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Mixing-driven CPV with two-body decays: experimental prospects

Marco Gersabeck (The University of Manchester)

TUPIFP, Warwick, 17/4/2018

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Mixing-driven CPV with two-body decays: experimental prospects

=LHCb (here)

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Looking back: CKM2010@Warwick

CP VIOLATION IN CHARM MIXING AT LHCb

Marco Gersabeck (CERN)
for the LHCb Collaboration

CKM Workshop 2010, Warwick, 9th September 2010

OPEN CHARM CROSS-SECTIONS

- First measurement at $\sqrt{s} = 7$ TeV
- Large uncertainties on theoretical extrapolations
- Can measure down to $p_T = 0$
- Access to all open charm hadrons
- Presented here:
  Preliminary cross-sections for D^0, D^{*+}, D^+, D_s^+ using $1.8 nb^{-1}$
- Work in progress:
  Cross-sections for D^0, D^{*+}, D^+, D_s^+, Λ_c^+ using $14 nb^{-1}$

Looking back:
CKM2010@Warwick

WHAT, WHEN & HOW?

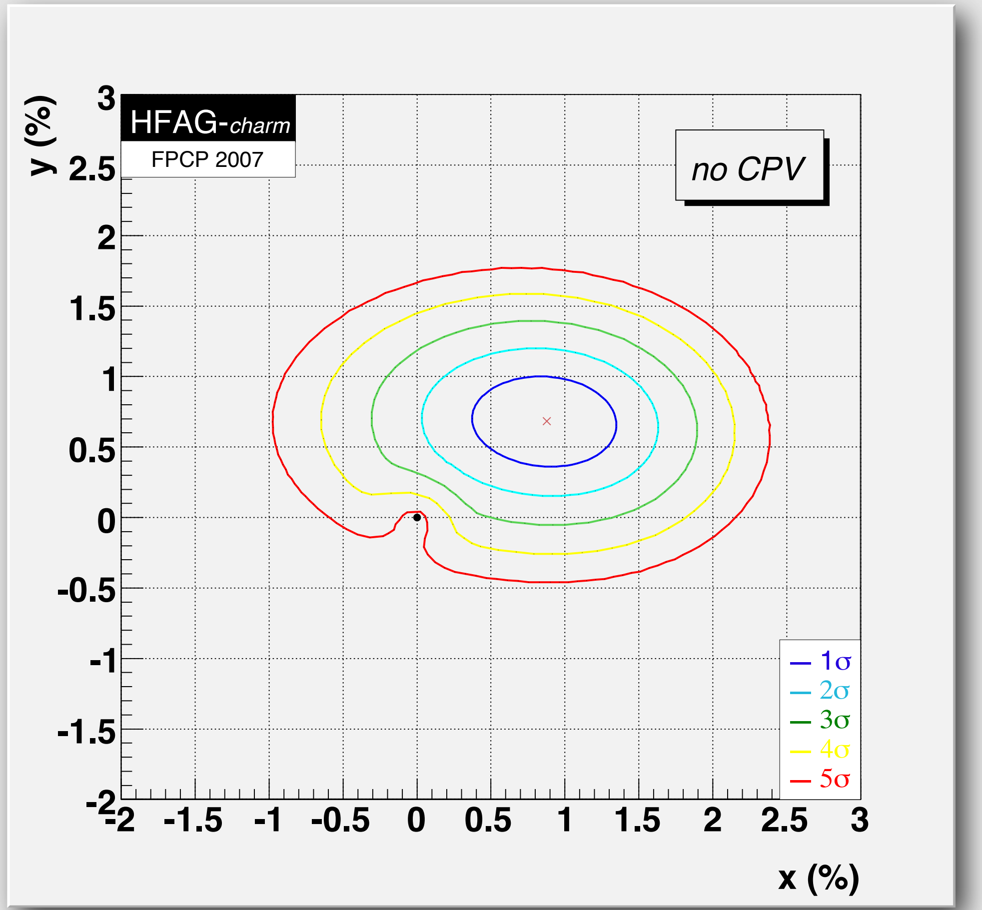
- Primary goal: making a **step forward in precision**
- All estimates to be taken with a large pinch of salt

CKM `10	3 pb^{-1}	Open charm cross-section measurements
Nov `10	20-50 pb^{-1}	Final, more precise open charm cross-sections published
Spring `11	>50 pb^{-1}	D^0 lifetime measurement via $D^0 \to K^-\pi^+$ Relative branching fractions, e.g. $D^0 \to K^-K^+$ and $D^0 \to K^-\pi^+$
Summer `11	~500 pb^{-1}	First LHCb measurement of y_{CP} & A_Γ
End `11 + x	~1 fb^{-1}	D^0 mixing via DCS $D^0 \to K^+\pi^-$ Mixing and CP violation via $D^0 \to K_S h^+h^-$

