Status & Perspectives of Charm (LHCb and Belle2)

Jolanta Brodzicka, University of Manchester

Trends in Flavour Physics

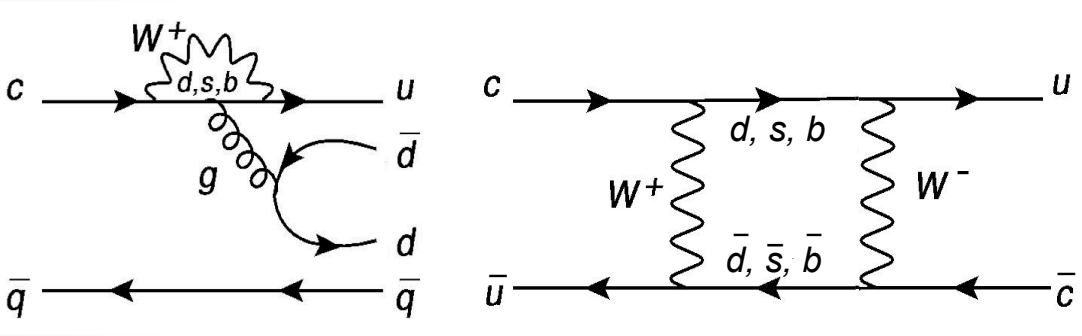
Paris, March 2017

MANCHESTER 1824
The University of Manchester

LHCb

Charm: complementary but difficult

- Unique access to up-type quarks
  (HF physics with top limited)
- Rare charm processes very suppressed in SM



needed for CPV mixing @ short distance

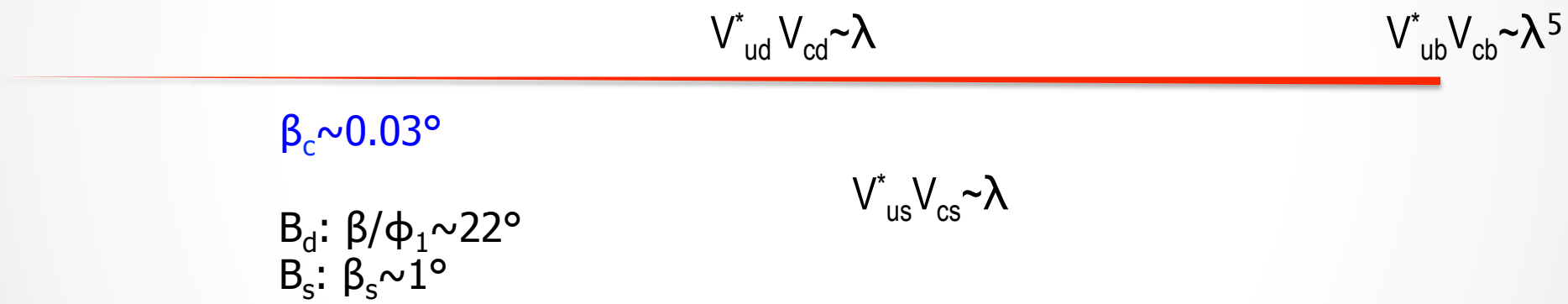
- b loop ~$V_{ub}V_{cb}(m_b/m_W)^2$
- s & d: GIM suppressed, cancel in U-spin limit

- d,s,b in loops: different NP particle/couplings?

- Large non-perturbative corrections (~$1/m_c$)

Theoretical reality, in short

- Charm Unitarity Triangle
- UT openness ⇨ CPV expected



- Increased CPV in decays dominated by penguins

Experimental reality, in short

- D^0-$\bar{D}^0$ mixing
  - established (= no-mixing excluded)
  - not measured precisely
- CPV
  - not observed yet
  - precision down to $O(10^{-3})$
  - becoming sensitive to SM charm CPV
- Rare decays
  - looking for signals, precision down to $O(10^{-8})$
  - not there yet to go beyond
    (asymmetries, γ polarisation, LFU, …)
  - will take B-brother path ASAP

Mixing & Indirect CPV

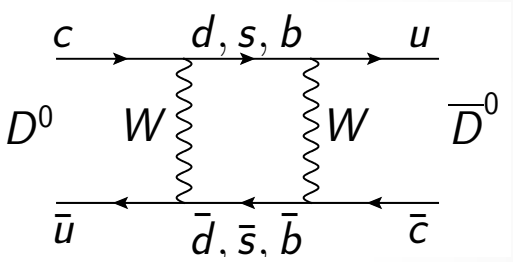
D^0-$\bar{D}^0$ mixing & Indirect CPV: basics

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

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

- Mixing frequencies x, y

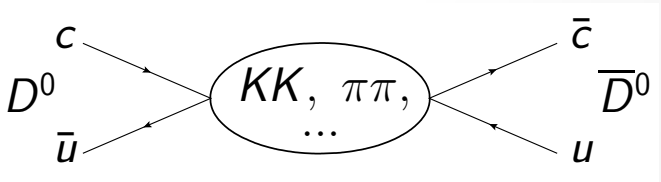
$$x = \frac{m_2 - m_1}{\Gamma} \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$



x~10⁻⁵

- CPV related to mixing (Indirect CPV)

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



x, y ~ 1%

difficult to calculate

- SM:

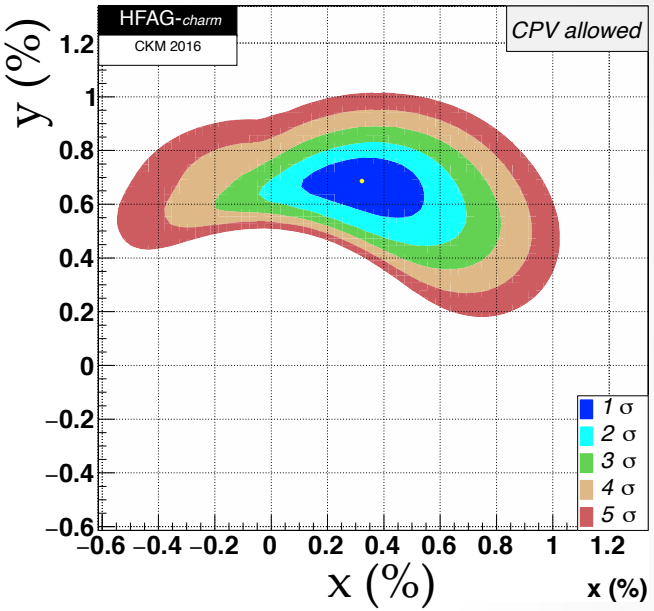
  x, y ~O(10^{-2}) with large uncertainty

  Indirect CPV universal, ~10^{-4}

Mixing & Indirect CPV: global fit

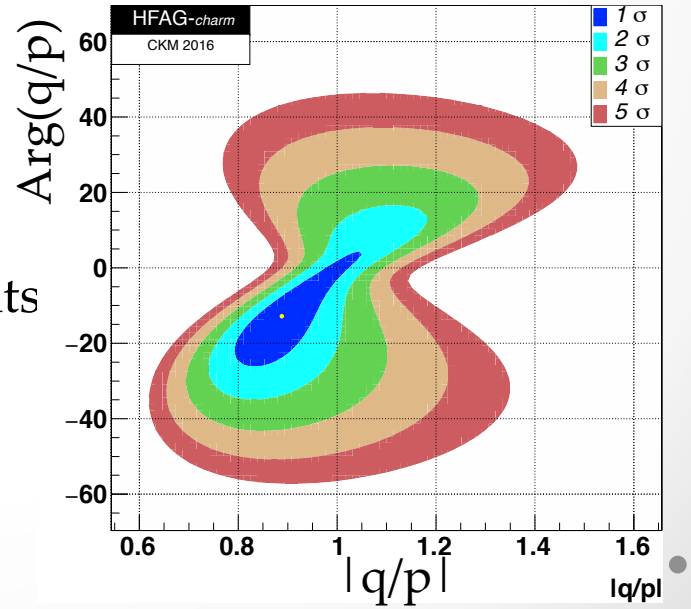
$$x = (0.32 \pm 0.14)\% \quad y = \left(0.69^{+0.06}_{-0.07}\right)\%$$

$$|q/p| = 0.89^{+0.08}_{-0.07} \quad \phi = \arg(q/p) = -12.9^{+9.9}_{-8.7}\ \text{deg}$$



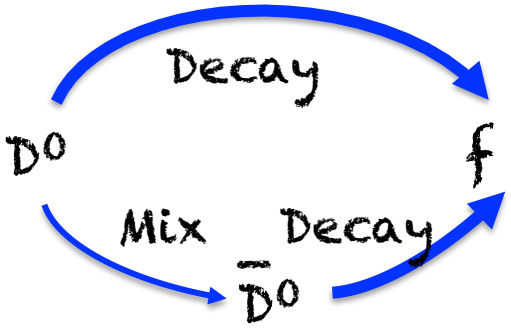
- No-mixing excluded by >11σ
- x still not significant
- No evidence for indirect CPV

- Mixing: search for NP *within* SM
- Why to bother?
  - To disentangle q/p from measurements
  - In case theory calculation improves



Mixing & Indirect CPV: methods/modes

- t-dependent analysis; t = D^0 decay time
- Best access through interference of decays & mixing

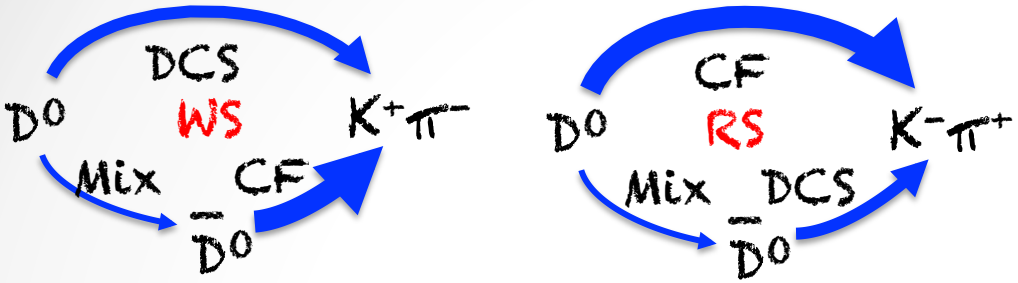


- Contribution from mixing itself ~x^2+y^2 ~$O(10^{-4})$
- $D^0 \to \bar{D}^0 \to K^- l \nu$ (purely from mixing) not yet observed

- Max sensitivity
  - both paths with similar rates (f = DCS)
  - large statistics (f = SCS)

PRL111, 251801(2013)
arXiv:1611.06143

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



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

Decay **Interference** **Mixing**

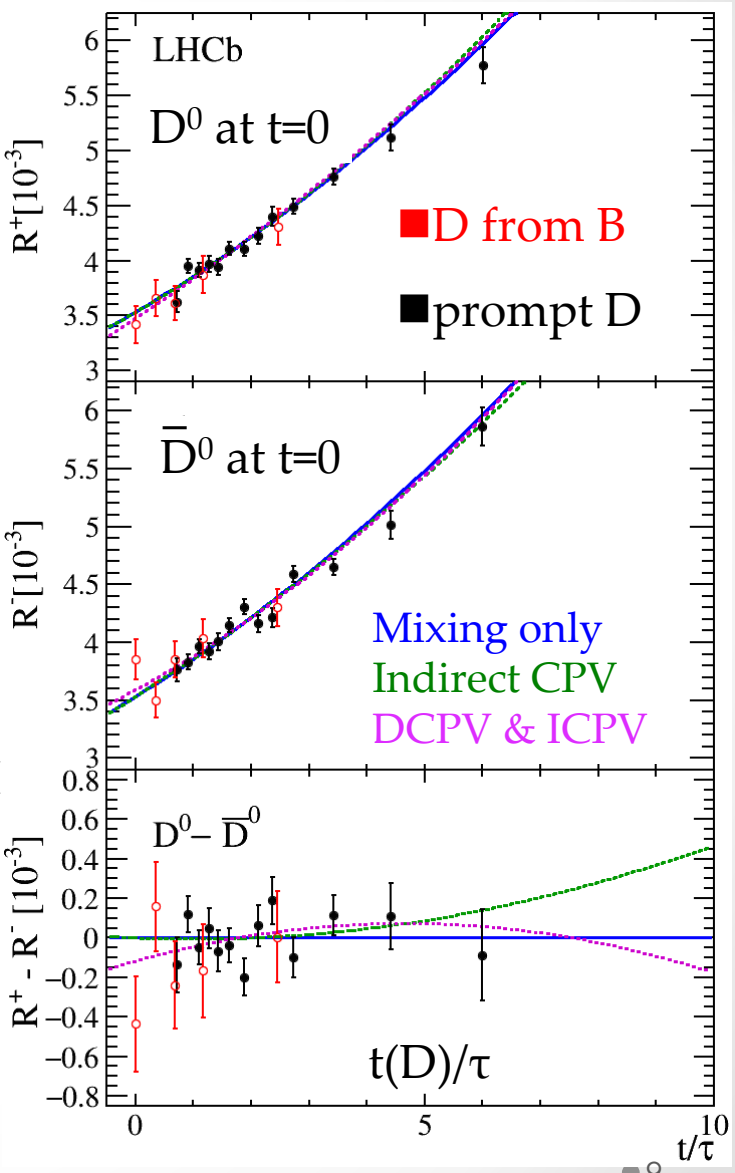
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta_{K\pi} & \sin\delta_{K\pi} \\ -\sin\delta_{K\pi} & \cos\delta_{K\pi} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

