$D\bar{D}$ mixing, CPV in charm sector, D decays

Selected results from experiments

Sergey Barsuk, LAL Orsay

Outline : 文藝復興時期的魅力物理學

- **$D\bar{D}$ mixing:** y_{CP} from lifetime difference, wrong sign $D^0 \to K\pi$
- **CP violation:** $D^+ \to K^- K^+ \pi^+$, $\phi\pi^+$, $D_{(s)}{}^+ \to K_S{}^0 h^+$, $D^0 \to \pi^-\pi^+$, $D^0 \to K^-K^+$, $D^0 \to 4h$
- **Rare decays:** $D_s{}^+$ leptonic decays, $D^0 \to K^+ \pi^- \pi^+ \pi^-$, $D^0 \to \mu^+ \mu^-$, $D_{(s)}{}^+ \to \pi^+ \mu^+ \mu^-$, $D_{(s)}{}^+ \to \pi^- \mu^+ \mu^+$, $D^0 \to \pi^+ \pi^- \mu^+ \mu^-$

Results from: BaBar, Belle II, CDF, LHCb

Also ongoing analyses in: DØ, BES

See also PIC 2012 reviews by E. Polycarpo and Y. Zheng

- Both flavour mixing and CP violation well-established in K and B sectors.
- Charm is the **unique up-type system**, where these effects can occur.
- Mass eigenstates vs. flavour eigenstates : $|D_{1,2}\rangle = p\,|D^o\rangle \pm q\,|\bar{D}^o\rangle$
- In the limit of CP conservation p = q (correction of $O(10^{-4})$ in the SM)
- Decay becomes modulated by mixing : $$\frac{e^{-\Gamma t}}{4}\Big(\underbrace{e^{\frac{\Delta\Gamma}{2}t}+e^{-\frac{\Delta\Gamma}{2}t}}_{\cosh\left(\frac{\Delta\Gamma}{2}t\right)} \pm 2\cos\Delta m t\Big)$$

Mixed : $\bar{D}^0 \to D^0$ or $D^0 \to \bar{D}^0$

Unmixed : $\bar{D}^0 \to \bar{D}^0$ or $D^0 \to D^0$

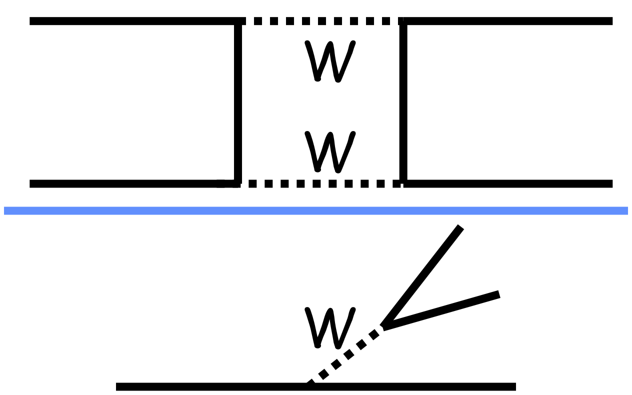
$$A_{mix}(t) \equiv \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})}(t) = \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}$$

Mixing parameters: $x=\Delta m/\Gamma$; $y=\Delta\Gamma/2\Gamma$

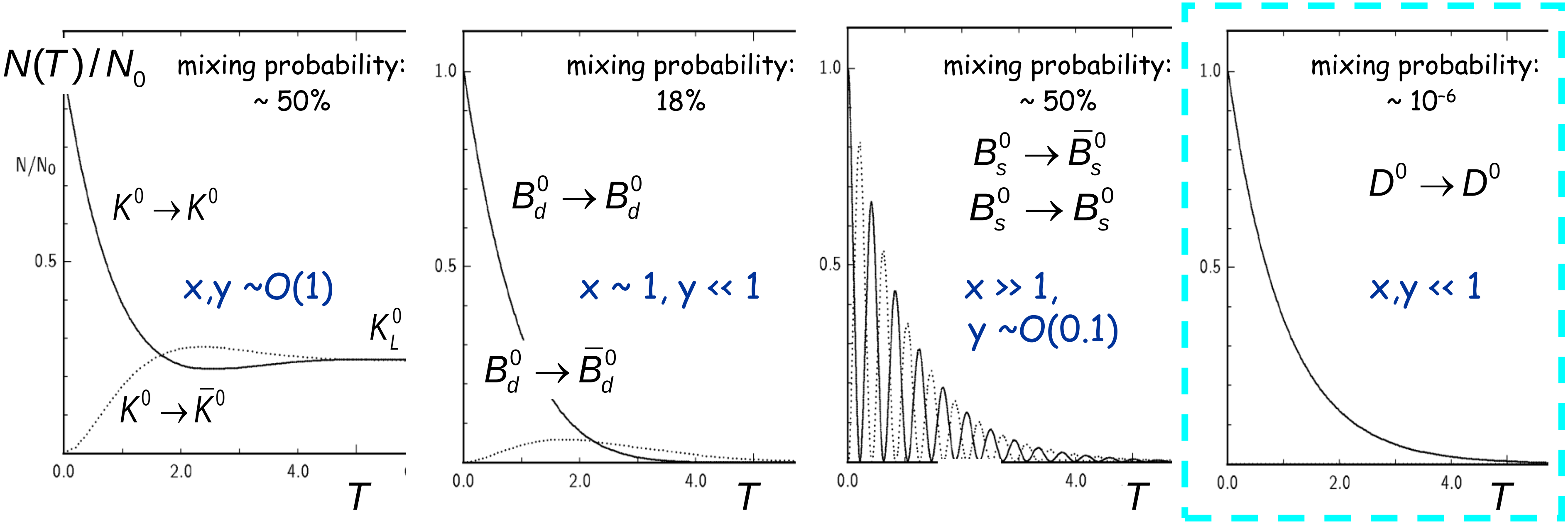
x: mixing frequency in units of lifetime

x>>1 rapid oscillation
x<<1 slow oscillation

x,y ~



Introduction : $D\bar{D}$ mixing and CPV in charm sector



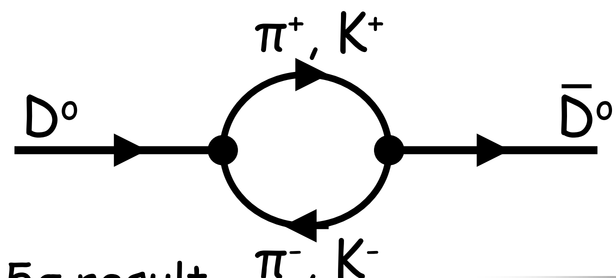
Discovered in 1950s, textbook to illustrate QM effects

Observed in 1987, first hint of the heavy top quark

Observed in 2006, rapid oscillations → high decay time resolution required

Observed in 2007, tiny effect → large samples and clean detection/ID required

- ❑ Unlike $B_{(S)}$ -mesons, no strong heavy (t) quark contribution to the box diagram, **contribution from b-quark suppressed by** λ^{10} by the CKM matrix elements !
- ❑ Non-perturbative long-range effects more difficult to calculate, typically 10^{-3} with large uncertainty e.g. **Falk,Grossman,Ligeti,Nir,Petrov PRD 69 114021**



- ❑ $D\bar{D}$ mixing well-established, but until 2013 no single 5σ result.

Introduction : $D\bar{D}$ mixing and CPV in charm sector

Three types of CPV

- **Direct CPV** between tree and penguin diagram → CSD (charged and neutral)
  expected to be up to few x $O(10^{-3})$ in the SM

  $A_f = \langle f|H|D\rangle$, $\bar{A}_{\bar{f}} = \langle \bar{f}|H|\bar{D}\rangle$, $\mathbf{|\bar{A}_{\bar{f}} / A_f| \neq 1}$

  Study:
  - asymmetries in 2-body SCS decays
  - asymmetries across the phase space in multi-body decays

- **CPV in mixing** (neutral)

  $\mathbf{|p| \neq |q|}$ or weak phase ϕ = $\mathbf{arg(q/p) \neq 0}$

  expected to be $O(10^{-4})$ in the SM

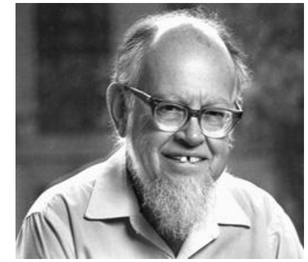
- **CPV in interference** between the decay to final state *f* with and without mixing → common final state (neutral)

  $\mathbf{arg(q/p\ \bar{A}_f/A_f) \neq 0}$

SM: single CP-violating phase → strong predictive power for CP asymmetries !

The Cabibbo-Kobayashi-Maskawa matrix

in Wolfenstein parametrization



elements relevant for charm sector

CS D decays, $D\bar{D}$-mixing

V_{ub} enters via loops

$$V_{CKM} = \begin{pmatrix} \boxed{\begin{matrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{matrix}} & \begin{matrix} V_{ub} \\ V_{cb} \end{matrix} \\ \begin{matrix} V_{td} & V_{ts} \end{matrix} & V_{tb} \end{pmatrix} = \begin{array}{c} u \\ c \\ t \\ \\ \end{array} \begin{array}{c} \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+A^2\lambda^5(1/2-\rho-i\eta) & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta)+A\lambda^5(\rho+i\eta)/2 & -A\lambda^2+A\lambda^4(1/2-\rho-i\eta) & 1-A^2\lambda^4/2 \end{pmatrix} \\ \begin{matrix} d & \qquad\qquad s & \qquad\qquad b \end{matrix} \end{array} + O(\lambda^6)$$

η - CP-violating phase

SM: DCPV of O(1%) in charm decays could signal new physics !

Examples of exercises / homework from theory to experiment

Grossman, Nir, Perez, PRL 103 (2009) 071602

1. If CPV is small, $\sin\phi \ll 1$ (valid for D system) :
   If violated, New Physics contributes to direct CPV.

$$\boxed{y/x = \frac{1 - |q/p|}{\tan\phi}}$$

For review see e.g. **Grossman, Kagan, Nir, PRD 75 (2007) 036008**

2. In the absence of direct CPV from NP, the CP asymmetries in CSD into final CP eigenstates are universal.

   In SM: $(a_{KK} - a_{\pi\pi})/(a_{KK} + a_{\pi\pi}) \sim 10^{-3}$ → Check

3. Separate **direct vs. indirect CPV** in CSD using time-integrated CP asymmetry measurements.
   Assuming negligible new CPV in CAD and DCSD, time-integrated CP asymmetry in CAD to CP eigenstate → universal indirect CP asymmetry.
   Subtract it from time-integrated CP asymmetry in CSD to CP eigenstate
   → **non-universal direct CP asymmetry**

4. Non-vanishing CP asymmetry in **charged D** decays → **direct CPV**.

Players in the charm sector

e+e- colliders

- B-factories : **BaBar**, **BELLE**, operating at $\Upsilon(4S)$ energies
  - Secondary charm from B-decays, $\sigma(B\bar{B})$ ~ 1.1 nb, > 10^9 $B\bar{B}$ pairs
  - Continuum production, $\sigma(c\bar{c})$ ~ 1.3 nb, > 10^9 charm hadron pairs
- $D\bar{D}$-factories, quantum correlations at $D\bar{D}$ threshold :
  - **CLEO-c**
  - now **BES**

→ Data scan around charmonium production, $\psi(2S) \to D\bar{D}$,
→ Clean data samples, beam energy constraint can be used

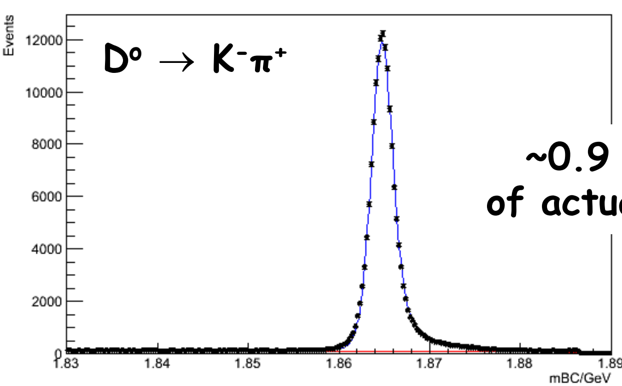
Simple signature for CP violation: $\psi(3770) \to D^0\overline{D^0} \to (CP\pm)(CP\pm)$
Also key ingredient for b-sector measurements

$\int$Ldt~0.8 fb^{-1} few x10^7 $\psi(2S)$ decays available at CLEO-c
$\int$Ldt~2.9 fb^{-1}, 21 M D^0 produced at BES III, sample 2010-2011

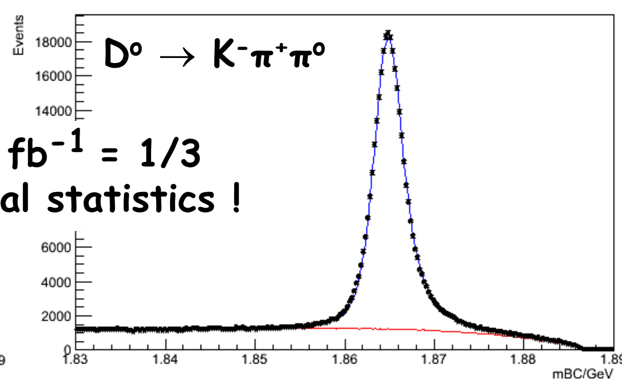
arXiv 1307.2022

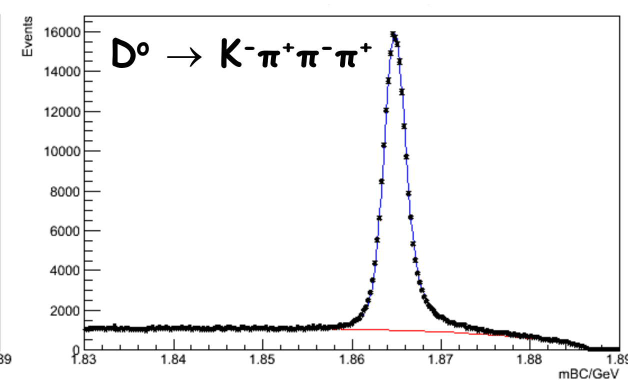
BES arXiv 1207.1171

BESIII Preliminary



~0.9 fb^{-1} = 1/3 of actual statistics !





Hadronic machines (challenging environment !): pp or p$\bar{p}$ colliders

- TEVATRON : **CDF**, **D0**
- LHC : **LHCb**

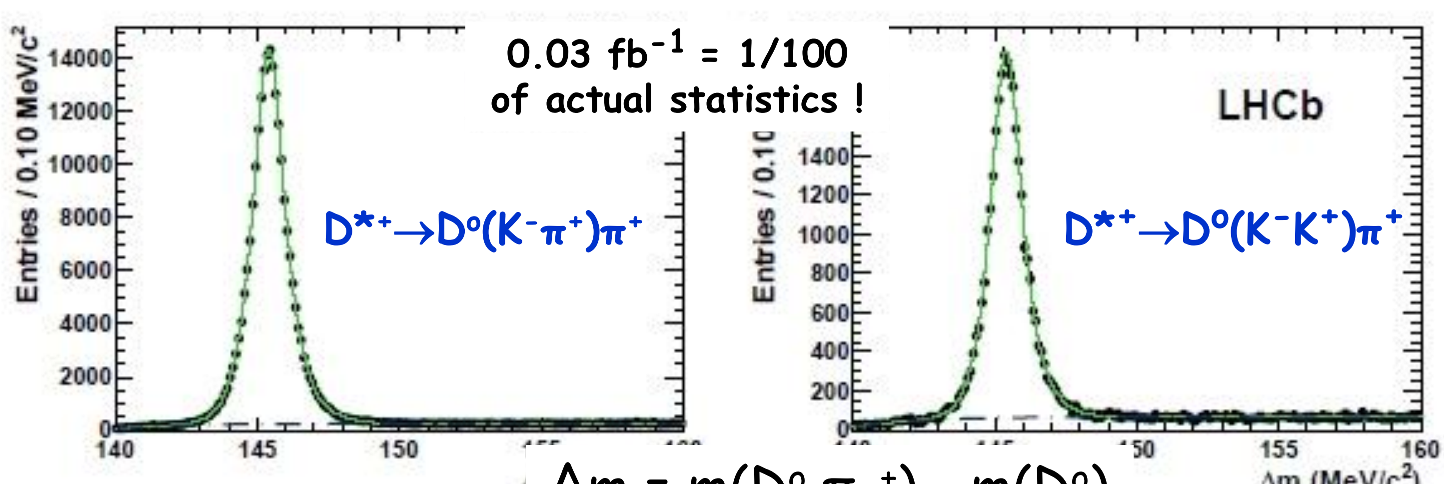
→ High cross-section CDF at small rapidities,
forward LHCb geometry, $\sigma(c\bar{c})_{\mathrm{LHCb,\,7\,TeV}}$ ~ 1400 μb
Nucl.Phys.B 871(2013), 1

→ ~350M reconstructed charm decays in $\int L dt$~1 fb^{-1} (2011), trigger limited !