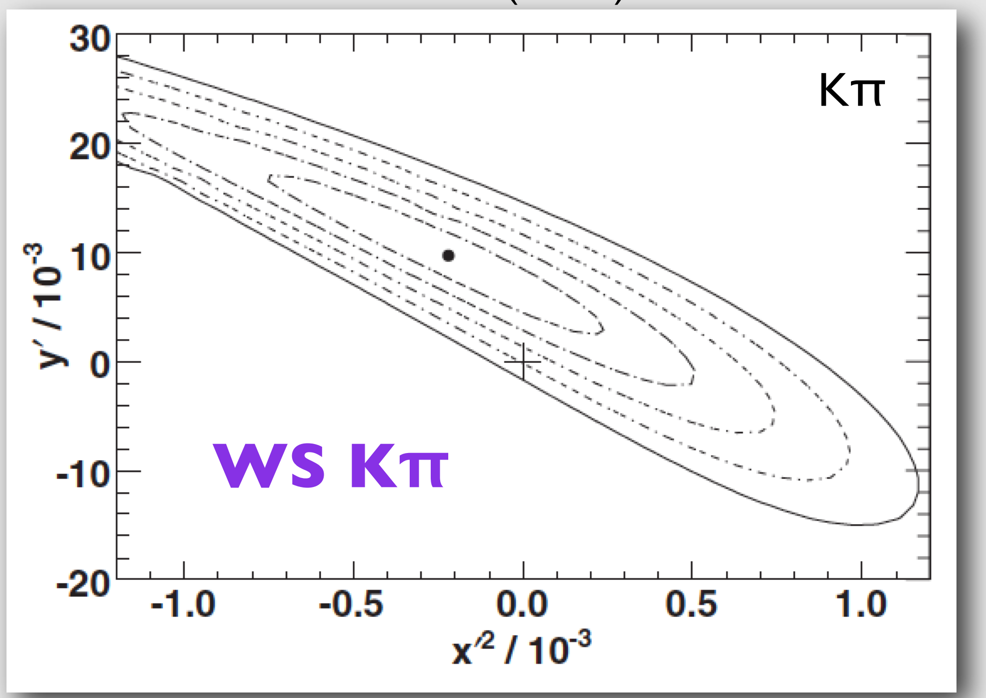
phew

Looking back:
CKM2010@Warwick

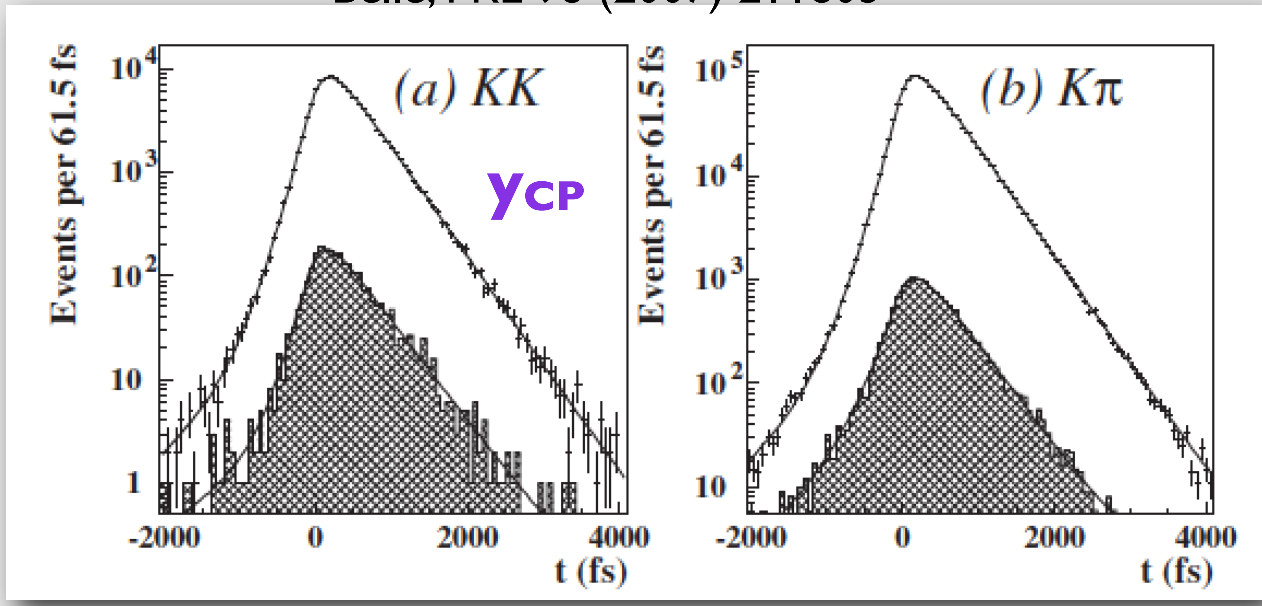
Mixing discovery



BABAR, PRL 98 (2007) 211802



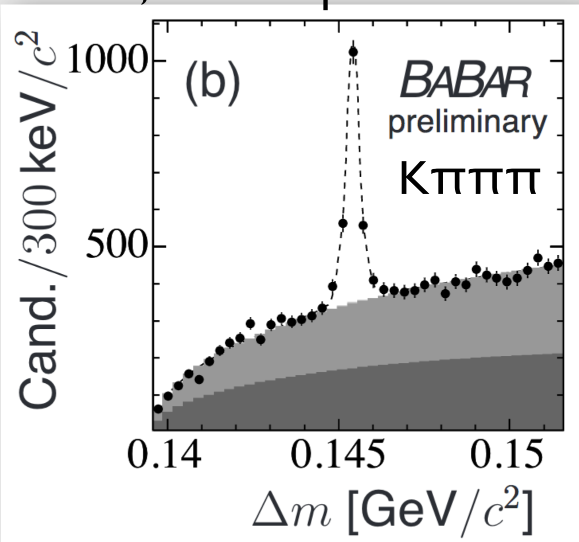
Belle, PRL 98 (2007) 211803



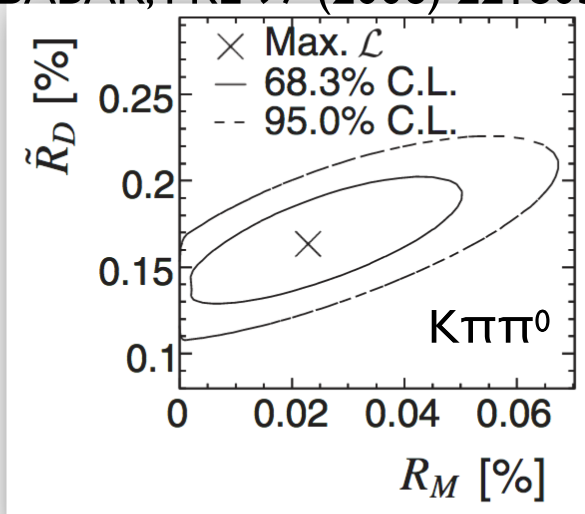
- Discovery through combination of measurements
- Mostly two-body

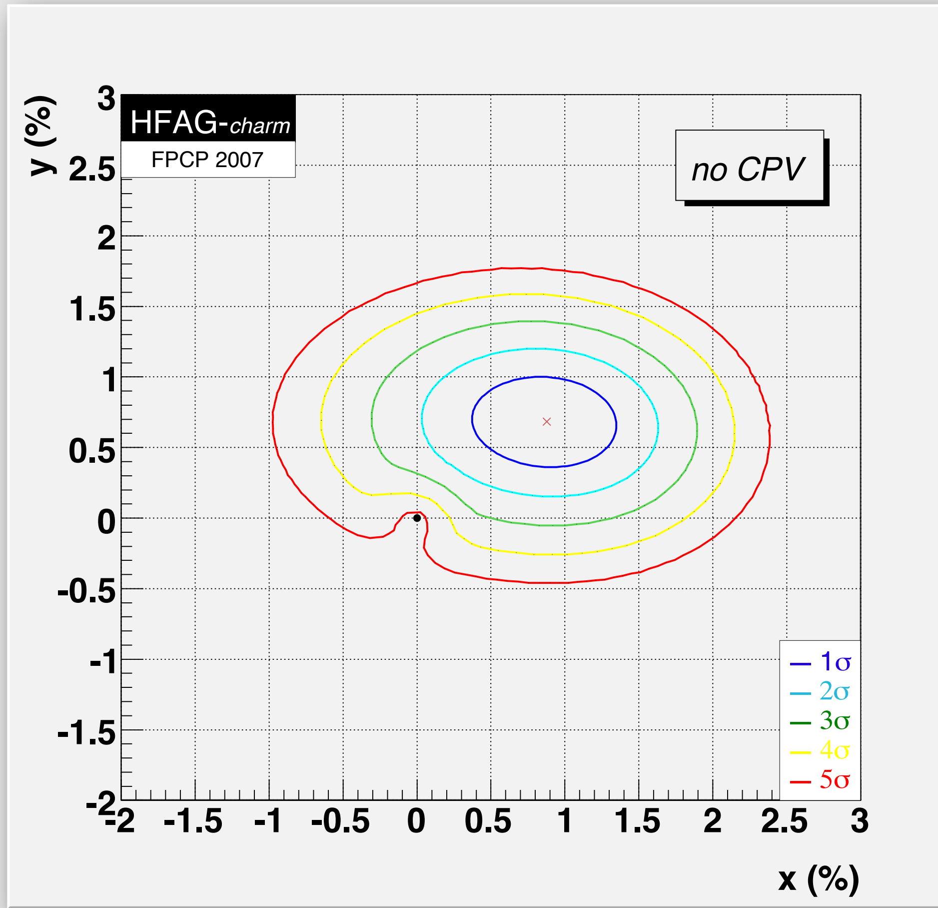
Mixing discovery

BABAR, arXiv:hep-ex/0607090

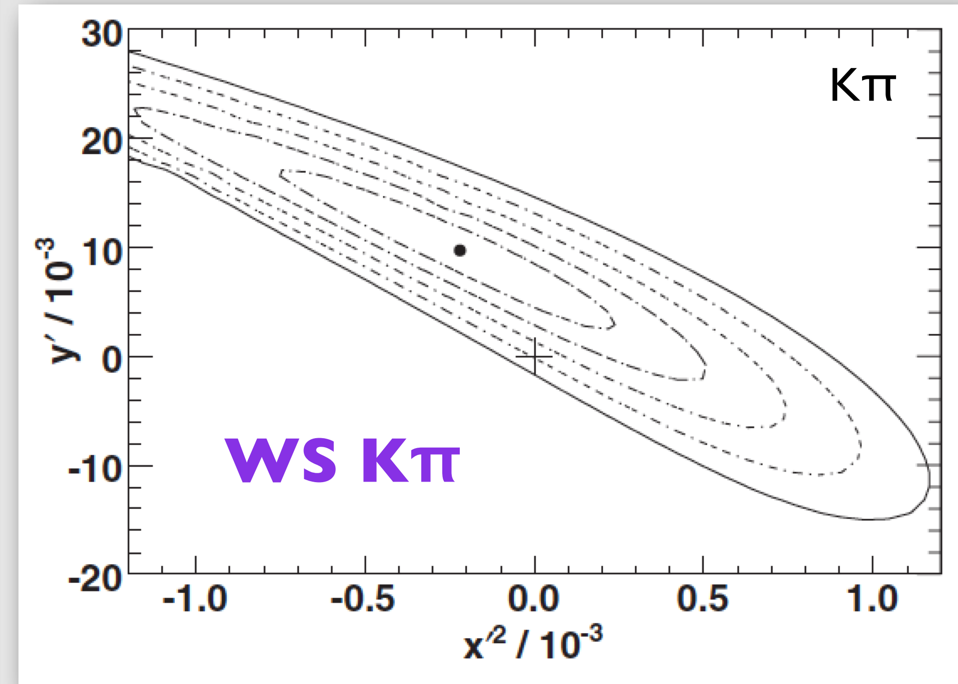


BABAR, PRL 97 (2006) 221803





BABAR, PRL 98 (2007) 211802



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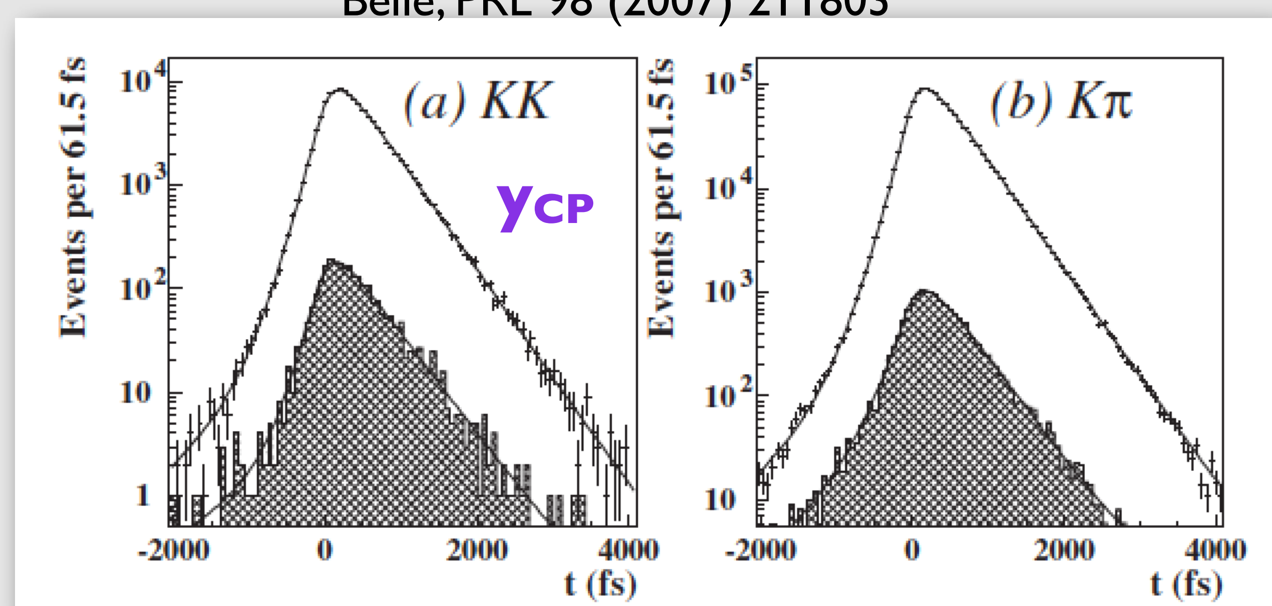
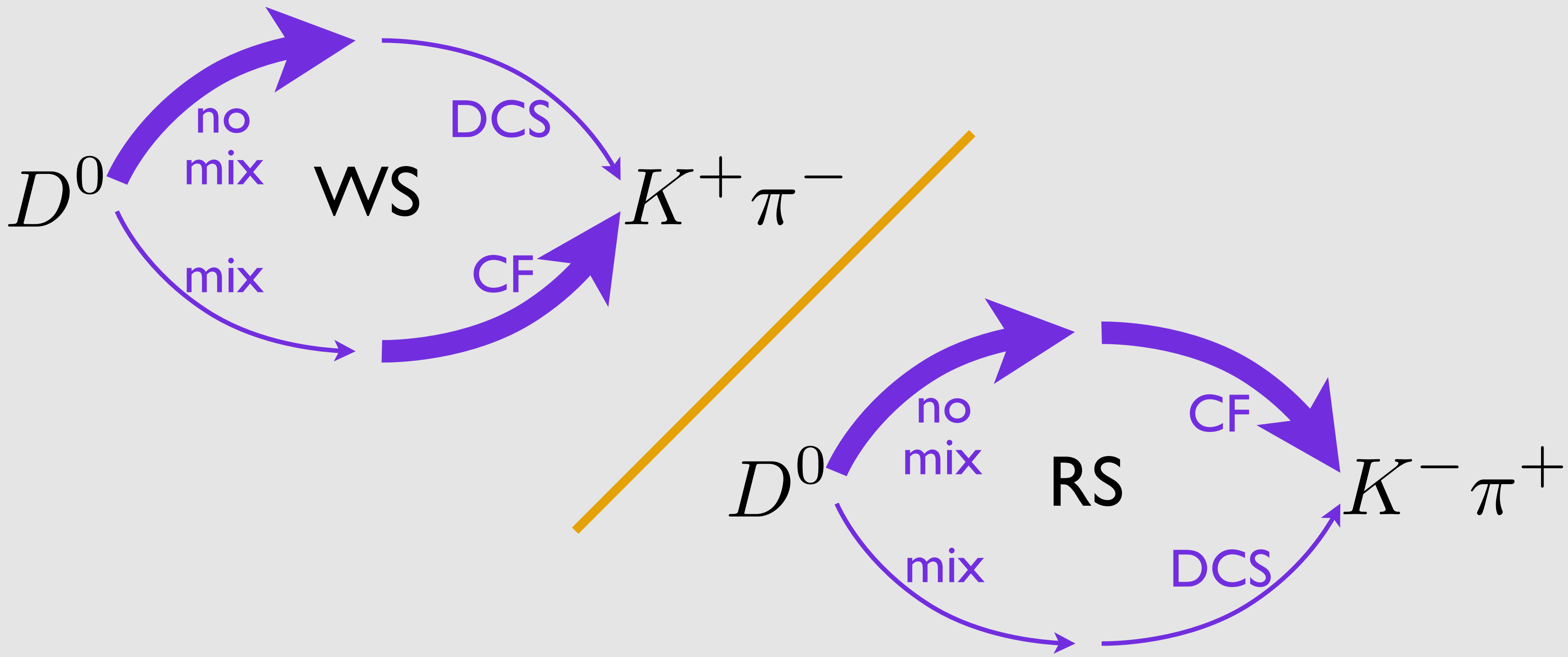
Belle, PRL 98 (2007) 211803



