Charm Physics at LHCb

FSP Meeting - Siegen, Germany

Andrea Contu

INFN

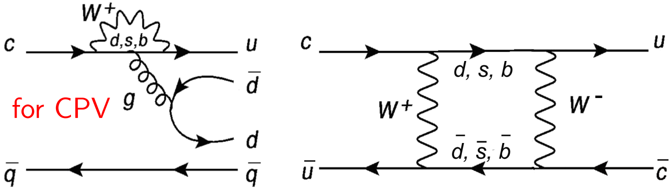
5-6 October 2017

Outline

Why study charm physics?

- Up-type quark: unique probe of NP in the flavour sector, complementary to studies in K and B systems
- Precision CKM physics in the B sectors needs input from charm
- Rare processes are very suppressed in the SM

Needed for CPV



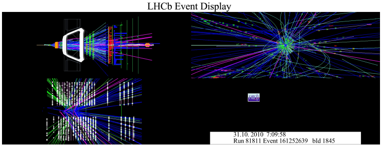
- New Physics may be hidden in the loops
- Long-distance contributions are non-negligible and precise theoretical predictions are difficult
- Charm is more of a "discovery tool"

Charm samples

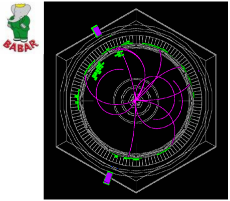
Type	Exp	$\sqrt{s}$	L_{int}	$\sigma(c\bar{c})$	$N(c\bar{c})$
	prompt $c\bar{c}$				
Hadron colliders	LHCb	7, 8 TeV	3/fb	1.4 mb	3.6×10^{12}
		13 TeV	2/fb +	2.6 mb	4.4×10^{12}
	CDF	2 TeV	10/fb	0.1 mb	2.3×10^{11}
	$c\bar{c}$ from continuum				
e^+e^- collider	Belle	10.6 GeV	1/ab	1.3 nb	1.3×10^{9}
	BaBar	10.6 GeV	550/fb	1.3 nb	0.7×10^{9}
	Charm factories at $D\bar{D}$ threshold				
	BESIII	3.7 GeV	3/fb	3 nb	20×10^{6}
	Cleo-c	3.7 GeV	0.8/fb	3 nb	5×10^{6}

Pros & Cons

- LHCb
  - Large combinatorial backgrounds
  - Decays with neutrals and missing particles are difficult
  - Excellent lifetime resolution due to the boost, $\sim 0.1\tau_D$
  - Huge $c\bar{c}$ production cross sections



- Belle/BaBar
  - Lower boost, poorer lifetime resolution
  - Clean environment
  - Excellent performance when dealing with neutrals/neutrinos



- BES/CLEO-c
  - No boost, no lifetime measurement
  - Practically no background
  - $\psi(3770) \to DD$, quantum coherence (can measure strong phases!)

Neutral D mesons mixing

Produced as flavour D^0 and $\bar{D}^0$ eigenstates, decay as mass eigenstates D_1 and D_2

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

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}$$

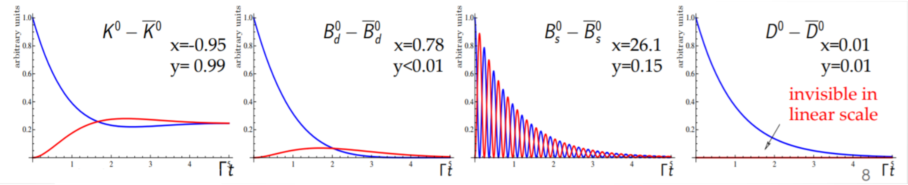
$$|D_1\rangle = p\,|D^0\rangle + q\,|\bar{D}^0\rangle$$
$$|D_2\rangle = p\,|D^0\rangle - q\,|\bar{D}^0\rangle$$

$$|q|^2 + |p|^2 = 1$$

Mixing occurs if $\Delta M = M_1 - M_2 \neq 0$ or $\Delta\Gamma = \Gamma_1 - \Gamma_2 \neq 0$

Mixing parameters

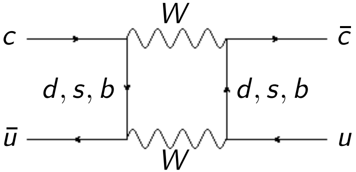
$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$



Tiny mixing in Charm!

