CHARM MIXING

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Flavour and the Fourth Family,
Durham, 15th September 2011

OUTLINE

- Charm mixing and fourth generation
- Existing measurements
- Status and prospects of LHCb
- Conclusion

CHARM MIXING

$x \equiv \frac{\Delta m}{\Gamma}$ $y \equiv \frac{\Delta\Gamma}{2\Gamma}$ $P(N^0 \to \overline{N^0}) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-T}(\cosh yT - \cos xT)$ $T \equiv \Gamma t$

	$K^0/\overline{K^0}$	$D^0/\overline{D^0}$	$B_d^0/\overline{B_d^0}$	$B_s^0/\overline{B_s^0}$
τ (ps)	89.58 ± 0.05, 51160 ± 200	0.4101 ± 0.0015	1.530 ± 0.009	1.470 ± 0.027
Γ (s^{-1})	5.59×10^9	2.4×10^{12}	6.5×10^{11}	6.8×10^{11}
x	0.946 ± 0.002	0.0097 ± 0.0028	0.776 ± 0.008	26.1 ± 0.5
y	-0.9965	0.0078 ± 0.0019	$\lvert y\rvert < 0.04$, 90% C.L.	$[0.09, -0.03]$, 95% C.L.

K_S, K_L — slow mixing — fast mixing

in D system not excluded that: $|\Gamma_{12}/M_{12}| \approx \mathcal{O}(1)$

therefore have to define

$$x_{12} \equiv 2|M_{12}|/\Gamma,\ y_{12} \equiv |\Gamma_{12}|/\Gamma,\ \phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$$

cannot simply assume $x = x_{12}$ and $y = y_{12}$

CHARM MIXING & 4th GEN: x_D

- Using

$$\lambda_d^{D^0} + \lambda_s^{D^0} + \lambda_b^{D^0} + \lambda_{b'}^{D^0} = 0 \qquad \lambda_x^{D^0} = V_{cx}V_{ux}^*$$

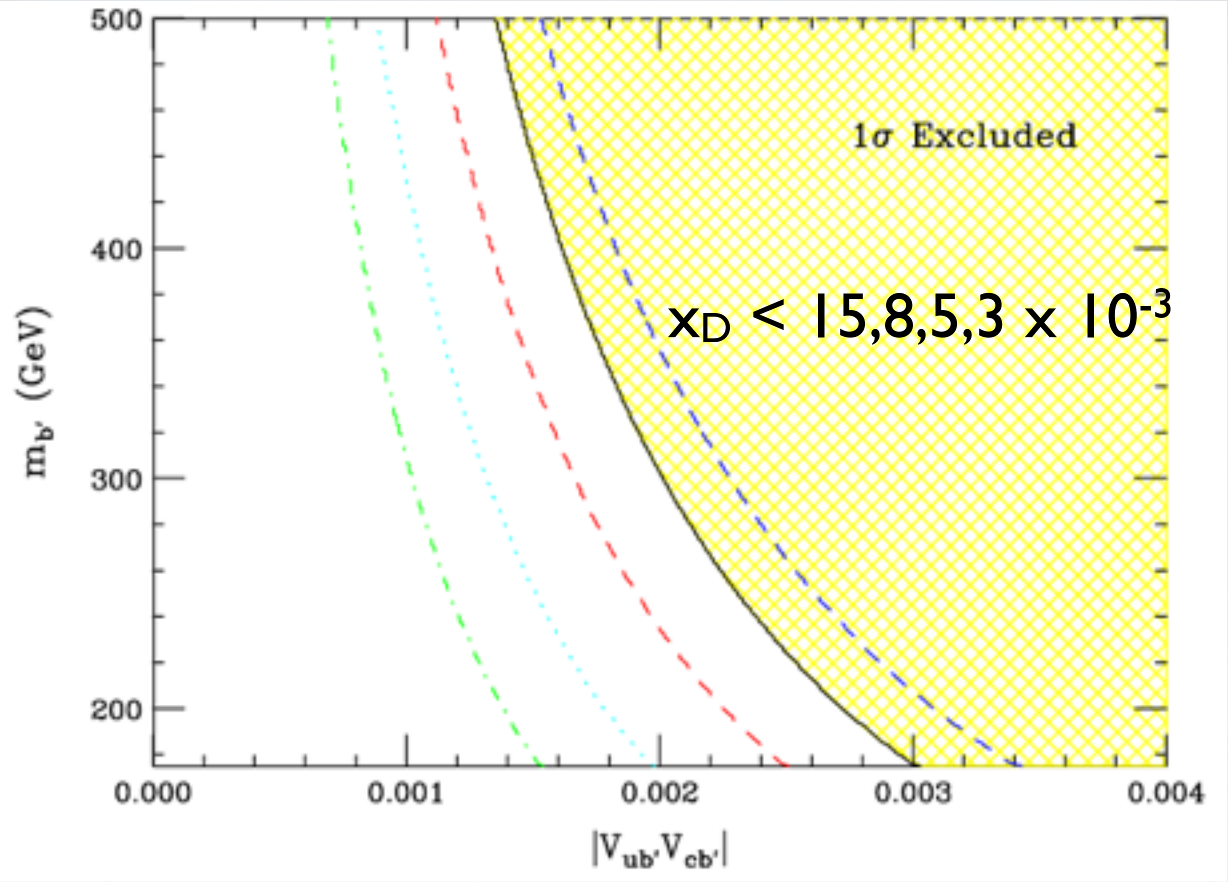
- leads to

$$\begin{aligned} M_{12}^{D^0} \propto\ & \lambda_s^2 S_0(x_s) + 2\lambda_s\lambda_b S(x_s, x_b) + \lambda_b^2 S_0(x_b) + \text{LD} && \text{SM3} \\ & + 2\lambda_s\lambda_{b'} S(x_s, x_{b'}) + 2\lambda_b\lambda_{b'} S(x_b, x_{b'}) + \text{LD} && \text{SM3/4 mix} \\ & + \lambda_{b'}^2 S_0(x_{b'}) && \text{SM4} \end{aligned}$$

- SD SM3 is very small; SD SM3/4 mixing is at least as small
- **SD SM4 can be significantly enhanced**
- **LD big unknown**

BOBROWSKI, LENZ, RIEDL, AND ROHRWILD PHYSICAL REVIEW D **79,** 113006 (2009)

x_D EXCLUSION



- x_D places stringent constraint on $|V_{ub'}V^*_{cb'}|$
- With a precise measurement need to know SM contribution for full interpretation

Eugene Golowich,[1] JoAnne Hewett,[2] Sandip Pakvasa,[3] and Alexey A. Petrov[4]
PHYSICAL REVIEW D **76,** 095009 (2007)

