MEASUREMENTS OF MIXING AND INDIRECT CP VIOLATION

Stefanie Reichert

The University of Manchester
on behalf of the LHCb collaboration

The 7th International Workshop on Charm Physics
20 May 2015

MANCHESTER 1824
The University of Manchester

LHCb

OUTLINE

- Introduction
- The LHCb detector
- Measurement of A_Γ from prompt and semileptonic decays
- Mixing measurement and search for CP violation in $D \to K\pi$ decays
- Conclusion

CHARM MIXING

- Mass eigenstates $|D_{1,2}\rangle$ with mass $m_{1,2}$ and width $\Gamma_{1,2}$
  → mixing occurs if $\Delta m \equiv m_2 - m_1 \neq 0$ or
  $\Delta\Gamma \equiv \Gamma_2 - \Gamma_1 \neq 0$

- $|D_{1,2}\rangle$ are linear combination of flavour states $|D^0\rangle$ and $|\overline{D}^0\rangle$

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

with $q, p \in \mathbb{C}$ satisfying $|q|^2 + |p|^2 = 1$

- Mixing parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/(2\Gamma)$

$$P(D^0 \to \overline{D}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left\{-\cos(x\Gamma t) + \cosh(y\Gamma t)\right\}$$

CP VIOLATION

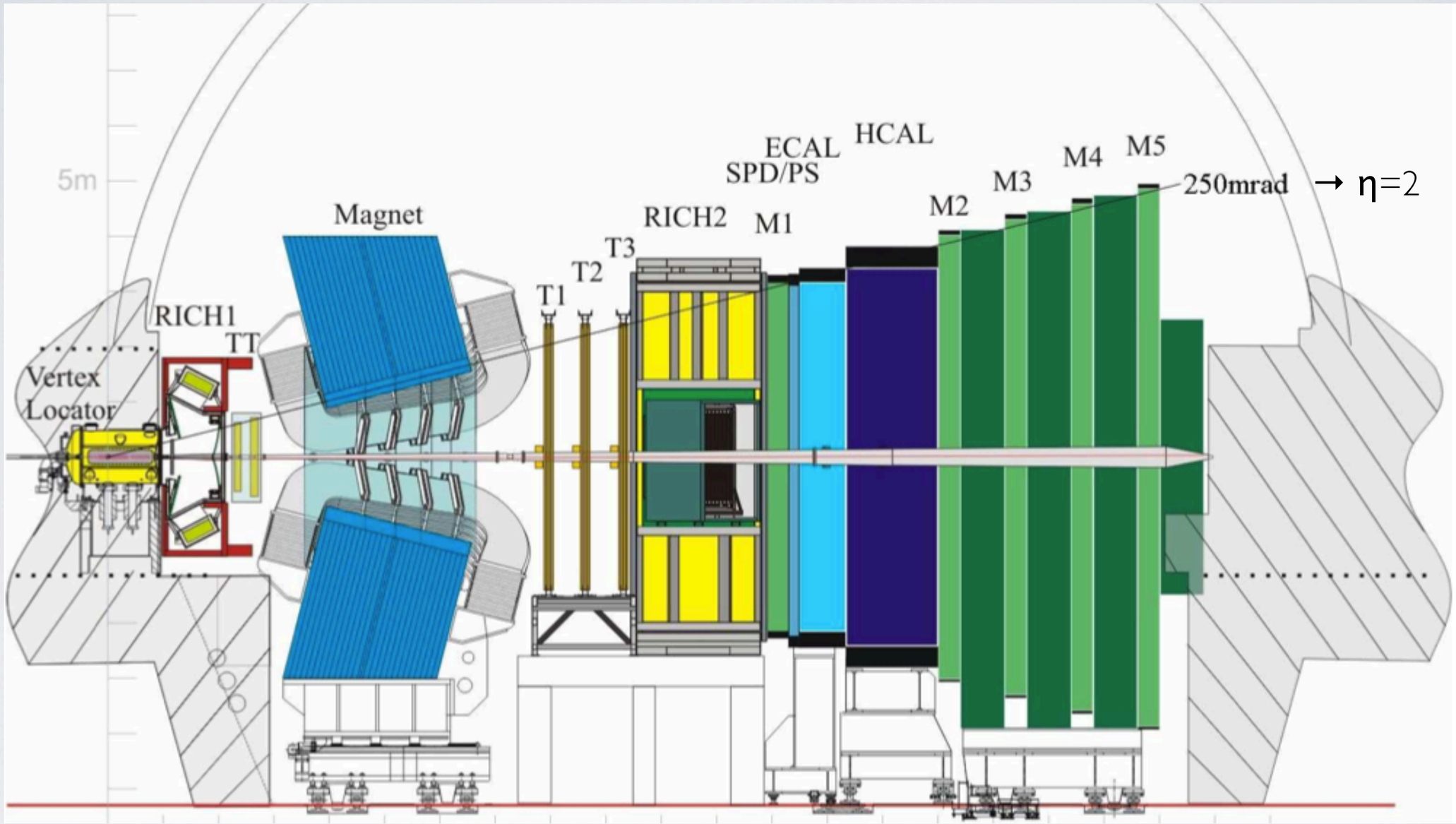
- CP violation searches in charm provide probe for new physics
- In SM, CPV expected to be small → enhancement hints at NP
- CPV in decay: $A_d \equiv (|A_f|^2 - |\bar{A}_{\bar{f}}|^2)/(|A_f|^2 - |\bar{A}_{\bar{f}}|^2)$
- CPV in mixing: $A_m \equiv (|q/p|^2 - |p/q|^2)/(|q/p|^2 + |p/q|^2)$
- CPV in interference through $\phi = \arg\left(\frac{q\,\bar{A}_{\bar{f}}}{p\,A_f}\right)$
- No strong evidence for CPV in charm[1].

direct

indirect CPV

[1] Averages of b-hadron, c-hadron, and tau-lepton properties as of summer 2014, Y. Amhis et al., arXiv:1412.7515

THE LHCb DETECTOR

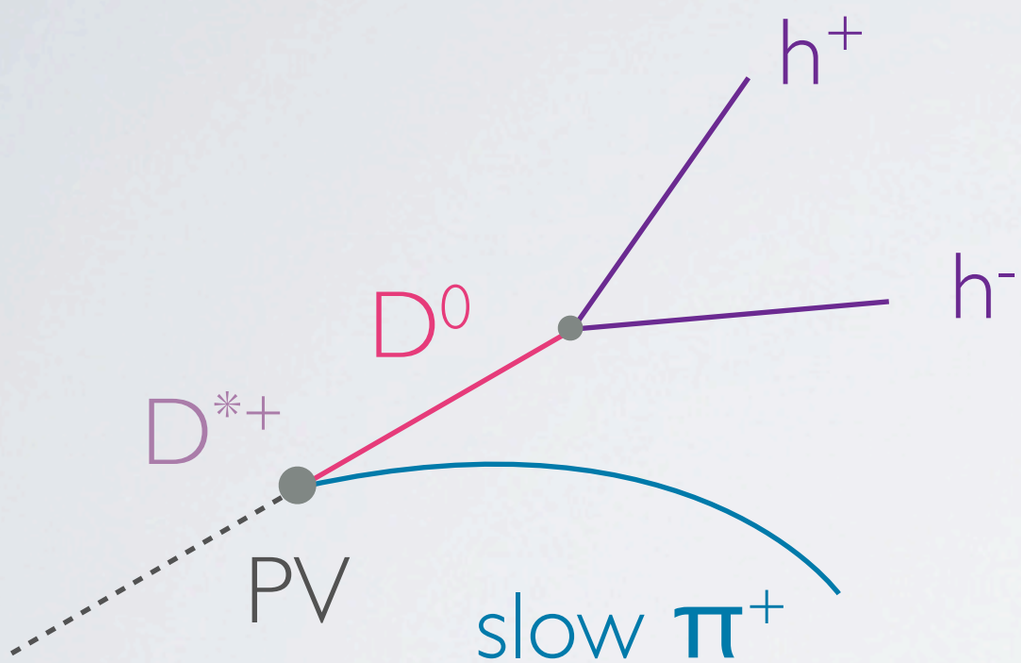


Forward spectrometer with acceptance $2 < \eta < 5$

Schematic taken from The LHCb detector at the LHC, The LHCb collaboration, J. Instrum. 3 S08005 (2008)

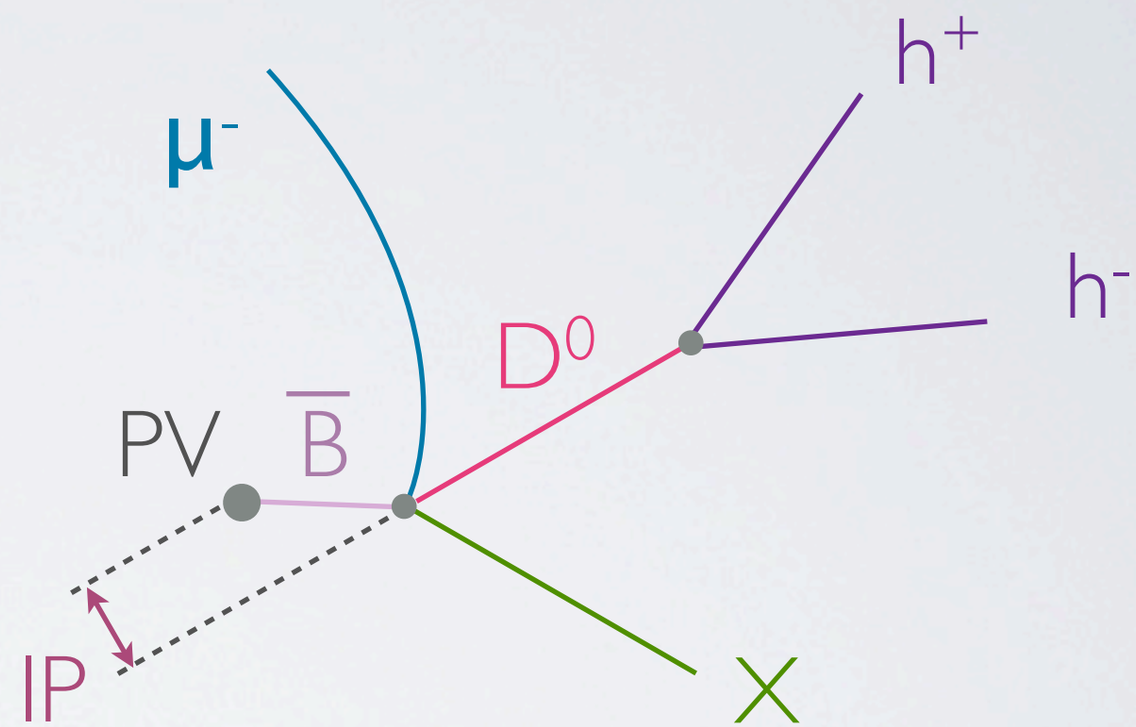
PROMPT AND SEMILEPTONIC

Prompt



Impact parameter (IP) ~ 0

Semileptonic



Impact parameter large

IP and related quantities allow to distinguish between prompt and semileptonic decays

A_Γ

PRL 112 (2014) 041801

- Asymmetry of the inverse effective lifetimes of D^0 and $\overline{D}^0$ decays to CP-even final states, e.g. $\pi^+\pi^-$ or K^+K^-

$$A_\Gamma = \frac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\overline{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\overline{D}^0}} \approx \left(\frac{A_d + A_m}{2}\right) y \cos\varphi - x \sin\varphi$$

expected below sensitivity

with $\varphi = arg(q, p)$

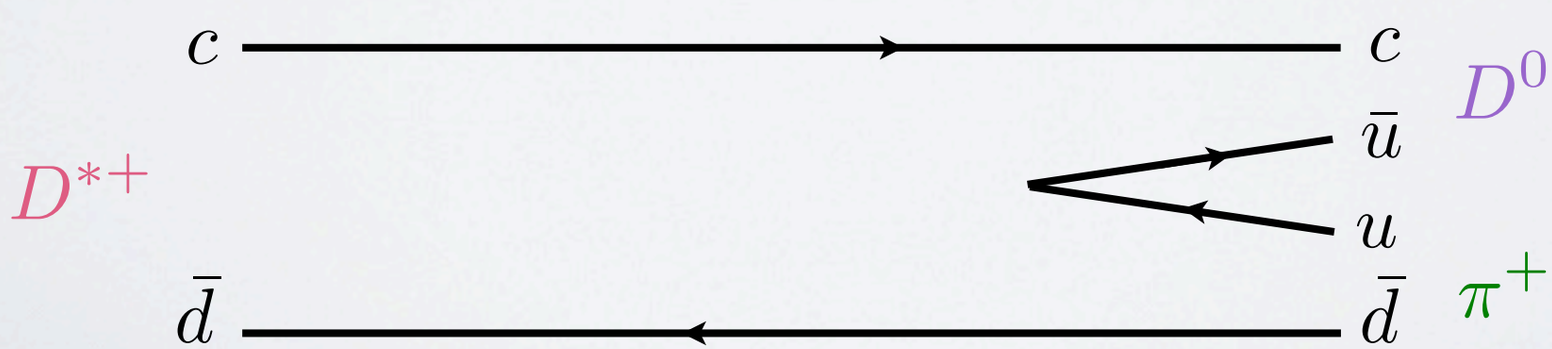
- Effective lifetimes are lifetimes measured using a single-exponential model

- SM: CP-violating phase ϕ independent of final state
  → Expect same results for A_Γ measured with kaons and pions

PROMPT A_Γ

PRL 112 (2014) 041801

- Measurement of $A_\Gamma(K^+K^-)$ and $A_\Gamma(\pi^+\pi^-)$ on 2011 dataset (1 fb^{-1} at $\sqrt{s}$(pp) = 7 TeV)
- D^0 flavour determined by π^+ charge from $D^{*+} \to D^0\pi^+$ decay produced directly in pp collisions (prompt)
- $D^0 \to K^+K^-$:Yield ~3.1M signal candidates, purity ~93%
- $D^0 \to \pi^+\pi^-$:Yield ~1.0M signal candidates, purity ~91%