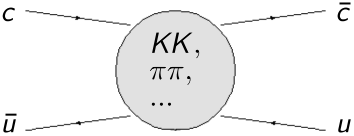
Contributions to x and y

Short distance



Mixing at quark level: $x \sim 10^{-5}$

Long distance

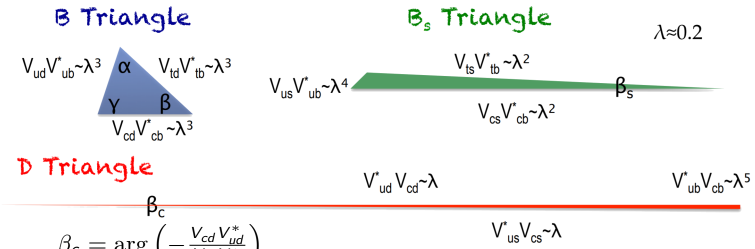


Mixing via final-state interaction: $x, y \sim 0.1\%$

New physics can only affect x (SUSY, leptoquarks, etc...)
Short distance in "easy" to calculate, but long distance is not $\rightarrow$ hard to identify NP

Neutral D mesons CPV

CPV in the SM arises from a complex phase in the CKM matrix which describes the quark mixing (2008 Nobel Prize to Kobayashi and Maskawa)
CKM unitarity imposes constraint on CKM elements, visualised as triangles



$$\beta_c = \arg\left(-\frac{V_{cd}V^*_{ud}}{V_{cs}V^*_{us}}\right)$$

- The shape of the "D triangle" (not to scale) implies almost total decoupling from third generation → CPV incredibly small
- Ideal place to look for NP!

Classification of CPV

DIRECT CPV
Different decay amplitudes for D and $\bar{D}$

$$A_f = \langle f|H|D\rangle \quad \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$
$$\bar{A}_{\bar{f}} = \langle \bar{f}|H|\bar{D}\rangle$$

- Observable: difference in decay rate between particles and antiparticles
- Only CPV type possible for charged charmed hadrons

CPV IN MIXING
Different mixing rates
$D^0 \to \bar{D}^0$ and $\bar{D}^0 \to D^0$

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

- Accessible using flavour specific decays

CPV IN INTERFERENCE
between mixing and decay

$$\phi = \arg\left(\frac{q\bar{A}_f}{pA_f}\right)$$

- Observable: difference in rates as a function of the decay time

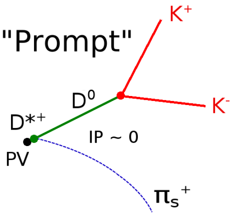
INDIRECT CPV (CPV in mixing + CPV in interference)
(Universal, does not depend on final state)

- Precision on indirect CPV (q/p and ϕ) depends on the knowledge of the mixing rate
- Need to measure x and y more and more precisely

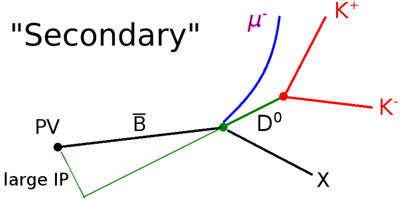
How to get the D flavour at production?

- Whether the decaying D meson is produced as D^0 or $\bar{D}^0$ needs to be determined to perform mixing and CPV measurements
- There are two possible tagging methods

$D^{*\pm}$-tag



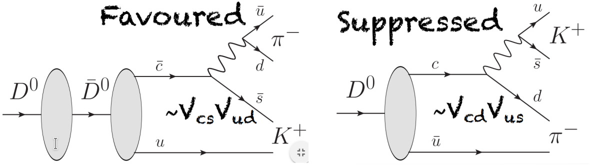
Semileptonic-tag



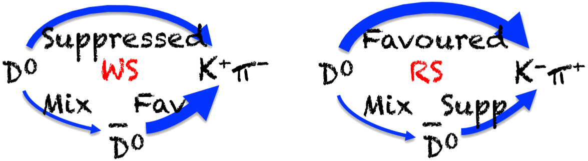
- Both samples used by LHCb, independent and complementary in lifetime coverage