CHARM MIXING & 4^{th} GEN: y_D

$$\Gamma_{12} = -\left(\lambda_s^2 \Gamma_{ss} + 2\lambda_s \lambda_d \Gamma_{sd} + \lambda_d^2 \Gamma_{dd}\right) \qquad \lambda_x = V_{cx} V_{ux}^*$$

unitarity

$$\Gamma_{12} = -\lambda_s^2 \left(\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd}\right) + 2\lambda_s \lambda_b \left(\Gamma_{sd} - \Gamma_{dd}\right) - \lambda_b^2 \Gamma_{dd}$$

GIM cancellation vs CKM suppression

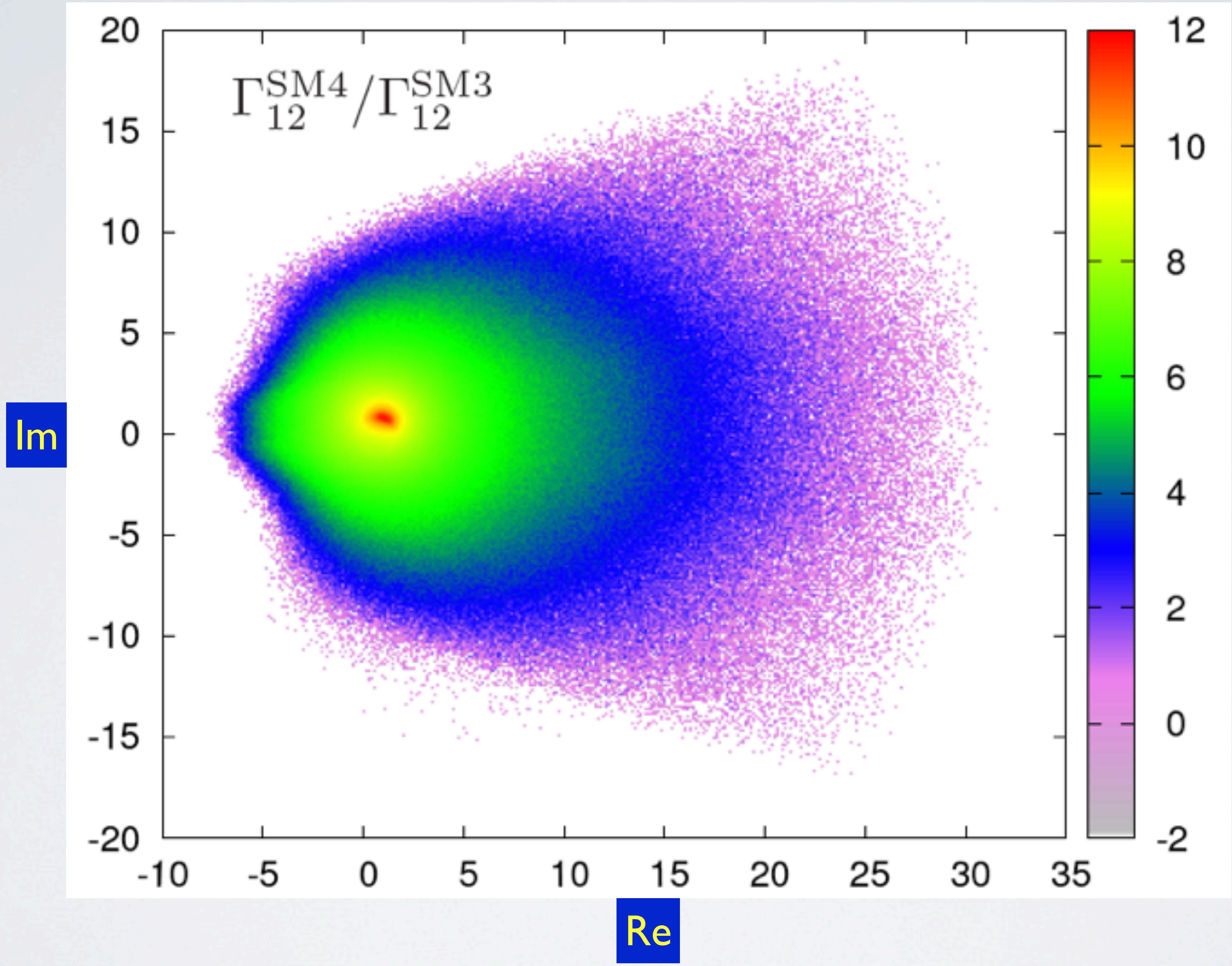
Enter the fourth generation

$$\Gamma_{12} = -\lambda_s^2 \left(\Gamma_{ss} - 2\Gamma_{sd} + \Gamma_{dd}\right) + 2\lambda_s (\lambda_b + \lambda_{b'}) \left(\Gamma_{sd} - \Gamma_{dd}\right) - (\lambda_b + \lambda_{b'})^2 \Gamma_{dd}$$