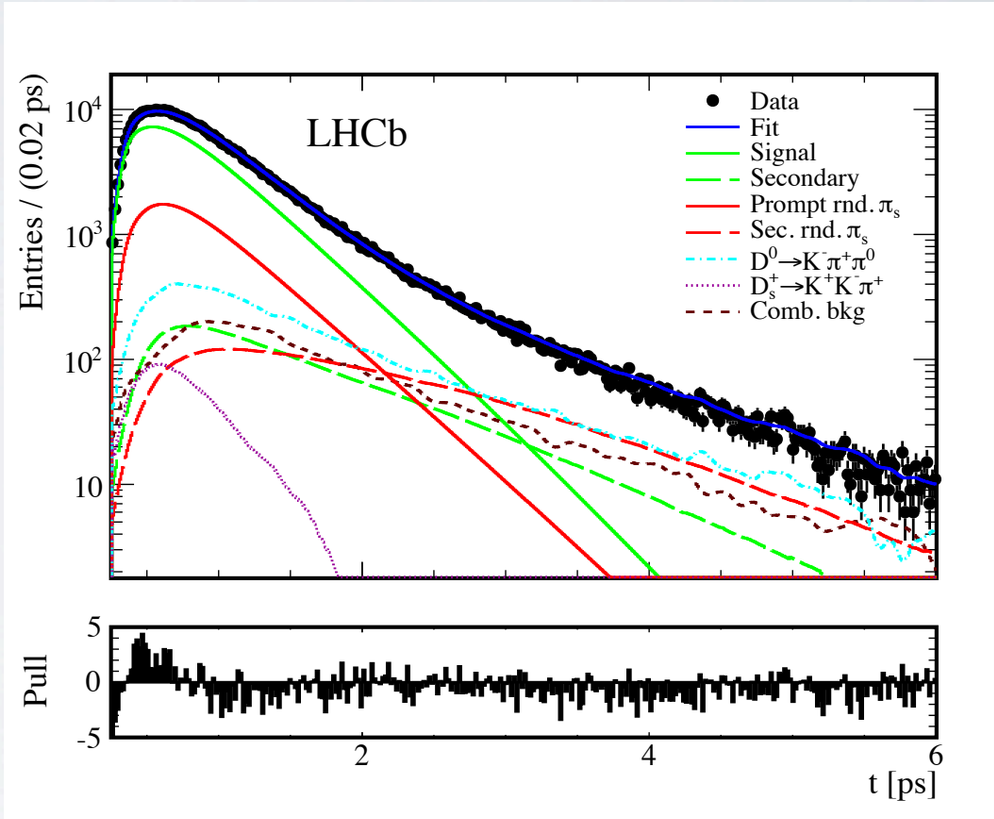


PROMPT A_Γ

PRL 112 (2014) 041801

$$A_\Gamma = \frac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\overline{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\overline{D}^0}}$$

- Fit to decay time and $\ln(\chi^2_{\rm IP})$ to extract effective lifetimes
- Dominant systematic uncertainty from per-candidate acceptance functions (data-driven)
- Results
  - $A_\Gamma(K^+K^-) = (-0.035 \pm 0.062 \pm 0.012)\%$
  - $A_\Gamma(\pi^+\pi^-) = (0.033 \pm 0.16 \pm 0.014)\%$



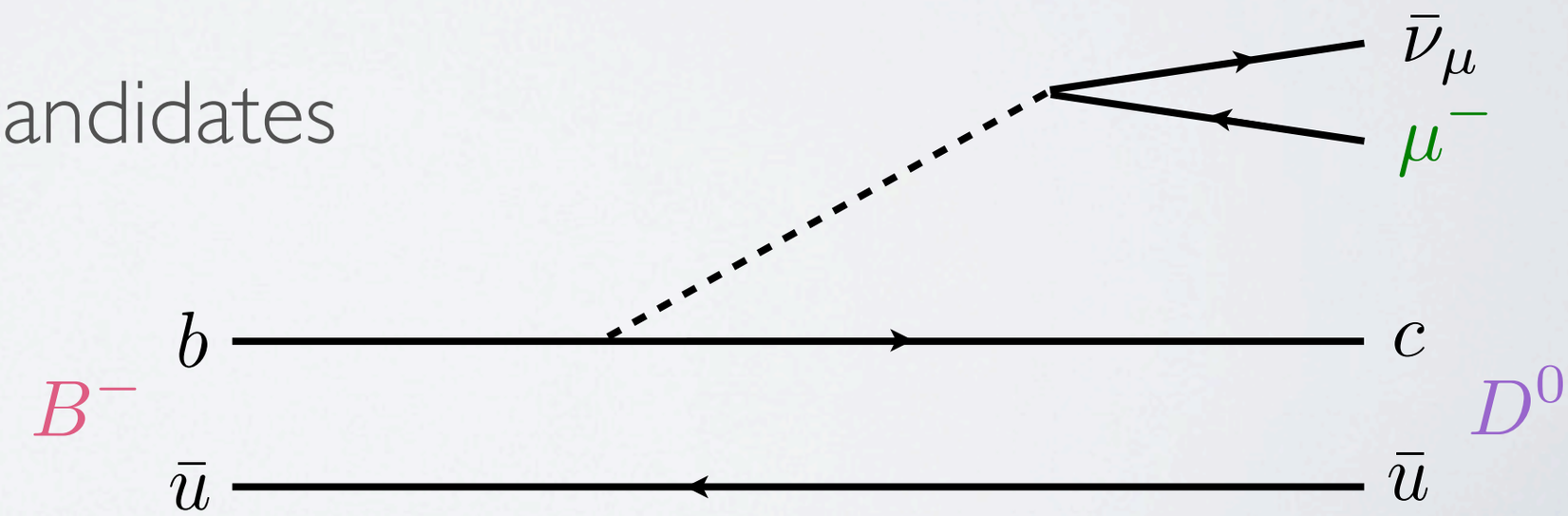
Fit of decay time to $\bar{D}^0 \to K^-K^+$

SEMILEPTONIC A_Γ

JHEP 04 (2015) 043

New at Charm 2015

- Measurement of $A_\Gamma(K^+K^-)$ and $A_\Gamma(\pi^+\pi^-)$ on combined 2011 & 2012 dataset (3 fb^{-1} at $\sqrt{s}$(pp) = 7 TeV, 8 TeV)
- D^0 flavour determined by μ^- charge from semileptonic B decay $B^-(\overline{B}^0) \to D^0\mu^-\bar{\nu}_\mu X$
- $D^0 \to K^+K^-$:
  Yield ~2.3M signal candidates
- $D^0 \to \pi^+\pi^-$:
  Yield ~0.8M signal candidates

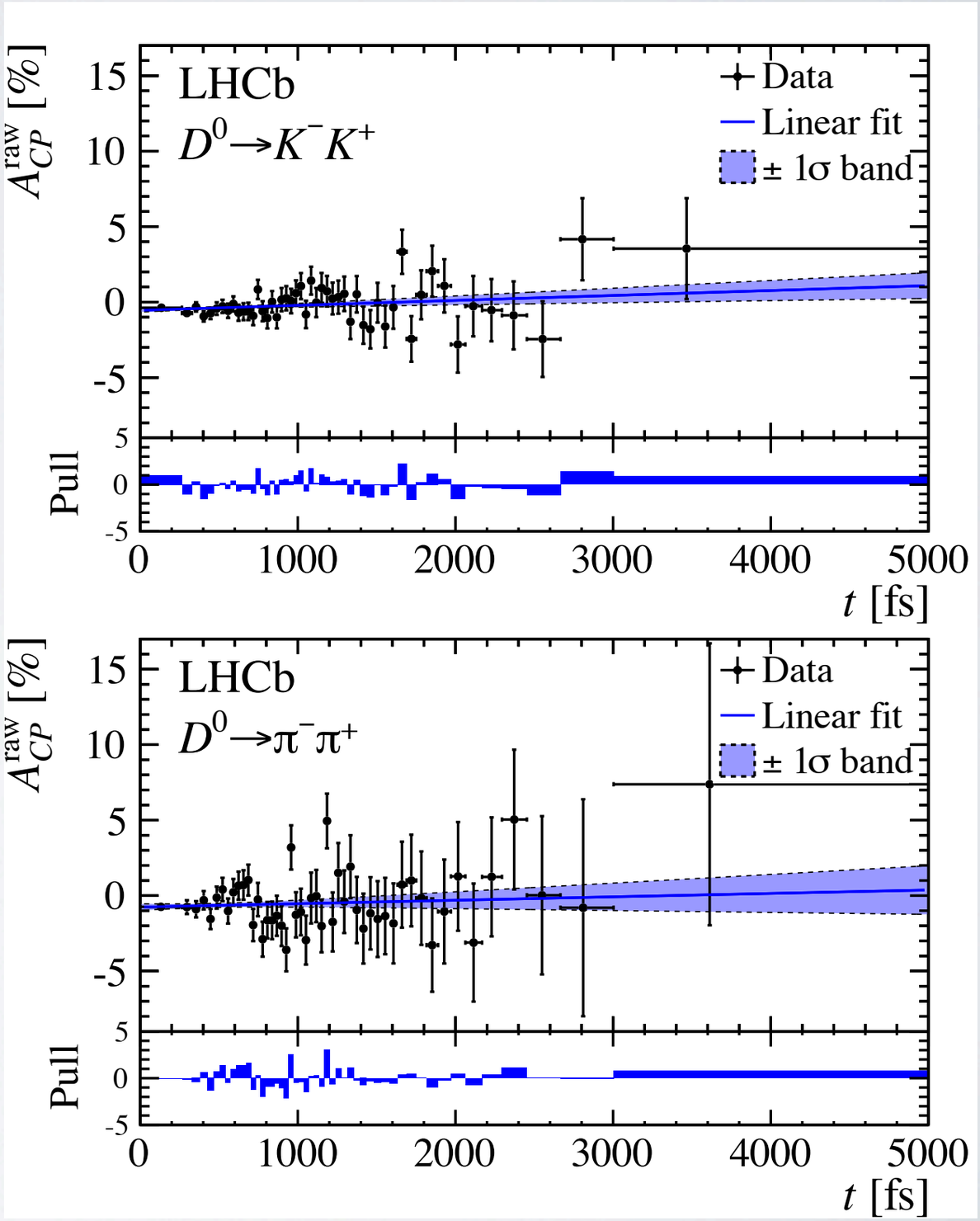


SEMILEPTONIC A_Γ

JHEP 04 (2015) 043

$$A_{CP}^{\rm raw}(t) \approx A_d - A_\Gamma \frac{t}{\tau}$$

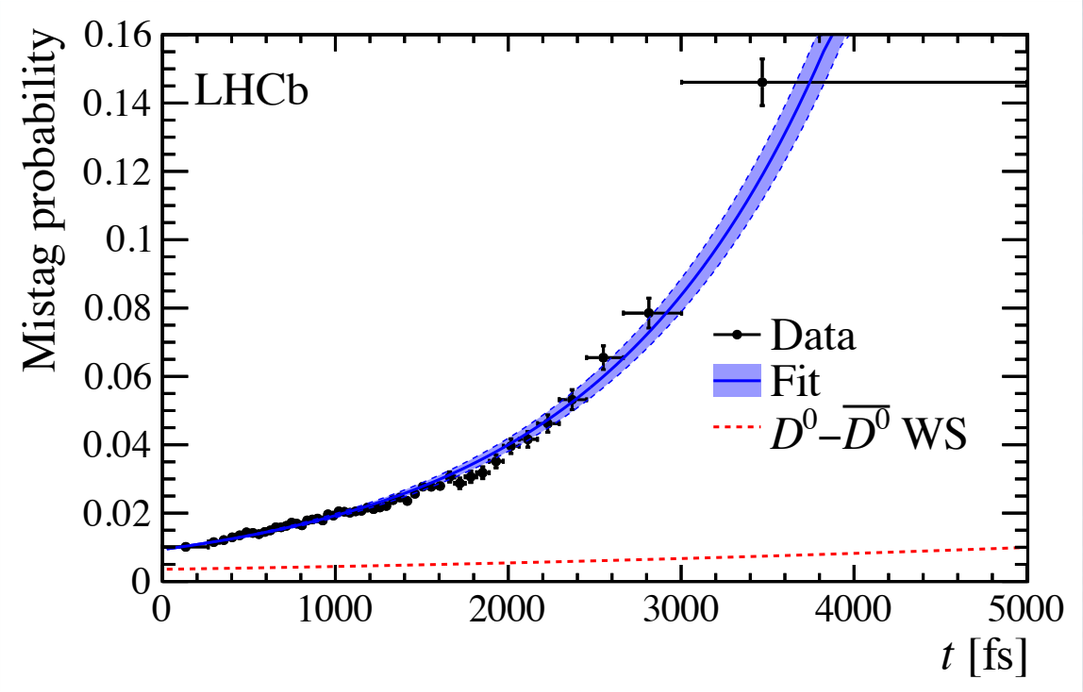
- Raw CP asymmetry determined from mass fits in 50 bins of decay time
- Simultaneous fits to $\overline{D}^0$ and D^0 samples
- A_Γ determined from χ^2 fit to time-dependent $A_{CP}^{\rm raw}(t)$



SEMILEPTONIC A_Γ

JHEP 04 (2015) 043

- Dominant systematic uncertainty from combination of random muon with D^0
  - mistag probability
  - uncertainty of mistag asymmetry