D^0 mixing

- The no-mixing scenario is now excluded thanks to the study of $WS/RS\ D^0 \to K\pi$ decays
- Right-Sign $D^0 \to K^-\pi^+$ is Cabibbo Favoured, Wrong-Sign $D^0 \to K^+\pi^-$ is Doubly Cabibbo Suppressed (the opposite for $\bar{D}^0$)



- The same final state can be reached directly or via a previous oscillation of the D flavour



D^0 mixing with WS/RS ratio

- The WS/RS ratio as a function of the D lifetime is therefore

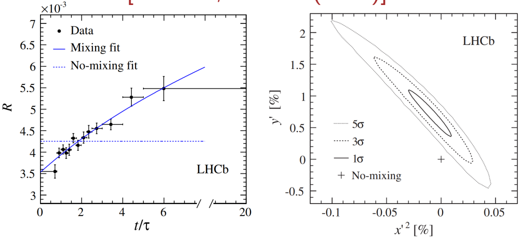
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)}(t) \simeq R_D + \sqrt{R_D}\, y' \frac{t}{\tau_D} + \frac{x'^2 + y'^2}{4} \frac{t}{\tau_D}$$

$R_D = BR_{DCS}/BR_{CF}$

(x' and y' are the usual x and y rotated by a “strong phase”, $\delta_{K\pi}$)

- LHCb was the first single experiment to exclude the no-mixing hypothesis at more than 5σ

[PRL110, 101802 (2013)]

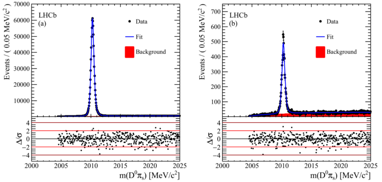


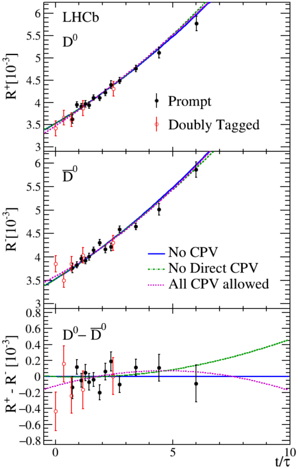
- R_D, x' and y' can be determined separately for D^0 and $\bar{D}^0$. Any difference would be a sign of CPV test → not seen so far

WS/RS mixing and CPV with doubly tagged decays

[PRD 95, 052004]

- New WS/RS measurement using D from $\bar{B} \to D^{*+}\mu^- X$ decays
- D^0 flavour is tagged both with the muon and the slow pion
- Lower stats but very high purity and additional coverage at low lifetimes





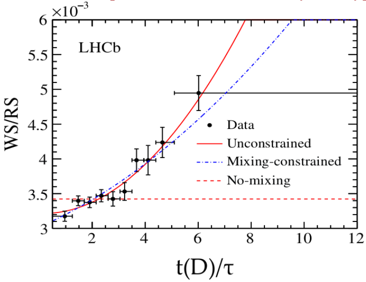
- Combining prompt+secondary:
  $x'^2 = (3.6 \pm 4.3) \times 10^{-5}$,
  $y' = (5.2 \pm 0.8) \times 10^{-3}$
- No evidence for CPV

WS/RS mixing with $D^0 \to K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$

- Similar approach as $D^0 \to K\pi$ but for rates integrated over the full phase space one has to introduce an averaged strong phase, $\delta_{K3\pi}$, and a coherence factor which accounts for dilution in sensitivity

$$R(t) = \frac{N_{WS}(t)}{N_{RS}}(t) \simeq R_D^{K3\pi} + \sqrt{R_D^{K3\pi}} R_{coh} y'' \frac{t}{\tau_D} + \frac{x''^2 + y''^2}{4} \frac{t}{\tau_D}$$

[PRL116, 241801 (2016)]



$$R_{coh} y'' = (0.3 \pm 1.8) \times 10^{-3}$$

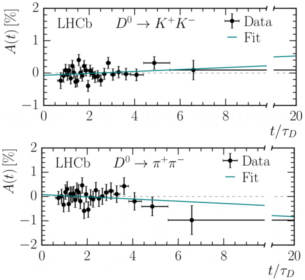
$$(x''^2 + y''^2)/4 = (4.8 \pm 1.8) \times 10^{-5}$$

