Mixing, CP Violation and Rare Decays

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PIC2016, Quy Nhon, September 2016

Outline

- Mixing, CPV and Rare Decays
  Why important and challenging?

- Why is charm special?
- Where and how is charm studied?

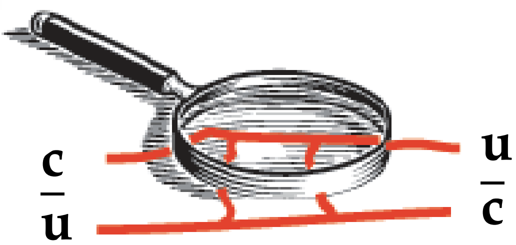
- Mixing and CPV: introduction & news
- Rare Decays: status so far & news

- Summary

Why rare processes are important?

- Test Standard Model ⇨ Find physics beyond SM ⇨ Identify it

- New Physics is a correction to SM
- Promising processes: wherever SM suppressed or forbidden
- Loop processes: new particles (off-shell) may be in the loops



- D^0-$\bar{D}^0$ mixing occurs via box diagram
- CP Violation 'needs' penguin contribution
- Rare decays by definition proceed via loop diagrams

Why is charm special?

- Complementary to strange and beauty sectors
- Unique access to system with up-type quarks
- Down-type quarks in loops: different New Particles?

- But…
- In SM rare processes are very suppressed
- QCD corrections are large (usually disadvantageous)

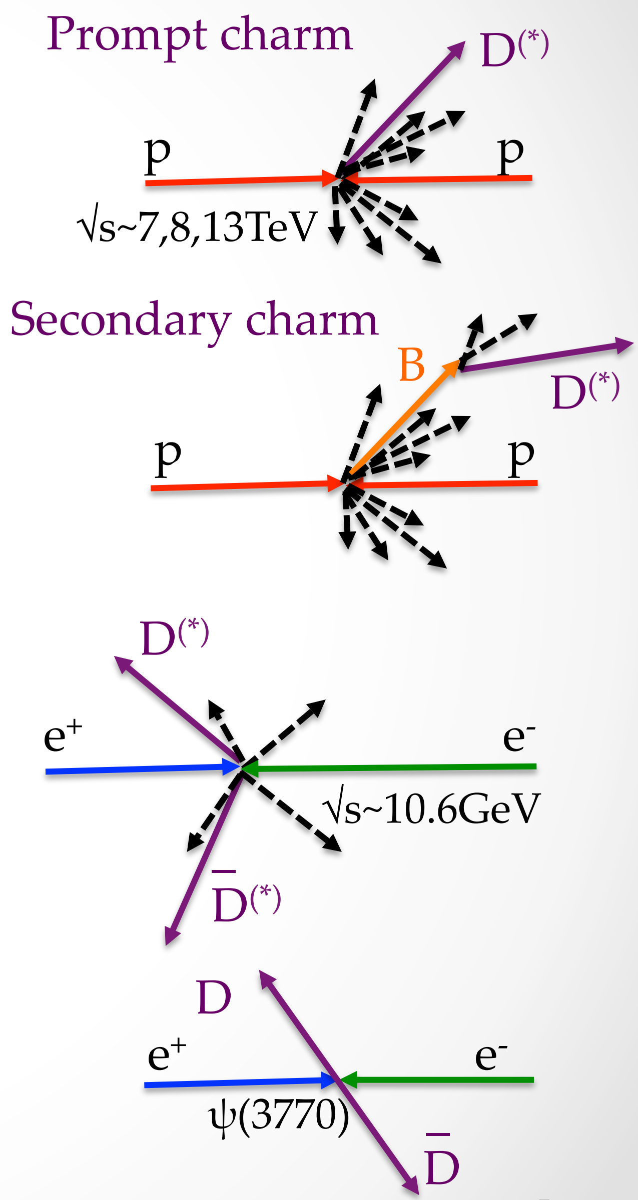
- Thus we need
- Large/clean data samples
- Precise estimation of SM contribution (penguin size)

"Everything is smaller in charm"

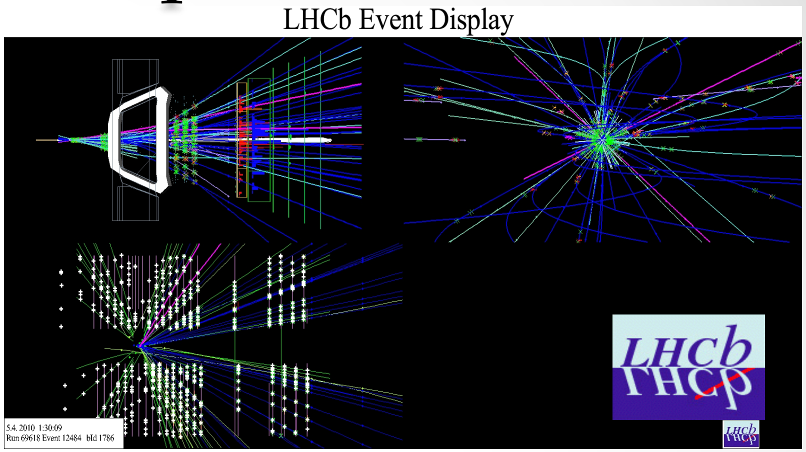
Mat Charles at CKM2014

Charm samples

type	exp	$\sqrt{s}$	L_{int}	$\sigma(c\bar{c})$	$N(c\bar{c})$
hadron colliders				prompt $c\bar{c}$	
	LHCb	7, 8 TeV	3/fb	1.4 mb	3.6×10^{12}
		13 TeV	1.3/fb +	2.6 mb	2.9×10^{12}
	CDF	2 TeV	10/fb	0.1 mb	2.3×10^{11}
e^+e^- colliders	B-Factories			$c\bar{c}$ from continuum	
	Belle	10.6 GeV	1000/fb	1.3 nb	1.3×10^{9}
	BaBar		550/fb		0.7×10^{9}
	Charm Factories @$D\bar{D}$ threshold				
	BESIII	3.7 GeV	3/fb	3 nb	20×10^{6}
	Cleo-c		0.8/fb		5×10^{6}



Pros and cons of charm experiments



- **LHCb**

☒ busy environment

☒ decays with γ's and neutrinos difficult

☑ D flight distance~10mm, $\sigma(t)\sim0.1\times\tau_{D0}$

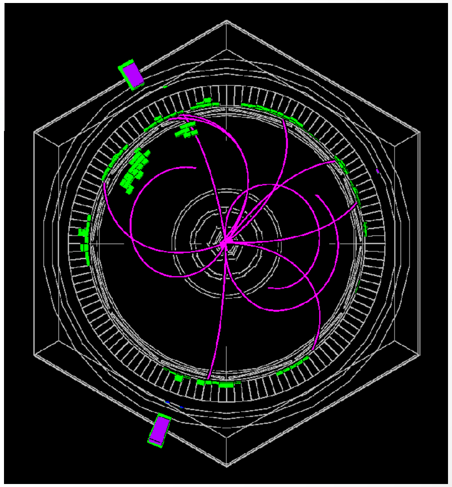
☑ magnet polarity reversed periodically

- **Belle/Babar**

☑ clean environment

☑ good for neutrals & decays with neutrinos

☐ D flight distance~200μm, $\sigma(t)\sim0.5\times\tau_{D0}$



- **BESIII/Cleo-c**

☑ background-free charm

☒ charm not boosted ⇨ no time measurement

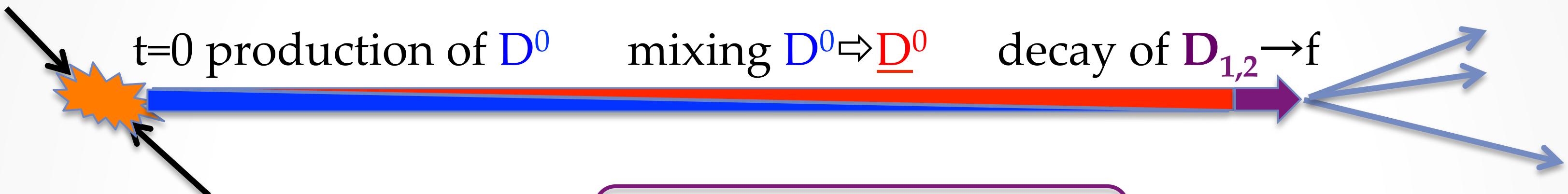
☑ $\psi(3770)\to D\underline{D}$ quantum coherence ⇨ $CP(D)\times CP(\underline{D})=-1$

Mixing and CP Violation

Why neutral mesons mix?

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

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

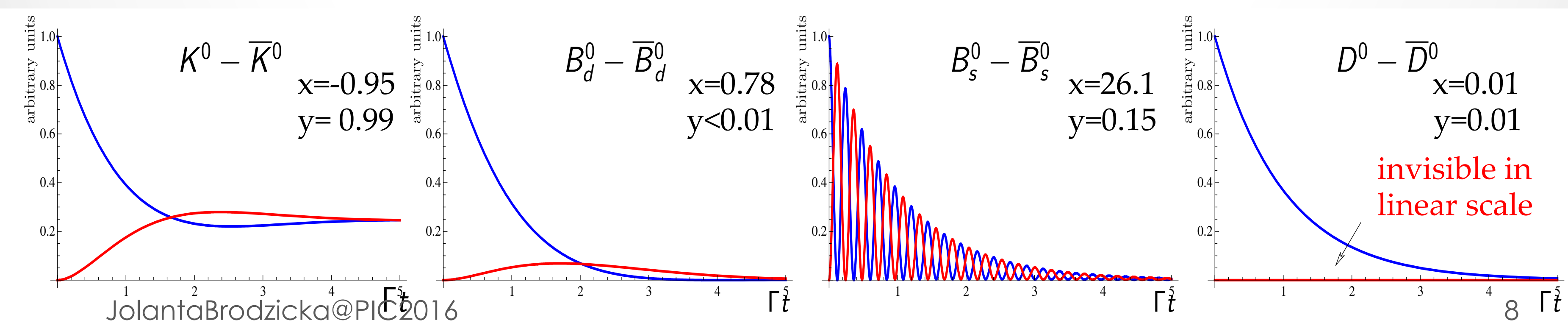


- **x, y** mixing frequencies $x = \frac{m_2 - m_1}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

- Probability that initial flavour unchanged/changed at time t

$$\mathcal{P}[D^0(t) \to D^0] \propto e^{-\Gamma t}\left[\cosh(\mathbf{y}\Gamma t) + \cos(\mathbf{x}\Gamma t)\right] \qquad \mathcal{P}[D^0(t) \to \overline{D}^0] \propto \left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[\cosh(\mathbf{y}\Gamma t) - \cos(\mathbf{x}\Gamma t)\right]$$

- Non-oscillating + oscillating terms in measured decay time

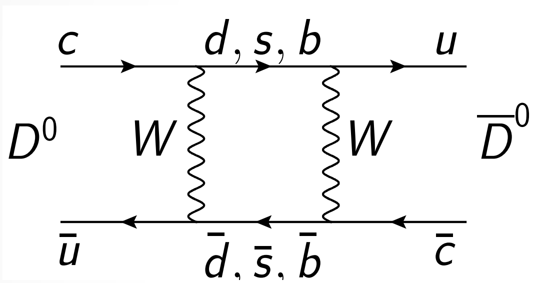


What's behind x & y?