potentially reduced CKM suppression

Bobrowski, Lenz, Riedl, Rohrwild, JHEP03(2010)009

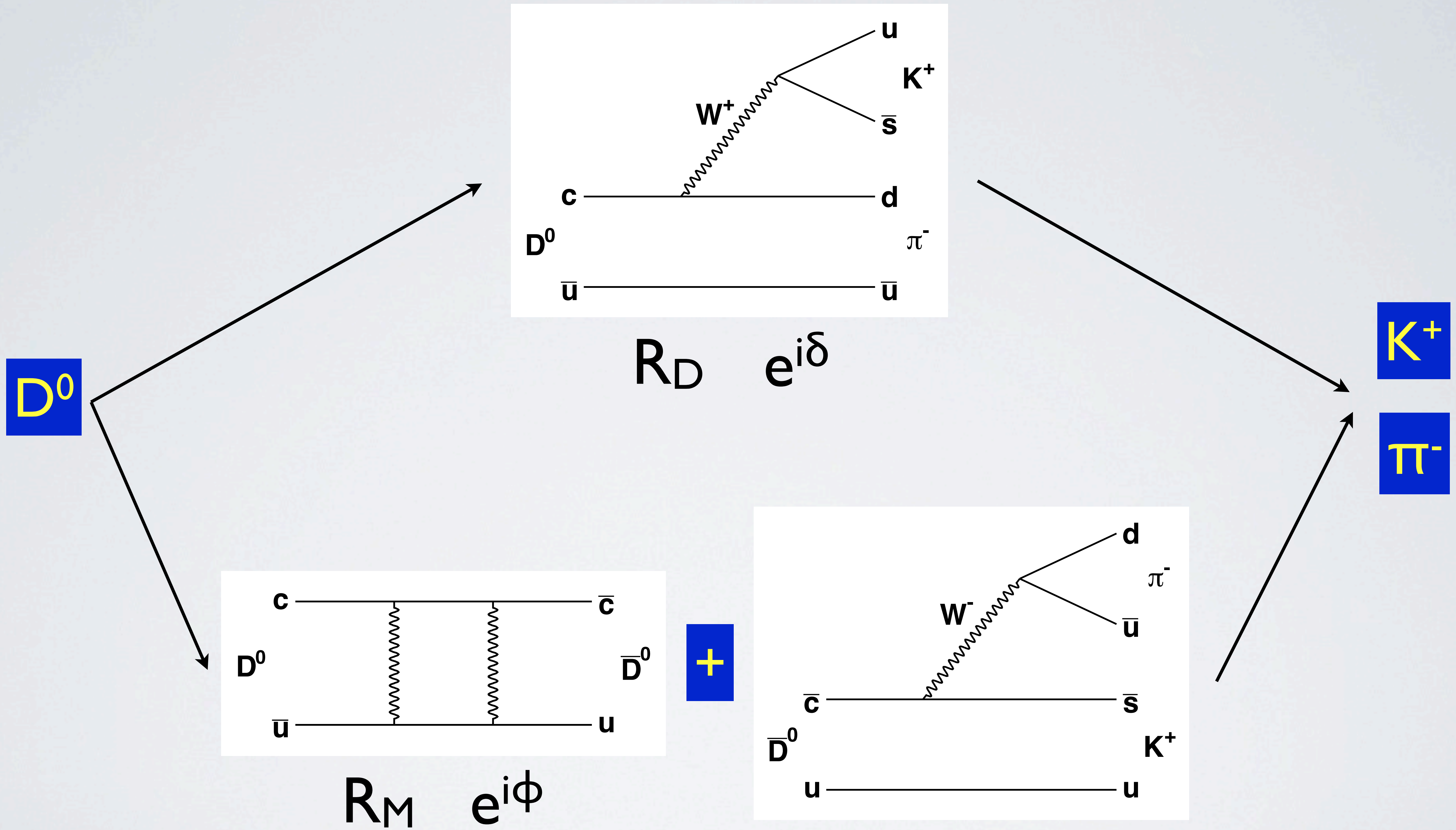
NEW PHYSICS AND Γ_{12}



Bobrowski, Lenz, Riedl, Rohrwild, JHEP03(2010)009

CHARM MIXING & CPV MEASUREMENTS

MIXING



D^0
u
K^+
W^+
$\bar{s}$
c
d
D^0
π^-
$\bar{u}$
$\bar{u}$
R_D $e^{i\delta}$
K^+
π^-
c
$\bar{c}$
D^0
$\bar{D}^0$
$\bar{u}$
u
R_M $e^{i\phi}$
+
d
π^-
W^-
$\bar{u}$
$\bar{c}$
$\bar{s}$
$\bar{D}^0$
K^+
u
u

MIXING

- Mixing parameters can be extracted from time evolution of wrong sign decay
- Exploiting the interference of the doubly Cabibbo suppressed amplitude and that of the mixing process followed by the Cabibbo favoured decay

$$\begin{aligned}\Gamma[D^0(t) &\rightarrow K^+\pi^-] = e^{-\Gamma t}\left|A_{K^-\pi^+}\right|^2 \\ &\times \left[R_D + \sqrt{R_D}R_m(y'\cos\phi - x'\sin\phi)\Gamma t + \frac{R_m^2}{4}(y'^2 + x'^2)(\Gamma t)^2\right]\end{aligned}$$

$$\begin{aligned}x' &\equiv x\cos\delta + y\sin\delta, \\ y' &\equiv y\cos\delta - x\sin\delta.\end{aligned}$$

Experiment	$R_D(10^{-3})$	$y'(10^{-3})$	$x'^2(10^{-3})$
BELLE [5]	3.64 ± 0.17	$0.6^{+4.0}_{-3.9}$	$0.18^{+0.21}_{-0.23}$
BABAR [6]	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
CDF [7]	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35

OTHER MODES

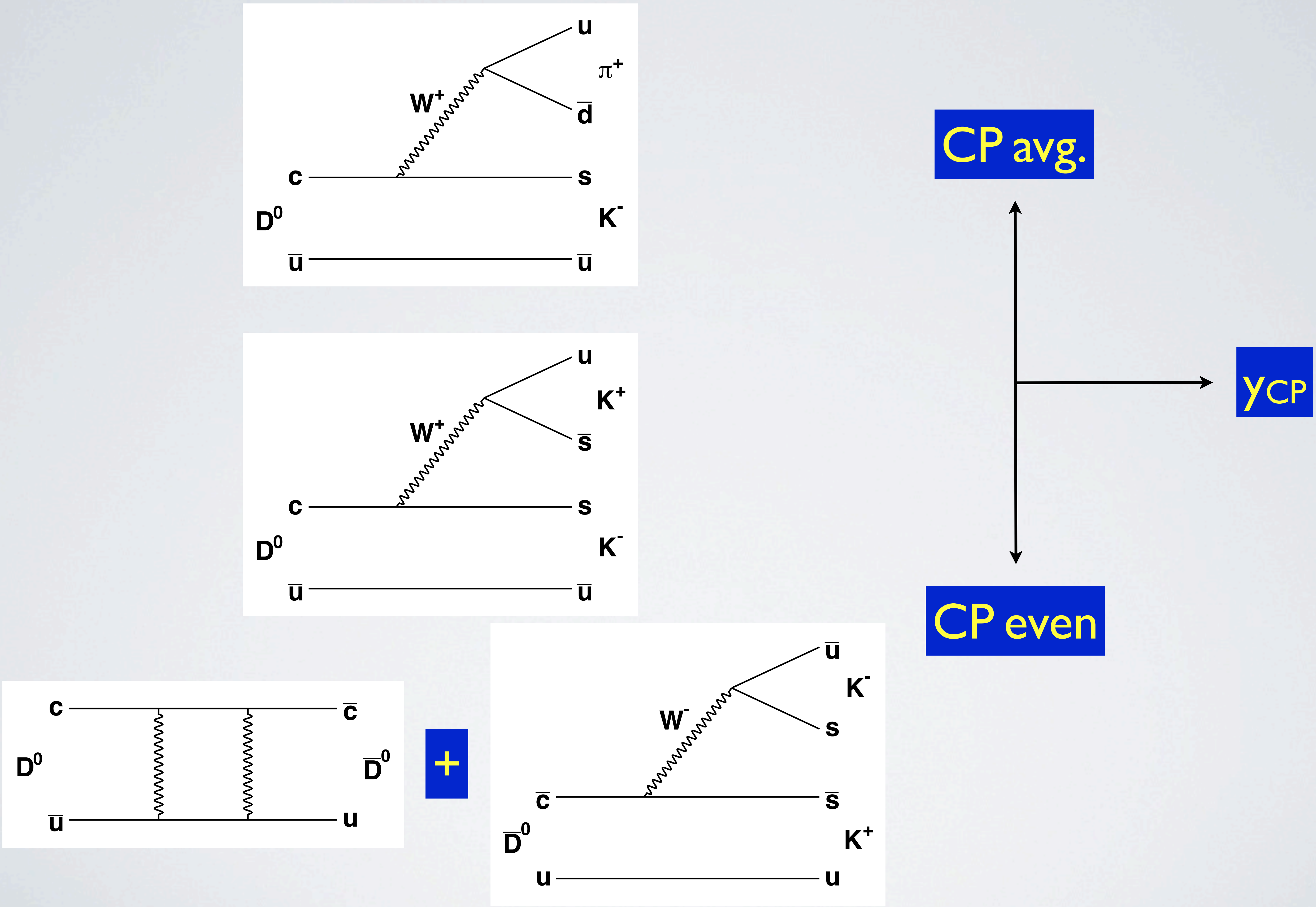
$$x'_{K\pi\pi^0} \equiv x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0},$$
$$y'_{K\pi\pi^0} \equiv y\cos\delta_{K\pi\pi^0} - x\sin\delta_{K\pi\pi^0}.$$