Indirect CPV through A_Γ

- Asymmetry in the effective lifetime between $D^0 \to h^+ h^-$ and $\bar{D}^0 \to h^+ h^-$ ($h^\pm = \pi^\pm, K^\pm$)

$$A_\Gamma = \frac{\tau^{eff}_{\bar{D}^0} - \tau^{eff}_{D^0}}{\tau^{eff}_{\bar{D}^0} + \tau^{eff}_{D^0}} \approx \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right| \right) y \cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right| \right) x \sin\phi$$

- Almost clean measurement of indirect CPV
- Most precise result from LHCb, Run1 data
- Fit the time evolution of the yields asymmetry, $A_{CP}(t) \approx A_0 - A_\Gamma \frac{t}{\tau}$

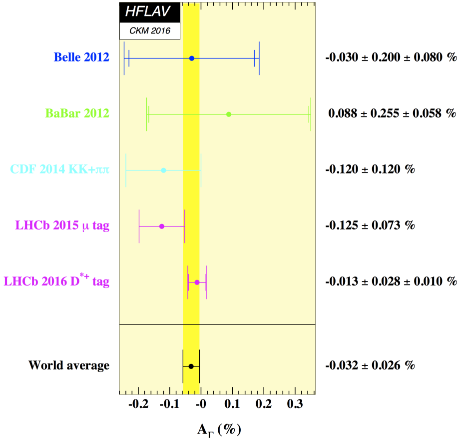


[PRL 118, 261803 (2017)]

$$A_\Gamma(KK) = (-0.3 \pm 0.32 \pm 0.10) \times 10^{-3}$$

$$A_\Gamma(\pi\pi) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$$

A_Γ status

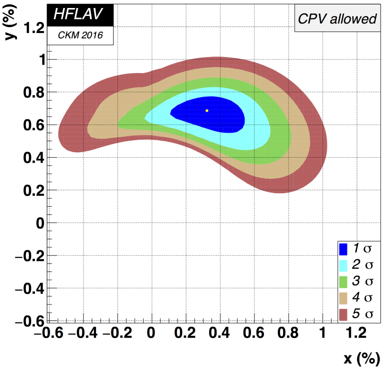


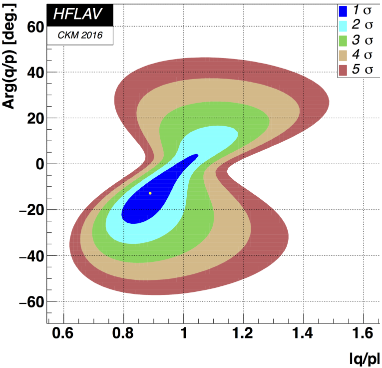
- Indirect CPV in SM is $\sim 10^{-4}$
- Approaching SM predictions and still statistically dominated!

Mixing and CPV in multibody decays: $D^0 \to K_S\pi^+\pi^-$

- Large statistics and rich dynamics, often referred to as "Golden Channel"
- Gives direct access to x, y, q/p and ϕ via a study of the time evolution of the Dalitz plane
- Most precise results from Belle with 1.2M signal events [PRD89 091103 (2014)]
  $x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$, $y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$,
  $|q/p| = (0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05})$, $\phi = (-6 \pm 11 \pm 3^{+3}_{-4})^\circ$
- One measurement of x and y from LHCb using 2011 data only [JHEP04(2016)033], not competitive with Belle
- LHCb has 2M evts in full Run1 datasets and large trigger efficiency gain in Run2, analyses ongoing, stay tuned...

