WG 7 Summary

Mixing and CP Violation in the D system

Adam Davis and Cheng-Wei Chiang

26th of November, 2021

The Conveners

Only one internet gremlin
“Strange things happen in full screen mode”

Thank you very much to the organizers and all the speakers!

Source: Wikimedia Commons

Disclaimer

This is an overview

All positive comments go directly to the speakers of the session

All negative go directly to us

Challenges in Charm System

- Charm quark scale (~1.3 GeV)
  - too light to have good heavy quark expansions
  - too heavy for chiral perturbation expansions
  - nonperturbative strong interaction coupling
  - many nearby hadronic resonances for rescattering effects
  - high precision calculations of Δm_D, $\Delta\Gamma_D$, strong phases, etc still theoretically challenging
- Resort to
  - flavor SU(3) symmetry (particularly strong phases)
  - Phenomenological assumptions (LD effects)
  - inclusion of symmetry breaking effects
  - higher-order calculations (particularly in mixing)
  - ...

Mixing and CPV in the D system

- Time-Dependent CP Asymmetry

$$A_{CP}(f(t)) = \frac{\Gamma\left(D^0 \to f(t)\right) - \Gamma\left(\bar{D}^0 \to f(t)\right)}{\Gamma\left(D^0 \to f(t)\right) + \Gamma\left(\bar{D}^0 \to f(t)\right)}$$

- Time-Integrated CP Asymmetry

$$A_{CP}(f) = a_{CP}^{dir}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}(f)$$

- Short-distance contributions within SM predict CPA of $\lesssim \mathcal{O}(10^{-4})$
  ➠ long-distance rescattering effects to be included

Mixing and CPV in the D system

- Mass eigenstates $\neq$ Flavour Eigenstates $\rightarrow$ Mixing!

$$|D_{12}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

- Redefine in terms of effective Hamiltonian

$$\hat{H} = \mathbf{M} - i\mathbf{\Gamma}$$

$$i\hbar\frac{d}{dt}\begin{pmatrix}|D^0(t)\rangle \\ |\overline{D}^0(t)\rangle\end{pmatrix} = \hat{H}\begin{pmatrix}|D^0(t)\rangle \\ |\overline{D}^0(t)\rangle\end{pmatrix}$$

$$x = \frac{\Delta M}{\Gamma}, y = \frac{\Delta\Gamma}{2\Gamma}$$

$$\frac{q}{p} = \left|\frac{q}{p}\right| e^{i\phi}$$

$$A_f = \langle f|H|D^0\rangle$$

$$\bar{A}_f = \langle f|H|\overline{D}^0\rangle$$

$$A_{\bar{f}} = \langle\bar{f}|H|D^0\rangle$$

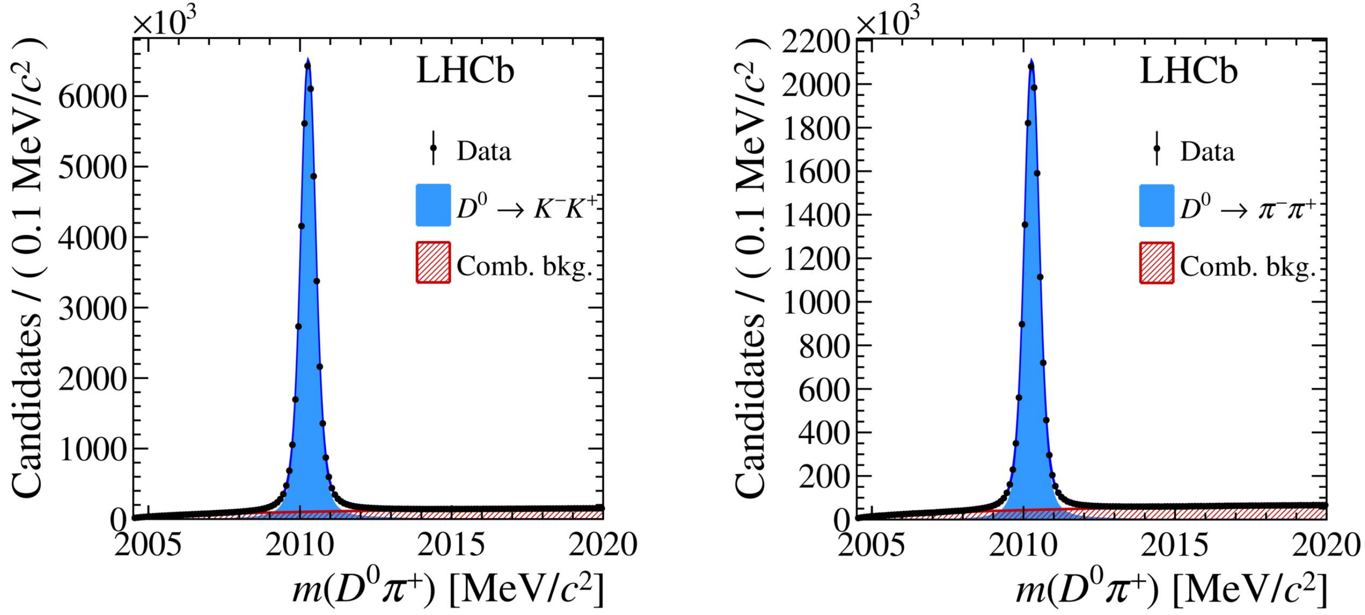
$$\bar{A}_{\bar{f}} = \langle\bar{f}|H|\overline{D}^0\rangle$$

Direct CPV

Bonza!

