

Charm physics at LHCb

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INFN Cagliari and CERN

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Outline

- Introduction
- Asymmetries in $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ [LHCb-PAPER-2018-020] **NEW**
- A_{CP} in $D^0 \rightarrow K_S K_S$ [LHCb-PAPER-2018-012] **NEW**
- $D^0 - \bar{D}^0$ mixing and CPV with $D^0 \rightarrow K^+ \pi^-$ [PRD 97 (2018) 031101]
- Ξ_{cc}^{++} lifetime measurement [LHCb-PAPER-2018-019] **NEW**
- Search for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ [LHCb-PAPER-2018-026] **BRAND NEW**
- Ω_c^0 baryon lifetime [LHCb-PAPER-2018-028] **BRAND NEW**
- Conclusions

Introduction

- In **indirect searches for new physics** charm
 - furnishes a unique probe of flavour physics in the up-quark sector: complementary to strange and bottom physics
 - gives complementary constraints to direct searches
- Precision measurements in charm are necessary as inputs for B physics and the measurement of the CKM angle γ
- Many null-tests available, one of them is the **search for CP violation**, which is expected to be small in SM (but not zero)
- One of few occasions to investigate **up-type quark FCNCs**: some NP models predict large enhancement in rates and asymmetries

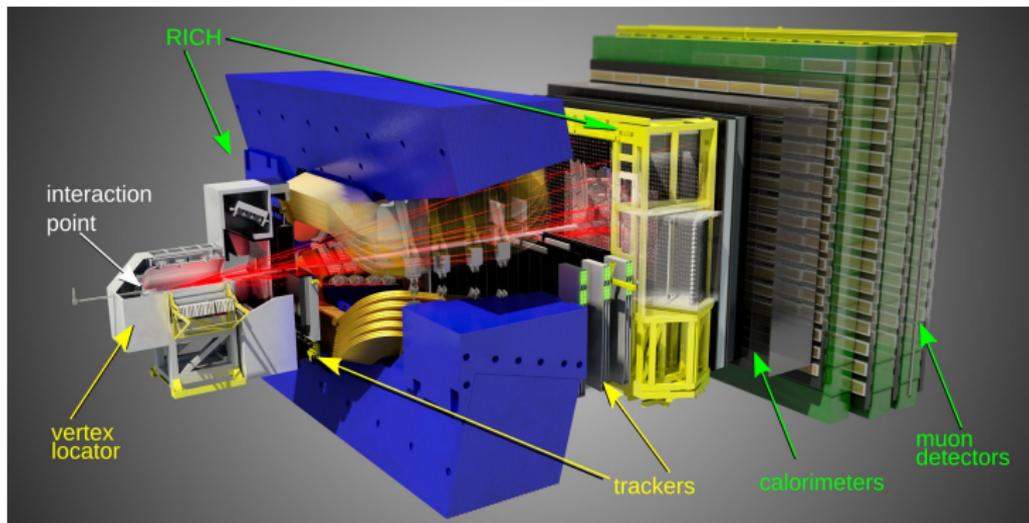


Introduction

Int. J. Mod. Phys. A 30 1530022 (2015)

Why at LHCb?

- perfect detector to study decays of heavy flavor
- excellent particle ID, momentum & vertex resolution
- largest sample of recorded charm decays: $\sim 5 \cdot 10^{12} D^0$ (Run 1)



Asymmetries in $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$

- First observation of the rarest charm decays [PRL 119 (2017) 181805] \rightarrow agreement with SM
- Measurement of **angular** and **CP asymmetries**
- Asymmetries are sensitive to SD in full range due to SD-LD interference
 - Null test for the SM
 - $\mathcal{O}(\text{few}\%)$ predictions for some NP models [JHEP 1304 135 (2013), PRD 87 054026 (2013)]