Mixing and Indirect CPV: Global fits

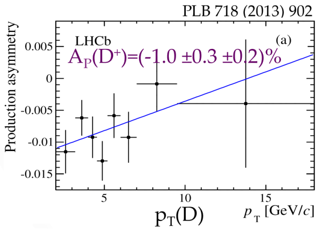


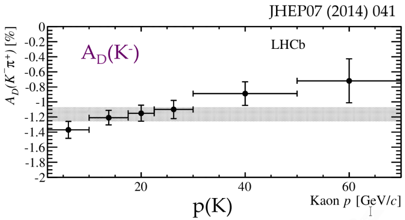


- No-mixing excluded at $> 11\sigma$ but x still not significant
- No evidence for indirect CPV $\rightarrow$ need LHCb upgrade

Direct CPV

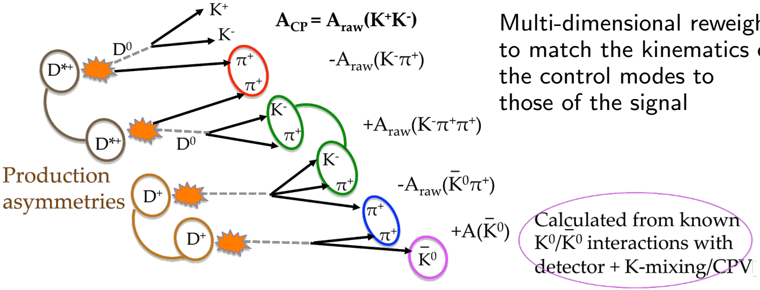
- Accessible to charged charm hadron
- Depends on decay mode, typically $A_{CP} < 10^{-3} - 10^{-4}$ for Singly Cabibbo Suppressed decays
- Arises from Tree-Penguin diagram interference
- Measurements are time independent
- Experimentally has to be disentangled from other asymmetries:
  - Production asymmetries: $\sigma(pp \to DX) \neq \sigma(pp \to \bar{D}X))$
  - Charge and momentum dependent detection asymmetries due to interactions with the detector material





Direct CPV

- The experimental observable is obvious: $A_{raw} = (N(D) - N(\bar{D}))/(N(D) + N(\bar{D}))$
- Correct raw asymmetry with control channels using small or negligible expected CPV (essentially CF decays) to determine A_{CP}
- Example for $A_{CP}(D^0 \to K^+K^-)$ using D^* tagged events



Multi-dimensional reweighting to match the kinematics of the control modes to those of the signal

ΔA_{CP} with $D^0 \to h^+h^-$ decays

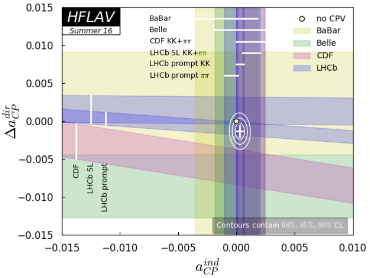
- Measure $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$
- Clean measurement, many systematics cancel at first order

$$\Delta A_{CP} \approx \left[A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi)\right] + \frac{\Delta\langle t\rangle}{\tau_D} A_{CP}^{ind}$$

- $\Delta A_{CP} < 0.6\%$ in the SM
- Most precise determination from LHCb [PRL 116, 191601 (2016)]

$$\Delta A_{CP} = (0.10 \pm 0.08 \pm 0.03)\%$$

Statistically limited!



No evidence of CPV yet

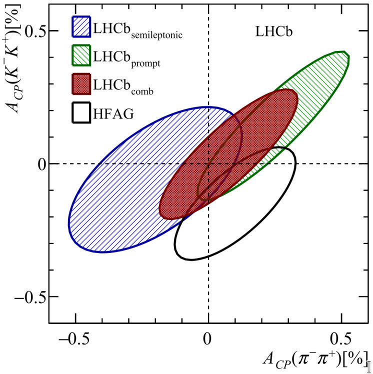
A_{CP} with $D^0 \to h^+h^-$ decays

- A_{CP} in $D^0 \to K^+K^-$ decays measured at LHCb both with semileptonic and prompt tag
- A_{CP} in $D^0 \to \pi^+\pi^-$ obtained using ΔA_{CP} measurement
- Leading in precision [PLB 767 (2017) 177-187]

$$A_{CP}(KK) = (0.04 \pm 0.12 \pm 0.10)\%$$

$$A_{CP}(KK) = (0.07 \pm 0.14 \pm 0.11)\%$$

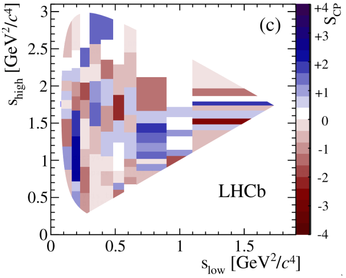
Statistical and systematic error comparable, but some systematics can potentially be reduced in the future