[Phys. Rev. Lett. 122 (2019) 211803](#)

Andrea Contu

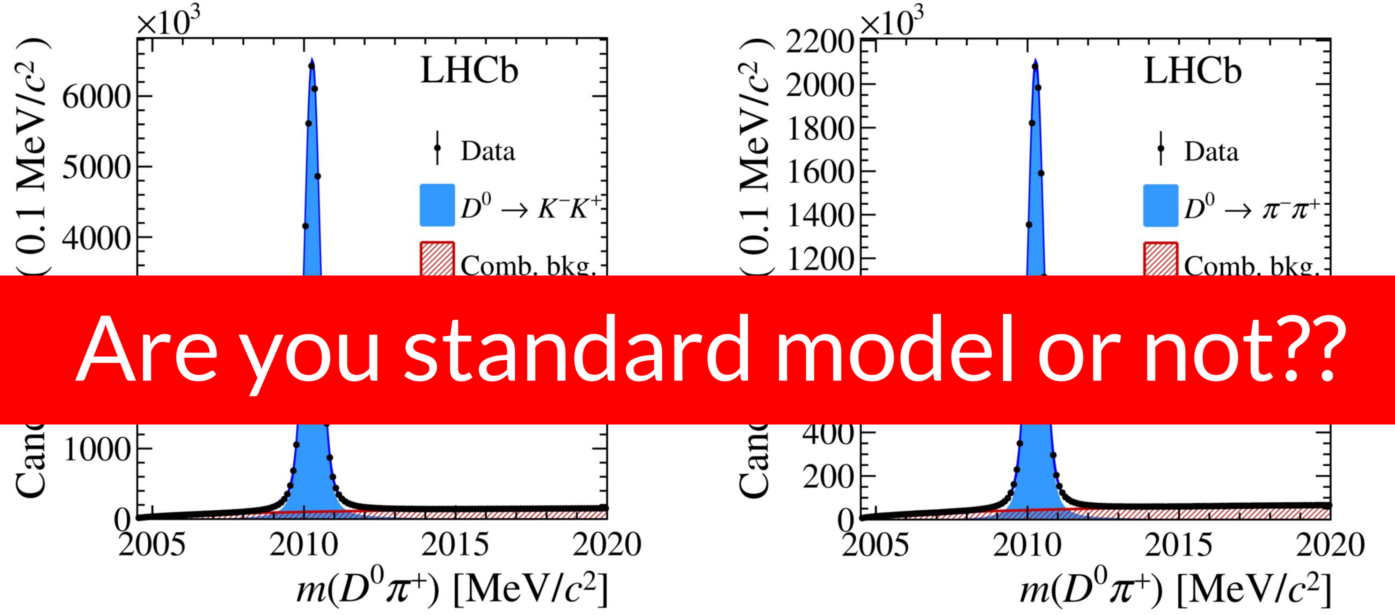


$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = (-15.4 \pm 2.9) \times 10^{-4}$$

Bonza!

[Phys. Rev. Lett. 122 (2019) 211803]

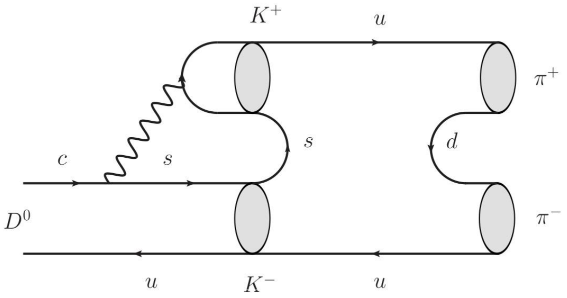
Andrea Contu



Are you standard model or not??

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = (-15.4 \pm 2.9) \times 10^{-4}$$

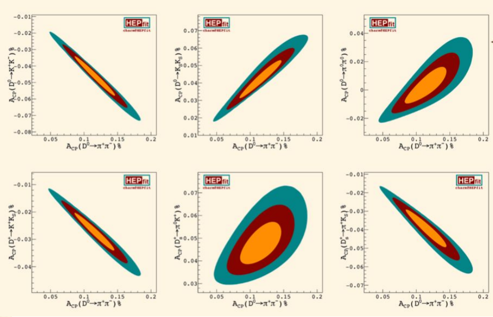
Progress on Theory



- Topological amplitude analysis (Hai-Yang Cheng)
  - include $SU(3)_F$ breaking effects from CF to SCS/DCS modes
  - include SD penguin amplitudes using QCDF (rescattering effects)
  - invoke LD rescattering to penguin-exchange amplitude
  - Also look into VP decays and identify six golden modes to test theory
  - Analogous to the PP case, predict CPA difference:

$$a_{CP}(K^+K^{*-}) - a_{CP}(\pi^+\rho^-) = (-1.61 \pm 0.33) \times 10^{-3}$$

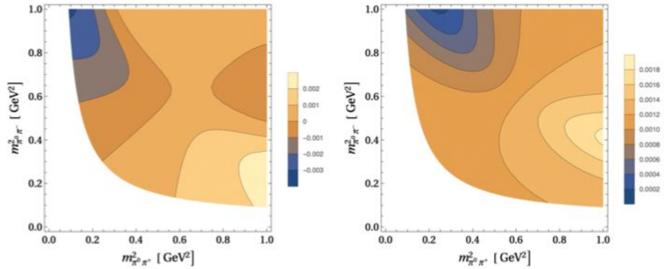
  - Dalitz analysis of local CPAs in 3-body D decays can provide more info
- Also account for $SU(3)_F$ breaking with final state interactions and shifts to amplitudes - fits to BFs allow for predictions of DCPV (Ayan Paul)
- Correlations stem from rescattering