- Using $\mathbf{D^0 \to K^- \pi^+ \pi^0}$: essentially just adding a $\boldsymbol{\pi^0}$
- Different strong phase to $\mathbf{D^0 \to K^- \pi^+}$; Dalitz plot dependence
- BaBar sensitivity ~0.6%-0.7%

$$\Gamma[D \to K\mu\nu_{WS}] = e^{-\Gamma t}\,|A_{K^-\mu\nu}|^2 \left[\cancel{R_D + \sqrt{R_D}\,y'\Gamma t} + \frac{1}{4}(y'^2 + x'^2)(\Gamma t)^2\right]$$

- Measure relative time-integrated rate of wrong-sign to right-sign $\mathbf{D^0 \to K\mu\nu}$ rate
- No DCS diagram, so no need for time-dependent study
- Need very high statistics to reach sensitivity
- Current HFAG average dominated by Belle measurement: $R_M = {}^1/_2(x^2 + y^2) = (0.0130 \pm 0.0269)\%$

MIXING & CP VIOLATION



MIXING & CP VIOLATION

- y_{CP} is measured as the lifetime ratio of two decay modes

$$y_{CP} = \frac{\hat{\Gamma}(D \to K^+K^-)}{\hat{\Gamma}(D \to K^-\pi^+)} - 1$$

- Without CP violation in mixing ($A_m = 0$, $\phi = 0$): $y_{CP} = y$

$$y_{CP} = y_D \cos(\phi) - x_D \sin(\phi) \left(\frac{A_m}{2} + A_{prod} \right)$$

- Interpretation as mixing measurement

$$|\lambda_{KK}|^{\pm 1} = 1 \pm A_M/2$$

- Difference of y_{CP} and y is sign for CP violation

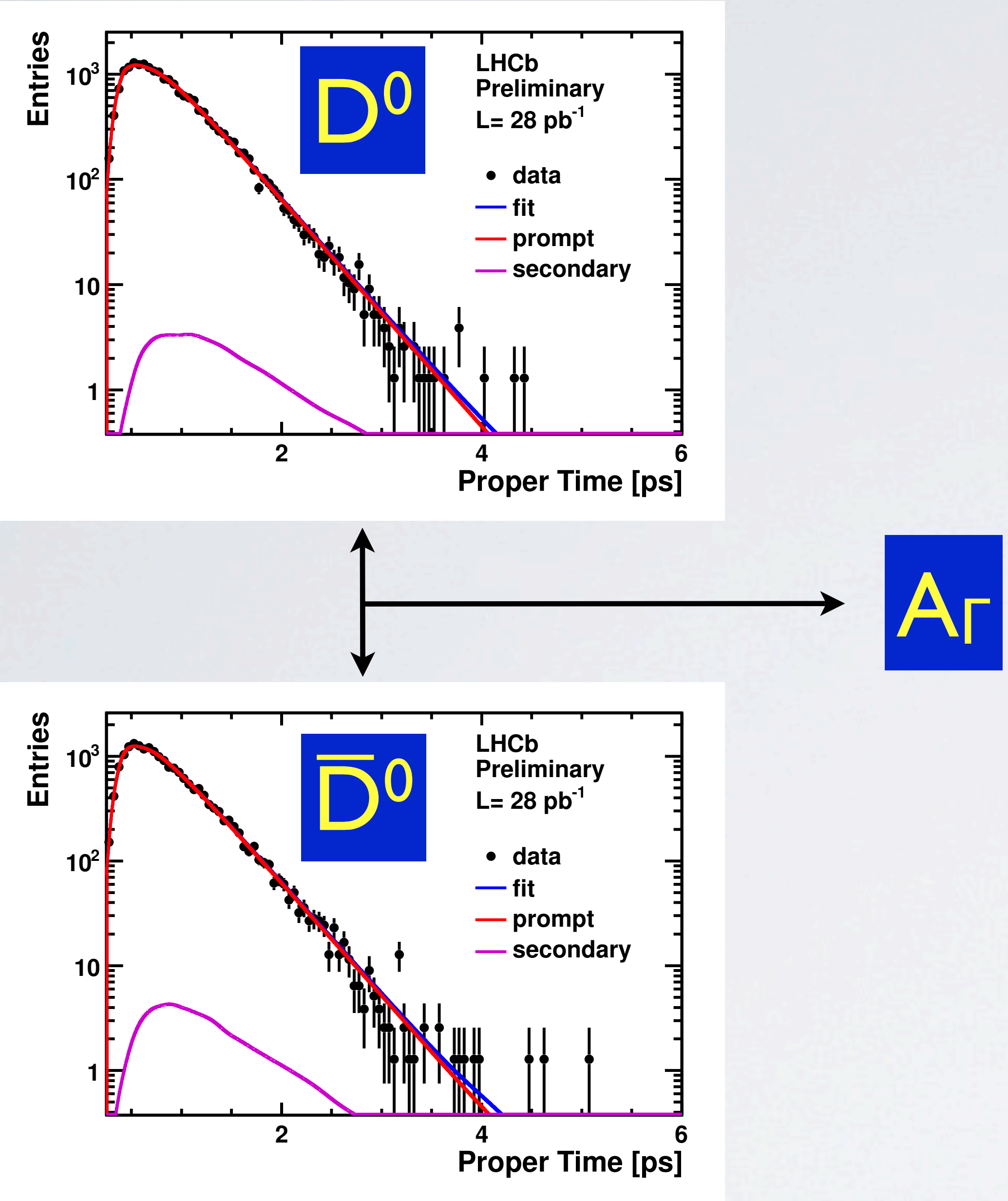
$$\arg(\lambda_{KK}) = \phi$$

- Production asymmetry (A_{prod}) cannot fake CP violation
- Problem: needs precise measurement of both y_{CP} and y to access CP violation

Experiment	$y_{CP}(10^{-3})$
BELLE [8]	$13.1 \pm 3.2 \pm 2.5$
BABAR (tagged) [9]	$10.8 \pm 3.3 \pm 1.9$
BABAR (untagged) [10]	$11.2 \pm 2.6 \pm 2.2$
LHCb Preliminary, 2010 data	$5.5 \pm 6.3 \pm 4.1$

