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Mixing and CP violation in charm

Marco Gersabeck (The University of Manchester)

on behalf of the LHCb collaboration
with results from BaBar, Belle, Belle II, and BESIII

FPCP 2018, Hyderabad, July 2018


GENERALI
PORSCHE
adidas

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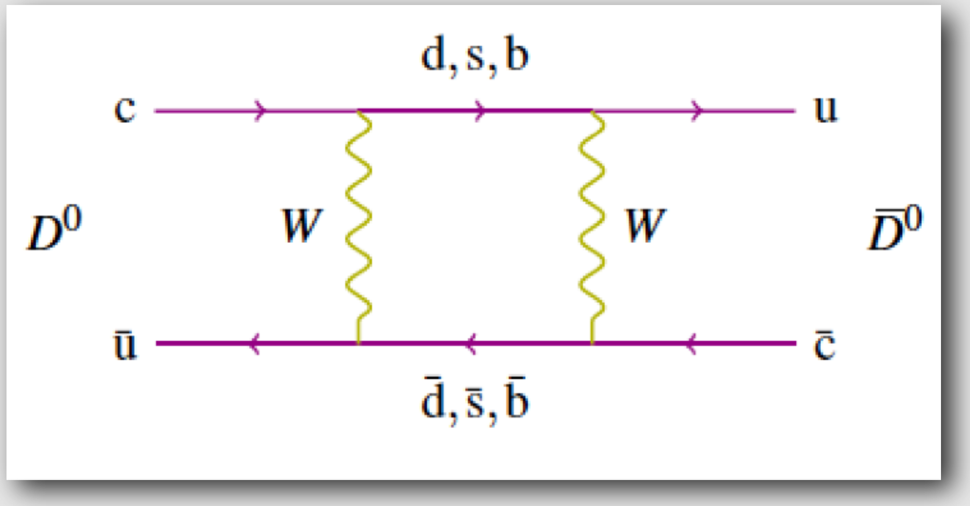
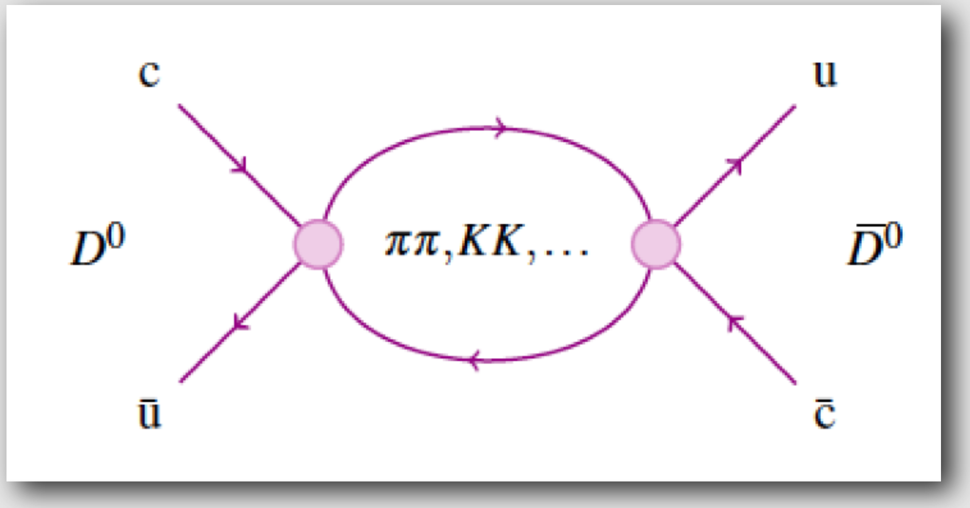
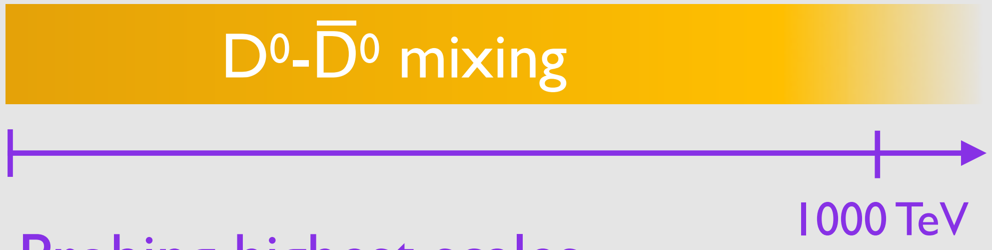
Introduction

Charm: hardly a triangle

- Only up-type quark to form weakly decaying hadrons
  - ➡ Unique physics access
- Mixing
  - ➡ Huge cancellations
  - ➡ Theoretically difficult
- CP violation
  - ➡ Predictions even smaller
- Need highest precision
- Huge LHCb dataset
  - ➡ Blessing and a curse