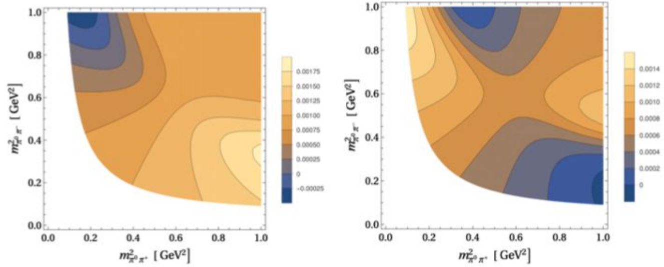
A_{CP} (D^0)	$(\mu \pm \sigma)$ (%) $\delta_i \to$ -ve	$(\mu \pm \sigma)$ (%) $\delta_i \to$ +ve	A_{CP} $(D^+_{(s)})$	$(\mu \pm \sigma)$ (%) $\delta_i \to$ -ve	$(\mu \pm \sigma)$ (%) $\delta_i \to$ +ve
$D^0 \to \pi^+\pi^-$	0.117 ± 0.020	0.118 ± 0.020	$D^+ \to K^+K_S$	-0.028 ± 0.005	-0.026 ± 0.005
$D^0 \to \pi^0\pi^0$	0.004 ± 0.009	0.079 ± 0.010	$D^+_s \to \pi^+K_S$	-0.040 ± 0.007	-0.036 ± 0.007
$D^0 \to K^+K^-$	-0.047 ± 0.008	-0.046 ± 0.008	$D^+_s \to \pi^0K^+$	0.048 ± 0.006	-0.003 ± 0.004
$D^0 \to K_SK_S$	0.043 ± 0.007	0.038 ± 0.007			

Progress on Theory (2)

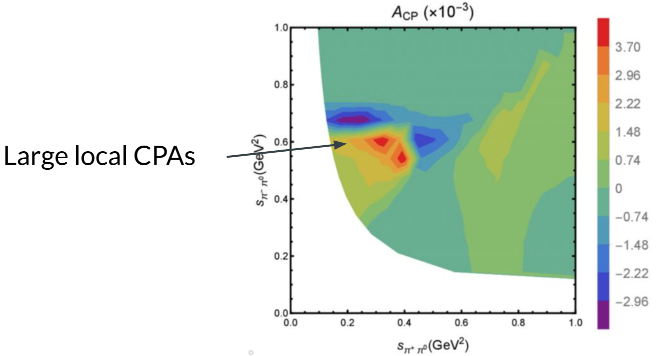
- Look further into testing O(1) rescattering effects using $\Delta U=0$ with $D^0 \to V^{\pm}P^{\mp} \to P^{\pm} P^0 P^{\mp}$(Avital Dery)
- Assumptions: Production/Detection asymmetry constant across Dalitz Plot
- 7 parameters to describe $D^0 \to \varrho^{\pm}\pi^{\mp} \to \pi^+\pi^-\pi^0$, 7 points on Dalitz plot enough
- Additional analogue to DACP using $K^* \pi$ and $\varrho^{\pm}\pi^{\mp}$? Pseudo 2-body decays have exact U-spin correspondence, but 3-body final states are not related by full $d \leftrightarrow s$ interchange
- Effects of finite width of $\varrho^{\pm}$ included (Hai-Yang Cheng)
- How to associate meaningfully two points on different Dalitz plots?
- Discussion focused on what's reasonable for experimental measurements



(a) $\tilde{R}^{P_1V_2} = \exp(i3\pi/2)$, $\tilde{R}^{P_2V_1} = \exp(i\pi/3)$ (b) $\tilde{R}^{P_1V_2} = \exp(i\pi/2)$, $\tilde{R}^{P_2V_1} = \exp(i\pi/3)$



(c) $\tilde{R}^{P_1V_2} = \frac{1}{2}\exp(i\pi/2)$, $\tilde{R}^{P_2V_1} = \exp(i\pi/3)$ (d) $\tilde{R}^{P_1V_2} = \exp(i\pi/2)$, $\tilde{R}^{P_2V_1} = \frac{1}{4}\exp(i\pi/3)$

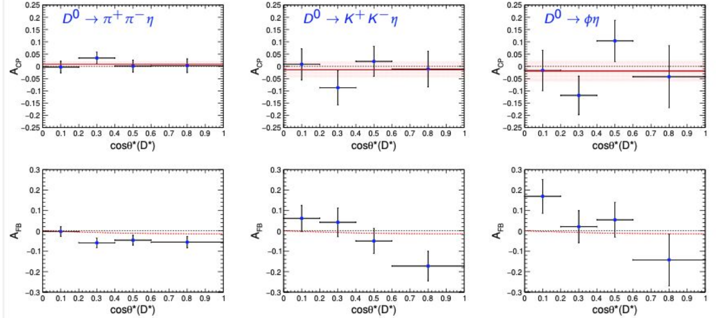


Experimental Pushes

<u>Belle</u>

Long-Ke Li

$$A_{CP} = \frac{A_{\rm corr}(\cos\theta^*) + A_{\rm corr}(-\cos\theta^*)}{2} \qquad A_{\rm FB} = \frac{A_{\rm corr}(\cos\theta^*) - A_{\rm corr}(-\cos\theta^*)}{2}$$



$$A_{CP}(D^0 \to \pi^+\pi^-\eta) = [0.9 \pm 1.2\,(\text{stat}) \pm 0.5\,(\text{syst})]\%,$$
$$A_{CP}(D^0 \to K^+K^-\eta) = [-1.4 \pm 3.3\,(\text{stat}) \pm 1.1\,(\text{syst})]\%,$$
$$A_{CP}(D^0 \to \phi\eta) = [-1.9 \pm 4.4\,(\text{stat}) \pm 0.6\,(\text{syst})]\%,$$