CP VIOLATION

CERN-LHCb-2011-046



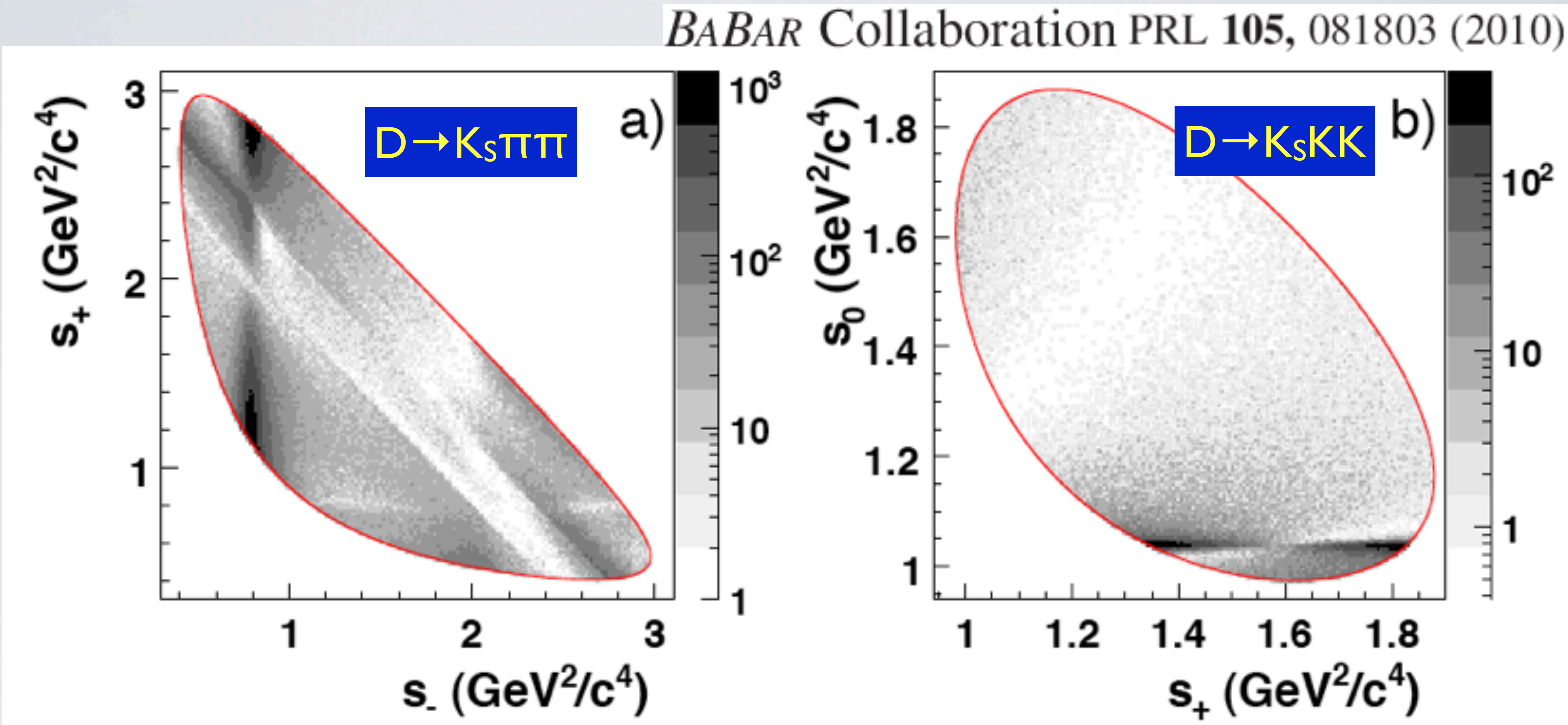
$$A_\Gamma = \frac{\hat{\Gamma}(D^0 \to K^+K^-) - \hat{\Gamma}(\bar{D}^0 \to K^+K^-)}{\hat{\Gamma}(D^0 \to K^+K^-) + \hat{\Gamma}(\bar{D}^0 \to K^+K^-)}$$

$$A_\Gamma = \tfrac{1}{2} A_M y \cos\phi - x \sin\phi$$

- **A_Γ** is measured from lifetime ratio of flavour tagged decays to CP eigenstates
- **$A_\Gamma \neq 0$** is a clear sign of CP violation

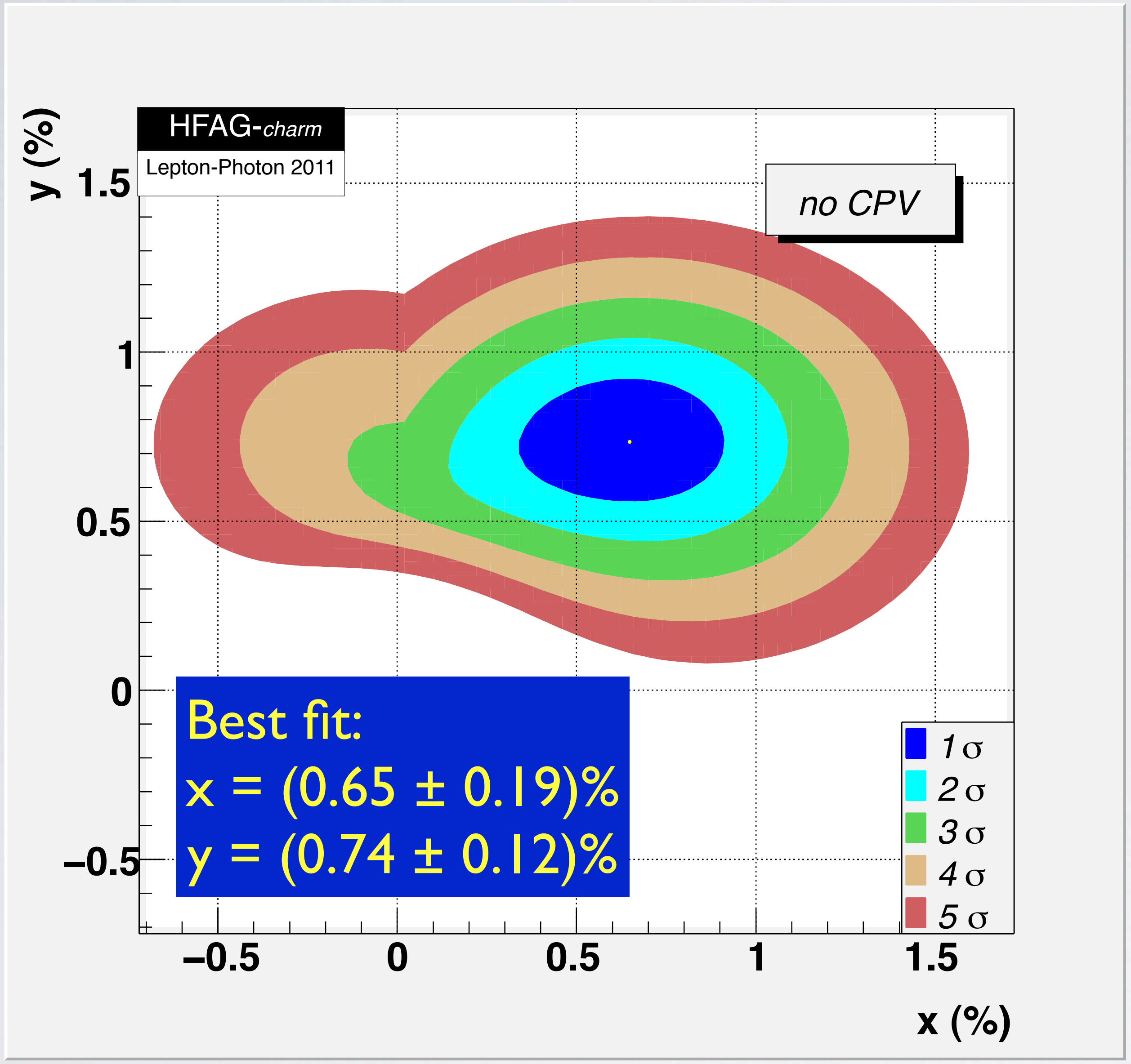
Experiment	$A_\Gamma (10^{-3})$
BELLE [8]	$0.1 \pm 3.0 \pm 1.5$
BABAR [9]	$2.6 \pm 3.6 \pm 0.8$
LHCb Preliminary, 2010 data	-5.9 ± 5.9 ± 2.1