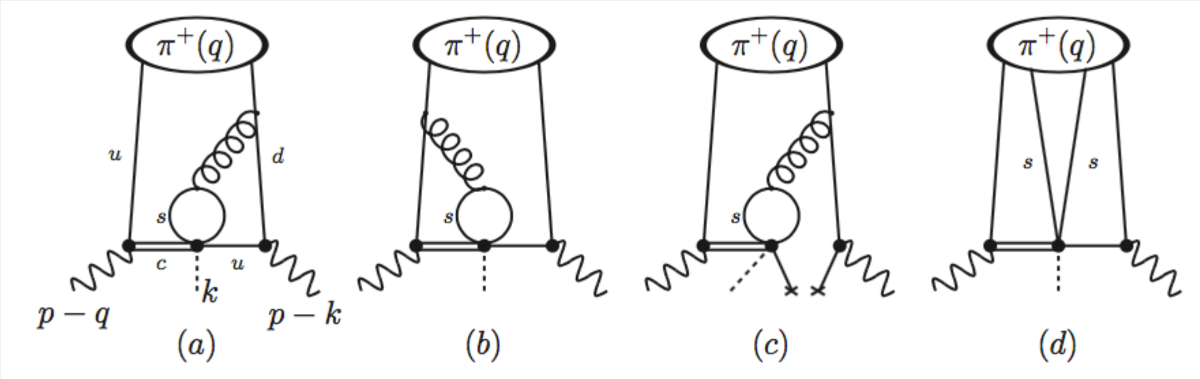


Probing highest scales

→ Isidori, Nir, Perez, ARNPS 60 (2010) 355

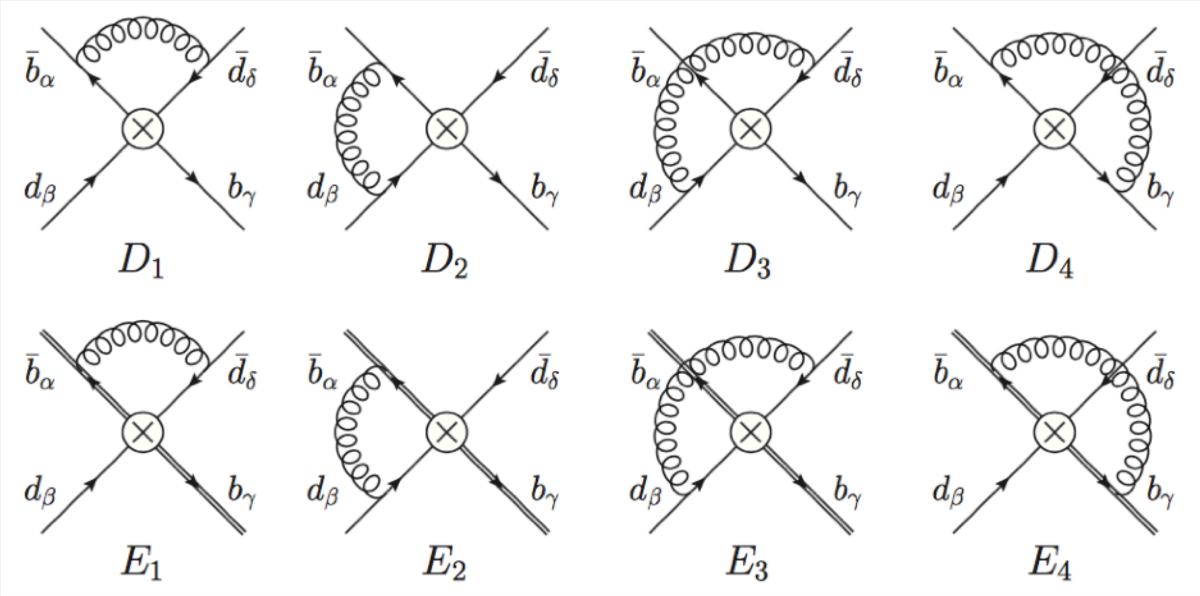
Theory updates

- Use light-cone sum rules based on quark-hadron duality to calculate penguin matrix elements for two-body decays
  - ➡ Predict $|A_{CP}(KK)-A_{CP}(\pi\pi)|<0.02\%$
  - ➡ Current WA sensitivity 0.07%



Khodjamirian, Petrov, PLB 774 (2017) 235

- Using HQET sum rules to determine dim-6 matrix elements and evaluate lifetime ratios
  - ➡ $$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|_{\text{exp}} = 2.536 \pm 0.019,$$
  - ➡ $$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|_{\text{PS}} = 2.70^{+0.74}_{-0.82}$$



Kirk, Lenz, Rauh JHEP 1712 (2017) 068

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Direct CP violation

Direct CP violation:

$$a_{CP}^{dir} \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\overline{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\overline{D}^0 \rightarrow f)}$$