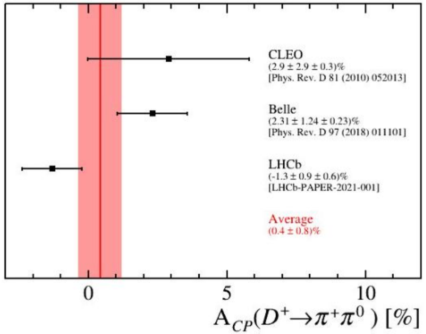
← First Measurements

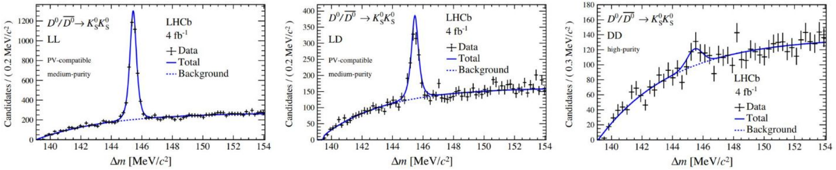
Decay mode	$A_{\rm raw}$	A_{CP}
$D_s^+ \to K^+\pi^0$	0.115 ± 0.045	$0.064 \pm 0.044 \pm 0.011$
$D_s^+ \to K^+\eta_{\gamma\gamma}$	0.046 ± 0.027	$0.040 \pm 0.027 \pm 0.005$
$D_s^+ \to K^+\eta_{3\pi}$	-0.011 ± 0.033	$-0.008 \pm 0.034 \pm 0.008$
$D_s^+ \to K^+\eta$	–	$0.021 \pm 0.021 \pm 0.004$
$D_s^+ \to \pi^+\eta_{\gamma\gamma}$	0.007 ± 0.004	$0.002 \pm 0.004 \pm 0.003$
$D_s^+ \to \pi^+\eta_{3\pi}$	0.008 ± 0.006	$0.002 \pm 0.006 \pm 0.003$
$D_s^+ \to \pi^+\eta$	–	$0.002 \pm 0.003 \pm 0.003$
$D_s^+ \to \phi\pi^+$	0.002 ± 0.001	–

<u>LHCb</u>

Andrea Contu

$$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$$
$$\mathcal{A}_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%$$
$$\mathcal{A}_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%$$
$$\mathcal{A}_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%$$





$A_{CP}(D^0 \to K_S^0 K_S^0)$ = (-3.1 ± 1.2 (stat.) ± 0.4 (syst.) ± 0.2 ($A_{CP}(D^0 \to KK)$))%

<u>BESIII</u>

Jim Libby

- Surprises happen e.g. doubly Cabibbo suppressed branching fraction for $D^+ \to K^+\pi^+\pi^-\pi^0$ [PRL **125** (2020) 14180]

$$B(D^+ \to K^+\pi^+\pi^-\pi^0) = (6.28 \pm 0.52) \times \tan^4\theta_C \times B(D^+ \to K^-\pi^+\pi^+\pi^0)$$

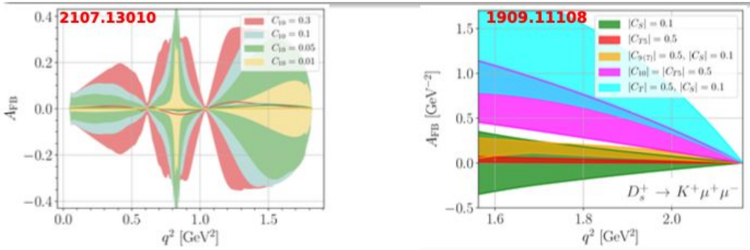
- A_{CP} = −0.04±0.06 (stat) ± 0.01 (syst)

14 BFs of 3- & 4-body D decays with η in final state → no significant ACP, precision 1-5%

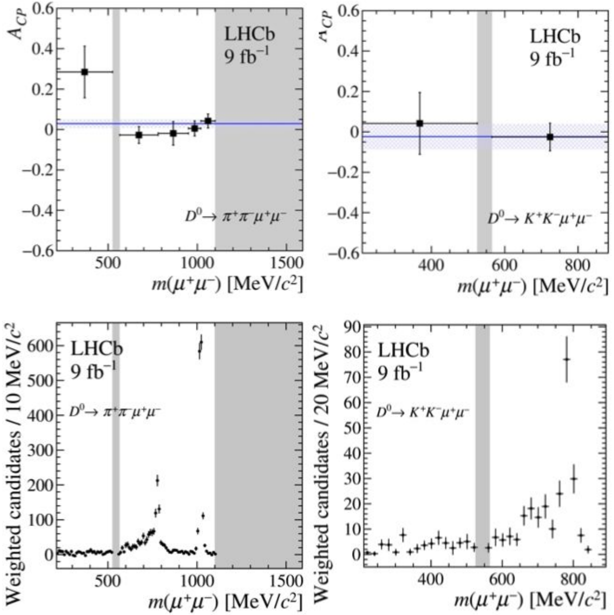
Push to Rare Decays

Marcel Golz

- Devise null tests in non-resonance regions to constrain WC's from EFT approach
- E.g. A_{FB} vs q^2 of Ds → K $\mu\mu$
- E.g. Lepton non-universality possibly at O(1 - 100)
- Plenty of opportunities in mesonic/baryonic modes