→ High boost, D^o flies ~3 mm before decaying

→ IP resolution for p_T > 2 GeV/c
CDF II (35 μm), LHCb (22 μm)

→ Clean sample due to precise tracking, vertexing and powerful PID

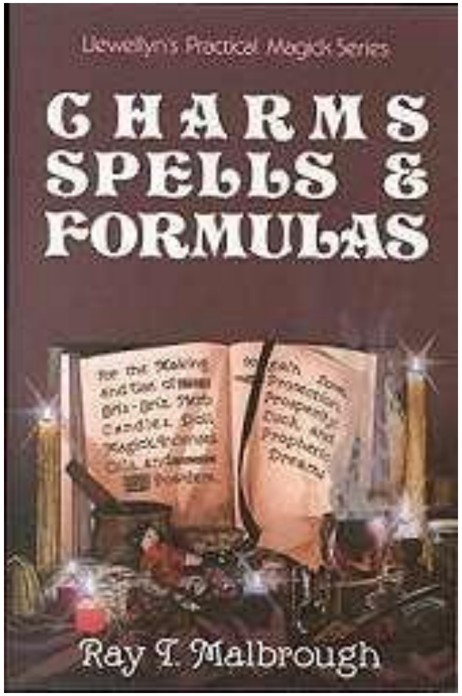


$\Delta m = m(D^o \pi_S^+) - m(D^o)$

JHEP 04 (2012) 129

2010 data, 0.03 fb^{-1}

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



Mixing via D^o lifetime difference

- Measure $y_{CP} = \dfrac{\Gamma^{CP=+} + \overline{\Gamma}^{CP=+}}{2\Gamma} - 1$

comparing lifetime of

$\overset{(-)}{D}{}^o \to K^- K^+$ and $\overset{(-)}{D}{}^o \to \pi^- \pi^+$ (CP=+),

and $D^o \to K\pi$ (mixture of CP=+ and CP=-)

- Assuming no CPV, measures directly **y**, and not **x',y'**

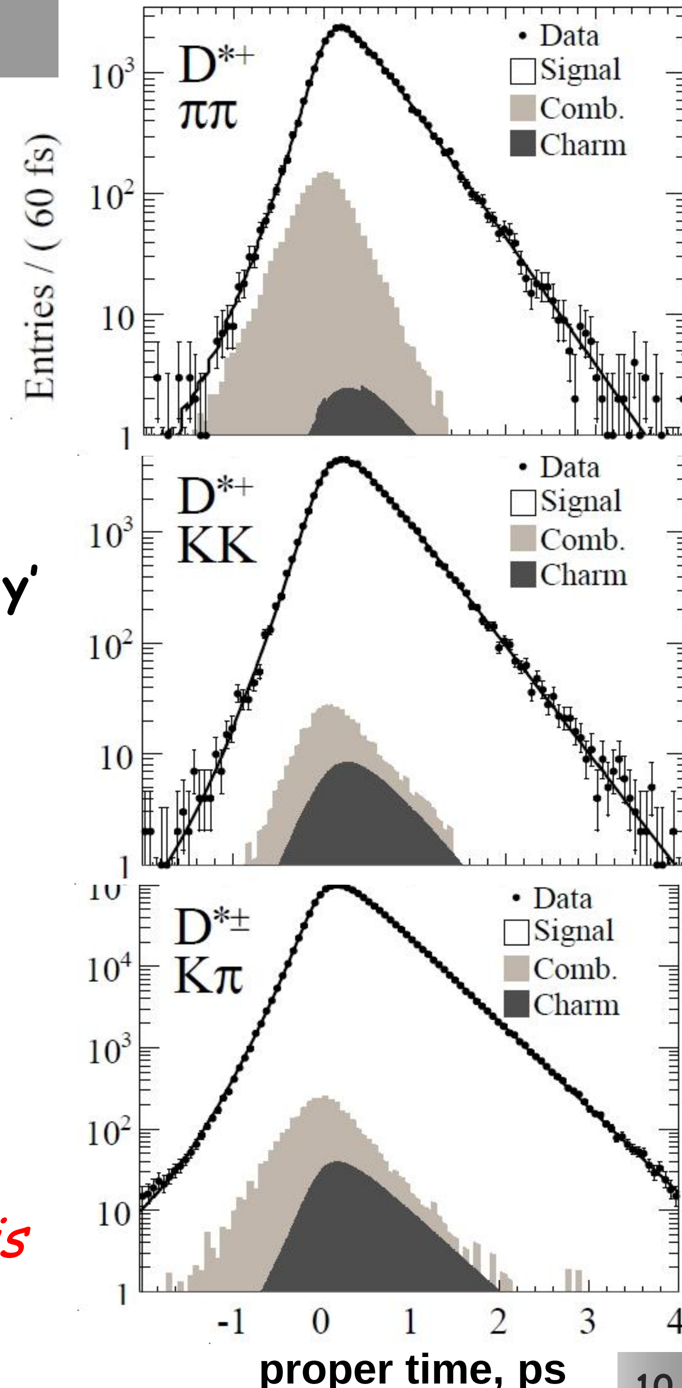
BaBar

PRD 87,012004 (2013)

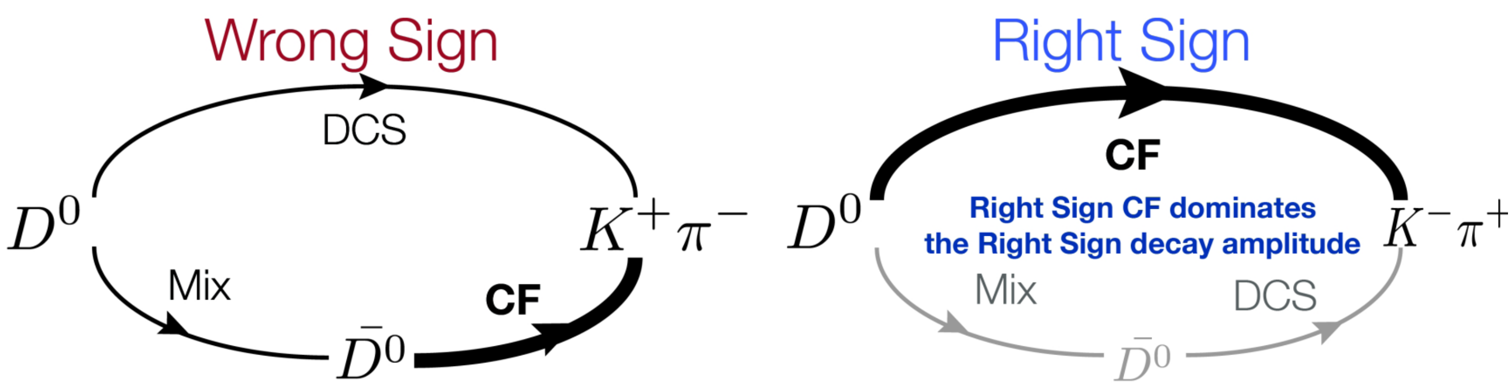
$\boxed{y_{CP} = (0.72 \pm 0.18 \pm 0.12)\%}$

- Most precise single measurement to date.

No mixing hypothesis excluded at 3.3σ.



Time-dependent "wrong-sign" decay rates:
cocktail of **mixing and DCS** decay amplitudes
in about equal portions according to your taste.



Assuming $|x|,|y| \ll 1$ and CP conservation,

Wrong sign: $dN_{ws}/dt \approx e^{-\Gamma t} \times [\, (x'^2+y'^2)/2 \cdot \Gamma^2 t^2/2 + D^2_{DCS} + D_{DCS} \cdot y' \cdot \Gamma t \,]$

mixing *DCSD* *interference*

Ratio: $N_{ws}/N_{rs}(t) \approx (x'^2+y'^2)/2 \cdot \Gamma^2 t^2/2 \underbrace{+ R_D + \sqrt{R_D} \cdot y' \cdot \Gamma t}_{\text{vanishes for SL decays}}$

x^2+y^2

$$\frac{\bar{A}(K^-\pi^+)}{A(K^-\pi^+)} = \sqrt{R_D}\, e^{-i\delta},\ \delta \text{ - strong phase between } A \text{ and } \bar{A}$$

$$y' = y\cos\delta - x\sin\delta$$
$$x' = x\cos\delta + y\sin\delta$$

x'^2, y'

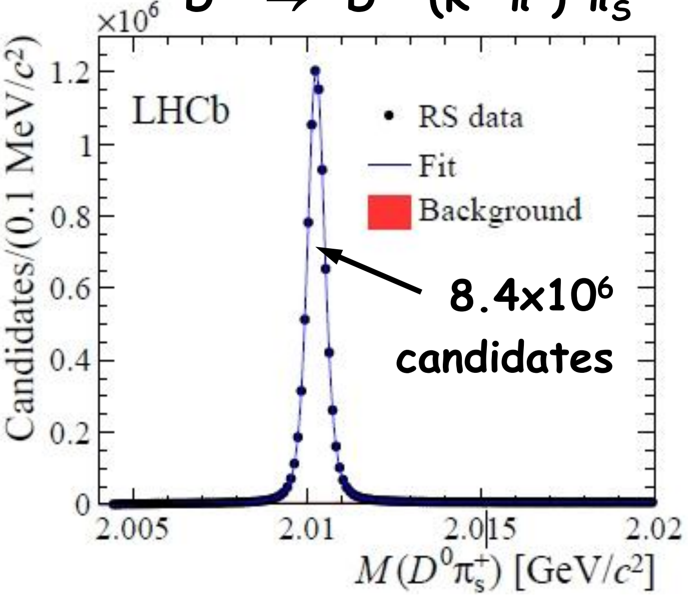
LHCb wrong sign $D^0 \to K\pi$ decay rate

PRL 110 (2013) 101802

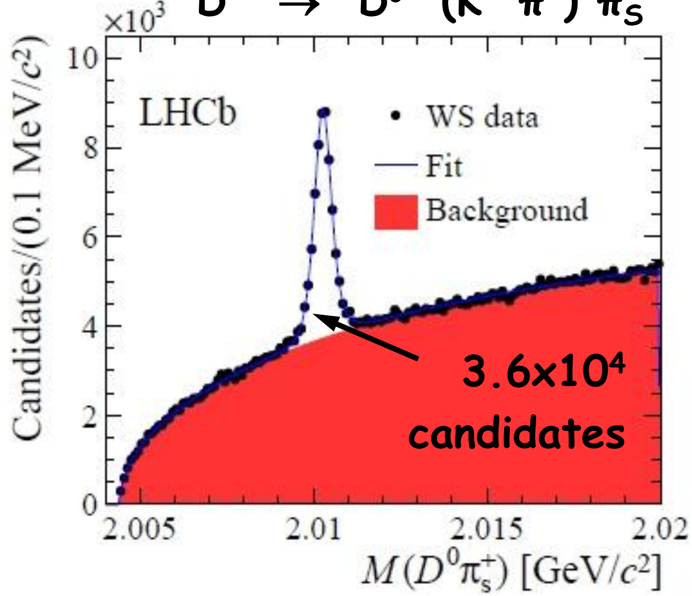
2011 data, 1 fb^{-1}

- Use prompt $D^{*+} \to D^0 \pi_S^+$
- Charge of soft pion tags the initial flavor of the D^0.
- D^0 and π_S^+ required to form a vertex constrained to PV.

$D^{*+} \to$ "D^0" ($K^- \pi^+$) π_S^+



$D^{*+} \to$ "D^0" ($K^+ \pi^-$) π_S^+

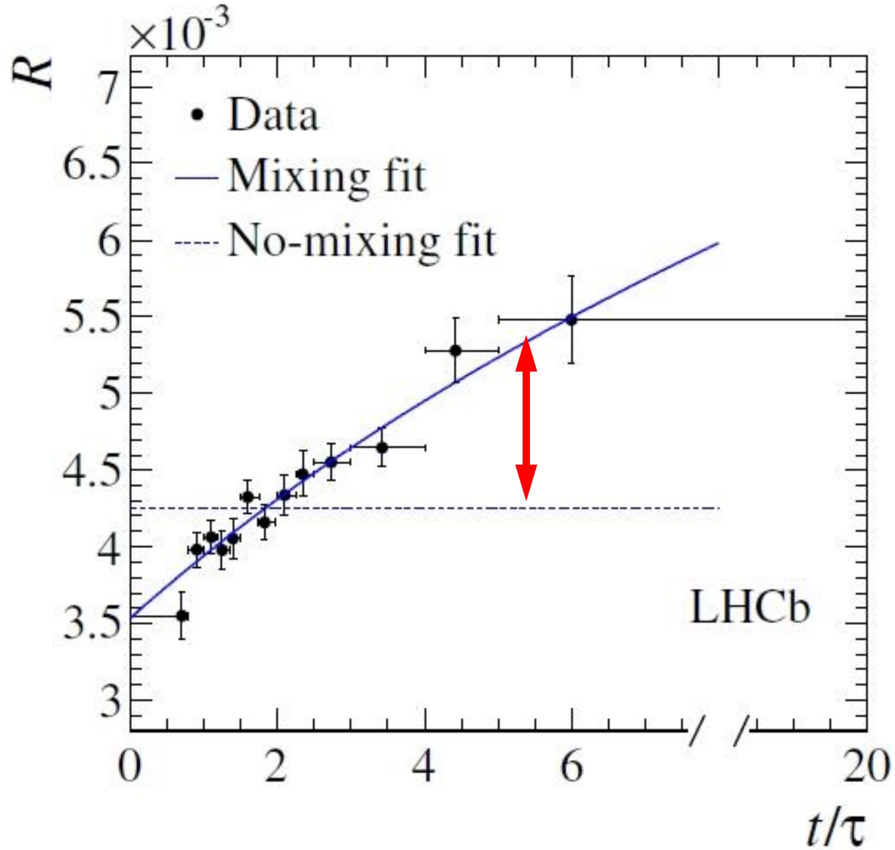


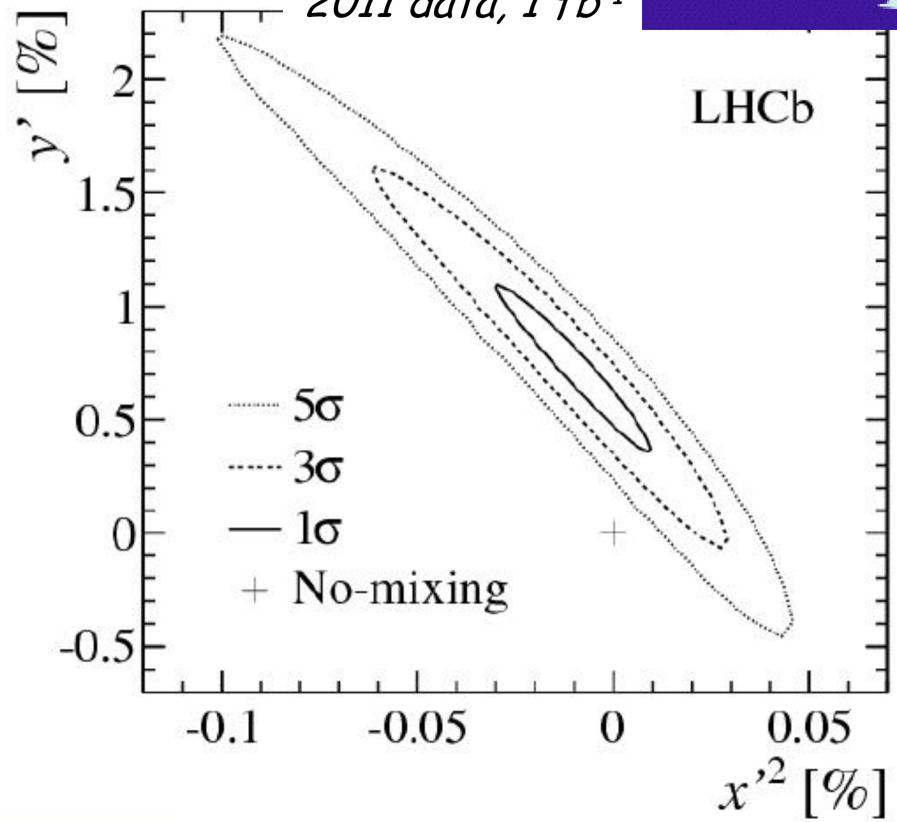
- Background of WS data dominated by real D^0 and a random pion.
- Contamination from $B \to D^0X$ reduced by IP cuts on D^0 and π_S^+.

- RS and WS yields determined in D^0 decay time bins
- Doubly misidentified RS events contribution to WS signal : $(0.4 \pm 0.2)\%$
- Residual contamination from secondary D^0 from b-decays : $(2.7 \pm 0.2)\%$

PRL 110 (2013) 101802

2011 data, 1 fb^{-1}





Fit type	Parameter	Fit result (10^{-3})
Mixing	R_D	3.52 ± 0.15
	y'	7.2 ± 2.4
	x'^2	-0.09 ± 0.13
No mixing	R_D	4.25 ± 0.04

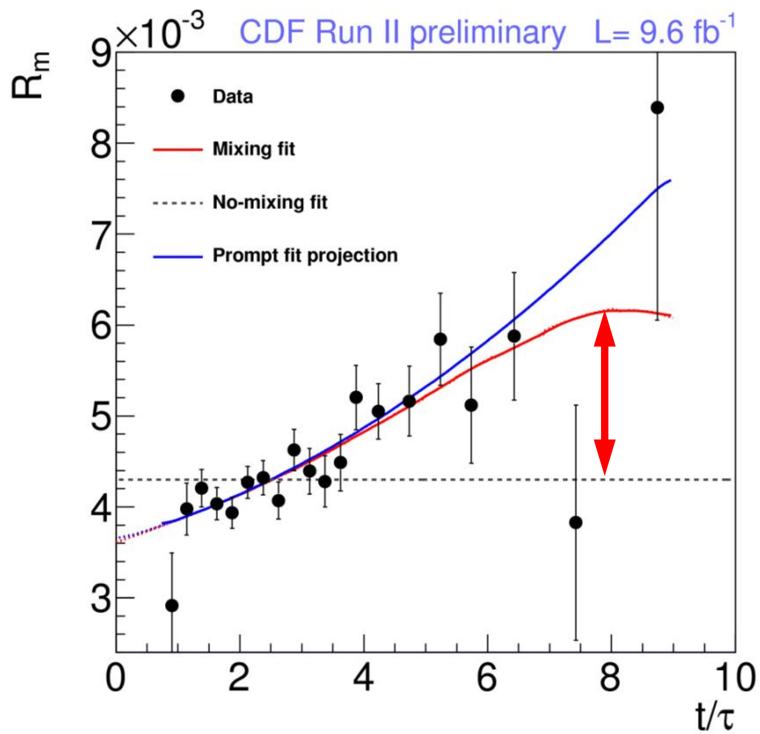
No mixing hypothesis excluded at > 9σ.