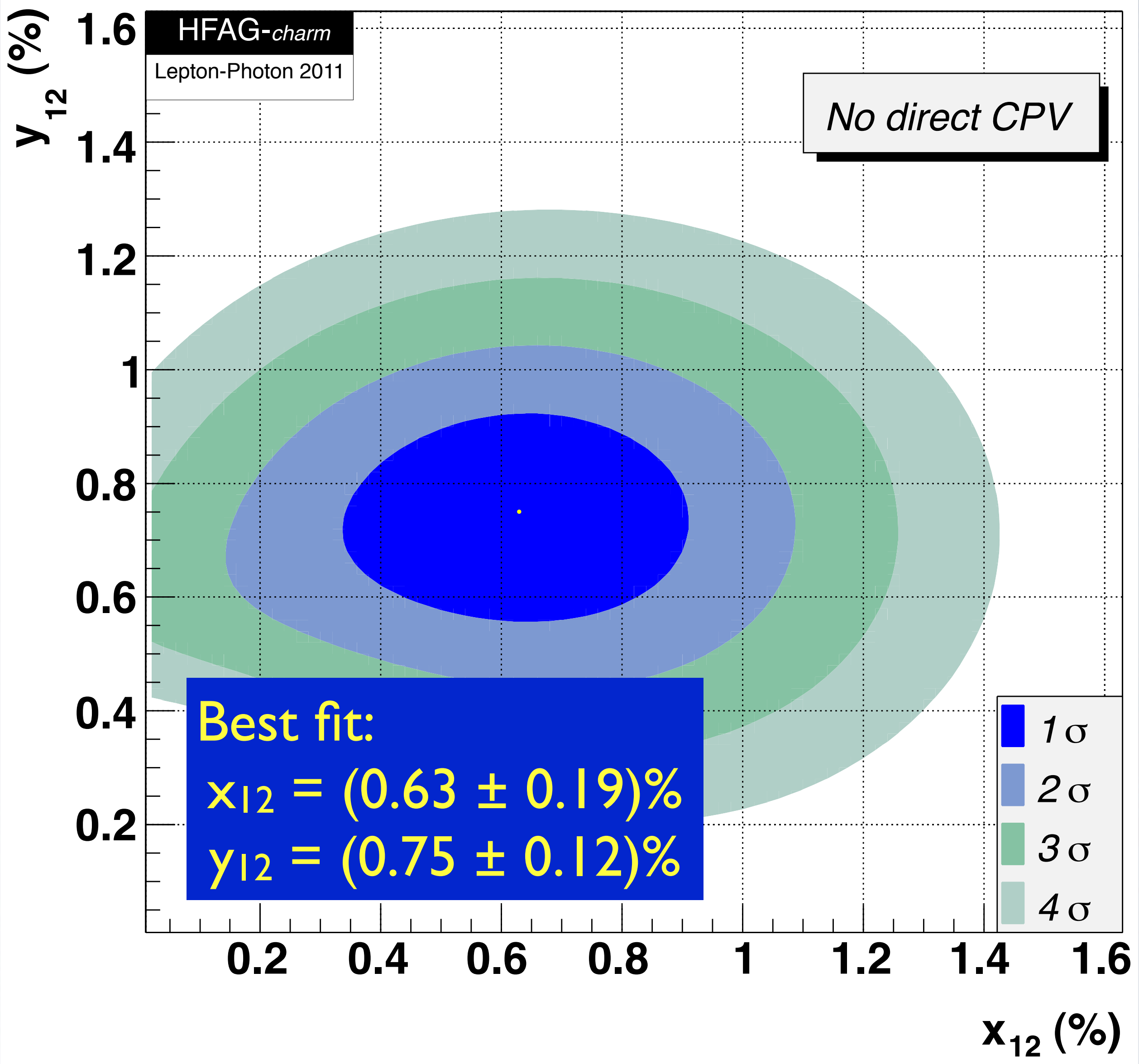
$D \to K_S hh'$



- Access to **x**, **y**, **|q/p|**, **ϕ** through time-dependent Dalitz plot fit
- Recent measurements by BaBar and Belle yield precision on **x** and **y** of **0.2%** - **0.3%**
- Belle extracts **|q/p|** and **ϕ** with precision of **~0.3**

