Charm CPV

[In practice: CPV, mixing and related]

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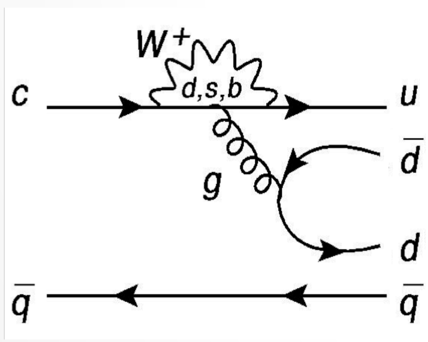
on behalf of LHCb

Implications Workshop
CERN, November 2017

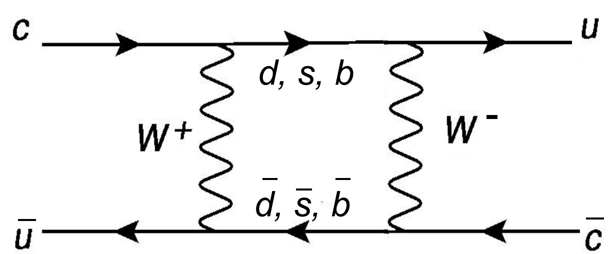
Charm: unique, complementary but difficult

- Unique access to up-type quarks
  (flavour physics with top quark limited)
- d, s, b quarks in loops: different NP particles/couplings?
  ⇨ complementary to strange and beauty

- Loops very suppressed in charm
  ⇨ CPV, mixing, rare decays suppressed in SM



Needed for CPV



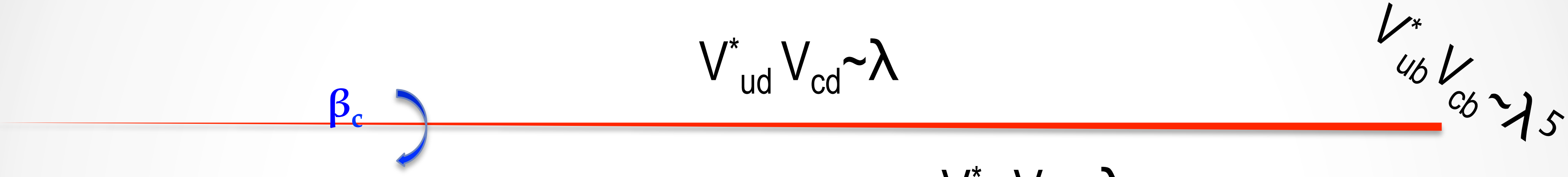
D^0-$\bar{D}^0$ mixing @ short distance

- b loop ~$V_{ub}V_{cb}(m_b/m_W)^2$
- s & d: GIM suppressed, cancel in U-spin limit

- Large non-perturbative corrections (~$1/m_c$) ⇨ difficult to calculate

Theoretical reality, in short

- Openness of charm Unitarity Triangle ⇨ CPV expected in SM



D^0: β_c~0.03°

B_d: β~22°
B_s: β_s~1°

- Direct CPV (in decays)
  - $O(10^{-3})$ in SCS decays w/ penguin contribution
  - $O(10^{-2})$ wherever penguin increased: $D^0 \to K_S K_S, K^{*0} K^{*0}$, $\varrho\gamma$, $\varphi\gamma$
- Indirect CPV (mixing related) ~$O(10^{-4})$

Experimental reality, in short

HFLAV Nov2016

- D^0-$\bar{D}^0$ mixing
  - established

  No-mixing hypothesis excluded by >11σ
  - x still not significant
- CPV
  - not observed yet
  - becoming sensitive to SM
  - indirect CPV precision: $O(10^{-4})$
  - direct CPV precision: down to $O(10^{-3})$
- Rare decays
  - looking for signals, precision down to $O(10^{-8})$
  - not there yet to go beyond (asymmetries, LFU, polarisations)

Mixing frequencies

$$x = (0.32 \pm 0.14)\%$$

$$y = (0.69^{+0.06}_{-0.07})\%$$

Indirect CPV parameters

$$|q/p| = 0.89^{+0.08}_{-0.07}$$

$$\phi = \arg(q/p) = -13^{+10}_{-9}\ \text{deg}$$

CPV if $|q/p| \neq 1$ or $\phi \neq 0$

This year news

- WS/RS $D^0 \to K\pi$ time evolution
  Run1+Run2, prompt charm from $pp \to D^{*\pm}X$ New

- A_Γ from $D^0 \to K^+K^-$, $\pi^+\pi^-$
  Run1, prompt charm PRL 118, 261803 (2017)

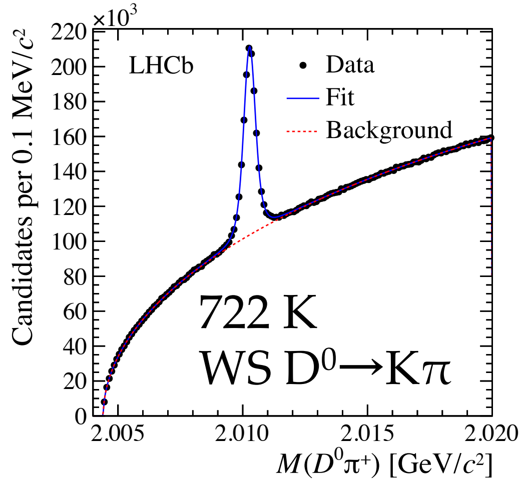
- ΔA_{CP} for $\Lambda_c \to p\pi^+\pi^-$ and $\Lambda_c \to pK^+K^-$
  Run1, secondary charm from $\Lambda_b \to \Lambda_c \mu \upsilon$ New

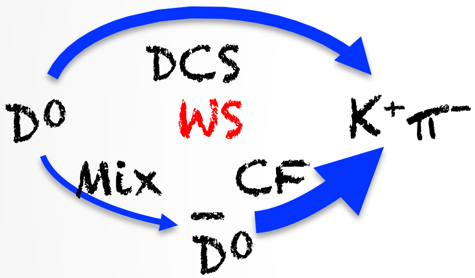
- Amplitude Analysis of $D^0 \to K^\pm\pi\pi\pi$,
  Run1, secondary charm from $B \to D^{*\pm}\mu\upsilon$ New

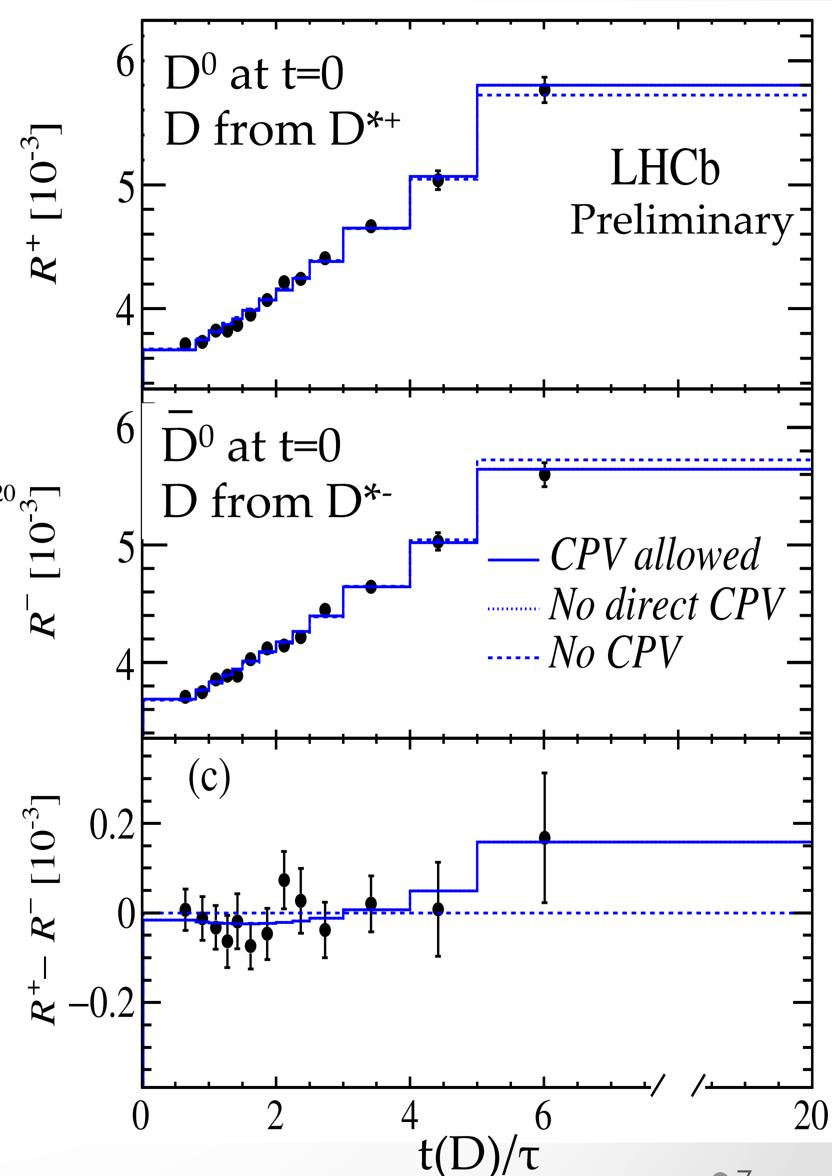
Mixing & Indirect CPV

Time-evolution of (Wrong-Sign) $D^0 \to K^+\pi^-$

- 2011-2016 data prompt charm







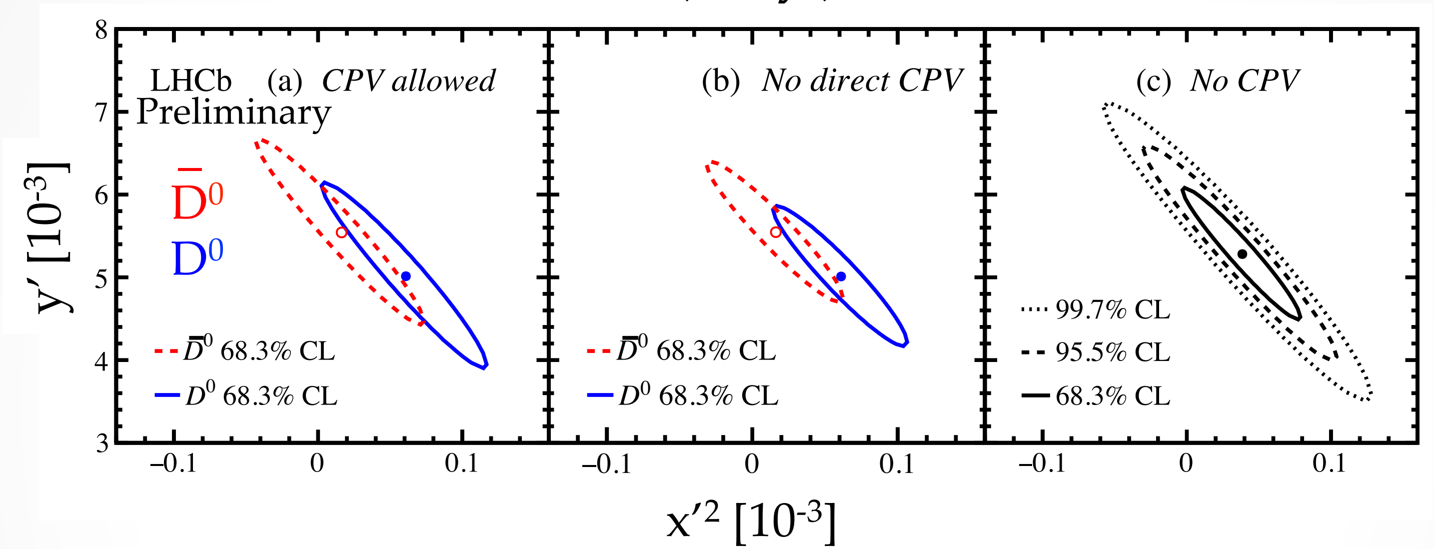
$$R(t) = \frac{N_{WS}}{N_{RS}}(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

Decay **Interference** **Mixing**

- $R^{\pm}(t)$ for D from $D^{*\pm}$ ⇨ measure CPV

WS $D^0 \to K^+\pi^-$: results

- Confidence-level contours on (x'^2, y')



- This study (2011-2016)

$$y' = (5.28 \pm 0.45 \pm 0.27) \times 10^{-3}$$

$$x'^2 = (3.9 \pm 2.3 \pm 1.4) \times 10^{-5}$$

$$1.00 < |q/p| < 1.35 \text{ @68\% } CL$$

LHCb (2011-2012) PRL111, 251801 (2013)

$$y' = (4.8 \pm 0.8 \pm 0.5) \times 10^{-3}$$

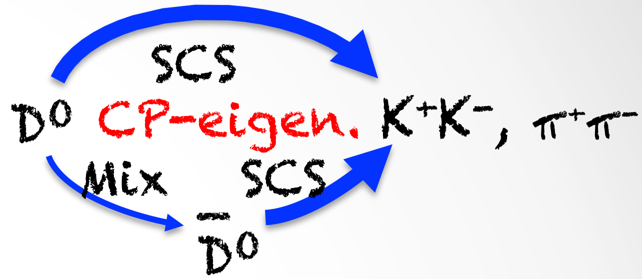
$$x'^2 = (5.5 \pm 4.2 \pm 2.6) \times 10^{-5}$$

- Direct CPV in DCS $D^0 \to K^+\pi^-$

$$A_{CP}^{direct} = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.01 \pm 0.81 \pm 0.42)\%$$

PRL 118, 261803 (2017)

A_Γ : quest for indirect CPV



- Does mixing affect D^0 and $\bar{D}^0$ differently?
- Easiest access via A_Γ

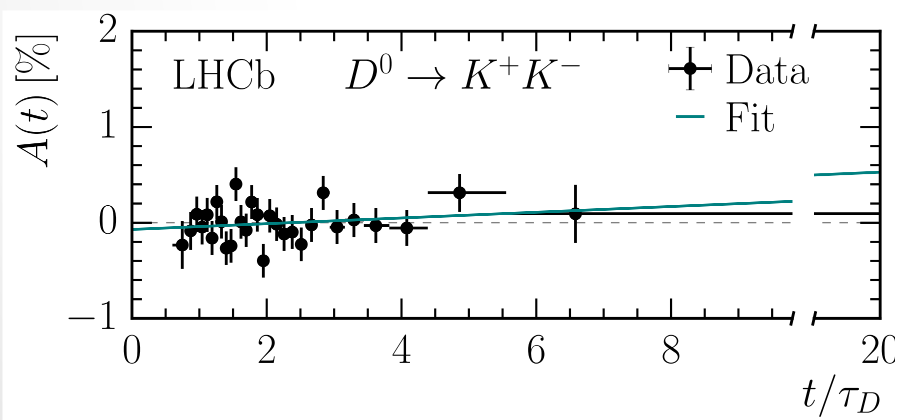
$$A_\Gamma = \frac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\overline{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} \simeq -A_{CP}^{\text{indirect}}$$