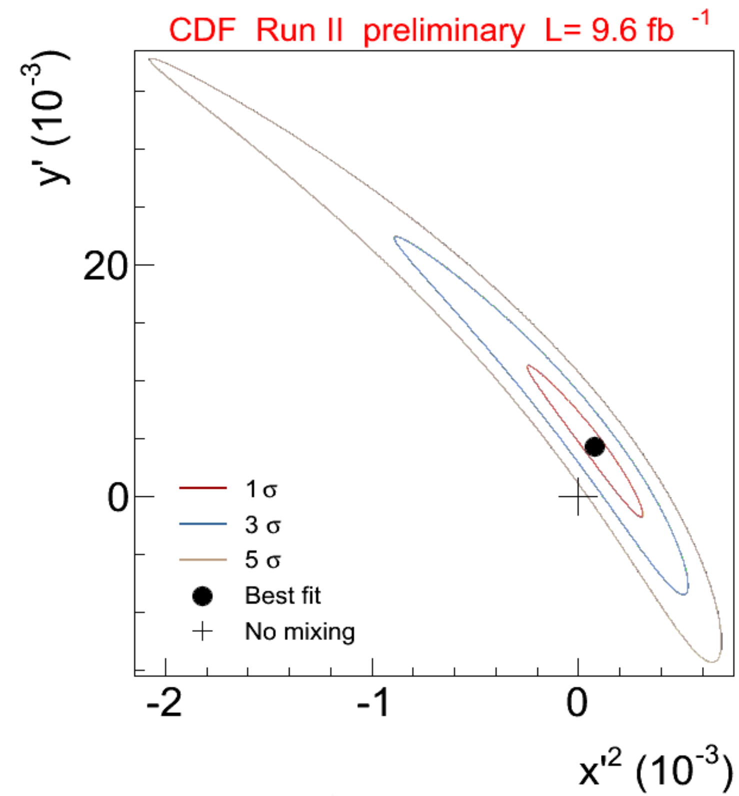
CDF: wrong sign $D^0 \rightarrow K\pi$ decay rate

CDF NOTE 10990 (2013)

9.6fb^{-1}

- Same technique
- Charge of soft pion tags the initial flavor of the D^0.
- Wrong sign: $D^{*+} \rightarrow$ "D^0" $(K^+ \pi^-)$ π_S^+



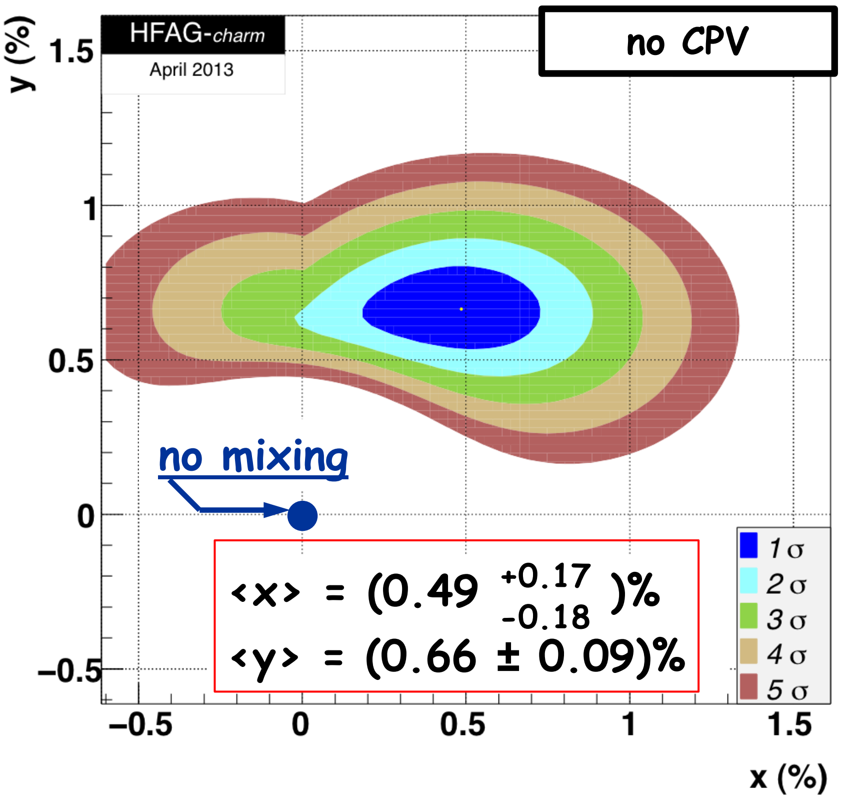


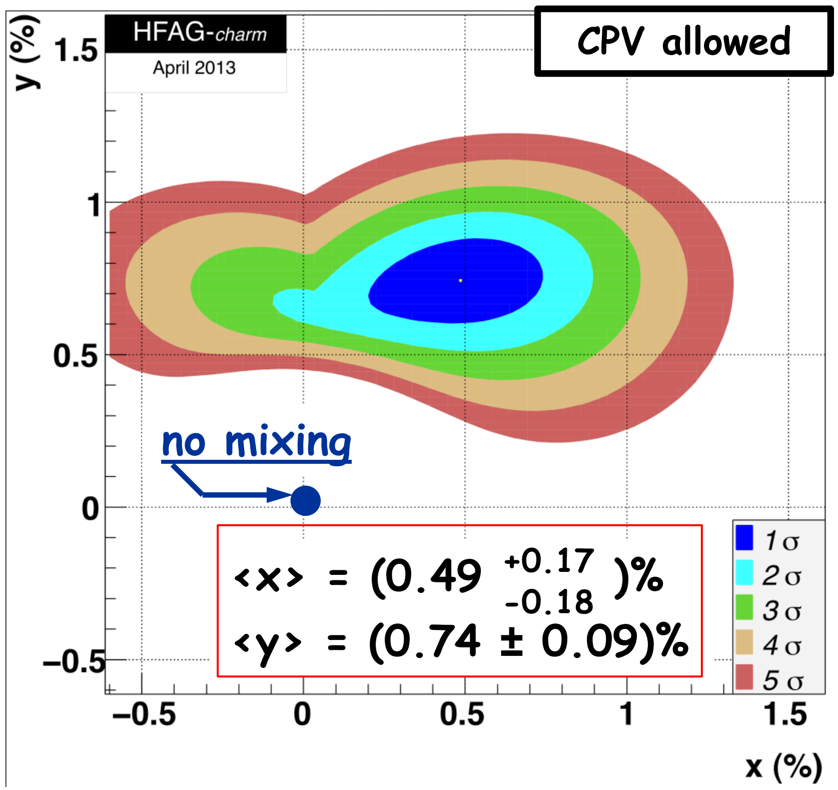
$R_D(10^{-3})$	$y'(10^{-3})$	$x'^2(10^{-3})$	σ no mixing
3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18	6.1

No mixing hypothesis excluded at > 6σ.

$D^0\bar{D}^0$ mixing : HFAG averages

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



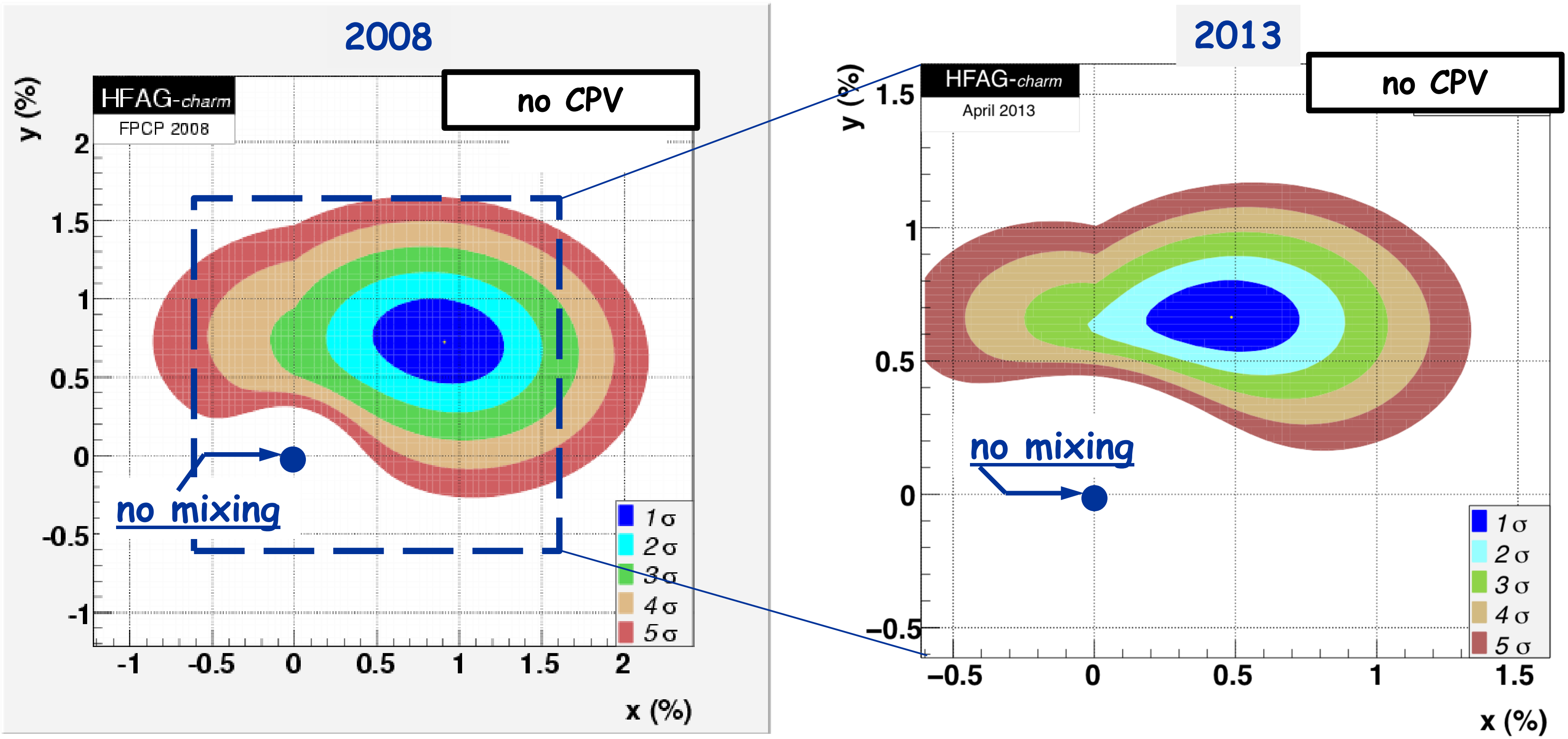


Wrong sign $D^0 \to K\pi$ latest results

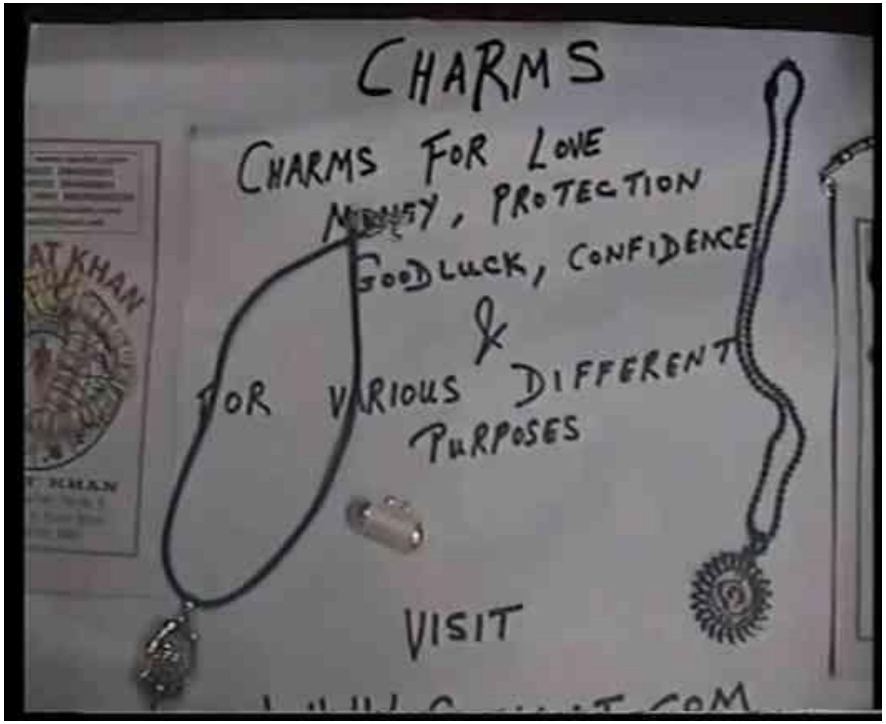
	R_D (10^{-3})	y' (10^{-3})	x'^2 (10^{-3})
LHCb	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13
Belle	3.64 ± 0.17	$0.6^{+4.0}_{-3.9}$	$0.18^{+0.21}_{-0.23}$
BaBar	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
CDF	3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18

$D^0\bar{D}^0$ mixing : HFAG average evolution over 5 years

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



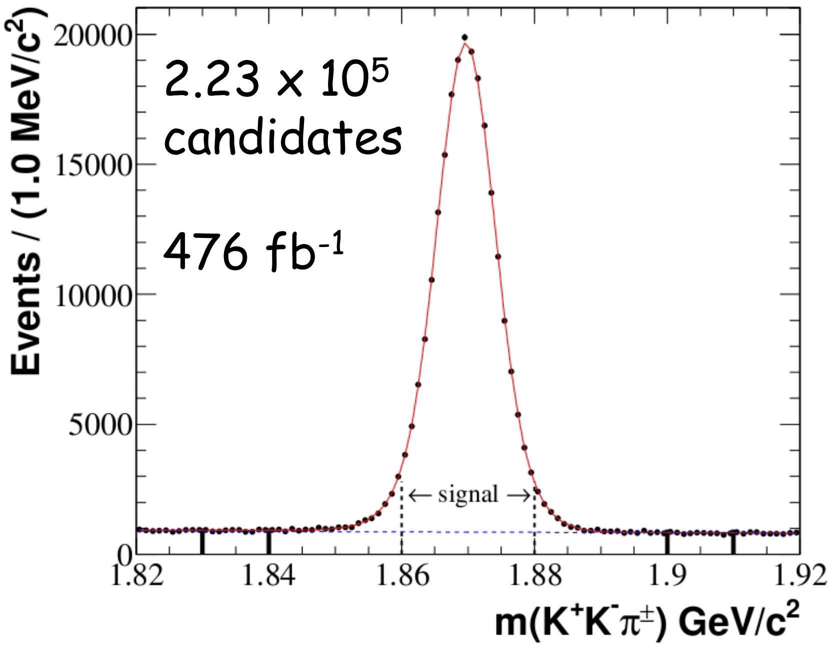
Search for CPV in charm sector



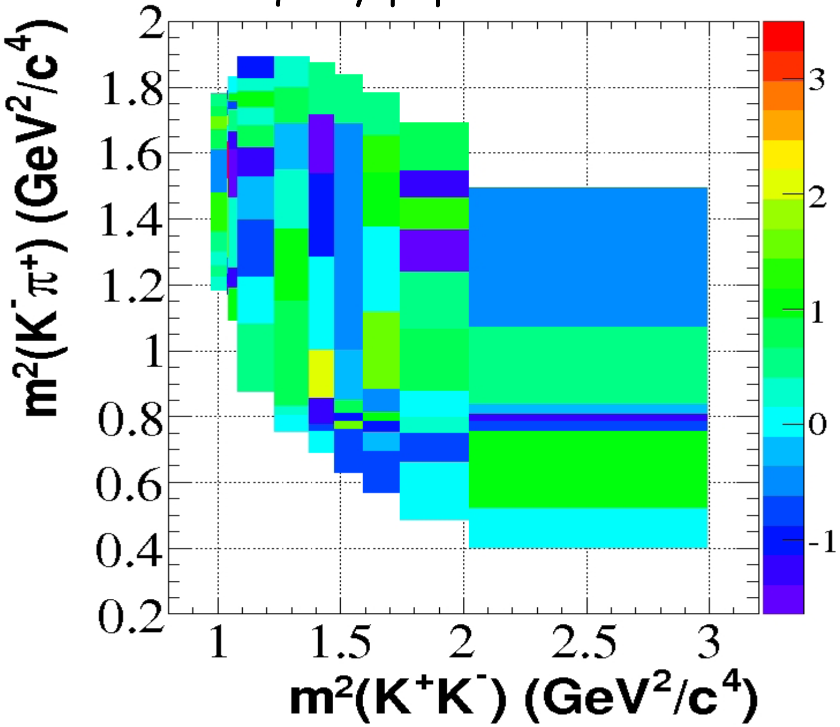
PRD 87,052010 (2013)

- Asymmetry in total rate:

$$A_{CP} = \frac{\Gamma(D^o \to f) - \Gamma(\overline{D}^o \to \overline{f})}{\Gamma(D^o \to f) + \Gamma(\overline{D}^o \to \overline{f})}$$



Normalized residuals of the *D* Dalitz plots in equally populated intervals

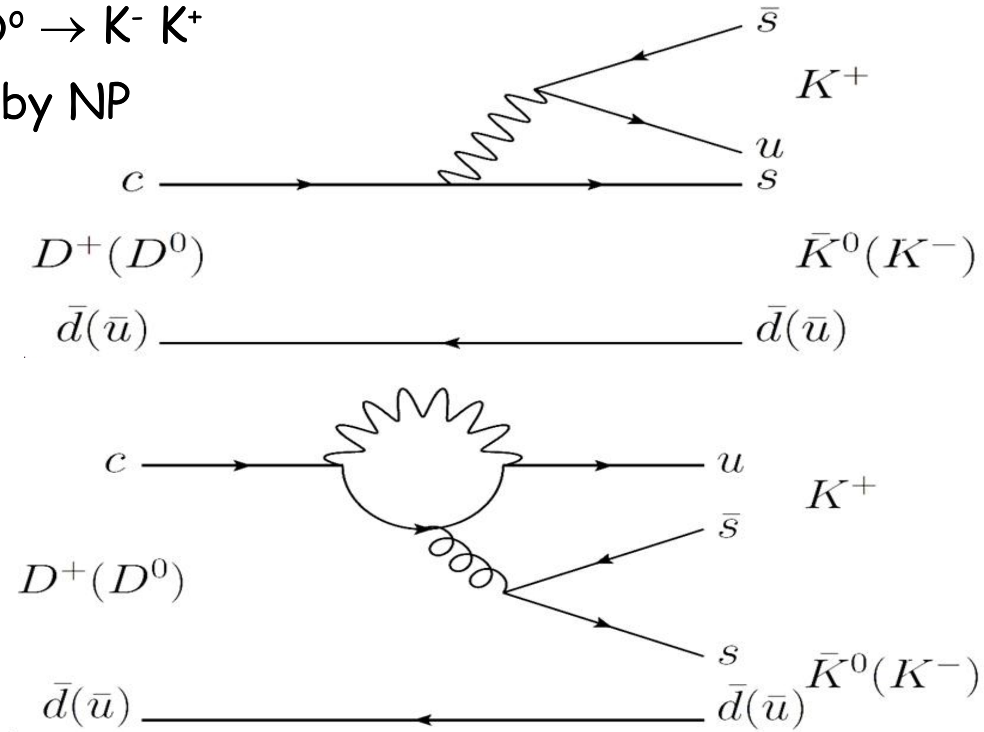


- Model-independent search over the Dalitz plot:
  p-value = 72% for no CPV
- Model-dependent search (simultaneous fit to the D^+ and D^- Dalitz plots):
  no indication of CPV in relative phases and magnitudes

$$\boxed{A_{CP} = (0.37 \pm 0.30 \pm 0.15)\%}$$

Search for CPV in $D_{(s)}^+ \to K_S^0 h^+$

- Similar diagrams for $D^+ \to K_S^0 K^+$ and $D^0 \to K^- K^+$
- Penguin contribution may be enhanced by NP



- $D^+ \to K_S^0 \pi^+$: direct CPV allowed from interference between CF and DCS amplitudes, negligible in SM.