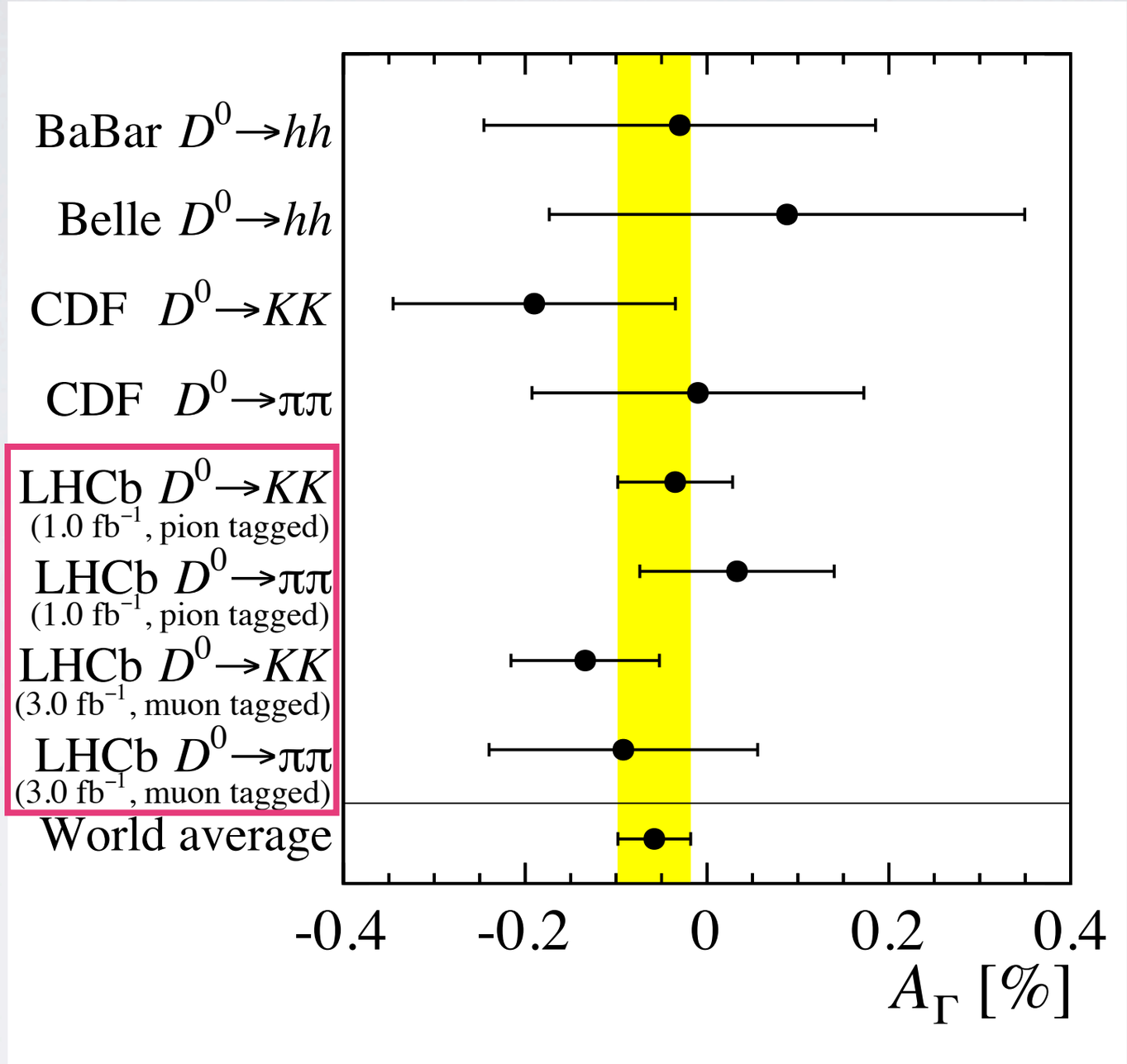


Time-dependent mistag probability measured with $D^0 \to K^-\pi^+$ decays

- Results
  - $A_\Gamma(K^+K^-) = (-0.134 \pm 0.077\,^{+0.026}_{-0.034})\%$
  - $A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145\,^{+0.025}_{-0.033})\%$

A_Γ

JHEP 04 (2015) 043



Phys. Rev. D 87, 012004

arXiv: 1212.3478v1[hep-ex]

Phys. Rev. D 90, 111103

Phys. Rev. D 90, 111103

PRL 112 (2014) 041801

PRL 112 (2014) 041801

JHEP 04 (2015) 043

JHEP 04 (2015) 043

JHEP 04 (2015) 043

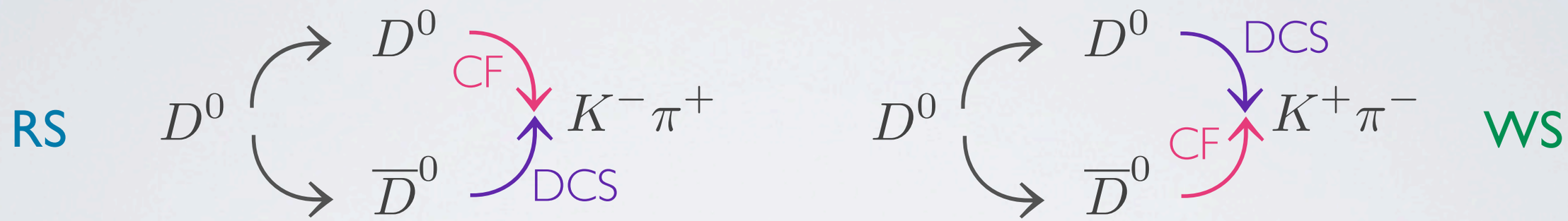
Assuming universal indirect CPV:

LHCb: $A_\Gamma = (-0.056 \pm 0.044)\%$, WA: $A_\Gamma = (-0.058 \pm 0.040)\%$

MIXING IN $D \to K\pi$ DECAYS

PRL 110 (2013) 101802

- Measurement of time-dependent ratio of $D^0 \to K^-\pi^+$ (RS) and $D^0 \to K^+\pi^-$ (WS) decays



- In limit of small mixing and for negligible CPV

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

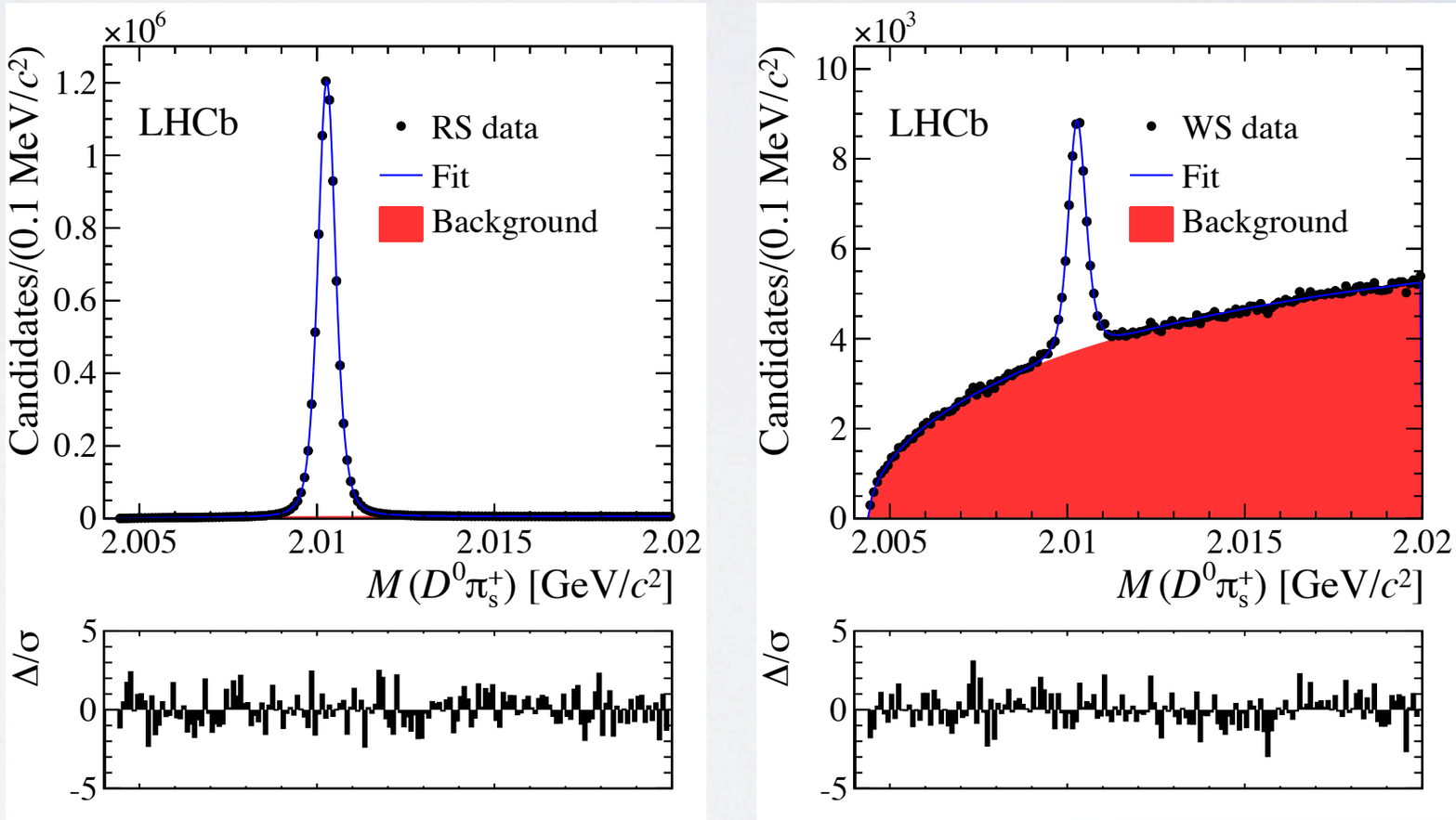
with $\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\overline{D}^0 \to K^+\pi^-) = -\sqrt{R_D}\, e^{-i\delta}$

- Acces to mixing: $x' \equiv x\cos\delta + y\sin\delta, y' \equiv y\cos\delta - x\sin\delta$

MIXING IN $D \to K\pi$ (2011)

PRL 110 (2013) 101802

- Measurement of mixing parameters x'^2, y' on 1fb^{-1}
- D^0 flavour tagged by π^+ charge from prompt $D^{*+} \to D^0\pi^+$
- Yields
  - RS: ~8M signal candidates
  - WS: ~ 36k signal candidates

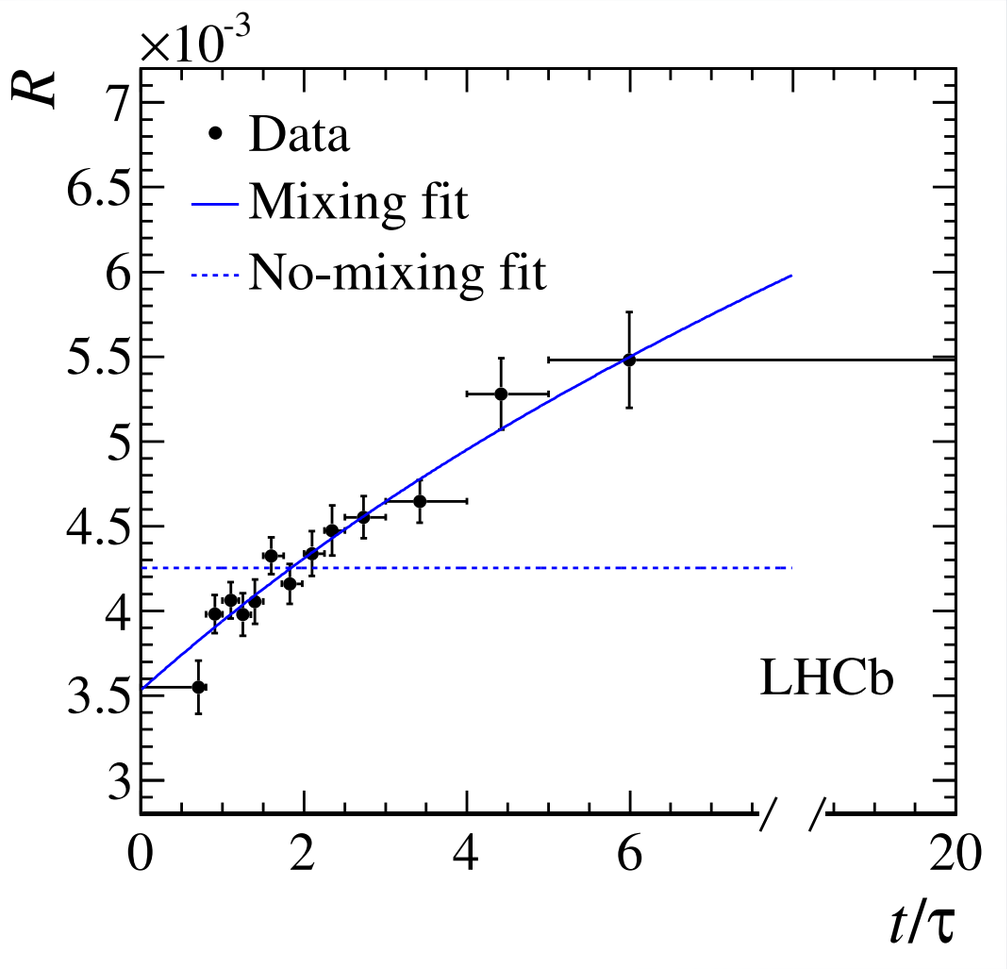


Time-integrated

MIXING IN $D \to K\pi$ (2011)

PRL 110 (2013) 101802

- Signal yields extracted in 13 bins of decay time → binned χ^2 fit to R(t)
- Systematic uncertainties not cancelling in R(t) from secondary charm and from partially reconstructed or misidentified D^0 mesons
- No mixing hypothesis excluded at 9.1σ

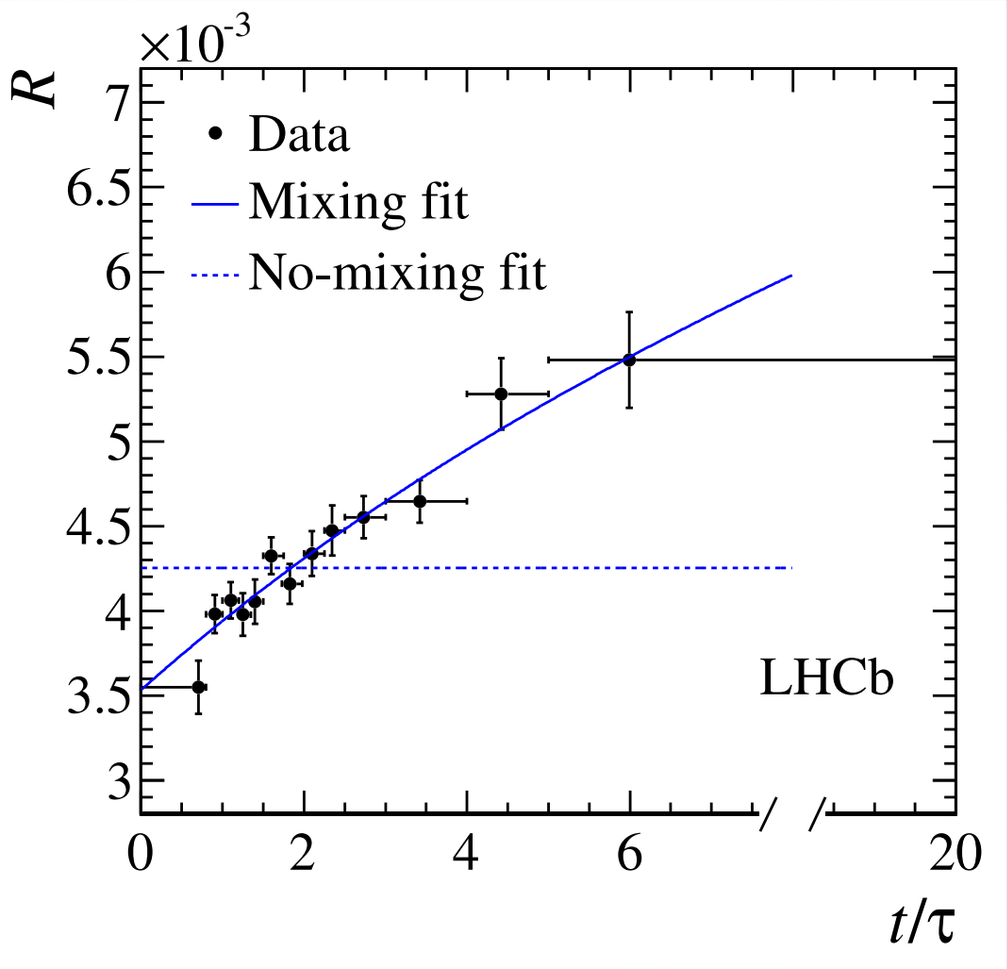


- $R_D = (3.52 \pm 0.15) \times 10^{-3}$
- $x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$
- $y' = (7.2 \pm 2.4) \times 10^{-3}$