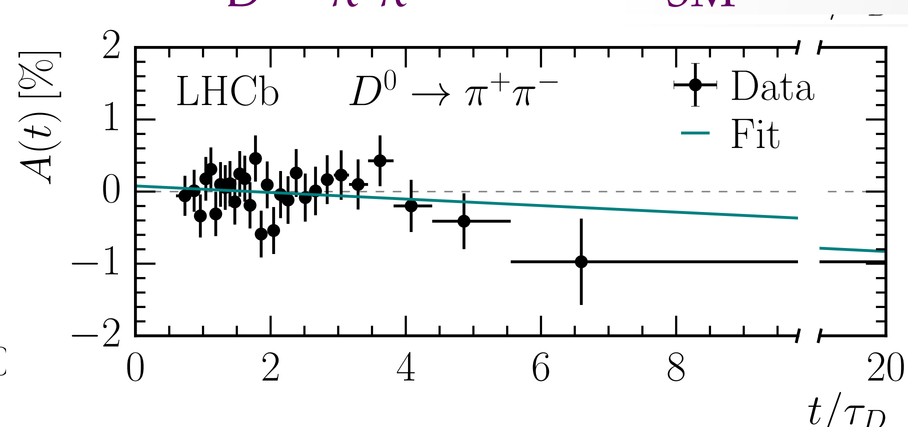
- Asymmetry of yields in t(D) bins: $A_{CP}(t) \simeq A_{CP}^{\text{direct}} - A_\Gamma \frac{t}{\tau_D}$

- 2011+2012 data, prompt charm

$D^0 \to K^+K^-$ ~10M

$D^0 \to \pi^+\pi^-$ ~3M





$A_\Gamma(KK) = (-0.030 \pm 0.032 \pm 0.010)\%$

$A_\Gamma(\pi\pi) = (+0.046 \pm 0.058 \pm 0.012)\%$

A_Γ: entering SM area

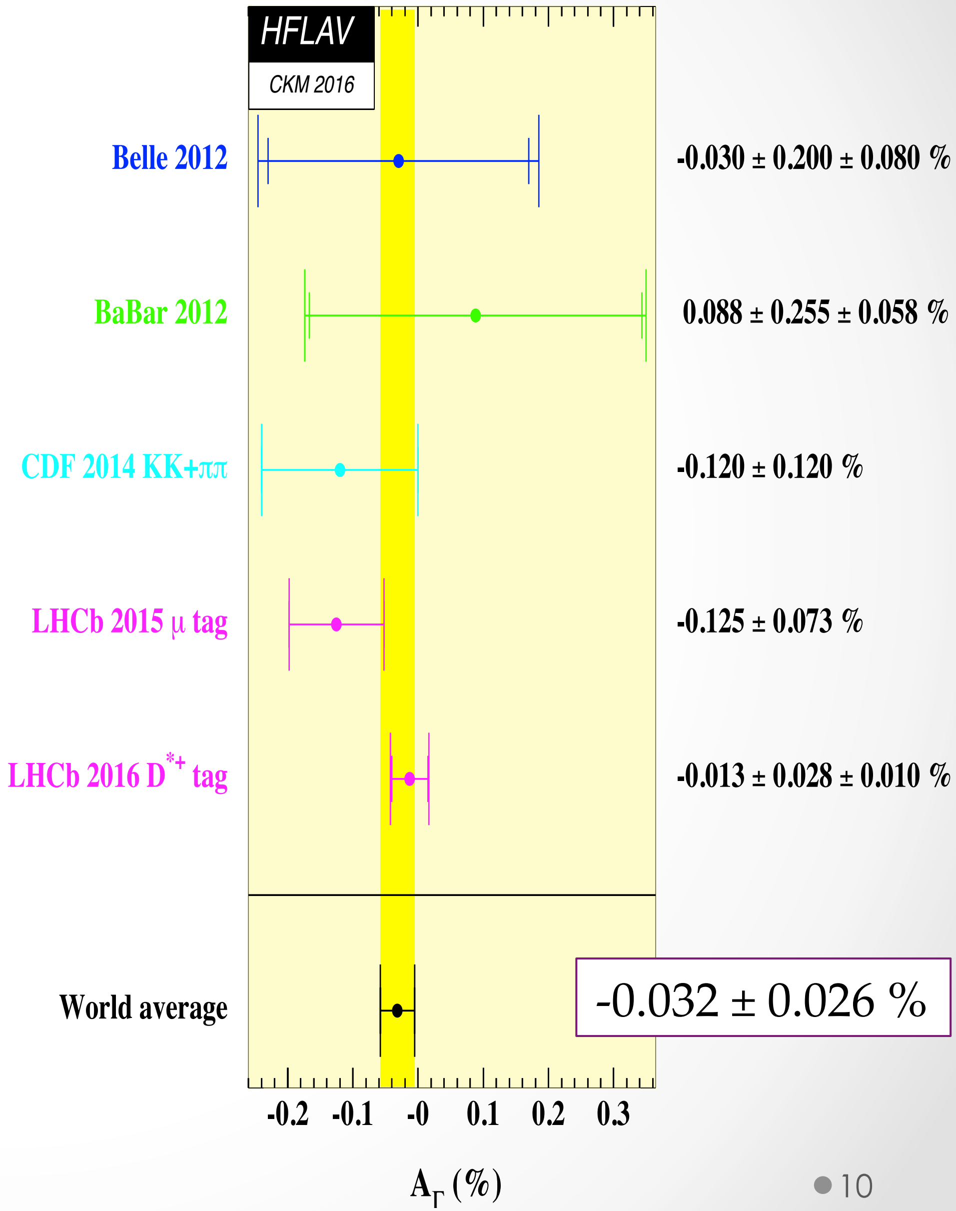
- Sensitivity: $O(10^{-4})$
  Limited by statistics
- Indirect CPV in SM ~10^{-4}

- A_Γ in terms of basic parameters

$$A_\Gamma = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi\right]$$

CPV in mixing — in mixing-decay interference

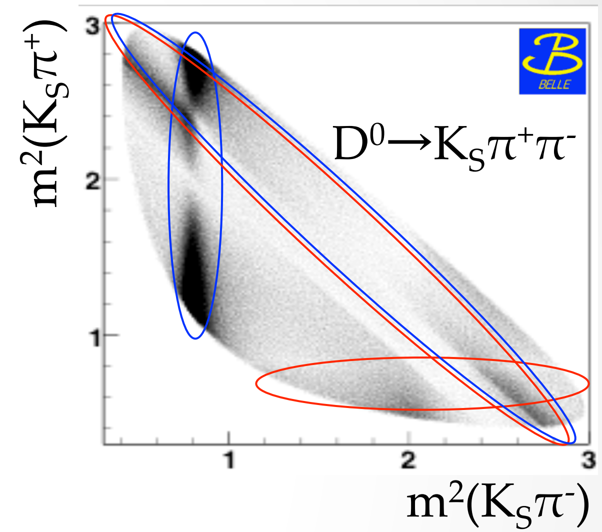
⇨ sensitivity to q/p depends on x



Multi-body decays are the (high)way

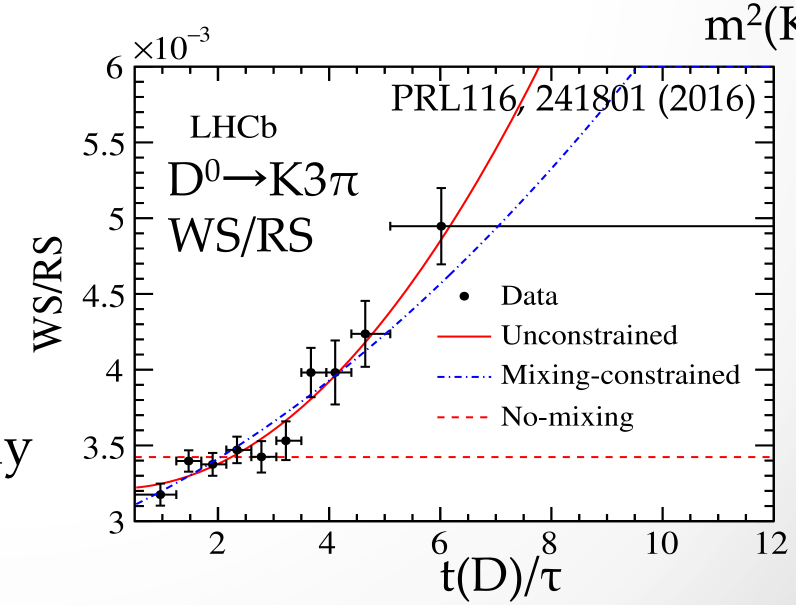
- Measure how phase space evolves with time [t-dep. Dalitz]

✓ **Direct access to x, y, |q/p|, ϕ**
✓ Access to amplitudes & phases ⇨ no external input
✓ No dilution from coherence factor
✗ Need model to describe resonances



- Sensitivity from $D^0 \to f$ & $D^0 \to \bar{f}$ interferences (large 'local' coherence factors are best)

- Golden modes
  - $D^0 \to K_S\pi^+\pi^-$
    Expect significant x with Run1+2
  - $D^0 \to K\pi\pi\pi$
    Needed for q/p
    So far phase-space integrated study



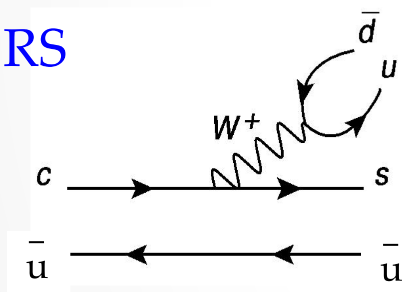
LHCb-PAPER-2017-040

Amplitude Analysis of $D^0 \to K^-\pi^+\pi^+\pi^-$ (RS) & $K^+\pi^-\pi^+\pi^-$ (WS)

- 2011-2012 data, D^0 from $B \to D^{*\pm}\mu\upsilon$
- 1^{st} analysis for WS, improved for RS
- time-integrated study (ignoring D-mixing)
- RS decays ≈ CF $c \to s\bar{d}u$ WS decays ≈ DCS $c \to d\bar{s}u$

  ⇨ different dynamics
- Dominating contributions:

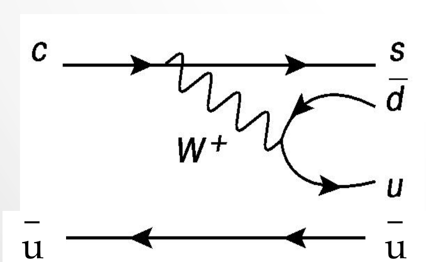
RS



$a_1(1260)^+$

Fit fraction~38%

K^-

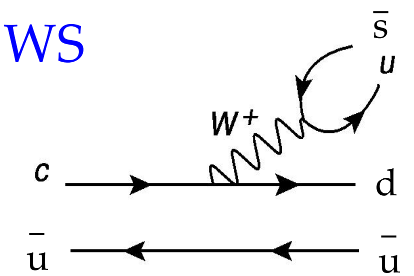


$\bar{K}^{*0}$

~22%

ϱ(770)

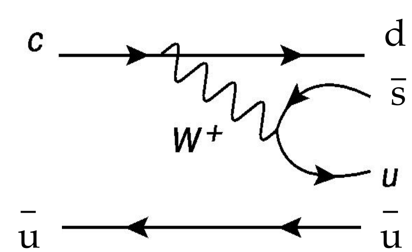
WS



$K_1(1270)^+$
$K_1(1400)^+$

~45%

π^-



K^{*0}

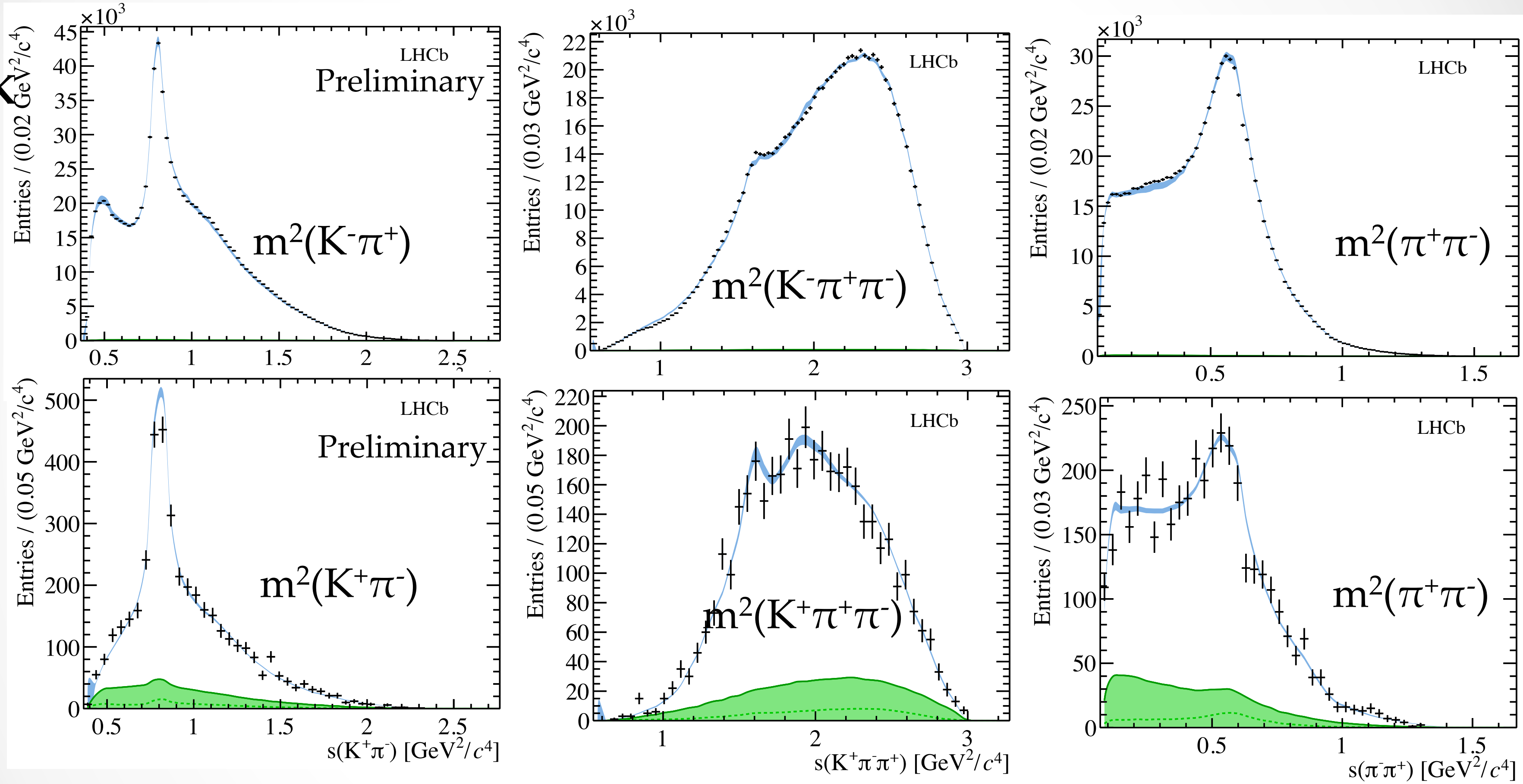
~28%

ϱ(770)