Angular asymmetries

- Forward backward asymmetry

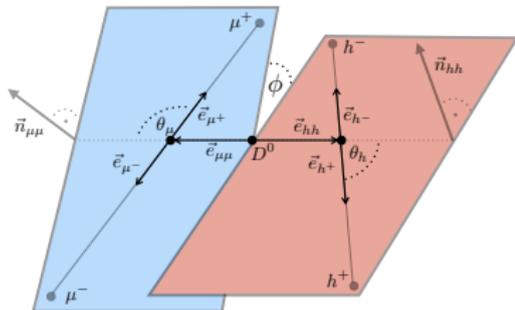
$$A_{FB} = \frac{\Gamma(\cos \theta_\mu > 0) - \Gamma(\cos \theta_\mu < 0)}{\Gamma(\cos \theta_\mu > 0) + \Gamma(\cos \theta_\mu < 0)}$$

- Triple product asymmetry

$$A_\phi = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)}$$

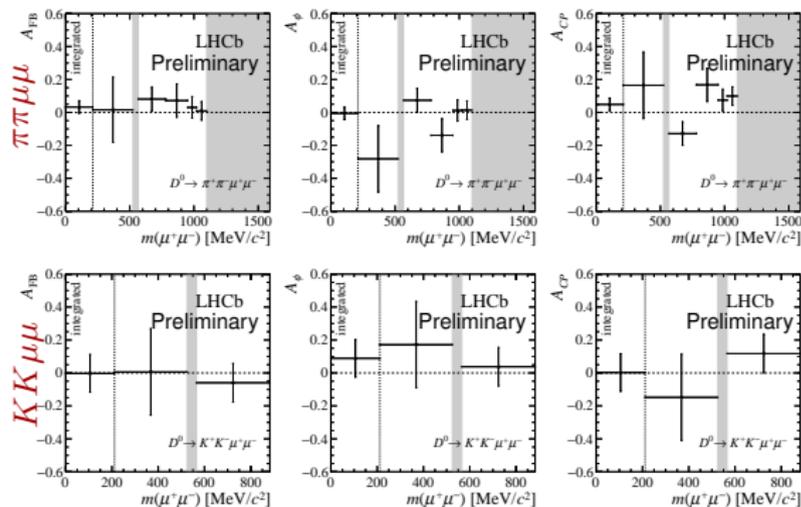
CP asymmetry

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow h^+ h^- \mu^+ \mu^-) - \Gamma(\bar{D}^0 \rightarrow h^+ h^- \mu^+ \mu^-)}{\Gamma(D^0 \rightarrow h^+ h^- \mu^+ \mu^-) + \Gamma(\bar{D}^0 \rightarrow h^+ h^- \mu^+ \mu^-)}$$



Asymmetries in $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$

[LHCb-PAPER-2018-020]



Asymmetries

$$A_{FB}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (3.3 \pm 3.7 \pm 0.6)\%$$

$$A_{\phi}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%$$

$$A_{CP}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (4.9 \pm 3.8 \pm 0.7)\%$$

$$A_{FB}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (0 \pm 11 \pm 2)\%$$

$$A_{\phi}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (9 \pm 11 \pm 1)\%$$

$$A_{CP}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (0 \pm 11 \pm 2)\%$$

compatible with SM predictions

[JHEP 04 135 (2013)]

- Asymmetries compatible with zero
- No dependency on dimuon mass

A_{CP} in $D^0 \rightarrow K_S K_S$

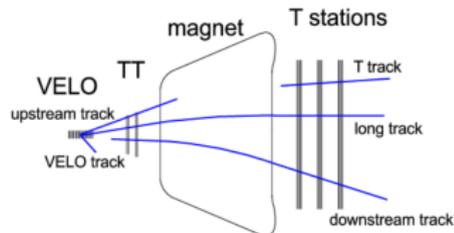
- Dataset: 2 fb^{-1} (2015 + 2016)
- Tagged decay $D^{*+} \rightarrow D^0 \pi^+$
- Measuring the raw asymmetry:

$$A_{raw}(K_S K_S) = A_{CP}(K_S K_S) + A_P + A_{tag}$$

- No detection asymmetries: D^0 daughters symmetric
- Removing production and tagging asymmetries by using $D^0 \rightarrow K^+ K^-$

$$\begin{aligned} \Delta A_{CP} &= A_{raw}(K_S K_S) - A_{raw}(K^+ K^-) \\ &= A_{CP}(K_S K_S) - A_{CP}(K^+ K^-) \end{aligned}$$