Mixing discovery: WS Kπ

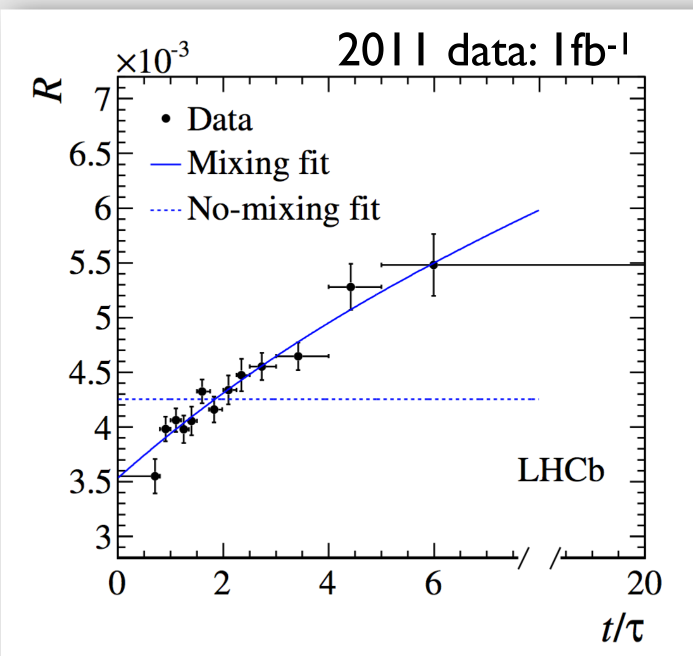
PRL 110 (2013) 101802



Using roughly 8.4×10^6 RS and 3.6×10^4 WS candidates

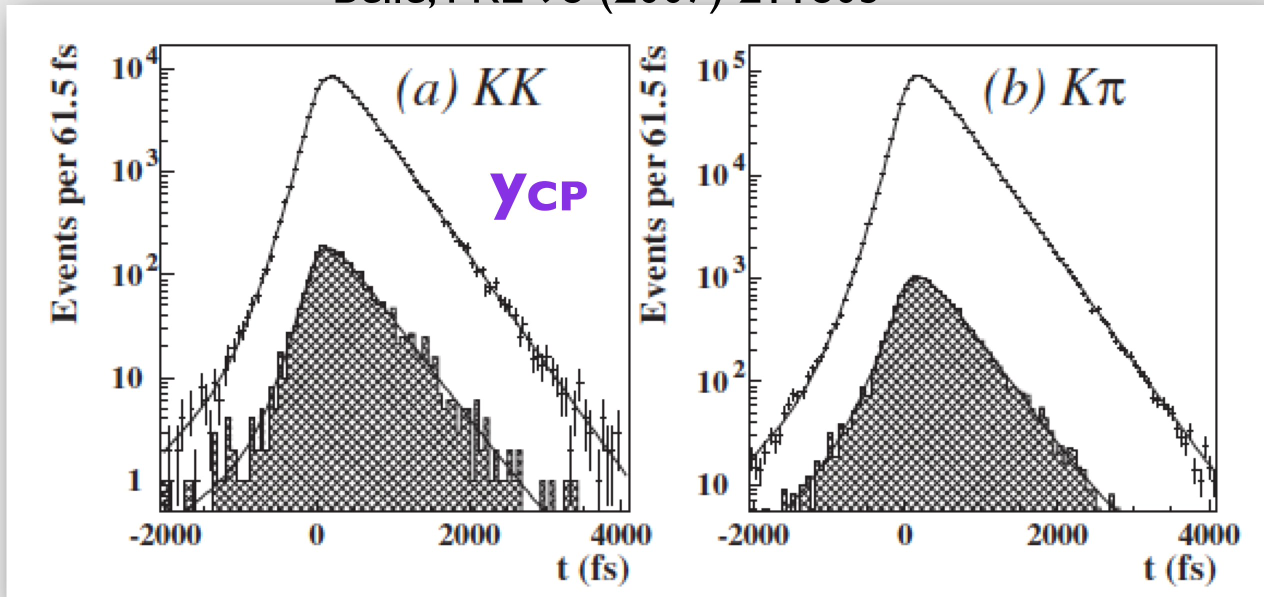
$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2+y'^2}{4}(\frac{t}{\tau})^2$$

- Rotation of mixing parameters by strong phase difference between CF and DCS amplitudes: x,y → x',y'
- Can get strong phase difference from external input (BESIII) or global fits