- $\delta_{K\pi}$: CF/DCS strong phase; from CLEO/BESIII

$$y' = (5.2 \pm 0.8) \times 10^{-3}$$
$$x'^2 = (3.6 \pm 4.3) \times 10^{-5}$$

$0.75 < |q/p| < 1.24$ @68% CL

- Most significant mixing, no CPV



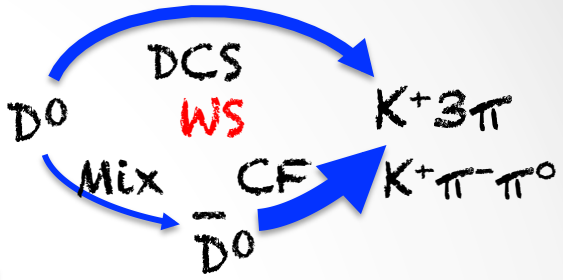
PRL116, 241801 (2016)

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

- Rates integrated over Phase Space

⇨ averaged strong phase & coherence factor

⇨ dilution of sensitivity



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

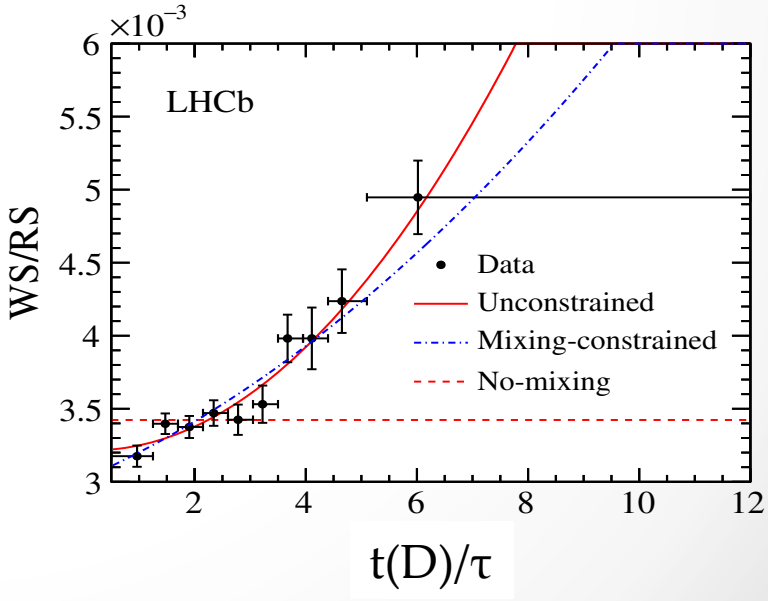
- R_{coh}~0 phase variation; R_{coh}~1 resonances in phase

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

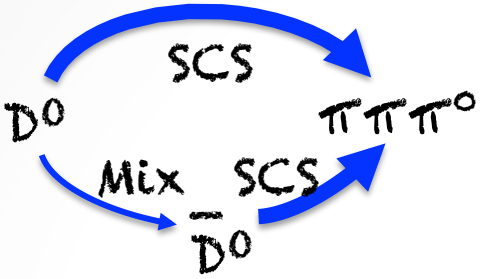
$$R_{coh} y'' = (0.3 \pm 1.8) \times 10^{-3}$$

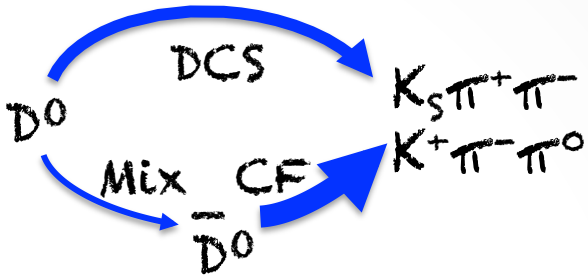
$$(x''^2 + y''^2)/4 = (4.8 \pm 1.8) \times 10^{-5}$$

- 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

$$\mathcal{P}\left[D^0(Dalitz;t)\right] \propto e^{-\Gamma t}\Big\{|A_f|^2[\cosh(y\Gamma t)+\cos(x\Gamma t)] + \left|\frac{q}{p}\overline{A}_f\right|^2[\cosh(y\Gamma t)-\cos(x\Gamma t)] - 2\Re\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sinh(y\Gamma t) - 2\Im\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sin(x\Gamma t)\Big\}$$

←decay $D^0 \to f$

←mixing $D^0 \to \bar{D}^0 \to f$

←interference of both

- Sensitivity depends on resonance interference

PRD89 091103 (2014)

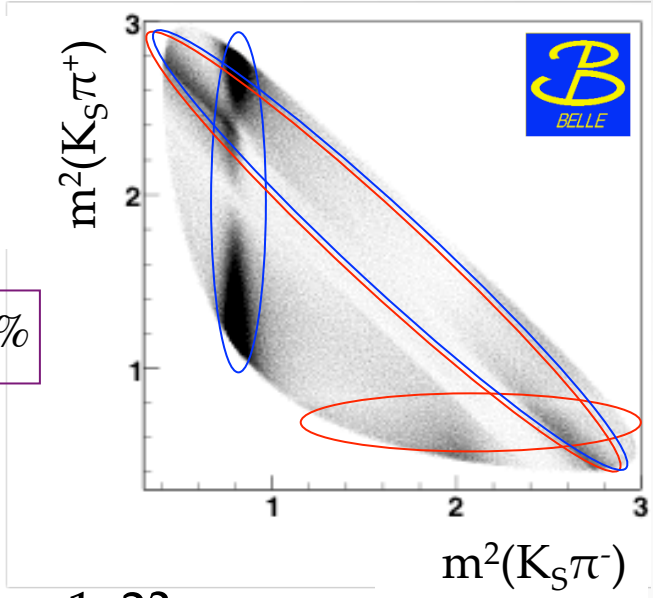
Dalitz(t) of $D^0 \to K_S\pi^+\pi^-$ golden mode

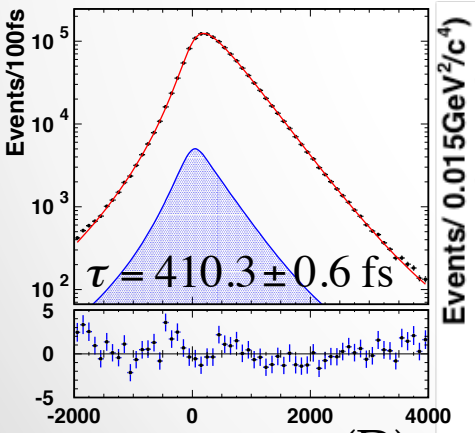
- Large statistics and rich dynamics
- Significant $D^0 \to f$ & $D^0 \to \bar{f}$ interferences
- Most precise x so far

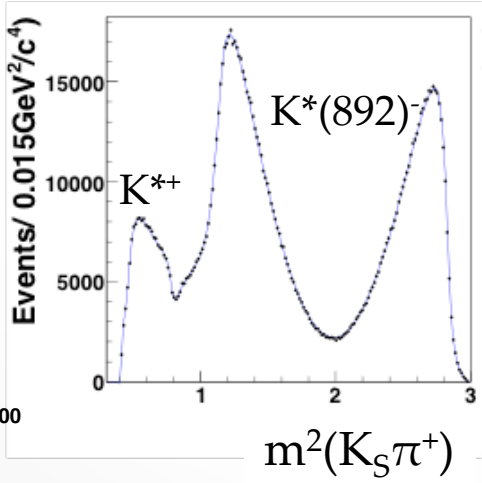
$$x = \left(0.56 \pm 0.19^{+0.04\ +0.06}_{-0.08\ -0.08}\right)\% \quad y = \left(0.30 \pm 0.15^{+0.04\ +0.03}_{-0.05\ -0.07}\right)\%$$

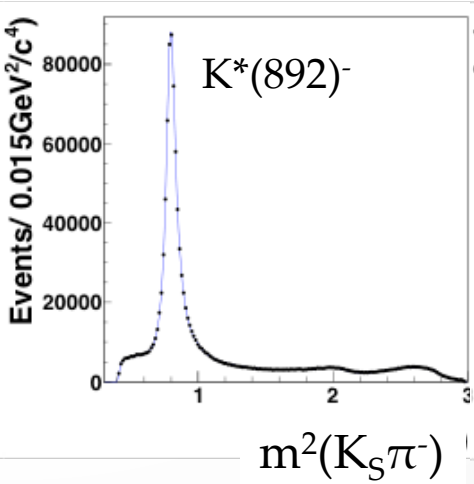
$$|q/p| = 0.90^{+0.16\ +0.05\ +0.06}_{-0.15\ -0.04\ -0.05} \quad \phi = \left(-6 \pm 11 \pm 3^{+3}_{-4}\right)^\circ$$

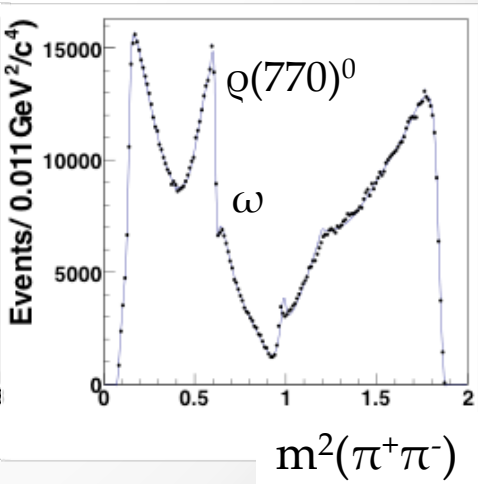
- Belle: 1.2M signal events
- LHCb: 2M in Run1. Significant x with Run1+2?







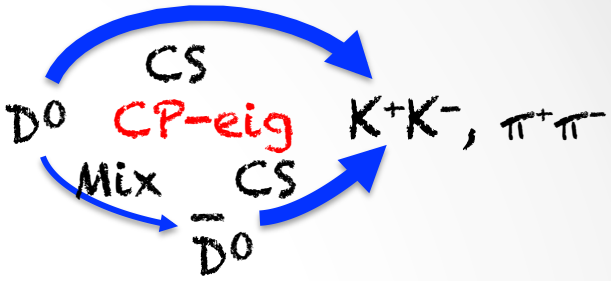




arXiv:1702.06490

CP-eigenstates: effective lifetimes

- Does mixing affect D^0 and $\bar{D}^0$ differently?
- Indirect CPV easiest to access via A_Γ

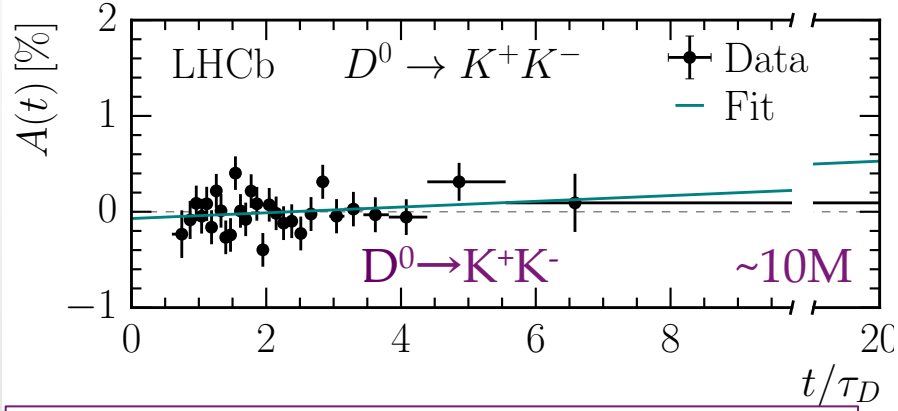


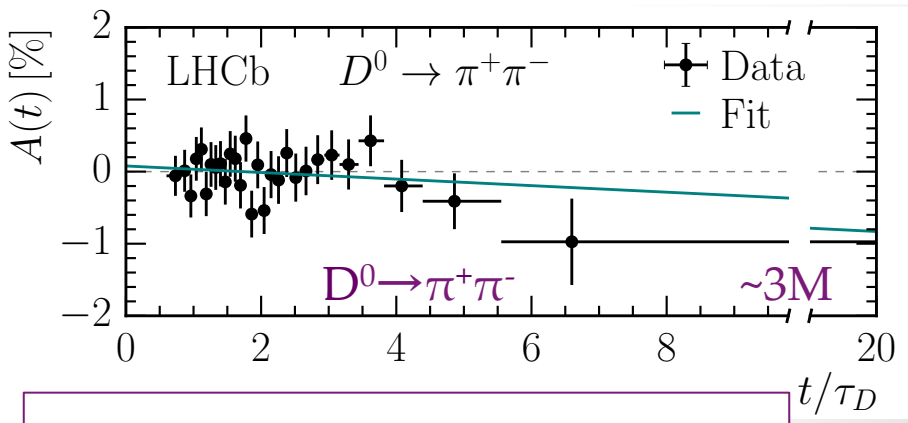
$$A_\Gamma = \frac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\overline{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} \simeq -A_{CP}^{\text{indirect}}$$