Direct CPV in multibody decays

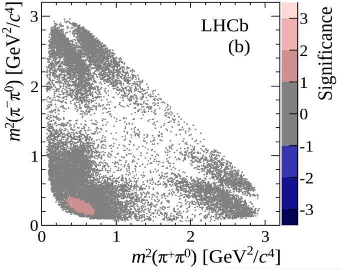
- Strong phases vary across phase space
  $\rightarrow$ look for local CPV in regions of the Dalitz plane
- Two possible approaches:
  - Model dependent: amplitude analysis to search for A_{CP} in resonances
  - Model independent: test compatibility of data with noCPV

Binned χ^2 in $D^+ \rightarrow \pi^+\pi^-\pi^+$



[PLB 728 (2014) 585]

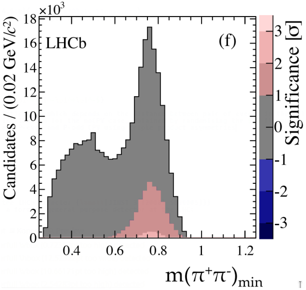
Unbinned (Energy Test) in $D^0 \rightarrow \pi^+\pi^-\pi^0$



[PLB 740 (2015) 158]

CPV in $D^0 \to \pi^+\pi^-\pi^+\pi^-$ [PLB 769 345-356]

- Define test statistic T, which depends on the distance between pair of events in the Dalitz plane
- Compare with T distribution for the noCPV case (obtained by randomising the D flavour) and get a p-value
- Distinguish between P-even and P-odd CPV using triple product asymmetries



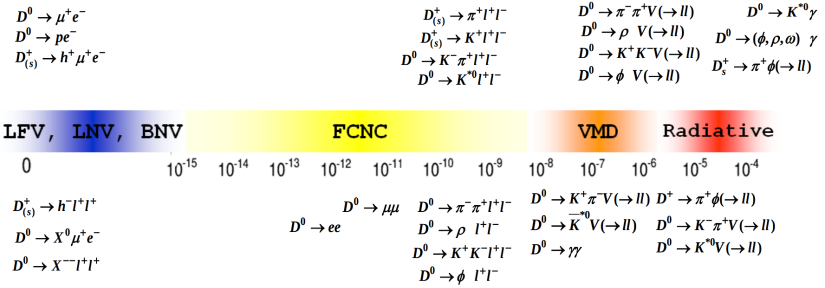
- P-even: p-value of 5%
- P-odd: p-value of 0.6%, 2.7σ significance for CPV
- Region of asymmetry seems to correspond to the $\rho^0 \to \pi^+\pi^-$
- Still no evidence but something to keep an eye on

Summary on Mixing and CPV

- D^0 mixing well established, precision on x and y should still be improved
- No evidence for direct or indirect CPV but approaching SM predictions
- Excellent prospects with multibody decays!
- Most measurements are statistically limited (sometimes thanks to cleverly constructed observables), no showstoppers for RunIII
- To keep in mind: often negligible CPV is assumed in control modes, this may become problematic in the long term

Charm Rare Decays

Wide variety of physics, ranging from forbidden to not-so-rare decays



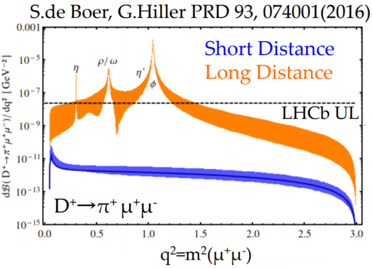
[PRD 66 (2002) 014009]

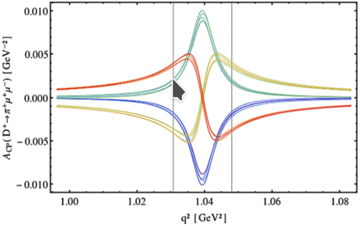
Short distance contributions to effective $c \to u$ transitions are tiny, branching fractions dominated by long distance contributions

SM predictions for the short distance part are normally $BF < 10^{-9}$, not yet there