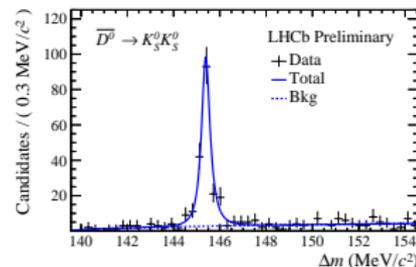
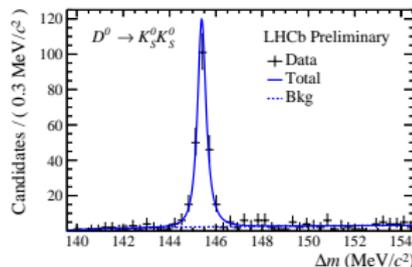
- Various type of tracks



- **LL**: two K_S decay in the VELO and have long tracks
- **LD**: one K_S has a long track and one decays downstream of the VELO

A_{CP} in $D^0 \rightarrow K_S^0 K_S^0$ [LHCb-PAPER-2018-012]

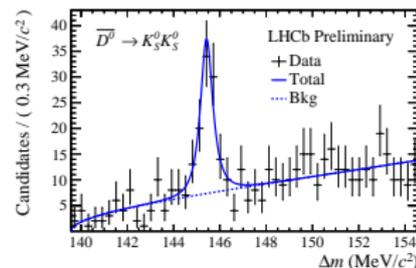
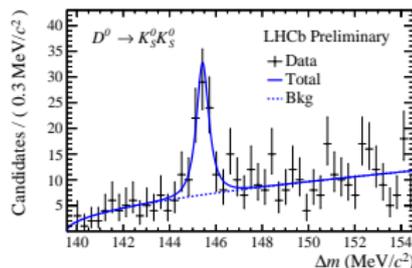
LL



overall yields

$$N_{sig} = 1067 \pm 41$$

LD



$$A_{CP} = (4.2 \pm 3.4 \pm 1.0)\%$$

- Compatible with Run 1 result $A_{CP} = (-2.9 \pm 5.2 \pm 2.2)\%$
- Average $A_{CP} = (2.0 \pm 2.9 \pm 1.0)\%$

$D^0 - \bar{D}^0$ mixing and CPV with $D^0 \rightarrow K^+ \pi^-$ [PRD 97 (2018) 031101]

- Data sample: 5 fb^{-1} (2011-2016)
- Use tagged $D^0 \rightarrow K^+ \pi^-$ decay
- Measure the time dependent ratio of Wrong-Sign $D^{*+} \rightarrow [K^+ \pi^-] \pi^+$ and Right-Sign $D^{*+} \rightarrow [K^- \pi^+] \pi^+$