MIXING IN $D \to K\pi$ (2011)

PRL 110 (2013) 101802

- Signal yields extracted in 13 bins of decay time → binned χ^2 fit to R(t)
- Systematic uncertainties not cancelling in R(t) from secondary charm and from partially reconstructed or misidentified D^0 mesons
- No mixing hypothesis excluded at 9.1σ

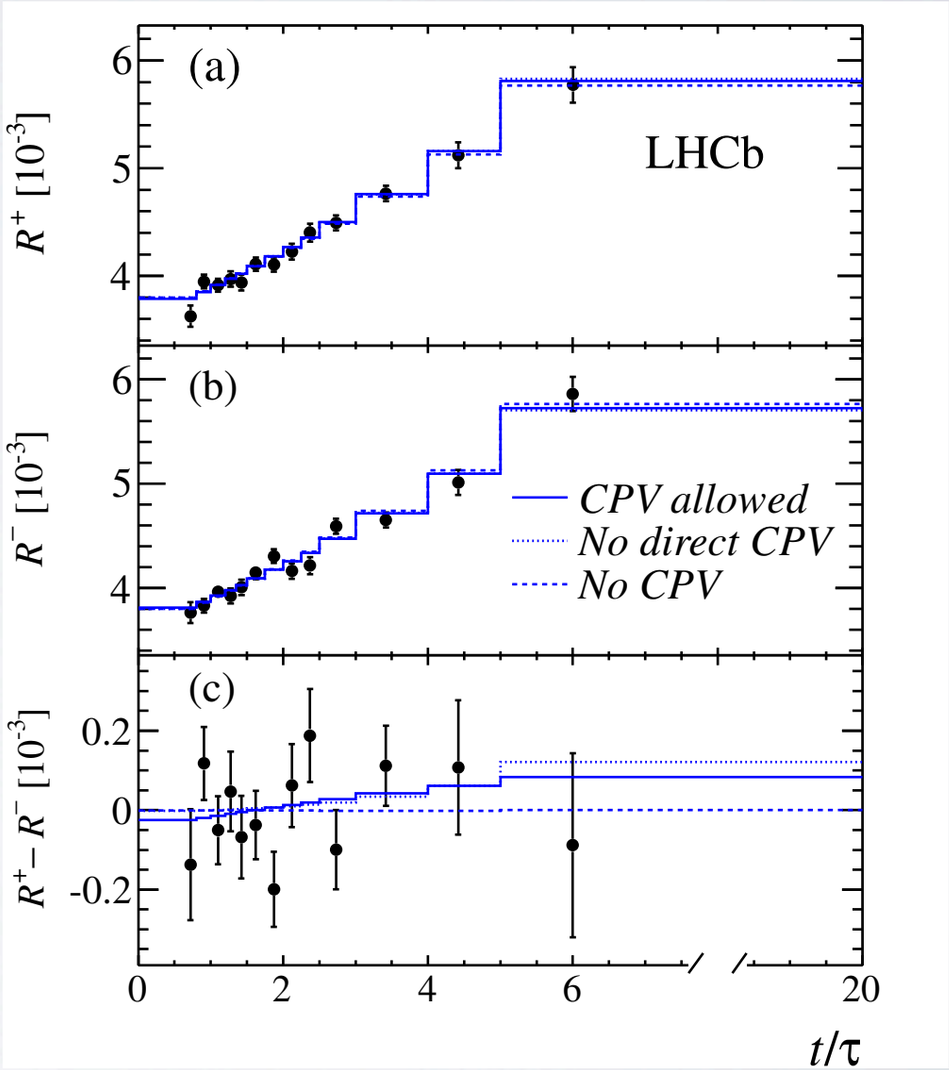


First observation of charm mixing in a single measurement

MIXING AND CPV IN $D \to K\pi$

PRL 111 (2013) 251801

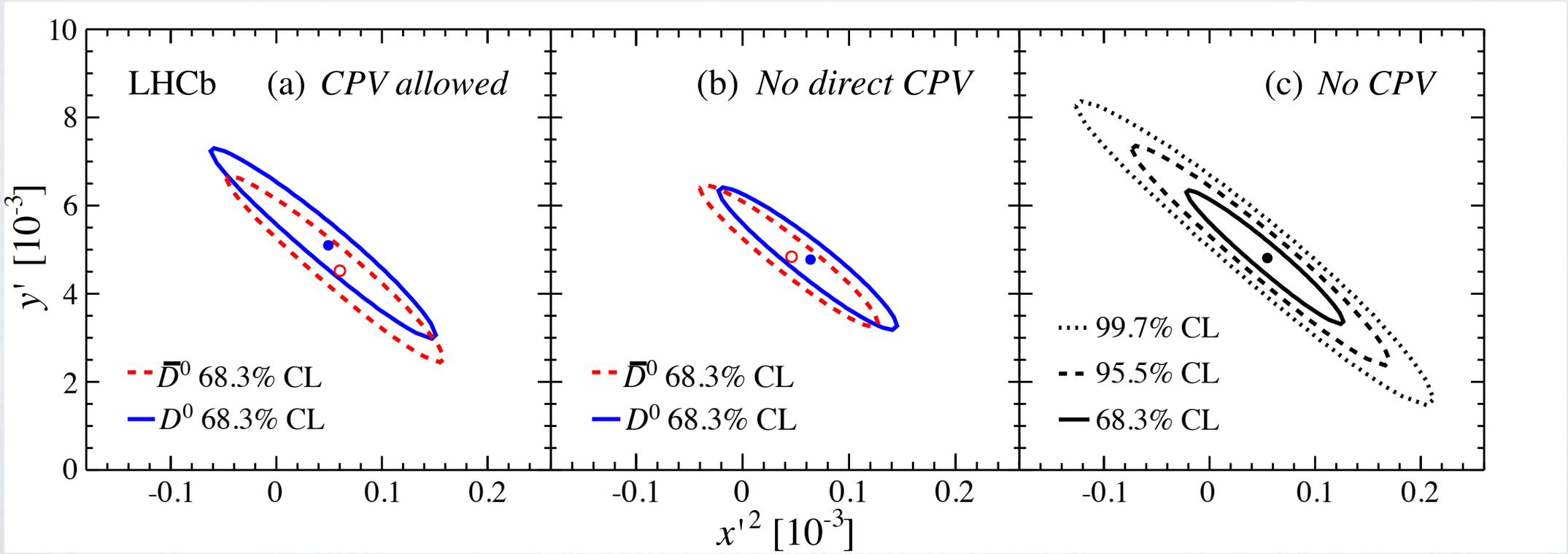
- Measurement of mixing parameters x'^2, y' on 3fb^{-1}
  → same method as in 1fb^{-1} analysis
- Yields
  - RS: ~53M signal candidates
  - WS: ~ 230k signal candidates
- Search for direct and indirect CPV by splitting into D^0 and $\overline{D}^0$ samples
  → three fitting scenarios



MIXING AND CPV IN $D \to K\pi$

PRL 111 (2013) 251801

- CPV search: Fit to $R^{\pm}(t)$ with parameter sets of $(R_D^{\pm}, x'^{2\pm}, y'^{\pm})$
  - Difference in $R_D^{\pm}$: direct CPV
  - Difference in (x'^{2+}, y'^{+}) and (x'^{2-}, y'^{-}): indirect CPV



MIXING AND CPV IN $D \to K\pi$

PRL 111 (2013) 251801

- Results for CP conservation
  - $R_D = (3.568 \pm 0.066) \times 10^{-3}$
  - $x'^2 = (5.5 \pm 4.9) \times 10^{-5}$
  - $y' = (4.8 \pm 1.0) \times 10^{-3}$

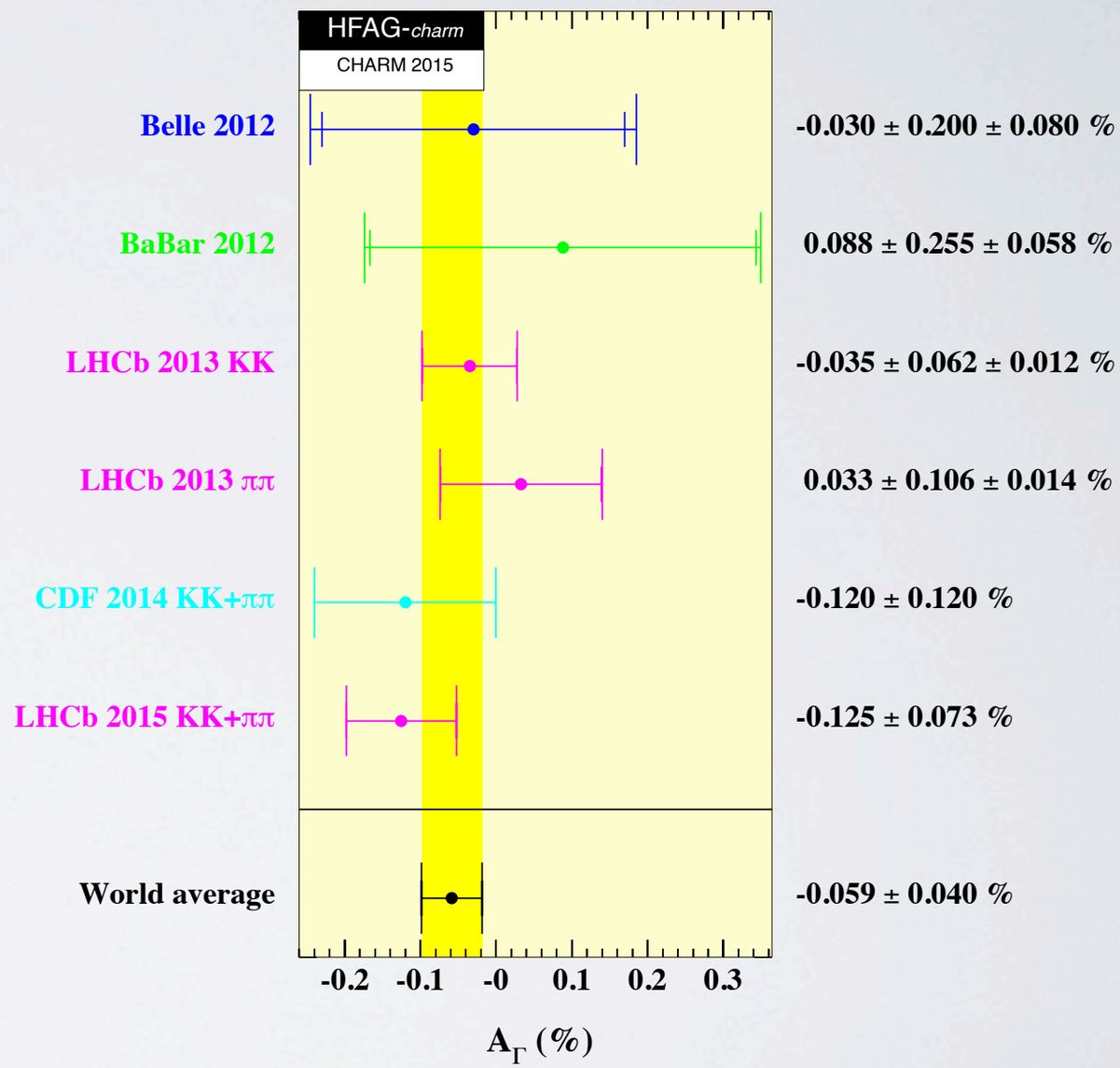
Results compatible with CP conservation.

- Results allowing for CPV
  - $A_D \equiv \frac{R^+ - R^-}{R^+ + R^-}$
    $= (-0.7 \pm 1.9)\%$
  - Fit performed with
    $x'^{\pm} \equiv |q/p|^{\pm 1}(x' \cos\phi \pm y' \sin\phi)$
    $y'^{\pm} \equiv |q/p|^{\pm 1}(y' \cos\phi \mp x' \sin\phi)$

yielding $0.75 < |q/p| < 1.24$ at 68.3% CL

CONCLUSION

- Search for CPV in charm provides probe of new physics
- LHCb's measurements of A_Γ dominate world average: combined precision 4×10^{-4}
- Mixing measured in $D \to K\pi$
- CPV results compatible with CP symmetry hypothesis
- LHC Run 2 will bring lots of exciting results!



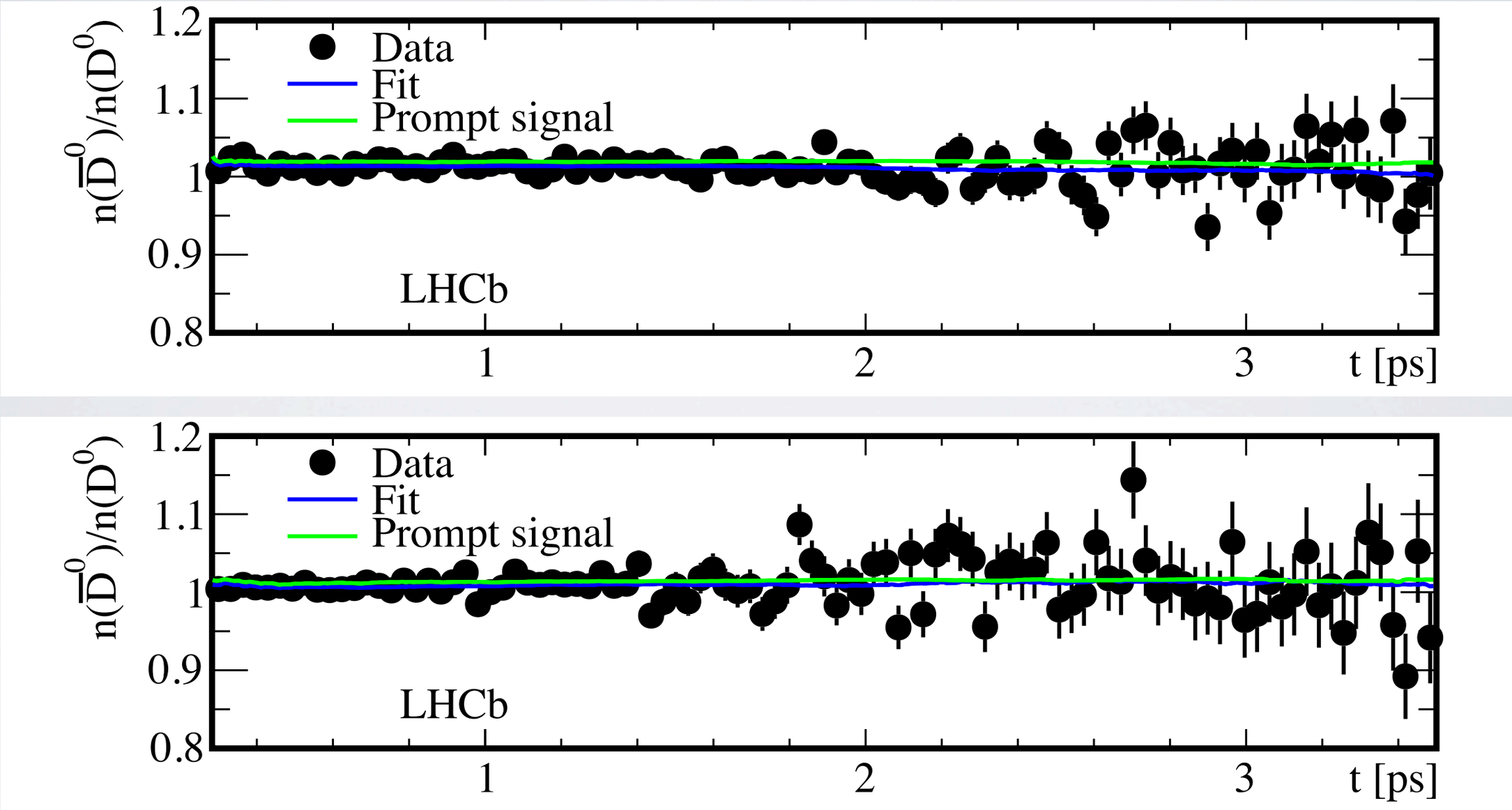
http://www.slac.stanford.edu/xorg/hfag/index.html

THANK YOU.