Amplitude Analysis of $D^0 \to K^- \pi^+ \pi^+ \pi^-$ (RS) & $K^+ \pi^- \pi^+ \pi^-$ (WS)

RS
900K

WS
3K



- Fit qualities:

  RS $\chi^2/\text{ndf} = 40483/32701 = 1.24$

  WS $\chi^2/\text{ndf} = 350/239 = 1.46$

background
model uncertainty

LHCb-PAPER-2017-040

$D^0 \to K3\pi$ toward mixing

- Coherence factor

  (interference between DCS and CF)

$$\int A_{K^-3\pi}(\mathbf{r}) A_{K^+3\pi}(\mathbf{r})\, d\mathbf{r} \Rightarrow R_{coh} e^{-i\delta_{K3\pi}}$$

- 5-dim bins of equal strong phase
- Large 'local' coherence factors

- Add t-dependence

  for charm mixing & CPV

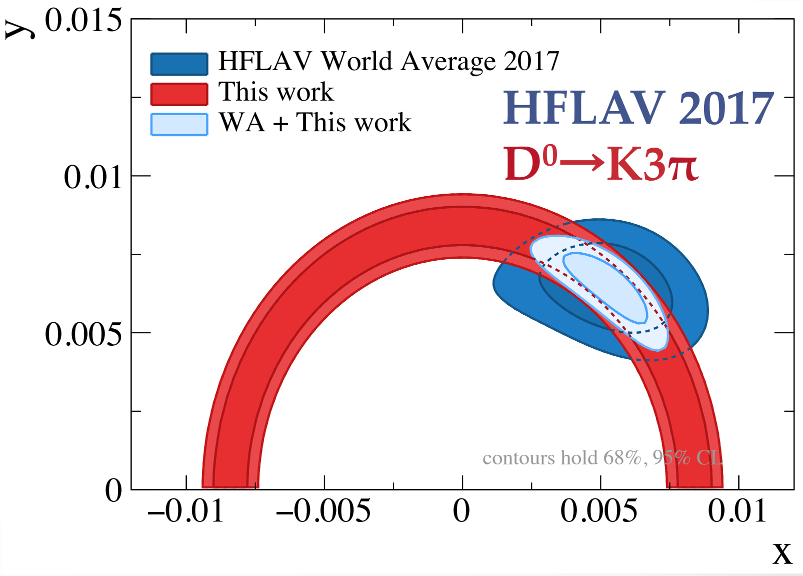
- Sensitivity study with prompt

  $D^0 \to K3\pi$ from 2015+2016

  (PhD by Dominik Müller)

Bin	$R_{K3\pi}$	$\delta_{K3\pi}$ [°]
Global	0.454 ± 0.020	128
1	0.701 ± 0.017	169 ± 3
2	0.691 ± 0.016	151 ± 1
3	0.726 ± 0.010	133 ± 1
4	0.742 ± 0.008	117 ± 1
5	0.783 ± 0.005	102 ± 2
6	0.764 ± 0.007	84 ± 3
7	0.424 ± 0.013	26 ± 3
8	0.473 ± 0.030	-149 ± 7

Preliminary



Direct CPV

Most precise
Very important

A_{CP} in two-body decays w/ penguin

	LHCb	Belle	BaBar	BESIII
Mode	A_{CP} [%]			
$D^0 \to K^+K^-$	+0.04 ± 0.12 ± 0.10	-0.32 ± 0.21 ± 0.09	+0.00 ± 0.34 ± 0.13	
$D^0 \to \pi^+\pi^-$	+0.07 ± 0.14 ± 0.11	+0.55 ± 0.36 ± 0.09	-0.24 ± 0.52 ± 0.22	
$D^0 \to K_s K_s$	-2.9 ± 5.2 ± 2.2	+0.00 ± 1.53 ± 0.17		
$D^0 \to \pi^0\pi^0$		-0.03 ± 0.64 ± 0.10		
$D^0 \to K_s \eta$		+0.54 ± 0.51 ± 0.16		
$D^0 \to K_s \eta'$		+0.98 ± 0.67 ± 0.14		
$D^+ \to K_s K^+$	+0.03 ± 0.17 ± 0.14	+0.08 ± 0.28 ± 0.14	+0.46 ± 0.36 ± 0.25	-1.5 ± 2.8 ± 1.6
$D^+ \to K_L K^+$				-3.0 ± 3.2 ± 1.2
$D^+ \to \phi\pi^+$	-0.04 ± 0.14 ± 0.14	+0.51 ± 0.28 ± 0.05		
$D^+ \to \eta\pi^+$		+1.74 ± 1.13 ± 0.19		
$D^+ \to \eta'\pi^+$	-0.61 ± 0.72 ± 0.55 ± 0.12	-0.12 ± 1.12 ± 0.17		
$D_s^+ \to K_s\pi^+$	+0.38 ± 0.46 ± 0.17	+5.45 ± 2.50 ± 0.33	+0.3 ± 2.0 ± 0.3	
$D_s^+ \to \eta'\pi^+$	-0.82 ± 0.36 ± 0.24 ± 0.27			

http://www.slac.stanford.edu/xorg/hfag/charm

$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

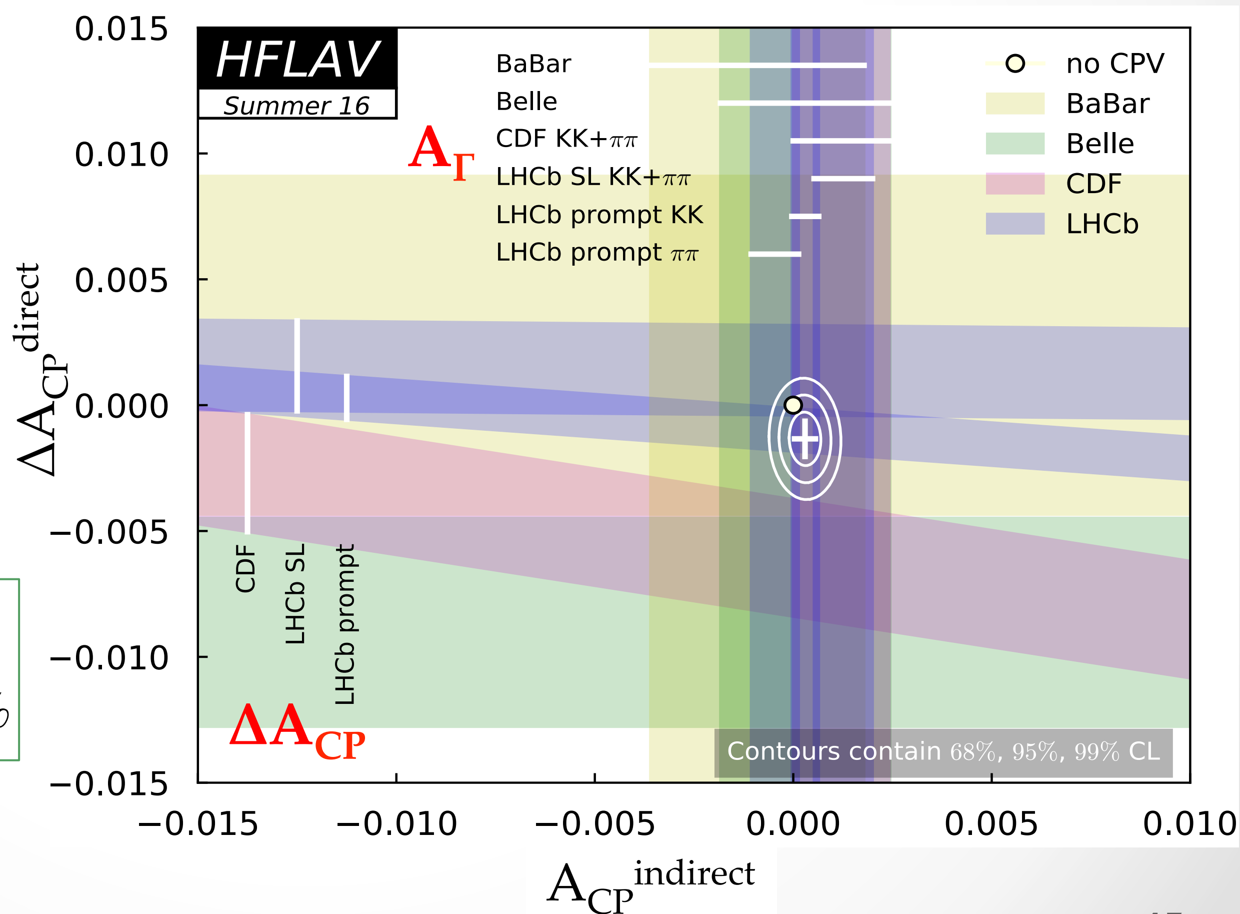
- Simple & sensitive

$$\Delta A_{CP} \simeq \left[A_{CP}^{\text{direct}}(KK) - A_{CP}^{\text{direct}}(\pi\pi)\right] + \frac{\Delta\langle t\rangle}{\tau_D} A_{CP}^{\text{indirect}}$$

- In SM: $|\Delta A_{CP}^{\text{direct}}| \leq 0.6\%$

- HFLAV average

$$\Delta A_{CP}^{direct} = (-0.13 \pm 0.07)\%$$
$$A_{CP}^{indirect} = (0.030 \pm 0.026)\%$$



Prospects for direct CPV searches

Precision down to $O(10^{-3})$, still no evidence

- Will improve by 6-7 times with LHCb 50/fb (in ~10 years)
- Important Belle2 input: $D^0 \to \pi^0\pi^0$, $D^0 \to K_S K_S$, $D^+ \to \pi^+\pi^0$

Exploit correlations, A_{CP} not enough

- Between modes related via Isospin or U-spin
- Model independent test of SM, model dependent test of NP
- e.g. SM sum rules:

$$A\left(D^+ \to \pi^+\pi^0\right) - \bar{A}\left(D^+ \to \pi^+\pi^0\right) = 0$$

$$\frac{1}{\sqrt{2}} A\left(\pi^+\pi^-\right) + A\left(\pi^0\pi^0\right) - \frac{1}{\sqrt{2}} \bar{A}\left(\pi^+\pi^-\right) - \bar{A}\left(\pi^0\pi^0\right) = 0$$

Look at DCS decays (strongly advertised by I.Bigi)

Explore charm baryons

- Nothing published yet!
- 1st evidence for CPV in baryons (in $\Lambda_b \to p3\pi$) Nature Phys. 13, 391-396 (2017)

ΔA_{CP} for $\Lambda_c \rightarrow pK^+K^-$ and $\Lambda_c \rightarrow p\pi^+\pi^-$

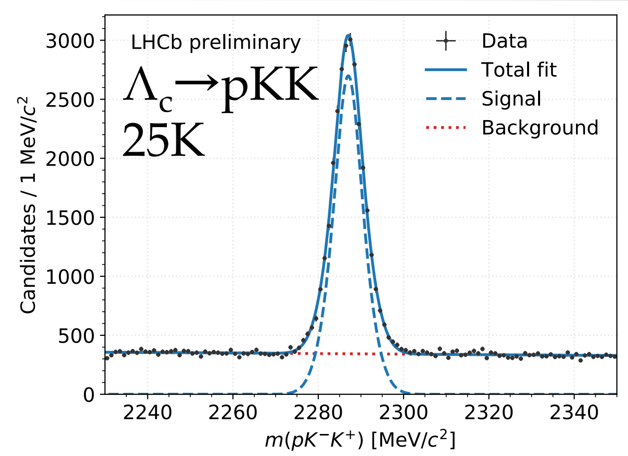
- SCS decays with penguin
- 2011-2012 data, Λ_c from $\Lambda^0_b \rightarrow \Lambda_c^- \mu^+ \upsilon$
- Global asymmetry

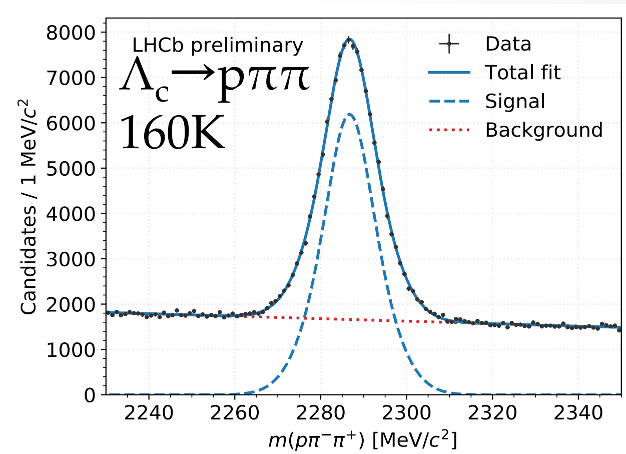
$$\Delta A_{CP} = A^{\text{Raw}}_{CP}(pK^-K^+) - A^{\text{Raw}}_{CP}(p\pi^-\pi^+) \approx A_{CP}(pK^-K^+) - A_{CP}(p\pi^-\pi^+)$$

- Asymmetries in Λ_b production & detection of $p/\bar{p}$, μ^-/μ^+ cancel out

$$\Delta A_{CP} = (0.30 \pm 0.91 \pm 0.61)\%$$

- 1^{st} CPV measurement for charm baryons
- Systematics dominated by MC size

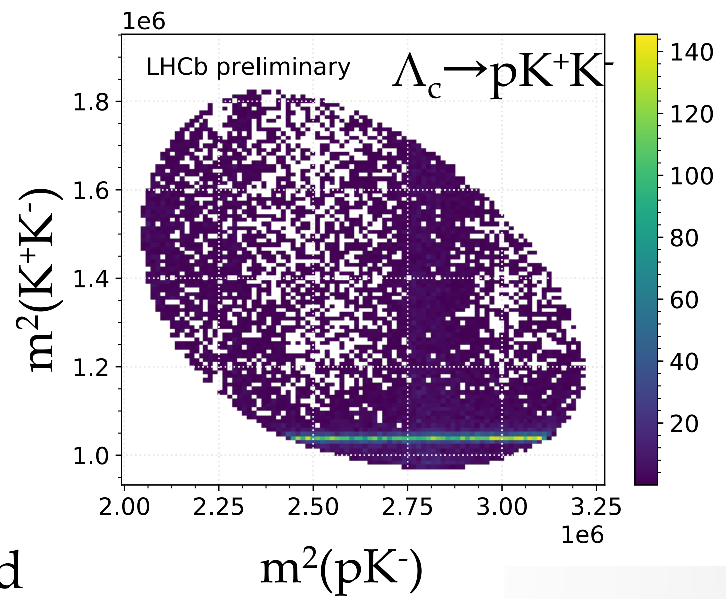




$$A^{\text{Raw}}_{CP}(pK^-K^+) = (3.72 \pm 0.78)\ \%$$
$$A^{\text{Raw}}_{CP}(p\pi^-\pi^+) = (3.42 \pm 0.47)\ \%$$

More with $\Lambda_c \to ph^+h^-$?

