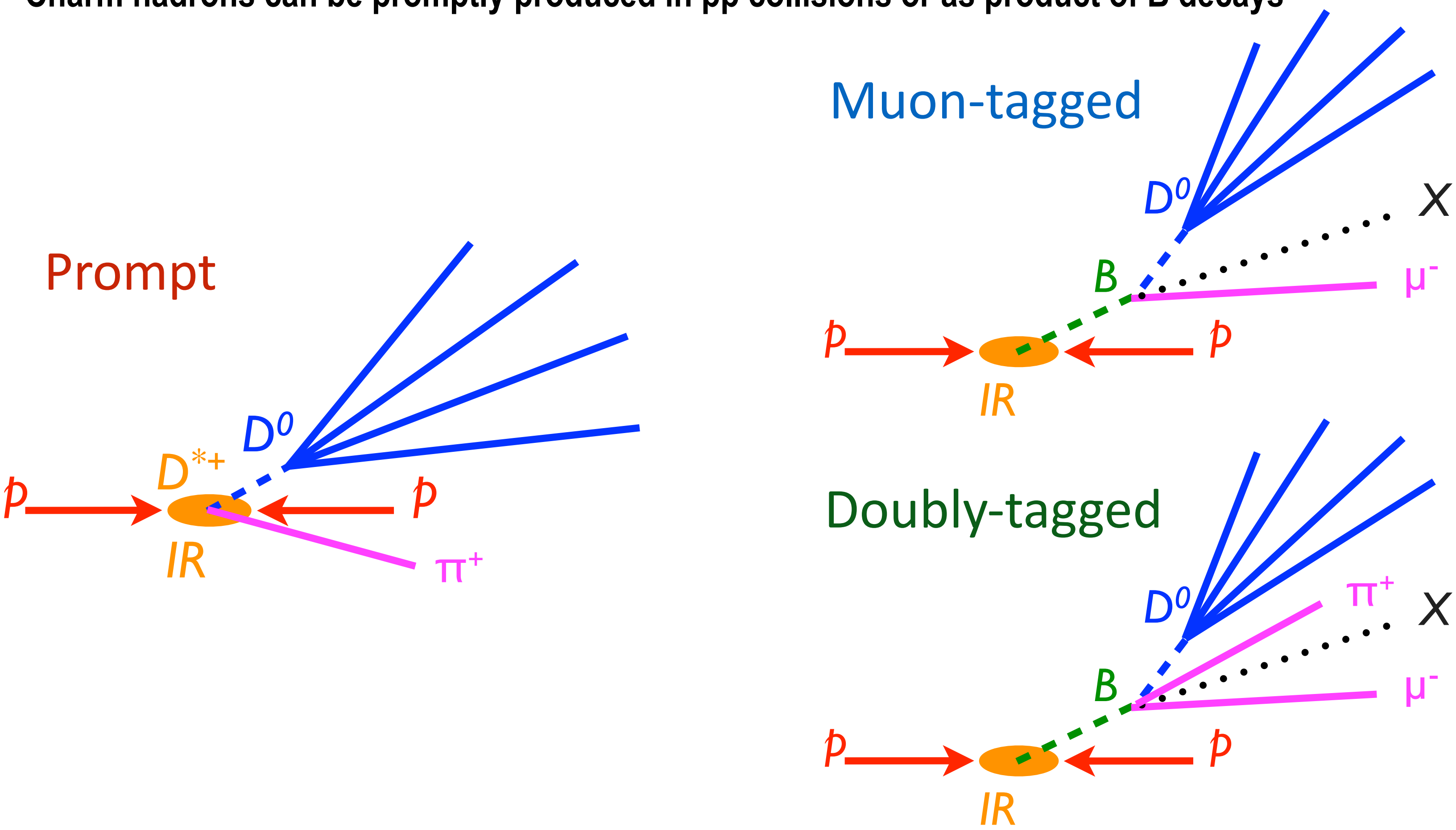
- Run2 data are very promising
- Improved trigger provides us unprecedented yields of Charm decays