BACKUP

PROMPT A_Γ

PRL 112 (2014) 041801

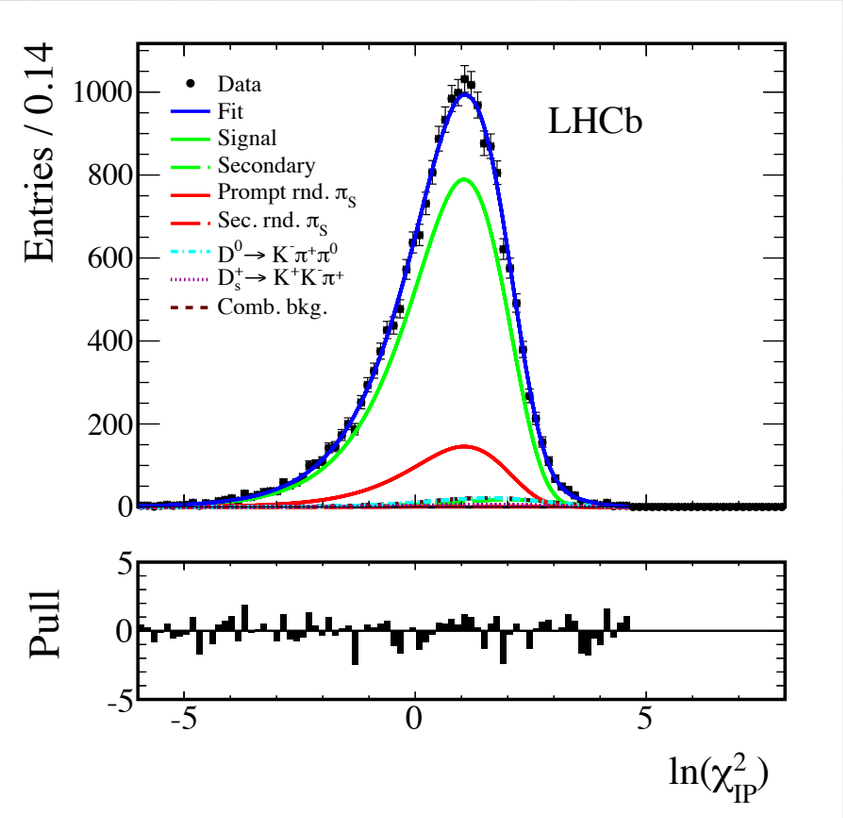


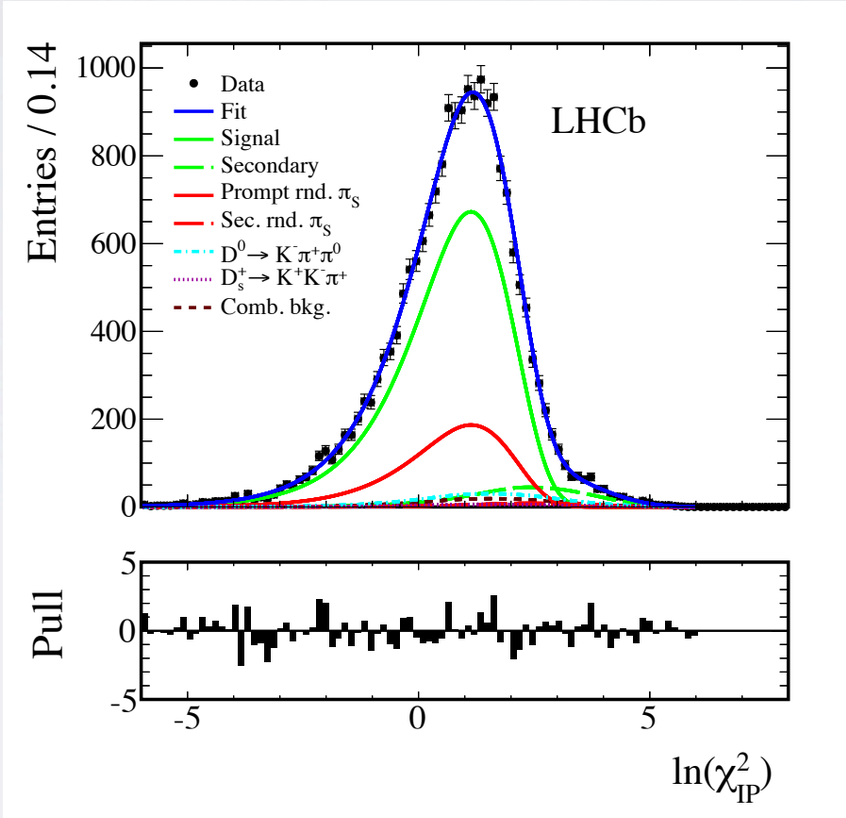
Ratio plot for $\overline{D}^0/D^0$ data (unbinned method)

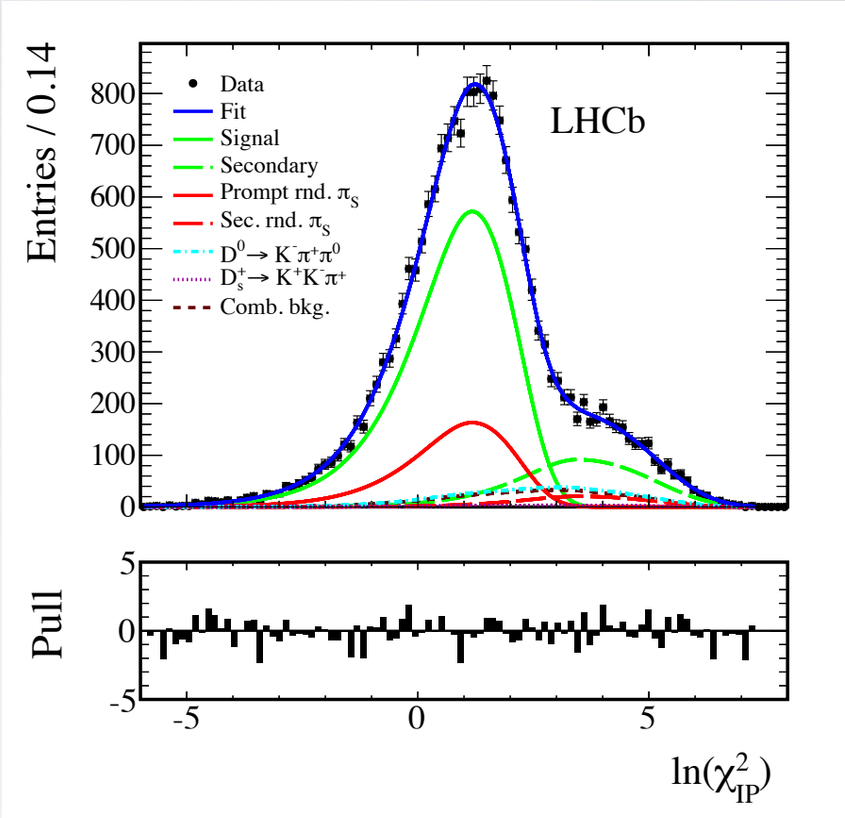
No significant slope → $A_\Gamma \sim 0$

PROMPT Ar

PRL 112 (2014) 041801







0.25–0.37 ps

0.74–0.78 ps

1.55–1.80 ps

Fits of $\ln(\chi^2_{\mathrm{IP}})$ to $\bar{D}^0 \to K^- K^+$

PROMPT A_Γ

PRL 112 (2014) 041801

- Alternative binned method as cross check
- Linear χ^2 mininmization of

binwidth

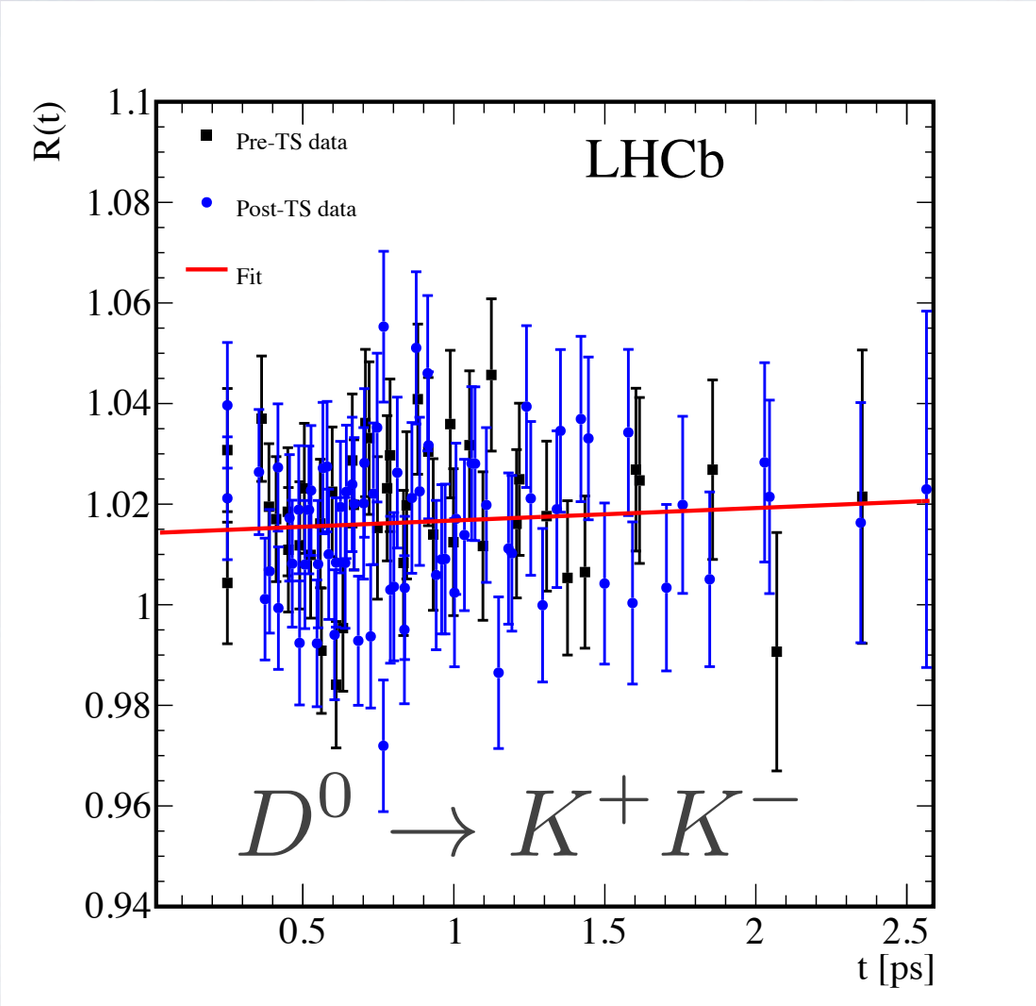
$$R(t) \approx \frac{N_{\bar{D}^0}}{N_{D^0}} \left(1 + \frac{2A_\Gamma}{\tau_{KK}} \cdot t\right) \frac{1 - \exp^{-\Delta t/\tau_{\bar{D}^0}}}{1 - \exp^{-\Delta t/\tau_{D^0}}}$$

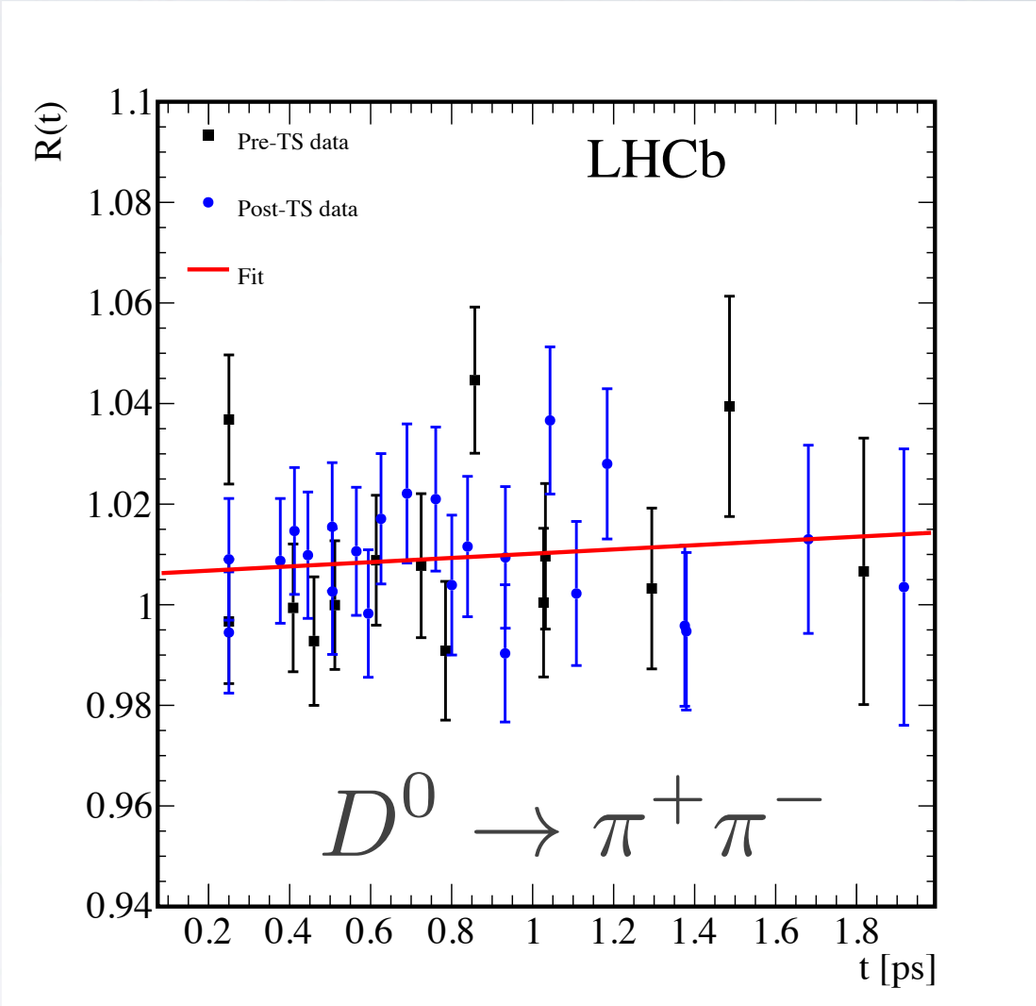
external input

- Results
  - $A_\Gamma(K^+K^-) = (0.050 \pm 0.065)\%$
  - $A_\Gamma(\pi^+\pi^-) = (0.085 \pm 0.122)\%$

PROMPT A_Γ

PRL 112 (2014) 041801





Decay-time dependent ratio R(t) (binned method)

PROMPT A_Γ

PRL 112 (2014) 041801

TABLE I. Systematic uncertainties, given as multiples of 10^{-3}. The first column for each final state refers to the unbinned fit method and the second column to the binned fit method.