- How about ΔA_{CP} in Phase-Space regions?
- CPV 'localised' through resonance interferences ⇨ better sensitivity, but difficult interpretation
- 5D phase space, reduces to Dalitz plot if Λ_c unpolarised
- Rich dynamics, amplitude analysis needed

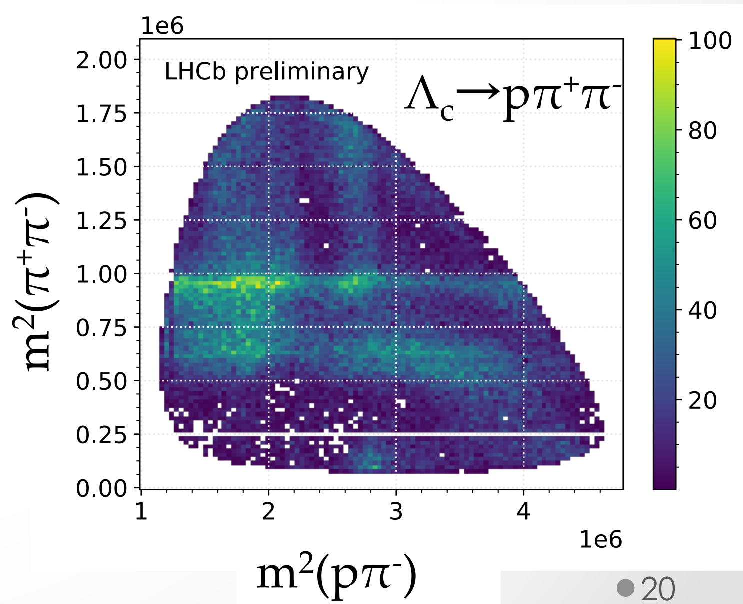


- For now BF's for SCS and DCS decays

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

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

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



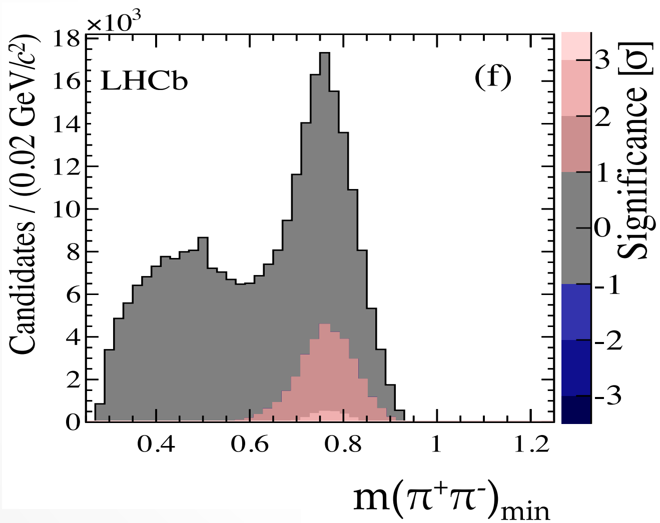
arXiv:1711.01157

P behind CP violation

- 2&3-body hadronic D decays: only P-even ampl. ⇨ CPV via C-violation
- 4-body D decays: also P-odd amplitudes ⇨ CPV via P-violation

- CPV P-even: $A_{CP} \sim \sin\Delta\phi_{weak}$ **$\sin\Delta\phi_{strong}$**
  P-odd: $A_{CP} \sim \sin\Delta\phi_{weak}$ **$\cos\Delta\phi_{strong}$** ⇦ complementary

- $D^0 \to \pi^+\pi^-\pi^+\pi^-$: P-odd CPV with 2.7σ significance (>3σ for some scenarios)



- P-odd: $D^0 \to \rho^0\rho^0$ in P-wave (~6%)
- Increased CPV significance points to $\rho^0 \to \pi^+\pi^-$

PLB 769 (2017) 345-356

- Λ_c decays: P-odd amplitudes already in 2 & 3-body channels!

Going rare

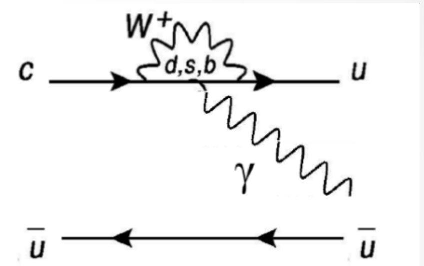
More by Simone Bifani on Wednesday

- The larger penguin contribution, the larger CPV

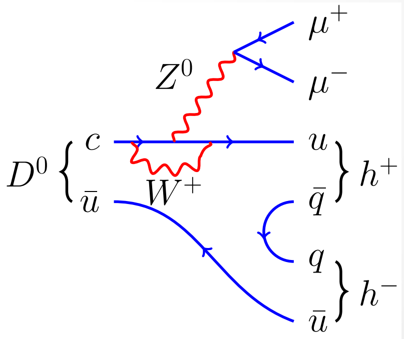
Radiative decays: there are signals to explore

- $A_{CP}(D^0 \rightarrow \rho^0\gamma) \leq 10\%$ de Boer, Hiller arXiv:1701.06392
- Full Belle data PRL118, 051801 (2017)

$$A_{CP}(D^0 \rightarrow \phi\gamma) = (-9.4 \pm 6.6 \pm 0.1)\%$$
$$A_{CP}(D^0 \rightarrow \rho^0\gamma) = (+5.6 \pm 15.1 \pm 0.6)\%$$



- LHCb Run2: at least double Belle signals



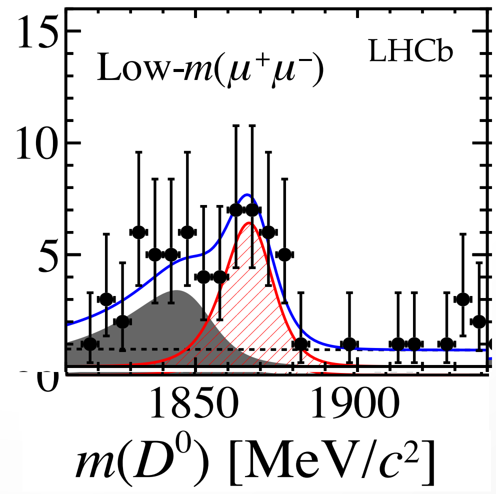
Leptonic decays: first signal!

- $D^0 \rightarrow \pi^+\pi^- \mu^+\mu^-$

  with $m(\mu^+\mu^-) < 525$ MeV

  $S = 27 \pm 6$ (5.4σ)

  PRL119, 181805 (2017)



Summary

- Pinning down the D-mixing frequencies
- Have a chance to get significant x with Run2 data

- CPV in charm still awaits discovery
- With Run2 data we are entering SM regime
- Observation first, then interpretation…

- With rare charm decays, we will take B-brother path ASAP

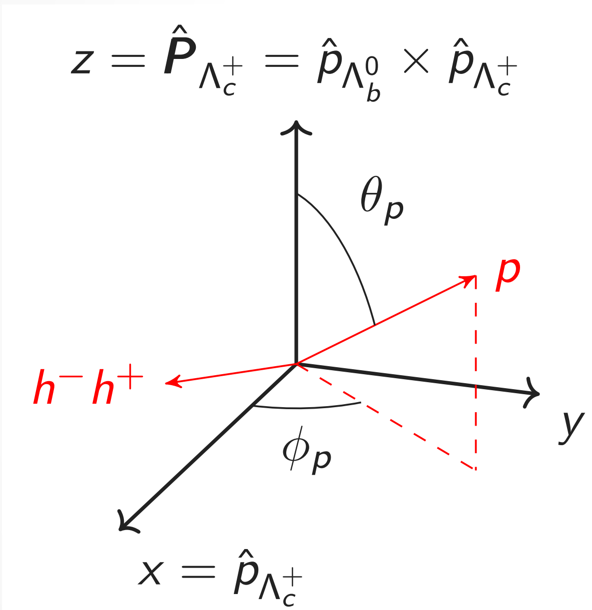
  P_5' for $D \to hh\,\mu^+\mu^-$? In ~10 years…

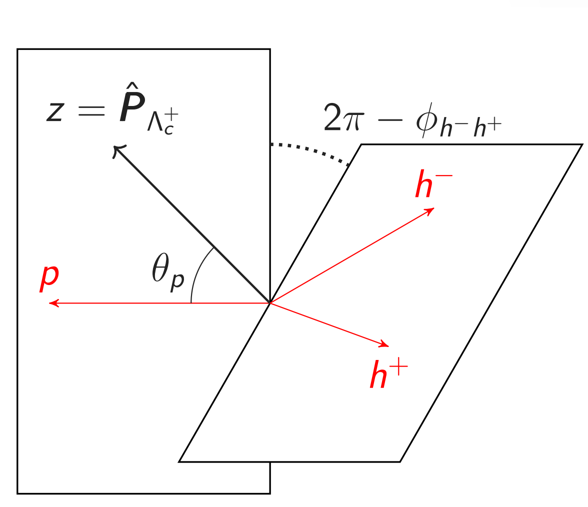
Backups

•

ΔA_{CP} for $\Lambda_c \to ph^+h^-$

- 5D phase space describing $\Lambda_c \to ph^+h^-$ dynamics:
  $m^2(ph^-)$, $m^2(h^+h^-)$, 3 angles in a coordinate system defined as:
  z: Λ_c polarisation axis (perp. to production plane), x: Λ_c flight direction in lab