- Standard Model underlying diagrams

Short distance

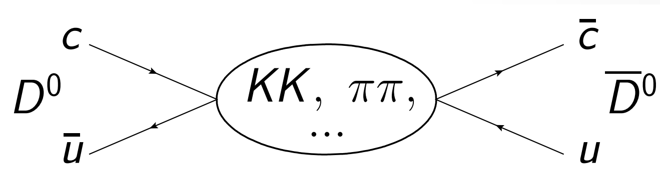
quark-level mixing: box diagram



$x \sim 10^{-5}$

Long distance

mixing via final-state interactions

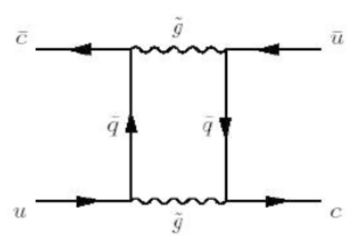


x, y ~ 1%

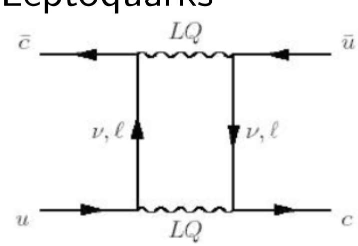
difficult to calculate

- New Physics can increase x

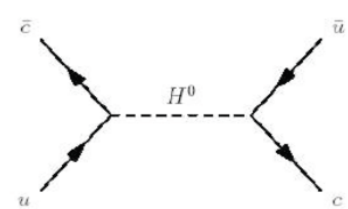
SUSY



Leptoquarks



Extended Higgs

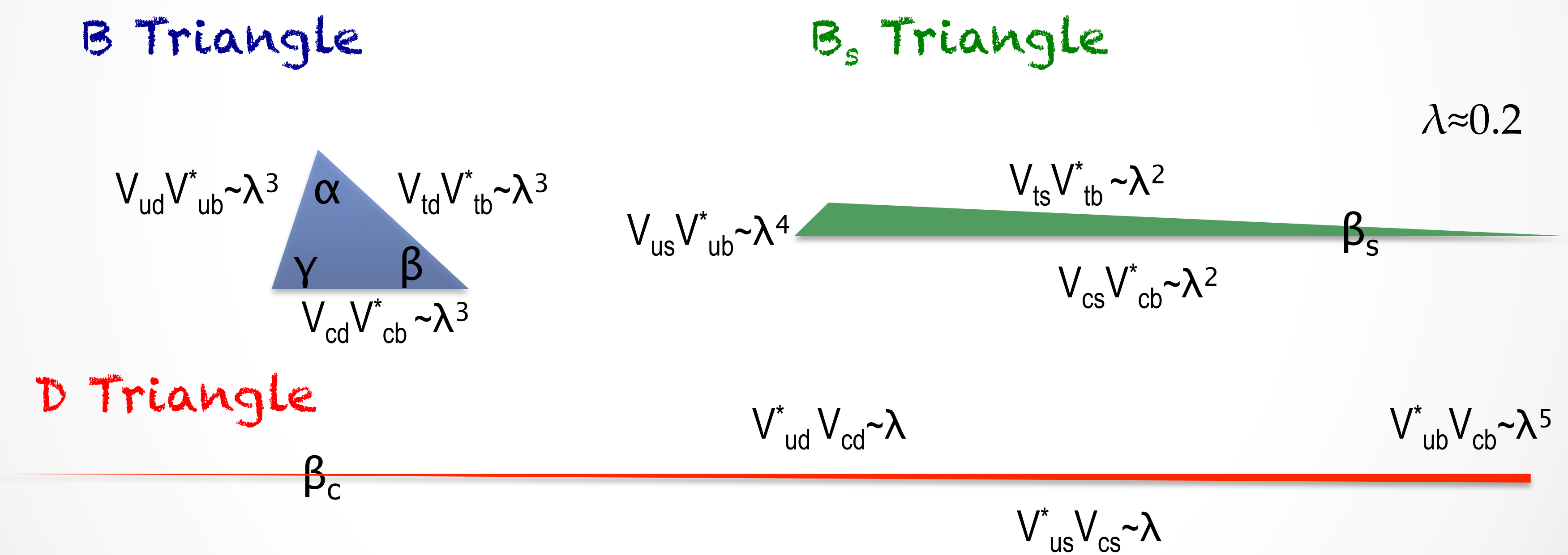


- Large uncertainties in SM mixing rate ⇨ difficult to identify NP

See CPV through Unitarity Triangles

- CPV in SM arises from complex phase in the CKM matrix
- CKM matrix is unitary ⇨ constraints on elements
  ⇨ if elements complex (=CPV) they form triangles

Nobel Prize 2008
Kobayashi & Maskawa



- Triangle openness indicates how large CPV expected
- D triangle ⇨ tiny CPV in preferred decays, larger CPV in rare decays

CP Violation: Types and Observables

direct CPV

In decays $|D \to f|^2 \neq |\bar{D} \to \bar{f}|^2 \Rightarrow |\bar{A}_{\bar{f}}/A_f|^2 \neq 1$

- Difference in rates for particles and antiparticles
- Depends on decay mode

indirect CPV

In mixing $|D^0 \to \bar{D}^0|^2 \neq |\bar{D}^0 \to D^0|^2 \Rightarrow |q/p| \neq 1$

In interference between mixing and decays $|D^0 \to \bar{D}^0 \to f + D^0 \to f|^2 \neq |\bar{D}^0 \to D^0 \to f + \bar{D}^0 \to f|^2$

- Difference in rates as function of D^0 decay-time ⇨ $\phi = \arg(q/p) \neq 0$
- Independent of decay mode
- Final states accessible for both D^0 and $\underline{D}^0$

t-dependent measurements of mixing/CPV

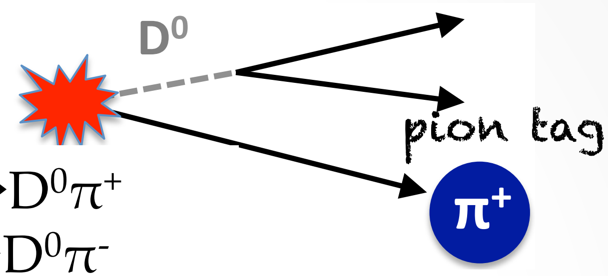
- Mixing and indirect CPV universal: don't depend on decay mode
- Only in D^0 decays

News

- $D^0 \rightarrow K\pi$, LHCb
- $D^0 \rightarrow K\pi\pi\pi$, LHCb
- $D^0 \rightarrow \pi\pi\pi^0$, BaBar
- A_Γ , LHCb

How to get flavour of D^0?

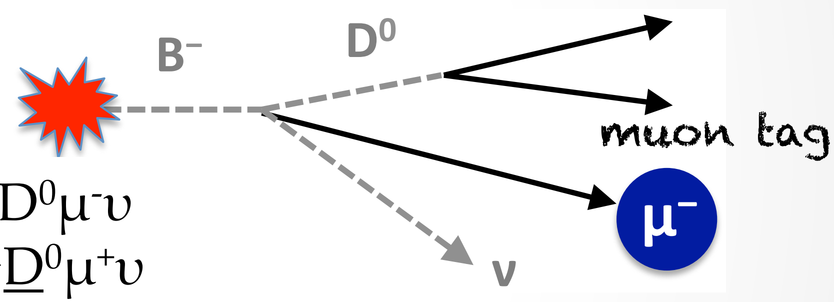
- Tag flavour at the production
  (then mixing changes flavour)



Prompt charm $pp \to D^{*\pm}$

$D^{*+} \to D^0\pi^+$
$D^{*-} \to \underline{D}^0\pi^-$

- D tagged with soft-pion charge



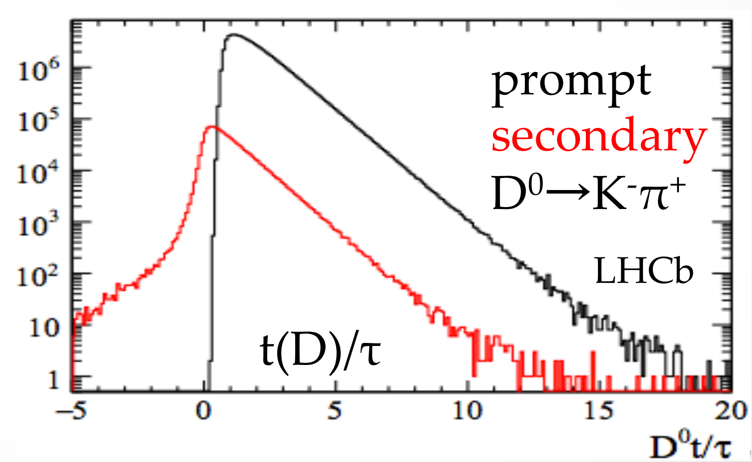
Secondary charm $pp \to B \to D$

$B^- \to D^0\mu^-\upsilon$
$B^+ \to \underline{D}^0\mu^+\upsilon$

- D tagged with muon charge

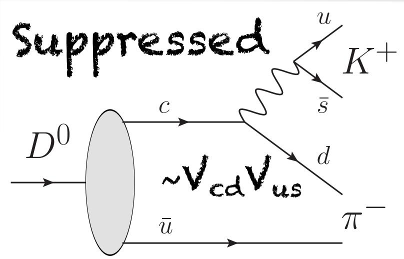
- LHCb uses both samples

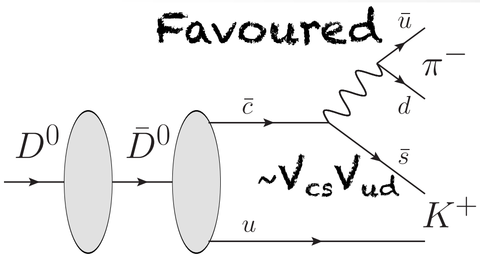
⇨ full coverage of D^0 decay time



Mixing observed in 2013 with $D^0 \to K\pi$

- $D^0 \to K^+\pi^-$ = Wrong-Sign, $D^0 \to K^-\pi^+$ = Right-Sign

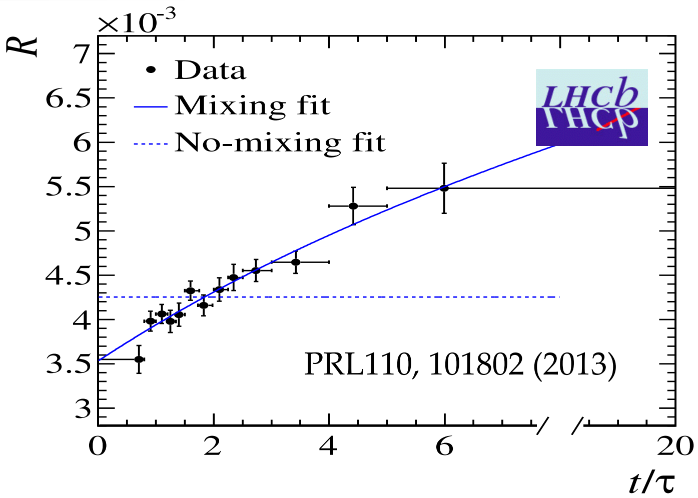


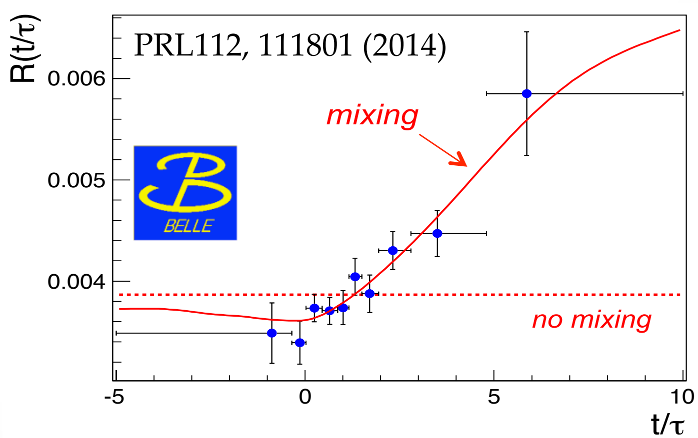


- WS/RS rate as a function of D^0 decay time

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

Decay
Interference Mixing & Decay
Mixing





~1000×τ(D^0) needed to see full oscillation!