$$R(t) = \frac{N(D^0 \rightarrow K^+ \pi^-)}{N(D^0 \rightarrow K^- \pi^+)}$$

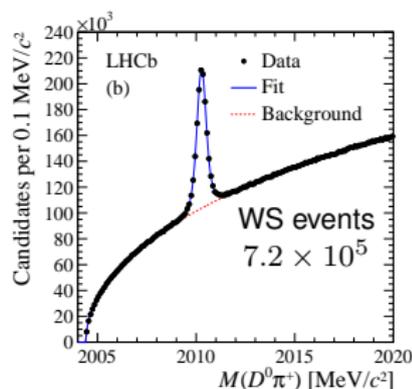
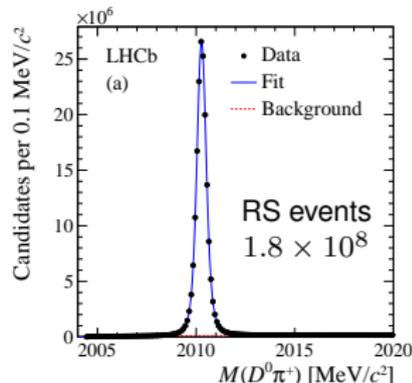
- The time dependence of the phase-space integrated decay rate ratio can be approximated by:

$$R(t) \approx R_D + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} + \left(\frac{t}{\tau}\right)^2$$

- Negligible CPV
- Limit of $x, y \ll 1$

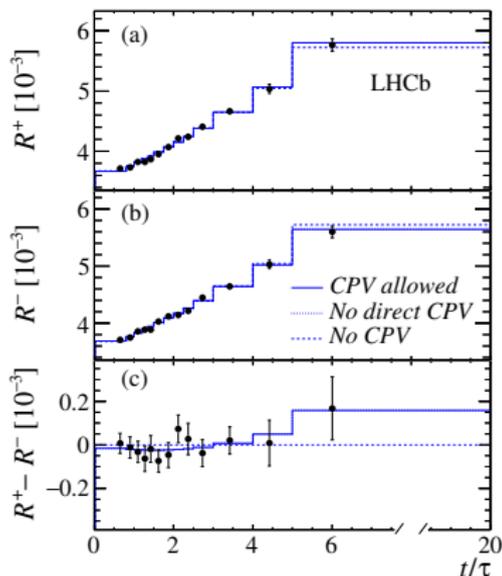
$$\begin{aligned} x' &\equiv x \cos \delta + y \sin \delta \\ y' &\equiv y \cos \delta - x \sin \delta \end{aligned}$$

- τ is the average D^0 lifetime
- R_D is the ratio of suppressed to- favored decay rates



$D^0 - \bar{D}^0$ mixing and CPV with $D^0 \rightarrow K^+ \pi^-$ [PRD 97 (2018) 031101]

- Fit efficiency - corrected data to extract $(x'^{\pm}, y'^{\pm}, R_D^{\pm})$ under three hypotheses



Direct and indirect CPV

Parameter	Value
R_D^+	$3.454 \pm 0.040 \pm 0.020$
y'^{+}	$5.01 \pm 0.64 \pm 0.38$
$(x'^{+})^2$	$0.061 \pm 0.032 \pm 0.019$
R_D^-	$3.454 \pm 0.040 \pm 0.020$
y'^{-}	$5.54 \pm 0.64 \pm 0.38$
$(x'^{-})^2$	$0.016 \pm 0.033 \pm 0.020$

No direct CPV

Parameter	Value
R_D	$3.454 \pm 0.028 \pm 0.014$
y'^{+}	$5.01 \pm 0.48 \pm 0.29$
$(x'^{+})^2$	$0.061 \pm 0.026 \pm 0.016$
y'^{-}	$5.54 \pm 0.48 \pm 0.29$
$(x'^{-})^2$	$0.016 \pm 0.026 \pm 0.016$

No CPV

Parameter	Value
R_D	$3.454 \pm 0.028 \pm 0.014$
y'	$5.28 \pm 0.45 \pm 0.27$
x'^2	$0.039 \pm 0.023 \pm 0.014$

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.1 \pm 8.1 \text{ (stat)} \pm 4.2 \text{ (syst)}) \times 10^{-3}$$