- $D_s^+ \to K_S^0 \pi^+$: similar diagrams to $D^+ \to K_S^0 K^+$

- The CP asymmetry in $D_{(s)}^+ \to K_S^0 h^+$ accounts also for the $K^0\bar{K}^0$ mixing:

$$A_{CP}^{D_{(s)}^+ \to K_S^0 h^+} = \frac{\Gamma(D_{(s)}^+ \to \bar{K}^0 h^+)\,\Gamma(\bar{K}^0 \to \pi^+\pi^-) - \Gamma(D_{(s)}^- \to K^0 h^-)\,\Gamma(K^0 \to \pi^+\pi^-)}{\Gamma(D_{(s)}^+ \to \bar{K}^0 h^+)\,\Gamma(\bar{K}^0 \to \pi^+\pi^-) + \Gamma(D_{(s)}^- \to K^0 h^-)\,\Gamma(K^0 \to \pi^+\pi^-)}$$

$$= \frac{A_{CP}^{D_{(s)}^+ \to \bar{K}^0 h^+} + A_{CP}^{\bar{K}^0}}{1 + A_{CP}^{D_{(s)}^+ \to \bar{K}^0 h^+} \times A_{CP}^{\bar{K}^0}} \approx A_{CP}^{D_{(s)}^+ \to \bar{K}^0 h^+} + A_{CP}^{\bar{K}^0}$$

Search for CPV in $D_{(s)}^+ \to K_S^0 h^+$

- A_{CP} obtained from the **asymmetry in signal yields** :

$$A_{raw}^{D_{(s)}^+ \to K_S^0 h^+} = \frac{N(D_{(s)}^+) - N(D_{(s)}^-)}{N(D_{(s)}^+) + N(D_{(s)}^-)} = A_{CP}^{D_{(s)}^+ \to K_S^0 h^+} + A_{FB}^{D_{(s)}^+} + A_{Det}^{K^+} + A_{Det}^{K^0}$$

- **Detector-induced asymmetries** determined by a data-driven method :

Forward-backward asymmetry A_{FB} is an odd function of $\cos \theta^*_D$

$$A_{FB}^{D_{(s)}^+} = \frac{1}{2} [A_{raw}^{K_S^0 h^+}(+\cos\theta^*_D) - A_{raw}^{K_S^0 h^+}(-\cos\theta^*_D)]$$

$A_{Det}^{K^+}$ determined from the CF (no CPV) $D^0 \to K^- \pi^+$ and $D_s^+ \to \phi \pi^+$ decays, assuming $A_{FB}^{D^0} = A_{FB}^{D_s^+}$:

$$A_{raw}^{D^0 \to K^- \pi^+} = A_{FB}^{D^0} + A_{Det}^{K^+} + A_{Det}^{\pi^+}$$

$$A_{raw}^{D_s^+ \to \phi \pi^+} = A_{FB}^{D_{(s)}^+} + A_{Det}^{\pi^+}$$

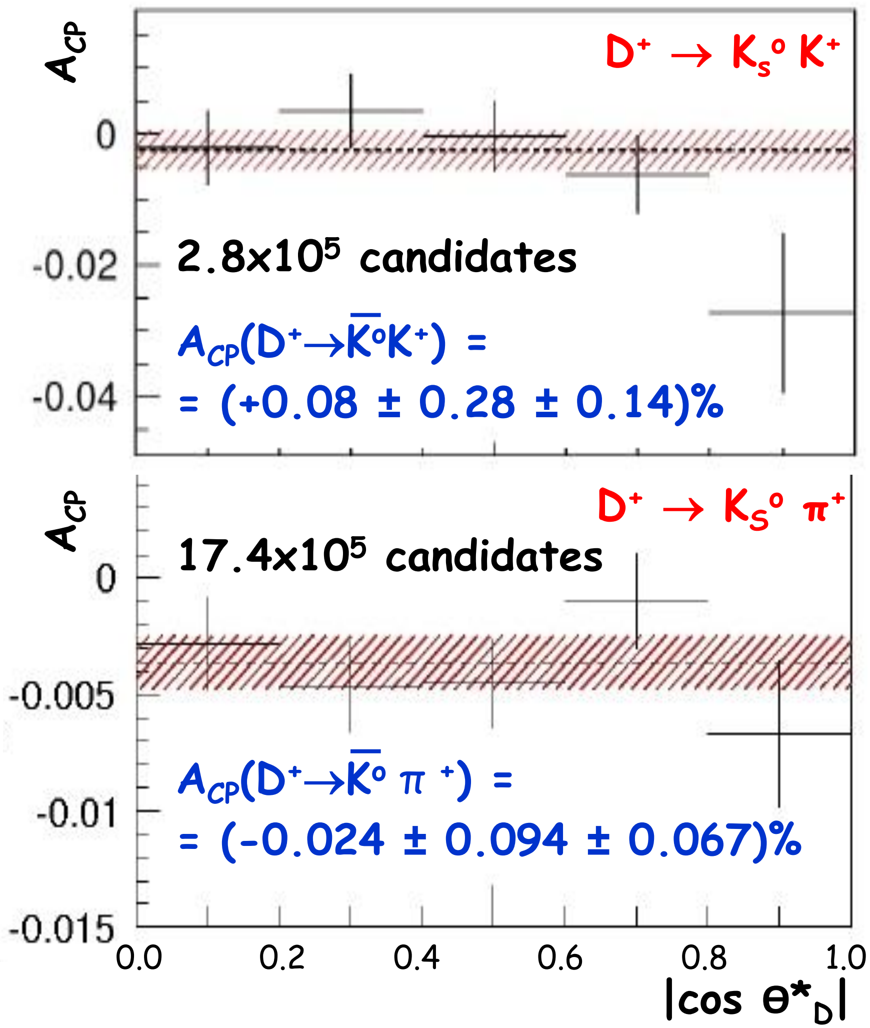
Detection asymmetry (BELLE) due to difference in interactions with matter for K^0 and $\overline{K^0}$ estimated numerically : $A_{Det}^{K^0} \approx 0.1\%$

B.R. Ko, E. Won, B. Golob, P. Pakhlov, PRD 84 (2011) 111501

Search for CPV in $D_{(s)}^+ \to K_S^0 h^+$

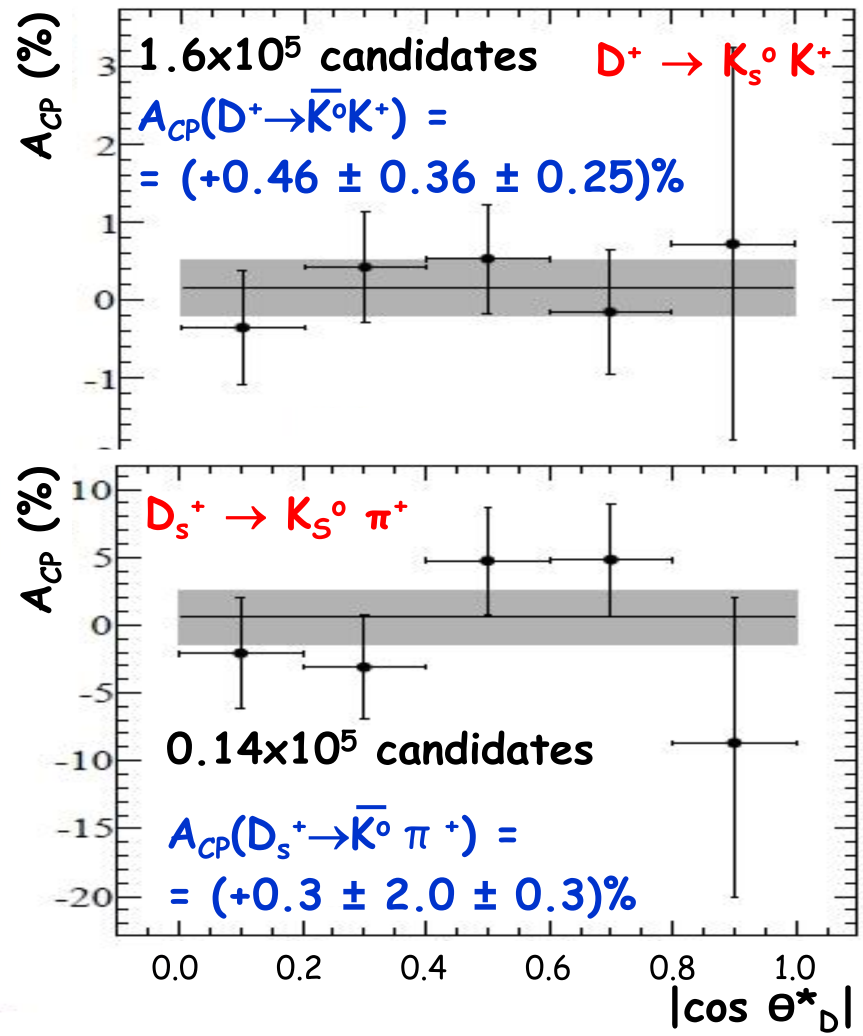
JHEP 02 (2013) 098
PRL 109 (2012) 021601

977 fb^{-1}



PRD 87 (2013) 052012

469 fb^{-1}



- CPV (charm only !) compatible with zero in all the three decay modes.

Search for direct CPV in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$

JHEP 1306 (2013) 112

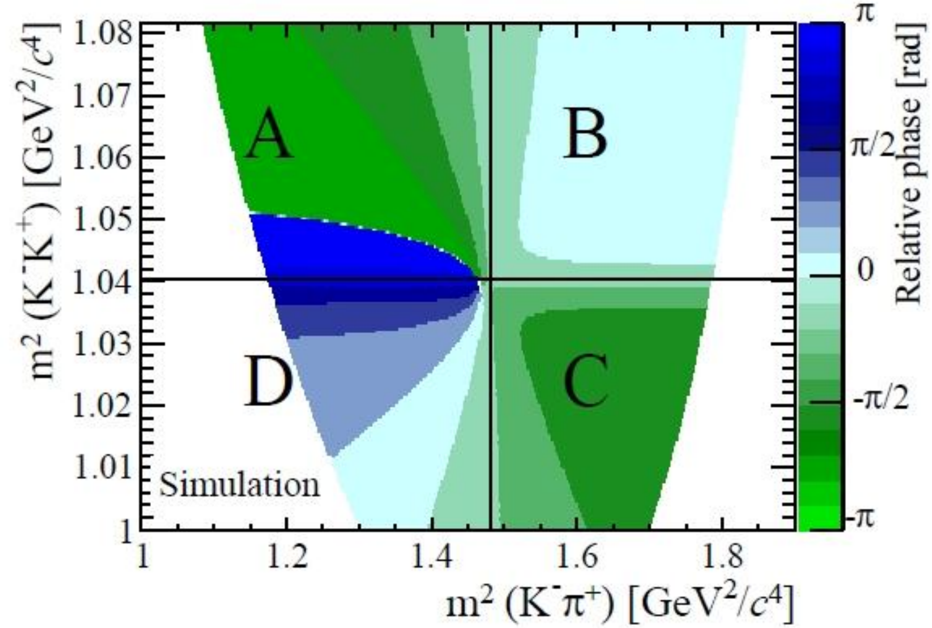
2011 data, 1 fb^{-1}

- Look for direct CPV in the ϕ region of the $D^+ \to K^-K^+\pi^+$ Dalitz plot :

$$A_{CP}^{D^+\to\phi\pi^+} = A_{raw}^{D^+\to\phi\pi^+} - A_{raw}^{D^+\to K_S\pi^+} + A_{CP}^{K^0-\bar{K}^0}$$

- A complementary observable, sensitive to asymmetries that change sign (according to the strong phase variation along the ϕ band, $1.00\ GeV/c^2 < M(K^+K^-) < 1.04\ GeV/c^2$)

$$A_{CP|S} = \tfrac{1}{2}\left[A_{raw}^{A} + A_{raw}^{C} - A_{raw}^{B} - A_{raw}^{D} \right]$$



- A concurrent measurement :

$$A_{CP}^{D_s^+\to K_S^0\pi^+} = A_{raw}^{D_s^+\to K_S^0\pi^+} - A_{raw}^{D_s^+\to\phi\pi^+} + A_{CP}^{K^0-\bar{K}^0}$$

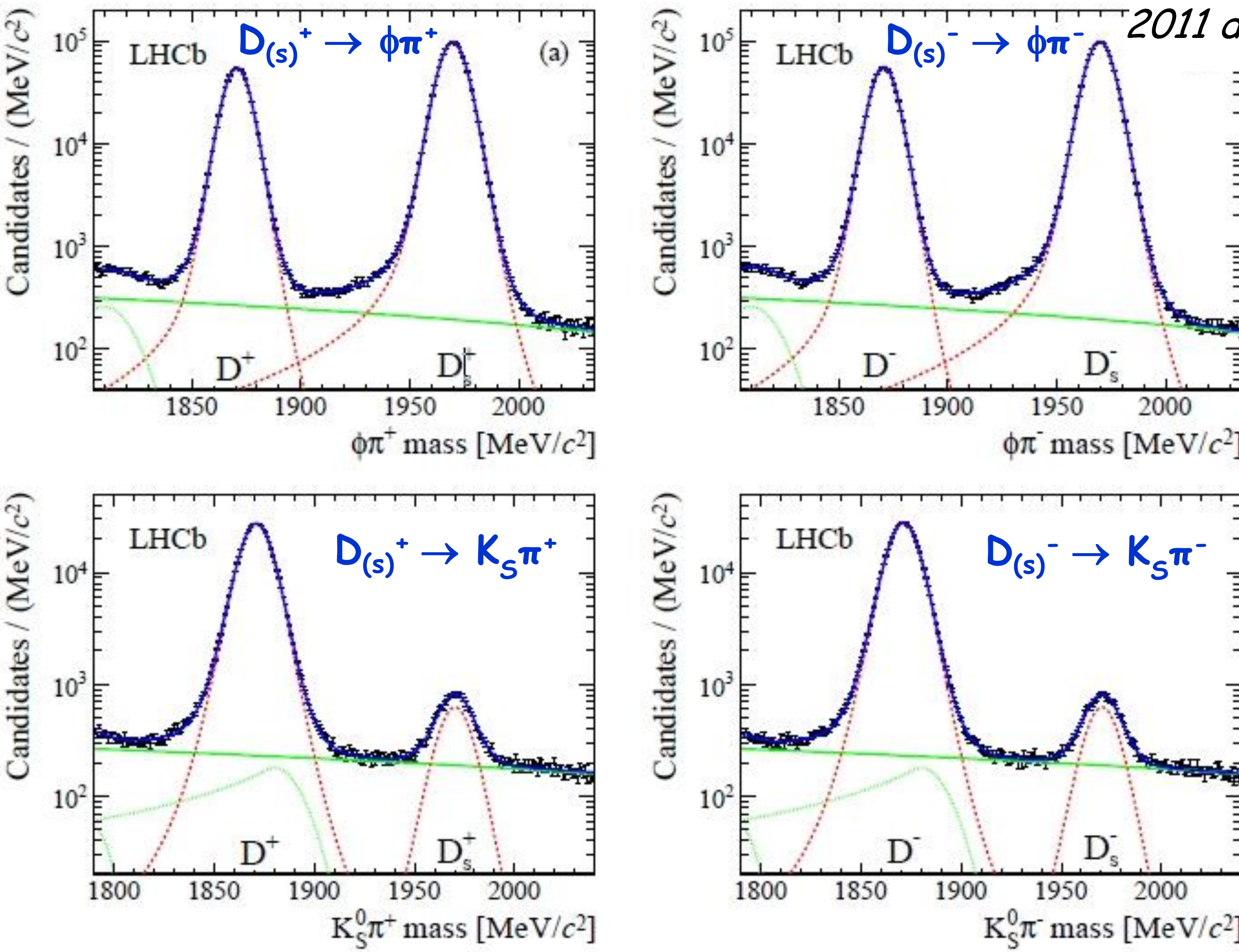
correction for CPV in neutral kaon system, $(-0.028 \pm 0.028)\%$
PLB 718 (2013) 902