Multibody decays with a dilepton pair

- Decays such as $D^{\pm}_{(s)} \to h^{\pm} l^{+} l^{-}$, $D^{0} \to h^{+} h^{-} l^{+} l^{-}$ have an overwhelming contribution from long-distance processes, through intermediate vector resonances in the dimuon spectrum

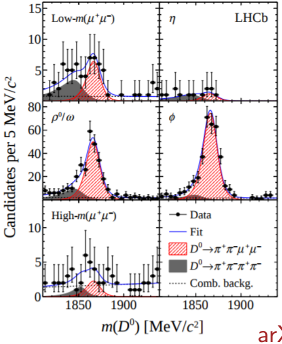


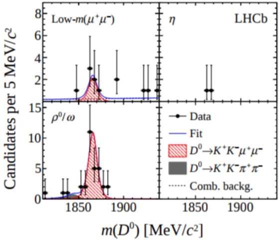


- Unlikely that NP could show up in the branching fraction
- But the richer dynamics allows to investigate A_{CP}, A_{FB} which can be up to a few percents in some NP scenarios

Observation of D^0 mesons decaying into $h^+h^-\mu^+\mu^-$

- Using 2/fb LHCb made the first observation of $D^0 \to \pi^+\pi^-\mu^+\mu^-$, $D^0 \to K^+K^-\mu^+\mu^-$





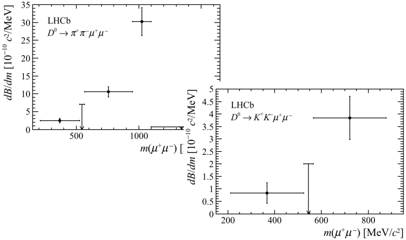
arXiv:1707.08377, accepted by PRL

- No attempt is made to distinguish between long and short distance contribution (although long distance should dominate)

Observation of D^0 mesons decaying into $h^+h^-\mu^+\mu^-$

- Measure differential and total BF (normalised to $\mathcal{B}(D^0 \to K^-\pi^+[\mu^+\mu^-]_{\rho^0/\omega})$ [PLB 757 (2016) 558-567])

$D^0 \to \pi^+\pi^-\mu^+\mu^-$		
$m(\mu^+\mu^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
Low mass	< 525	$7.8 \pm 1.9 \pm 0.5 \pm 0.8$
η	525–565	$< 2.4\,(2.8)$
ρ^0/ω	565–950	$40.6 \pm 3.3 \pm 2.1 \pm 4.1$
ϕ	950–1100	$45.4 \pm 2.9 \pm 2.5 \pm 4.5$
High mass	> 1100	$< 2.8\,(3.3)$
$D^0 \to K^+K^-\mu^+\mu^-$		
$m(\mu^+\mu^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
Low mass	< 525	$2.6 \pm 1.2 \pm 0.2 \pm 0.3$
η	525–565	$< 0.7\,(0.8)$
ρ^0/ω	> 565	$12.0 \pm 2.3 \pm 0.7 \pm 1.2$



- Total branching fractions: arXiv:1707.08377, accepted by PRL

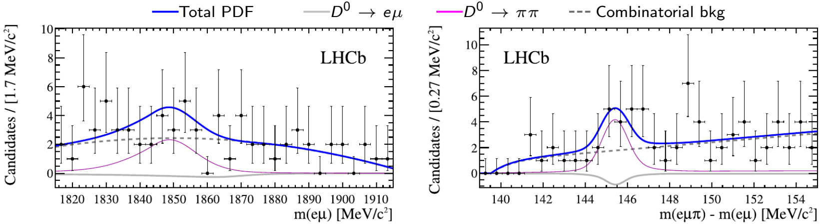
$$\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$
$$\mathcal{B}(D^0 \to K^-K^+\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

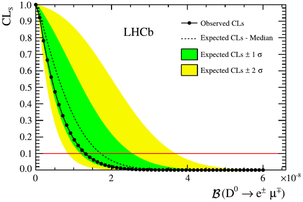
Rarest charm decays! Compatible with SM predictions [JHEP 04(2013)135]

- Statistics is enough to perform first asymmetry measurements!