Mixing from WS/RS $D^0 \rightarrow K\pi$

- With secondary charm
- WS & RS signal yields in t bins ⇨

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

$$R_D = \frac{BR(Suppressed\ D^0 \rightarrow K\pi)}{BR(Favoured\ D^0 \rightarrow K\pi)}$$

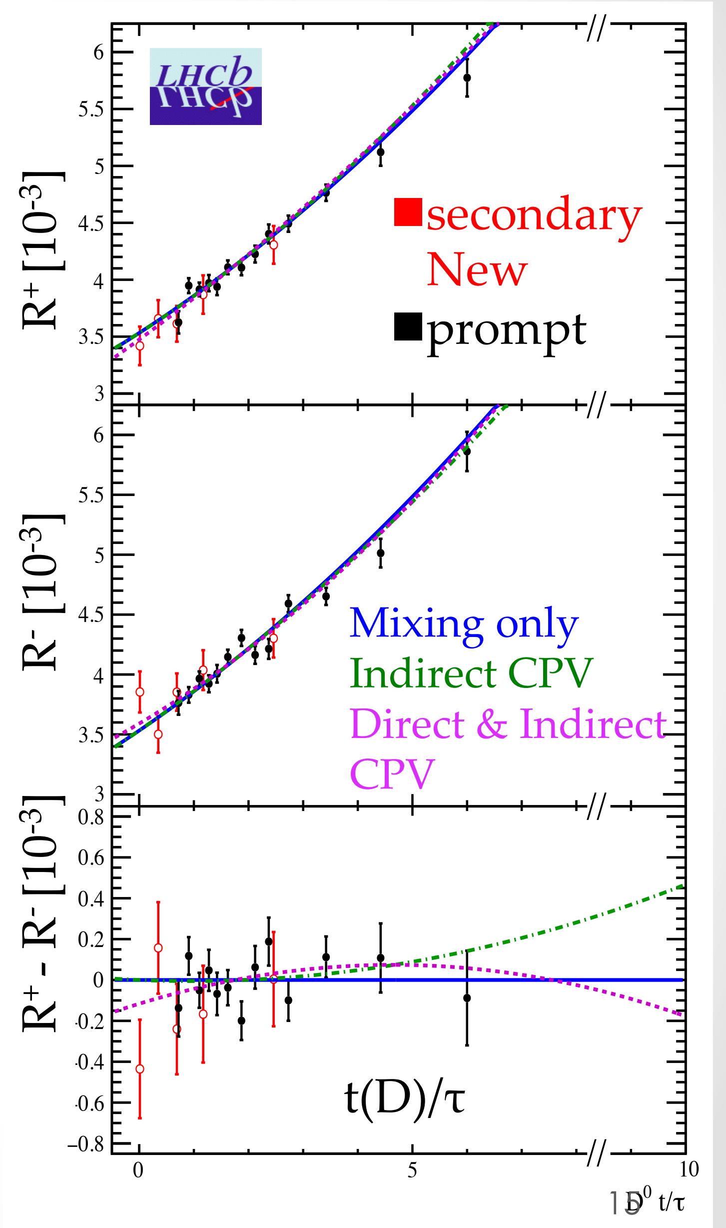
rotated x, y $\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta_{K\pi} & \sin\delta_{K\pi} \\ -\sin\delta_{K\pi} & \cos\delta_{K\pi} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$

- $\delta_{K\pi}$: Fav/Supp strong phase (from Cleo/BES)

- $R^{\pm}(t)$ for D produced as $D^0/\bar{D}^0$ ⇨ $R_D^{\pm}$, $x'^{2\pm}$, $y'^{\pm}$
- CPV if x, y, R_D differ for two flavours

- No evidence for CPV

$$R_D = (3.53 \pm 0.05) \times 10^{-3}$$
$$y' = (5.2 \pm 0.8) \times 10^{-3}$$
$$x'^2 = (3.6 \pm 4.3) \times 10^{-5}$$



PRL116, 241801 (2016)

New mixing with $D^0 \to K\pi\pi\pi$

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

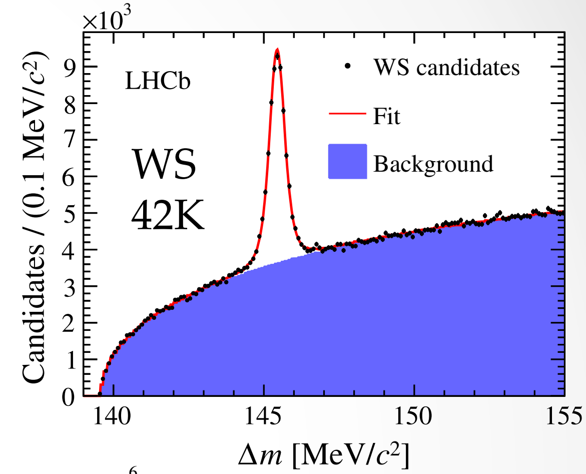
$$R(t) = \frac{N_{WS}}{N_{RS}}(t) \simeq R_D^{K3\pi} + \sqrt{R_D^{K3\pi}}\, R_{coh}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

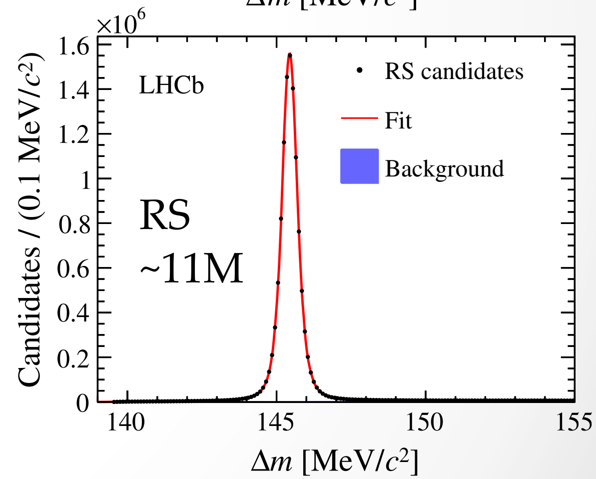
- Integrated over 5D phase space ⇨dilution

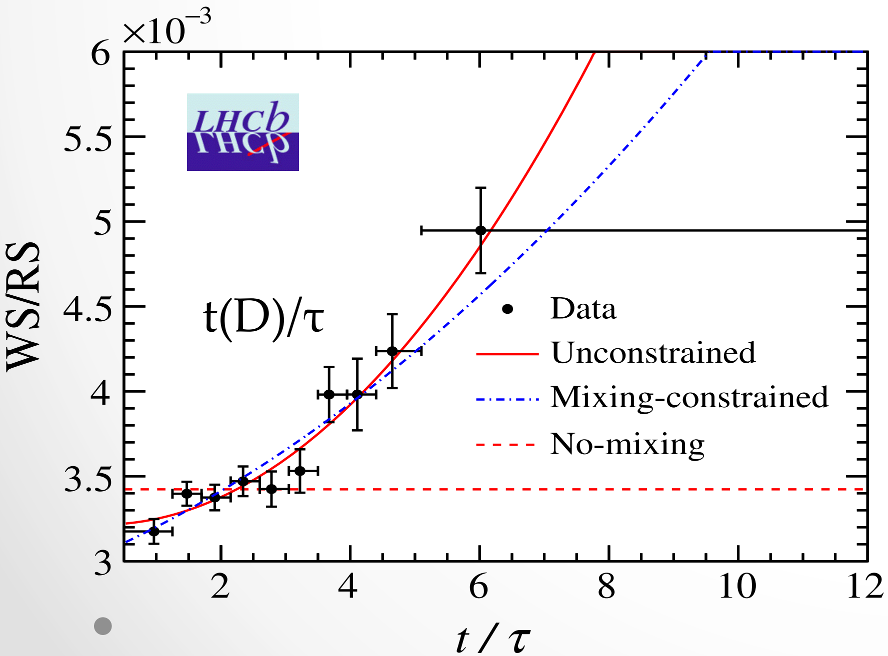
⇨ averaged strong phase and coherence factor

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

Δm=M($D^0\pi^+$)-M(K3π)







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

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

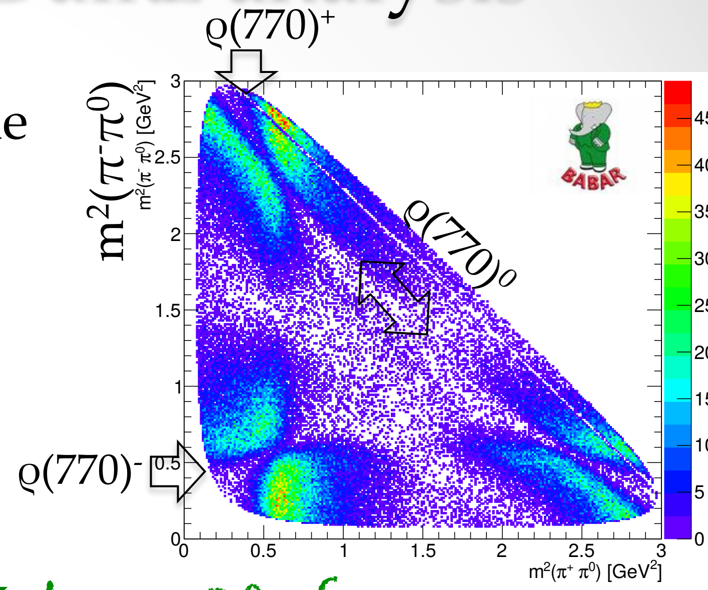
PRD93, 112014 (2016)

$D^0 \to \pi^+\pi^-\pi^0$: t-dependent Dalitz analysis

- Measure how phase-space evolves with time

✗ Need model to describe resonances.
  ρ(770)→ππ dominate

✓ Access to interfering amplitudes and their phases,
  no coherence factor dilution, **direct access to x&y**