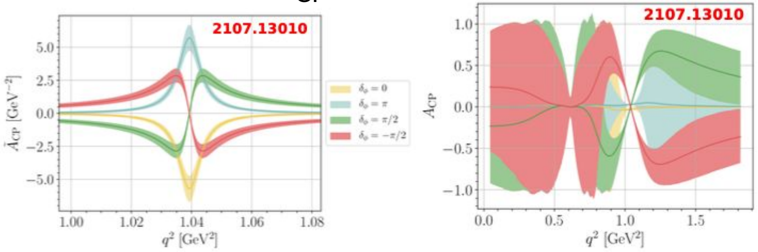


Andrea Contu + D. Brundu in WG 3



$m(\mu^+\mu^-)$ [MeV/c^2]	A_{CP} [%]
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	
< 525	$28 \pm 13 \pm 1$
525–565	–
565–780	$-2.7 \pm 4.1 \pm 0.4$
780–950	$-1.9 \pm 5.8 \pm 0.4$
950–1020	$0.5 \pm 3.7 \pm 0.4$
1020–1100	$4.2 \pm 3.4 \pm 0.4$
> 1100	–
Full range	$2.9 \pm 2.1 \pm 0.4$
$D^0 \to K^+K^-\mu^+\mu^-$	
< 525	$4 \pm 15 \pm 1$
525–565	–
> 565	$-2.5 \pm 6.8 \pm 0.6$
Full range	$-2.3 \pm 6.3 \pm 0.6$

- Leverage ϕ region to control strong phases for A_{CP} vs q^2

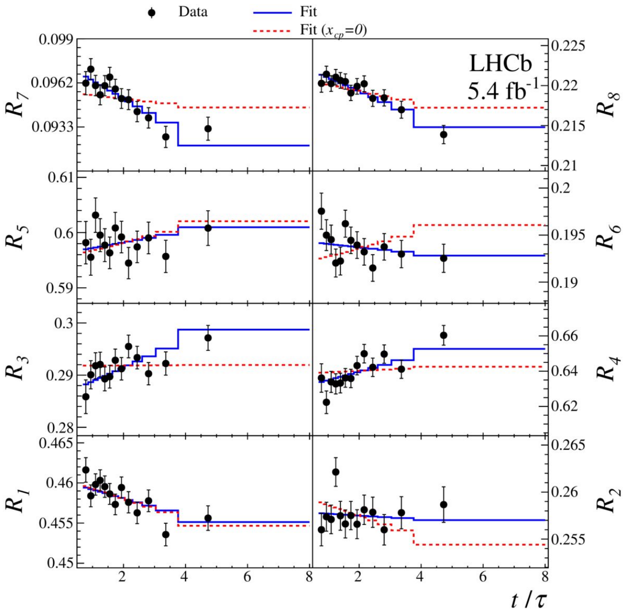


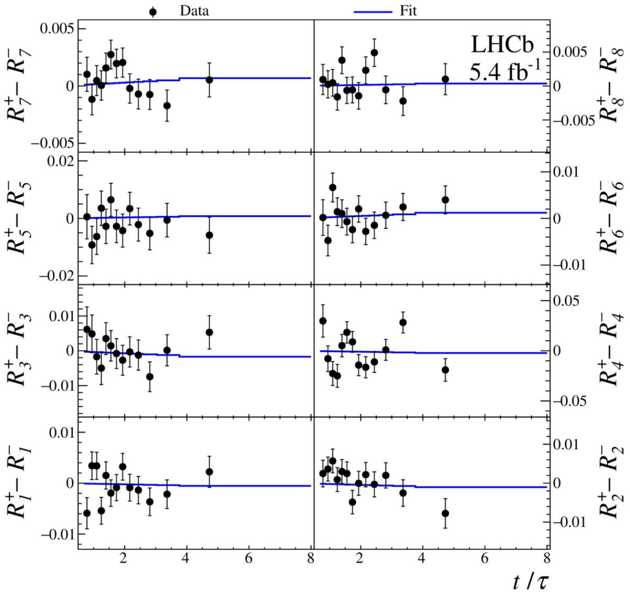
"Turn a bug into a feature"

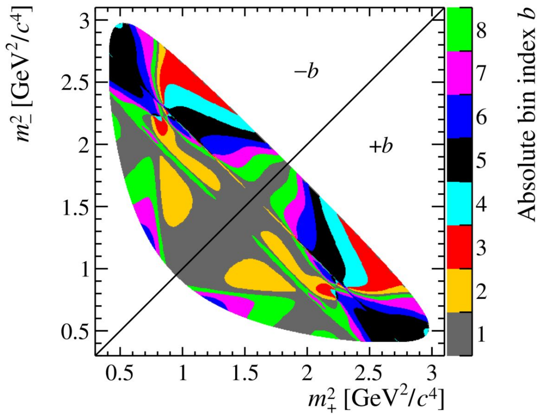
Mixing and Indirect CPV

Bonza!