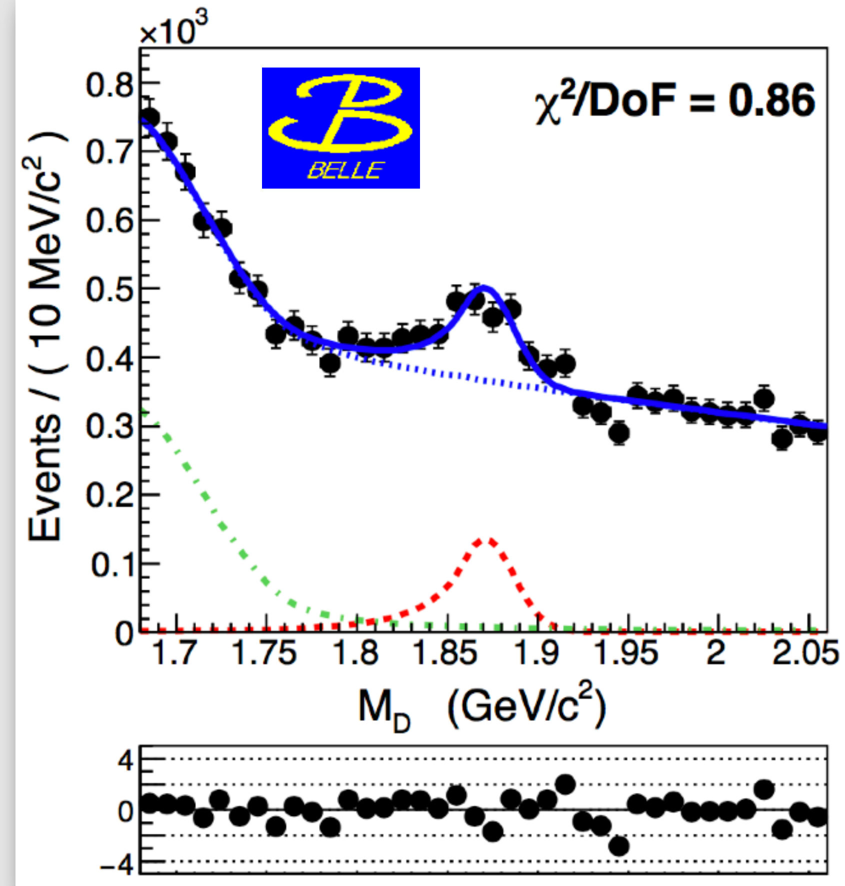
D^+ decays

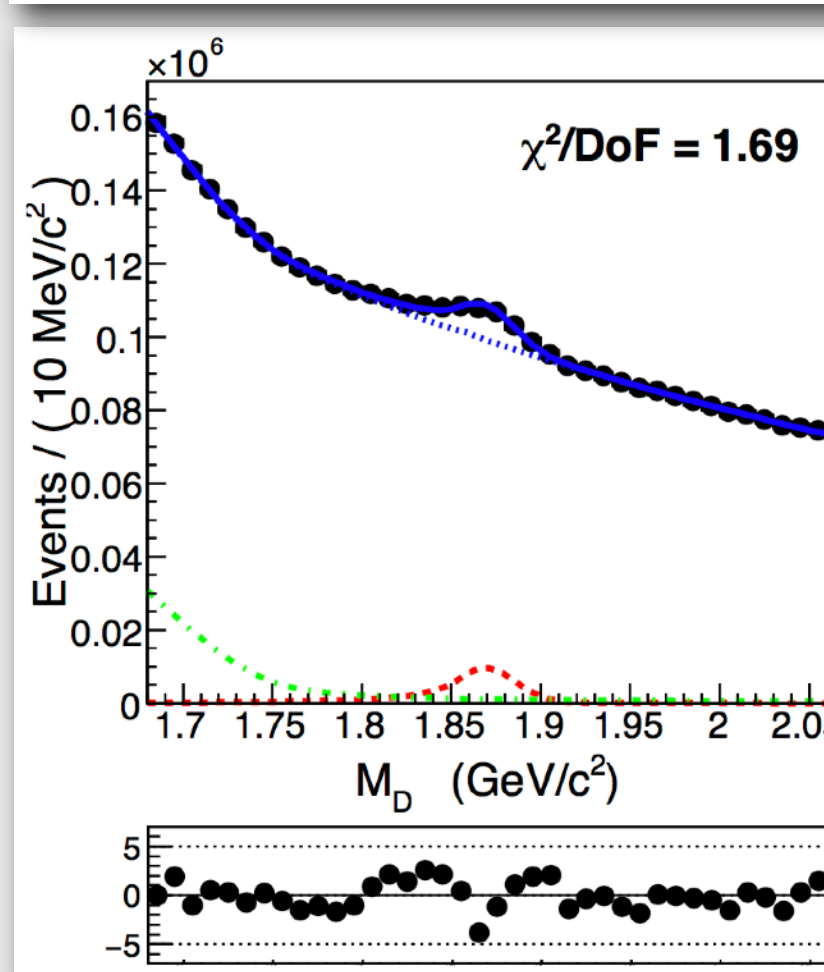
- $D^+ \to \pi^+\pi^0$ decays expected to have negligible SM CP violation due to heavily-suppressed loop contributions
  - ➡ Equally useful to test $D \to \pi\pi$ sum rules (Grossman, Kagan, Zupan, PRD 2012)
  - ➡ Only $D^0 \to \pi\pi$ measured to sub-% precision
- New Belle measurement (Phys. Rev. D97 (2018) 011101)
  - ➡ Normalised with $D^+ \to \pi^+ K_S$
- Systematics:

Source	$D \to \pi\pi$ tagged	$D \to \pi\pi$ untagged
Signal shape	± 0.02	± 0.23
Peaking background shape	± 0.19	± 0.22
$\Delta A_{\rm raw}$ measurement	± 0.19	± 0.32
$A_{CP}(D \to K^0_S \pi)$ measurement	± 0.12	
Total (combined A_{CP} measurement)	± 0.23	