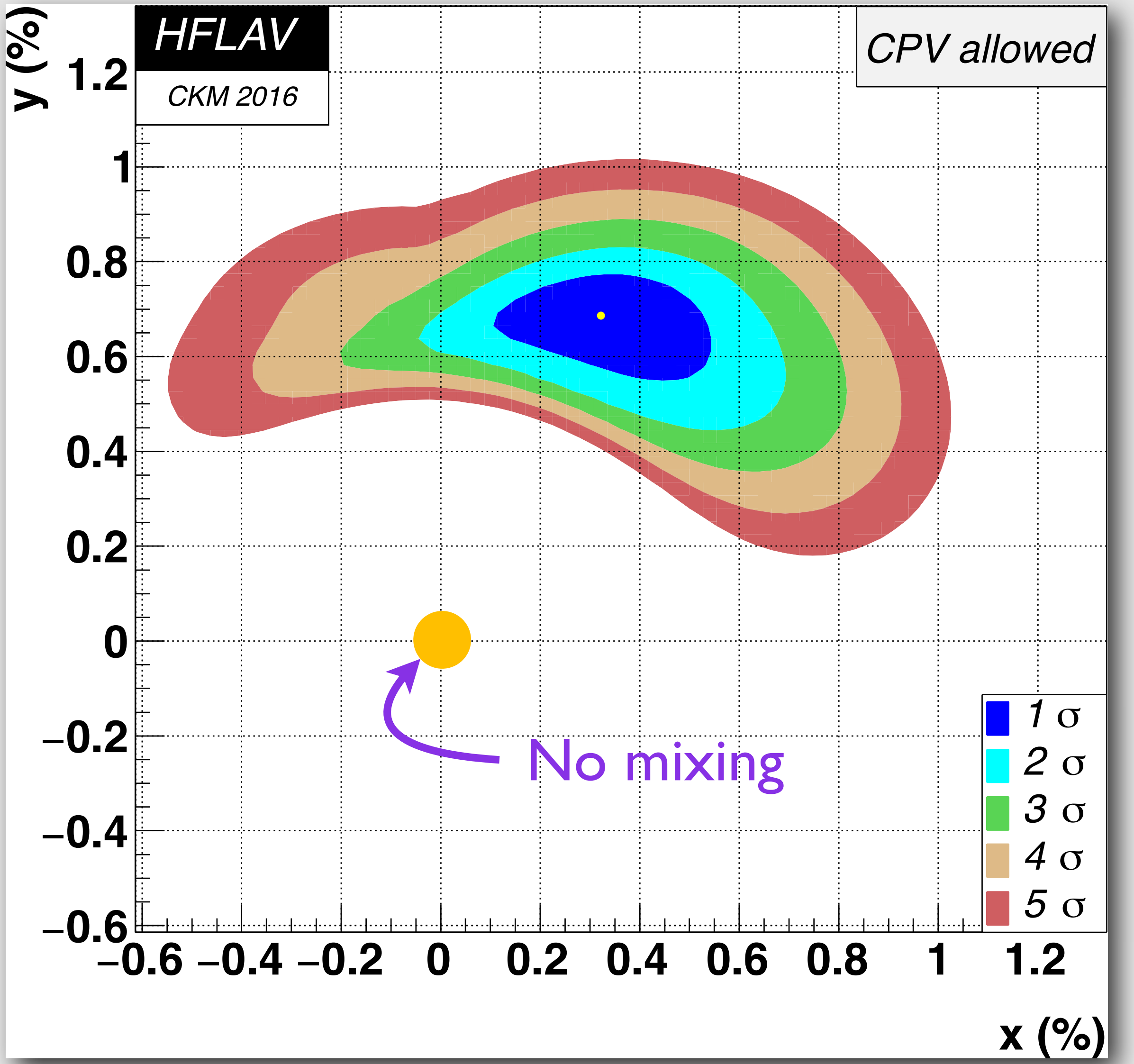
Mixing discovery: y_{CP}

Belle, PRL 98 (2007) 211803



- Measure effective lifetime in decays to CP eigenstate
- Compare to CF mode to get nominal τ_D
- Without CPV, CP eigenstate overlaps with physical state, hence measure $\Delta\Gamma$ or y
  - ➡ CPV can cause second order deviations of y_{CP} from y
- Very challenging as control of decay-time acceptance of different final states required to very high precision
  - ➡ Probably not first priority due to reduced sensitivity to CPV

Mixing nowadays



- Mixing established
  - ➡ x≠0 still open question

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Mixing-related CP violation

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

Mixing:

$x \equiv (m_2 - m_1)/\Gamma$

$y \equiv (\Gamma_2 - \Gamma_1)/2\Gamma$

CP violation:

$|q/p| \neq 1$

$\phi \equiv \arg(q/p) \neq 0, \pi$

Indirect CP violation:

$$a_{CP}^{ind} = -a_m\, y \cos\phi - x \sin\phi$$

with $a_m \approx \pm(|^q/_p|^2 - 1)$

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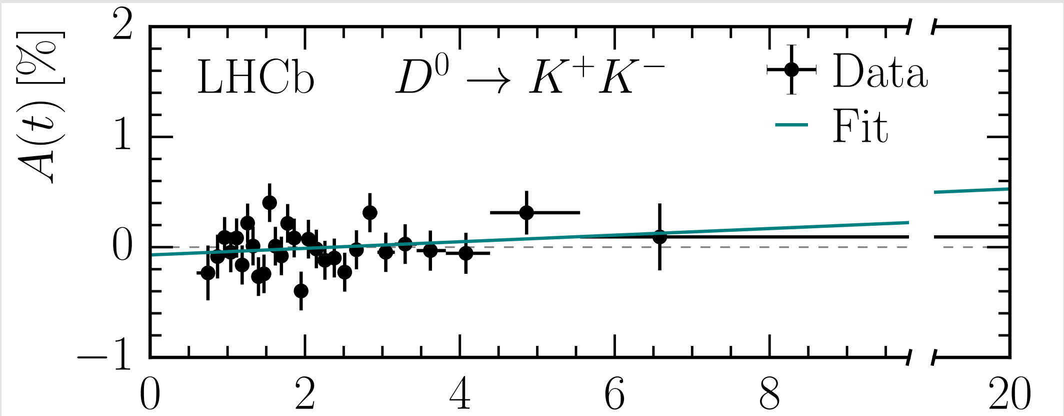
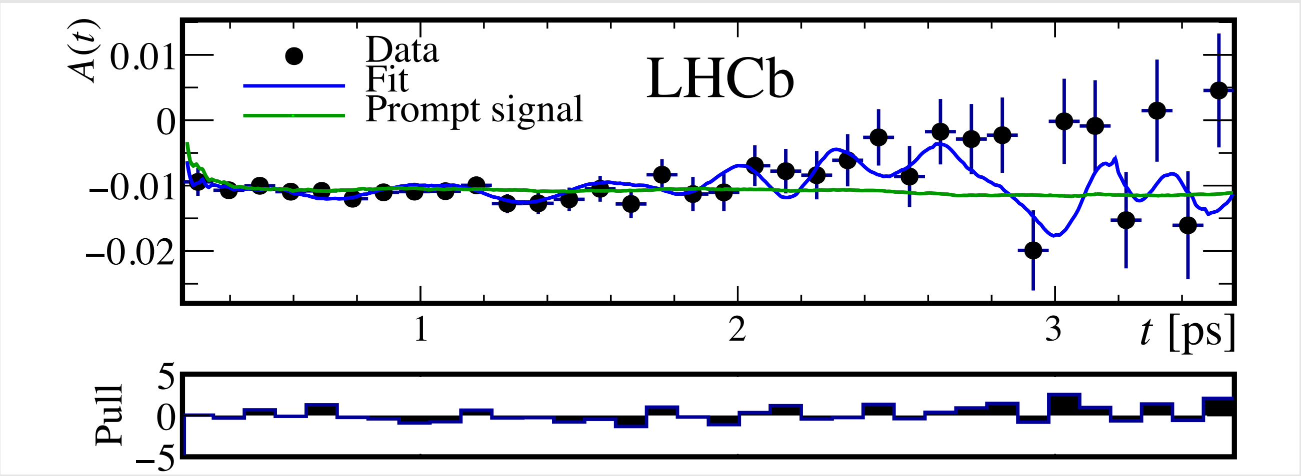
$A_\Gamma = -a_{CP}^{ind}$

- Measure asymmetry of effective lifetimes of D^0 and $\overline{D}^0$ decays to CP eigenstate
  - ➡ =0 if physical states are CP eigenstates
  - ➡ ≠0 implies CP violation
- Two methods, two final states, one result
  - ➡ $A_\Gamma(K^+K^-)= (-0.30\pm0.32\pm0.10)\times10^{-3}$
  - ➡ $A_\Gamma(\pi^+\pi^-)= (+0.46\pm0.58\pm0.12)\times10^{-3}$



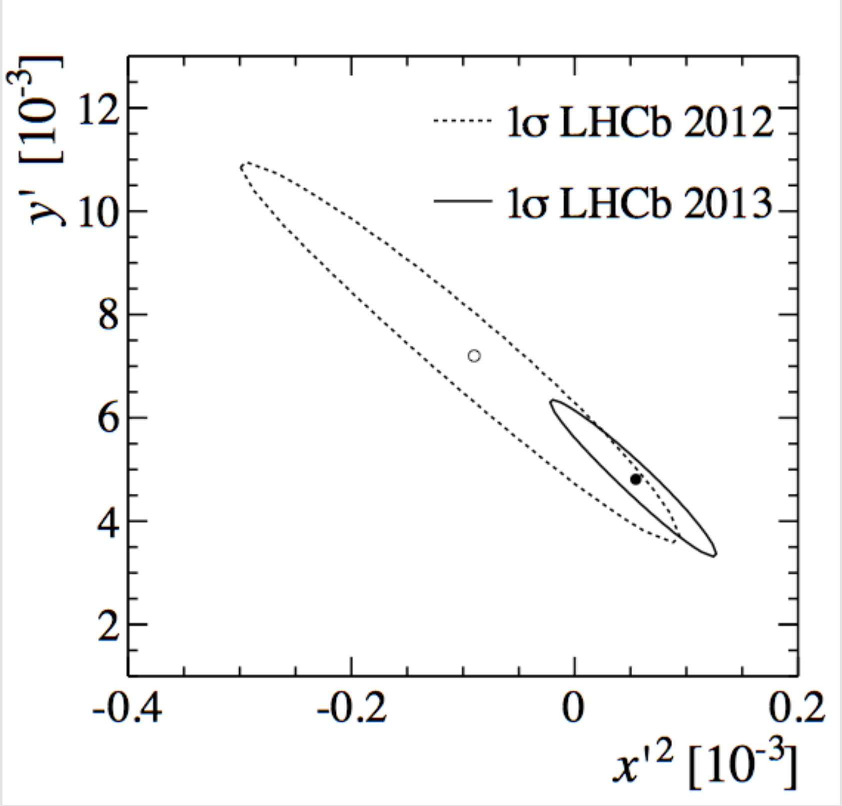
PRL 118 (2017) 261803



CP violation with DCS

PRL 111 (2013) 251801

- D→Kπ again
- Update with 3 fb^{-1}
- Split by flavour to search for CP violation
  - ➡ $x'^{\pm} = |q/p|^{\pm 1}(x' \cos\Phi \pm y' \sin\Phi)$
  - ➡ $y'^{\pm} = |q/p|^{\pm 1}(y' \cos\Phi \mp x' \sin\Phi)$
- Very good sensitivity to |q/p| for small ϕ
- No indication for CP violation