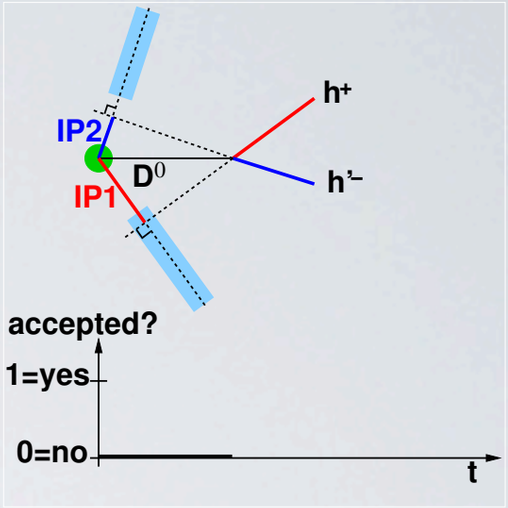
Source	$A_\Gamma^{\rm unb}(KK)$	$A_\Gamma^{\rm bin}(KK)$	$A_\Gamma^{\rm unb}(\pi\pi)$	$A_\Gamma^{\rm bin}(\pi\pi)$
Partially reconstructed backgrounds	±0.02	±0.09	±0.00	±0.00
Charm from b decays	±0.07	±0.55	±0.07	±0.53
Other backgrounds	±0.02	±0.40	±0.04	±0.57
Acceptance function	±0.09	$\cdots$	±0.11	$\cdots$
Magnet polarity	$\cdots$	±0.58	$\cdots$	±0.82
Total systematic uncertainty	±0.12	±0.89	±0.14	±1.13

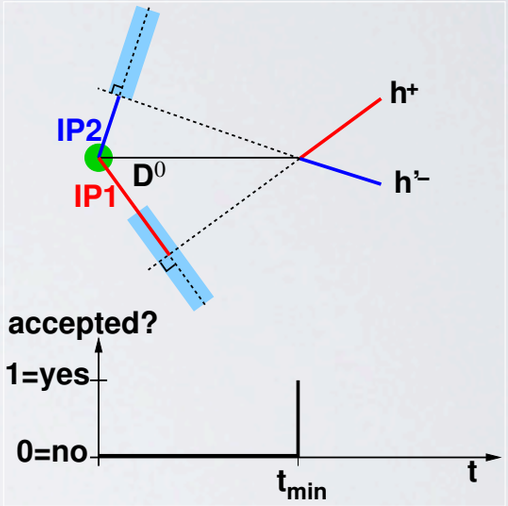
Summary of systematic uncertainties

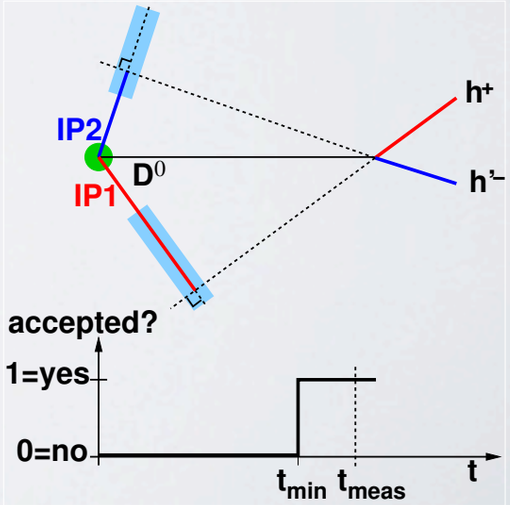
PROMPT A_Γ

JHEP 04 (2012) 129

- A_Γ relies on absolute lifetime measurements
  → correct lifetime-biasing effects
- Acceptance function is determined for each candidate and for all possible decay times
  → steps in acceptance (turning points TP)
- TP determined by moving PV in steps along direction of D^0 momentum
  → at each step, evaluate selection decision
  → value of acceptance function at decay time