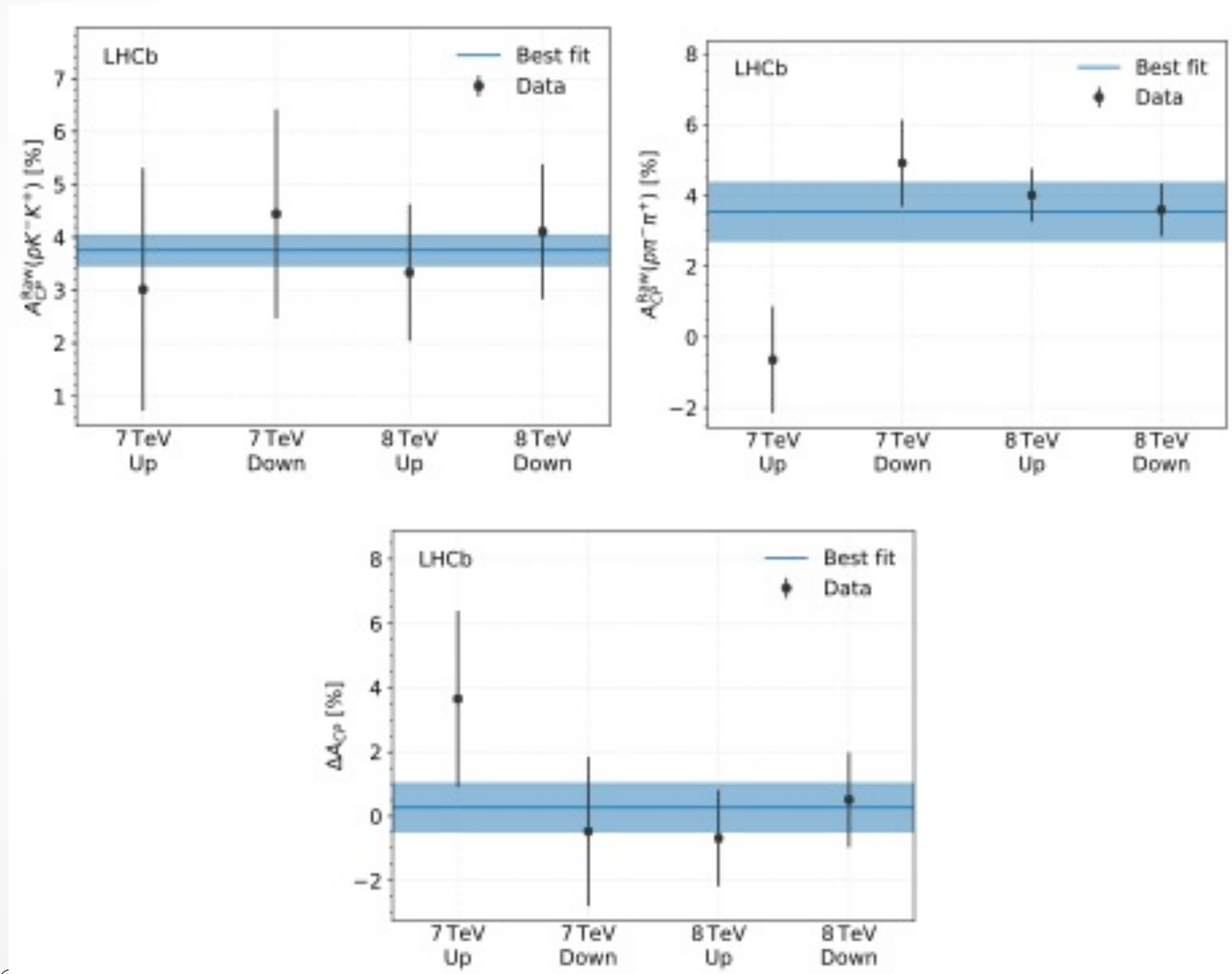


θ_p, ϕ_p: proton polar and azimuthal angles
ϕ_{hh}: acoplanarity angle

- for unpolarised Λ_c PS reduces to the two inv. masses

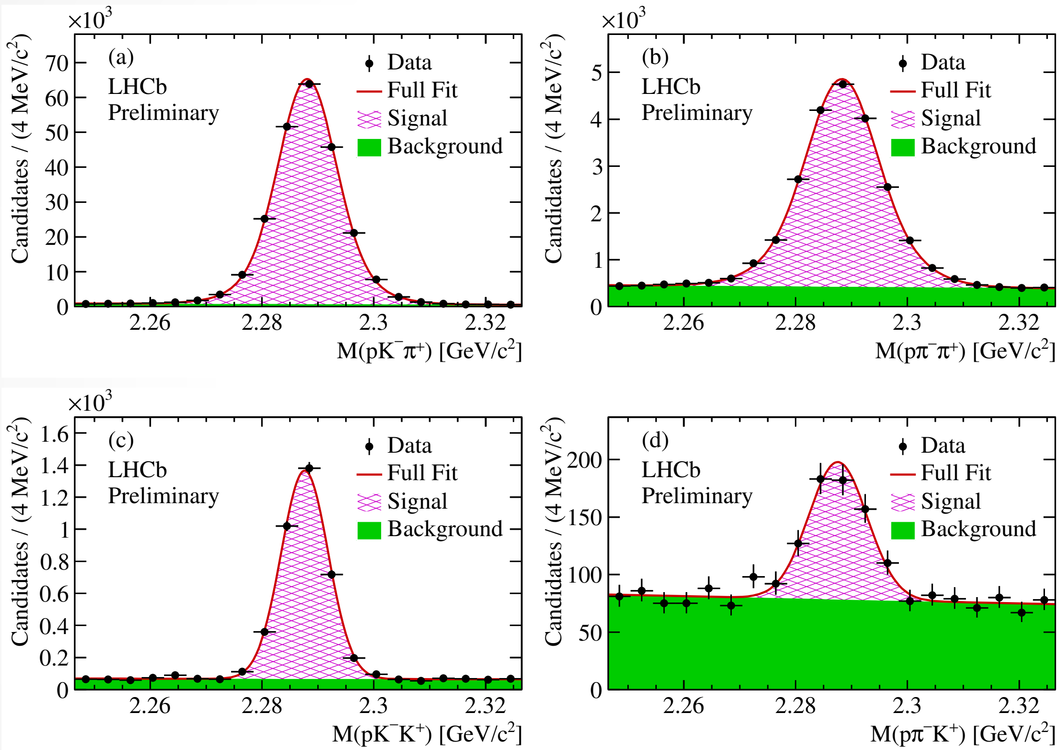
ΔA_{CP} for $\Lambda_c \rightarrow p h^+ h^-$

- Extra asymmetries: $A_{CP}^{\mathrm{Raw}}(f) \approx A_{CP}(f) + A_P^{\Lambda_b^0} + A_D^{\mu} + A_D^{f}$



BF of $\Lambda_c \to ph^+h^-$

- 2011 data, Λ_c from $\Lambda^0_b \to \Lambda_c^- \mu^+ \upsilon$ (prompt charm as x-check)



	Mode	Yield
SL	$\Lambda_c^+ \to pK^-\pi^+$	226851±522
	$\Lambda_c^+ \to p\pi^-\pi^+$	19584±207
	$\Lambda_c^+ \to pK^-K^+$	3420±62
	$\Lambda_c^+ \to p\pi^-K^+$	392±35
Prompt	$\Lambda_c^+ \to pK^-\pi^+$	58115±1561
	$\Lambda_c^+ \to p\pi^-\pi^+$	7480±328
	$\Lambda_c^+ \to pK^-K^+$	766±61

SL analysis systematic [%]	$\Lambda_c^+ \to p\pi^-\pi^+$	$\Lambda_c^+ \to pK^-K^+$	$\Lambda_c^+ \to p\pi^-K^+$
PID selection efficiency ratio	2.0	1.4	2.0
Unknown $\Lambda_c^+ \to phh'$ decay structure	1.1	0.7	1.7
Finite simulation statistics	0.3	0.3	0.3
Trigger efficiency ratio	0.6	0.8	0.3
Total	2.4	1.8	2.7

$D^0 \to K3\pi$ Amplitude Analysis

- $D^0 \to K^- \pi^+ \pi^+ \pi^-$ (RS)

	Fit Fraction [%]
$K^*(892)^0 \rho(770)^0$	$7.34 \pm 0.08 \pm 0.47$
$[K^*(892)^0 \rho(770)^0]^{L=1}$	$6.03 \pm 0.05 \pm 0.25$
$[K^*(892)^0 \rho(770)^0]^{L=2}$	$8.47 \pm 0.09 \pm 0.67$
$\rho(1450)^0 K^*(892)^0$	$0.61 \pm 0.04 \pm 0.17$
$[\rho(1450)^0 K^*(892)^0]^{L=1}$	$1.98 \pm 0.03 \pm 0.33$
$[\rho(1450)^0 K^*(892)^0]^{L=2}$	$0.46 \pm 0.03 \pm 0.15$
$\rho(770)^0 [K^- \pi^+]^{L=0}$	$0.93 \pm 0.03 \pm 0.05$
$\alpha_{3/2}$	
$K^*(892)^0 [\pi^+ \pi^-]^{L=0}$	$2.35 \pm 0.09 \pm 0.33$
$f_{\pi\pi}$	
β_1	
$a_1(1260)^+ K^-$	$38.07 \pm 0.24 \pm 1.38$
$K_1(1270)^- \pi^+$	$4.66 \pm 0.05 \pm 0.39$
$K_1(1400)^- [K^*(892)^0 \pi^-] \pi^+$	$1.15 \pm 0.04 \pm 0.20$
$K_2^*(1430)^- [K^*(892)^0 \pi^-] \pi^+$	$0.46 \pm 0.01 \pm 0.03$
$K(1460)^- \pi^+$	$3.75 \pm 0.10 \pm 0.37$
$[K^- \pi^+]^{L=0} [\pi^+ \pi^-]^{L=0}$	$22.04 \pm 0.28 \pm 2.09$

$D^0 \to K^+ \pi^- \pi^+ \pi^-$ (WS)

	Fit Fraction [%]
$K^*(892)^0 \rho(770)^0$	$9.62 \pm 1.58 \pm 1.03$
$[K^*(892)^0 \rho(770)^0]^{L=1}$	$8.42 \pm 0.83 \pm 0.57$
$[K^*(892)^0 \rho(770)^0]^{L=2}$	$10.19 \pm 1.03 \pm 0.79$
$\rho(1450)^0 K^*(892)^0$	$8.16 \pm 1.24 \pm 1.69$
$K_1(1270)^+ \pi^-$	$18.15 \pm 1.11 \pm 2.30$
$K_1(1400)^+ [K^*(892)^0 \pi^+] \pi^-$	$26.55 \pm 1.97 \pm 2.13$
$[K^+ \pi^-]^{L=0} [\pi^+ \pi^-]^{L=0}$	$20.90 \pm 1.30 \pm 1.50$

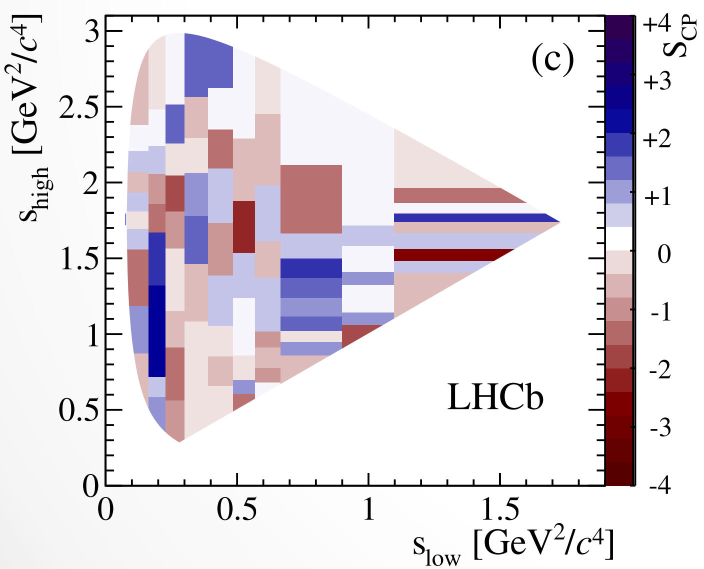
PLB 728 (2014) 585
PLB 740 (2015) 158

Direct CPV in multibody decays

- Strong phases vary in Phase Space ⇨ local CPV asymmetries
- Model dependent: A_{CP} for resonances (amplitude analysis)
- Model independent: test data consistency with no-CPV, give p-value

binned χ^2 (S_{CP} method)

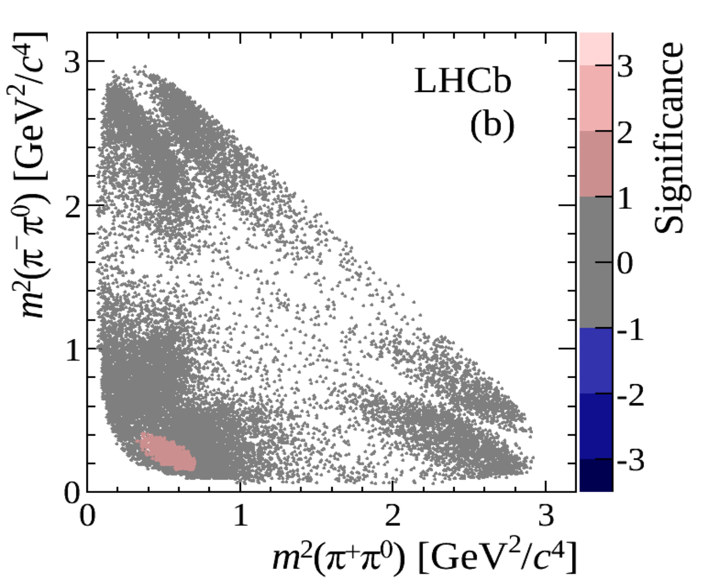
$D^+ \to \pi^+\pi^+\pi^-$ p-value = 50÷100%



Significance of asymmetry in Dalitz bins

unbinned (Energy Test)

$D^0 \to \pi^+\pi^-\pi^0$ p-value = 2÷5%



Significance of asymmetry for each event

Direct CPV in 4-body decays

- Access to P-odd amplitudes ⇨ CPV via P-violation
  [P-odd amplitude e.g. D→VV in P-wave]
- 2&3-body D decays: P-even ampl. only ⇨ CPV via C-violation
  [Baryons: P-odd also in 2&3-body decays]
- CPV in P-even ampl: $A_{CP} \sim \sin\Delta\phi_{weak}$ $\mathbf{\sin\Delta\phi_{strong}}$
  P-odd ampl: $A_{CP} \sim \sin\Delta\phi_{weak}$ $\mathbf{\cos\Delta\phi_{strong}}$ ⇦ complementary
- Triple-product method (aka T-odd): sensitive to P-odd CPV **only**

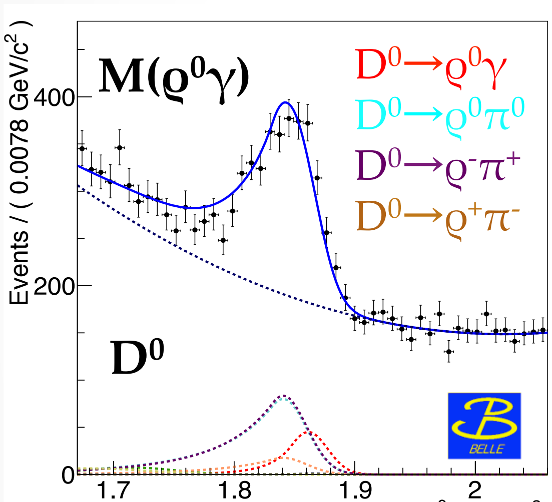
Mode	$A_{CP}^{P\text{-odd}}$ [10^{-3}]	Exp	Ref
$D^0 \to K_S \pi^+ \pi^- \pi^0$	$-0.3 \pm 1.4^{+0.2}_{-0.8}$	Belle	arXiv:1703.05721
$D^0 \to K^+ K^- \pi^+ \pi^-$	$1.8 \pm 2.9 \pm 0.4$	LHCb	JHEP10 (2014) 005
$D^+ \to K_S K^+ \pi^+ \pi^-$	$-12 \pm 10 \pm 5$	Babar	PRD84 031103(2011)

Triple product:
$$C_T \equiv \vec{p}_1 \cdot \left(\vec{p}_2 \times \vec{p}_3\right)$$

PRL118, 051801 (2017)
PRD 93, 051102 (2016)

Decays with photon(s)

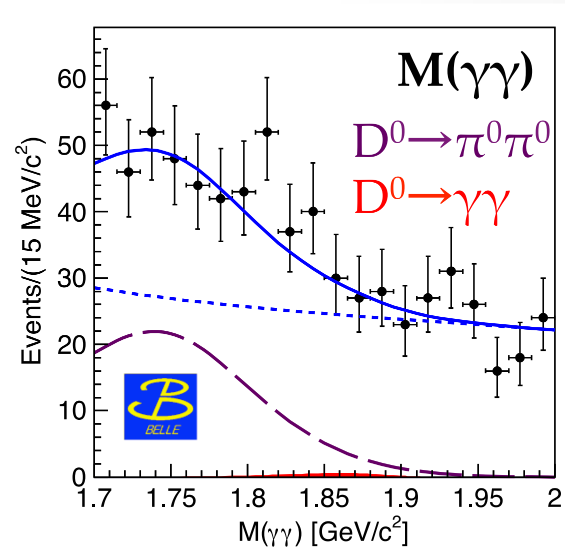
- Theory problem: LongDistance ~ $10^3 \times$ ShortDistance
- NP probes: A_{CP}, γ polarisation (t-dep. analysis or polarised $\Lambda_c \to p\gamma$)
- Experimental problem: π^0 background



BF($D^0 \to \varrho\gamma$)=$(1.8 \pm 0.3 \pm 0.1) \times 10^{-5}$

$$A_{CP}(D^0 \to \overline{K}^{*0}\gamma) = (-0.3 \pm 2.0 \pm 0.0)\%$$
$$A_{CP}(D^0 \to \phi\gamma) = (-9.4 \pm 6.6 \pm 0.1)\%$$
$$A_{CP}(D^0 \to \rho^0\gamma) = (+5.6 \pm 15.1 \pm 0.6)\%$$