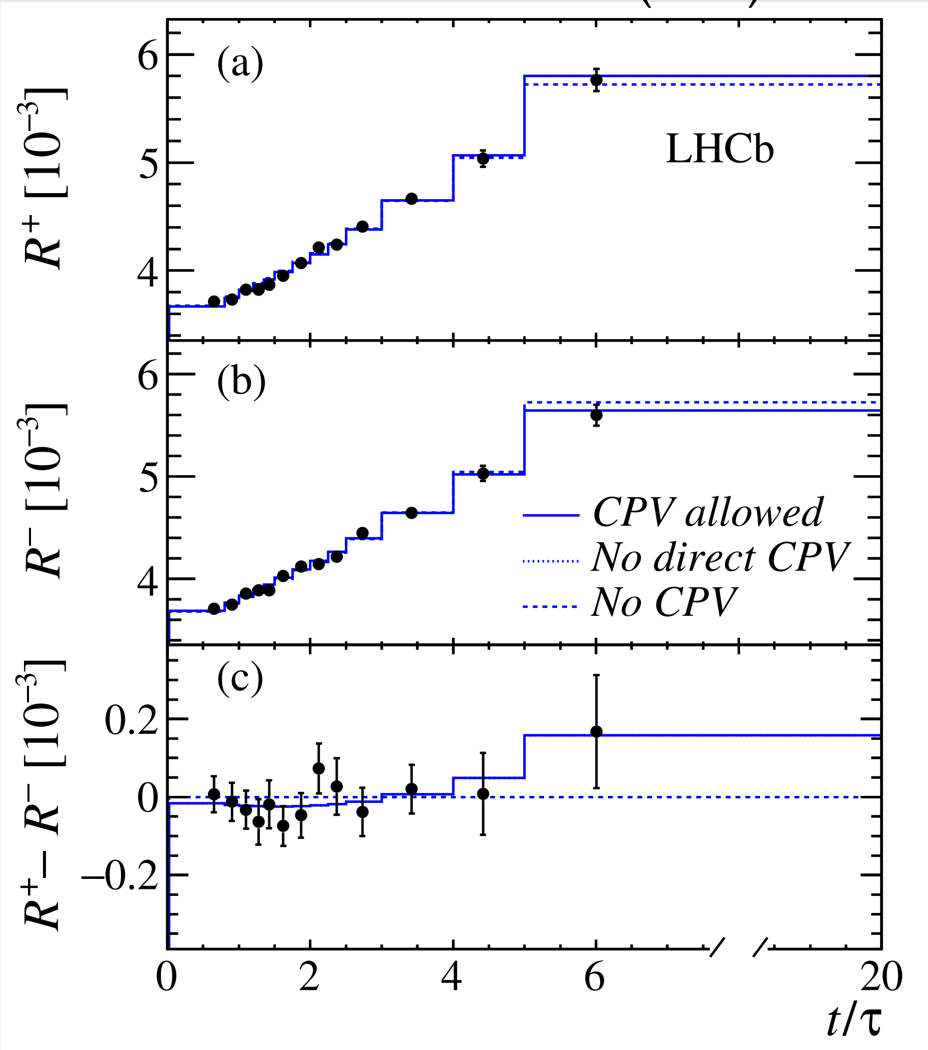


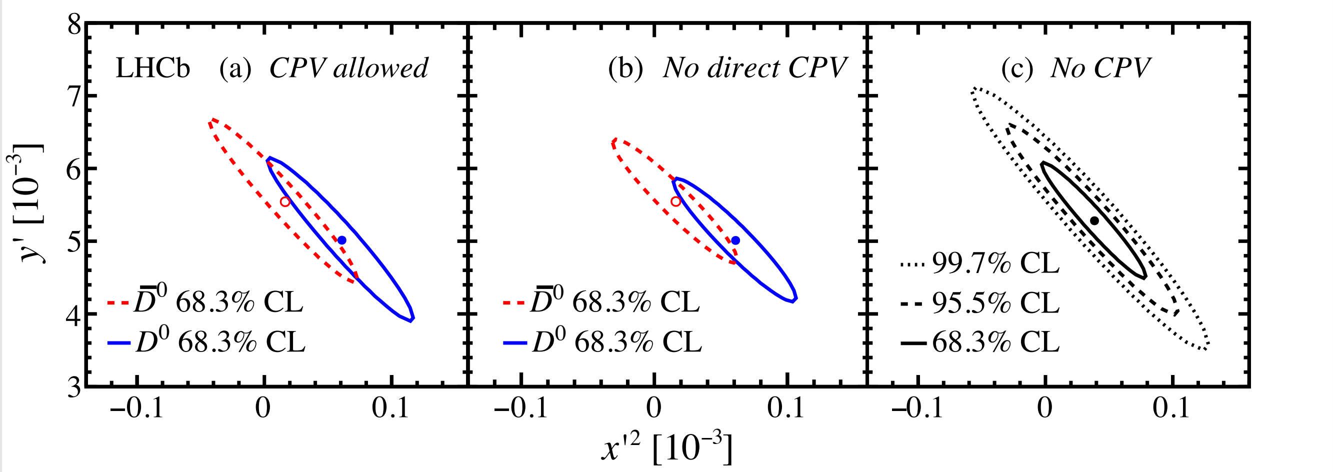
R_D^+	$[10^{-3}]$	$3.545 \pm 0.082 \pm 0.048$
y'^+	$[10^{-3}]$	$5.1 \pm 1.2 \pm 0.7$
x'^{2+}	$[10^{-5}]$	$4.9 \pm 6.0 \pm 3.6$
R_D^-	$[10^{-3}]$	$3.591 \pm 0.081 \pm 0.048$
y'^-	$[10^{-3}]$	$4.5 \pm 1.2 \pm 0.7$
x'^{2-}	$[10^{-5}]$	$6.0 \pm 5.8 \pm 3.6$

New WS Kπ

- Latest measurement based on 2011-2016 data
  - ➡ 180M favoured and 0.7M suppressed decays
- Twice as precise as previous results
- Still no sign for CPV

PRD 97 (2018) 031101





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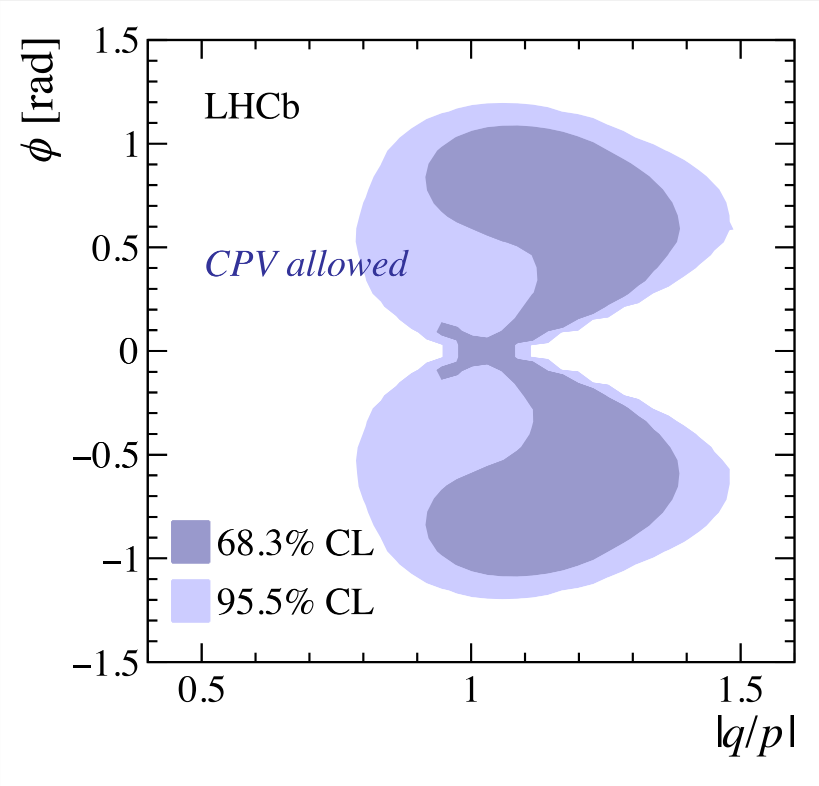
New WS Kπ

- Results

Results $[10^{-3}]$		Correlations					
		Direct and indirect *CP* violation					
Parameter	Value	R_D^+	y'^+	$(x'^+)^2$	R_D^-	y'^-	$(x'^-)^2$
R_D^+	$3.454 \pm 0.040 \pm 0.020$	1.000	−0.935	0.843	−0.012	−0.003	0.002
y'^+	$5.01 \pm 0.64 \pm 0.38$		1.000	−0.963	−0.003	0.004	−0.003
$(x'^+)^2$	$0.061 \pm 0.032 \pm 0.019$			1.000	0.002	−0.003	0.003
R_D^-	$3.454 \pm 0.040 \pm 0.020$				1.000	−0.935	0.846
y'^-	$5.54 \pm 0.64 \pm 0.38$					1.000	−0.964
$(x'^-)^2$	$0.016 \pm 0.033 \pm 0.020$						1.000
		No direct *CP* violation					
Parameter	Value	R_D	y'^+	$(x'^+)^2$	y'^-	$(x'^-)^2$	
R_D	$3.454 \pm 0.028 \pm 0.014$	1.000	−0.883	0.745	−0.883	0.749	
y'^+	$5.01 \pm 0.48 \pm 0.29$		1.000	−0.944	0.758	−0.644	
$(x'^+)^2$	$0.061 \pm 0.026 \pm 0.016$			1.000	−0.642	0.545	
y'^-	$5.54 \pm 0.48 \pm 0.29$				1.000	−0.946	
$(x'^-)^2$	$0.016 \pm 0.026 \pm 0.016$					1.000	
		No *CP* violation					
Parameter	Value	R_D	y'	x'^2			
R_D	$3.454 \pm 0.028 \pm 0.014$	1.000	−0.942	0.850			
y'	$5.28 \pm 0.45 \pm 0.27$		1.000	−0.963			
x'^2	$0.039 \pm 0.023 \pm 0.014$			1.000			