$m^2(\pi^+\pi^0)$

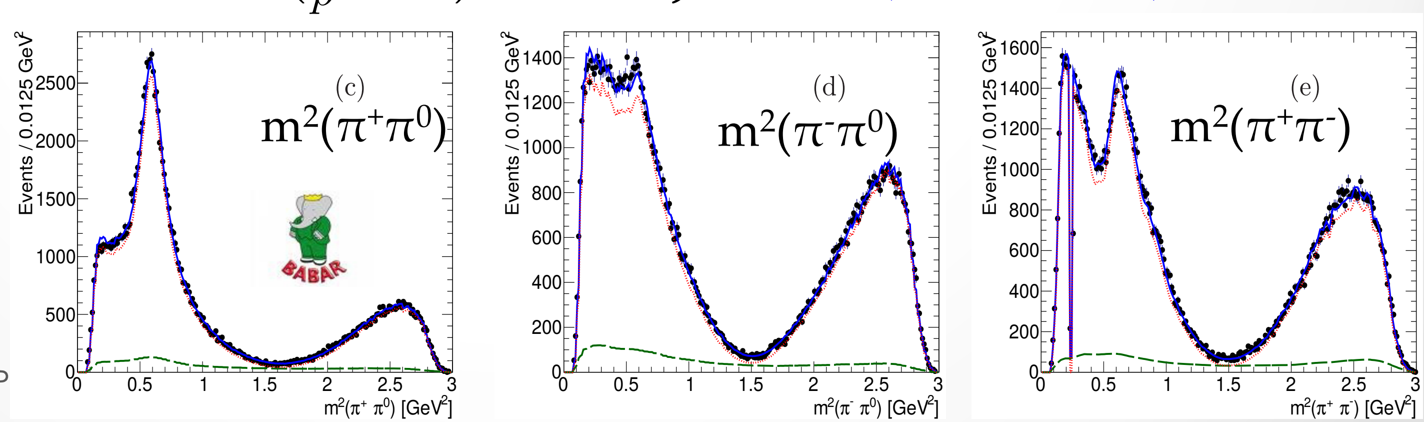
- Rate for D produced at t=0 as D^0

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

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

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

$$x = (1.5 \pm 1.2 \pm 0.6)\%$$
$$y = (0.2 \pm 0.9 \pm 0.5)\%$$



LHCB-CONF-2016-009
LHCB-CONF-2016-010

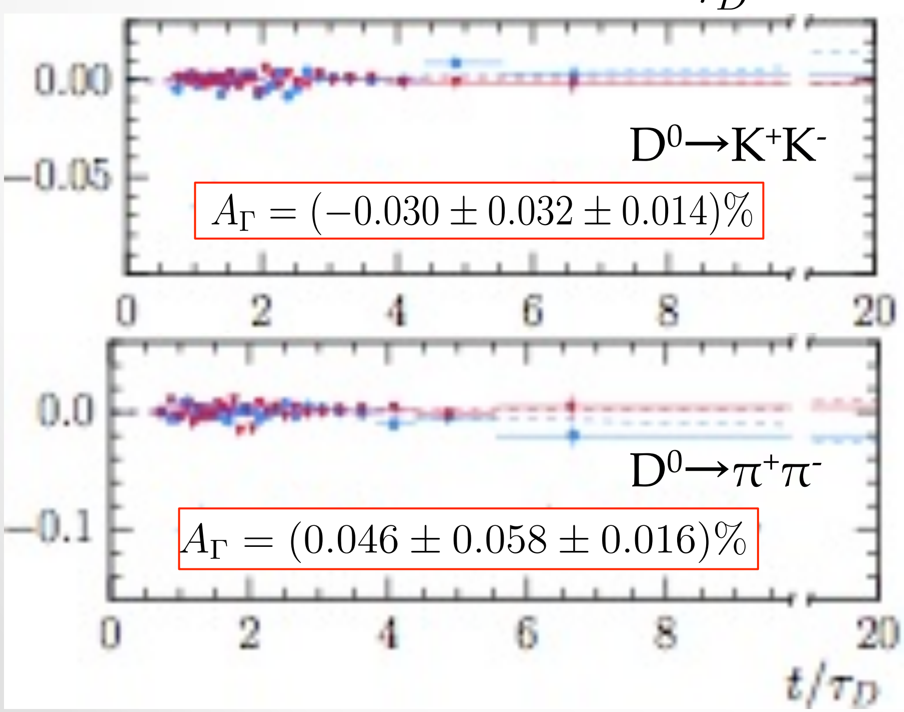
A_Γ: quest for indirect CPV

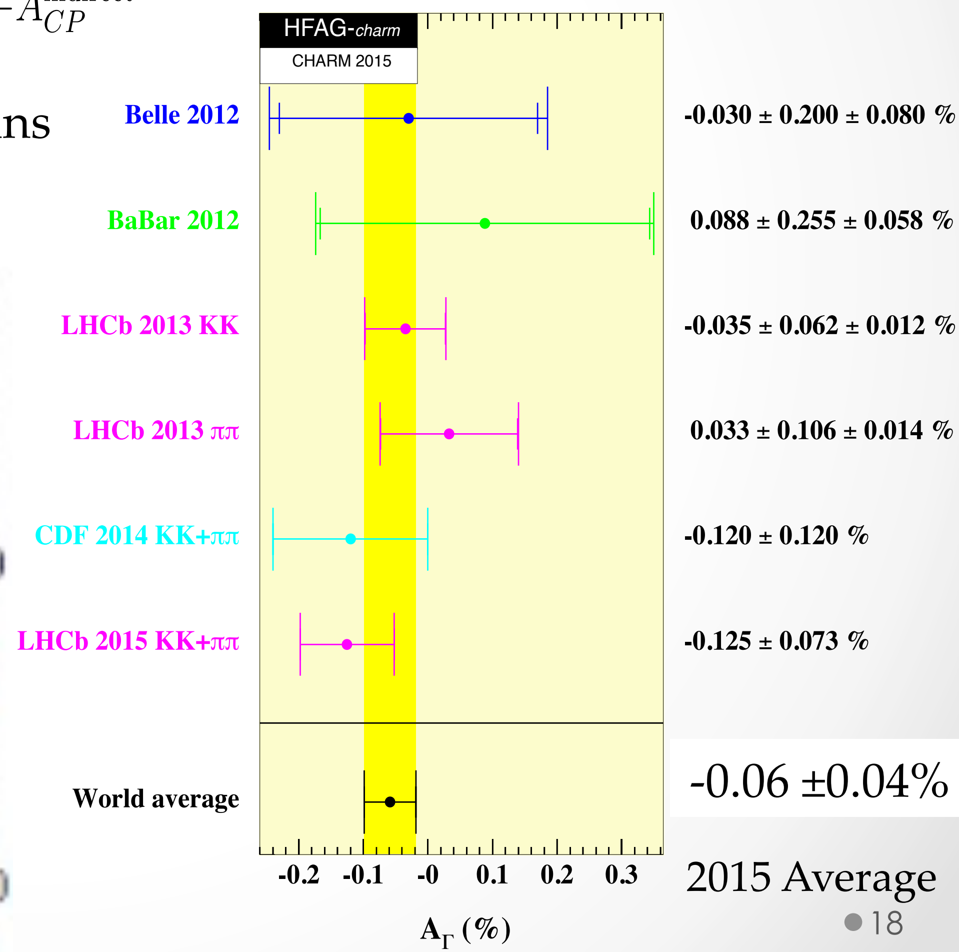
- In SM indirect CPV is small ~10^{-4}
- Easiest via A_Γ = asymmetry of 'effective' lifetimes of CP eigenstates

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

- Binned: asymmetry of yields in t-bins

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



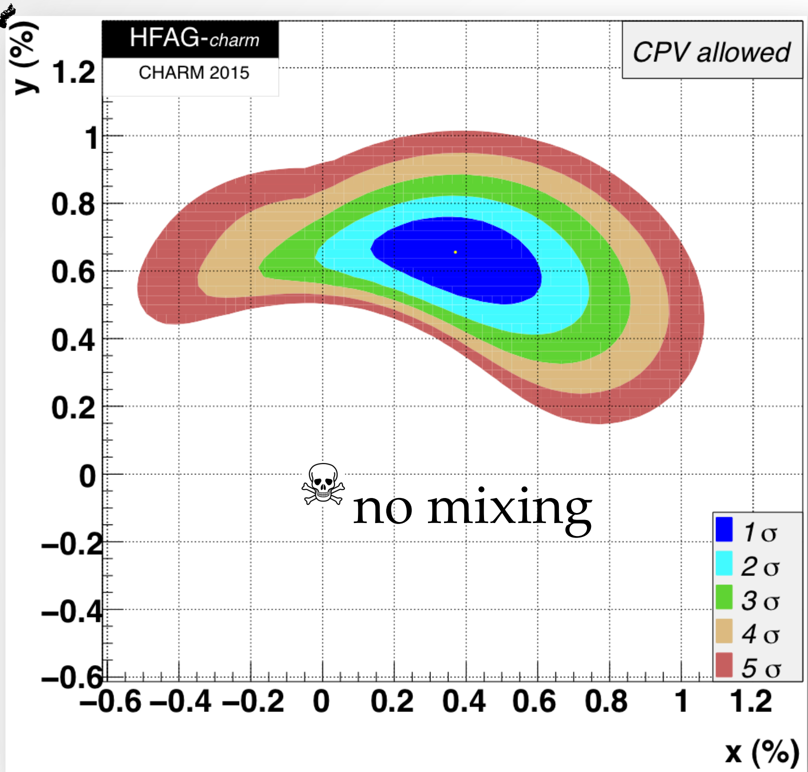


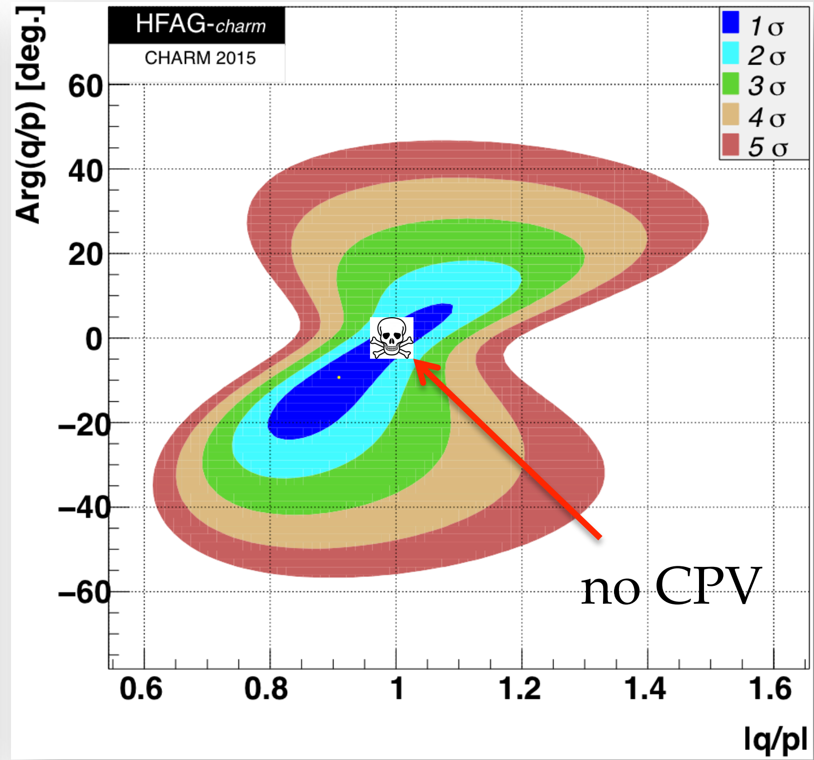
-0.06 ±0.04%

2015 Average

Mixing/Indirect CPV from global fit

As of 2015



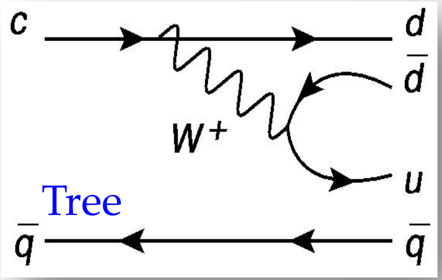


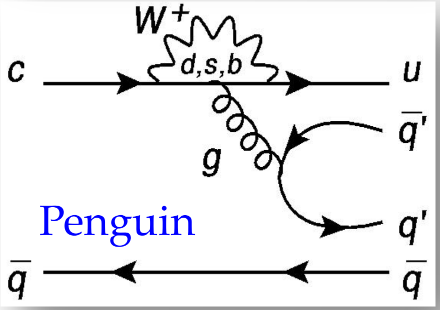
$x = (0.37 \pm 0.16)\%$ $y = \left(0.66^{+0.07}_{-0.10}\right)\%$ $|q/p| = 0.91^{+0.12}_{-0.08}$ $\arg(q/p) = -9.4^{+11.9}_{-9.8}$

- x still not significant
  Best sensitivity from t-dep. Dalitz for $D^0 \to K_s \pi^- \pi^+$, ongoing in LHCb
- No indirect CPV. Need data from BelleII and LHCb upgrade

Direct CPV = in decays (time-independent)

- Depends on decay mode ⇨ study many modes
- Needs two amplitudes with different weak & strong phases
  ⇨ decays with Tree + Penguin
- Penguin in charm is tiny (no t-quark in loop)
  ⇨ in SM direct CPV **$\leq 10^{-3} \div 10^{-2}$**
- Not observed yet