No CPV

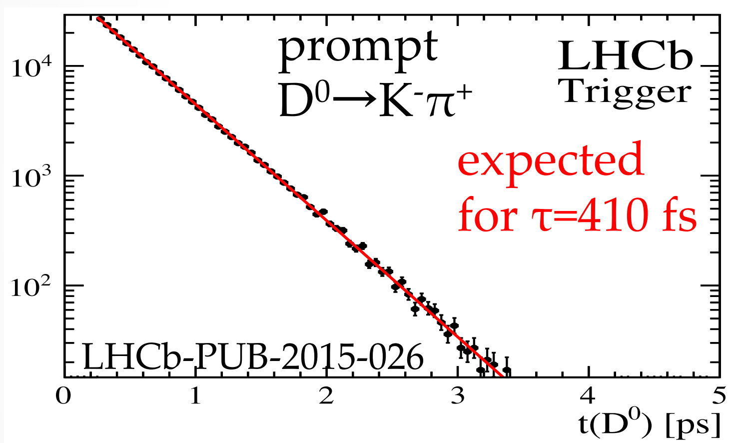


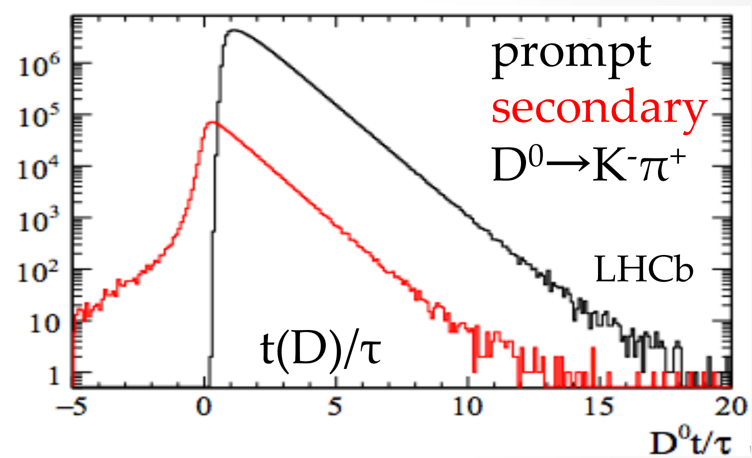
BF($D^0 \to \gamma\gamma$) < 8.5×10^{-7}

- LHCb competitive in $D^0 \to \varrho\gamma$, $\phi\gamma$, $K^*\gamma$
- Belle2 dominated: $D^0 \to \gamma\gamma$, $D^+ \to \varrho^+\gamma$, $\Lambda_c \to p\gamma$
- Belle2 wrt Belle: merged π^0, $\gamma \to e^+e^-$ conversion
- LHCb upgrade: improved ECAL(?)

Experimental aspects & prospects

- **t-acceptance**: LHCb triggers distort prompt charm
- Prompt + sec charm ⇨ full coverage of decay time
- Lifetime-unbiased triggers in Run-2

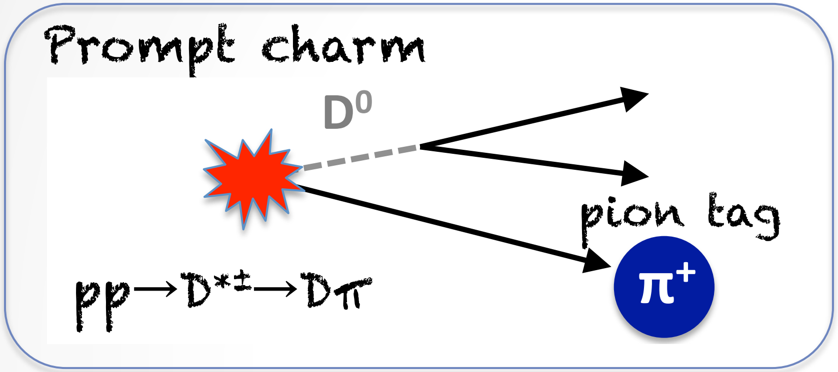


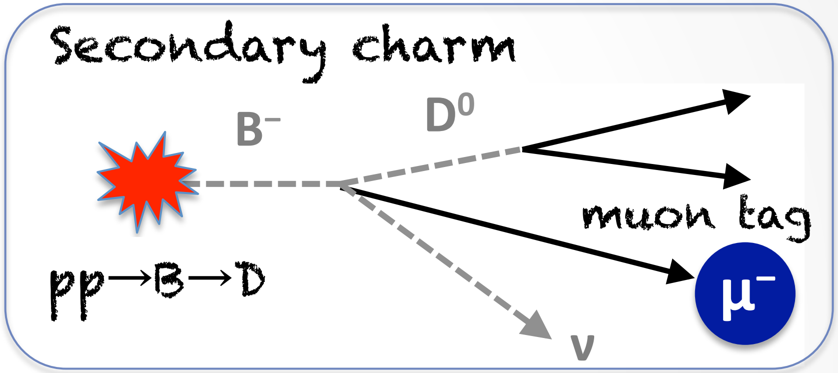


- **t-resolution**
- good at LHCb: ~50fs
- improved at Belle2 wrt Belle: ~250fs ➔~150fs

Experimental aspects & prospects

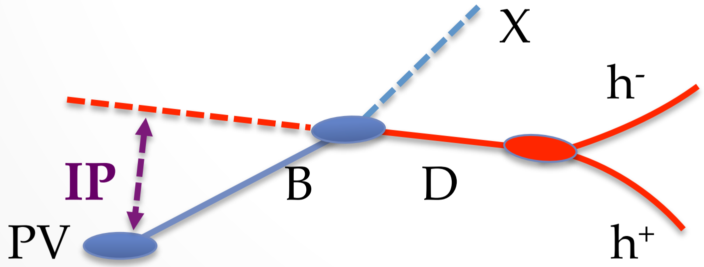
- **flavour tagging** at t=0. Defines charm samples

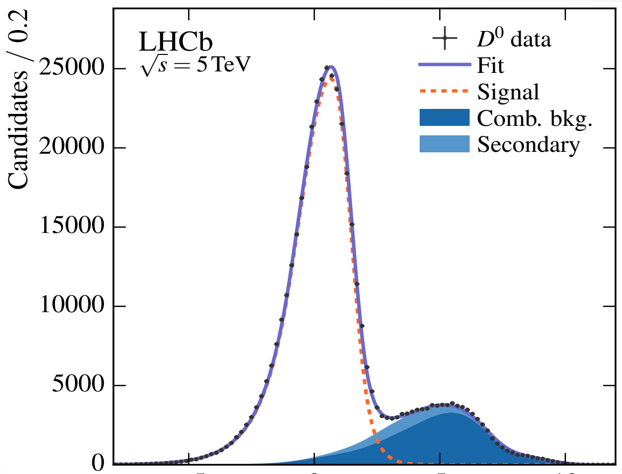




- LHCb uses both; Belle prompt

- **prompt/sec separation**, nontrivial at LHCb





arXiv:1610.02230

- Lifetime biasing; may need better approach

‘Extra’ asymmetries to account for

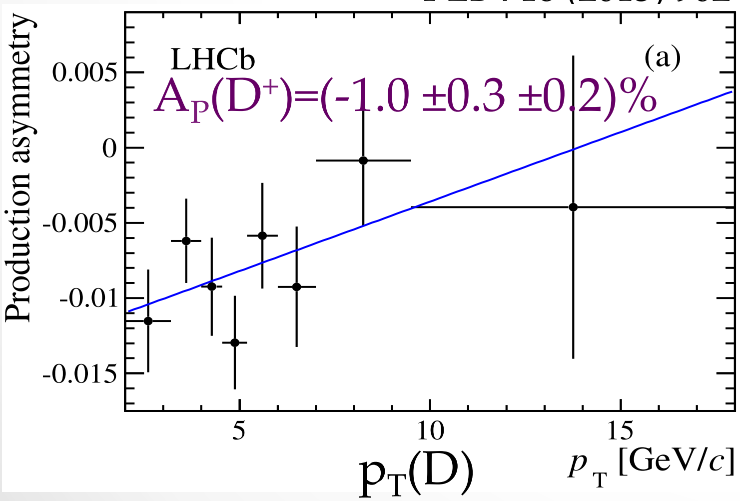
Production asymmetry

- $e^+e^- \rightarrow \gamma/Z^*$ interference ⇨ FB asymmetry;
  easy to disentangle from CPV
- pp: $\sigma(\Lambda_c^+) > \sigma(\Lambda_c^-)$ ⇨ $\sigma(D^+) < \sigma(D^-)$ to compensate (Asym~1%)

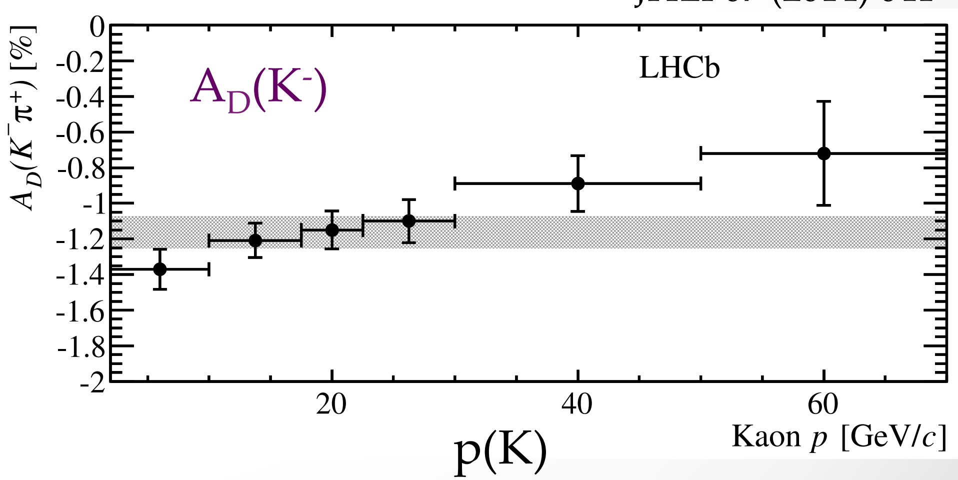
Detection asymmetries (K^+ vs K^-, π^+ vs π^-)

- different interactions with detector material: $\sigma(pK^-) > \sigma(pK^+)$
- depend on particle momentum

PLB 718 (2013) 902



JHEP07 (2014) 041

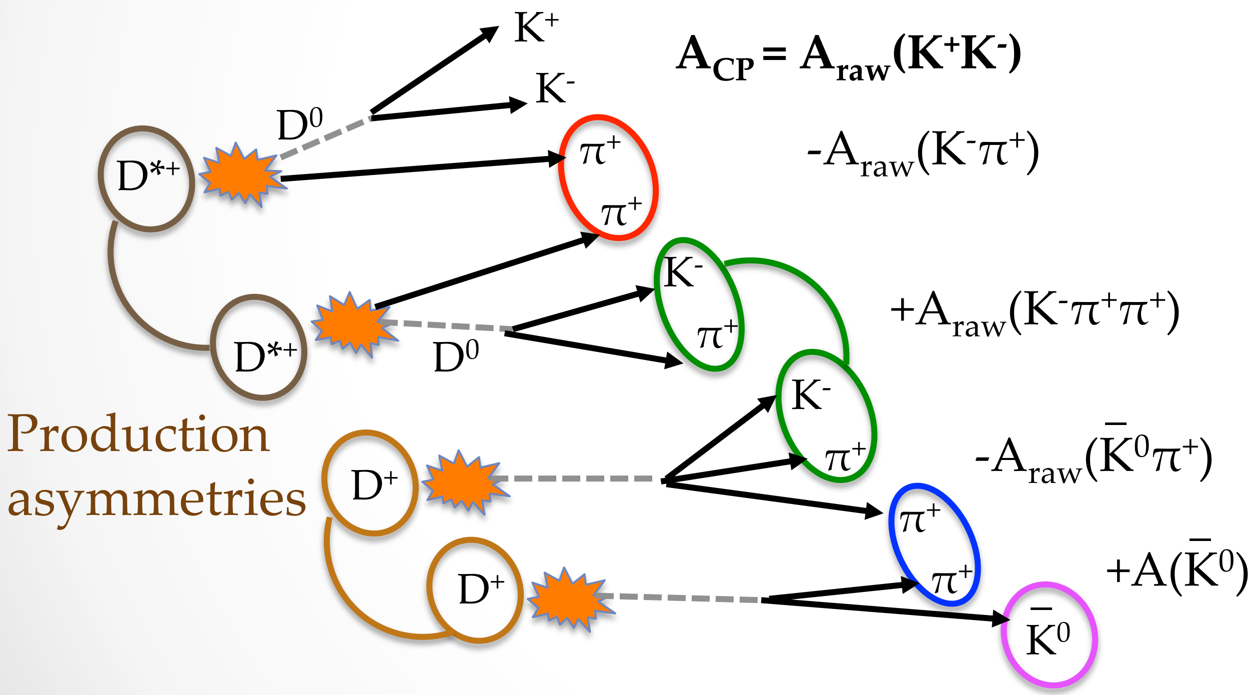


From raw asymmetry to CP asymmetry

Correct with CF control modes

- Overconstrain system with additional channels
- $A_{CP}(D^0 \to K^+K^-)$ case

$$A_{raw} = \frac{N(D) - N(\overline{D})}{N(D) + N(\overline{D})}$$



Multi-dim reweighting to match kinematics of signal & control modes

Calculated from known $K^0/\overline{K}^0$ interactions with detector + K-mixing/CPV

- Assume no CPV in CF or include related uncertainty?