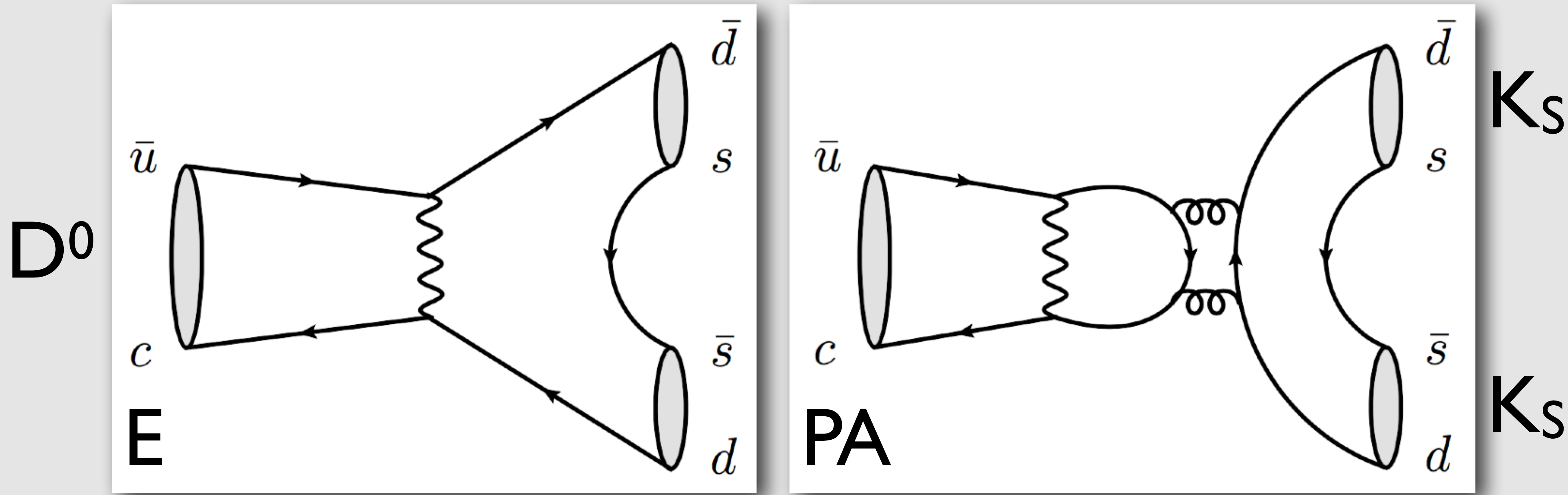
Result:

$$A_{CP}(D^+ \to \pi^+\pi^0) = [+2.31 \pm 1.24(\text{stat.}) \pm 0.23(\text{syst.})]\%$$





$D^0 \to K_S K_S$



- CP violation in $D^0 \to K_S K_S$ predicted to be as large as 1.1% (Nierste, Schacht, PRD 2015)
  - ➡ Suppression of Exchange (E) and Penguin Annihilation (PA) diagrams allows for large interference
- Previous Belle measurement (PRL 119 (2017) 171801):
  - ➡ $A_{CP} = (-0.02 \pm 1.53 \pm 0.17)\%$

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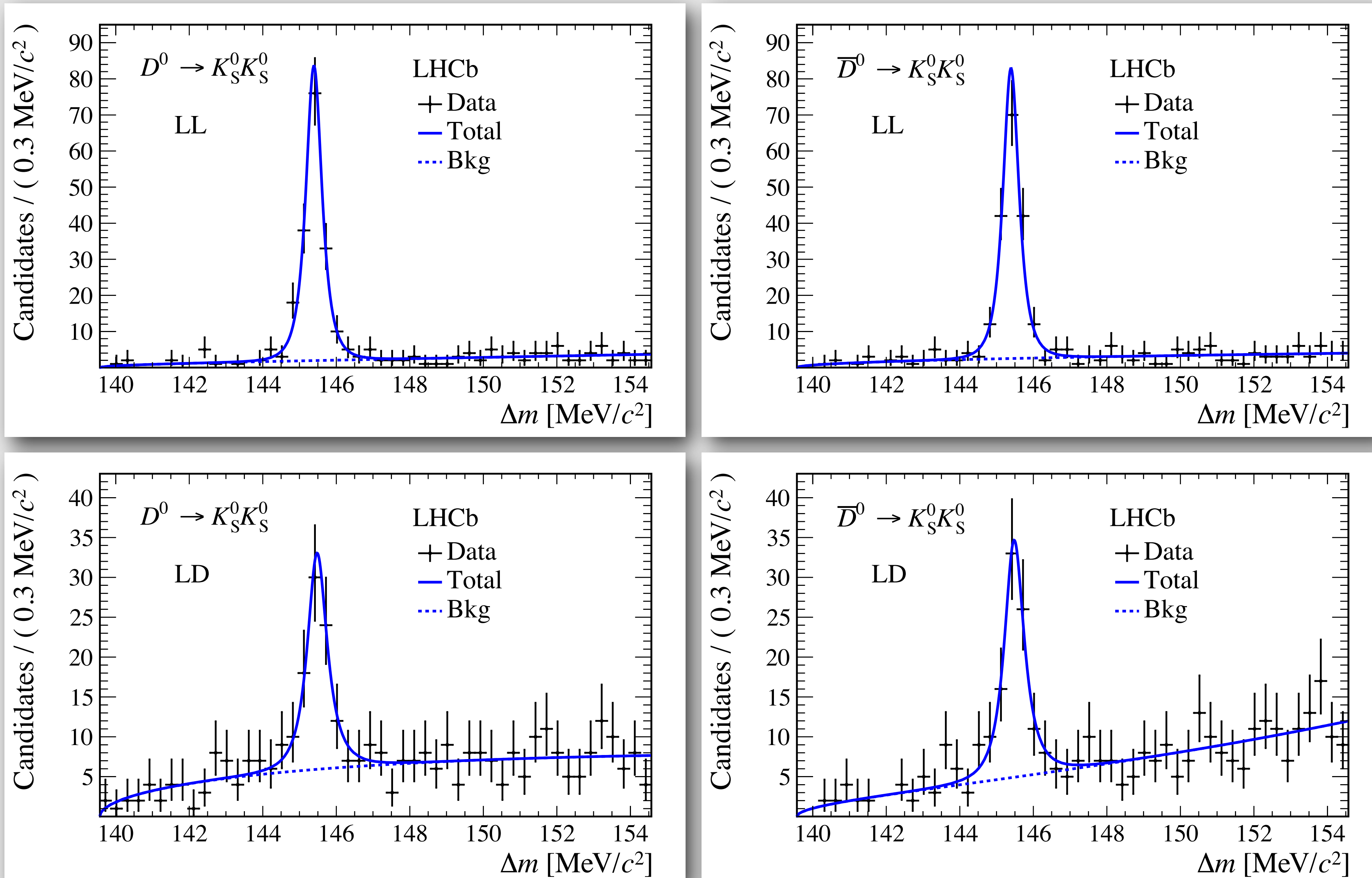
$D^0 \to K_S K_S$ - II