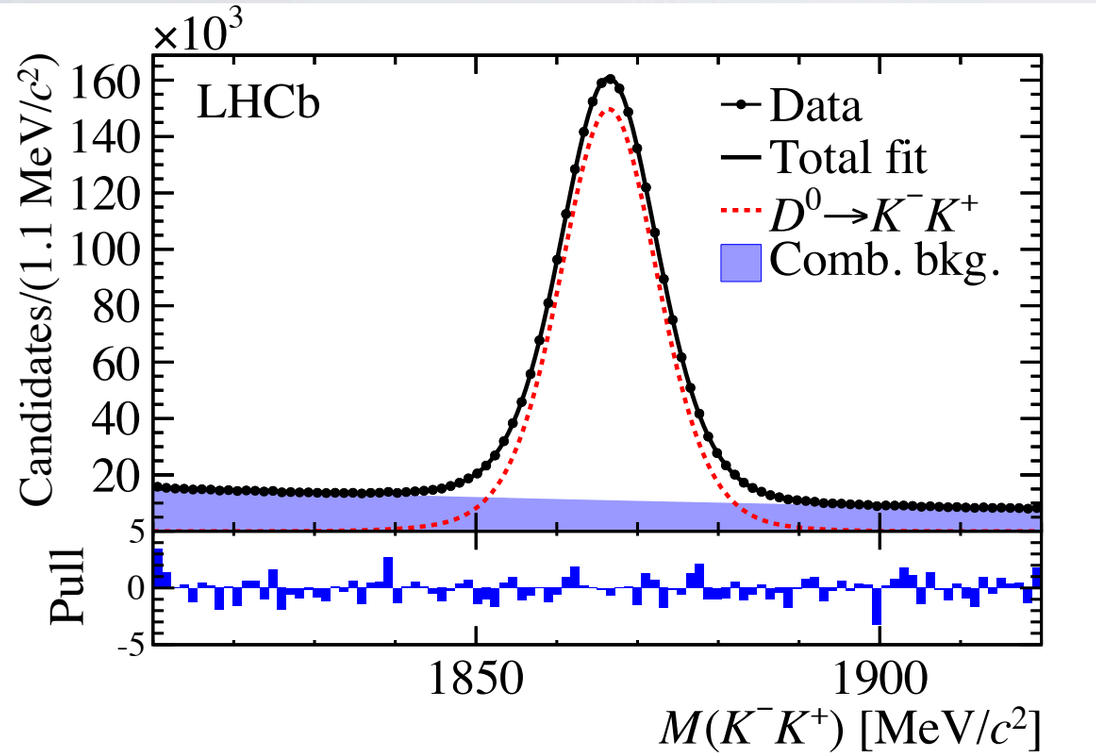


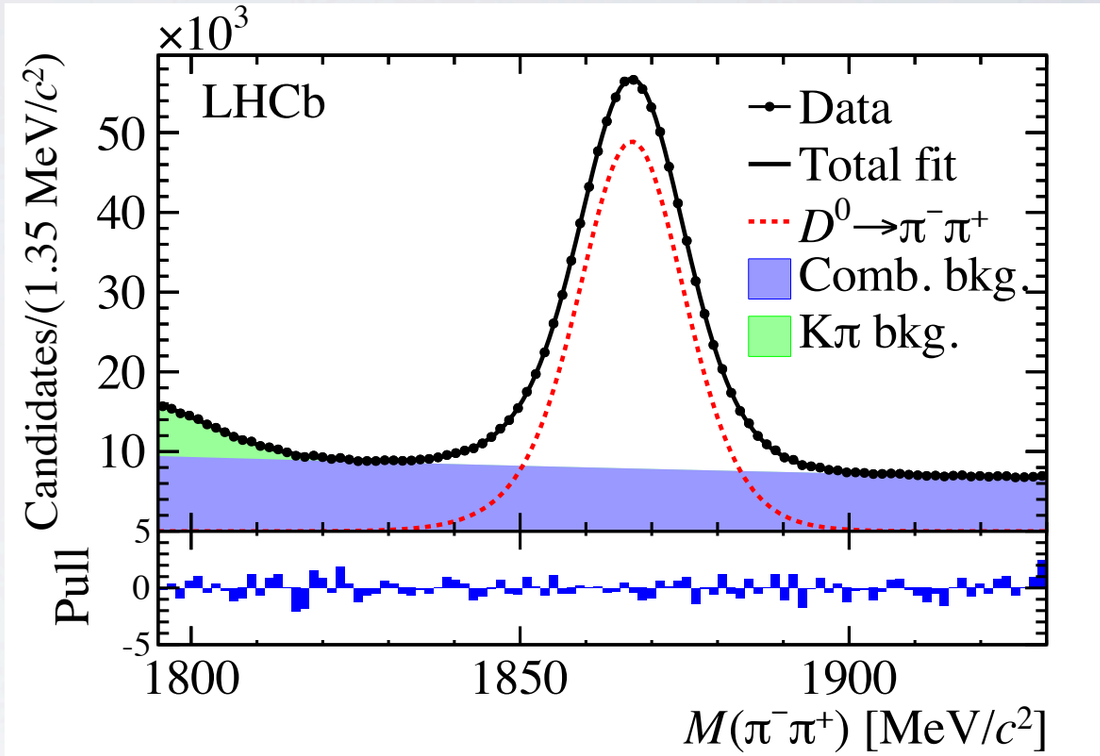




SEMILEPTONIC A_Γ

JHEP 04 (2015) 043

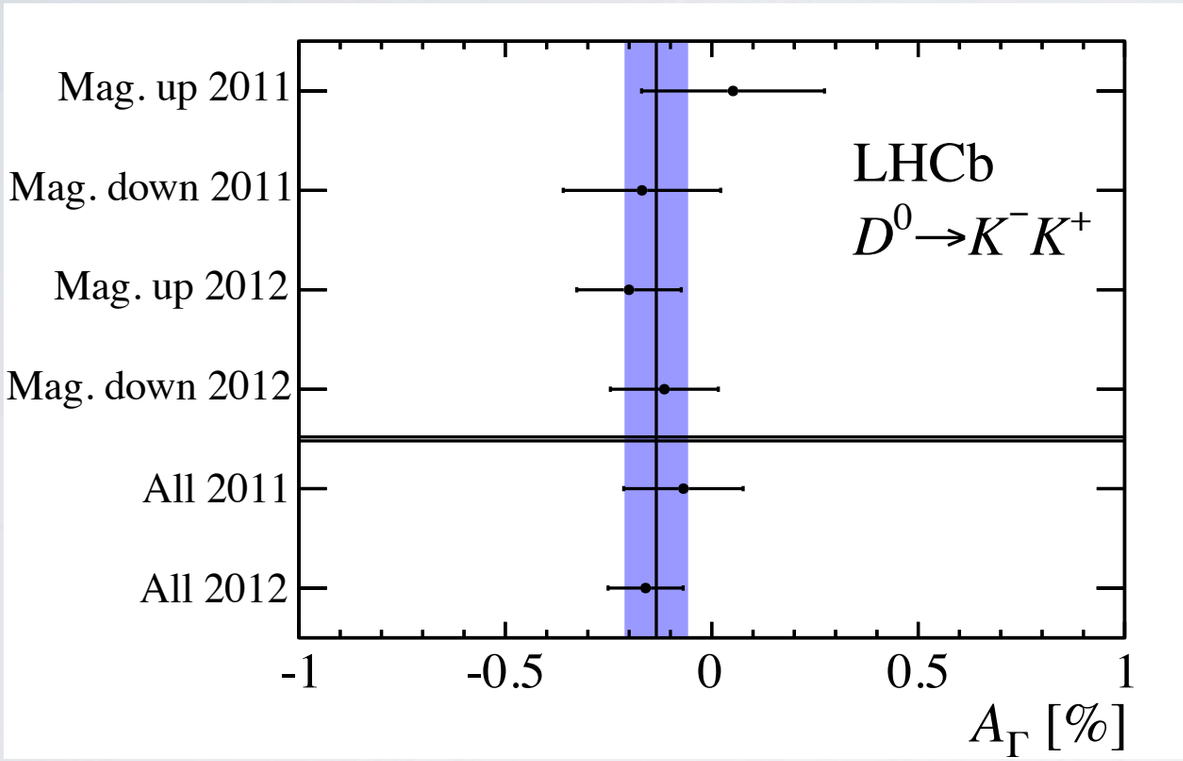


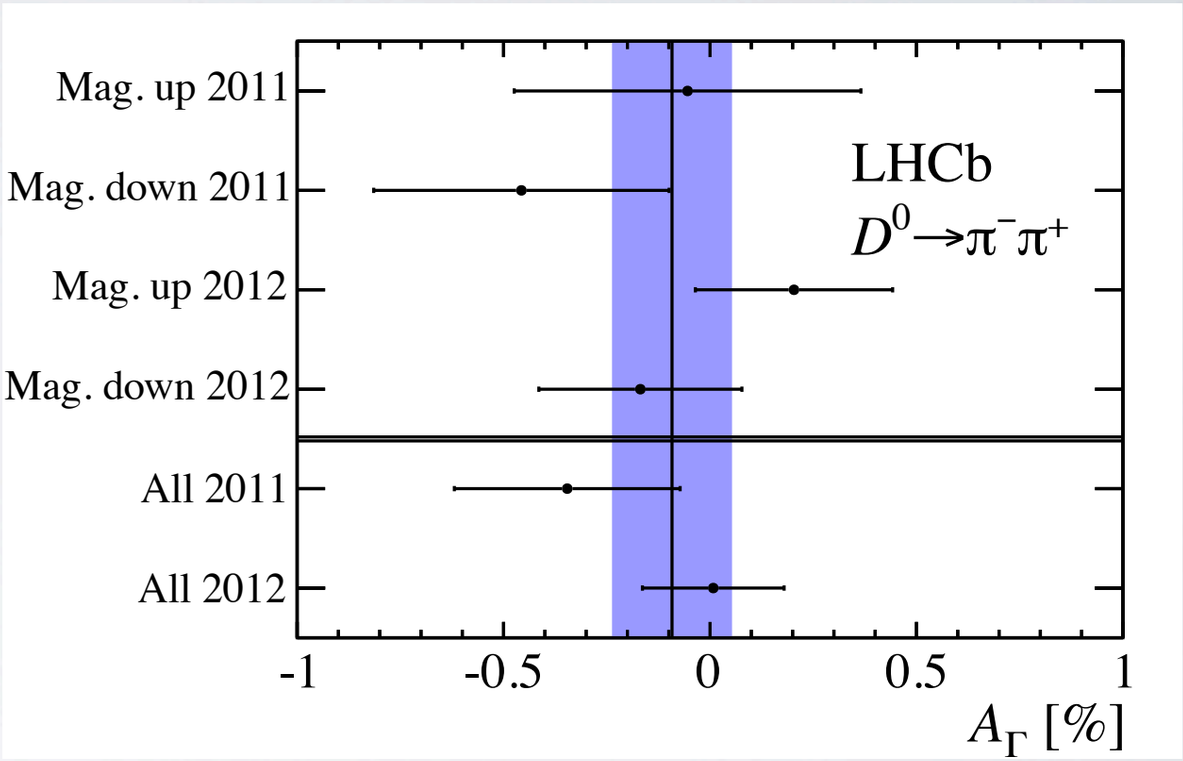


Invariant mass distributions

SEMILEPTONIC A_Γ

JHEP 04 (2015) 043



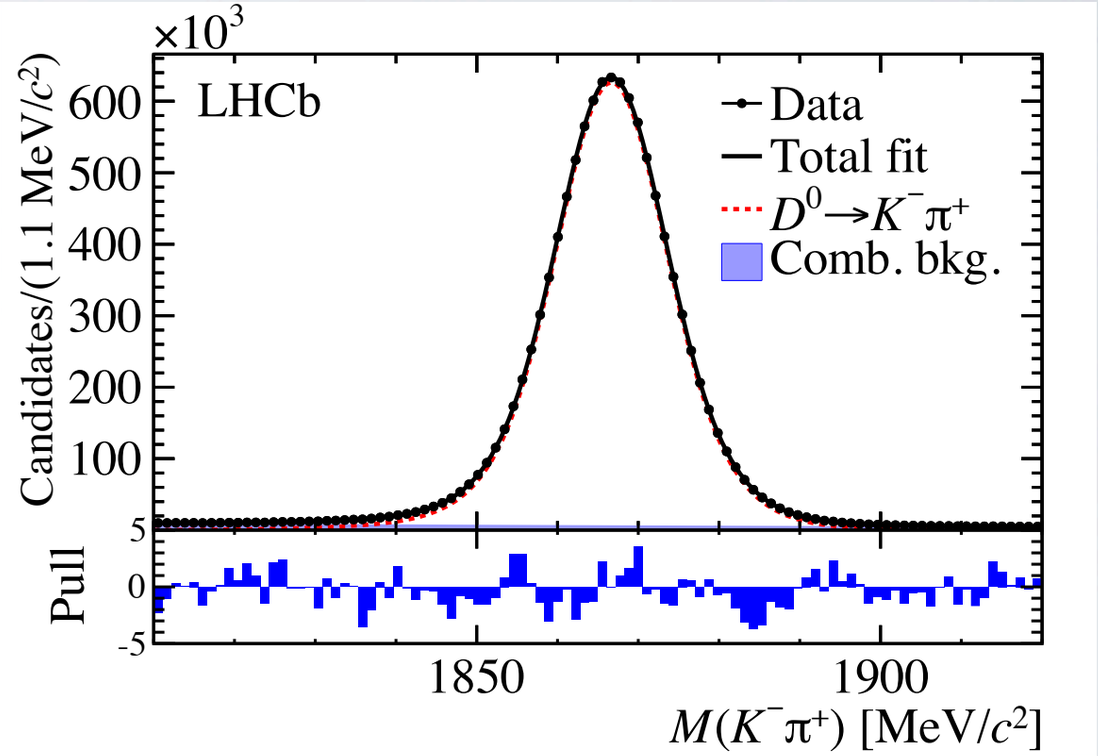


A_Γ results split by magnet polarity and year

SEMILEPTONIC A_Γ

JHEP 04 (2015) 043

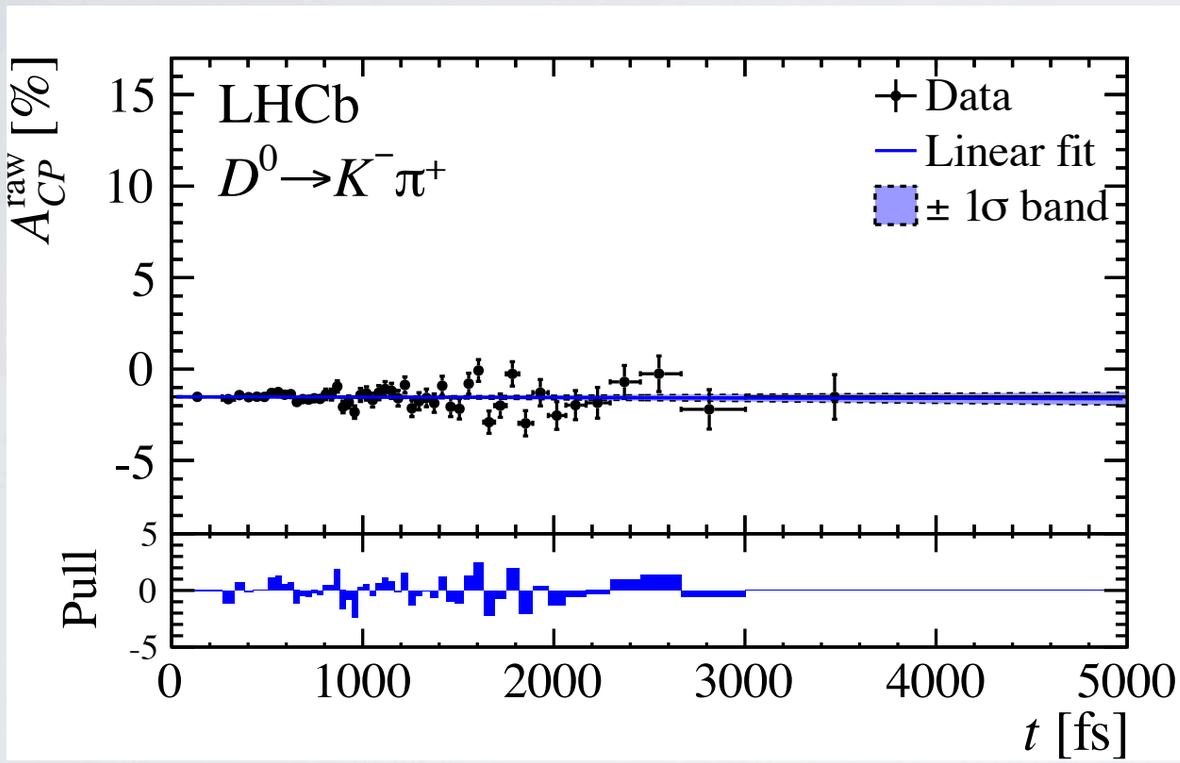
- Control channel $D^0 \to K^-\pi^+$ used to study mistag
- CF decay
  - direct CPV negligible
  - indirect CPV suppressed
- Half of available sample analysed ~ 11.3M signal candidates

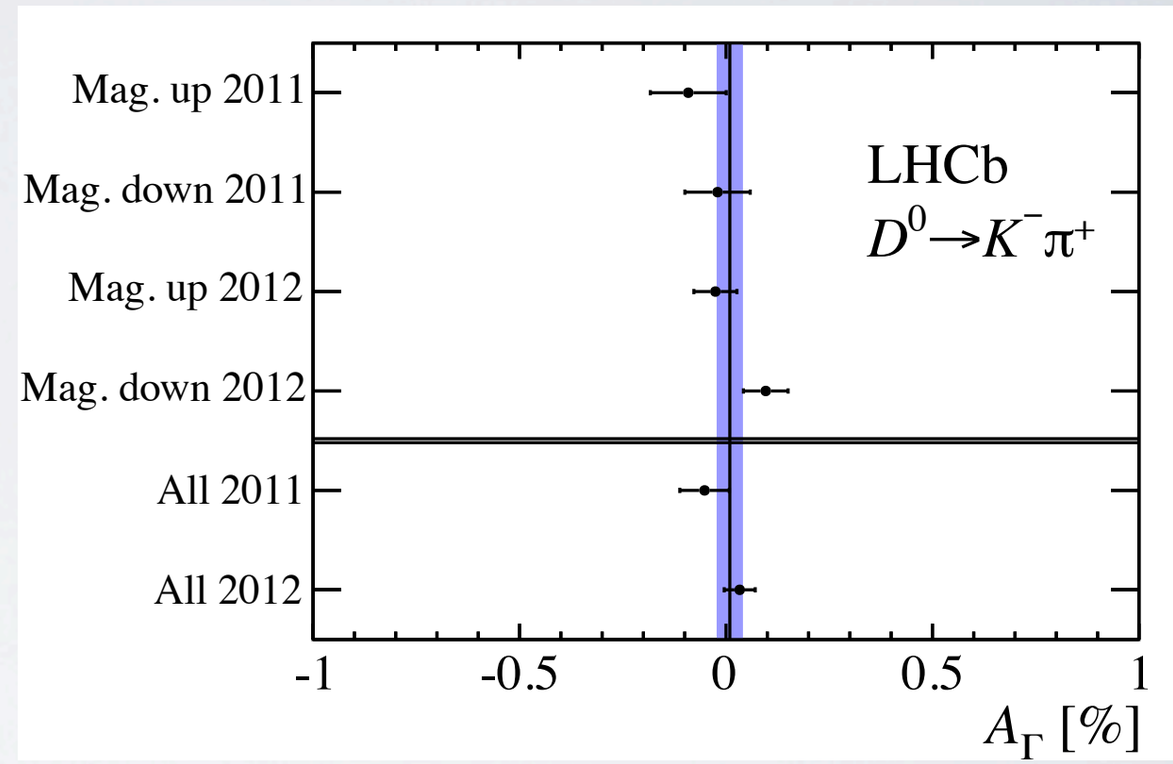


Invariant mass distribution

SEMILEPTONIC A_Γ

JHEP 04 (2015) 043





Left: Fit to $A_{CP}^{\rm raw}(t)$ on control channel $D^0 \to K^- \pi^+$

Right: A_Γ results split by magnet polarity and year

SEMILEPTONIC A_Γ

JHEP 04 (2015) 043

Table 1: Contributions to the systematic uncertainty of $A_\Gamma(K^-K^+)$ and $A_\Gamma(\pi^-\pi^+)$. The constant and multiplicative scale uncertainties are given separately.

Source of uncertainty	$D^0 \to K^-K^+$		$D^0 \to \pi^-\pi^+$	
	constant	scale	constant	scale
Mistag probability	0.006%	0.05	0.008%	0.05
Mistag asymmetry	0.016%		0.016%	
Time-dependent efficiency	0.010%		0.010%	
Detection and production asymmetries	0.010%		0.010%	
D^0 mass fit model	0.011%		0.007%	
D^0 decay-time resolution		0.09		0.07
B^0–$\overline{B}^0$ mixing	0.007%		0.007%	
Quadratic sum	0.026%	0.10	0.025%	0.09

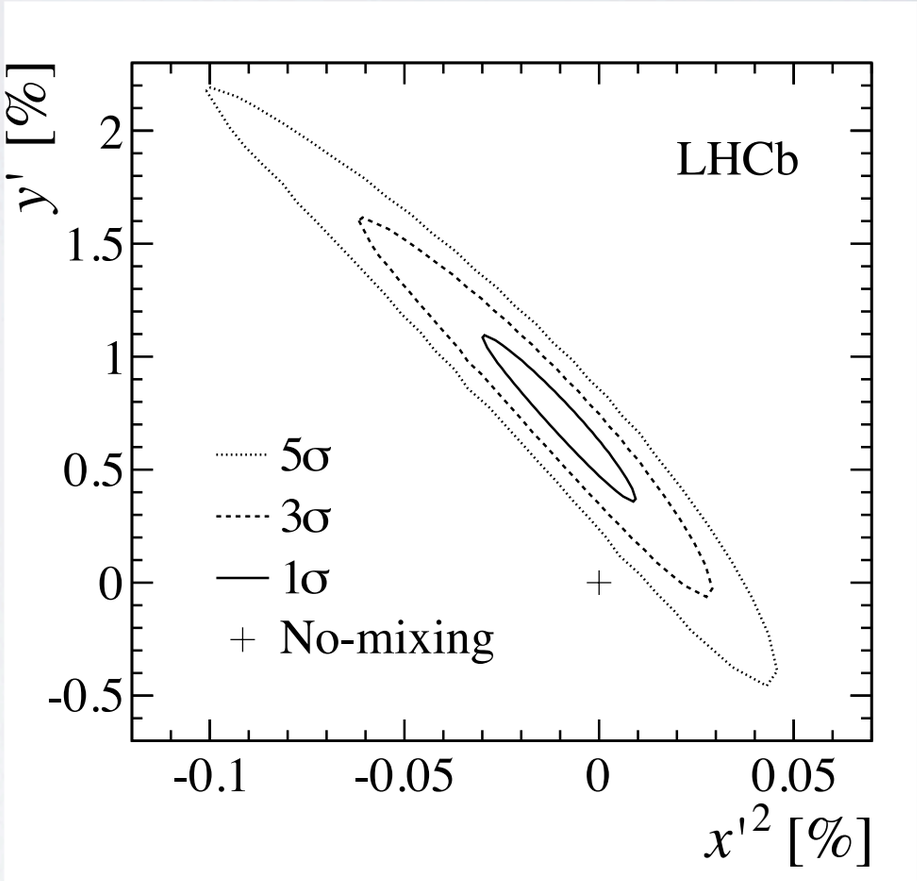
Summary of systematic uncertainties

MIXING IN $D \to K\pi$ (2011)

PRL 110 (2013) 101802

TABLE I. Results of the time-dependent fit to the data. The uncertainties include statistical and systematic sources; ndf indicates the number of degrees of freedom.