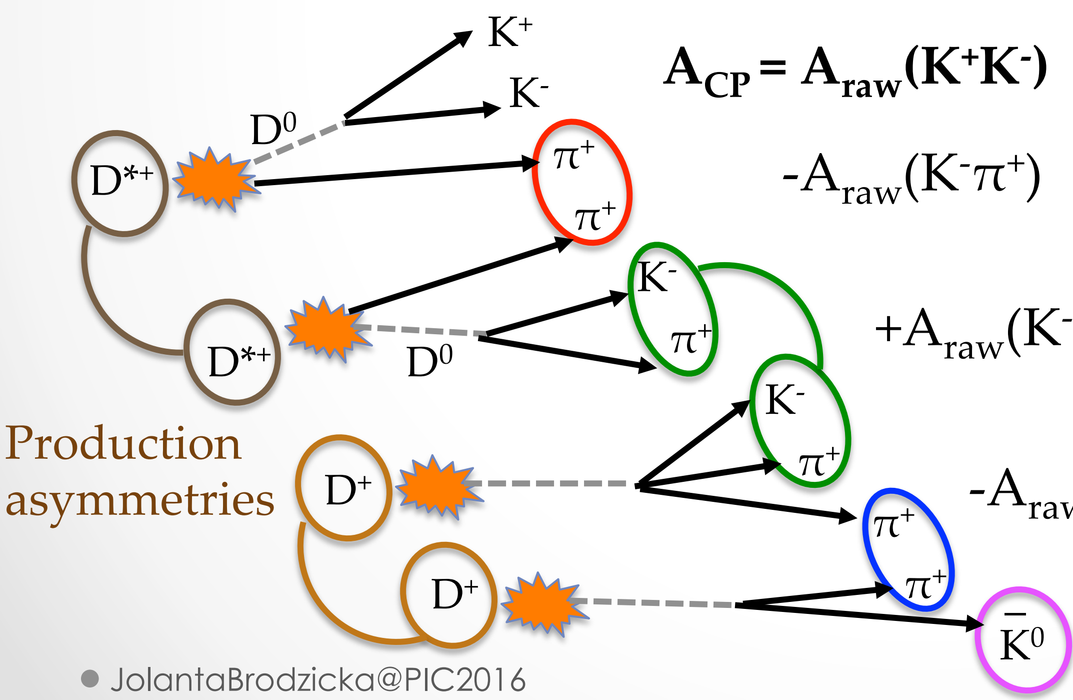


News

- 2-body decays
  - ΔA_{CP}, LHCb
  - $A_{CP}(D^0 \to K^+K^-)$, LHCb
  - $A_{CP}(D^0 \to K_sK_s)$, Belle
  - $A_{CP}(D_{(s)}^+ \to \eta'\pi^+)$, LHCb
- Multibody decays
  - $D^0 \to \pi^+\pi^-\pi^+\pi^-$, LHCb

'Extra' asymmetries to account for

- **Production asymmetry** of charm hadrons
- pp: $\sigma(\Lambda_c^+) > \sigma(\Lambda_c^-)$ ⇨ $\sigma(D^+) < \sigma(D^-)$ to compensate
- $e^+e^- \to \gamma/Z^*$ interference ⇨ FB asymmetry
- **Detection asymmetries** between K^+ and K^-, π^+ and π^-
- different interactions with detector material, $\sigma(pK^-) > \sigma(pK^+)$
- **Correct with control modes** (CP symmetric)



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

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

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

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

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

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

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

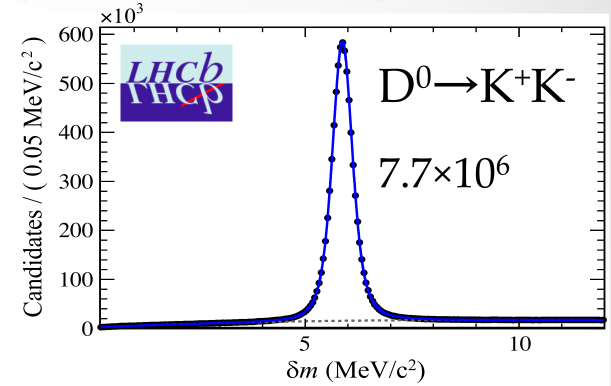
PRL 116, 191601 (2016)

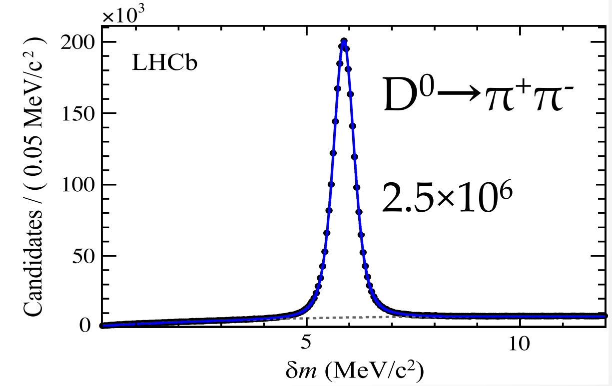
$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

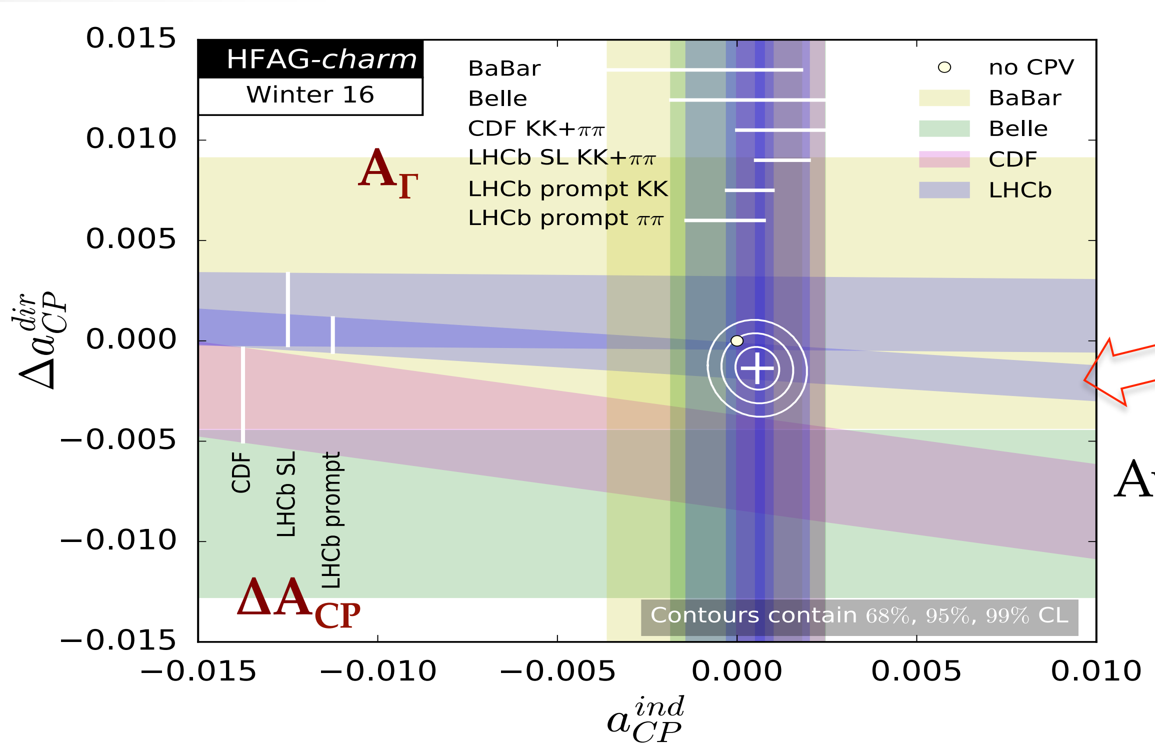
- Sensitive & simple

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

- In SM $|\Delta A_{CP}^{\rm direct}| \leq 0.6\%$
- New LHCb: prompt charm, full Run I
- ΔA_{CP} & A_Γ results ⇨ fit $\Delta A_{CP}^{\rm direct}$ & $A_{CP}^{\rm indirect}$







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

Most precise!

Average consistent with no CPV

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

$$A_{CP}^{indirect} = (0.06 \pm 0.04)\%$$

LHCB-PAPER-2016-035

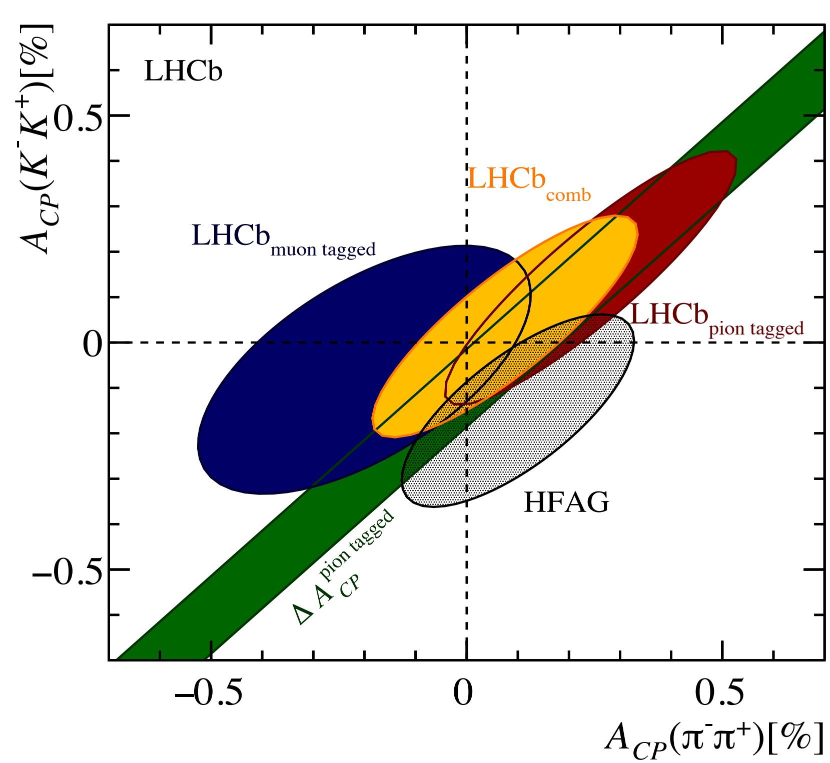
$A_{CP}(D^0 \to K^+K^-)$ & $A_{CP}(D^0 \to \pi^+\pi^-)$

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

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

- Combine with ΔA_{CP} for pion tagged sample ⇨

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



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

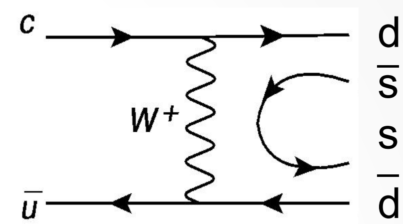
  ⇨ LHCb combination

- Both A_{CP}'s consistent with zero

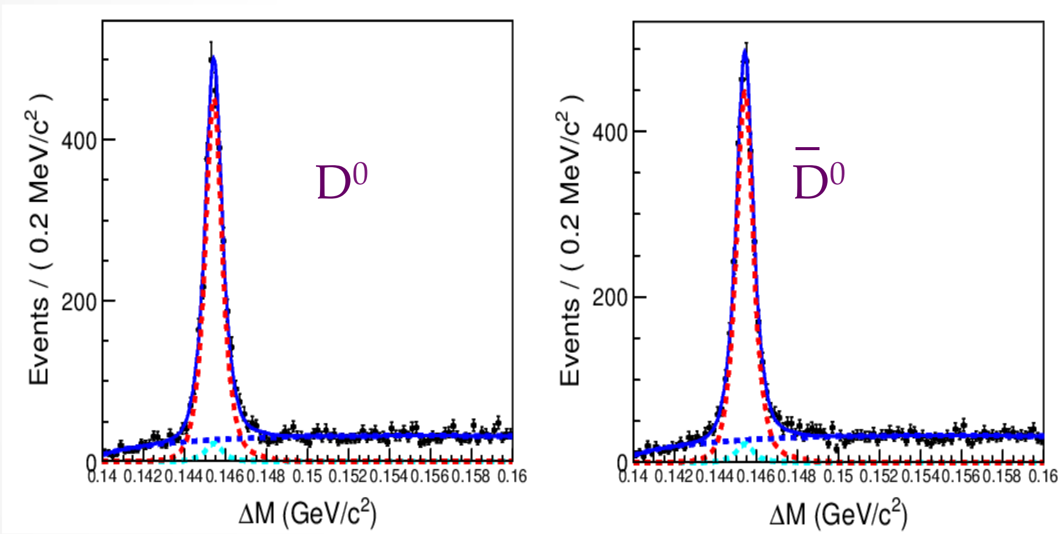
Belle-CONF-1609

$A_{CP}(D^0 \rightarrow K_s K_s)$

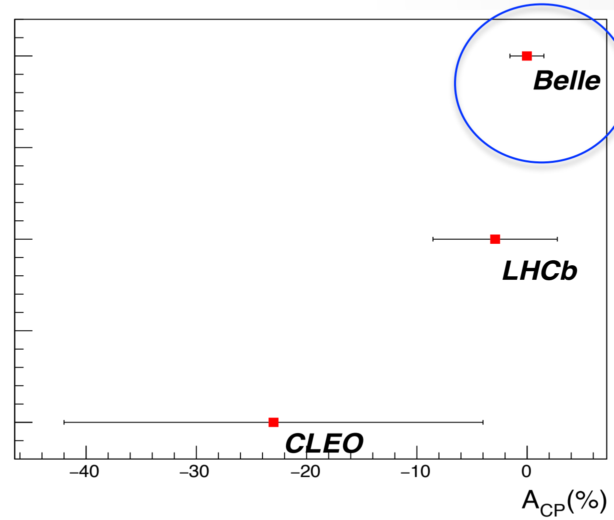
- Suppressed at tree level (W-exchange)
- CPV may be enhanced in SM up to ~1.1%