Lepton flavour violation: search for $D^0 \to e^+\mu^-$ decay

- LFV is effectively forbidden in the SM but predicted to occur in some NP scenarios





No evidence seen

Best limit from LHCb [PLB 754 (2016) 167]

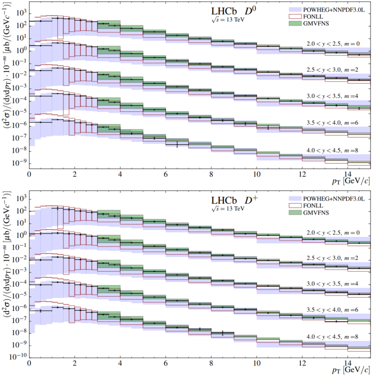
$BF(D^0 \to e\mu) < 1.3(1.6) \times 10^{-8}$ at 90(95)%CL

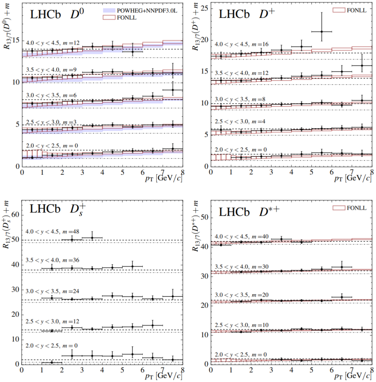
Summary of rare decays

- Steady progress over the years, not NP yet
- Orders of magnitude better than previous experiments on fully charged final states
- Signal seen on multibody decays, now moving to asymmetries!
- ...and to electrons
- The future of rare charm decays at LHCb (Upgrade in particular) looks very bright
- Expect some results on radiative decays as well (traditionally Belle's territory)...

Cross-section measurements

- Probes QCD, hadronisation... ...HE neutrinos in cosmic rays.

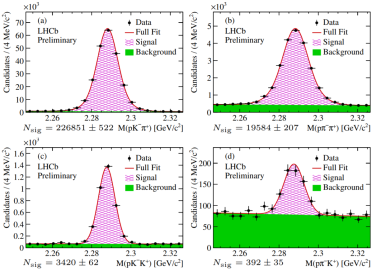




- Have a look at [JHEP05(2017)074] for more results

What about charm baryons?

- World best measurements on $\Lambda_c \to phh'$ BF ratios [LHCb-PAPER-2017-026, in prep.] following those by Belle and BESIII



$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.70 \pm 0.03(\text{stat}) \pm 0.03(\text{syst}))\ \%,$$

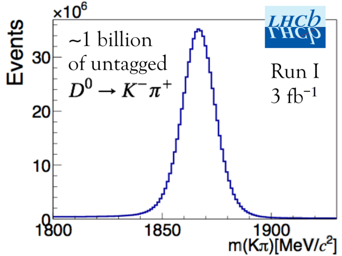
$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (7.44 \pm 0.08(\text{stat}) \pm 0.18(\text{syst}))\ \%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (0.165 \pm 0.015(\text{stat}) \pm 0.005(\text{syst}))\ \%$$

- Direct CPV and rare processes can be searched for in baryon decays
- LHCb may be the only player in the foreseeable future
- First CPV and rare decay searches already being performed at LHCb, stay tuned

The role of Charm at LHCb

- Besides being interesting per-se, charm physics is a training ground for B physics: *the charm yields of today are the beauty yields of tomorrow*



- Many challenges we will face in the B case have been already encountered or will be encountered soon in charm physics
- In particular, the understanding of detector asymmetries is essentially driven by charm physics
- Charm physics at LHCb is already in the upgrade era wrt to B-physics (Turbo stream)
- Charm is a powerful tool to drive our strategy for the future...

Conclusions

- LHCb is currently the main player in Charm physics
- No competition on final states with only charged tracks in the foreseeable future
- Search for CPV is reaching incredible precisions, approaching SM predictions. Still no evidence but intriguing hints in multibody decays
- Systematic limit still far ahead, we can probe at least one order of magnitude more precision just increasing the statistics
- Increasing importance of rare decays, improved limits but (finally) some sizeable signals in dilepton modes $\rightarrow$ new window of opportunity
- Stay tuned for results on charm baryons

Charm physics needs the LHCb Upgrade (and viceversa)