- Analysis in 12 bins of p_T, η

Search for direct CPV in $D^+ \to \phi\,\pi^+$ and $D_s^+ \to K_S^0\,\pi^+$

JHEP 1306 (2013) 112

2011 data, 1 fb^{-1}



signal

combinatorial background

background from $D_S^+ \to \phi\pi^+\pi^0$

1.6×10^6 $D^+ \to \phi\,\pi^+$

3.0×10^6 $D_s^+ \to \phi\,\pi^+$

signal

combinatorial background

background from $D_S^+ \to K_S\pi^+\pi^0$, $D_S^+ \to K_S K^+$

1.1×10^6 $D^+ \to K_S\,\pi^+$

2.5×10^4 $D_s^+ \to K_S\,\pi^+$

$A_{CP}\ (D^+ \to \phi\,\pi^+) = (-0.04 \pm 0.14 \pm 0.13)\%$

$A_{CP|S}\ (D^+ \to \phi\,\pi^+) = (-0.18 \pm 0.17 \pm 0.18)\%$

$A_{CP}\ (D_s^+ \to K_S^0\,\pi^+) = (+0.61 \pm 0.83 \pm 0.13)\%$

→ *No evidence for CPV*

- Time-dependent CP asymmetry for D^0 decays to a CP eigenstate f:

$$A_{CP}(f,t) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \approx a_{CP}^{dir}(f) + t/\tau\, a_{CP}^{ind}$$

universal to a good approximation

$$\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+) = a_{CP}^{dir}(K^- K^+) - a_{CP}^{dir}(\pi^- \pi^+) + \Delta\langle t\rangle/\tau\, a_{CP}^{ind}$$

difference in average decay time

- Tag D^0 flavour using prompt $D^{*+} \to D^0 \pi_S^+$

$$A_{raw}(f) = \frac{N(D^{*+} \to D^0 \pi_S^+) - N(D^{*-} \to \bar{D}^0 \pi_S^-)}{N(D^{*+} \to D^0 \pi_S^+) + N(D^{*-} \to \bar{D}^0 \pi_S^-)}$$

- To first order $A_{raw}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_S^+) + A_P(D^{*+})$

- $A_D(K^- K^+) = A_D(\pi^- \pi^+) = 0$, $A_D(\pi_S^+)$ and $A_P(D^{*+})$ independent of f

  ➔ $\Delta A_{CP} = A_{raw}(K^- K^+) - A_{raw}(\pi^- \pi^+)$

Search for time-integrated CPV in $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$: D* tag

Status of measurements by the end of 2012

Exp.	Ref.	ΔA_{CP} (%)
LHCb	PRL 108 (2012) 111602	$-0.82 \pm 0.21 \pm 0.11$
CDF	PRL 109 (2012) 111801	$-0.62 \pm 0.21 \pm 0.10$
BELLE	arXiv:1212.1975 (prelim.)	$-0.87 \pm 0.41 \pm 0.06$
BaBar	PRL 100 (2008) 061803	$+0.24 \pm 0.62 \pm 0.26$

Agreement with no CP violation : CL = 2.0×10^{-5}

- BaBar, BELLE and CDF also quoted individual asymmetries for $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ channels with partially cancelled systematics in the ratio.

- LHCb update 2013

LHCb-CONF-2013-003

2011 data, 1 fb^{-1}

2.2×10^6 $D^0 \to K^- K^+$
0.7×10^6 $D^0 \to \pi^- \pi^+$

$\Delta \langle t \rangle / \tau = (11.19 \pm 0.13 \pm 0.17)\%$

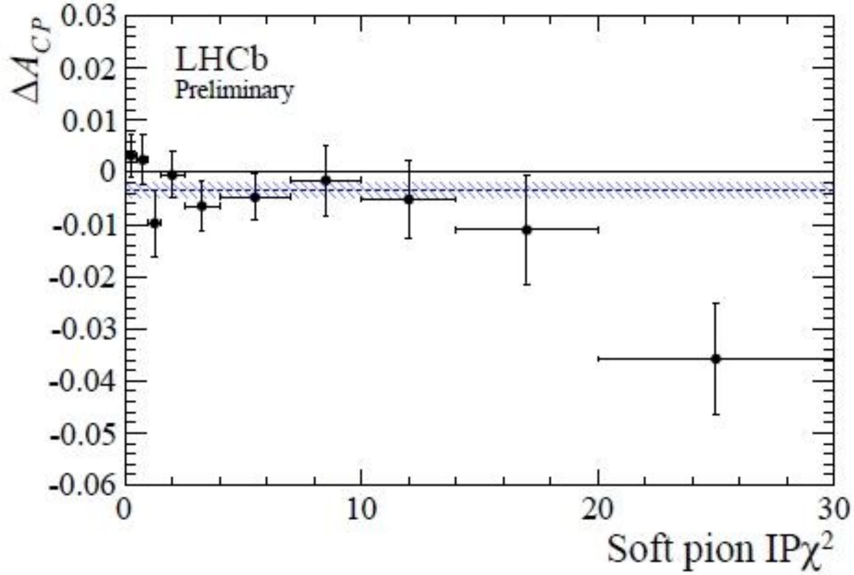
ΔA_{CP} : tag D^0 via prompt D^{*+}, LHCb update 2013

LHCb-CONF-2013-003

2011 data, 1 fb^{-1}

- Fiducial cuts to exclude kinematic regions with large π_S^+ detection asymmetry.
- IP cut to reduce contamination from D^0 originated from b-hadron decays.
- Constrain the D^{*+} vertex to match the PV improves ΔM resolution.
- Data divided into several disjoint samples (magnet polarity, hardware trigger).
- Signal yields extracted from a fit to $\Delta M = M(h^- h^+ \pi^+) - M(h^- h^+) - M(\pi^+)$
- Weighting to account for differences in kinematics of two final states, needed for proper cancellation of production and detection asymmetries

source	Uncertainty(%)
Fiducial cut	0.02
Peaking Background	0.04
Fit model	0.03
Multiple candidates	0.01
Weighting	0.01
Soft pion IP$_{\chi^2}$	0.08
Total	0.10



ΔA_{CP} = (-0.34 ± 0.15 ± 0.10)%

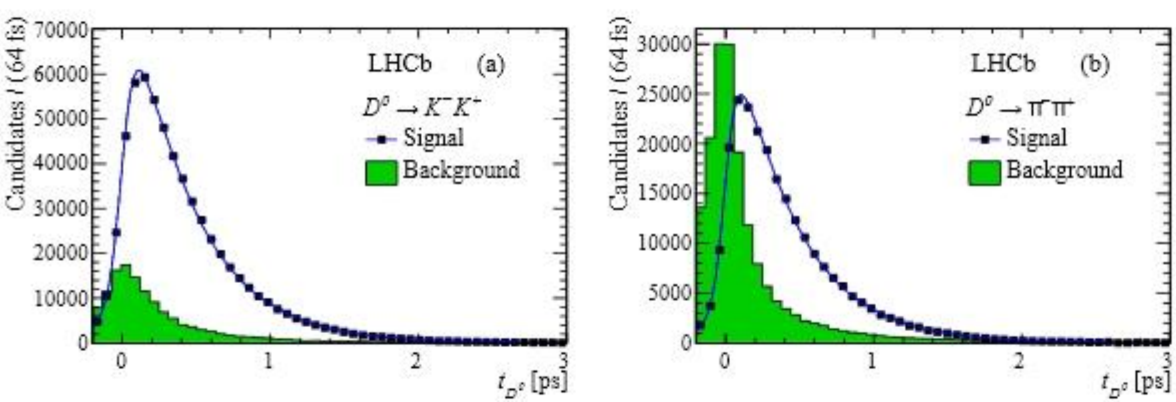
- Tag D^o flavour using muon sign in $b \to D^o \mu X$
- Statistically independent from the prompt D* sample.
- Lower rate vs. higher trigger efficiency.
- Different trigger composition and systematics.

$$A_{raw} = \frac{\Gamma(D^o \to f)\, \varepsilon(\mu^-)\, P(D^o) - \Gamma(\bar{D}^o \to f)\, \varepsilon(\mu^+)\, P(\bar{D}^o)}{\Gamma(D^o \to f)\, \varepsilon(\mu^-)\, P(D^o) + \Gamma(\bar{D}^o \to f)\, \varepsilon(\mu^+)\, P(\bar{D}^o)} \approx A_{CP}{}^f + A_D{}^\mu + A_P{}^B$$

$$\Delta A_{CP} = A_{raw}\,(K^- K^+) - A_{raw}\,(\pi^- \pi^+) \approx A_{CP}\,(K^- K^+) - A_{CP}\,(\pi^- \pi^+)$$

PLB 723 (2013) 33

2011 data, 1 fb^{-1}



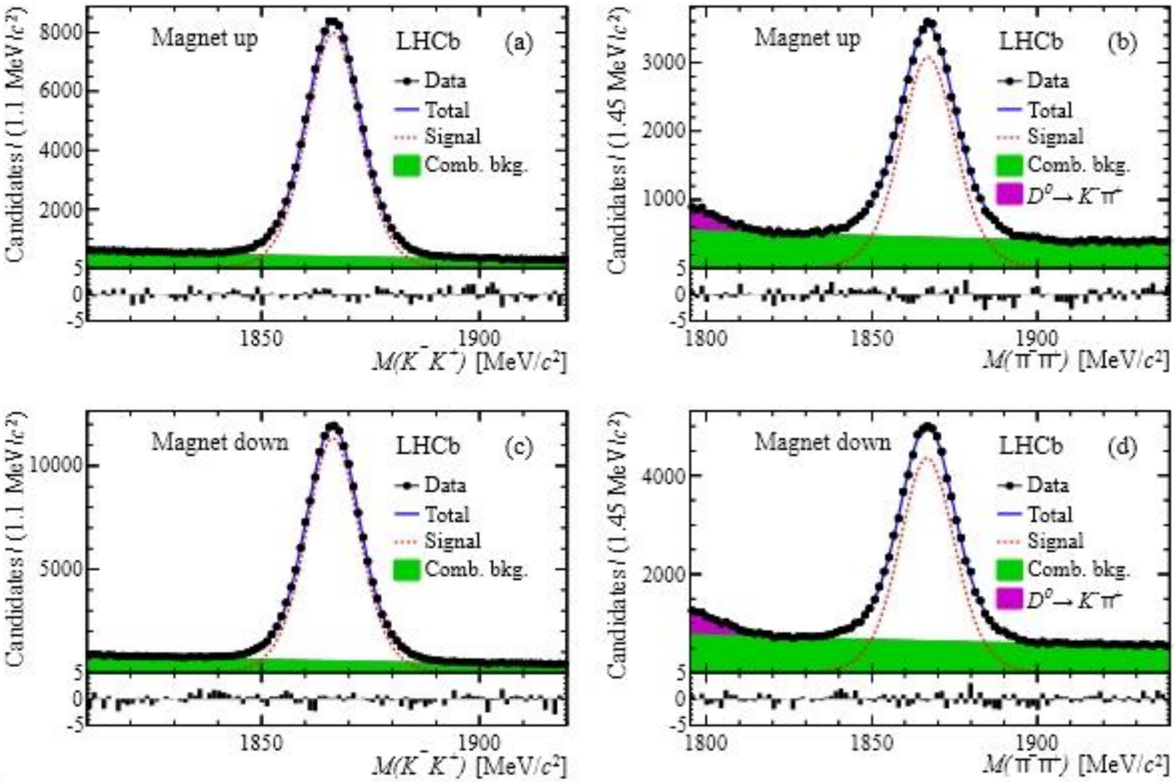
$\Delta \langle t \rangle / \tau = (1.8 \pm 0.7)\%$

$\rightarrow \Delta A_{CP} \approx \Delta a_{CP}^{dir}$

ΔA_{CP} : tag D° via semileptonic b-decays

5.6×10^5 $D^0 \to K^- K^+$ 2.2×10^5 $D^0 \to \pi^- \pi^+$ PLB 723 (2013) 33

2011 data, 1 fb^{-1}



- Raw asymmetries from a **simultaneous fit of four data subsets**
- **Weighting** to account for differences in kinematics of two final states, needed for proper cancellation of production and detection asymmetries
- Flavor tagging validated on data

$b \to D^0 \mu X$ ΔA_{CP} = (+0.49 ± 0.30 ± 0.14)%

PLB 723 (2013) 33

Prompt D^* ΔA_{CP} = (-0.34 ± 0.15 ± 0.10)%

LHCb-CONF-2013-003

$\boxed{\Delta A_{CP} = (-0.15 \pm 0.16)\%}$

No evidence for CPV

Multi-body D^0 decays : $D^0 \to K^- K^+ \pi^- \pi^+$, $D^0 \to \pi^- \pi^+ \pi^- \pi^+$

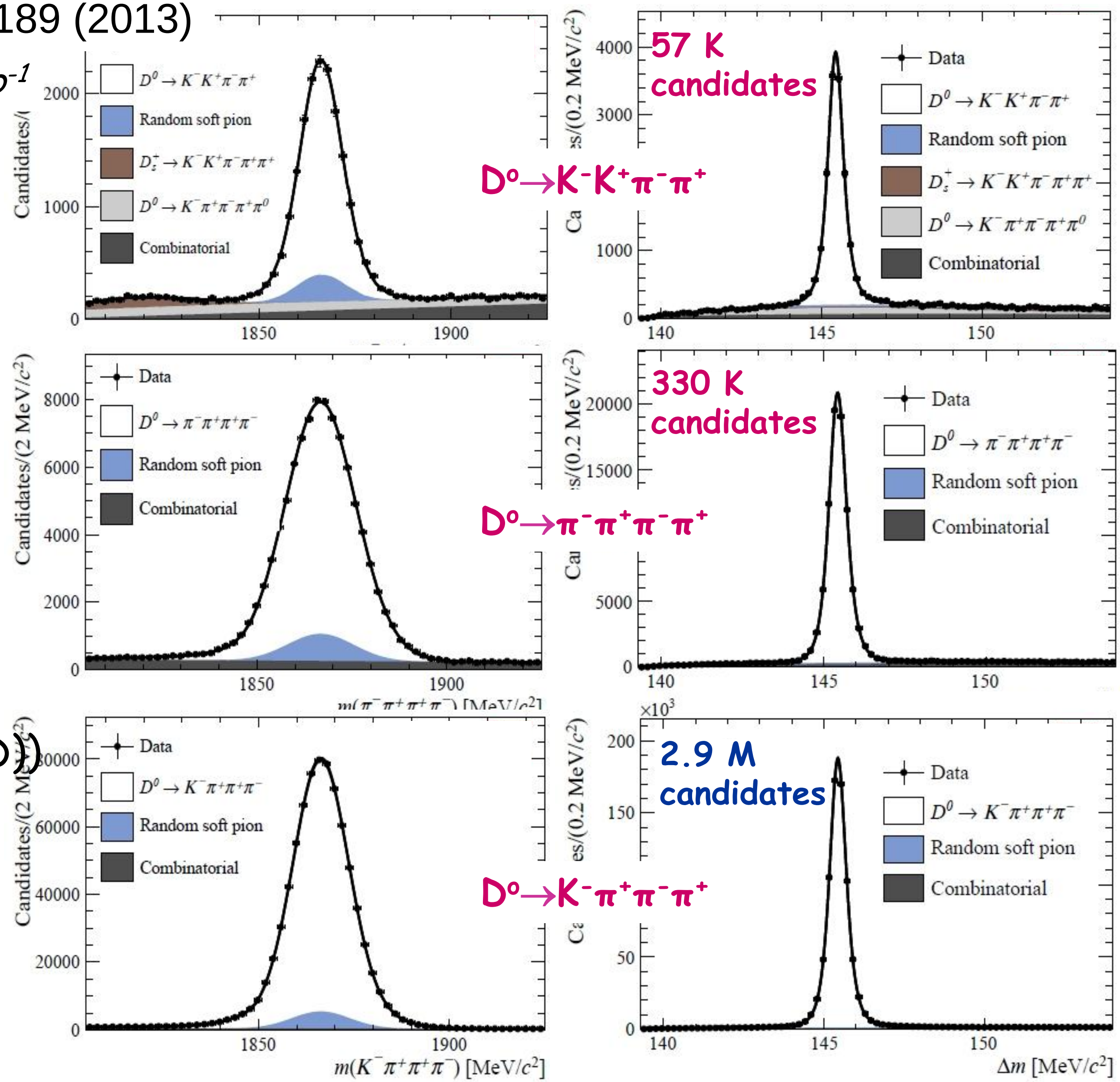
- Majority of D^0 non-CP eigenstates are resonances.
  - → Dalitz-plot like techniques allow to sum up several resonances
    - → Increased statistics
    - → Extract information about strong phase
- Many resonances in $\mathbf{D^0 \to K^- K^+ \pi^- \pi^+}$: $D^0 \to \phi\, \rho$, $K_1(1270)^\pm\ K^\mp$, $K^*(1410)^\pm\ K^\mp$, …
  and $\mathbf{D^0 \to \pi^- \pi^+ \pi^- \pi^+}$: $D^0 \to \rho\, \rho$, $a_1(1260)^+\ K^-$, …
- Tree and penguin CS amplitudes
- Look for direct CPV in regions of 4-body phase space → 5 combinations of 2- and 3-body invariant mass squared
- Multi-dimensional analysis in future, $D^0 \to (1, 2, 3, 4)$: $s(1, 2)$, $s(2, 3)$, $s(3, 4)$, $s(1, 2, 3)$, $s(2, 3, 4)$
- Use prompt sample $D^{*+} \to D^0 \pi_S^+$
- No direct CPV assumed in $D^0 \to K^- \pi^+ \pi^- \pi^+$, use as control channel