PRD 97 (2018) 031101



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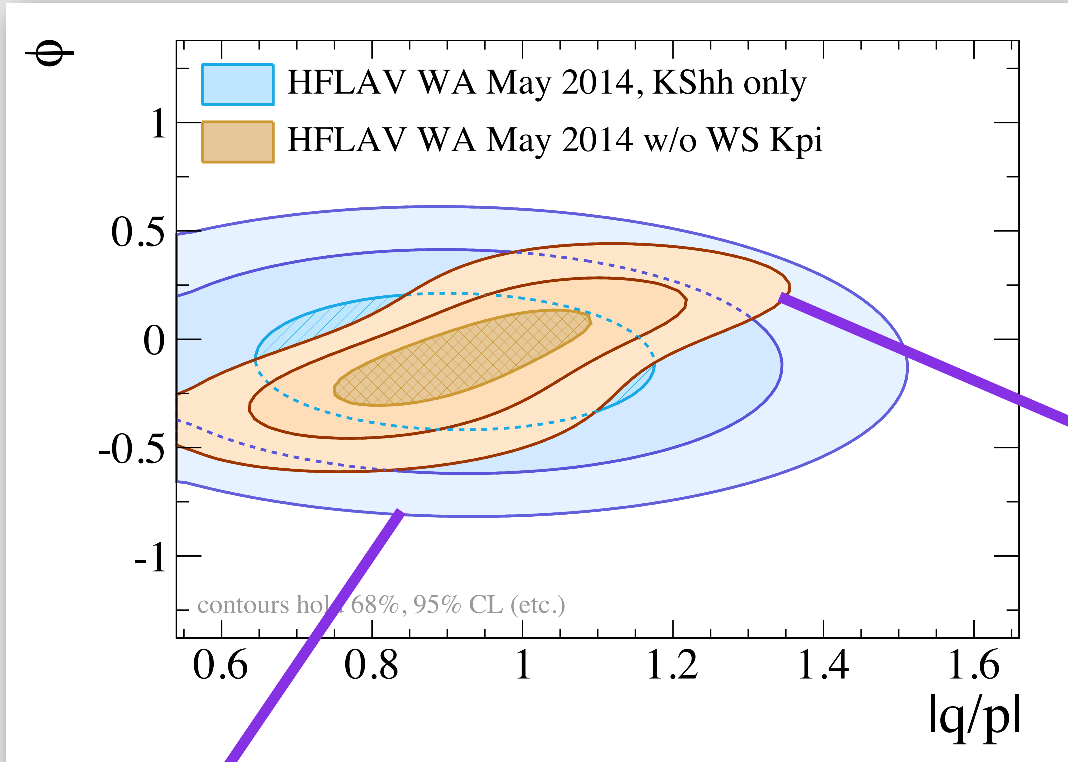
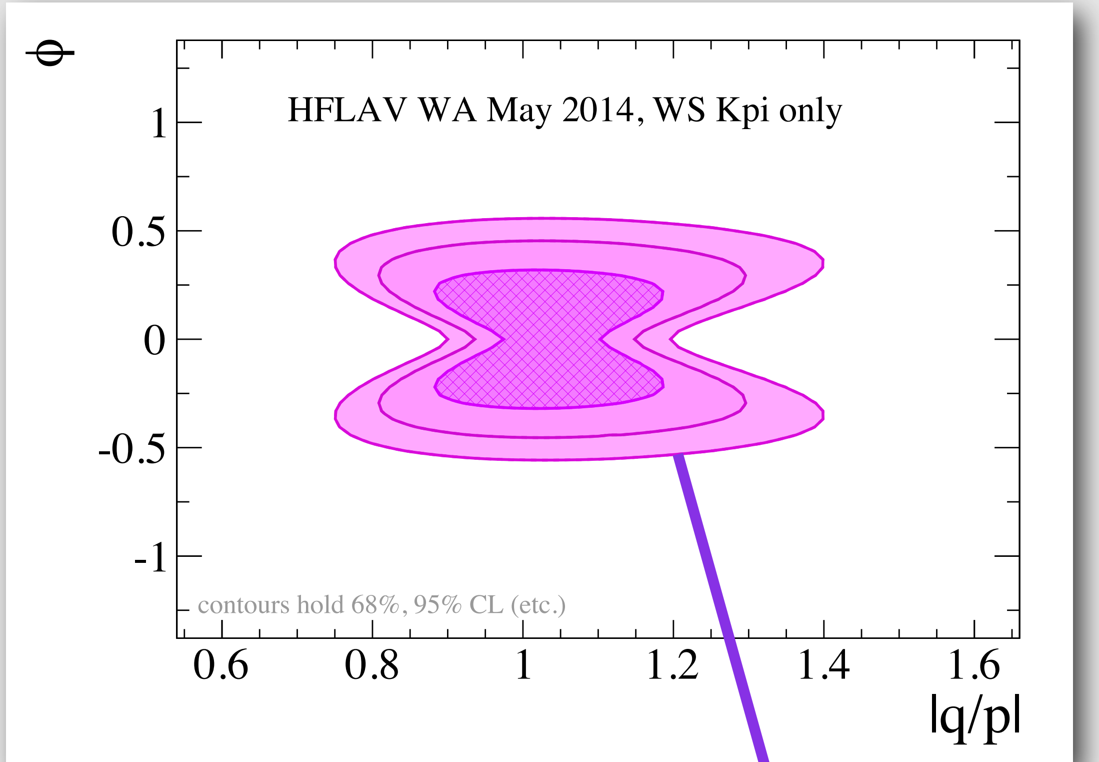
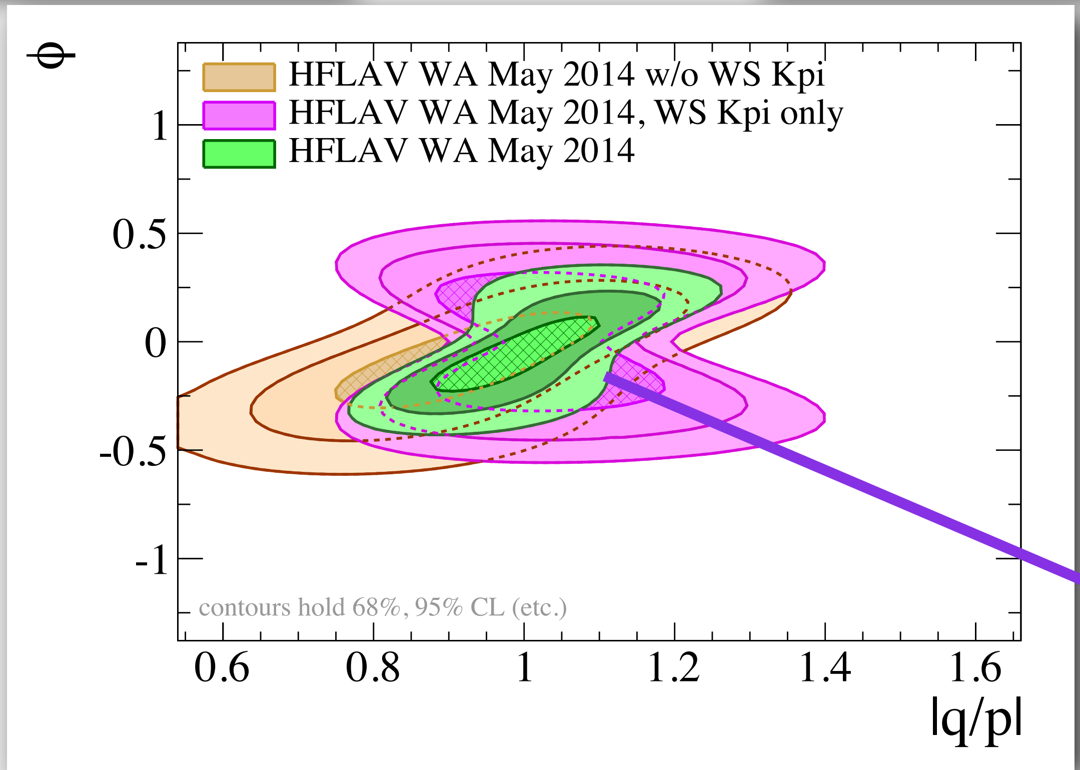
Contributions