Direct CPV

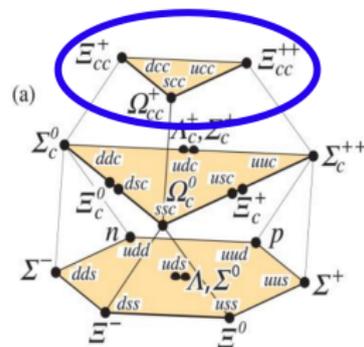
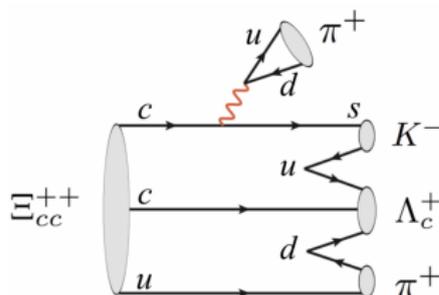


Ξ_{cc}^{++} lifetime measurement [LHCb-PAPER-2018-019]

- A significant structure consistent with Ξ_{cc}^{++} observed in LHCb 2016 data [\[PRL 119, 112001 \(2017\)\]](#)
- Measured mass is consistent with theoretical range of predictions

$$m(\Xi_{cc}^{++}) = 3621 \pm 0.72 \text{ (stat)} \pm 0.31 \text{ (syst)} \text{ MeV}/c^2$$

- Measuring **lifetime** to establish the weak nature of its decay and for comparison with theoretical predictions
- Using the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decay



Large ambiguity in lifetime theoretical predictions [\[arXiv:9807354\]](#), [\[arXiv:9901323\]](#)

Search for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ [LHCb-PAPER-2018-026]

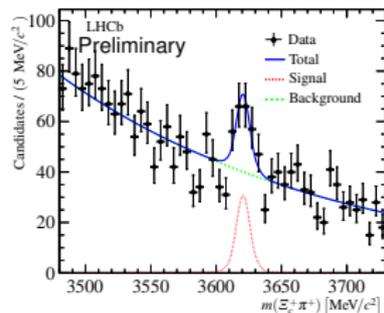
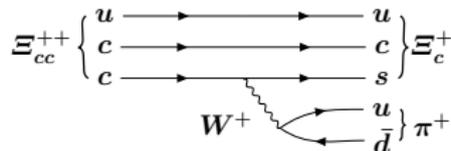
- Searching for new decay modes is critical to understand the dynamics of weak decays of doubly heavy baryons
- Search for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$
- Data sample: 1.7 fb^{-1} (13 TeV)
- Normalisation: $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$
- Significant peak: 91 ± 20 events
- The mass is measured to be

$$m(\Xi_{cc}^{++}) = 3620 \pm 1.5 \text{ (stat)} \pm 0.4 \text{ (syst)} \pm 0.3(\Xi_c^+) \text{ MeV}/c^2$$

consistent with the previous result!

- The ratio of branching fraction is

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \rightarrow pK^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \rightarrow pK^- \pi^+)} = 0.035 \pm 0.009 \text{ (stat)} \pm 0.003 \text{ (syst)}$$



Ω_c^0 baryon lifetime [LHCb-PAPER-2018-028]

- Charm baryon lifetimes are known much less precisely than charm mesons ones
- The expected lifetime hierarchy should be

$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$$

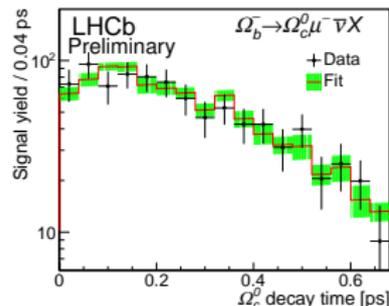
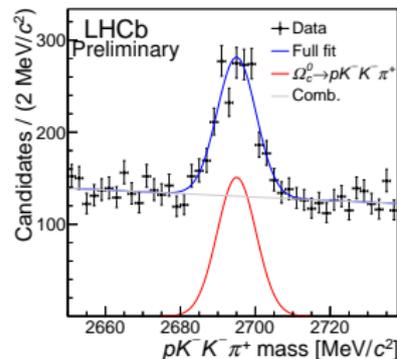
and current measurements are consistent with this hierarchy