- Asymmetry of yields in t(D) bins

$$A_{CP}(t) \simeq A_{CP}^{\text{direct}} - A_\Gamma \frac{t}{\tau_D}$$

- LHCb 2012 data, prompt charm





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

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

A_Γ: entering SM area

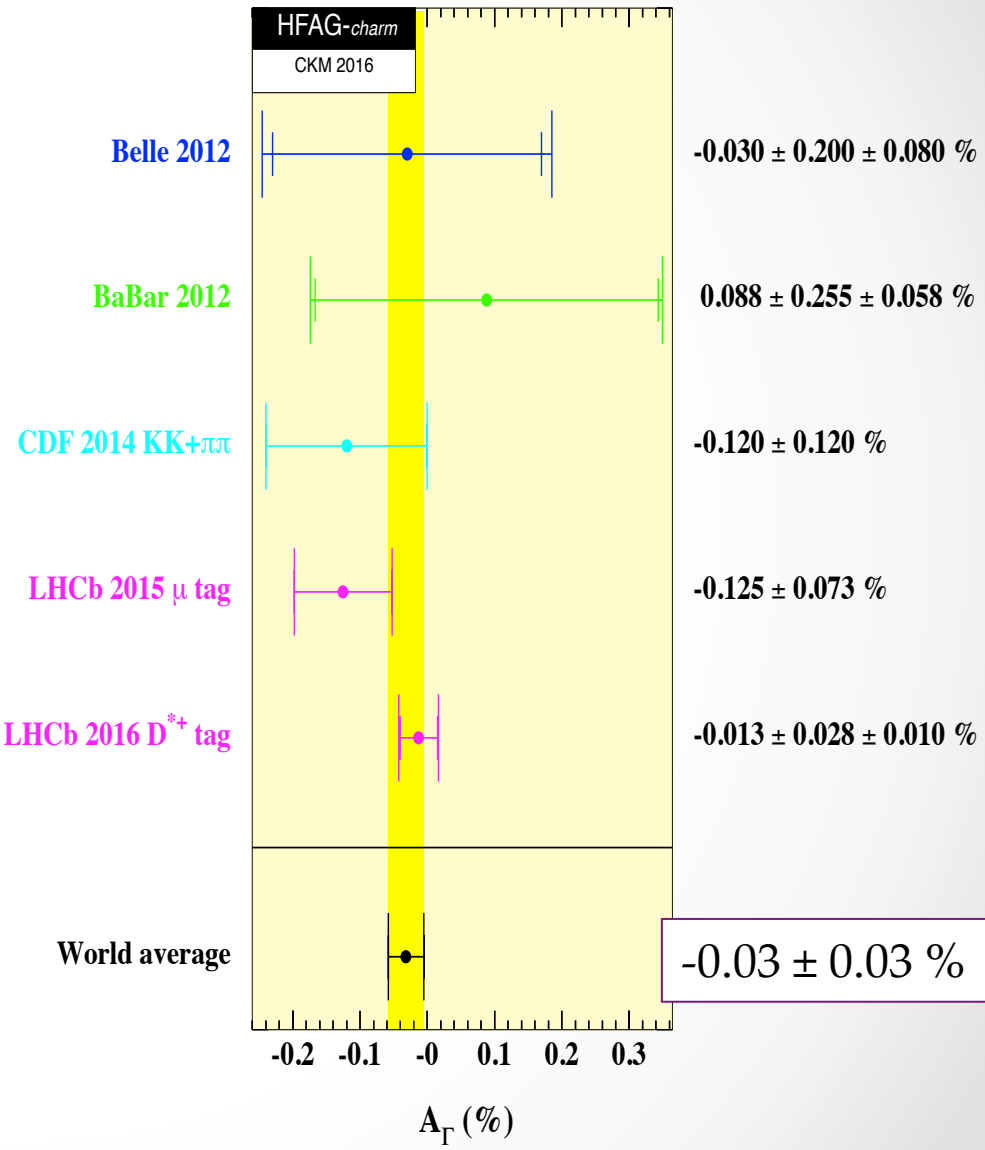
- Sensitivity of O(10^{-4})
  Limited by statistics
- Indirect CPV in SM ~10^{-4}

- 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 mix-decay interference

⇨ sensitivity to q/p depends on x



published ongoing

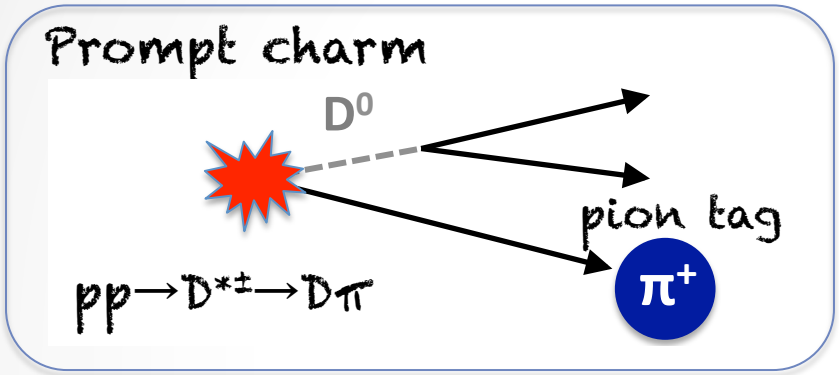
Mixing & ICPV: modes/methods

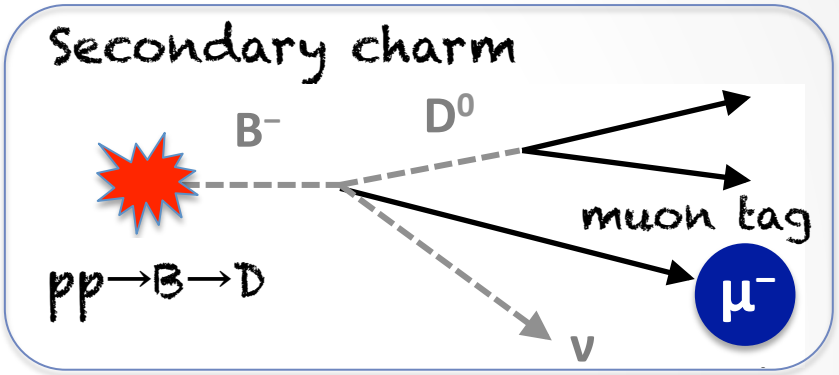
D^0 Mode	Method	Observ.	Exp.	Caveat
$K\pi$	WS/RS (t)	x'^2, y', $\|q/p\|$	LHCb (Run2) CDF Belle Babar	external input: $\delta_{K\pi}$
$K3\pi$	WS/RS (t)	x''^2, y''	LHCb	external input: $\delta_{K3\pi}$, R_{coh}
$K\pi\pi^0$	WS/RS (t)		Belle	
KK, $\pi\pi$	effective τ	A_Γ, y_{CP}	LHCb (Run2) CDF Belle Babar	mixing/CPV entangled
$K_S\pi\pi$	Dalitz-bins(t)	x, y	LHCb	δ_{strong} in Dalitz bins
$K_S\pi\pi$	Dalitz-bins(t)	x, y, q/p	Belle LHCb	Dalitz model
K_SKK	Dalitz(t)		Babar	Dalitz model
$\pi\pi\pi^0$	Dalitz(t)		Babar	Dalitz model
$K3\pi$	PhaseSpace(t)		LHCb	5-D model for WS&RS
$K_S\pi\pi\pi^0$	PhaseSpace(t)		?	5-D amplitude model

- Won't get far with 2-body decays. Multibody decays is a must
- Will model error limit us? Millions of events difficult to model
- For binned approach we need input from BESIII

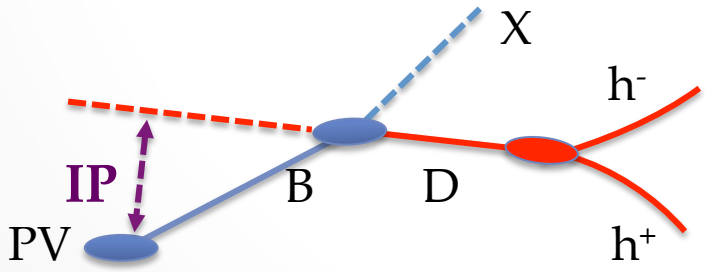
Experimental aspects & prospects

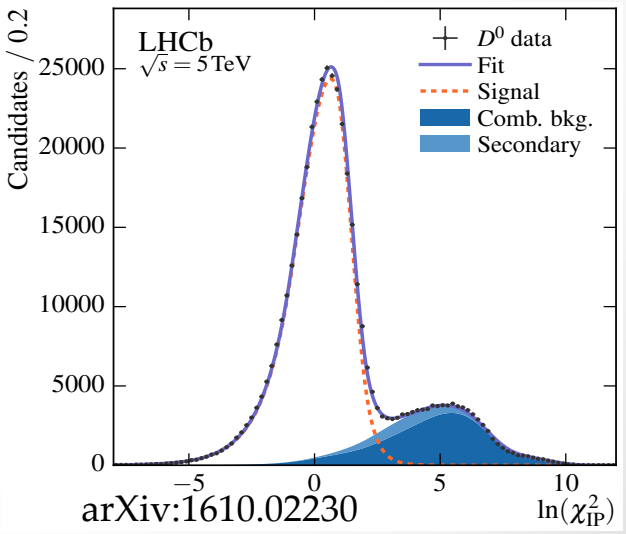
- **flavour tagging** at t=0. Defines charm samples





- LHCb uses both; Belle prompt
- **prompt/sec separation**, nontrivial at LHCb

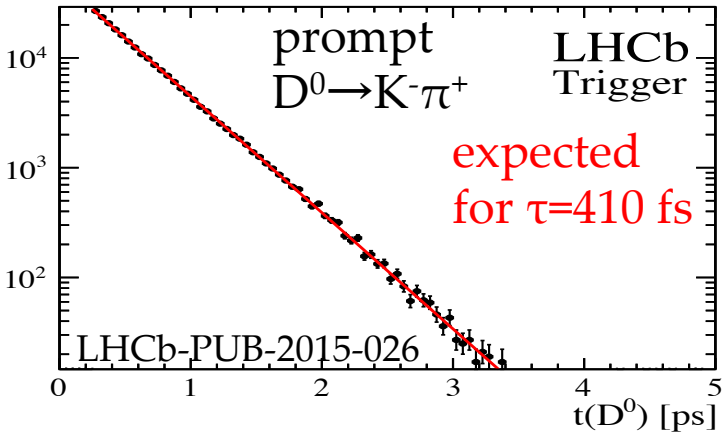


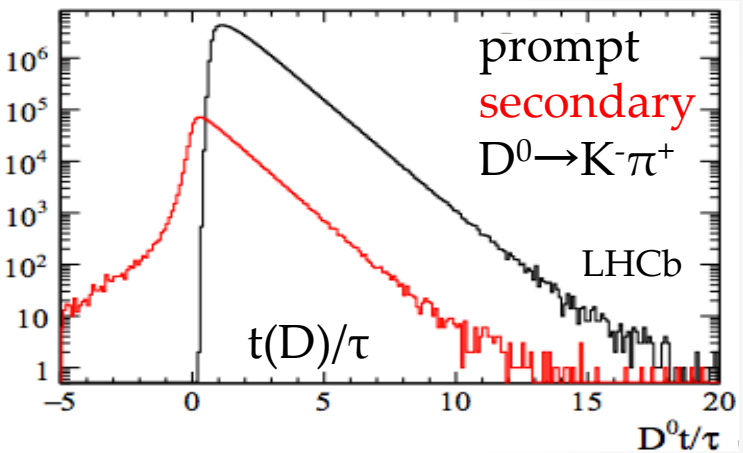


- Lifetime biasing; may need better approach

Experimental aspects & prospects

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

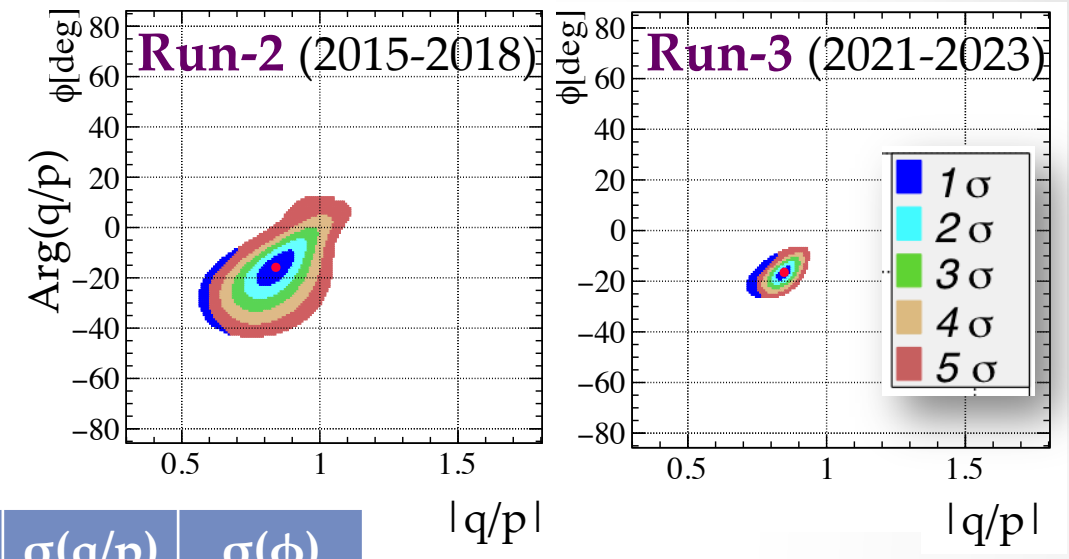




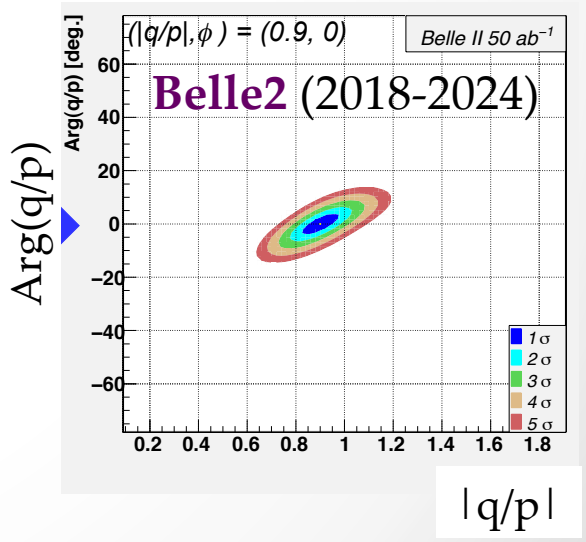
- **t-resolution**
- good at LHCb: ~50fs
- improved at Belle2 wrt Belle: ~250fs ➔~150fs