D^0-$\bar{D}^0$ mixing & Indirect CPV: basics

- Flavour eigenstates D^0 [cu] $\bar{D}^0$ [$\underline{c}$u] ⇨ mass eigenstates D_1 D_2 [$m_{1,2}$ $\Gamma_{1,2}$]

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

- Mixing frequencies x, y

$$x = \frac{m_2 - m_1}{\Gamma} \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

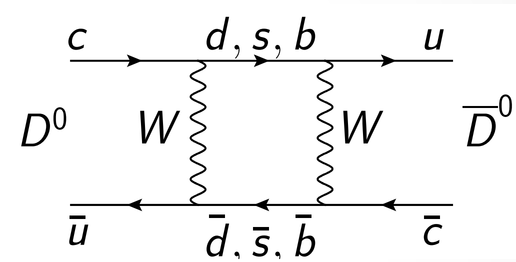
- CPV related to mixing (Indirect CPV)

$$\left|q/p\right| \neq 1 \quad \phi = \arg\left(q/p\right) \neq 0$$

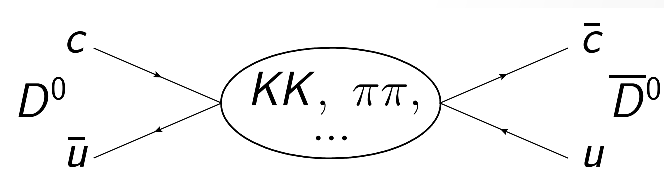
- SM:

  x, y ~O(10^{-2}) with large uncertainty

  Indirect CPV universal, ~10^{-4}



x~10^{-5}



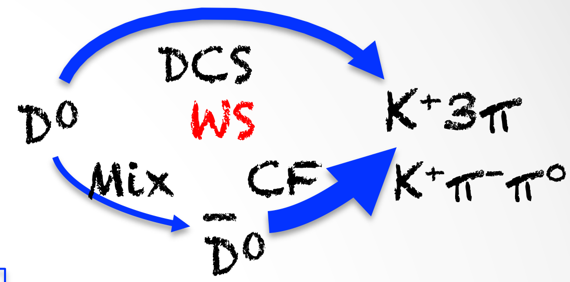
x, y ~ 1%

difficult to calculate

PRL116, 241801 (2016)

Wrong Sign Decays: $D^0 \to K3\pi$

- Rates integrated over Phase Space
- ⇨ averaged strong phase & coherence factor
- ⇨ dilution of sensitivity



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

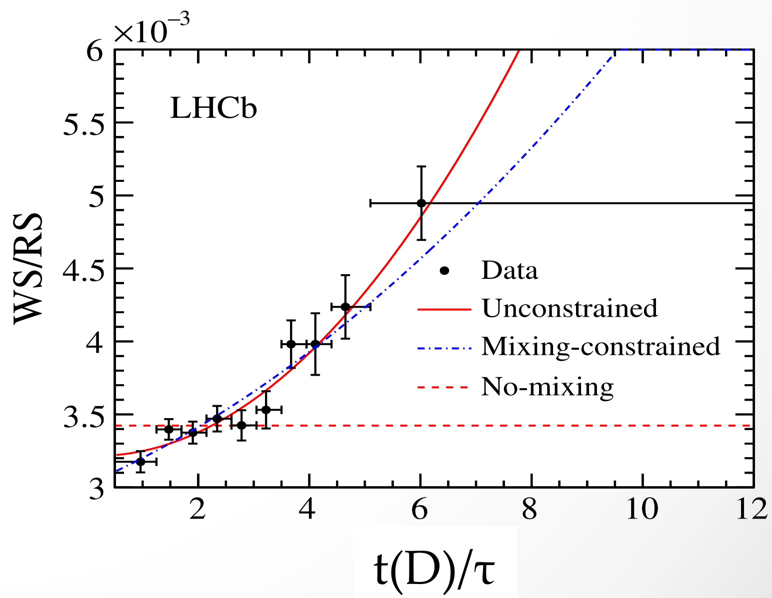
- R_{coh}~0 phase variation; R_{coh}~1 resonances in phase

$$\int A_{K^-3\pi}(\mathbf{r}) A_{K^+3\pi}(\mathbf{r})\, d\mathbf{r} \Rightarrow R_{coh} e^{-i\delta_{K3\pi}}$$

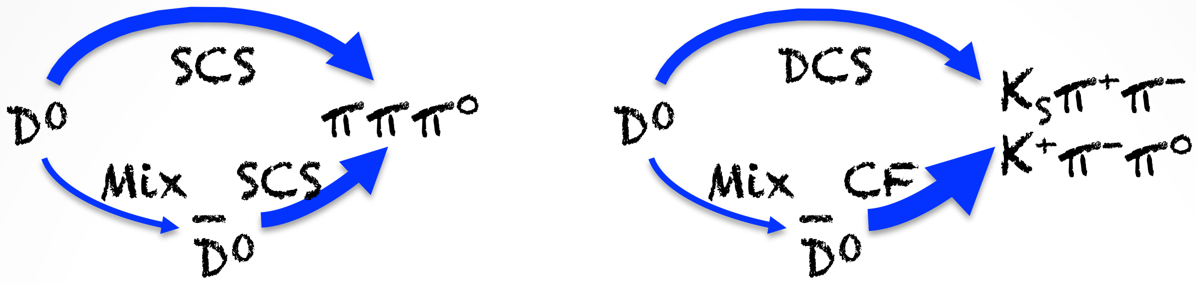
$$R_{coh} y'' = (0.3 \pm 1.8) \times 10^{-3}$$

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

- Measurement w/o PS integration expected to have large sensitivity



Multibody decays: time evolution of Dalitz



✓ **Direct access to x, y, q/p**

✗ Need model to describe resonances

✓Access to amplitudes & phases ⇨ no external input

✓No dilution from coherence factor

$$\mathcal{P}\left[D^0(Dalitz;t)\right] \propto e^{-\Gamma t}\Big\{|A_f|^2[\cosh(y\Gamma t)+\cos(x\Gamma t)] \quad \leftarrow \text{decay } D^0\to f$$

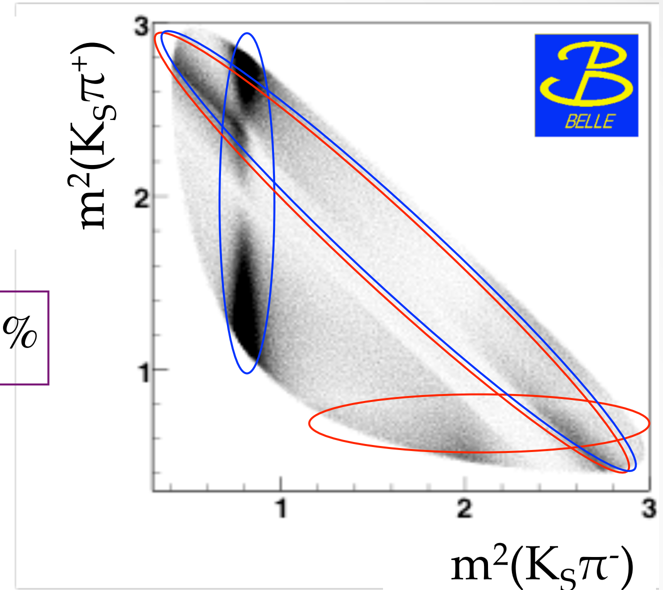
$$+\left|\frac{q}{p}\overline{A}_f\right|^2[\cosh(y\Gamma t)-\cos(x\Gamma t)] \quad \leftarrow \text{mixing } D^0\to\bar{D}^0\to f$$

$$-2\Re\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sinh(y\Gamma t)-2\Im\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sin(x\Gamma t)\Big\} \quad \leftarrow \text{interference of both}$$

- Sensitivity depends on resonance interference

PRD89 091103 (2014)

Dalitz(t) of $D^0 \to K_S \pi^+ \pi^-$ golden mode

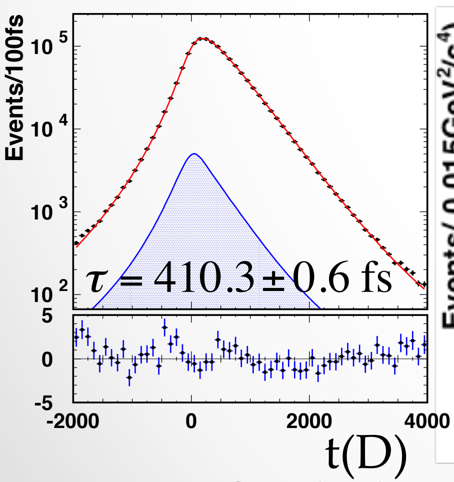


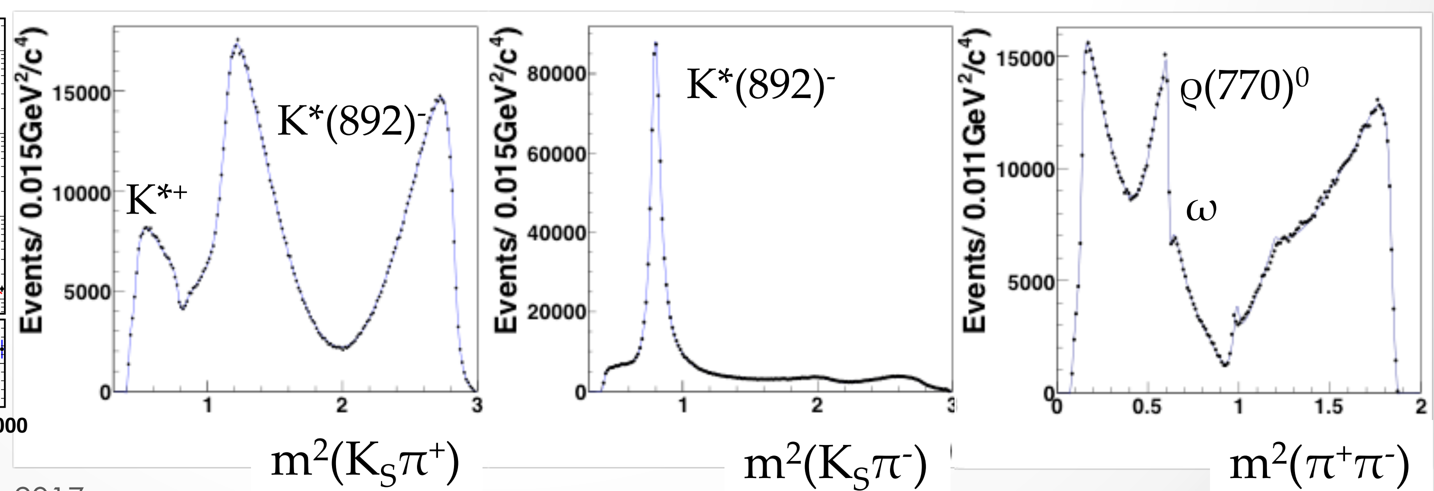
- Large statistics and rich dynamics
- Significant $D^0 \to f$ & $D^0 \to \bar{f}$ interferences
- Most precise x so far

$$x = \left(0.56 \pm 0.19 {}^{+0.04}_{-0.08} {}^{+0.06}_{-0.08}\right)\% \quad y = \left(0.30 \pm 0.15 {}^{+0.04}_{-0.05} {}^{+0.03}_{-0.07}\right)\%$$

$$|q/p| = 0.90 {}^{+0.16}_{-0.15} {}^{+0.05}_{-0.04} {}^{+0.06}_{-0.05} \quad \phi = \left(-6 \pm 11 \pm 3 {}^{+3}_{-4}\right)^\circ$$

- Belle: 1.2M signal events
- LHCb: 2M in Run1. Significant x with Run1+2?

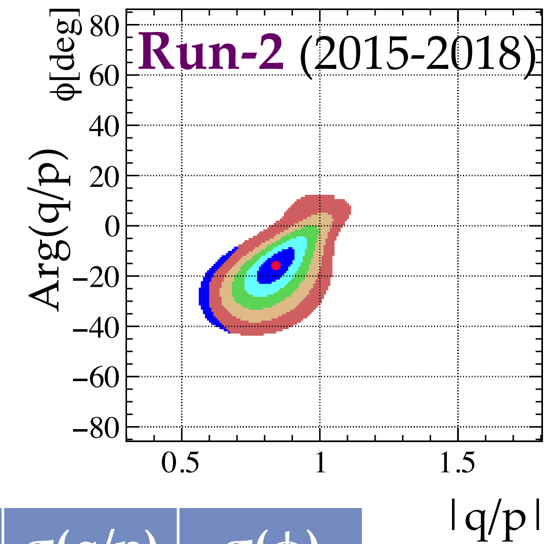


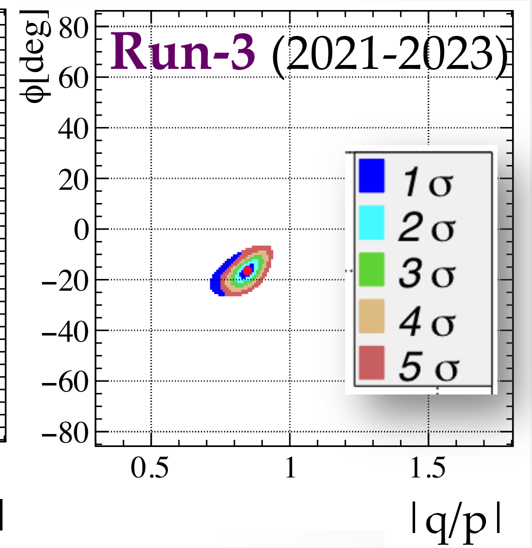


A.Davis @ 6^{th} Implications Workshop
A.Schwartz @ Charm2016

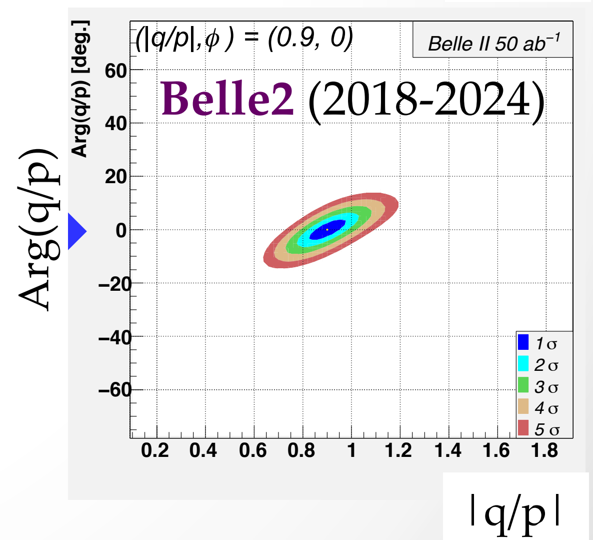
Future of mixing & ICPV

- Dominated by LHCb
- Significant x with Run1+2?