- Using semileptonic $\Omega_b^- \rightarrow \Omega_c^0 \mu^- \bar{\nu}_\mu X$ with $\Omega_c^0 \rightarrow p K^- K^- \pi^+$
- To reduce the uncertainties measure the ratio with the D^+ lifetime, with $D^+ \rightarrow K^- \pi^+ \pi^+$
- Data sample: 1.0 fb^{-1} (7 TeV) + 2.0 fb^{-1} (8 TeV)
- Lifetime is measured to be

$$\tau_{\Omega_c^0} = 268 \pm 21 \text{ (stat)} \pm 10 \text{ (syst)} \pm 2 \text{ (} D^+ \text{)} \text{ fs}$$

four times larger than, and inconsistent with the world average value of (69 ± 12) fs from fixed target experiments

[PLB 561(2003) 41], [PLB 358(1995) 151], [PLB 357 (1995) 678]



Conclusions

- LHCb is a charm factory
- Many new and interesting physics results available
- Charm mixing and indirect CP violation are very promising probes for indirect searches of new physics
- $D^0 - \bar{D}^0$ mixing have reached an unprecedented precision
- LHCb is playing an important role also in measurements with charmed baryons, which could re-ignite further theoretical work to understand baryon structure
- With coming data LHCb will reach the precision to observe CP violation as expected by SM and will be a leading player in searching for indirect CP violation with charm decays
- New analyses and updates will come for Run 1 and Run 2 data

Conclusions

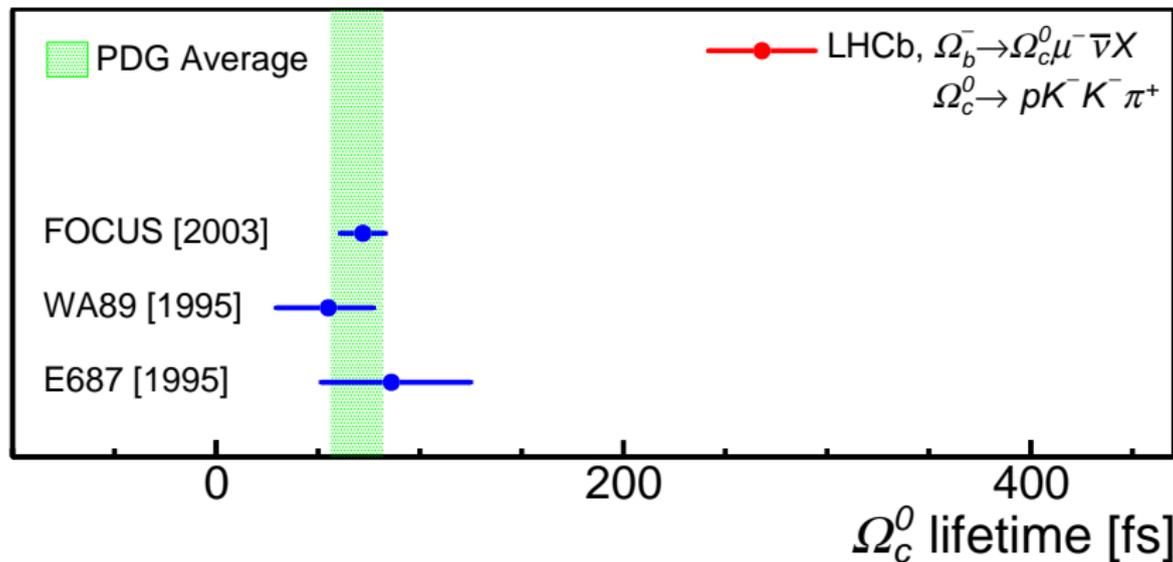
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Thanks for your attention!