Future of mixing & ICPV

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

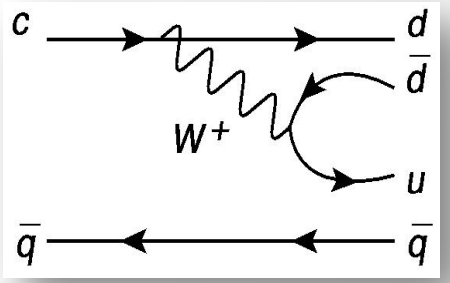


	σ(x) [10^{-3}]	σ(y) [10^{-3}]	σ(q/p) [10^{-3}]	σ(ϕ) [mrad]
HFAG 2016	1.4	0.7	80	173
Run-1 (2011 - 2012)	1.1	0.8	65	119
Run-2 (2015 - 2018)	0.8	0.6	47	83
Run-3 (2021 - 2023)	0.3	0.2	17	32

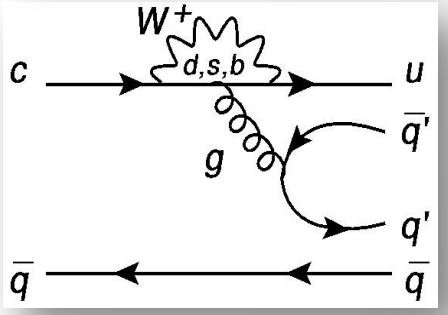


- LHCb: √N scaling of stat & syst
- Belle: includes irreducible syst

Direct CPV



- Depends on decay mode
- Within SM:
  - from Tree-Penguin interference (expected in SCS decays)
  - $A_{CP} \leq 10^{-3} \div 10^{-2}$
- From time independent measurements



'Extra' asymmetries to account for

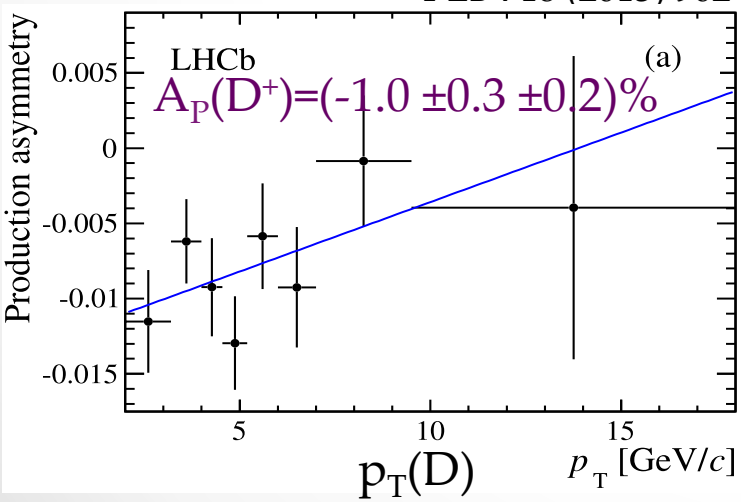
Production asymmetry

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

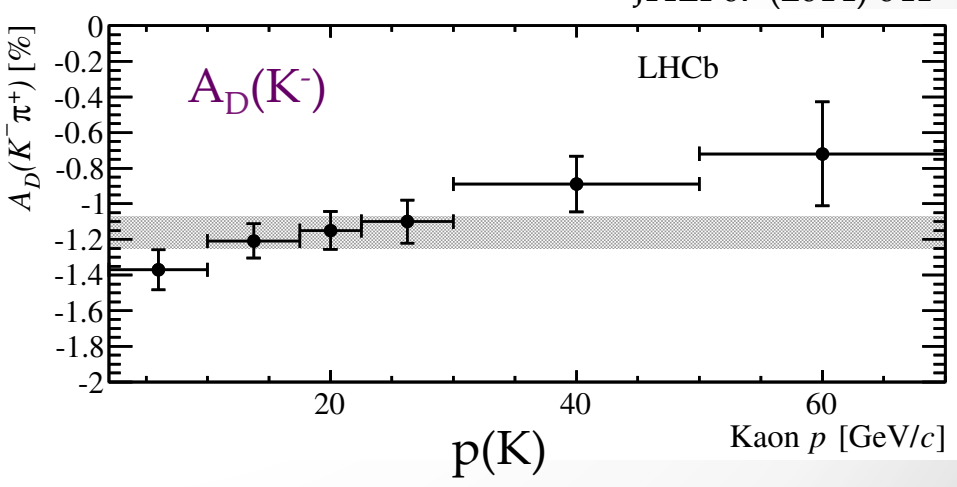
Detection asymmetries (K^+ vs K^-, π^+ vs π^-)

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

PLB 718 (2013) 902



JHEP07 (2014) 041

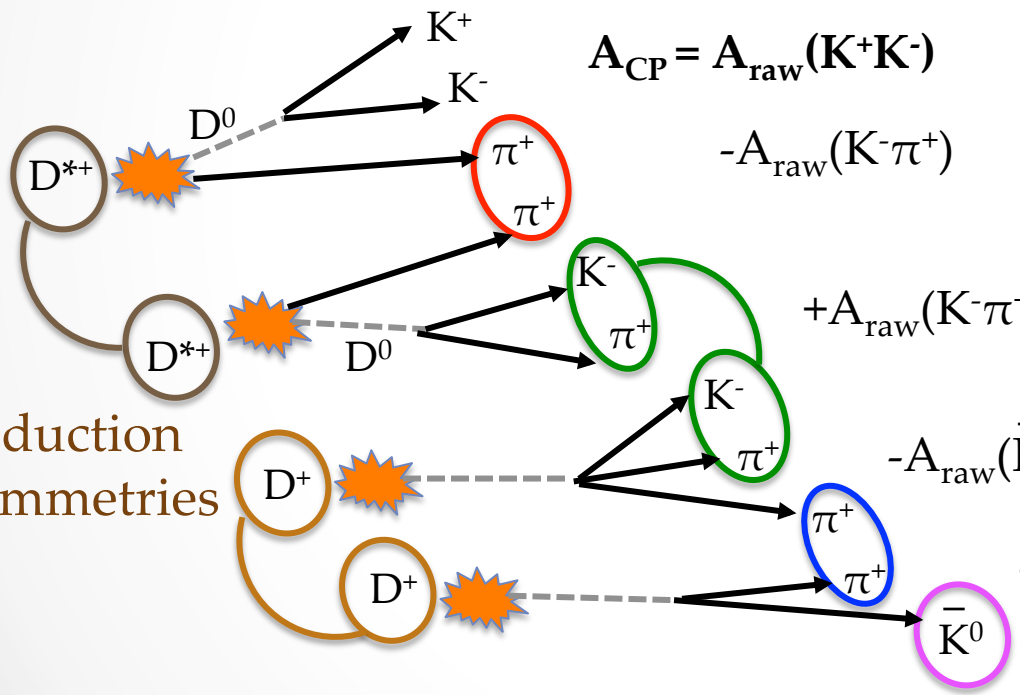


From raw asymmetry to CP asymmetry

Correct with CF control modes

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

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



$A_{CP} = A_{raw}(K^+K^-)$

$-A_{raw}(K^-\pi^+)$

$+A_{raw}(K^-\pi^+\pi^+)$

$-A_{raw}(\bar{K}^0\pi^+)$

$+A(\bar{K}^0)$

Production asymmetries

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

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

- Assume no CPV in CF or include related uncertainty?

Most precise
Very important

A_{CP} in 2-body SCS decays

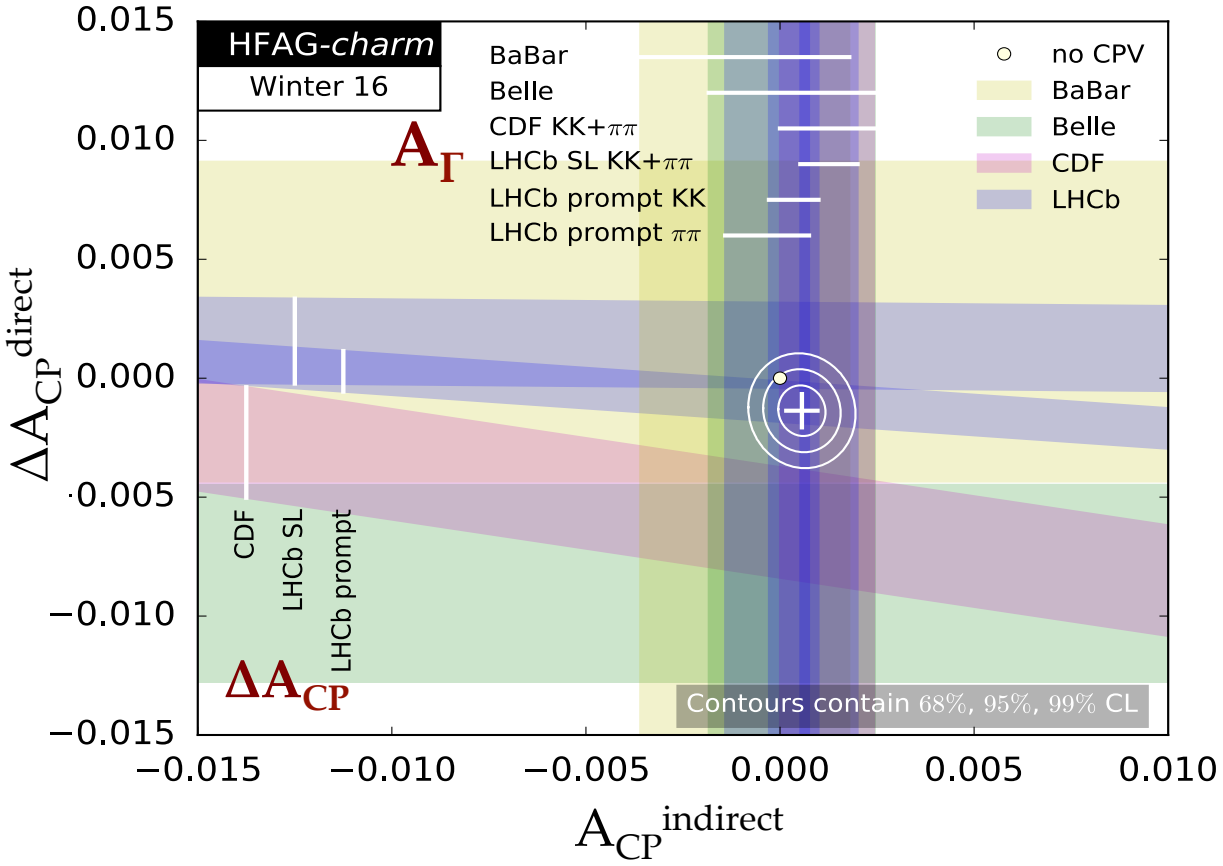
	LHCb	Belle	BaBar	BESIII
Mode		A_{CP} [%]		
$D^0 \to K^+K^-$	+0.04 ± 0.12 ± 0.10	-0.32 ± 0.21 ± 0.09	+0.00 ± 0.34 ± 0.13	
$D^0 \to \pi^+\pi^-$	+0.07 ± 0.14 ± 0.11	+0.55 ± 0.36 ± 0.09	-0.24 ± 0.52 ± 0.22	
$D^0 \to K_sK_s$	-2.9 ± 5.2 ± 2.2	+0.00 ± 1.53 ± 0.17		
$D^0 \to \pi^0\pi^0$		-0.03 ± 0.64 ± 0.10		
$D^0 \to K_s\eta$		+0.54 ± 0.51 ± 0.16		
$D^0 \to K_s\eta'$		+0.98 ± 0.67 ± 0.14		
$D^+ \to K_sK^+$	+0.03 ± 0.17 ± 0.14	+0.08 ± 0.28 ± 0.14	+0.46 ± 0.36 ± 0.25	-1.5 ± 2.8 ± 1.6
$D^+ \to K_LK^+$				-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