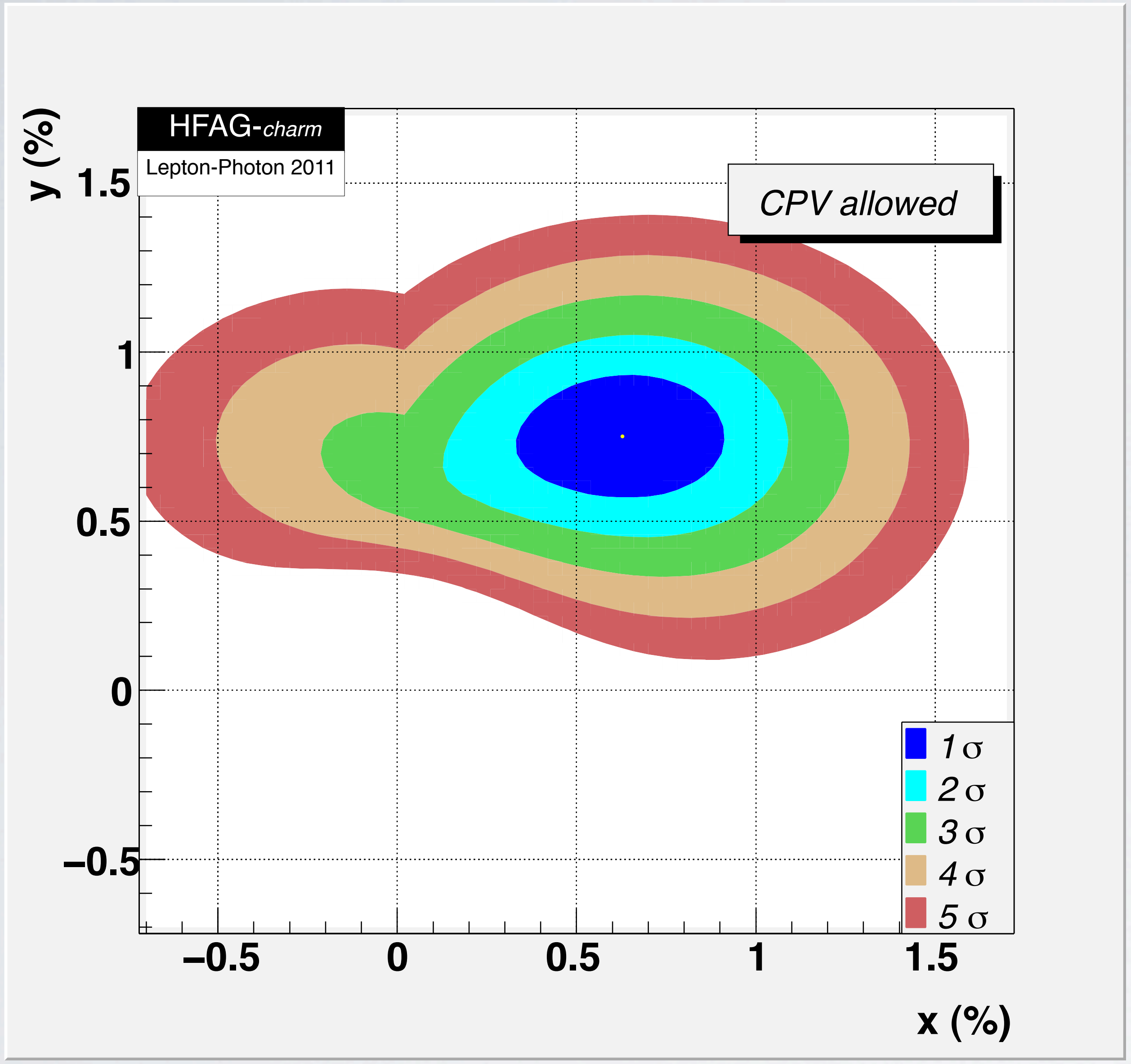
COMBINATIONS NO CPV

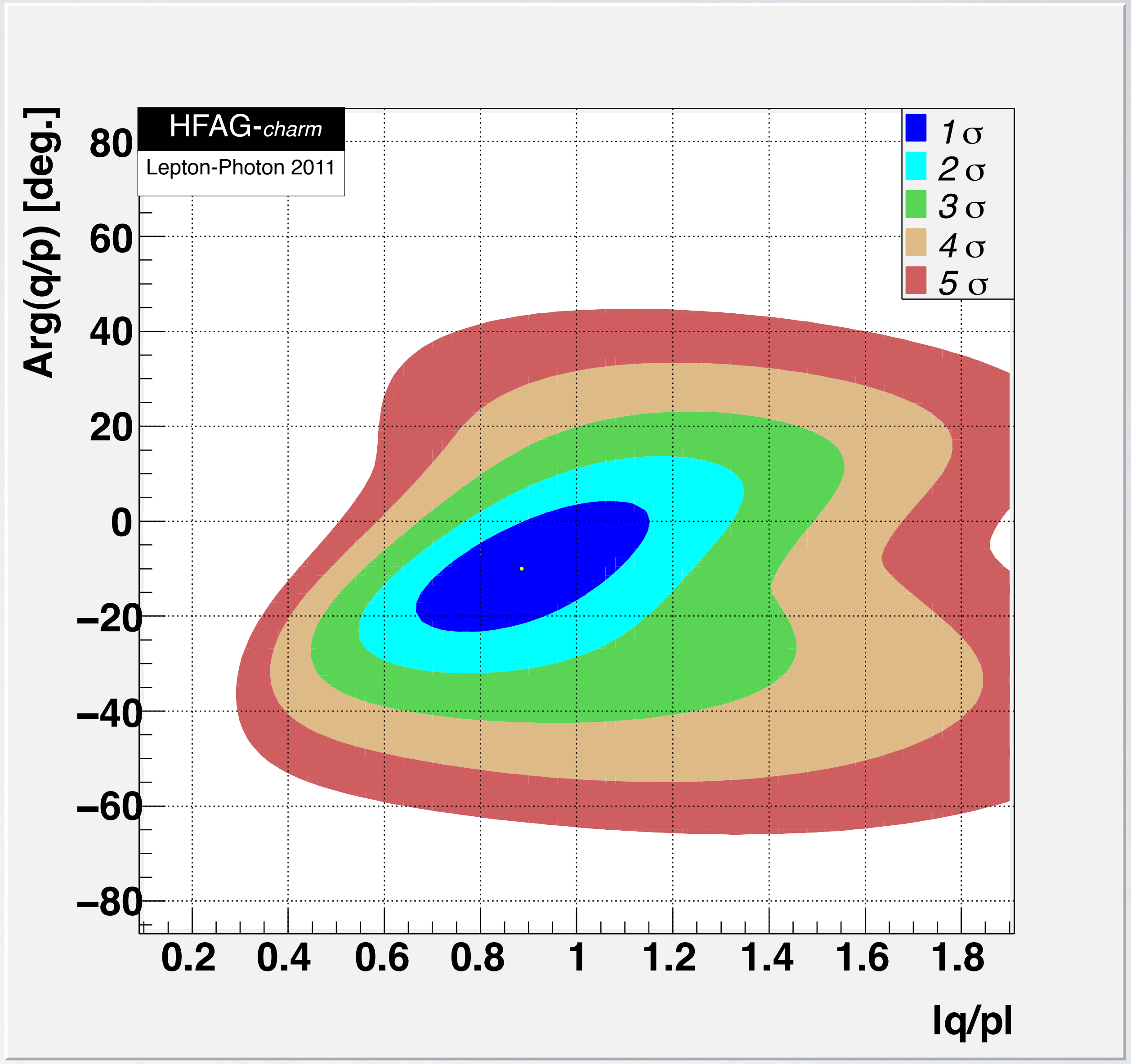




- New HFAG averages
- Added fit directly to $\mathbf{x_{12}}$ and $\mathbf{y_{12}}$ under the assumption of no direct CPV
  following Kagan, Sokoloff, Phys.Rev. D80 (2009) 076008