Daniel Červenkov







$$\Delta x = (-0.27 \pm 0.18(\text{stat}) \pm 0.01(\text{syst})) \times 10^{-3} \qquad x_{CP} = (3.97 \pm 0.46(\text{stat}) \pm 0.29(\text{syst})) \times 10^{-3}$$

$$\Delta y = (0.20 \pm 0.36(\text{stat}) \pm 0.13(\text{syst})) \times 10^{-3} \qquad y_{CP} = (4.59 \pm 1.20(\text{stat}) \pm 0.85(\text{syst})) \times 10^{-3}$$

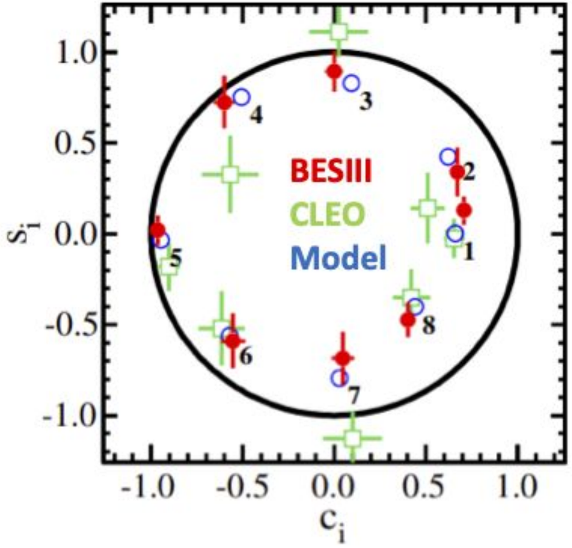
$$R_{bj}^{\pm} \approx \frac{r_b + \sqrt{r_b}\,\mathrm{Re}\left[X_b^*(z_{CP} \pm \Delta z)\right]\langle t\rangle_j + \frac{1}{4}\left[|z_{CP} \pm \Delta z|^2 + r_b \mathrm{Re}(z_{CP}^2 - \Delta z^2)\right]\langle t^2\rangle_j}{1 + \sqrt{r_b}\,\mathrm{Re}\left[X_b(z_{CP} \pm \Delta z)\right]\langle t\rangle_j + \frac{1}{4}\left[\mathrm{Re}(z_{CP}^2 - \Delta z^2) + r_b|z_{CP} \pm \Delta z|^2\right]\langle t^2\rangle_j}$$

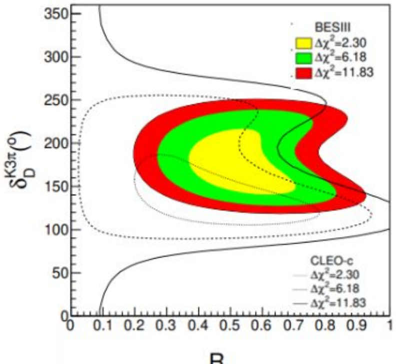
$z_{CP} = -y_{CP} - ix_{CP}, \Delta z = -\Delta y - i\Delta x$

Exploit Synergies

BES III
Jim Libby

- One vital input to Ks $\pi\pi$ bin flip is strong phase differences c_i and s_i
- Also crucial for extraction of γ/ϕ_3
- Discussion point - What binning is the best? Current binning is driven by γ/ϕ_3, are there better binnings? As Statistically limited, there is no limitation on the BESIII side
- Other measurements as well
  - coherence factors in K3π and K$\pi\pi^0$
  - $\delta_{K\pi}$
  - Other modes to look at?



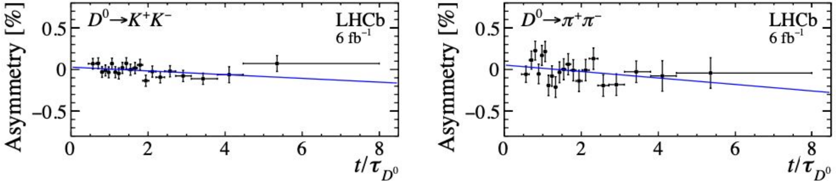


	c_i	s_i
1	$0.708 \pm 0.020 \pm 0.009$	$0.128 \pm 0.076 \pm 0.017$
2	$0.671 \pm 0.035 \pm 0.016$	$0.341 \pm 0.134 \pm 0.015$
3	$0.001 \pm 0.047 \pm 0.019$	$0.893 \pm 0.112 \pm 0.020$
4	$-0.602 \pm 0.053 \pm 0.017$	$0.723 \pm 0.143 \pm 0.022$
5	$-0.965 \pm 0.019 \pm 0.013$	$0.020 \pm 0.081 \pm 0.009$
6	$-0.554 \pm 0.062 \pm 0.024$	$-0.589 \pm 0.147 \pm 0.031$
7	$0.046 \pm 0.057 \pm 0.023$	$-0.686 \pm 0.143 \pm 0.028$
8	$0.403 \pm 0.036 \pm 0.017$	$-0.474 \pm 0.091 \pm 0.027$

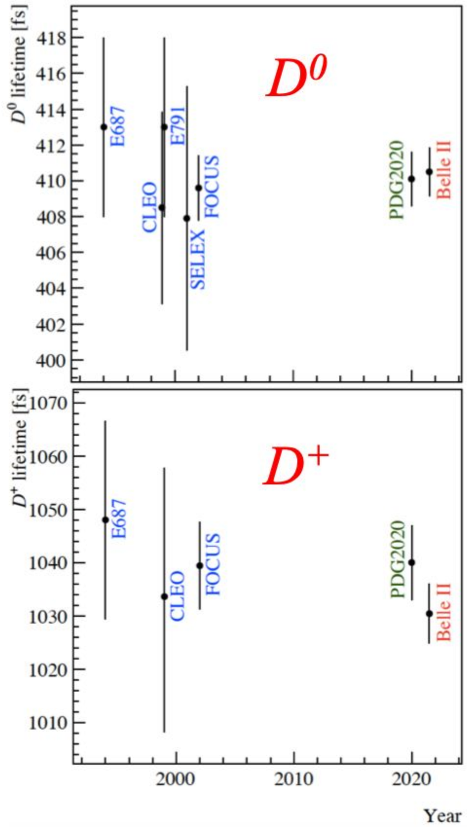
More experimental results!