$\Delta M = M(D^0\pi^+) - M(K_s K_s)$



$$A_{CP}(K_S K_S) = (-0.02 \pm 1.53 \pm 0.17)\%$$

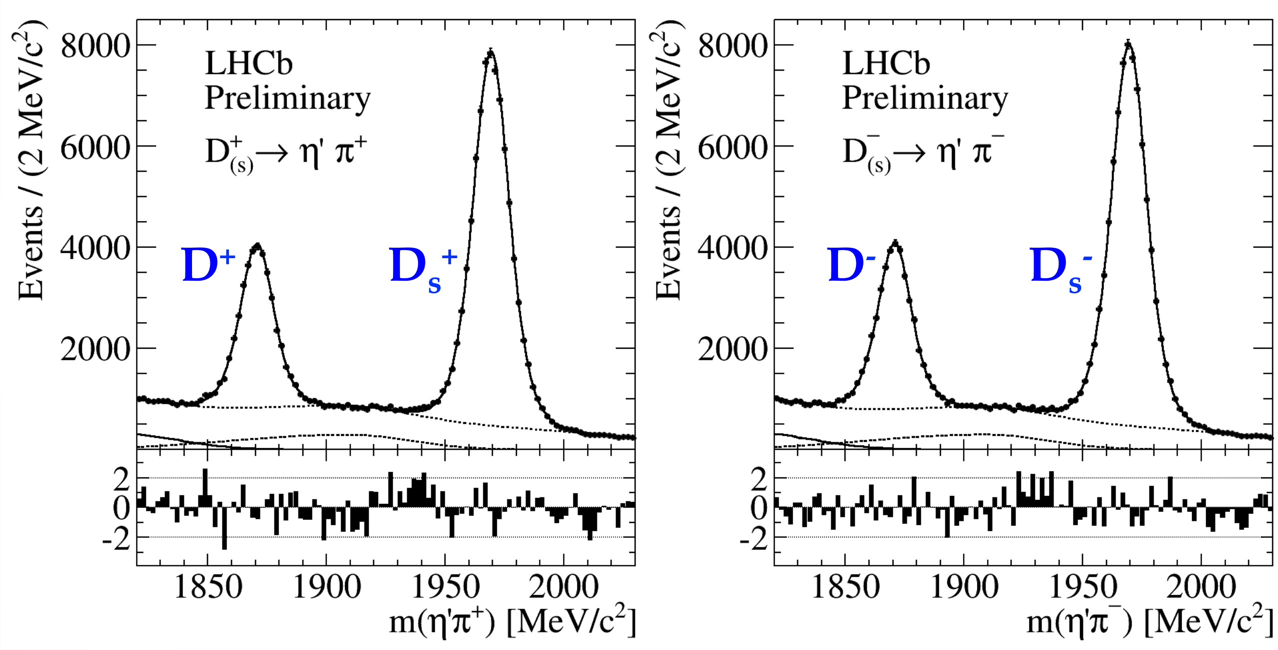


- Note: K_s reconstruction at Belle easier than at LHCb

LHCB-PAPER-2016-041

A_{CP} in $D_{(s)}^{+} \to \eta' \pi^{+}$

- Charged $D_{(s)}$ = flavour 'self-tagged' by pion charge
- $\eta' \to \pi^+ \pi^- \gamma$ photon in final state ⇨ large background



$$\mathcal{A}_{CP}(D^{\pm} \to \eta' \pi^{\pm}) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12)\ \%$$
$$\mathcal{A}_{CP}(D_s^{\pm} \to \eta' \pi^{\pm}) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27)\ \%$$

- 3rd uncertainty from Belle input on A_{CP} in control modes $D^+ \to K_S \pi^+$ and $D_s^+ \to \varphi \pi^+$

Most precise
Very important

A_{CP} in 2-body decays (with penguin)

	LHCb	Belle	BaBar	BESIII
Mode	A_{CP} [%]			
$D^0 \to K^+K^-$	+0.04 ± 0.12 ± 0.10 New	-0.32 ± 0.21 ± 0.09	+0.00 ± 0.34 ± 0.13	
$D^0 \to \pi^+\pi^-$	+0.07 ± 0.14 ± 0.11 New	+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 New		
$D^0 \to \pi^0\pi^0$		-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 New
$D^+ \to K_LK^+$				-3.0 ± 3.2 ± 1.2 New
$D^+ \to \phi\pi^+$	-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 New	-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 New			

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

Most precise
Very im

- Precision up to 10^{-3}, still no evidence
- Exploit correlations between isospin-related modes
- Mainly mesons are studied!

  Need to measure A_{CP} in charm baryons

Mod				I
$D^0\to$				
$D^0\to\pi^+\pi^-$	+0.07 ± 0.14 ± 0.11 New	+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 New		
$D^0\to\pi^0\pi^0$		-0.03 ± 0.64 ± 0.10		
$D^0\to K_s\eta$		+0.54 ± 0.51 ± 0.16		
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$D^+\to K_LK^+$				-3.0 ± 3.2 ± 1.2 New
$D^+\to\phi\pi^+$	-0.04 ± 0.14 ± 0.14	+0.51 ± 0.28 ± 0.05		
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$D_s^+\to\eta'\pi^+$	-0.82 ± 0.36 ± 0.24 ± 0.27 New			

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

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

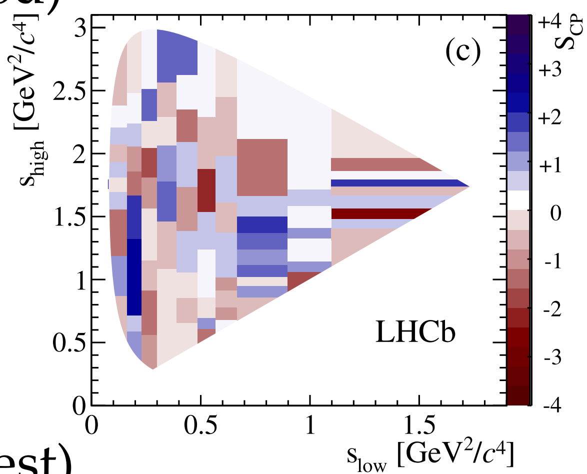
CPV in multi-body decays

- Strong phases vary in phase space ⇨ local asymmetries
- Model independent methods: test if data consistent with no-CPV

⇨ binned χ^2 (S_{CP} method)

$D^+ \to \pi^+\pi^+\pi^-$

p-value = 50÷100%



$$S^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}} \quad \alpha = \frac{N(D^+)}{N(D^-)}$$

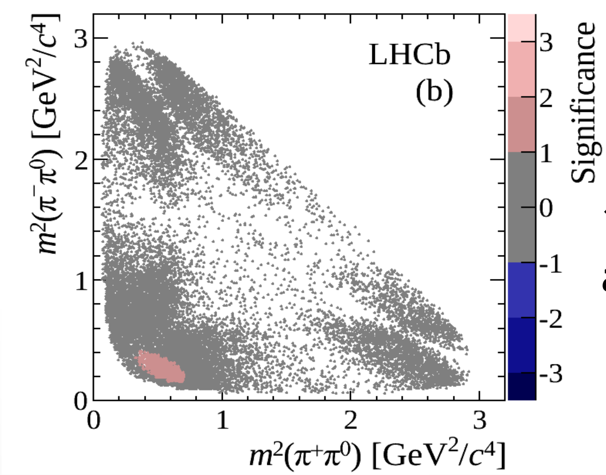
$$\chi^2 = \sum (S^i_{CP})^2$$

🡐 Significance of asymmetry in Dalitz bins

⇨ unbinned (Energy Test)

$D^0 \to \pi^+\pi^-\pi^0$

p-value = 2÷5%



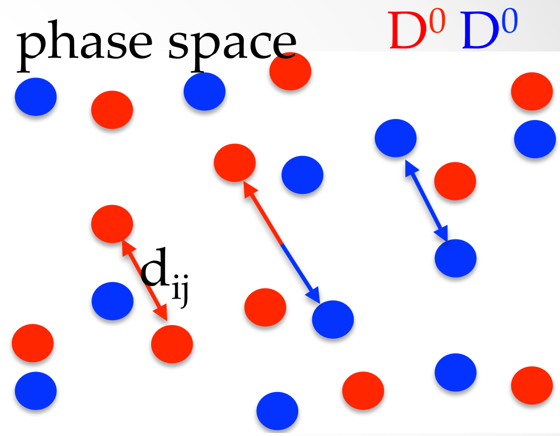
🡐 Significance of local asymmetry for each event

LHCB-PAPER-2016-044

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

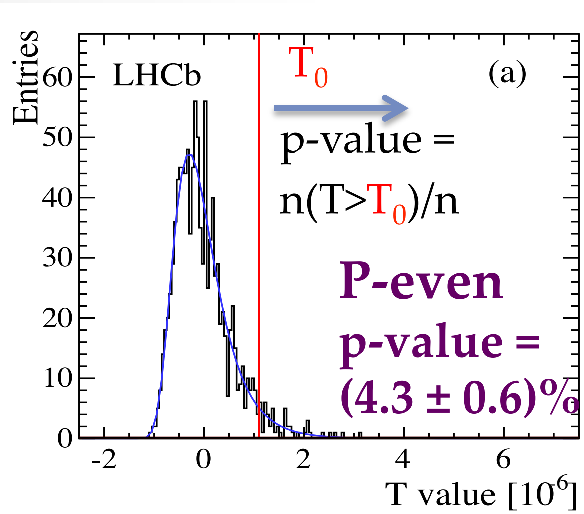
- Statistical comparison of two distributions
- Test statistics: based on distances of event pairs
- Compare with T distribution for no CPV case (randomize D^0 flavour)

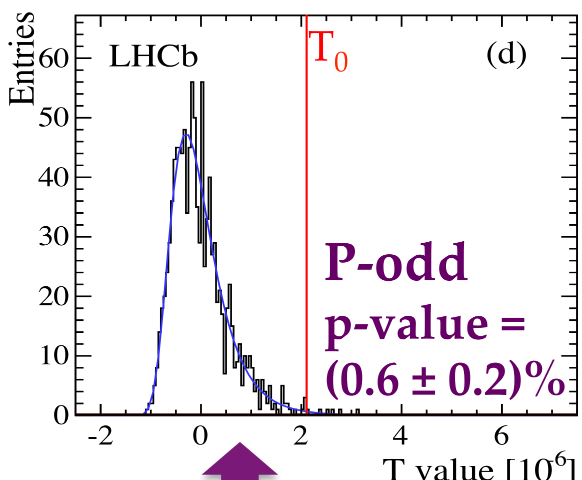
- 5-D phase space: $m^2(\pi\pi)$, $m^2(\pi\pi\pi)$ ⇨ **P-even**
- Use triple product sign to access **P-odd** CPV



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

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





Marginally consistent with no CPV (~2.5σ)