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

- Sensitive & simple $\Delta A_{CP} \simeq \left[A_{CP}^{\text{direct}}(KK) - A_{CP}^{\text{direct}}(\pi\pi)\right] + \frac{\Delta\langle t\rangle}{\tau_D} A_{CP}^{\text{indirect}}$
- In SM: $|\Delta A_{CP}{}^{\text{direct}}| \leq 0.6\%$
- HFAG average

$$\Delta A_{CP}^{direct} = (-0.14 \pm 0.07)\%$$
$$A_{CP}^{indirect} = (0.06 \pm 0.04)\%$$



Prospects for direct CPV searches

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

- Will improve by 6÷7 times with LHCb 50/fb or Belle2 50/ab
- Important Belle(2) 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:

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

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

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

Explore charm baryons

- Nothing published yet!
- 1st evidence for CPV in baryons (in $\Lambda_b \to p3\pi$) arXiv:1609:05216

PLB 728 (2014) 585

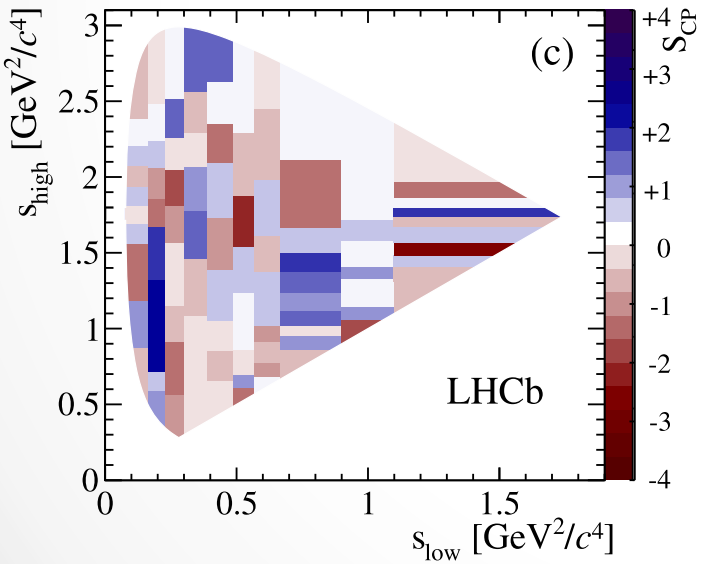
PLB 740 (2015) 158

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)

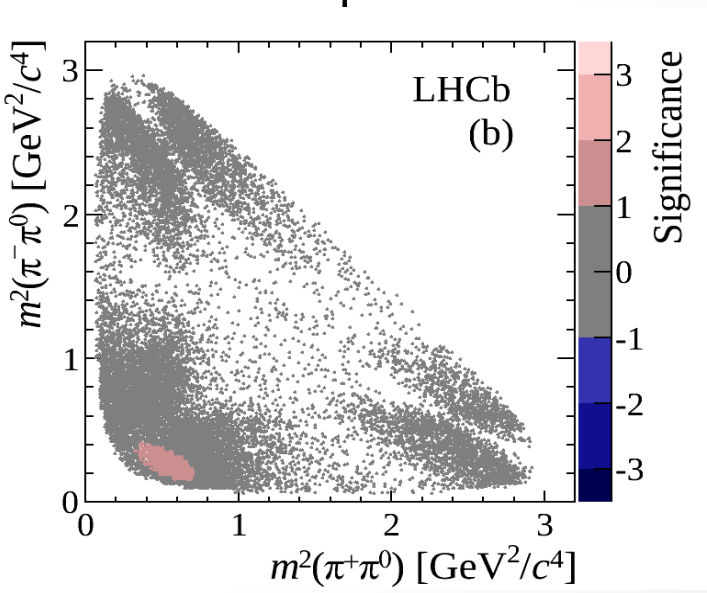
$\mathbf{D^+ \to \pi^+\pi^+\pi^-}$ p-value = 50÷100%



Significance of asymmetry in Dalitz bins

unbinned (Energy Test)

$\mathbf{D^0 \to \pi^+\pi^-\pi^0}$ 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}~sin$\Delta\phi_{weak}$ **sin$\Delta\phi_{strong}$**
  P-odd ampl: A_{CP}~sin$\Delta\phi_{weak}$ **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
$D^+ \to K_SK^+\pi^+\pi^-$	$-12 \pm 10 \pm 5$	Babar	PRD84 031103(2011)

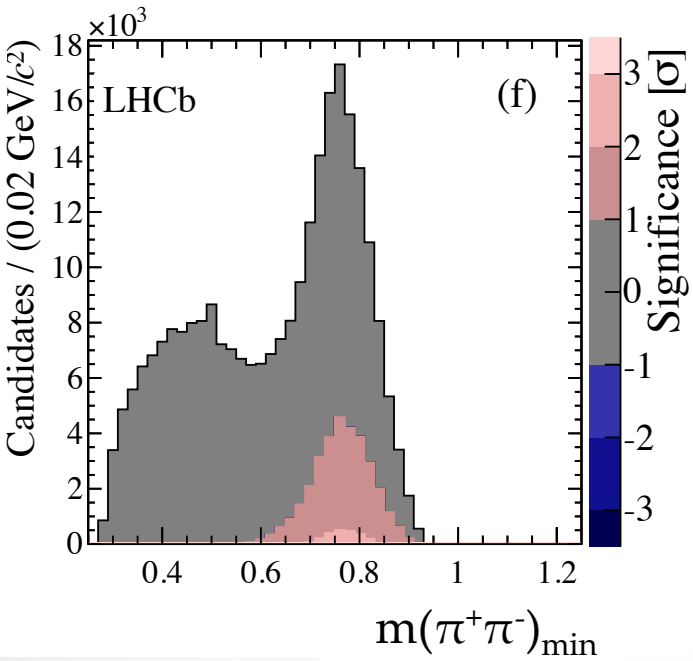
Triple product:
$C_T \equiv \vec{p}_1 \cdot \left(\vec{p}_2 \times \vec{p}_3\right)$

arXiv:1612.03207
accepted by PLB

Direct CPV in 4-body decays

- $D^0 \to \pi^+\pi^- \pi^+\pi^-$: P-even & P-odd CPV tested separately
- Separated with D flavour & triple-product sign
- Testing hypothesis of no-CPV with Energy Test

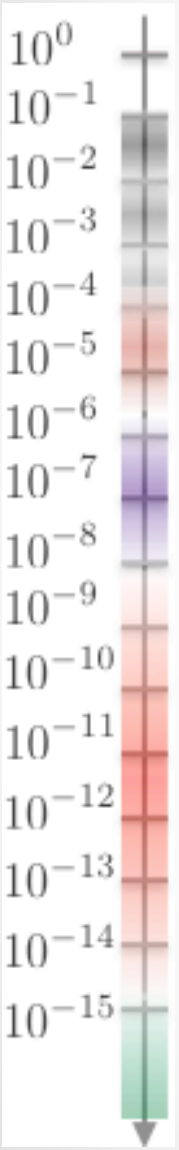
- No-CPV in P-even: p-value~5%
- No-CPV P-odd: p-value~0.6% ⇨ **significance of CPV: 2.7σ**



- Region of increased asymmetry significance points to $\rho^0 \to \pi^+\pi^-$
- P-odd: $D^0 \to \rho^0\rho^0$ in P-wave (~6%)

Rare decays

Spectrum of charm decays

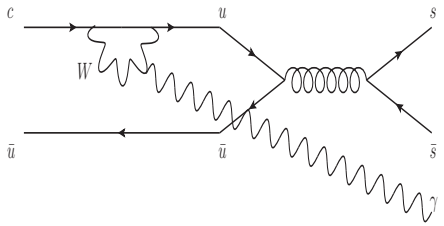


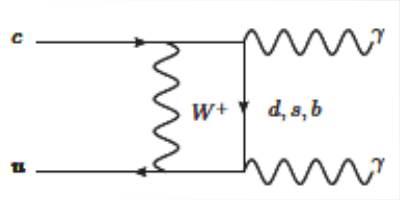
Cabibbo favoured

Singly Cabibbo suppressed

Doubly Cabibbo suppressed

Radiative $D \to K^{*}\gamma,\ \phi\gamma,\ \varrho\gamma$





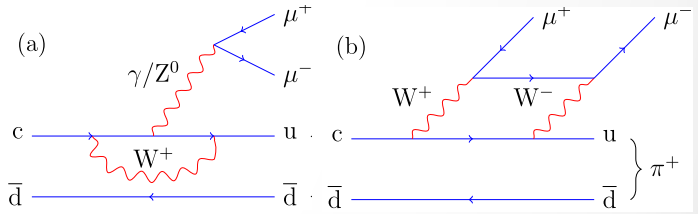
Vector-Meson Dominance $D \to hh' V(\to l^{+}l^{-})$

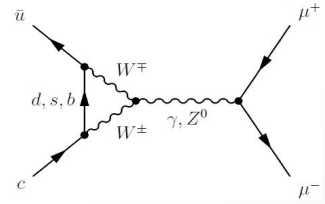
$D \to \gamma\gamma$

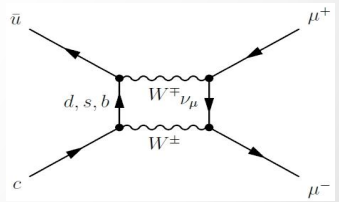
Flavour Changing $D \to hl^{+}l^{-}$ $D \to hh'l^{+}l^{-}$

Neutral Current

$D \to e^{+}e^{-}$ $D \to \mu^{+}\mu^{-}$







Lepton Number Violating

Lepton Flavour Violating

$D \to e\mu$

$D \to he\mu$ $D \to hl^{+}l^{+}$

Precision down to $O(10^{-8})$

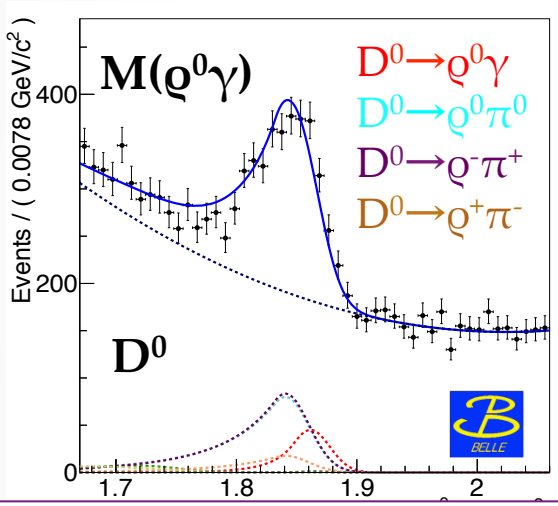
Status of rare charm decays

Decay	Note	SM predict.	BF or best UL	Exp.
$D^0 \to K^*\gamma$	Radiative	$\sim 10^{-4}$	$(4.7 \pm 0.2 \pm 0.2) \times 10^{-4}$	Belle
$D^0 \to \varphi\gamma$	" "	$\sim 10^{-5}$	$(2.8 \pm 0.2 \pm 0.1) \times 10^{-5}$	Belle
$D^0 \to \varrho\gamma$	" "	$\sim 10^{-6}$	$(1.8 \pm 0.3 \pm 0.1) \times 10^{-5}$	Belle
$D^0 \to \gamma\gamma$	" "	$(1 \div 3) \times 10^{-8}$	$< 8.5 \times 10^{-7}$	Belle
$D^+ \to \pi^+\mu^+\mu^-$	FCNC, $\mu\mu$ non-resonant	$\sim 10^{-9}$	$< 8.3 \times 10^{-8}$	LHCb
$D_s^+ \to \pi^+\mu^+\mu^-$	" "	$\sim 10^{-9}$	$< 4.8 \times 10^{-7}$	LHCb
$D^+ \to \pi^+/K^+ e^+e^-$	FCNC, full e^+e^- spectrum	$10^{-8} \div 10^{-6}$	$< 0.3 / 1.2 \times 10^{-6}$	BESIII
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	FCNC, $\mu\mu$ non-resonant	$\sim 10^{-9}$	$< 7.4 \times 10^{-7}$	LHCb
$D^0 \to \mu^+\mu^-$	FCNC	$10^{-13} \div 10^{-12}$	$< 7.6 \times 10^{-9}$	LHCb
$D^0 \to e^+e^-$	FCNC	$10^{-13} \div 10^{-12}$	$< 7.9 \times 10^{-8}$	Belle
$D^0 \to \upsilon\bar{\upsilon}$	Helicity suppressed	$\sim 10^{-30}$	$< 8.8 \times 10^{-5}$	Belle
$D^0 \to e^+\mu^-$	Lepton Flavour Violating	0	$< 1.6 \times 10^{-8}$	LHCb
$D^+ \to \pi^-\mu^+\mu^+$	Lepton Number Violating	0	$< 2.5 \times 10^{-8}$	LHCb
$D_s^+ \to \pi^-\mu^+\mu^+$	" "	0	$< 1.4 \times 10^{-7}$	LHCb
$D^+ \to \pi^-/K^- e^+e^+$	" "	0	$< 1.2 / 0.6 \times 10^{-6}$	BESIII

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

Decays with photon(s)

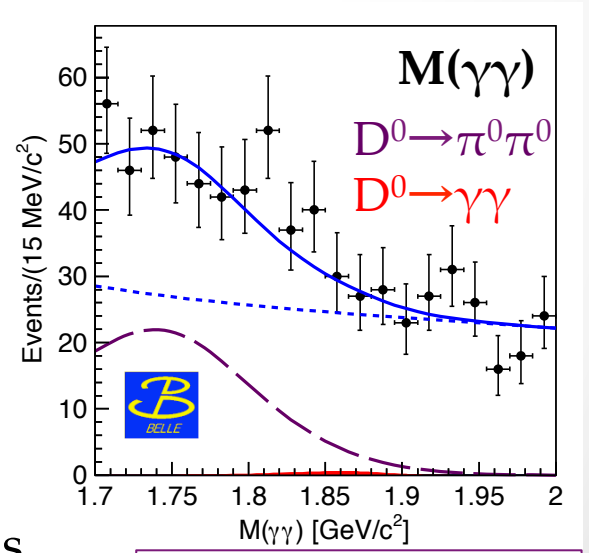
- Theory problem: LongDistance ~ 10^3 × ShortDistance
- NP probes: A_{CP}, γ polarisation (t-dep. analysis or polarised $\Lambda_c \to p\gamma$)
- Experimental problem: π^0 background



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

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

No CPV



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

- 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, $\gamma \to e^+e^-$ conversions
- LHCb upgrade: improved ECAL(?)