<u>LHCb</u>
Daniel Červenkov

$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4} \qquad \Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$$



<u>Belle II</u>
Soeren Prell



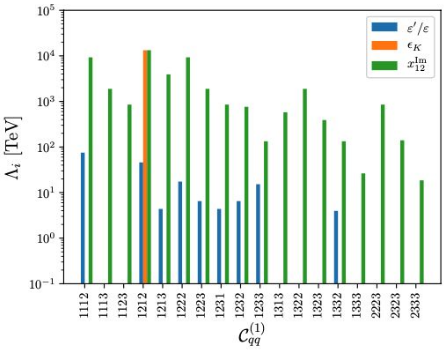
$$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8 \text{ fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1 \text{ fs}$$

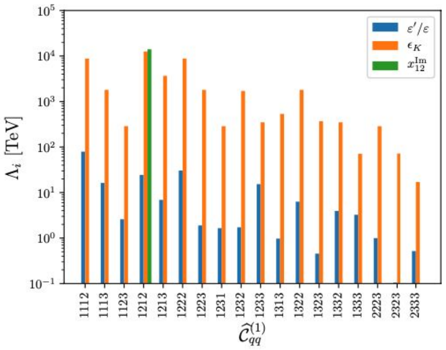
$$\tau(D^+)/\tau(D^+) = 2.510 \pm 0.015$$
(accounted for correlated systematic uncertainties)

- LHCb continues to exploit their large sample of Charm
- Belle II has made new precision measurements of the D^0/D^+ lifetime → TDCPV measurements ready, only awaiting integration of luminosity

A Bigger Picture

Pushes on Theory





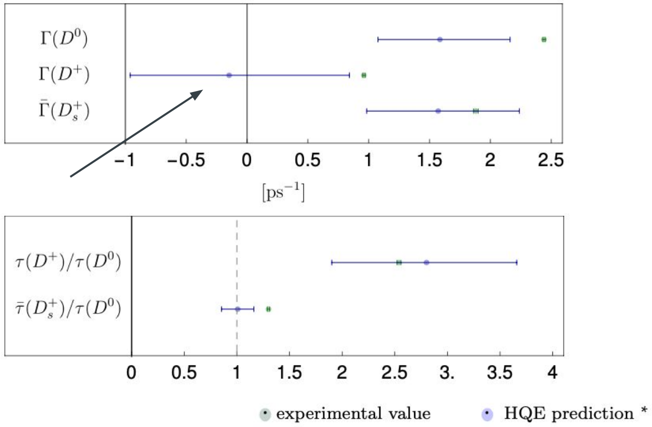
Jason Aebischer

- Concentrate on M_{12} in this work
- Use SMEFT to evaluate bounds on new physics contributions
- Master formula in WET (2 loop QCD running)/SMEFT (1 loop SMEFT-WET matching) done
- Leads to mixing between up/down bases - should consider simultaneously

Maria Laura Piscopo

Use HQE to explore charm lifetimes and hence Γ_{12}

Need to include higher-dim operators



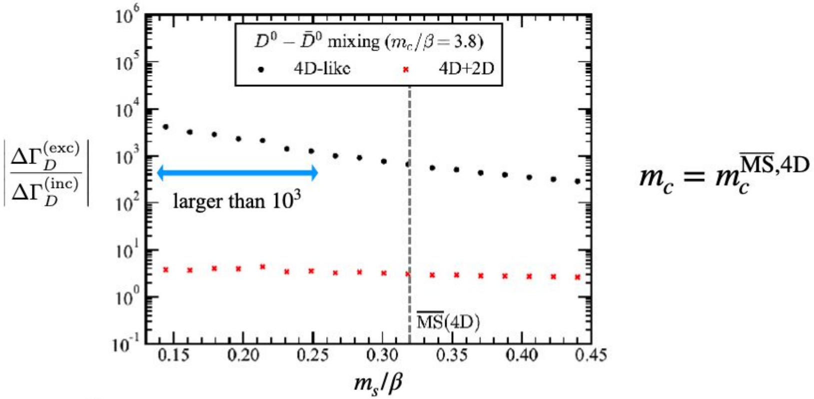
- HQE Fails for charm mixing, but OK for lifetimes?
- Need further inclusive D-> X ell nu measurements to help constrain
- NLLO-QCD corrections at d=6, Higher power corrections coming

- Long discussion on negative lifetime prediction which is not present in ratios

Pushes on Theory (2)

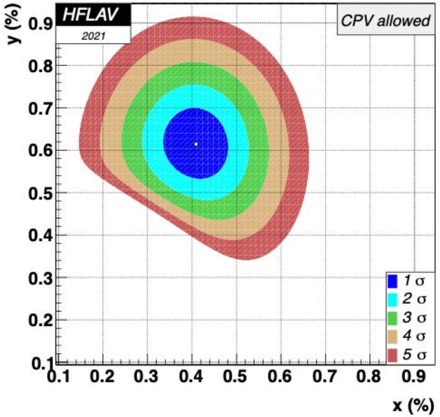
Hiroyuki Umeeda

- Exclusive approach to Γ_{12} generally unsatisfactory and relying on data inputs
- Investigate Quark-Hadron duality violation in 't Hooft's model using a resonance-based method
- $\Delta\Gamma_D$ enhanced by more than $O(10^3)$ confirmed for the range of $0.14 < m_s/\beta < 0.25$, if the phase space function is given by 4D-like one.
- Analogous calculation of Δm_D still missing