arXiv:1806.01642

- LHCb 2015+16 data:

$$\mathcal{A}^{CP}(D^0 \to K^0_S K^0_S) = (4.2 \pm 3.4 \pm 1.0)\%,$$

- Combined with 2011-12 data:

$$\mathcal{A}^{CP}(D^0 \to K^0_S K^0_S) = (2.0 \pm 2.9 \pm 1.0)\%.$$

JHEP 10 (2015) 055

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

$D^0 \to hh\mu\mu$

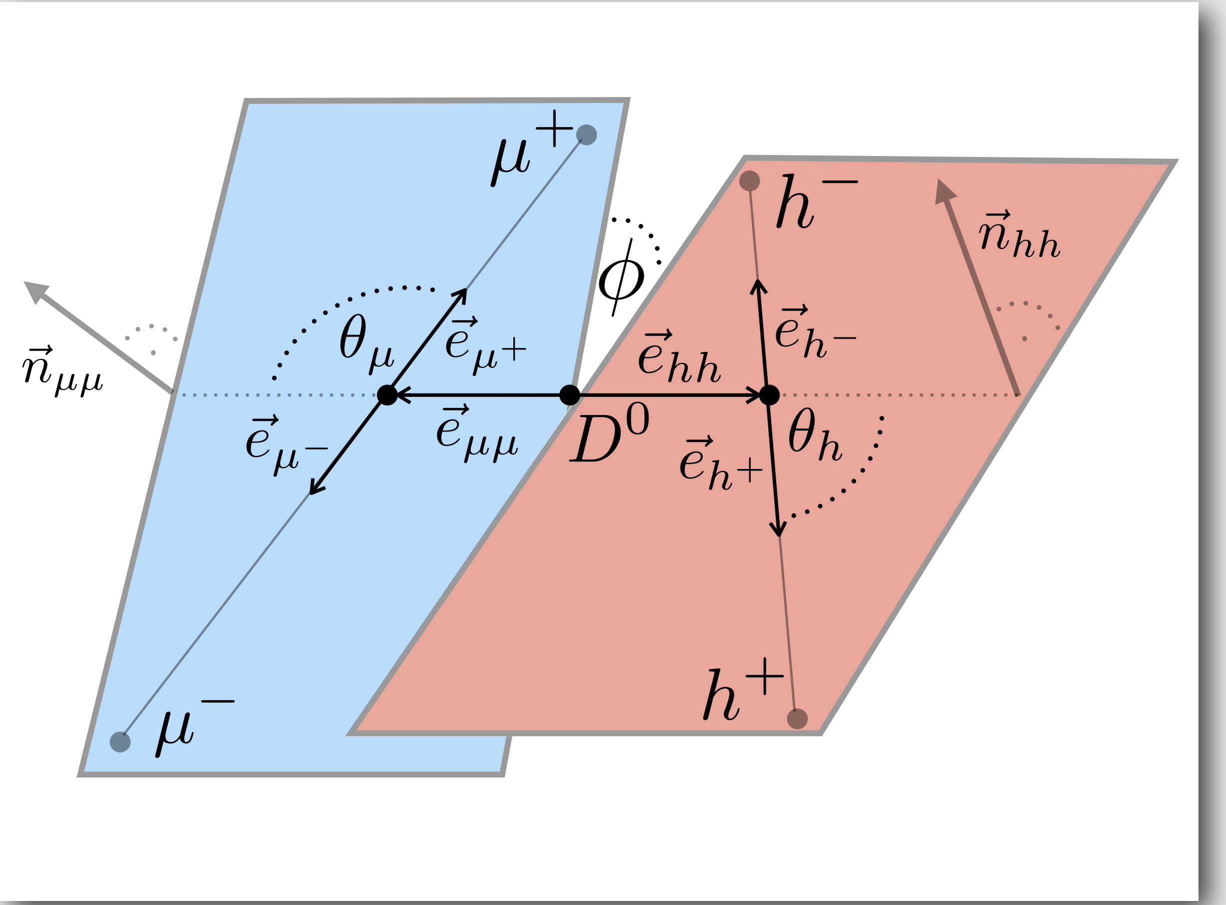
See talk by M. Chrzaszcz

- Four-body decays offer
  - ➡ Spectrum of interfering resonances
  - ➡ Several ways of searching for CPV
  - ➡ Rare decays may have larger interference effects = CP violation
- Measure:

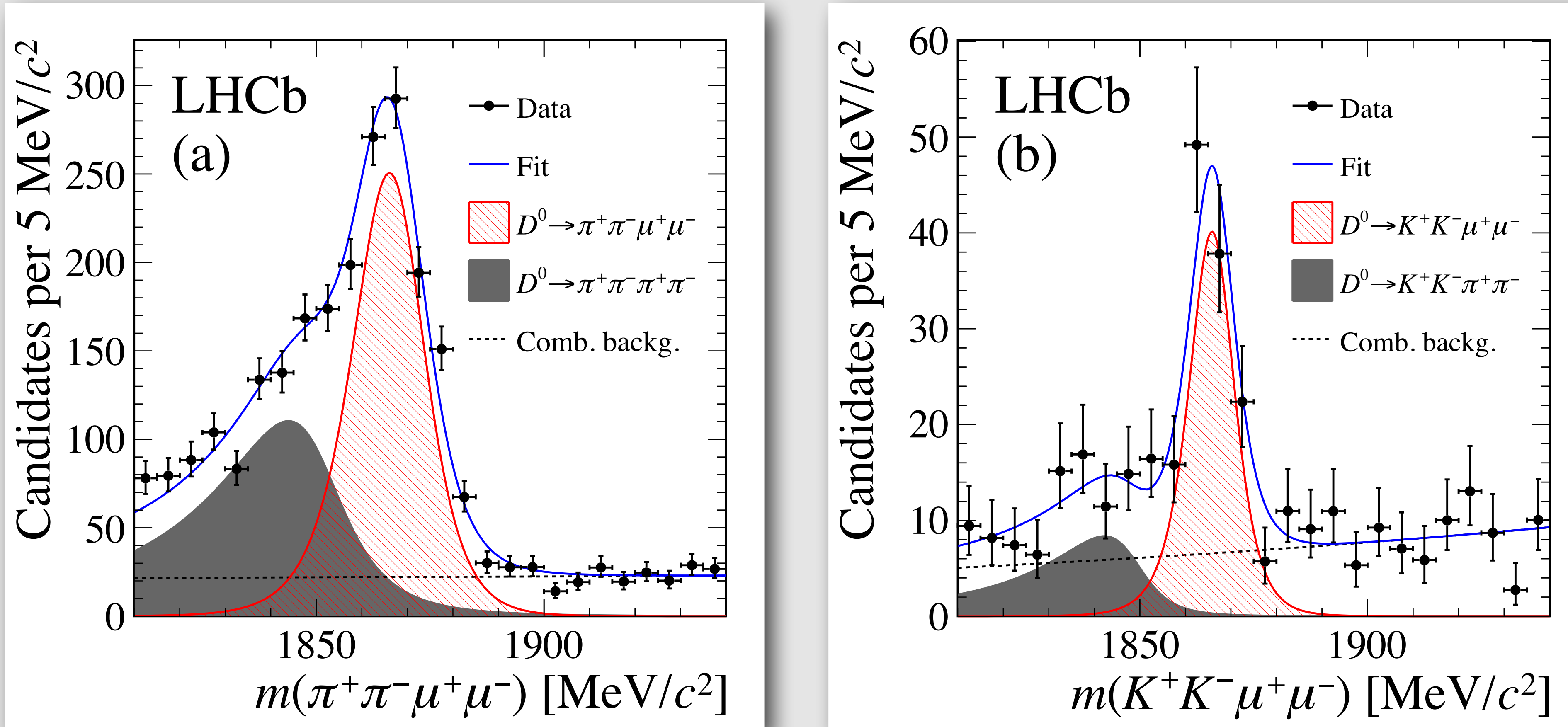
$$A_{\mathrm{FB}} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)},$$

$$A_{2\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)},$$

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)},$$



$D^0 \to hh\mu\mu$ - II



arXiv:1806.10793

- LHCb 2011-16 data (5 fb^{-1})
- Includes significant signal in low-mass region (<525 MeV/c^2)
- A_{CP} normalised to $D^0 \to K^+K^-$