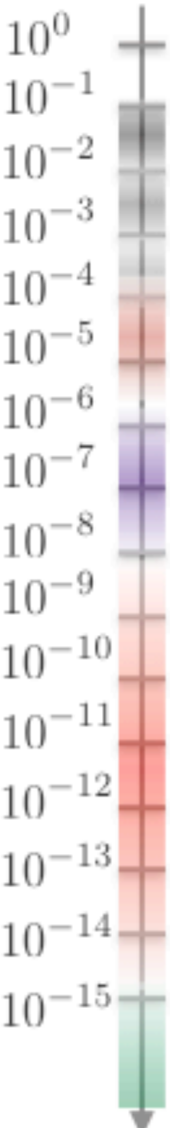
CP

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

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

Rare Decays

Spectrum of charm decays

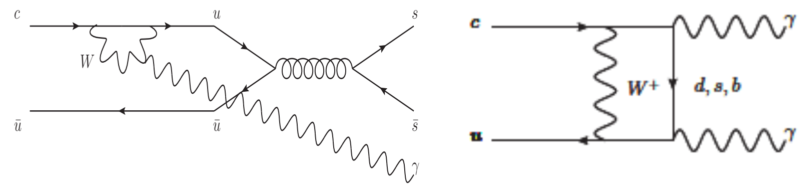


Cabibbo favoured

Singly Cabibbo suppressed

Doubly Cabibbo suppressed

Discussed so far



Radiative

$D^0 \to \overline{K}^{*0}\gamma,\ \phi\gamma,\ \omega\gamma,\ \rho^0\gamma$

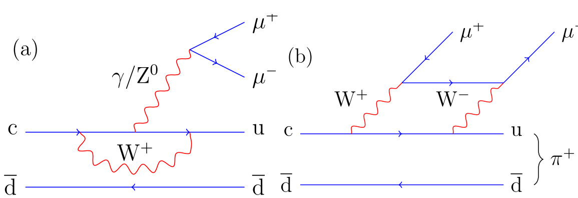
Vector Meson Dominance

$D^0 \to \rho V(\to \ell\ell),\ \pi^-\pi^+ V(\to \ell\ell)$

$D^0 \to \phi V(\to \ell\ell),\ K^-K^+ V(\to \ell\ell)$

$D^0 \to \overline{K}^{*0} V(\to \ell\ell),\ K^+\pi^- V(\to \ell\ell)$

$D^0 \to \gamma\gamma$



Flavour Changing Neutral Current

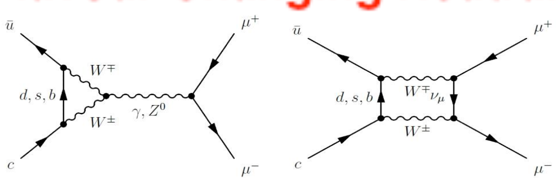
$D^0 \to \mu^-\mu^+$

$D^0 \to e^-e^+$

$D \to h\ell^+\ell^-$

$D \to hh'\ell^-\ell^+$

$D \to V\ell^+\ell^-$



Lepton/Baryon Number Violating

$D \to (h)e^-\mu^+$

Lepton Flavor Violating

$D \to (h)\ell^+\ell^+$

Rare charm decays: state of art

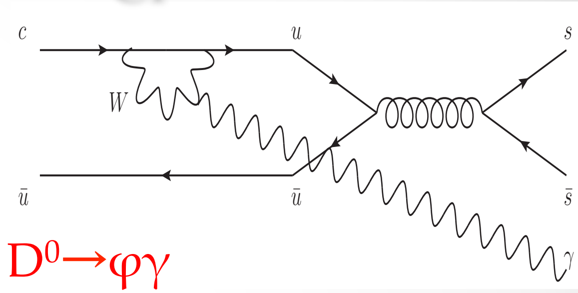
Sensitivity up to O(10^{-8})

Decay	Note	SM predict.	BF or best UL	Exp.
$D^0 \to K^*\gamma$ New	Radiative	$\sim 10^{-4}$	$(4.66 \pm 0.21 \pm 0.18)\times 10^{-4}$	Belle
$D^0 \to \varphi\gamma$ New	" "	$\sim 10^{-5}$	$(2.76 \pm 0.20 \pm 0.08)\times 10^{-5}$	Belle
$D^0 \to \rho\gamma$ New	" "	$\sim 10^{-6}$	$(1.77 \pm 0.30 \pm 0.08)\times 10^{-5}$	Belle
$D^0 \to \gamma\gamma$ New	" "	$(1 \div 3)\times 10^{-8}$	$< 8.5 \times 10^{-7}$	Belle
$D^+ \to \pi^+\mu^+\mu^-$	FCNC, μμ 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
$D^+ \to \pi^+/K^+ e^+e^-$ New	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, μμ 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
$D^0 \to \upsilon\underline{\upsilon}$ New	Helicity suppressed	$\sim 10^{-30}$	$< 8.8 \times 10^{-5}$	Belle
$D^0 \to e^+\mu^-$ New	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
$D^+ \to \pi^-/K^- e^+e^-$ New	" "	0	$< 1.2 / 0.6 \times 10^{-6}$	BESIII

arXiv:1603.03257

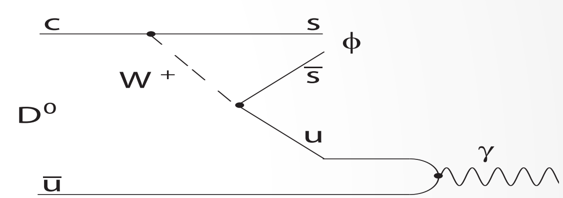
$D^0 \to K^{*0}\gamma$, $\varphi\gamma$, $\varrho^0\gamma$: BF & A_{CP}

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

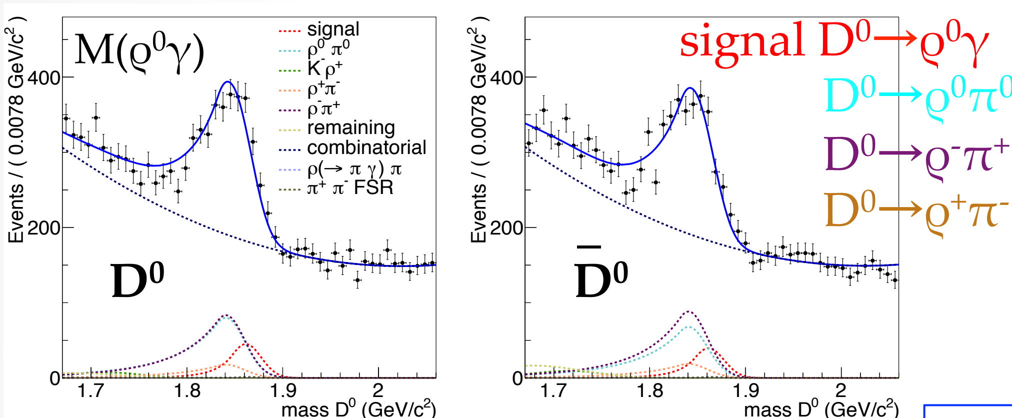


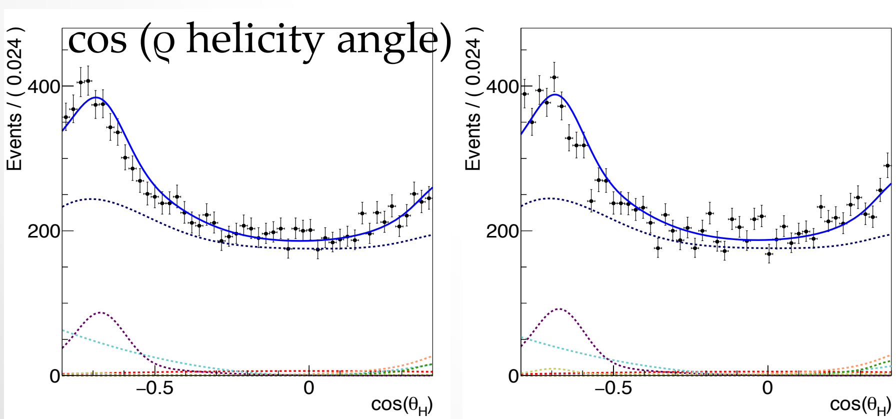
$D^0 \to \varphi\gamma$

Short distance contribution



Long distance via Vector Meson Dominance





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

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

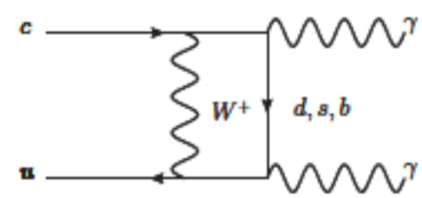
No CPV

PRD 93, 051102 (2016)

$D^0 \to \gamma\gamma$

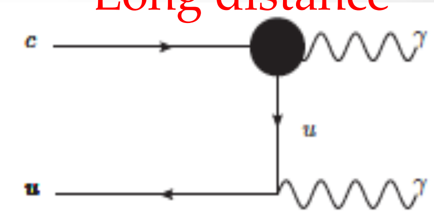
- BF within SM ~10^{-8}
- With SUSY up to ~6×10^{-6}

Short distance



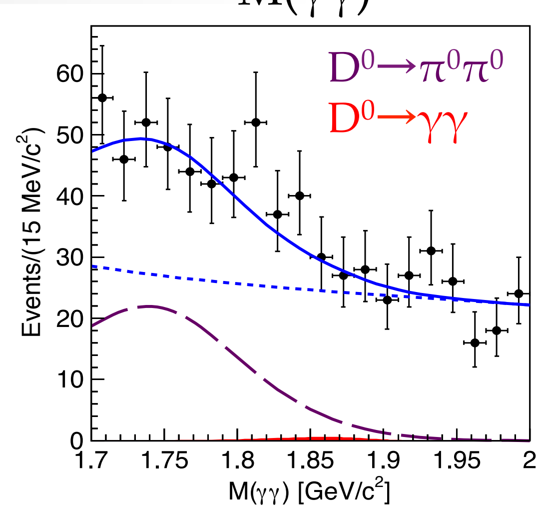
$\mathcal{B}_{SD} \simeq (4-8)\times10^{-12}$

Long distance

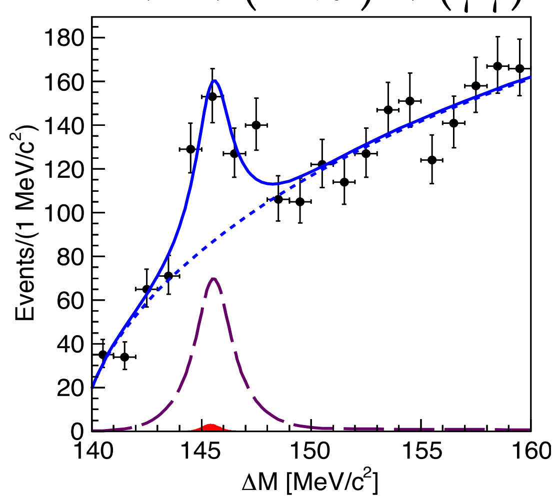


$\mathcal{B}_{LD} \simeq (1-3)\times10^{-8}$

M(γγ)

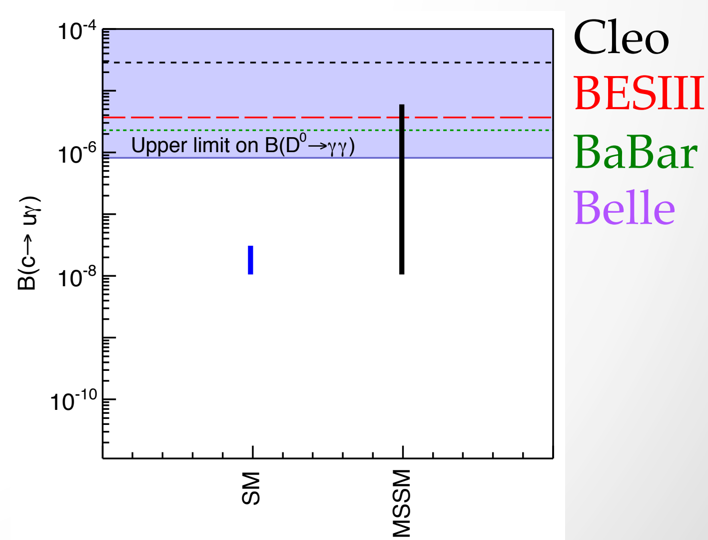


ΔM=M(D0π+)-M(γγ)