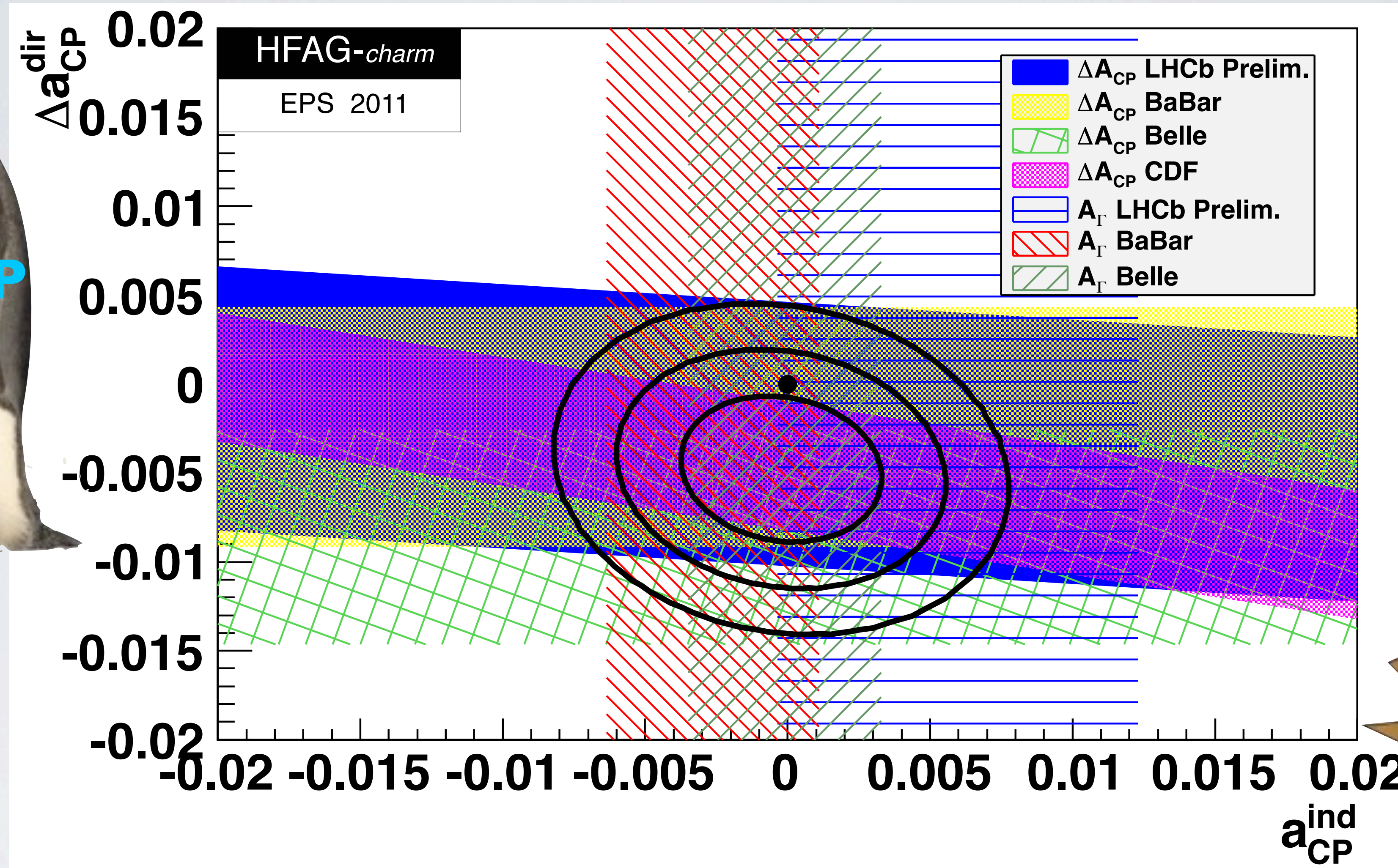
COMBINATIONS

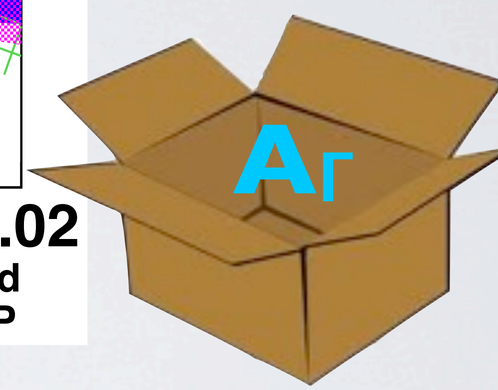




- New HFAG averages
- Allowing for CPV
- Practically no change on **x, y** compared to no CPV fit

DIRECT CPV





- General fit for direct and indirect CPV
- **$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = \Delta a_{CP}^{dir} + \Delta\langle t\rangle/\tau \cdot a_{CP}^{ind}$**
- No CPV C.L. **20%**

PROSPECTS

CURRENT STATUS AT LHCb

- Work ongoing to significantly advance mixing measurements
- Existing measurements of y_{CP} and A_Γ based on 2010 data within reach of current best measurements (about a factor 2-3 worse)
- Measurement of time-integrated WS/RS rate of $D^0 \to K^- \pi^+$ showed principal feasibility of making WS measurements at LHCb

LHCb Preliminary

	WS/RS of $D \to K\pi$ decays (%)
$R_{measured}$	$0.442 \pm 0.033\,(stat.)\ \pm 0.042\,(sys.)$
$R_{acc\,cor}$	$0.409 \pm 0.031\,(stat.)\ \pm 0.039(sys.)\ ^{+0.028}_{-0.020}\,(sys.\ mixing)$
$R(PDG)$	0.380 ± 0.018

- Trigger selections in place to select large sample of $D^0 \to K_S hh$ decays

PROSPECTS AT LHCb

- Expect measurements of y_{CP} and A_Γ based on 2011 data to reach precision of $\sim 10^{-3}$; **few 10^{-4}** feasible before upgrade
- Mixing measurement with $D^0 \rightarrow K^-\pi^+$ based on 2011 data expected to be competitive
- 2011 sample of $D^0 \rightarrow K_S hh$ decays should equal existing dataset; significant improvements over coming years
- $D^0 \rightarrow K^-\pi^+\pi^0$ feasible in principle but lower priority
- Charm physics will benefit greatly from upgrade
  → rule out any NP phase space that may be left
- Super-B factories will build on the success of their predecessors
  → better access to neutral modes than LHCb

CONCLUSIONS

- Charm mixing well established
- Entering phase of precision measurements
- Continuously excluding 4th generation phase space
- Need to know SM contribution to charm mixing to be able to interpret precision charm mixing measurements
- CPV sensitivity reaching very promising region