Multi-body D^0 decays : $D^0 \to K^- K^+ \pi^- \pi^+$, $D^0 \to \pi^- \pi^+ \pi^- \pi^+$

arXiv:1308.3189 (2013)

2011 data, 1 fb^{-1}

- Use prompt sample $D^{*+} \to D^0 \pi_S^+$
- Tag D^0 flavour using π_S
- Signal extraction via sPlot technique
- Fit (m, Δm) plane to extract sWeights, ($m(D)$, $\Delta m = m(D\,\pi_S^+) - m(D)$)



arXiv:1308.3189 (2013)

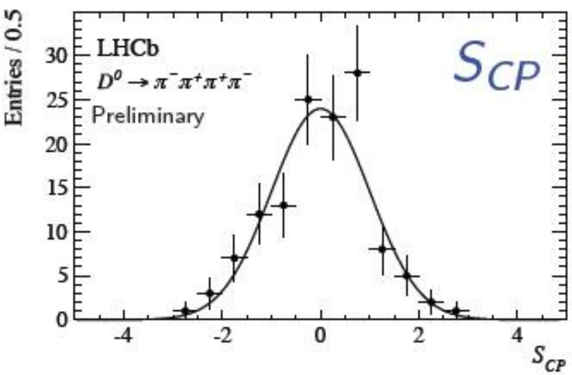
2011 data, 1 fb^{-1}

- Miranda method: signicance in equally populated bins of 5D phase space :

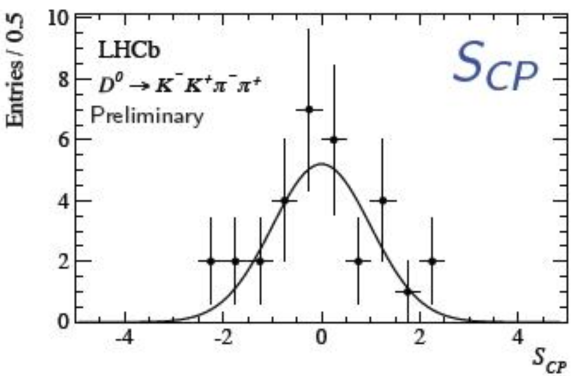
$$s^i_{CP} = \frac{N_i(D^0) - \alpha\, N_i(\bar{D}^0)}{\sqrt{\alpha\,(\,\sigma_i^2\,(D^0) - \sigma_i^2\,(\bar{D}^0)\,)}}\ ,\quad \alpha = \frac{\Sigma_i\, N_i(D^0)}{\Sigma_i\, N_i(\bar{D}^0)}$$

- No CPV = Gaussian distribution

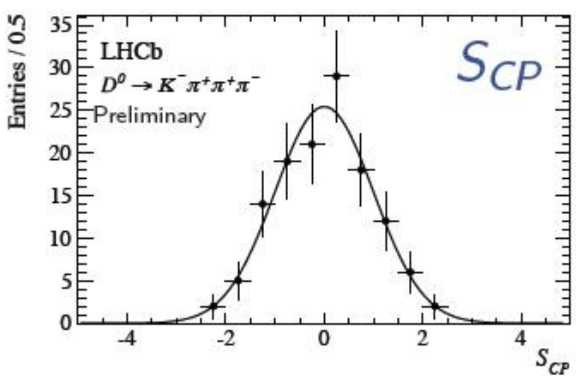
$D^0 \to \pi^- \pi^+ \pi^- \pi^+$



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



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

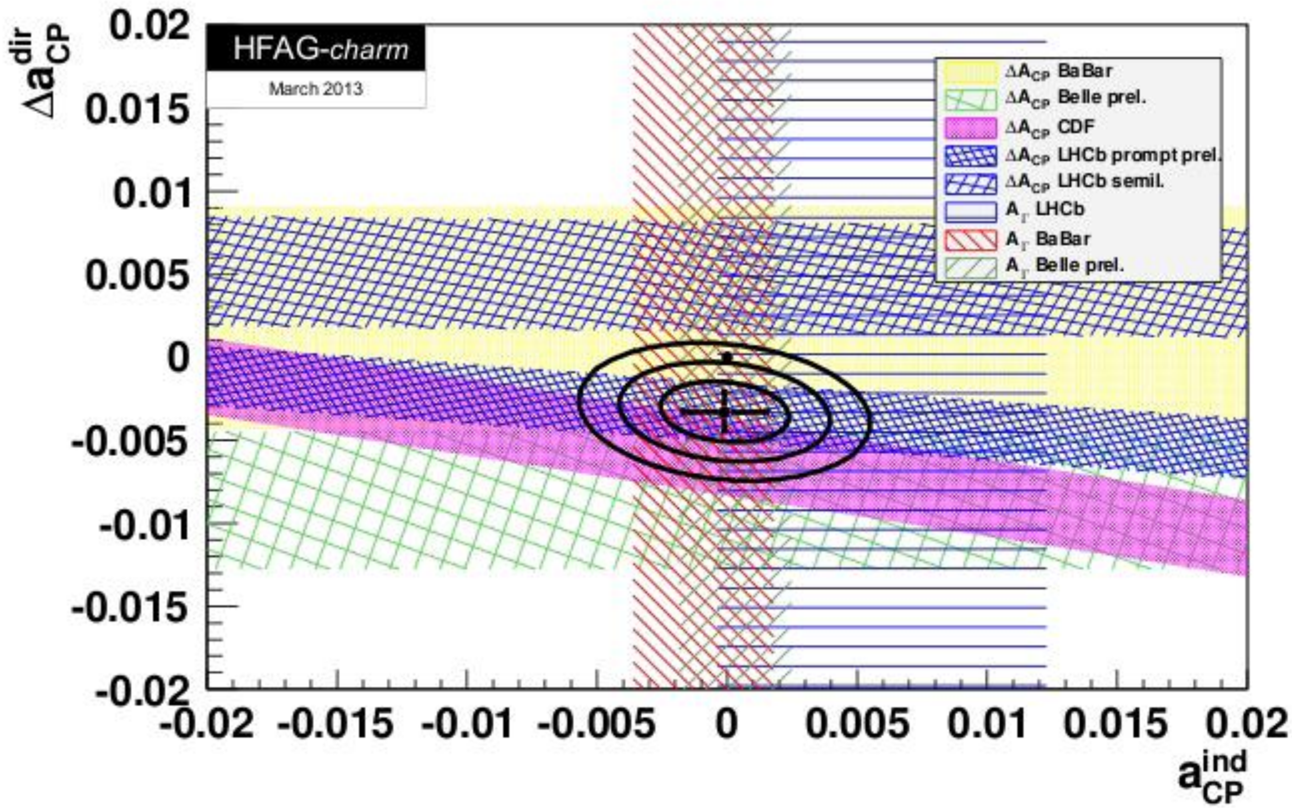


Consistent with no CPV

No evidence for local asymmetries

ΔA_{CP} : HFAG average

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



Data consistent with no CPV at CL = 2.1%

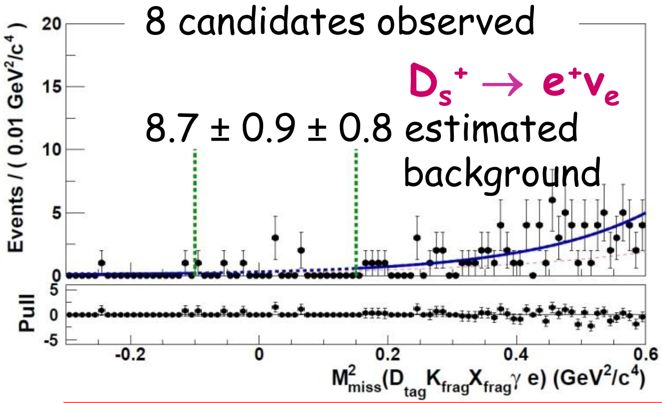
Δa_{CP}^{dir} = (-0.329 ± 0.121)%, a_{CP}^{ind} = (-0.010 ± 0.162)%

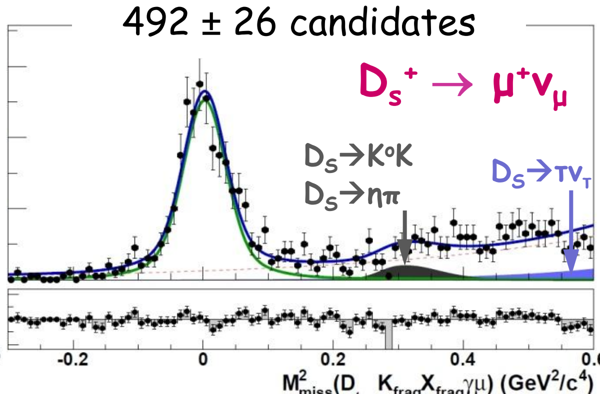
No evidence (yet) of CPV in D sector

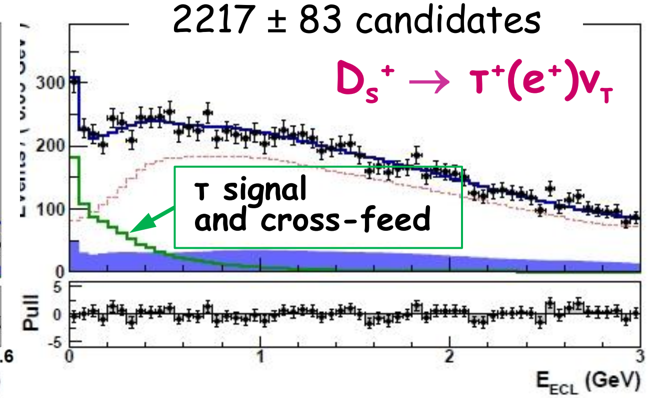
Charm decays: selected results

D_s^+ leptonic decays

- Inclusive counting of D_s^+ arXiv:1307.6240 (2013)
- $e^+e^- \to c\bar{c} \to D_{tag}\, K_{frag}\, X_{frag}\, D_s^{*-},\ D_s^{*-} \to D_s^- \gamma$ *913 fb^{-1}*

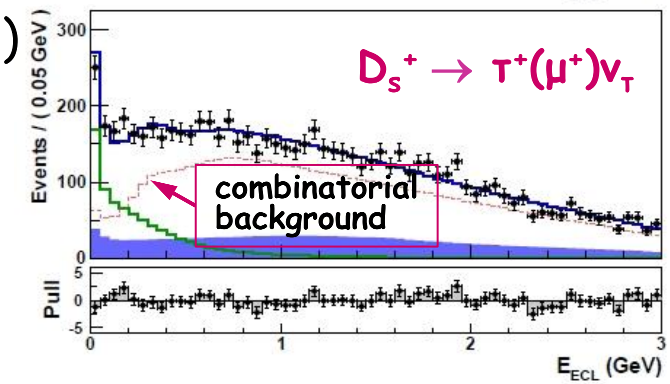






- $\boxed{BR(D_s^+ \to e^+\nu_e) < 0.83 \times 10^{-4}\ @\ 90\%\ CL}$ (10^{-7} in SM)

  most stringent UL



- $BR(D_s^+ \to \mu^+\nu_e) = (5.31 \pm 0.28 \pm 0.20)\ 10^{-3}$

  $BR(D_s^+ \to \tau^+\nu_e) = (5.70 \pm 0.21\ ^{+0.31}_{-0.30})\ 10^{-3}$

Lepton flavour universality:

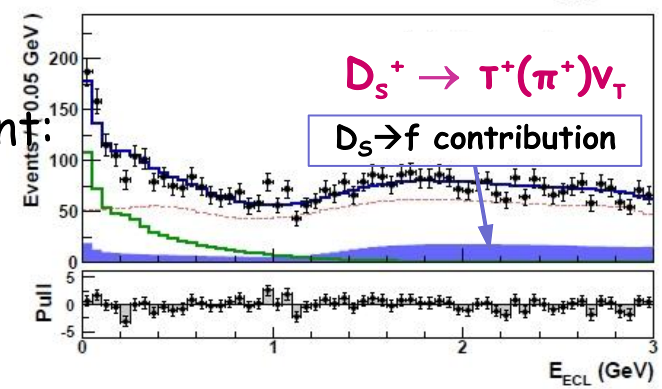
$\boxed{R^{D_s}_{\tau/\mu} = 10.73 \pm 0.69\ ^{+0.56}_{-0.53}}$ SM: $R^{D_s}_{\tau/\mu} = 9.762 \pm 0.031$

- D_s^+ **decay constant**, single most precise measurement:

$\boxed{f_{D_s^+} = (255.5 \pm 4.2_{stat.} \pm 4.8_{syst.} \pm 1.8_{\tau_{D_s}})\ \mathrm{MeV}}$

No more tension with unquenched LQCD :

$f_{D_s^+} = (248 \pm 2.5)$ MeV *PRD 82 (2010) 114504*



Wrong sign $D^0 \to K^+\pi^-\pi^+\pi^-$ decay

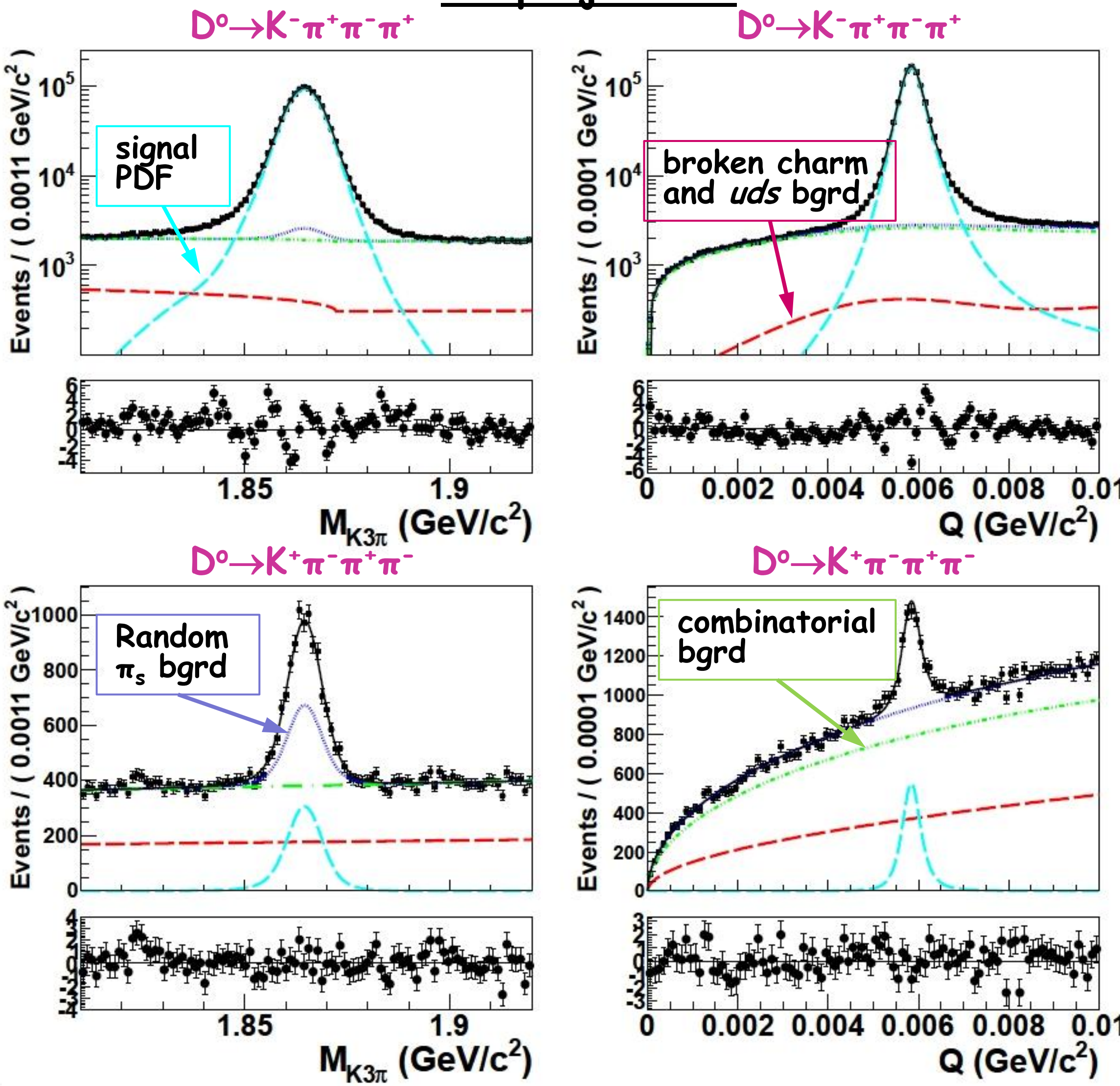
arXiv:1307.5935 (2013)

- Important for mixing studies
- $\mathbf{R_{WS}} = \Gamma_{DCSD}/\Gamma_{CAD} = (x'^2+y'^2)/2 + \mathbf{R_D} + a \cdot y' \cdot \sqrt{\mathbf{R_D}}$