Fit type (χ^2/ndf)	Parameter	Fit result (10^{-3})	Correlation coefficient R_D	y'	x'^2
Mixing (9.5/10)	R_D	3.52 ± 0.15	1	-0.954	$+0.882$
	y'	7.2 ± 2.4		1	-0.973
	x'^2	-0.09 ± 0.13			1
No mixing (98.1/12)	R_D	4.25 ± 0.04			

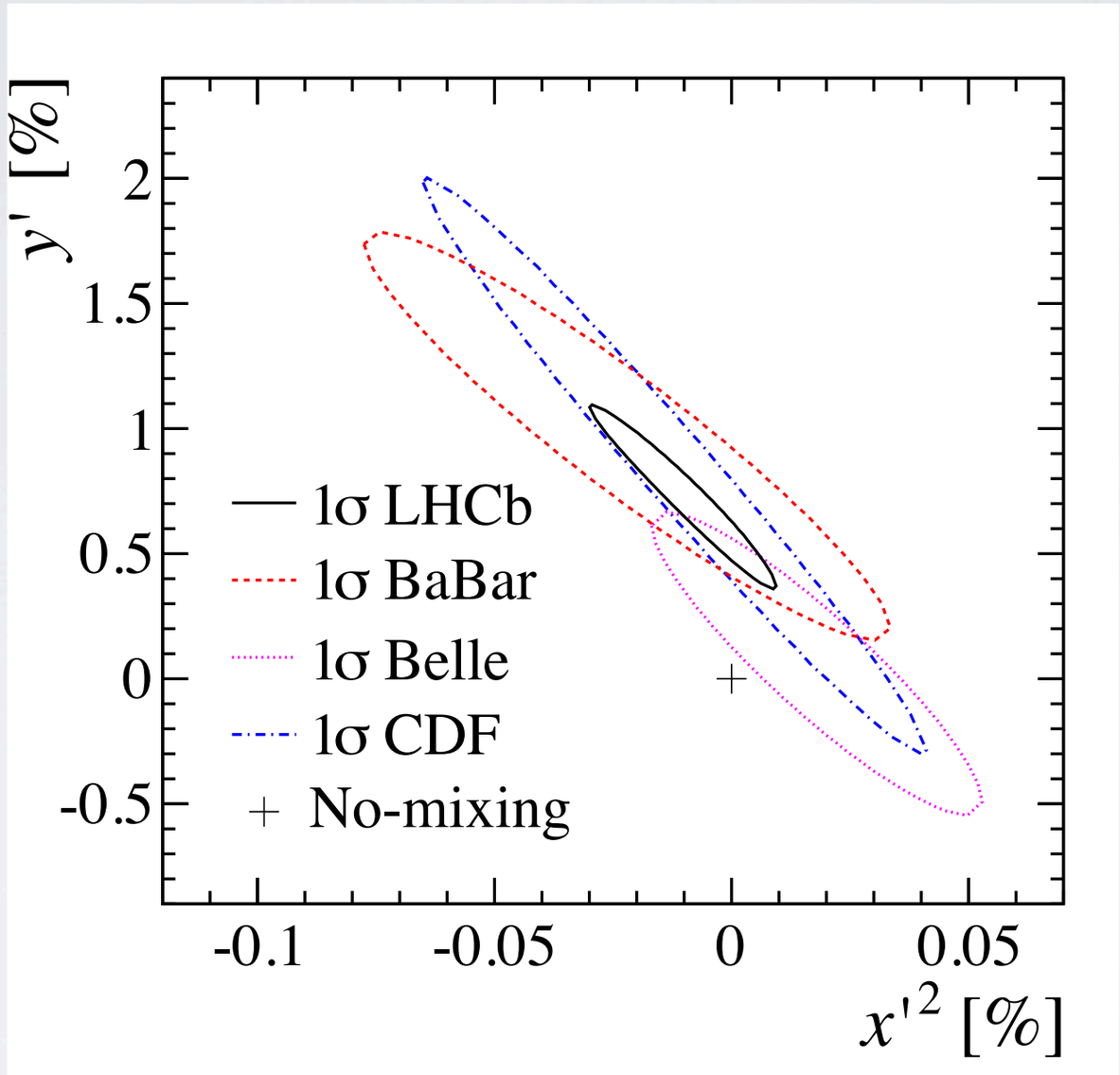


Left: Results of the mixing and no-mixing fit

Right: CL regions in the (x'^2, y') plane

MIXING IN $D \to K\pi$ (2011)

PRL 110 (2013) 101802



BaBar: PRL 98 (2007) 211802
Belle: PRL 96 (2006) 151801
CDF: PRL 100 (2008) 121802

Allowed 68% CL regions in the (x'^2, y') plane as measured by LHCb, BaBar, Belle and CDF

MIXING AND CPV IN $D \to K\pi$

PRL 111 (2013) 251801

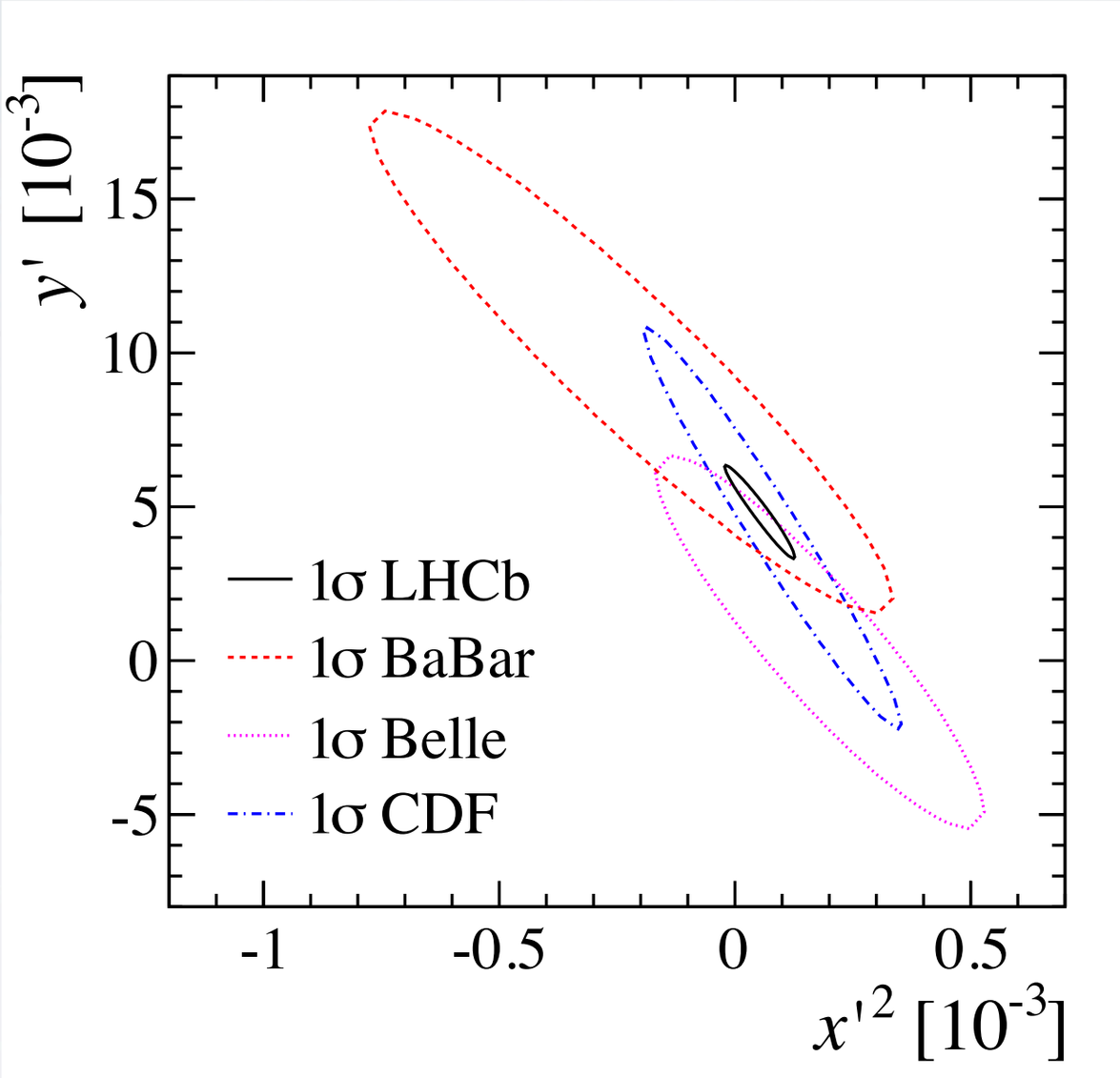
- Results for the three different fit scenarios allowing for
  - direct and indirect CPV
  - indirect CPV
  - no CPV

TABLE I. Results of fits to the data for different hypotheses on the CP symmetry [27]. The reported uncertainties are statistical and systematic, respectively; ndf indicates the number of degrees of freedom.

Parameter	Value
Direct and indirect 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})	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf	85.9/98
No direct CP violation	
R_D (10^{-3})	$3.568 \pm 0.058 \pm 0.033$
y'^+ (10^{-3})	$4.8 \pm 0.9 \pm 0.6$
x'^{2+} (10^{-5})	$6.4 \pm 4.7 \pm 3.0$
y'^- (10^{-3})	$4.8 \pm 0.9 \pm 0.6$
x'^{2-} (10^{-5})	$4.6 \pm 4.6 \pm 3.0$
χ^2/ndf	86.0/99
No CP violation	
R_D (10^{-3})	$3.568 \pm 0.058 \pm 0.033$
y' (10^{-3})	$4.8 \pm 0.8 \pm 0.5$
x'^2 (10^{-5})	$5.5 \pm 4.2 \pm 2.6$
χ^2/ndf	86.4/101

MIXING IN $D \to K\pi$ (2011)

PRL 110 (2013) 101802

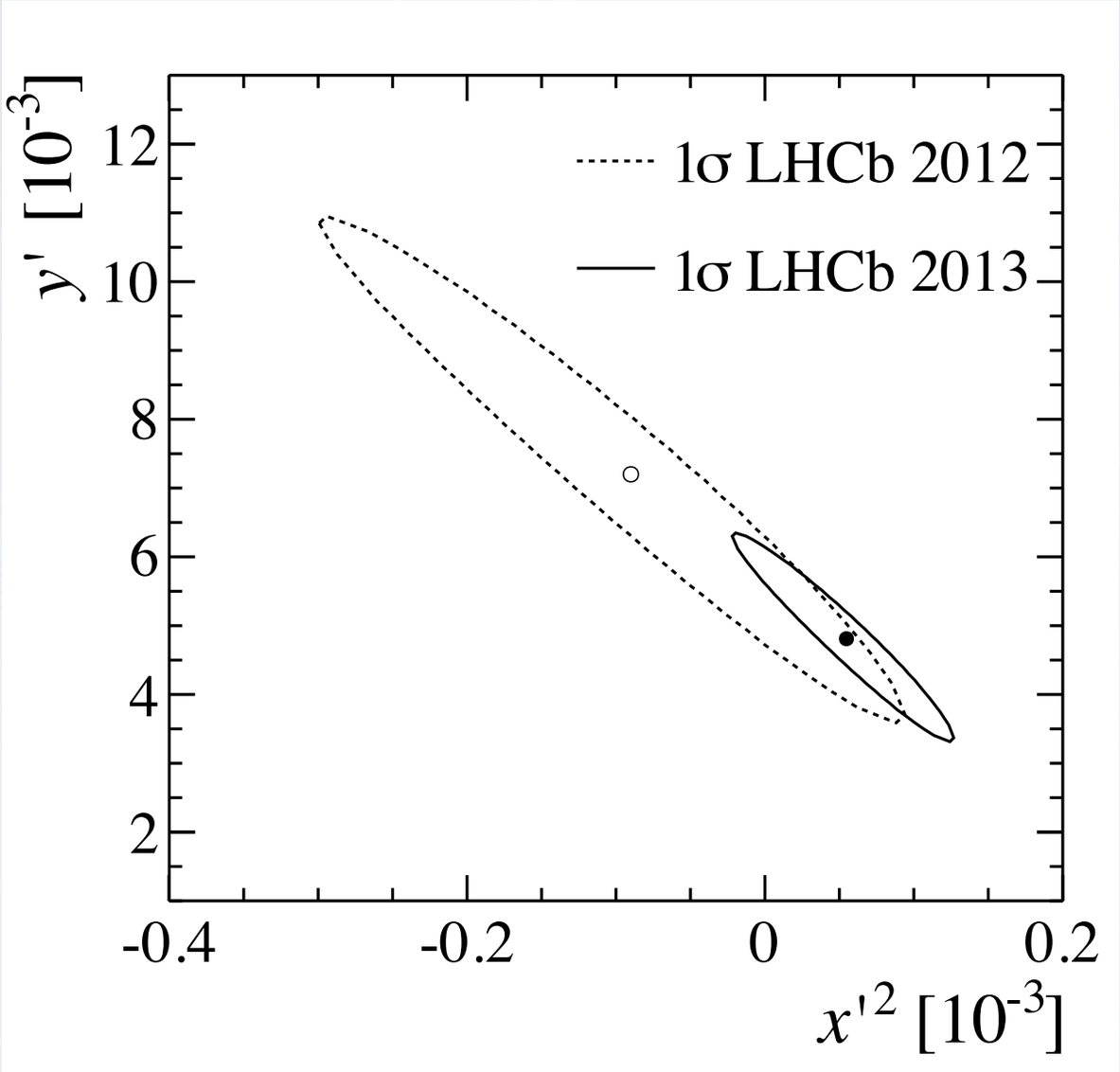


BaBar: PRL 98 (2007) 211802
Belle: PRL 96 (2006) 151801
CDF: arXiv: 1309.4078 (2013)

Allowed 68% CL regions in the (x'^2, y') plane as measured by LHCb, BaBar, Belle and CDF

MIXING IN $D \to K\pi$

PRL 111 (2013) 251801



PRL 110 (2013) 101802

PRL 111 (2013) 251801

Allowed 68% CL regions in the (x'^2, y') plane for the $1\,\mathrm{fb}^{-1}$ (LHCb 2012) and $3\,\mathrm{fb}^{-1}$ (LHCb 2013) analyses