Precise constraints if x and y provided, mostly from A_Γ



Direct access to |q/p| and φ from K_Shh



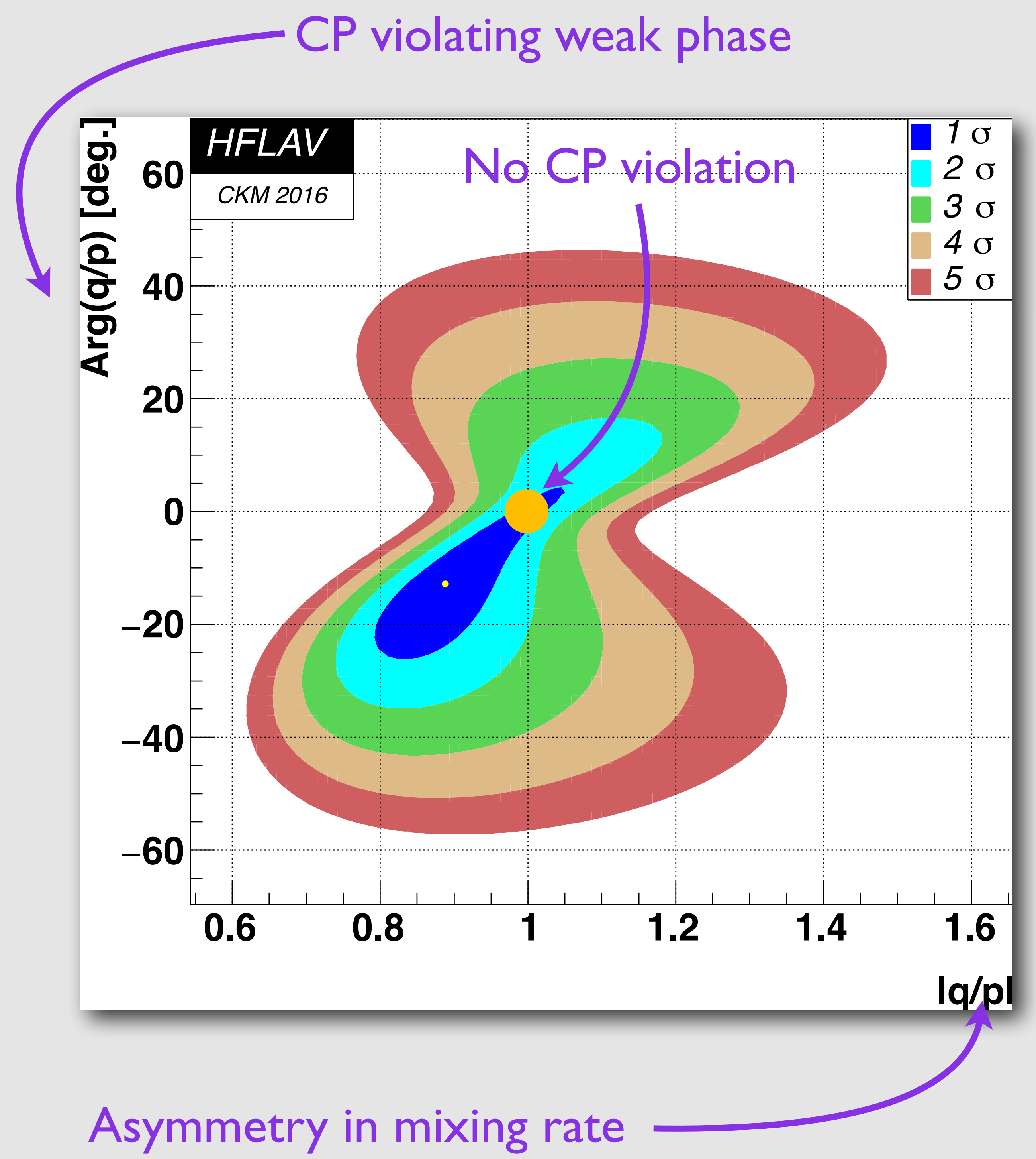
WS Kπ: symmetric in φ,

good sensitivity to |q/p| for small φ

Full average following intersection of contours

CP violation overview

- No sign of CP violation
- Update in progress…



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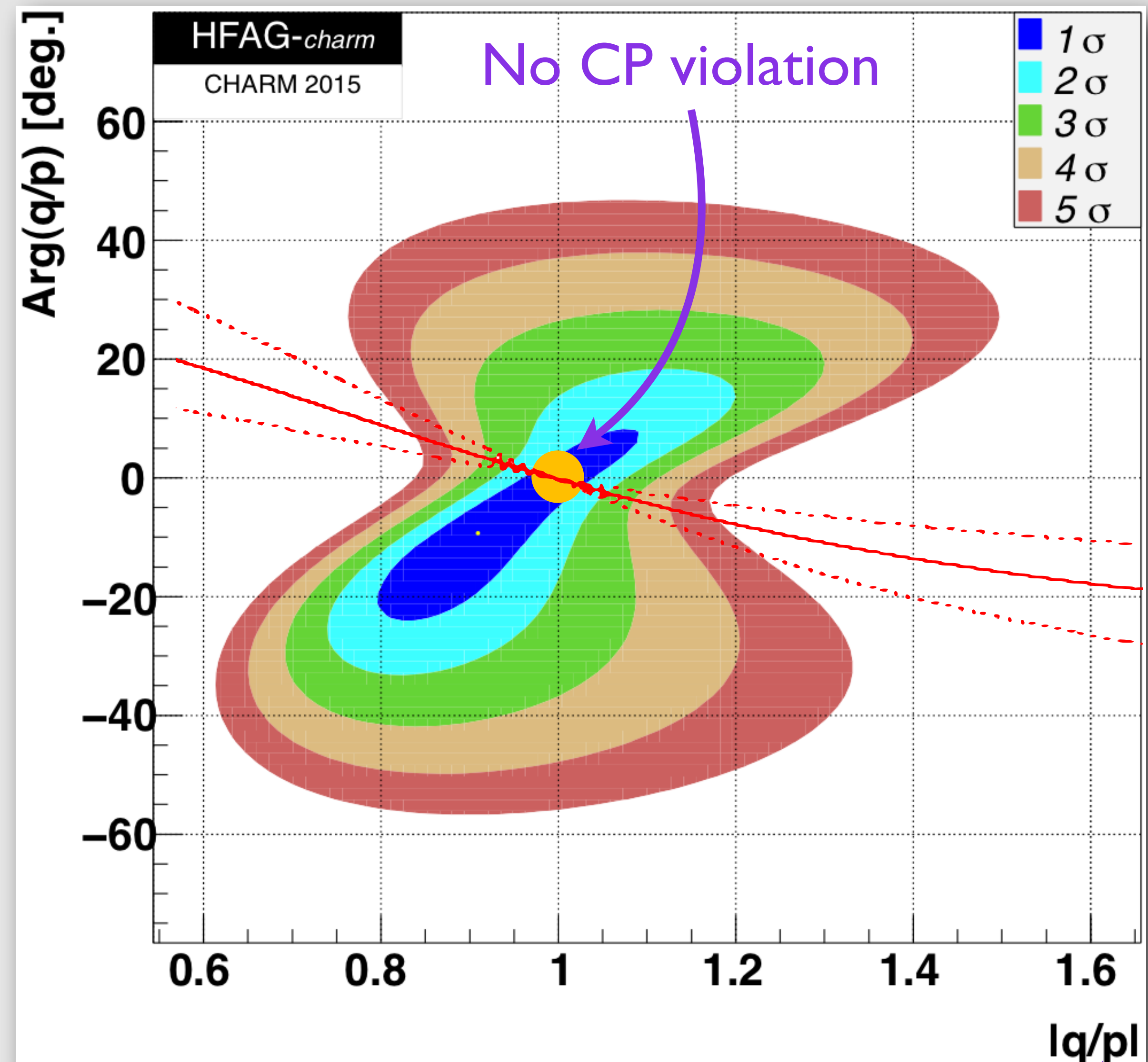
Can we do better?

- Superweak constraint
  - ➡ Assumes no new decay-specific weak phase
  - ➡ Cuichini et al. (2007)
  - ➡ Kagan, Sokoloff (2009)
- Reducing to 3 parameters
  - ➡ $\tan\Phi \approx (1-|q/p|)x/y$
- Consider WS measurement with $\Phi \approx 0$
  - ➡ $y'^{\pm} = |q/p|^{\pm 1}(y' \cos\Phi \mp x' \sin\Phi)$
- Different parametrisation
  - ➡ $x_{12}, y_{12}, \Phi_{12}$
- Current sensitivity already very good
  - ➡ $\sigma(\Phi_{12}) = 1.7°$

CP violating weak phase



Asymmetry in mixing rate

Can we do better?

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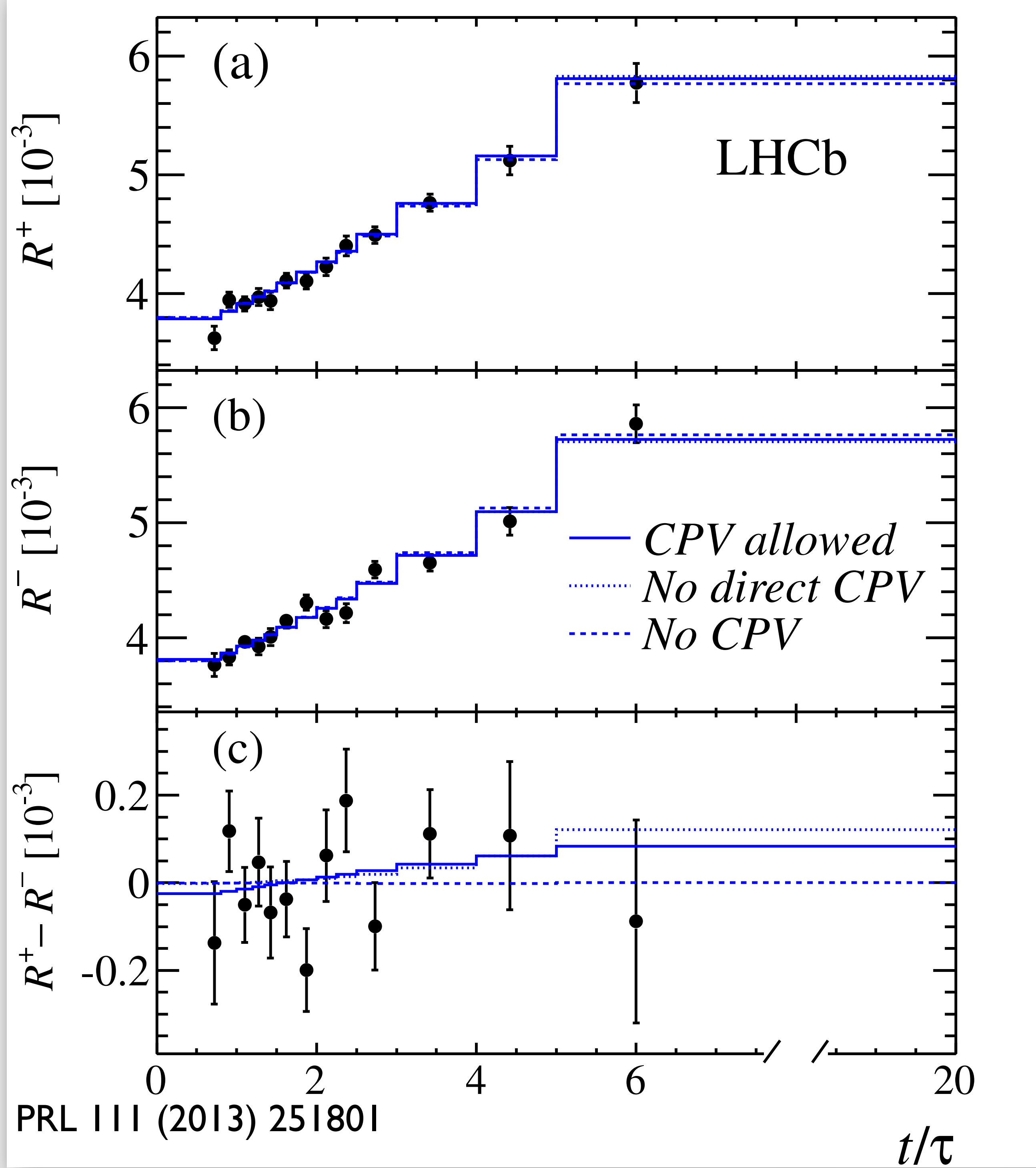