Backup

Ω_c^0 lifetime measurements

FOCUS	$72 \pm 11 \pm 11$ fs	$\Xi^- K^- \pi^+ \pi^+$, $\Omega^- \pi^+$
E687	$86^{+27}_{-20} \pm 28$ fs	$\Sigma^+ K^- K^- \pi^+$
WA89	$55^{+13}_{-11} \text{ }^{+18}_{-23}$ fs	$\Xi^- K^- \pi^+ \pi^+$, $\Omega^- \pi^+ \pi^+ \pi^-$



Ω_c^0 lifetime measurement: FOCUS

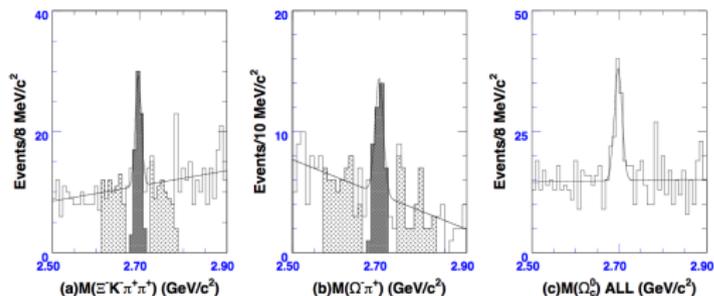
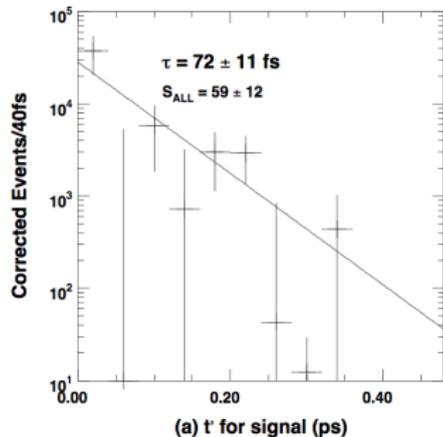


FIG. 1: Invariant mass distributions for Ω_c^0 candidates: (a) Reconstructed mass of $\Xi^- K^- \pi^+ \pi^+$. There are 38 ± 9 events at a mass of $2696.5 \pm 1.9 \text{ MeV}/c^2$. (b) Reconstructed mass of $\Omega^- \pi^+$. There are 23 ± 7 events at a mass of $2699.4 \pm 3.4 \text{ MeV}/c^2$. (c) Combined invariant mass distribution. There are 64 ± 14 events at a mass of $2697.5 \pm 2.2 \text{ MeV}/c^2$. We define the signal region (hatched area) to be within 2σ of the fitted mass value and the two sideband regions (dotted area) are 4 – 12σ from the fitted mass value.



Ω_c^0 lifetime measurement: WA89

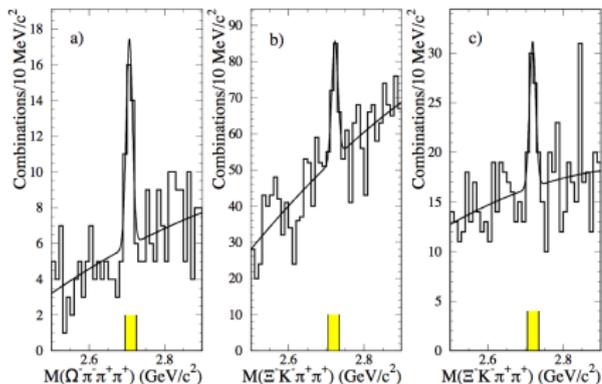


Figure 3: Mass distributions for three different final states: a) $\Omega^- \pi^+ \pi^- \pi^+$, b) $\Xi^- K^- \pi^+ \pi^+$ from carbon, c) $\Xi^- K^- \pi^+ \pi^+$ from all targets with positively RICH identified kaon. The shaded region denotes the signal band.