	σ(x) [10^{-3}]	σ(y) [10^{-3}]	σ(q/p) [10^{-3}]	σ(φ) [mrad]
HFAG 2016	1.4	0.7	80	173
Run-1 (2011 - 2012)	1.1	0.8	65	119
Run-2 (2015 - 2018)	0.8	0.6	47	83
Run-3 (2021 - 2023)	0.3	0.2	17	32

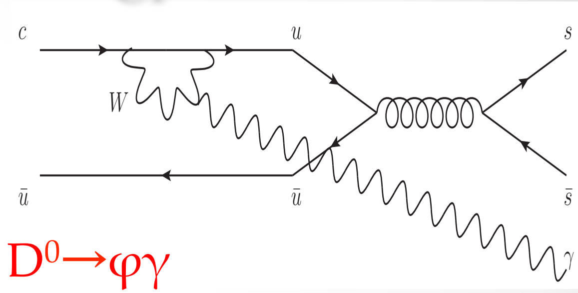


- LHCb: √N scaling of stat & syst
- Belle: includes irreducible syst

PRL118, 051801 (2017)

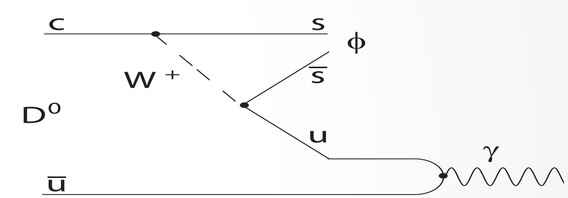
$D^0 \to K^{*0}\gamma$, $\varphi\gamma$, $\rho^0\gamma$: BF & A_{CP}

- BF's poorly measured. No CPV analysis before
- Large CPV within SM, up to a few %
- First observation of $D^0 \to \rho(770)\gamma$

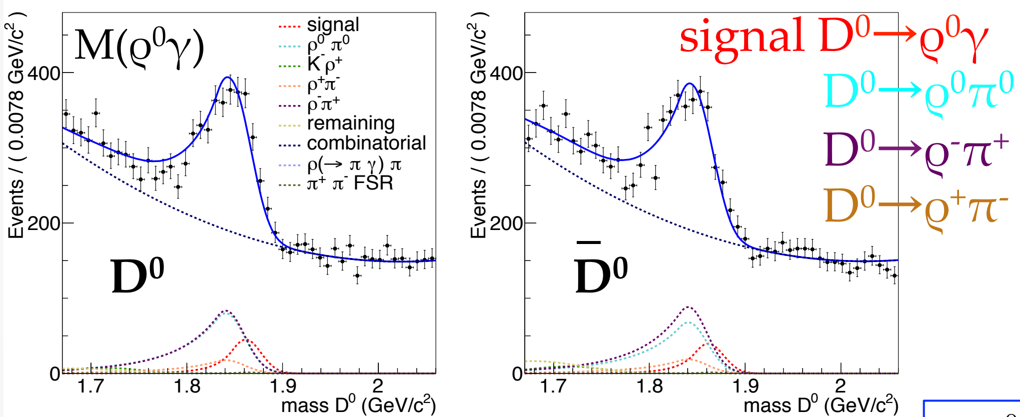


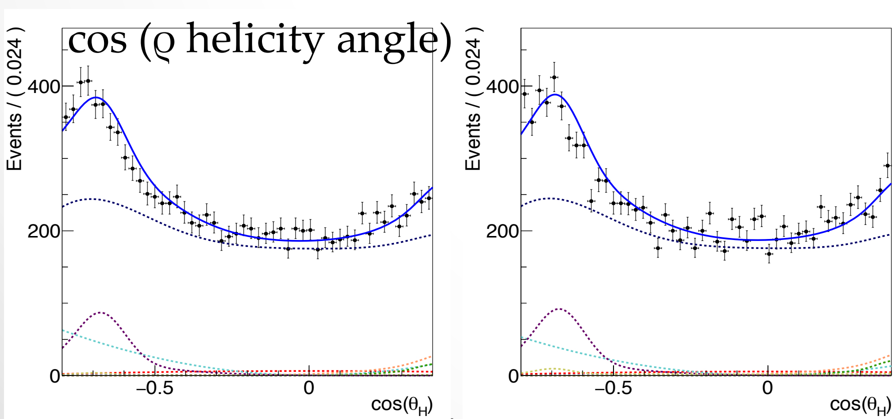
$D^0 \to \varphi\gamma$

Short distance contribution



Long distance via Vector Meson Dominance





$$\mathcal{B}(D^0 \to \overline{K}^{*0}\gamma) = (4.66 \pm 0.21 \pm 0.18) \times 10^{-4}$$
$$\mathcal{B}(D^0 \to \phi\gamma) = (2.76 \pm 0.20 \pm 0.08) \times 10^{-5}$$
$$\mathcal{B}(D^0 \to \rho^0\gamma) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5}$$

$$A_{CP}(D^0 \to \overline{K}^{*0}\gamma) = (-0.3 \pm 2.0 \pm 0.0)\%$$
$$A_{CP}(D^0 \to \phi\gamma) = (-9.4 \pm 6.6 \pm 0.1)\%$$
$$A_{CP}(D^0 \to \rho^0\gamma) = (+5.6 \pm 15.1 \pm 0.6)\%$$

No CPV

PLB 767 (2017) 177-187

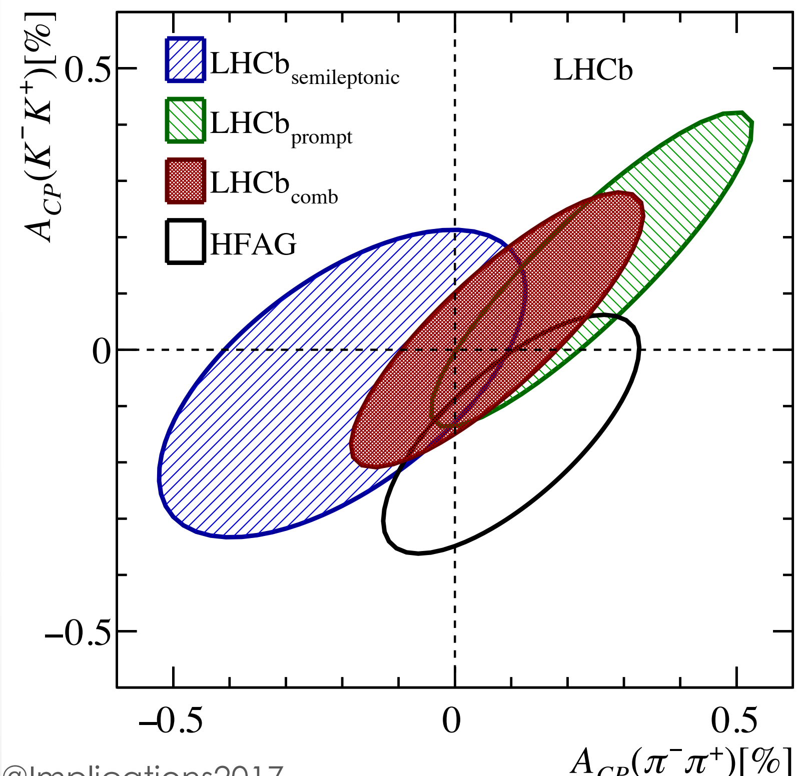
$A_{CP}(D^0 \to K^+K^-)$ & $A_{CP}(D^0 \to \pi^+\pi^-)$

- Individual A_{CP}(KK), pion-tagged sample

$$A_{CP}(K^+K^-) = (0.14 \pm 0.15 \pm 0.10)\%$$

- Combine with ΔA_{CP} ⇨

$$A_{CP}(\pi^+\pi^-) = A_{CP}(K^+K^-) - \Delta A_{CP} = (0.24 \pm 0.15 \pm 0.11)\%$$



- Combine with results from muon-tagged sample
  JHEP07, 041 (2014)
  ⇨ LHCb combination

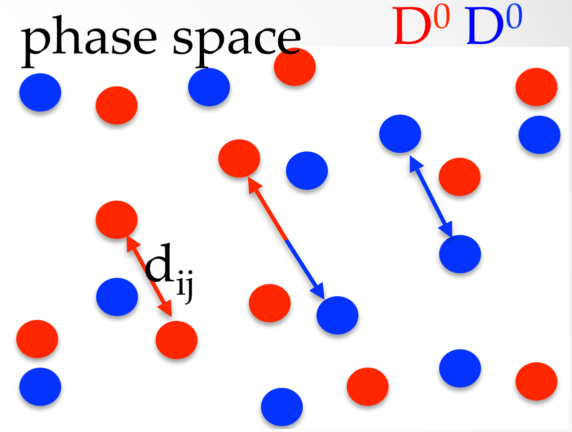
- Both A_{CP}'s consistent with zero

PLB 769 (2017) 345-356

Search for CPV in $D^0 \to 4\pi$ with Energy Test

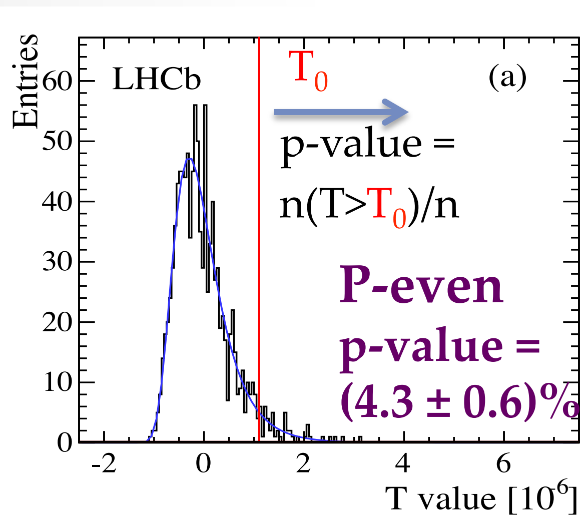
- Statistical comparison of two distributions
- Test statistics: based on distances of event pairs
- Compare with T distribution for no CPV case (randomize D flavour)

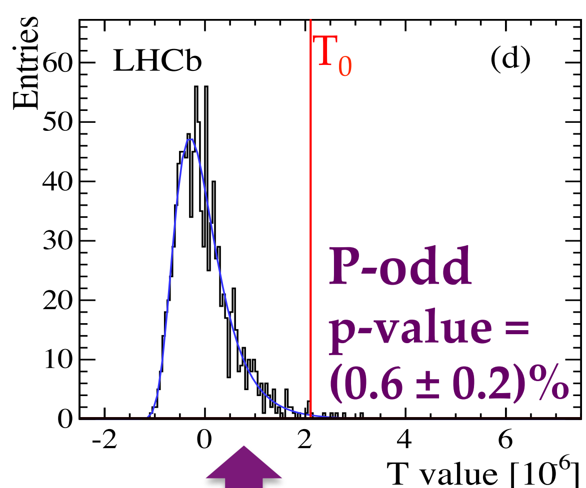
- 5-dim phase space: $m^2(\pi\pi)$, $m^2(\pi\pi\pi)$ ⇨ **P-even**
- Use triple-product sign to access **P-odd** CPV



$$T = \langle d_{ij} \rangle_{DD} + \langle d_{ij} \rangle_{\bar{D}\bar{D}} - \langle d_{ij} \rangle_{D\bar{D}}$$

D^0-D^0 $\bar{D}^0$-$\bar{D}^0$ D^0-$\bar{D}^0$





Marginally consistent with no CPV (~2.7σ)

CP

I D $C_T>0$	**III** $\bar{D}$ $-\bar{C}_T>0$
II D $C_T<0$	**IV** $\bar{D}$ $-\bar{C}_T<0$

$$C_T \equiv \vec{p}_{\pi^+} \cdot \left(\vec{p}_{\pi^+} \times \vec{p}_{\pi^-} \right)$$

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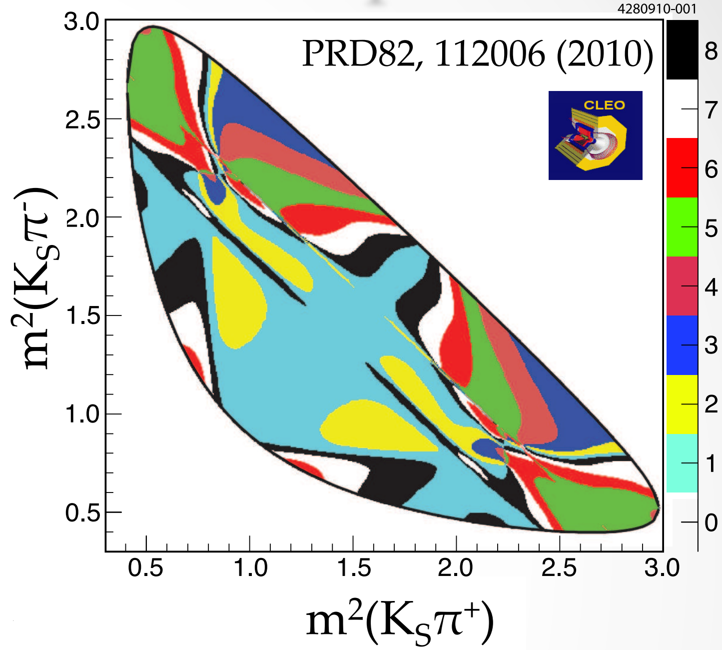
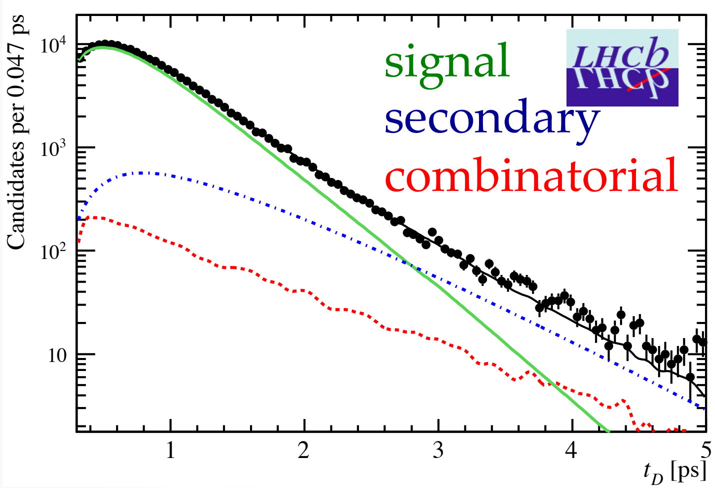
$D^0 \to K_S\pi\pi$, t-dep. Dalitz, model independent

- $D^0 \to K_S\pi\pi$ is a golden mode for mixing
- Binned approach to Dalitz
- Strong phases & fractions from Cleo-c
- Fit t(D) with data driven acceptance





$$x = (-0.86 \pm 0.53 \pm 0.17)\%$$
$$y = (+0.03 \pm 0.46 \pm 0.13)\%$$
$$\tau_D = (410.9 \pm 1.1)\ \text{fs}$$

- This is with 2011 data: 180K signal

  K_S decayed inside vertex detector

- Ongoing for 2012 data: ~2M prompt+sec

  Also K_S decayed outside vertex detector

Belle: 1.2M signal

$$x = \left(0.56 \pm 0.19\,^{+0.04}_{-0.08}\,^{+0.06}_{-0.08}\right)\%$$

$$y = \left(0.30 \pm 0.15\,^{+0.04}_{-0.05}\,^{+0.03}_{-0.07}\right)\%$$

PRD89 091103 (2014)