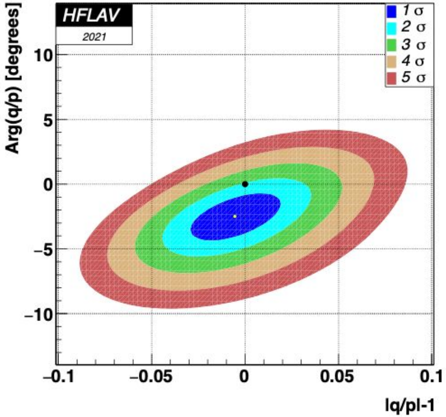
points: based only on the 4D-like phase space
crosses: based on the 4D-like phase space + 2D-specific one

Global Fits



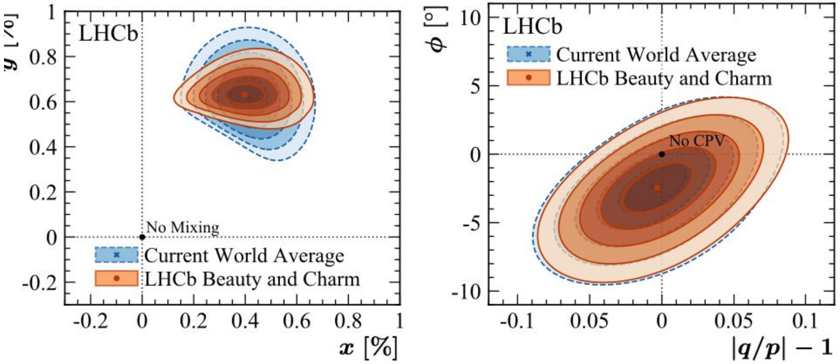
No mixing point (x,y) = (0,0):
$\Delta\chi^2$ = 2099, excluded at ≫ 11.5σ

HFLAV
Alan Schwartz

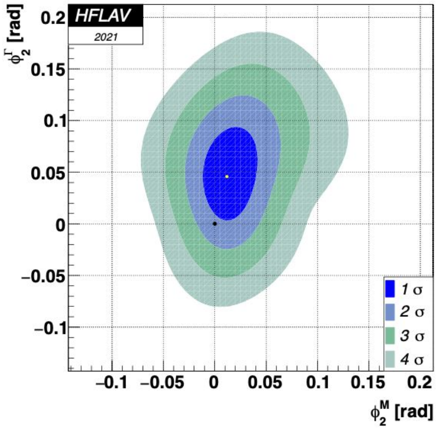


No CPV point (|q/p|, φ) = (1,0):
$\Delta\chi^2$ = 5.633, excluded at 1.6σ

LHCb
Daniel Červenkov



Using new description from Kagan/Silvestrini, fit separately for absorptive and dispersive phases



- Is the future to fit B+D simultaneously for ultimate precision? What about K?

Summary of the Summary

Charm is even more charming than before

Direct CPV established
$x>0$ @ $>8\,\sigma$

There are many new results in the pipeline on both theory and experimental side

Barely touched on baryons in this workshop

Watch this space

Backup

Parameter	No CPV	No direct CPV in DCS decays	CPV-allowed	CPV-allowed 95% CL Interval
x (%)	$0.44^{+0.13}_{-0.15}$	0.409 ± 0.048	$0.409^{+0.048}_{-0.049}$	[0.313, 0.503]
y (%)	0.63 ± 0.07	$0.603^{+0.057}_{-0.056}$	$0.615^{+0.056}_{-0.055}$	[0.509, 0.725]
$\delta_{K\pi}$ (°)	$8.9^{+8.9}_{-9.8}$	$5.5^{+8.3}_{-9.9}$	$7.2^{+7.9}_{-9.2}$	[−12.6, 21.8]
R_D (%)	0.344 ± 0.002	0.343 ± 0.002	0.343 ± 0.002	[0.340, 0.347]
A_D (%)	–	–	-0.70 ± 0.36	[−1.40, 0.00]
$\|q/p\|$	–	1.005 ± 0.007	0.995 ± 0.016	[0.96, 1.03]
ϕ (°)	–	$-0.18^{+0.28}_{-0.29}$	-2.5 ± 1.2	[−4.91, −0.19]
$\delta_{K\pi\pi}$ (°)	$21.8^{+23.5}_{-23.9}$	$22.3^{+21.9}_{-23.0}$	$23.0^{+21.8}_{-22.9}$	[−22.6, 64.9]
A_π(%)	–	0.027 ± 0.137	0.045 ± 0.137	[−0.22, 0.31]
A_K(%)	–	-0.133 ± 0.136	-0.113 ± 0.137	[−0.38, 0.15]
x_{12} (%)	–	0.409 ± 0.048		[0.314, 0.503]
y_{12} (%)	–	$0.603^{+0.057}_{-0.056}$		[0.495, 0.715]
ϕ_{12}(°)	–	$0.58^{+0.91}_{-0.90}$		[−1.20, 2.42]
χ^2/d.o.f.	$98.68/52 = 1.90$	$66.27/53 = 1.25$	$63.64/51 = 1.25$	

$$\phi_2^M = (0.7 \pm 1.0)^\circ$$
$$\phi_2^\Gamma = (2.6 \pm 1.7)^\circ$$