791 fb^{-1}

Belle II

Fit projections



- **Wrong-sign ratio**, the most precise measurement to date:

$$\mathbf{R_{WS} = (0.324 \pm 0.008 \pm 0.007)\%}$$

- By combining R_{WS} with (x,y) from HFAG and a and δ from CLEO *PRD 80 (2009) 031105*, DCSD to CAD ratio:

$$\mathbf{R_D = (0.327\ ^{+0.019}_{-0.016})\%}$$

- Using PDG value for CAD,

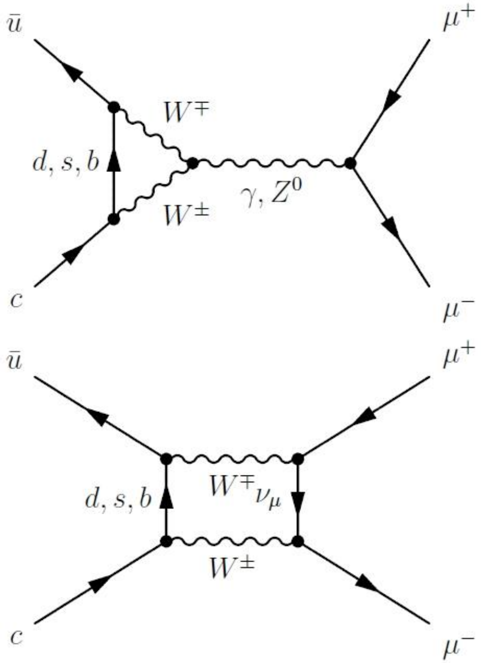
$$\mathbf{BR(D^0 \to K^+\pi^-\pi^+\pi^-) = (2.61 \pm 0.06\ ^{+0.09}_{-0.08}) \times 10^{-4}}$$

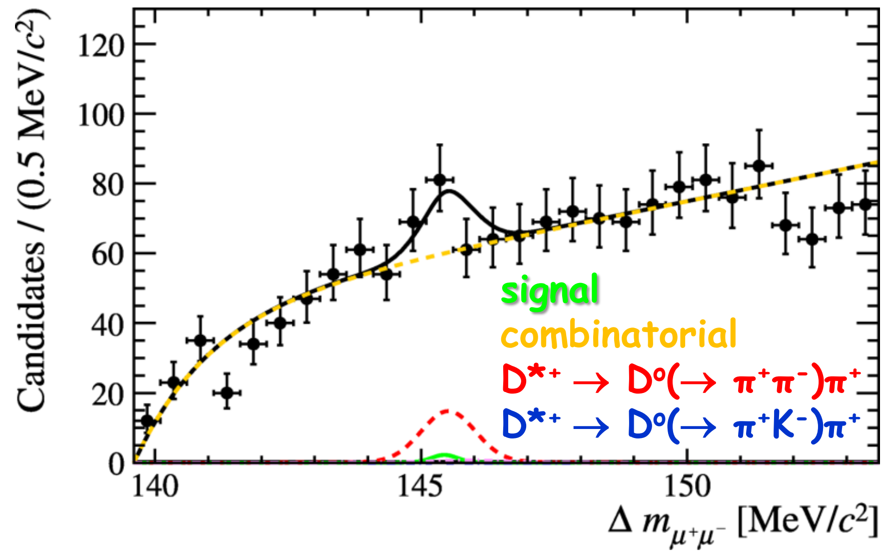
PDG: $(2.61\ ^{+0.21}_{-0.19}) \times 10^{-4}$

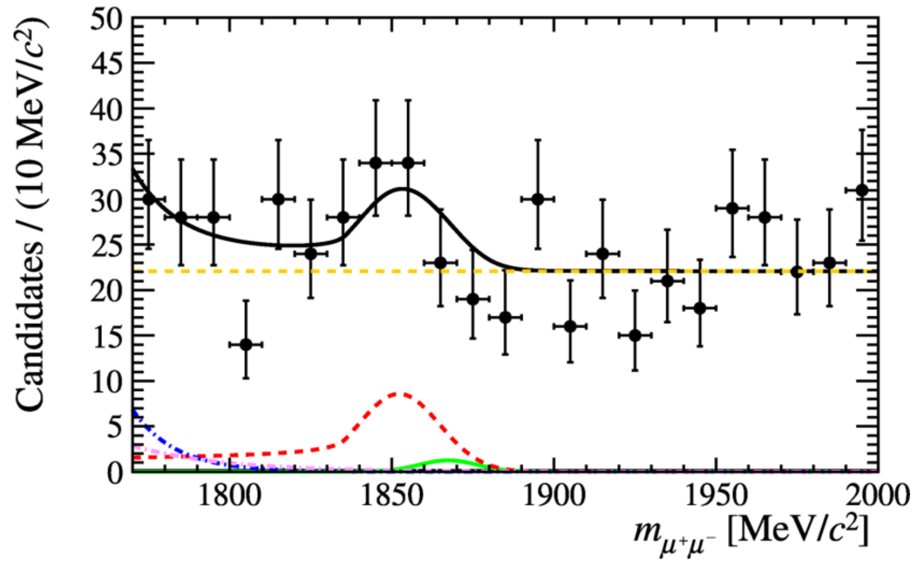
- SM prediction: 10^{-13} - 10^{-11}

PLB 725 (2013) 16

2011 data, 0.9 fb^{-1}







- Use D^0 from $D^{*+} \to D^0 (\to \mu^+ \mu^-) \pi_S^+$
- 2D fit

$m(\mu^+ \mu^-)$ vs. $\Delta m = m(\mu^+ \mu^- \pi_S^+) - m(\mu^+ \mu^-)$

- Most stringent (20 times better than previous) UL :

$BR(D^0 \to \mu^+ \mu^-) < 7.6 \times 10^{-9}$ @ 95% CL

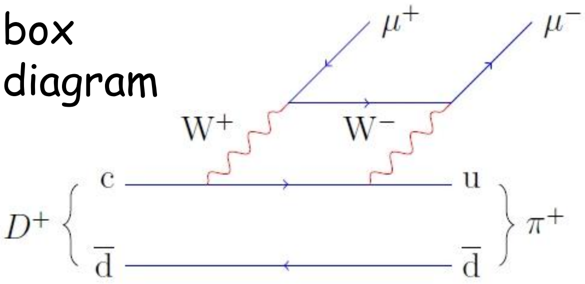
Rare decays $D_{(S)}^+ \to \pi^+ \mu^+ \mu^-$, $D_{(S)}^+ \to \pi^- \mu^+ \mu^+$

PLB 724 (2013) 203

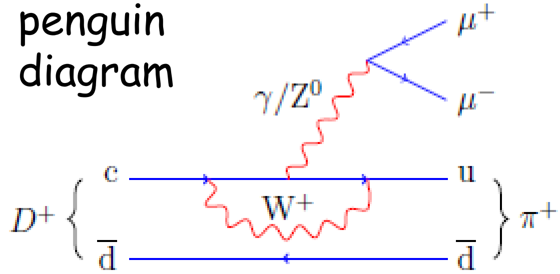
2011 data, 1 fb^{-1}

- In SM, FCNC's BR could reach 10^{-9}

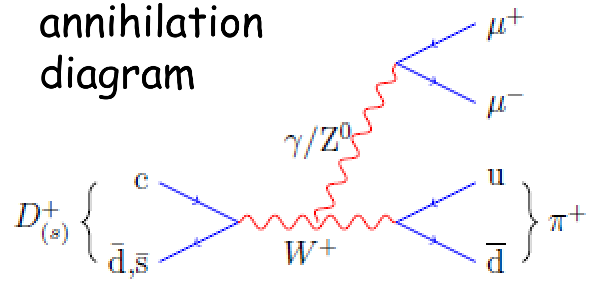
box diagram



penguin diagram



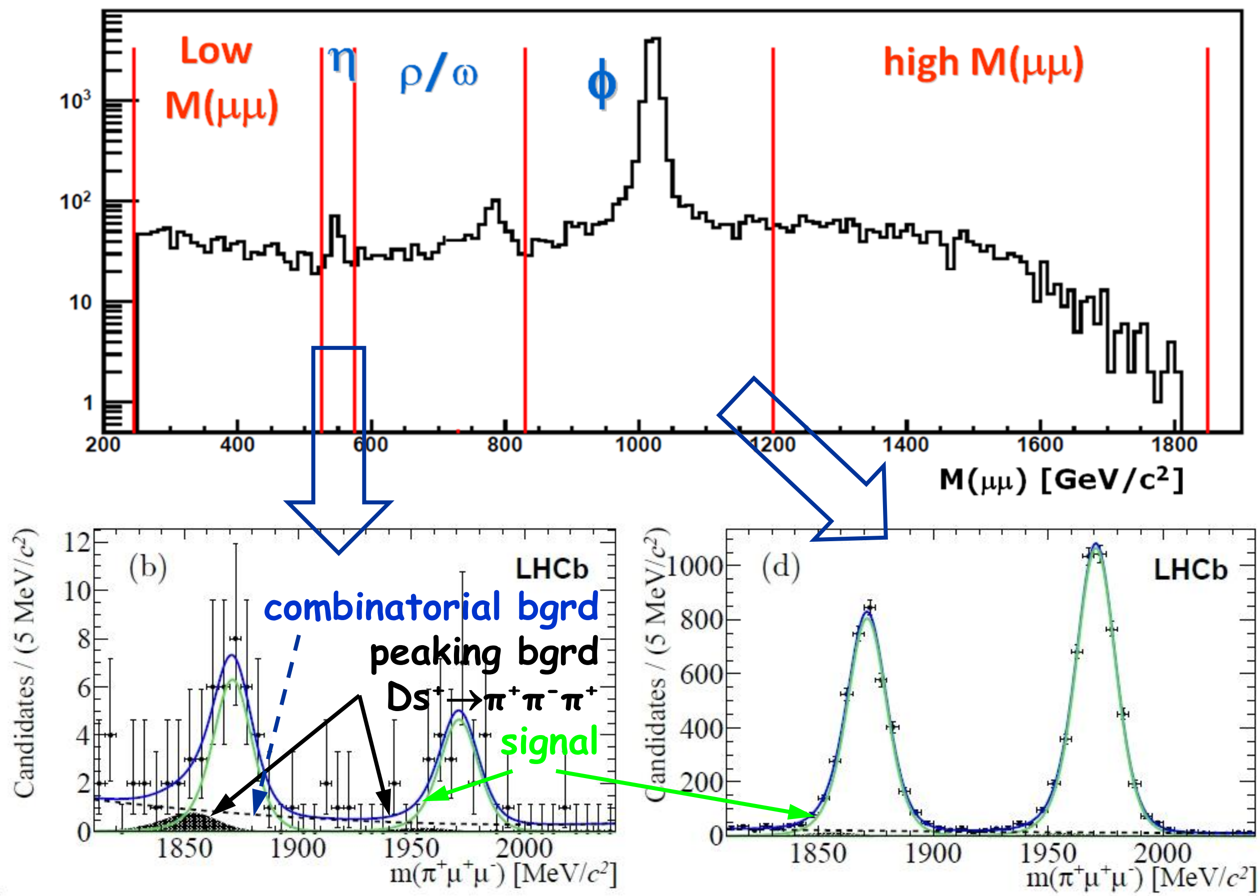
annihilation diagram



- NP may increase BR to ~10^{-8}

  PRD 83 (2011) 114006

- Probe NP in regions not clouded by resonances
- Check η, ρ/ω, ϕ regions for positive signals, and normalization

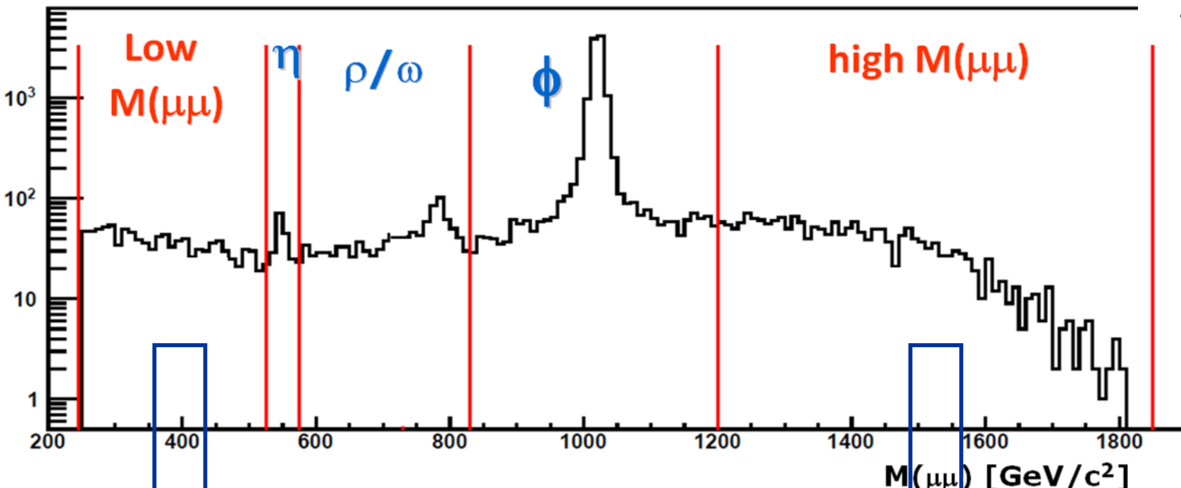


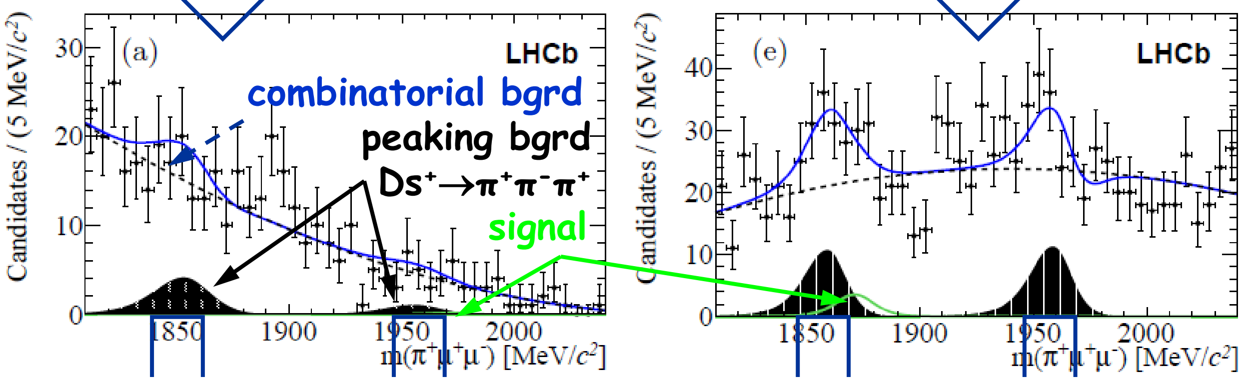
Rare decays $D_{(s)}^+ \to \pi^+ \mu^+ \mu^-$, $D_{(s)}^+ \to \pi^- \mu^+ \mu^+$

❑ Probe NP in regions not clouded by resonances

PLB 724 (2013) 203

2011 data, 1 fb^{-1}





Upper limits BR($D_{(s)}^+ \to \pi^+ \mu^+ \mu^-$), $\times 10^{-8}$ @ 90(95)% CL

2.0 (2.5) **6.9 (7.7)** **2.6 (2.9)** **16.0 (18.6)**

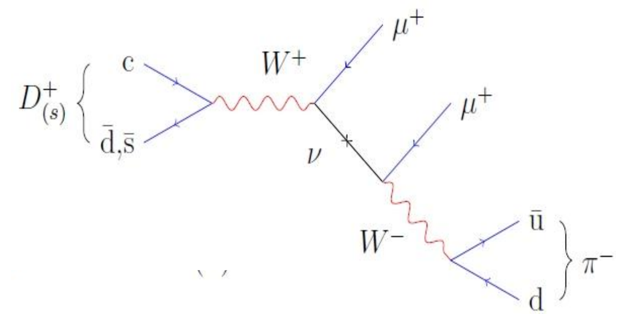
Total:

BR($D^+ \to \pi^+ \mu^+ \mu^-$) < 7.3 (8.3) $\times 10^{-8}$ @ 90(95)% CL

BR($D_s^+ \to \pi^+ \mu^+ \mu^-$) < 41 (48) $\times 10^{-8}$ @ 90(95)% CL

❑ Search for $D_{(s)}^+ \to \pi^- \mu^+ \mu^+$, same sign muons

❑ **Lepton number violation** via non-SM particle, e.g. **Majorana neutrino**



Upper limits, @ 90(95)% CL

BR($D^+ \to \pi^- \mu^+ \mu^+$) < 2.2 (2.5) $\times 10^{-8}$

BR($D_s^+ \to \pi^- \mu^+ \mu^+$) < 12 (14) $\times 10^{-8}$

❑ New world best limits ($\times$ 50 compared to previous results)

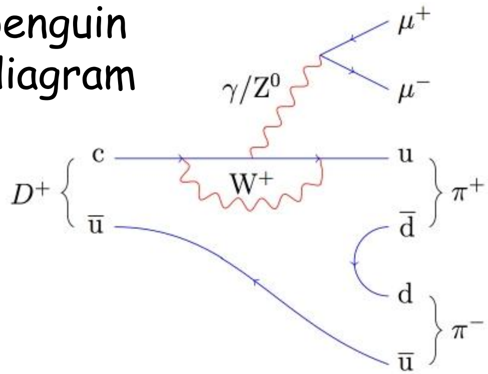
Rare decay $D^0 \to \pi^+ \pi^- \mu^+ \mu^-$