PRL 111 (2013) 251801

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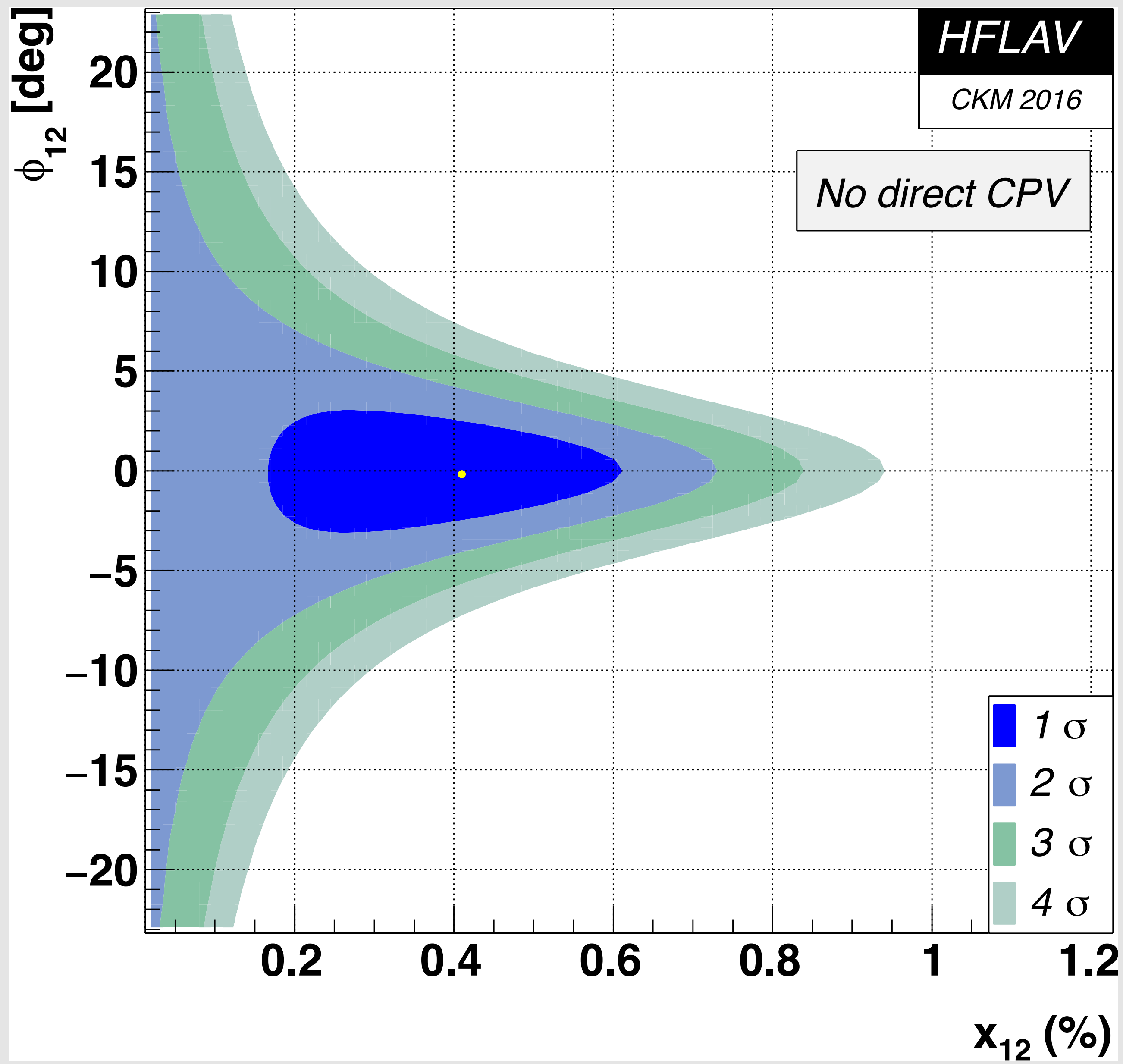
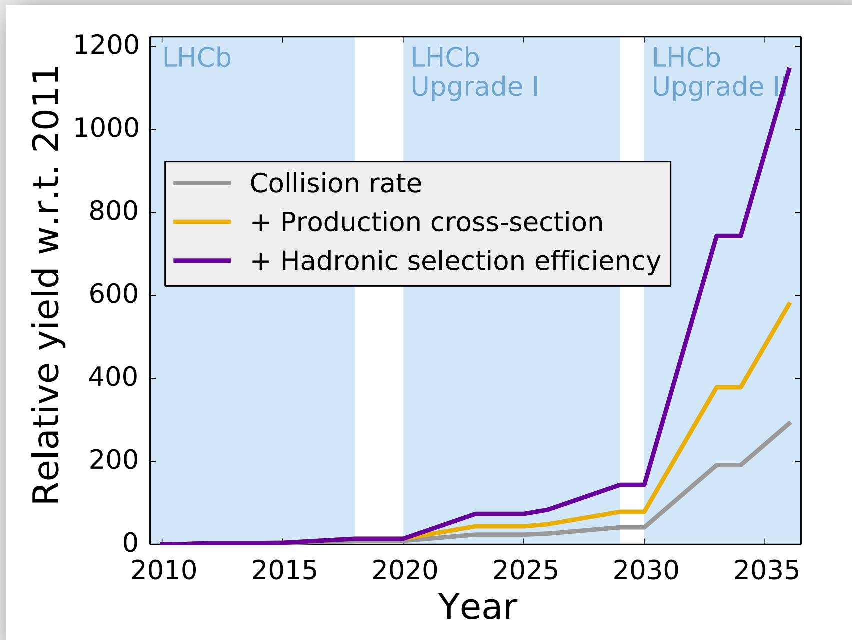
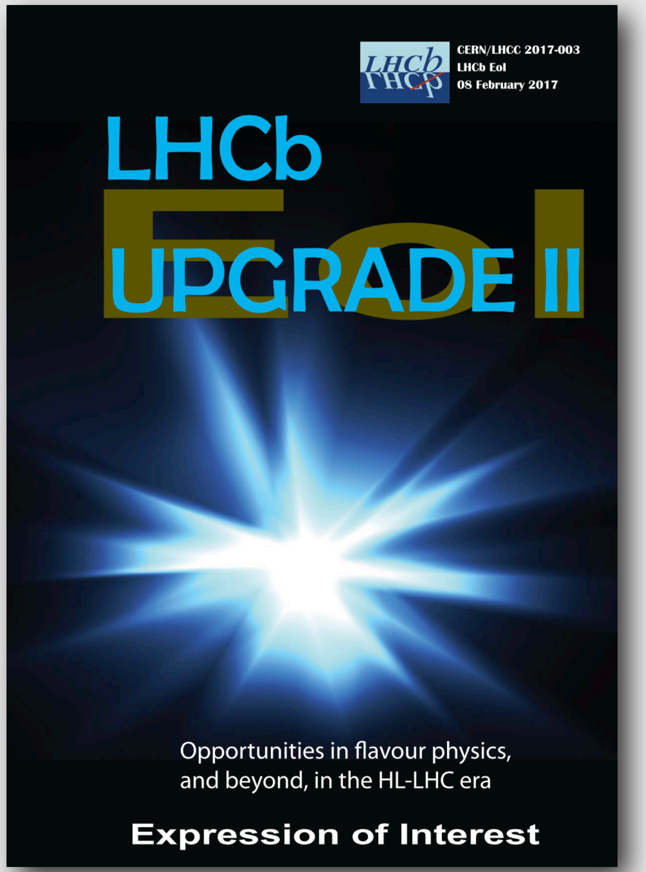


LHCb Upgrades

- Charm CP violation may well be discovered soon
- Will require much more data to
  - ➡ Identify underlying sources
  - ➡ Challenge SM level in both direct and indirect CPV
- LHCb is the best bet for charm for the foreseeable future
  - ➡ Best shot at BSM physics in the up-quark sector





Number games

- Anticipating 10^{-5} precision
- Requires CF control sample of 5×10^{10} candidates
- Requires readiness to estimate systematic effects to this level of precision before we even know their sources

➡ No known show-stoppers, but already sensitive to second-order effects

Table 6.4: Extrapolated signal yields, and statistical precision on indirect CP violation.

Sample (lumi $\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1-2 (9 fb^{-1})	Prompt	77M	0.011%	25M	0.02%
Run 1-4 (50 fb^{-1})	Prompt	1G	0.0031%	305M	0.0057 %
Run 1-6 (300 fb^{-1})	Prompt	5.7G	0.0013%	1.8G	0.0024 %

Table 6.1: Extrapolated signal yields, and statistical precision on the mixing and *CP*-violation parameters, from the analysis of promptly-produced WS $D^{*+} \to D^0(\to K^+\pi^-)\pi^+$ decays. Signal yields of promptly-produced RS $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays are typically 250 times larger.

Sample ($\mathcal{L}$)	Yield ($\times10^6$)	$\sigma(x'^2)$	$\sigma(y')$	$\sigma(A_D)$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	1.8	1.5×10^{-5}	2.9×10^{-4}	0.51%	0.12	10°
Run 1–4 (50 fb^{-1})	25	3.9×10^{-6}	7.6×10^{-5}	0.14%	0.03	4°
Run 1–5 (300 fb^{-1})	170	1.5×10^{-6}	2.9×10^{-5}	0.05%	0.01	1°

Conclusion

- Mixing discovery over 10 years ago
  - ➡ But do D^0 and $\overline{D}^0$ mesons oscillate, i.e. is $x \neq 0$?
  - ➡ Should answer this very soon
- Now:
  - ➡ LHCb in its last year of data taking, BESIII, (and still BaBar, Belle)
- Next:
  - ➡ New facilities: Belle II, LHCb upgrades, …
  - ➡ In terms of two-body charm only LHCb relevant
- Challenges ahead
  - ➡ Both technical (sample sizes) and physics-related (yet unknown systematics)
  - ➡ Responsibility to make the most of LHCb and ensure we achieve 10^{-5} precision in charm