Decays with leptons: hot topic in B

- Trendy $K\mu\mu$
- Searches for $D_{(s)}^{+}\to K/\pi\, l^+l^-$
- Any good $q^2=m^2(l^+l^-)$ range?
  Tails from charmonia?
- Remember about $\Lambda_c\to p l^+l^-$

- Testing LFU in charm?

✗ $D\to h l^+l^-$, $hh l^+l^-$ too rare

? Tauonic decays

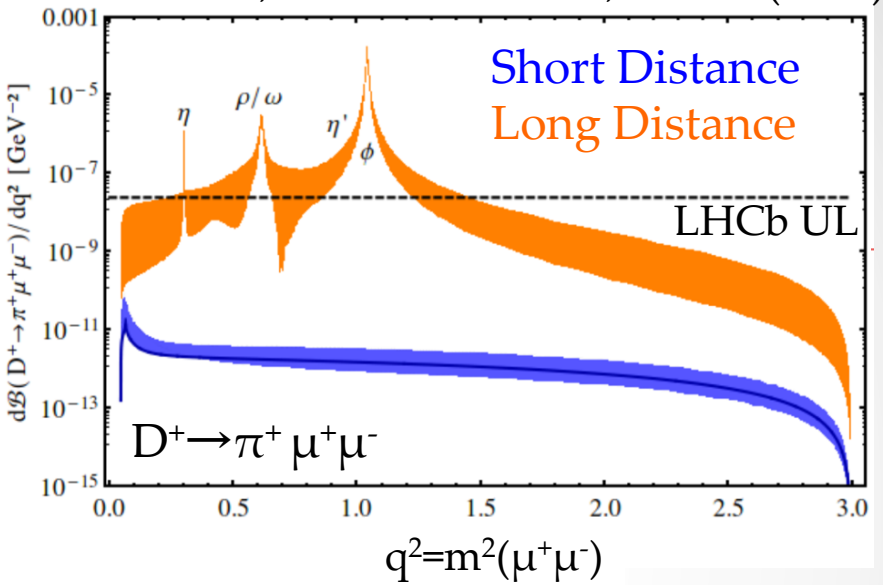
$$\frac{BF\left(D_s^+\to\tau\nu\right)}{BF\left(D_s^+\to\mu\nu\right)}=9.95\pm0.57$$

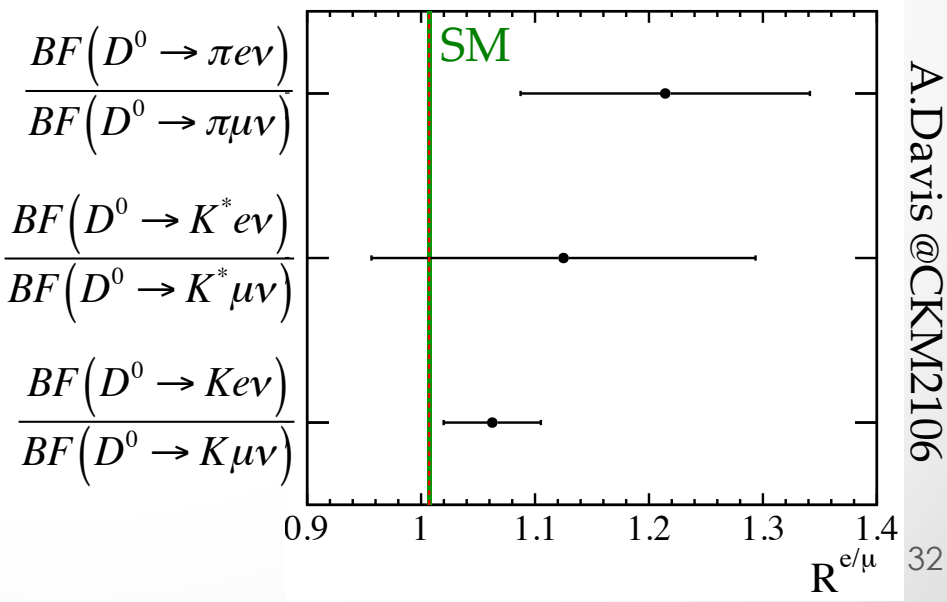
SM: 9.76 ± 0.03

✓ Semileptonic decays

- LHCb & electrons = troubles
  Belle2 input needed

S.de Boer, G.Hiller PRD 93, 074001(2016)





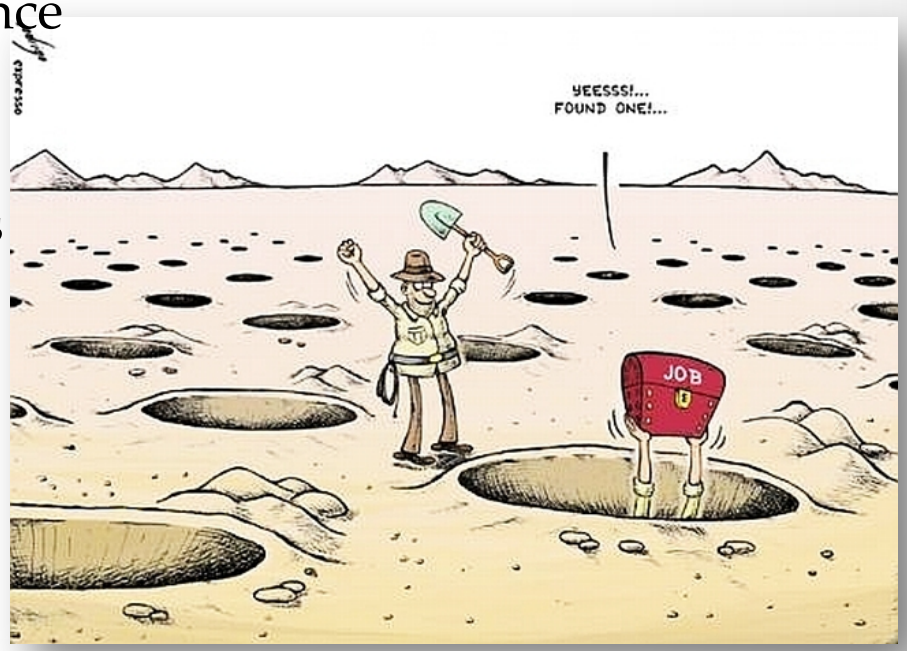
Summary

- Still analyzing LHCb Run-1 data
- Increasing precision on x&y mixing parameters
- x still not measured well
- Indirect CPV searches with precision down to 10^{-4}

- Huge effort in searching for CPV in charm decays
- Sensitivity up to 10^{-3}, still no evidence
- How small can be CPV in SM?

- Searching for signals in rare decays
- Precision down to 10^{-8}

- Charm needs
  BelleII & LHCb upgrade

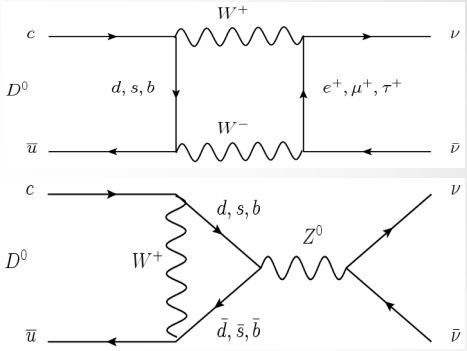


Backups

-

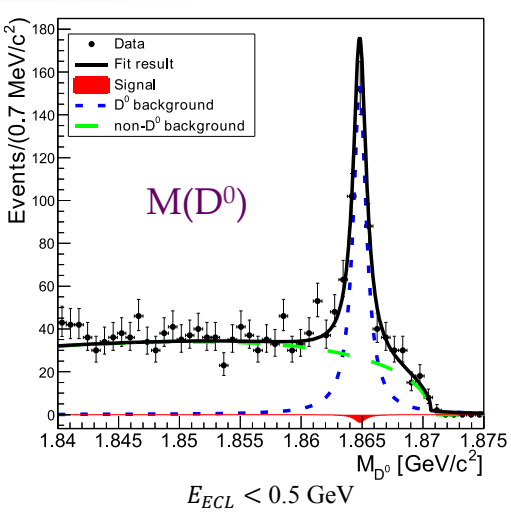
Belle-CONF-16xx

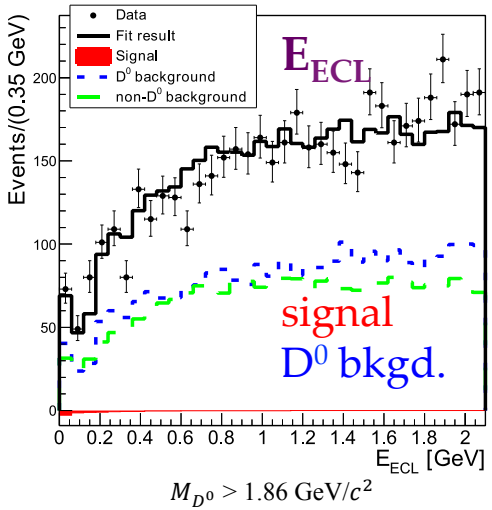
$D^0 \to \nu\underline{\nu}$ (a.k.a invisible)

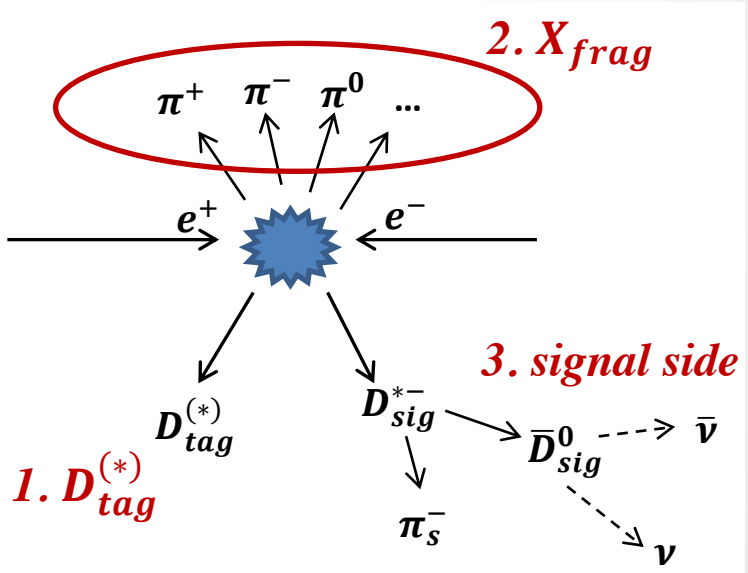


- Helicity suppression by $(m_\nu/m_D)^2$ ⇨ BF~10^{-30}
- With light Dark Matter up to ~10^{-15}

- Reconstruct event fully except for D^0 signal
- D^0 signal in a recoil mass ⇨ inclusive D^0
- Require no extra particles and study residual energy in calorimeter ⇨ exclusive D^0







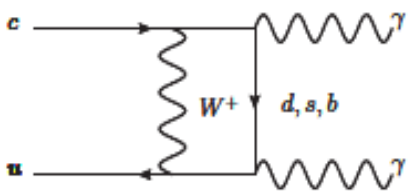
$\mathcal{B}(D^0 \to \text{invisible}) < 8.8 \times 10^{-5}$ at 90% C.L. First search!