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

- Most restrictive limit so far



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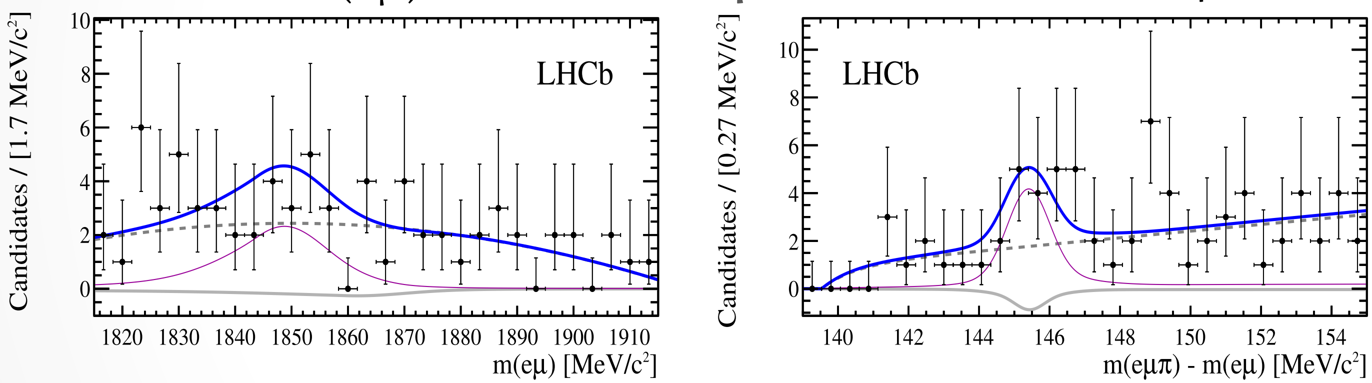
$D^0 \to e^+\mu^-$

- Lepton Flavour Violating decay ⇨ forbidden in SM
- With SUSY ~10^{-6}

  With multiple Higgs doublets $< 7\times10^{-10}$

$D^0 \to \pi^+\pi^-$

M(eμ) $D^0 \to e\mu$ $M(D^0\pi^+)$-M(eμ)



$$\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3\ (1.6) \times 10^{-8}\ @90\ (95)\%\ \text{C.L.}$$

- Improved by factor 10 previous Belle UL

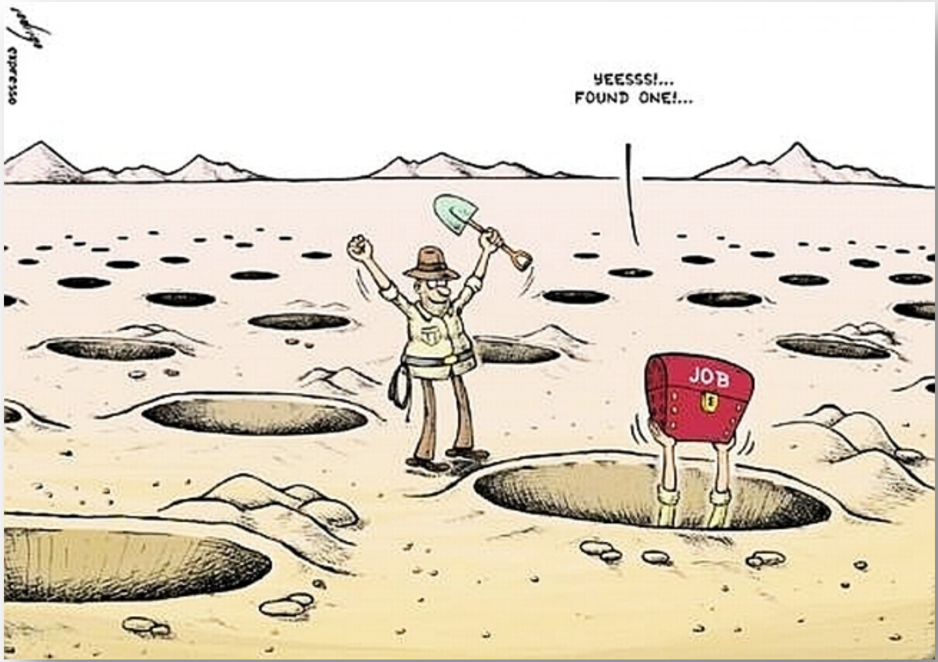
Summary

- Increasing precision on x&y mixing parameters
- x still not measured well
- Indirect CPV searches with precision up 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?

- Setting new limits on rare decays
  Start probing down to 10^{-8}

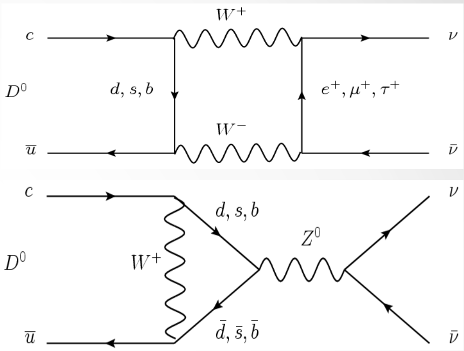
- Charm needs
  BelleII & LHCb upgrade



Backups

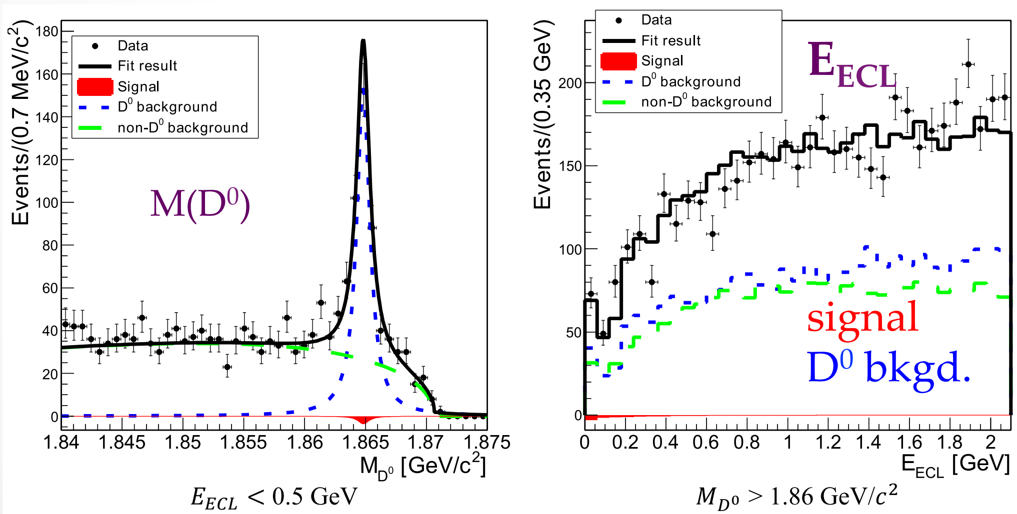
Belle-CONF-16xx

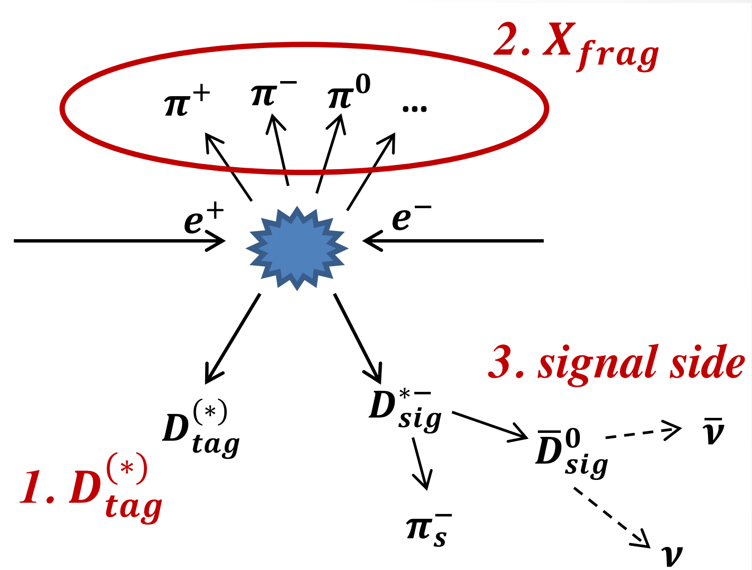
$D^0 \to \upsilon\bar{\upsilon}$ (a.k.a invisible)



- Helicity suppression by $(m_\upsilon/m_D)^2$ ⇨ 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





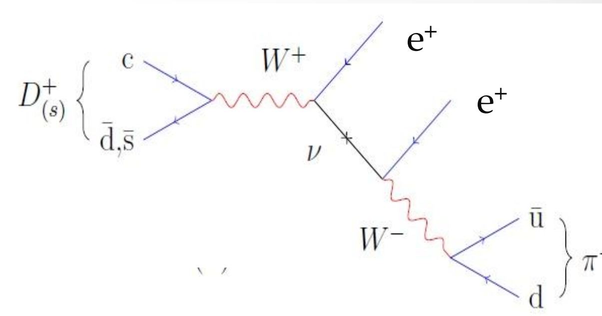
$\mathcal{B}(D^0 \to \text{invisible}) < 8.8 \times 10^{-5}$ at 90% C.L.

First search!

Shown at Charm2016

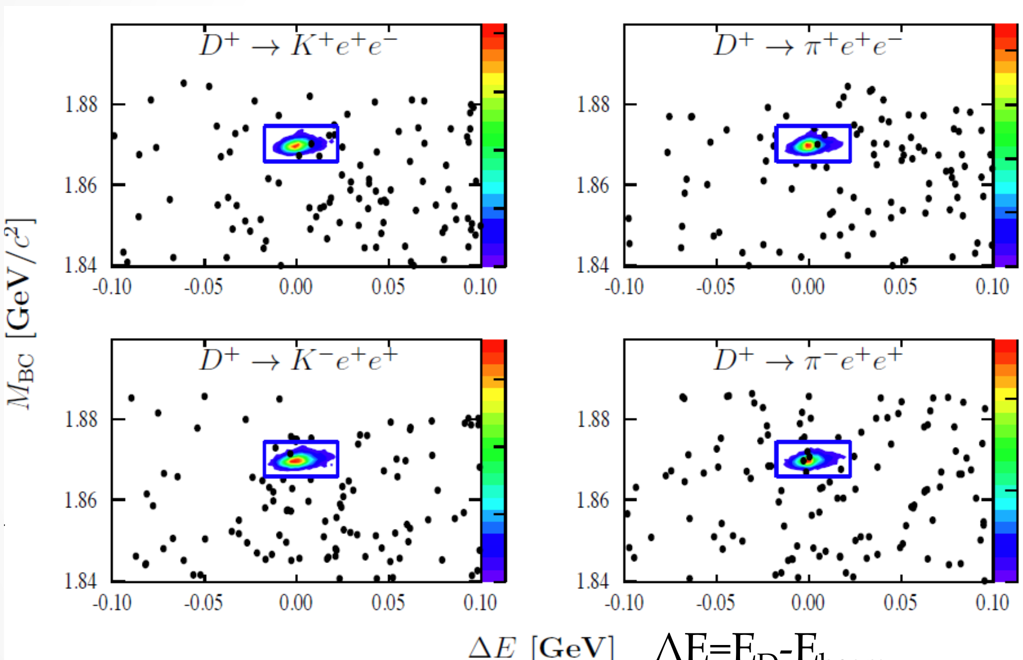
$D^+ \to \pi^+/K^+ e^+e^-$ & $D^+ \to \pi^-/K^- e^+e^+$

- $D^+ \to \pi^+/K^+ e^+e^-$ in SM: $10^{-8} \div 10^{-6}$
- $D^+ \to \pi^-/K^- e^+e^+$ is Lepton Flavour Violating
  ⇨ forbidden in SM



$D^+ \to \pi^- e^+e^+$ through Majorana neutrinos

M(D+)



$\Delta E = E_D - E_{beam}$

- No signal found

$\mathcal{B}(D^+ \to K^+e^+e^-) < 1.2 \times 10^{-6}$	$\mathcal{B}(D^+ \to \pi^+e^+e^-) < 0.3 \times 10^{-6}$
$\mathcal{B}(D^+ \to K^-e^+e^+) < 0.6 \times 10^{-6}$	$\mathcal{B}(D^+ \to \pi^-e^+e^+) < 1.2 \times 10^{-6}$