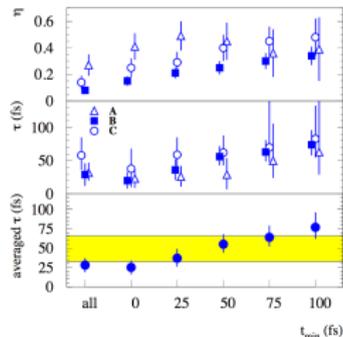


Figure 7: Results of the likelihood fits (see text) for the different samples and their dependence on the lower decay time cut t_{\min} used in the fit. The shaded area represents the size of the full systematic error. Sample A) denotes $\Omega^- \pi^+ \pi^- \pi^+$, sample B) $\Xi^- K^- \pi^+ \pi^+$ from the carbon target and sample C) $\Xi^- K^- \pi^+ \pi^+$ with identified K^- .

Ω_c^0 lifetime measurement: E687

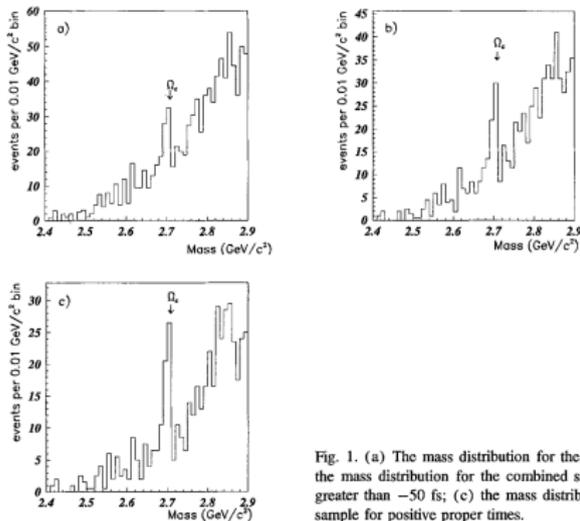


Fig. 1. (a) The mass distribution for the combined sample; (b) the mass distribution for the combined sample for proper times greater than -50 fs; (c) the mass distribution for the combined sample for positive proper times.

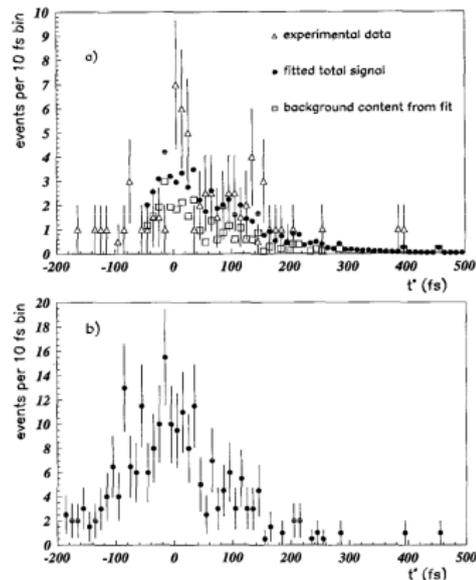


Fig. 2. The observed proper time (t^*) distributions for the combined sample: (a) in the signal region. The solid circles are the total signal obtained from the fit while the squares are the background contribution. Note that the fit results start from $t^* > -50$ fs, corresponding to the final choice of t_{cut}^* (see text); (b) in the sidebands. (The sizes of the sidebands are given in the text).

Ω_c^0 lifetime measurement: conclusion

- Most theory/pheno papers expect Ω_c^0 lifetime to be the shortest, due to large constructive PI between s-quarks in final state. This result turns that expectation upside down!
 - At $\mathcal{O}(1/m_c^2)$: poor quantitative understanding of spin-spin interaction?
 - At $\mathcal{O}(1/m_c^3)$: poor quantitative understanding of PI or W-exchange processes ?
- Could re-ignite further theoretical work to understand baryon structure, and the impact on their treatment in the HQE.
- Other charm baryon lifetimes to follow in the coming months.