PRD 93, 051102 (2016)

$D^0 \to \gamma\gamma$

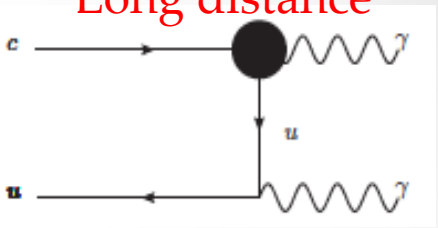
- BF within SM ~10^{-8}
- With SUSY up to ~6×10^{-6}

Short distance



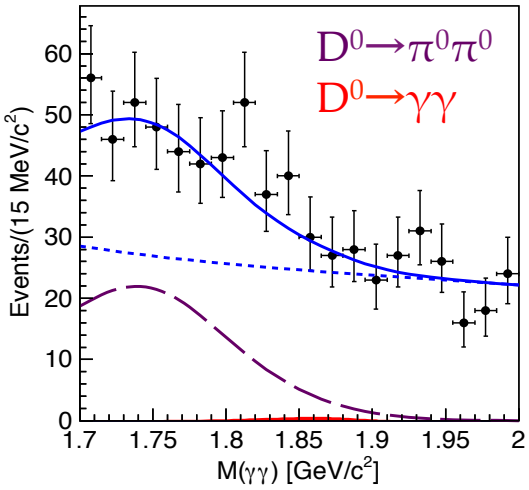
$\mathcal{B}_{SD} \simeq (4-8)\times10^{-12}$

Long distance

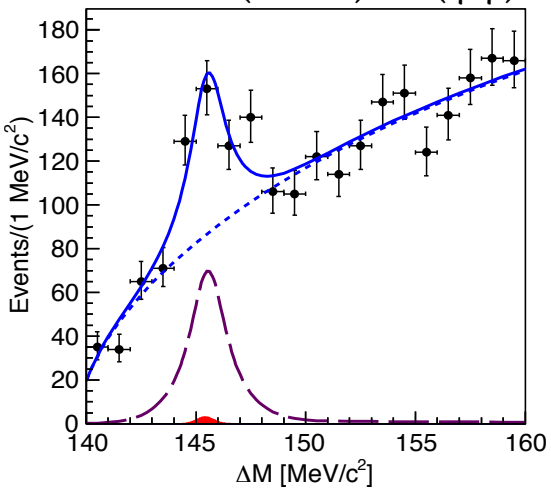


$\mathcal{B}_{LD} \simeq (1-3)\times10^{-8}$

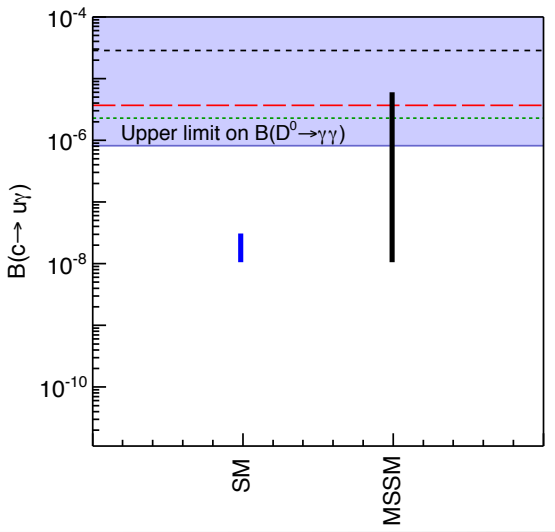
M(γγ)



ΔM=M($D^0\pi^+$)-M(γγ)



$\mathcal{B}(D^0 \to \gamma\gamma) < 8.5\times10^{-7}$ @ 90%C.L.



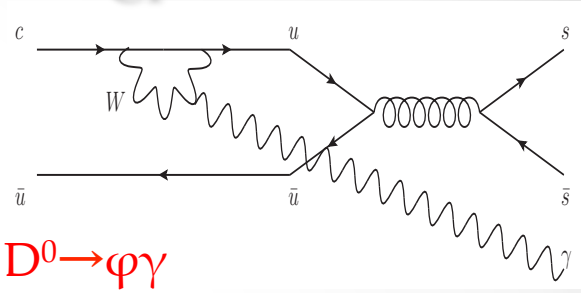
Cleo
BESIII
BaBar
Belle

- Most restrictive limit so far

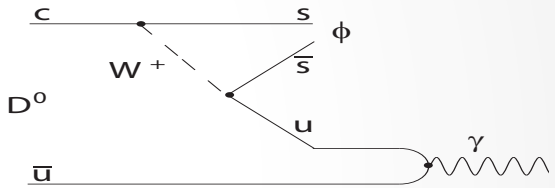
PRL118, 051801 (2017)

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

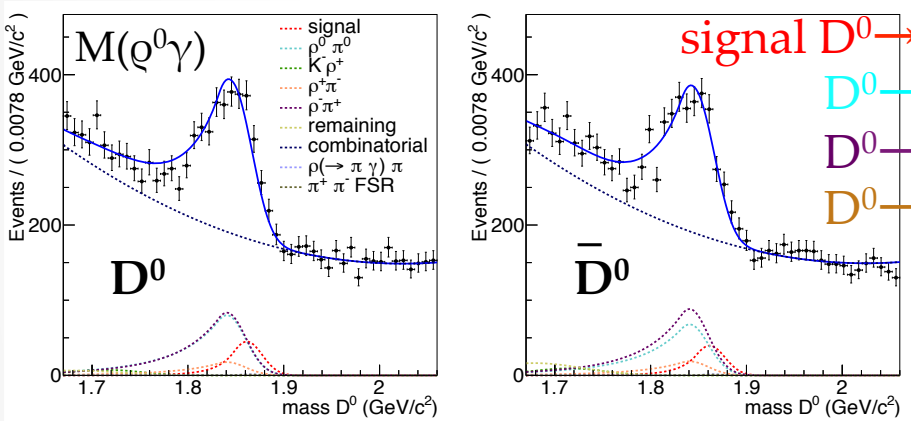
- BF's poorly measured. No CPV analysis before
- Large CPV within SM, up to a few %
- First observation of $D^0 \to \varrho(770)\gamma$

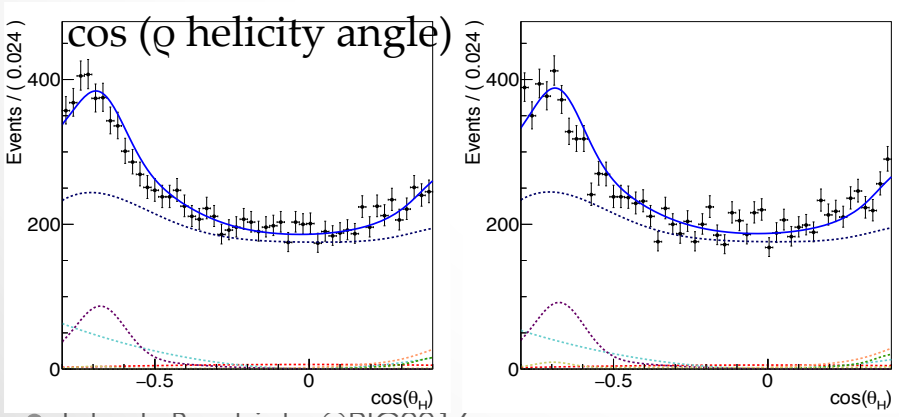


$D^0 \to \varphi\gamma$
Short distance contribution



Long distance via Vector Meson Dominance





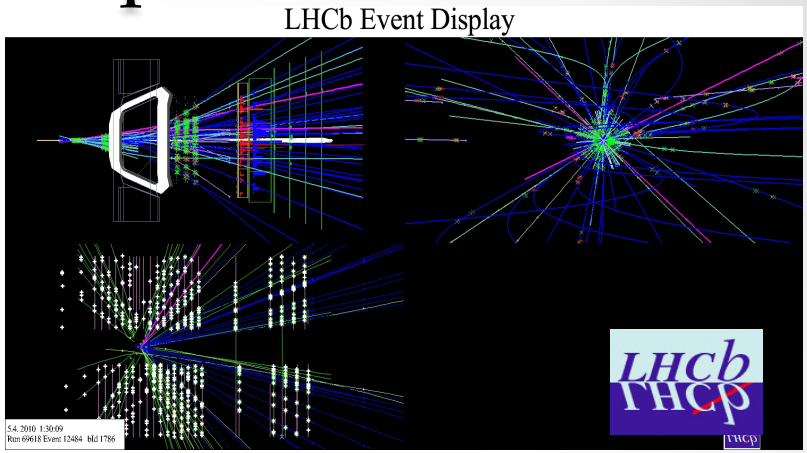
$$\mathcal{B}(D^0 \to \overline{K}^{*0}\gamma) = (4.66 \pm 0.21 \pm 0.18) \times 10^{-4}$$
$$\mathcal{B}(D^0 \to \phi\gamma) = (2.76 \pm 0.20 \pm 0.08) \times 10^{-5}$$
$$\mathcal{B}(D^0 \to \rho^0\gamma) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5}$$

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

No CPV

Pros & cons of charm experiments

- **LHCb**



☑ large x-section

☒ busy environment, nontrivial triggers

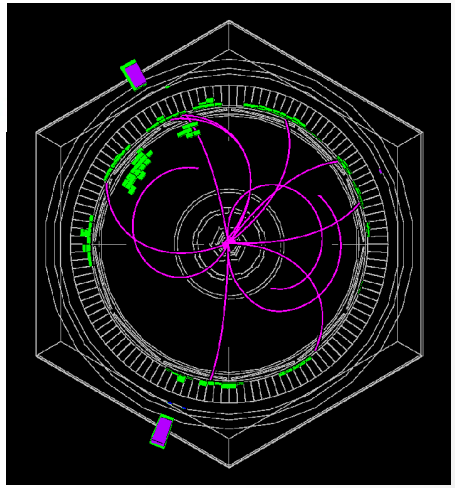
☒ decays with γ's and neutrinos difficult

☑ D flight distance~10mm, $\sigma(t)\sim 0.1\times\tau_D$

☑ magnet polarity reversed periodically

☒ asymmetric production of charm/anti-charm

- **Belle/BaBar**



☑ clean environment

☑ good for neutrals & decays with neutrinos

☐ D flight distance~200μm, $\sigma(t)\sim 0.5\times\tau_D$

- **BESIII/Cleo-c**

☑ background-free charm

☒ charm not boosted ⇨ no time measurement

☑ $\psi(3770)\rightarrow D\bar{D}$ quantum coherence ⇨ $CP(D)\times CP(\bar{D})=-1$

LHCb changes & will change more

- **LHCb Run-1** (2010-2012) Collected 3 fb^{-1}

  Finalizing charm analyses. Still more to come

- **LHCb Run-2** (2015-2018) Collect 5 fb^{-1} (2 fb^{-1} already collected)

  Improved triggers & computing. First results (charm x-section)

- **LHCb Run-3, Run-4** (2021-2023, 2026-2029)

  Major New Experiment: LHCb Upgrade Phase-I

  Collect >50 fb^{-1} data

  L ~$2x10^{33}$ cm^{-2} s^{-1}

- **LHCb Run-5** (2031-)