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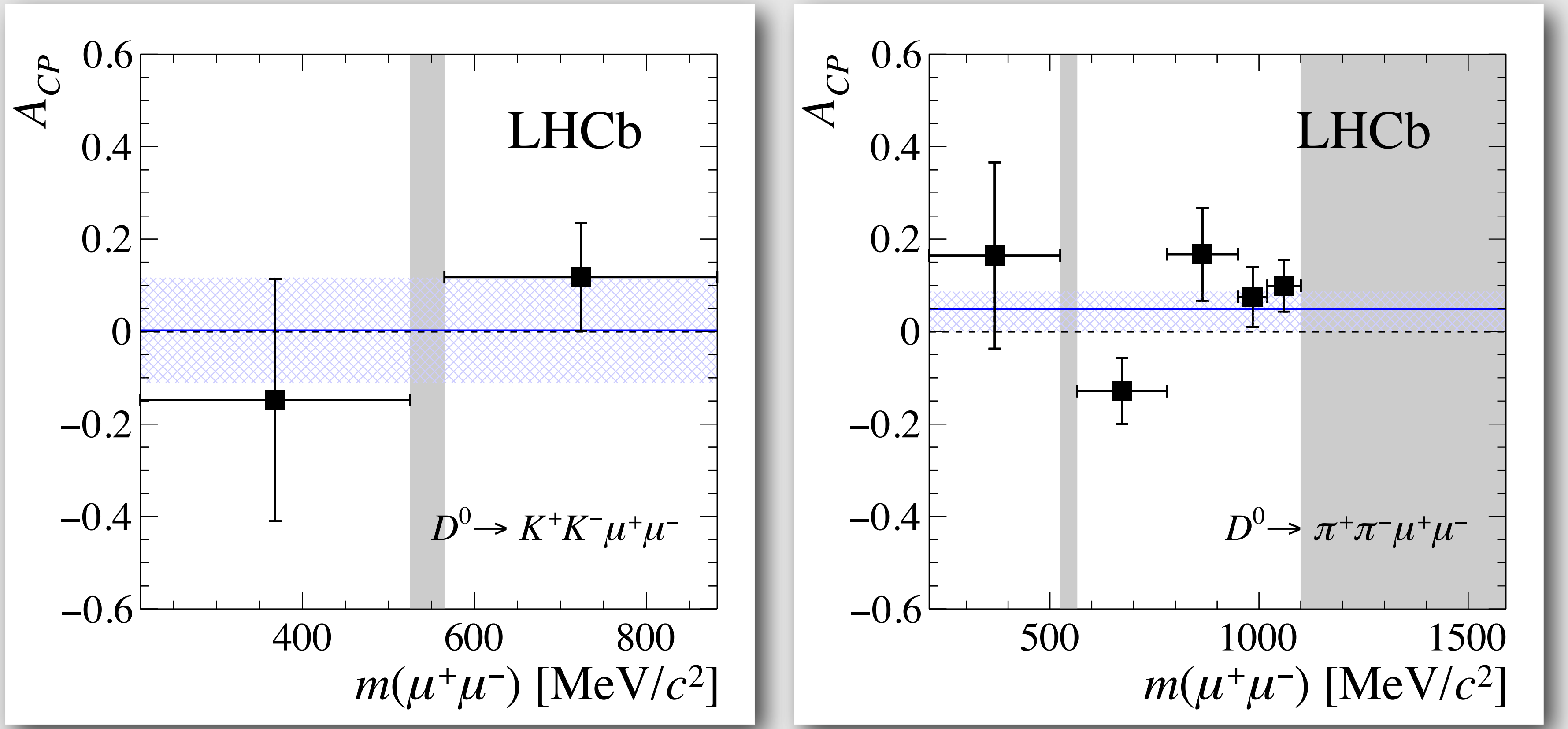
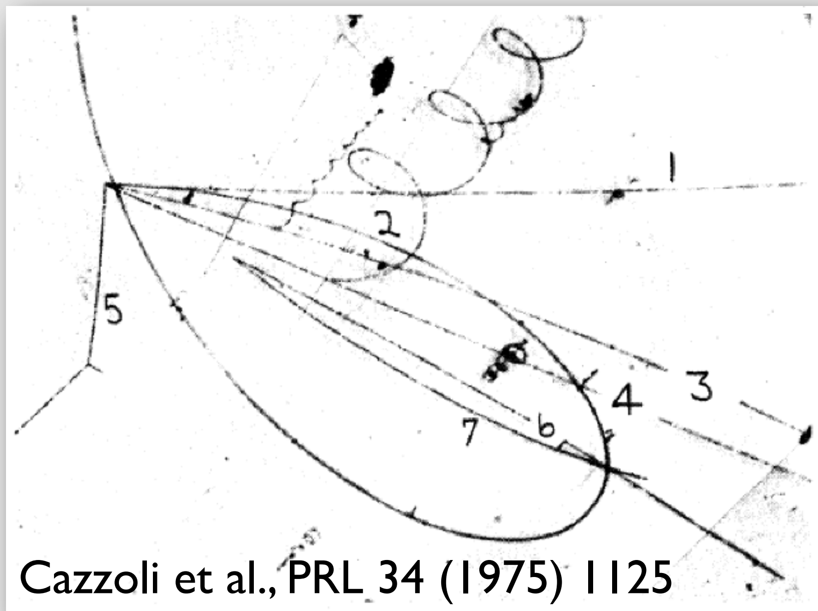
$D^0 \to hh\mu\mu$ - III