LHCb-PAPER-2013-50

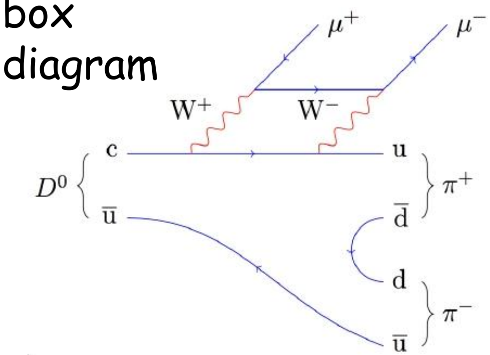
2011 data, 1 fb^{-1}

- In SM, FCNC's BR could reach 10^{-9}

penguin diagram



box diagram

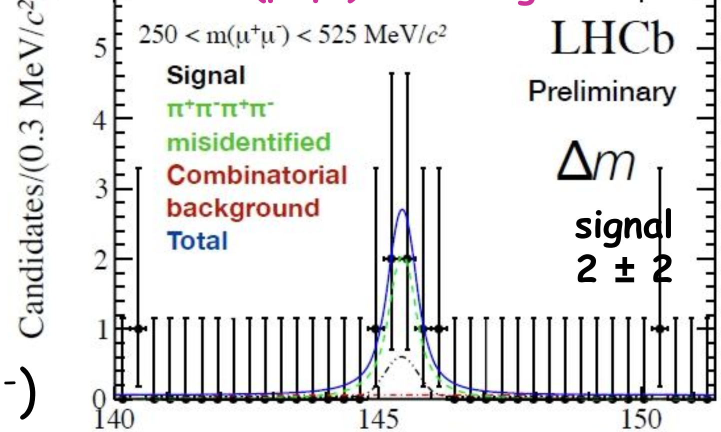


- Use D^0 from $D^{*+} \to D^0 (\to \pi^+ \pi^- \mu^+ \mu^-) \pi_S^+$
- 2D fit:

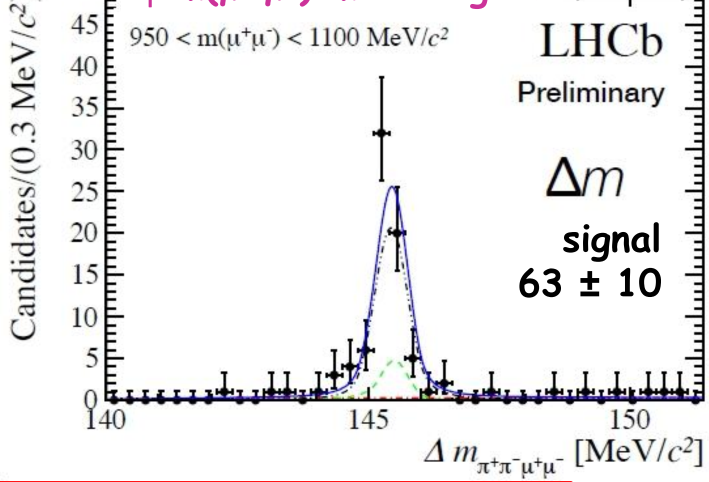
$m(\pi^+\pi^-\mu^+\mu^-)$ vs. $\Delta m = m(\pi^+\pi^-\mu^+\mu^- \pi_S^+) - m(\pi^+\pi^-\mu^+\mu^-)$ in each $m(\mu^+ \mu^-)$ bin

- $D^0 \to \pi^+ \pi^- (\mu^+ \mu^-)_\phi$ normalization channel

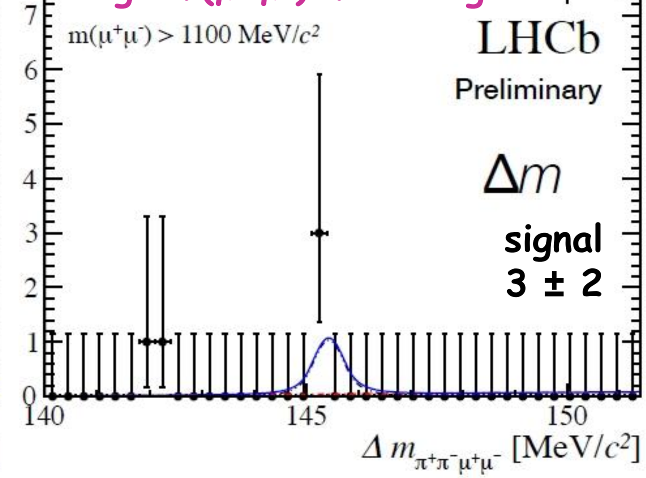
low $m(\mu^+ \mu^-)$ mass region



ϕ $m(\mu^+ \mu^-)$ mass region



high $m(\mu^+ \mu^-)$ mass region



- $\boxed{BR(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 7.4 \times 10^{-7} \text{ @ } 90\% \text{ CL}}$ (x 70 improvement)

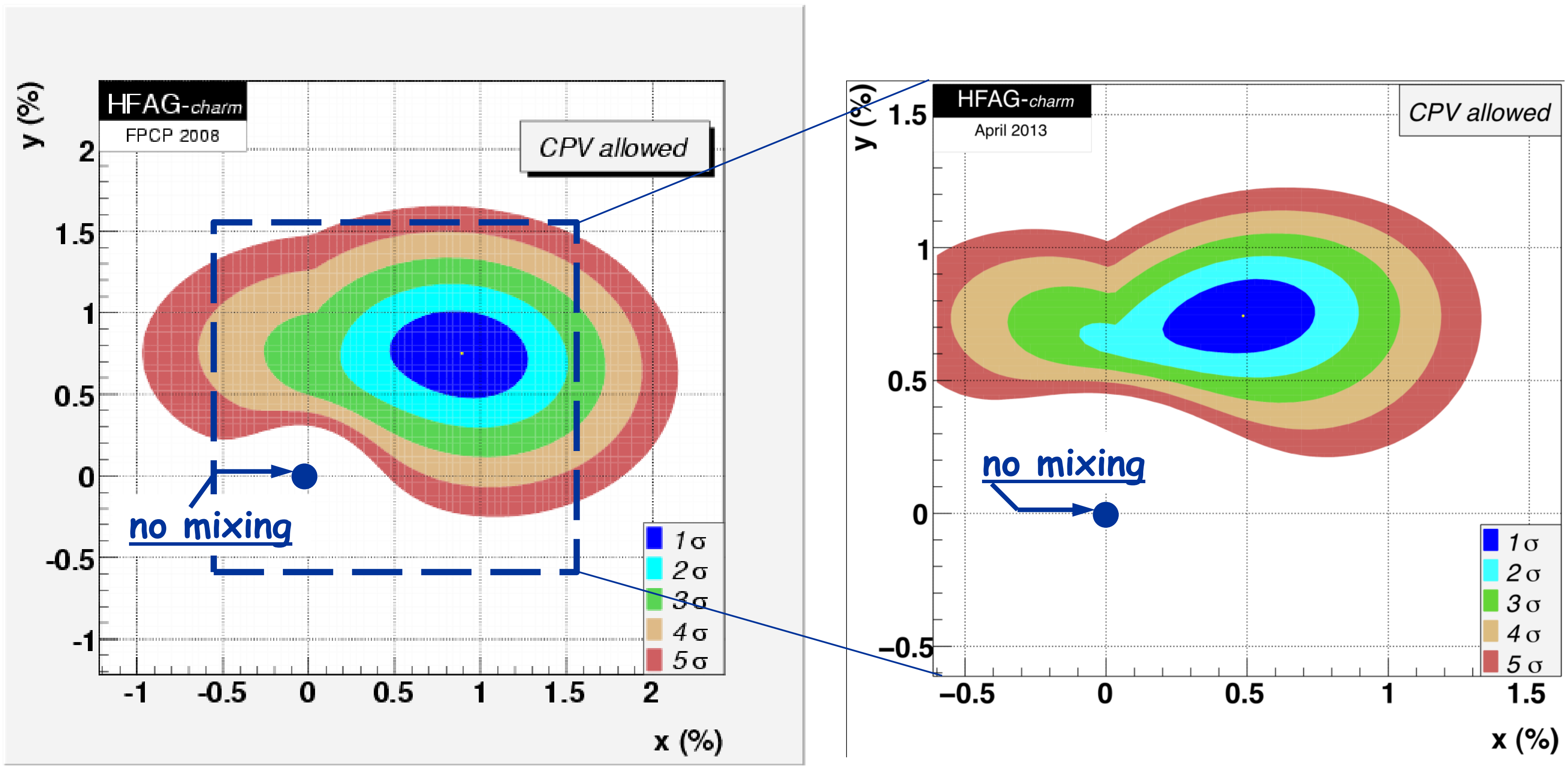
Summary

- ❑ Impressive progress over the last years, thanks to the efforts of many experiments
- ❑ Huge samples of high quality data from both e+e- and hadronic machines available
- ❑ Low background (even at hadron machines !) in many **charm rare decays** searches → continuously improving sensitivities
- ❑ **Charm mixing** is well established : x ~ y (~ few x 10^{-3}) as suggested by Standard Model, now precise single measurements !
- ❑ Search for **CPV in charm sector** yields an imprortant test of SM, large values would unambiguously point to the New Physics contribution
- ❑ Sensitivity of the CP tests in charm sector will soon approach SM tolerated values
- ❑ New delicious 2012 sample of 2 fb^{-1} from LHCb is being explored (statistics x 3 !)
- ❑ SuperBELLE and upgraded LHCb: new players to come

Backup

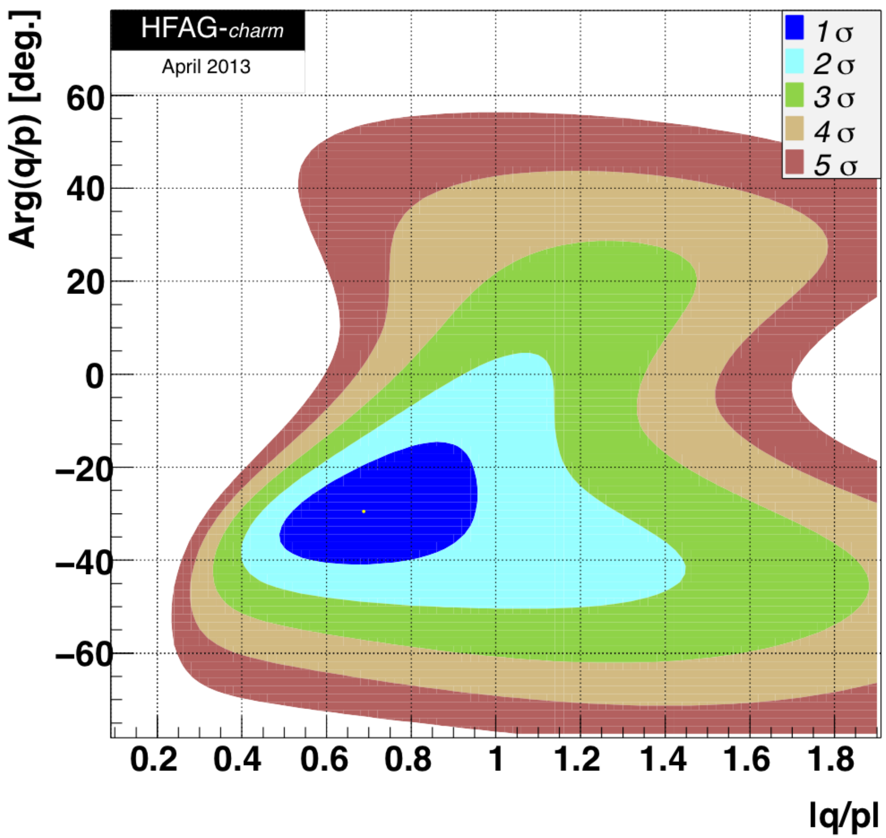
$D^0\bar{D}^0$ mixing : HFAG average over 5 years

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



$D^0\bar{D}^0$ mixing : HFAG averages

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



ΔA_{CP} : tag D^o via prompt D^{*+}, LHCb update 2013

Updated LHCb result from 1.0 fb^{-1}:

$$\Delta A_{CP} = (-0.34 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}))\%$$

Differences from previous result:

1) New reconstruction changed the selected signal events (600 fb^{-1}):

a) 15% of signal events no longer selected;
b) 17% (K^-K^+) and 34% ($\pi^-\pi^+$) new events selected:

ΔA_{CP}: (-0.82±0.21)% $\rightarrow$ (-0.55±0.21)%.

2) Including new data (+ 400 fb^{-1}) : $\Delta A_{CP} = (-0.55 \pm 0.21) \rightarrow (-0.45 \pm 0.16)\%$.

3) Constraining the soft pion and the D^0 to originate from a primary vertex:

ΔA_{CP}: (-0.45±0.16)% $\rightarrow$ (-0.34±0.15)%.

2012 data set (2 fb^{-1}) currently being analysed.

ΔA_{CP} : tag D° via semileptonic b-decays

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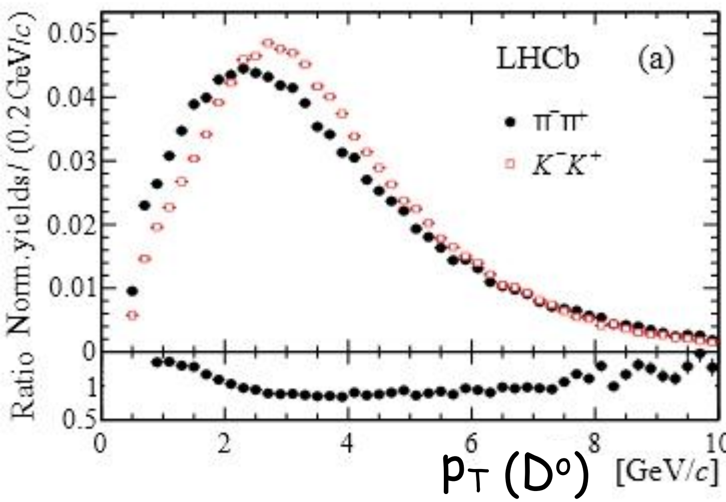
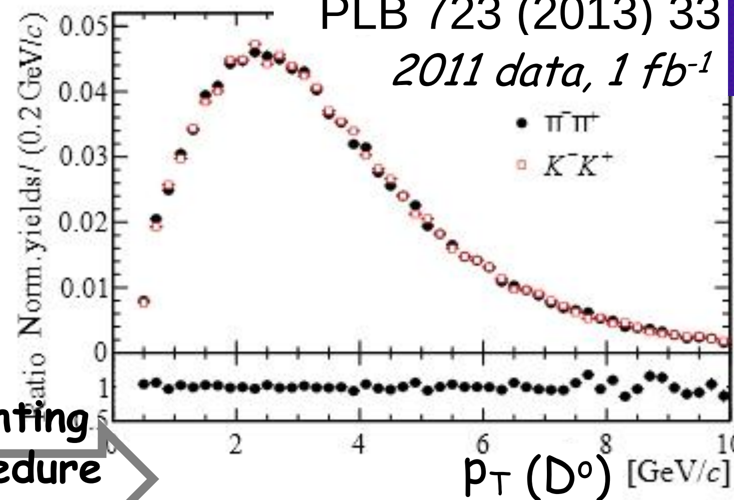
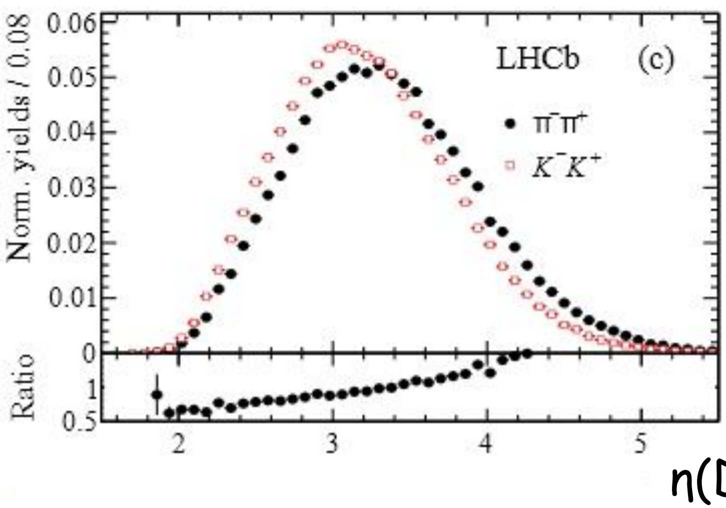
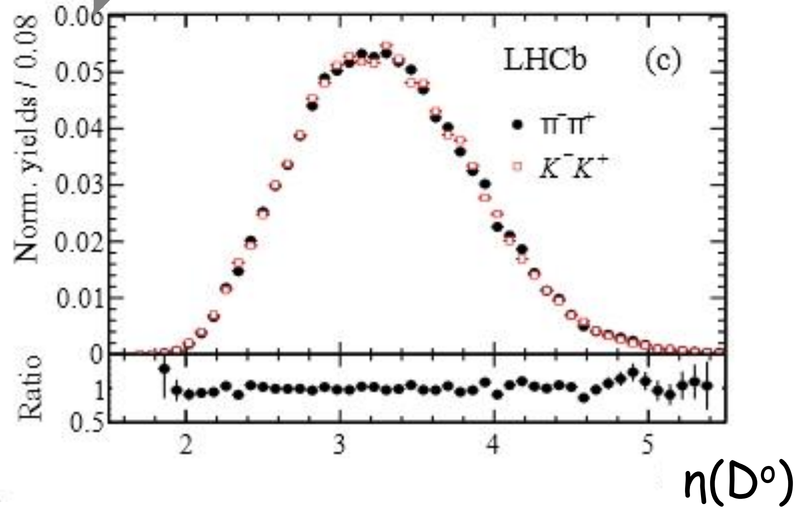
2011 data, 1 fb^{-1}



weighting procedure







b → D° μ X ΔA_{CP} = (+0.49 ± 0.30 ± 0.14)%

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Prompt D* ΔA_{CP} = (-0.34 ± 0.15 ± 0.10)%

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ΔA_{CP} = (-0.15 ± 0.16)%

No evidence for CPV