Spares

Prompt and Secondary Decays

Two Ways of Selecting and Tagging Charm Hadrons at LHCb

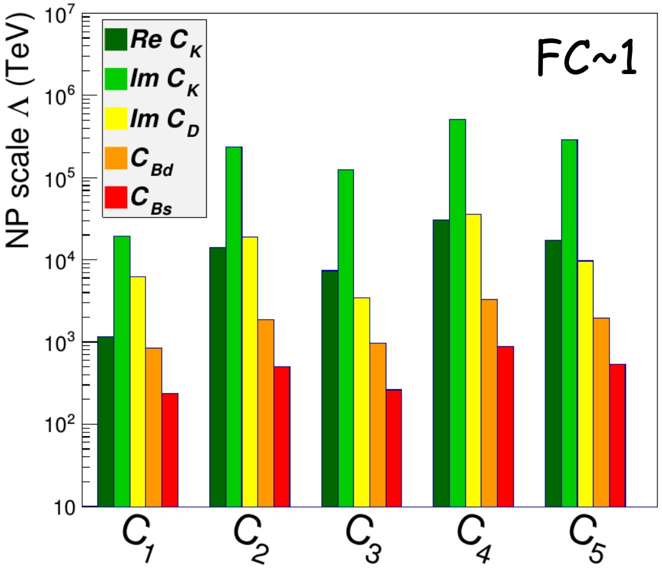
- Charm hadrons can be promptly produced in pp collisions or as product of B decays

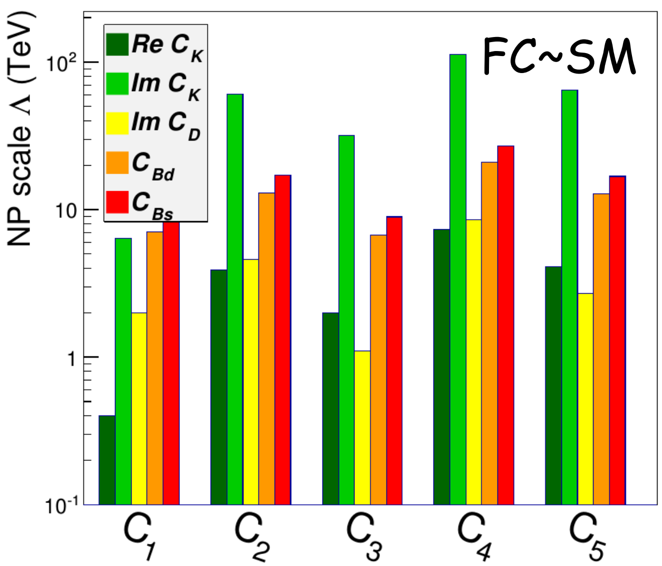


New Physics and Indirect CPV in Charm

Comparison with other meson mixing

Λ (TeV)	K	D	B_d	B_s
FC~1	5×10^5	3.5×10^4	3.3×10^3	880
FC~SM	113	8.5	21	27





Marco Ciuchini Charm 2016 – 8 September 2016 – Bologna (IT) Page 18

$D^0 \to K^0_S\pi^+\pi^-$ 2011 Systematic Uncertainties

Table 1: Systematic uncertainties on x and y. The statistical uncertainties, which include the uncertainties associated with the CLEO parameters (c_i, s_i), are shown for comparison.

Source	$x\,(\times 10^{-2})$	$y\,(\times 10^{-2})$
Fit bias	0.021	0.020
Decay time resolution	0.065	0.039
Turning point (TP) resolution	0.020	0.022
Invariant mass resolution	0.073	0.028
Prompt/secondary TP distributions	0.051	0.023
Efficiency over phase space	0.057	0.071
Tracking efficiency parameterisation	0.015	0.025
Kinematic boundary	0.012	0.006
Combinatorial background	0.061	0.052
Treatment of secondary D decays	0.046	0.025
Uncertainty from T_i	0.079	0.056
Uncertainties from $(m_D, \Delta m)$ fits	0.000	0.000
Uncertainties from lifetime fit	0.020	0.043
D^0 background	0.001	0.006
Variation of signal components across the phase space	0.013	0.017
Total systematic uncertainty	0.171	0.134
Statistical uncertainty	0.527	0.463