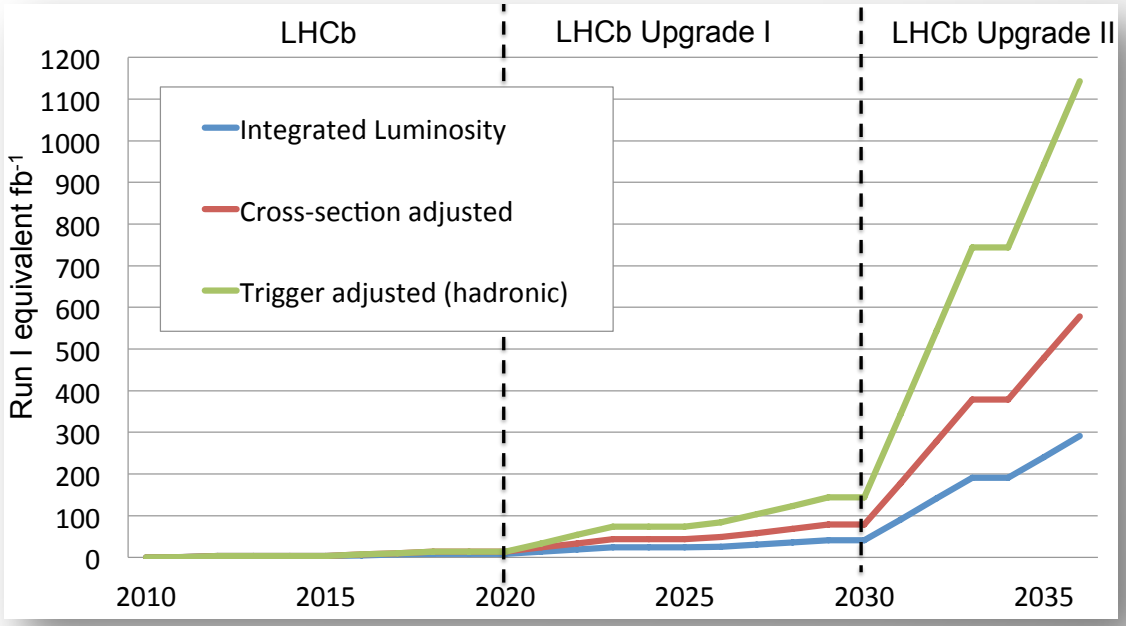
  LHCb Upgrade Phase-II

  Plans in discussion

  Collect ~300 fb^{-1} data

  L ~$2x10^{34}$ cm^{-2} s^{-1}

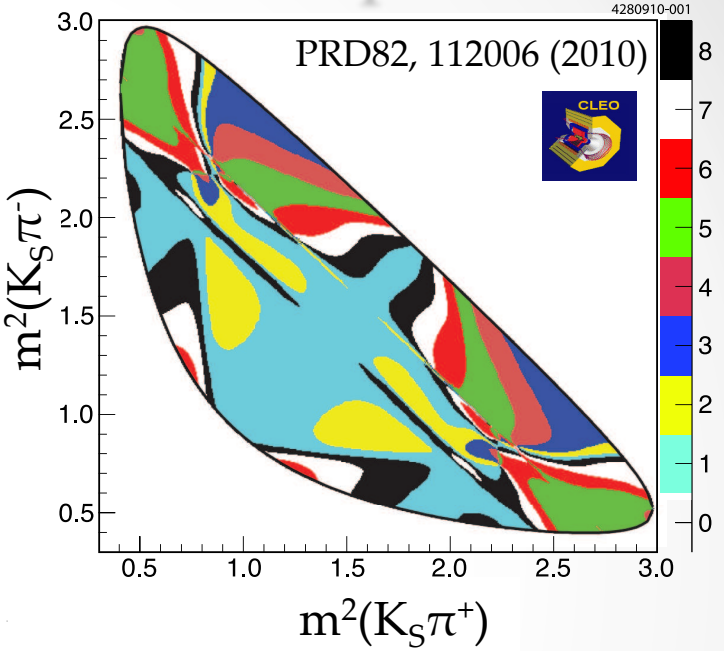
C.Parkes@Charm2016

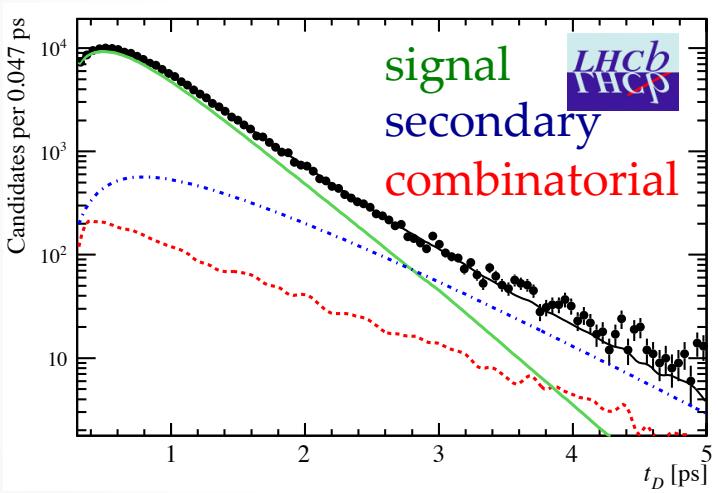


JHEP 04, 033 (2016)

$D^0 \to K_S \pi\pi$, 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

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

PRD89 091103 (2014)

arXiv:1610.09476

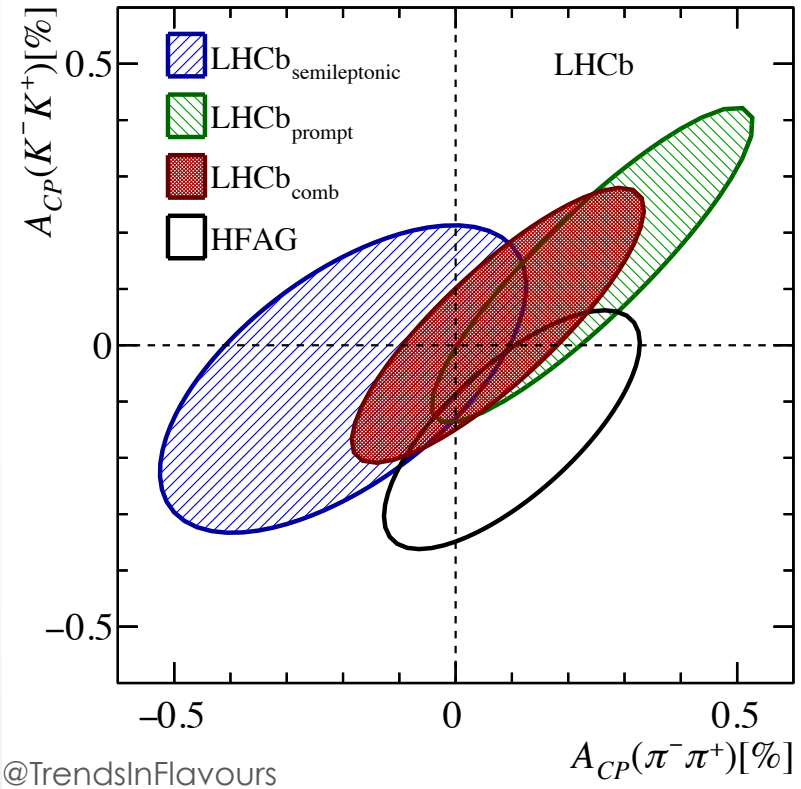
$A_{CP}(D^0 \to K^+K^-)$ & $A_{CP}(D^0 \to \pi^+\pi^-)$

- 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

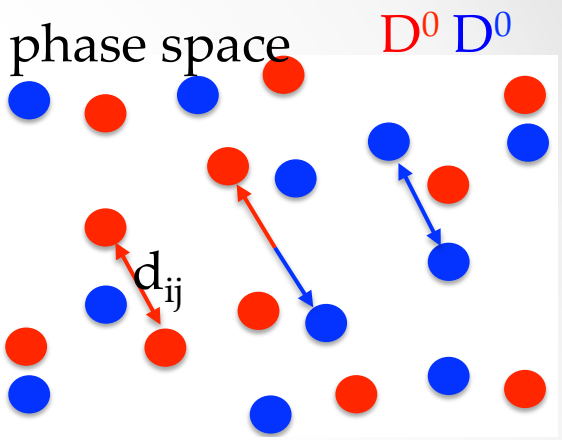
- Both A_{CP}'s consistent with zero

arXiv:1612.03207

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

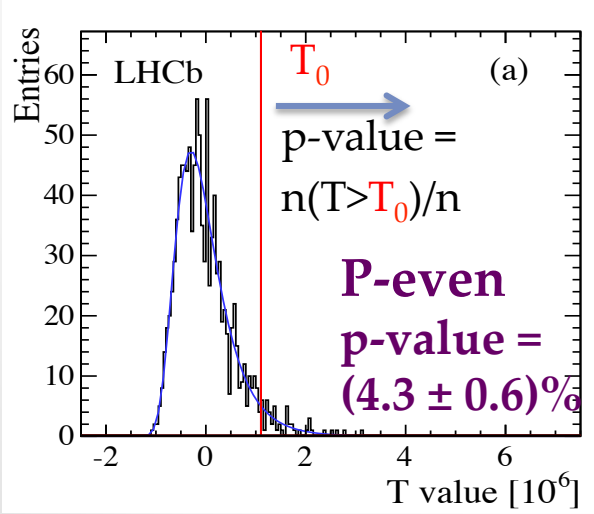
- Statistical comparison of two distributions
- Test statistics: based on distances of event pairs
- Compare with T distribution for no CPV case (randomize D flavour)

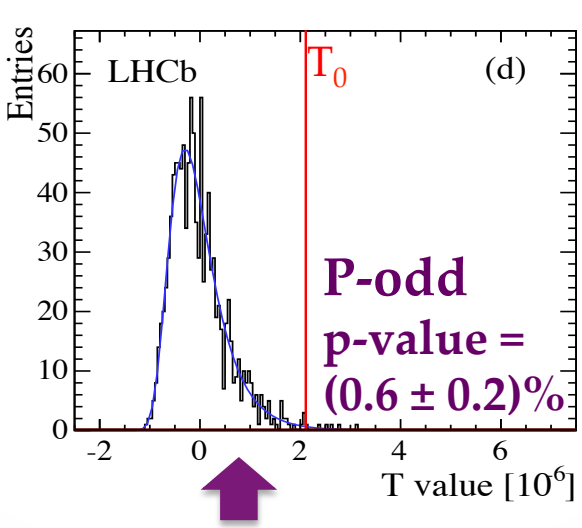
- 5-dim phase space: $m^2(\pi\pi)$, $m^2(\pi\pi\pi)$ ⇨**P-even**
- Use triple-product sign to access **P-odd** CPV



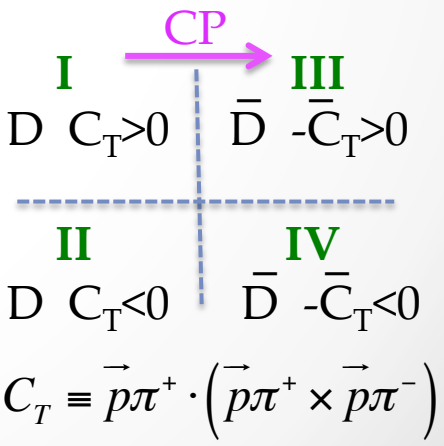
$$T = \langle d_{ij} \rangle_{DD} + \langle d_{ij} \rangle_{\bar{D}\bar{D}} - \langle d_{ij} \rangle_{D\bar{D}}$$

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





Marginally consistent with no CPV (~2.7σ)



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

Direct CPV with Belle2

Marko Staric, CKM 2014:

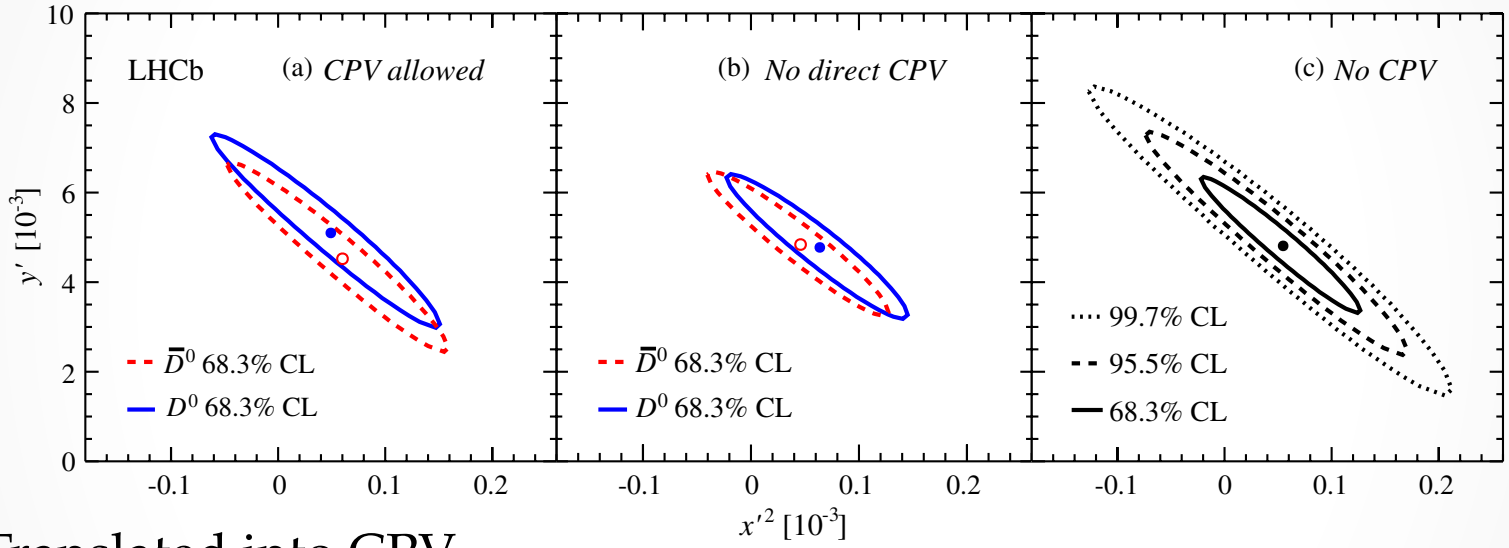
$$\sigma_{\text{Belle II}} = \sqrt{(\sigma^2_{\text{stat}} + \sigma^2_{\text{syst}}) \cdot \frac{\mathcal{L}_{\text{Belle}}}{50\ \text{ab}^{-1}} + \sigma^2_{\text{irred}}}$$

mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K^0_S\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.03
$D^0 \to K^0_S\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K^0_S\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K^0_S\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03
$D^+ \to K^0_S K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D^+_s \to K^0_S\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D^+_s \to K^0_S K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

PRL 111, 251801 (2013)

CPV from WS/RS $D^0 \to K\pi$

- Prompt sample, Run-1
- 2-dim confidence regions for measured x'^2 and y'



- Translated into CPV

$$A_{CP}^{direct} = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.7 \pm 1.9)\%$$

$$x^{\pm\prime} = \left|\frac{q}{p}\right|^{\pm 1}(x' \cos\phi \pm y' \sin\phi)$$

$$y^{\pm\prime} = \left|\frac{q}{p}\right|^{\pm 1}(y' \cos\phi \mp x' \sin\phi)$$

$$0.75 < |q/p| < 1.24 \ @68\% \ CL$$

WS/RS $D^0 \to K3\pi$

- Constrain x&y from WA
- Get averaged strong phase & coherence factor