arXiv:1806.10793

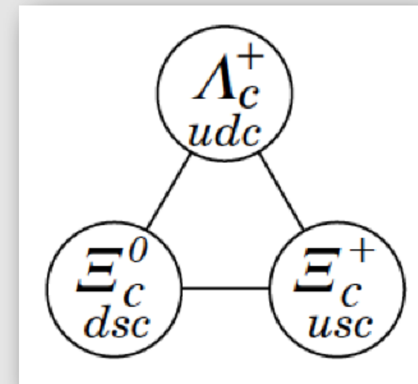


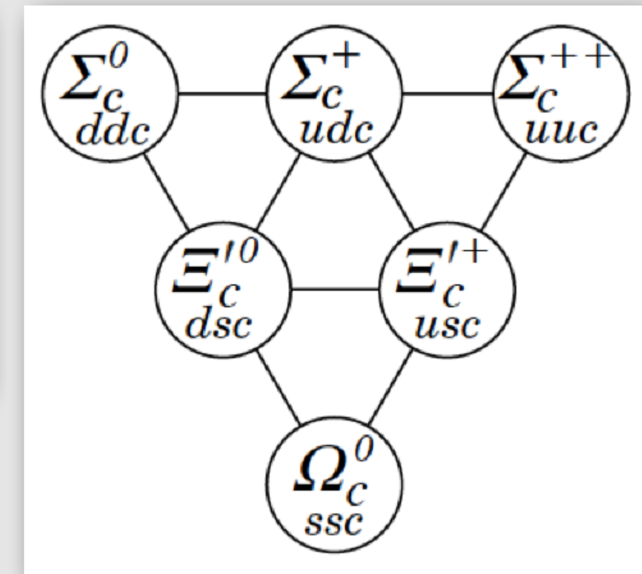
$m(\mu^+\mu^-)$ [MeV/c^2]	Efficiency-weighted yields Signal	Misid. back.	Comb. back.	Signal asymmetries A_{FB} [%]	$A_{2\phi}$ [%]	A_{CP} [%]
			$D^0 \to \pi^+\pi^-\mu^+\mu^-$			
< 525	90 ± 17	233 ± 25	108 ± 22	$2 \pm 20 \pm 2$	$-28 \pm 20 \pm 2$	$17 \pm 20 \pm 2$
525–565	–	–	–	–	–	–
565–780	326 ± 23	253 ± 24	145 ± 21	$8.1 \pm 7.1 \pm 0.7$	$7.4 \pm 7.1 \pm 0.7$	$-12.9 \pm 7.1 \pm 0.7$
780–950	141 ± 14	159 ± 15	89 ± 14	$7 \pm 10 \pm 1$	$-14 \pm 10 \pm 1$	$17 \pm 10 \pm 1$
950–1020	244 ± 16	63 ± 13	43 ± 9	$3.1 \pm 6.5 \pm 0.6$	$1.2 \pm 6.4 \pm 0.5$	$7.5 \pm 6.5 \pm 0.7$
1020–1100	258 ± 14	33 ± 9	44 ± 9	$0.9 \pm 5.6 \pm 0.7$	$1.4 \pm 5.5 \pm 0.6$	$9.9 \pm 5.5 \pm 0.7$
> 1100	–	–	–	–	–	–
Full range	1083 ± 41	827 ± 42	579 ± 39	$3.3 \pm 3.7 \pm 0.6$	$-0.6 \pm 3.7 \pm 0.6$	$4.9 \pm 3.8 \pm 0.7$
			$D^0 \to K^+K^-\mu^+\mu^-$			
< 525	32 ± 8	5 ± 13	124 ± 20	$13 \pm 26 \pm 4$	$9 \pm 26 \pm 3$	$-33 \pm 26 \pm 4$
525–565	–	–	–	–	–	–
> 565	74 ± 9	39 ± 7	48 ± 8	$1 \pm 12 \pm 1$	$22 \pm 12 \pm 1$	$13 \pm 12 \pm 1$
Full range	110 ± 13	49 ± 12	181 ± 19	$0 \pm 11 \pm 2$	$9 \pm 11 \pm 1$	$0 \pm 11 \pm 2$

Baryons



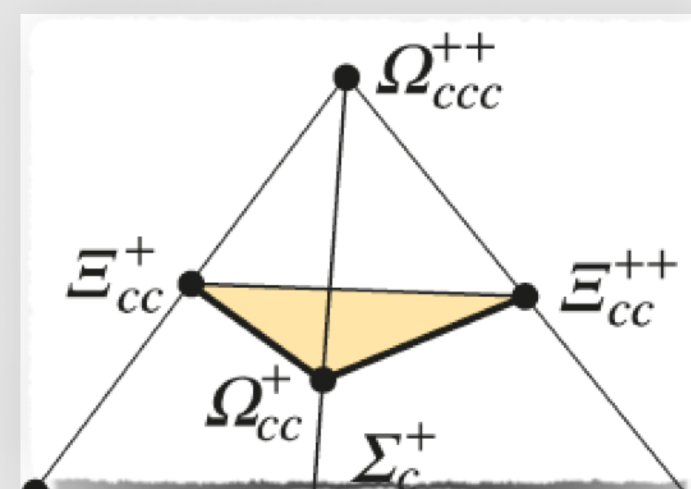
Cazzoli et al., PRL 34 (1975) 1125





- Ground state singly-charmed baryons known
  - ➡ Lifetimes between 3% and 17% uncertainties
- Picture of doubly-charmed baryons still evolving
  - ➡ Not to mention Ω_{ccc}
- What level of CP violation should we expect?

More in the next talk

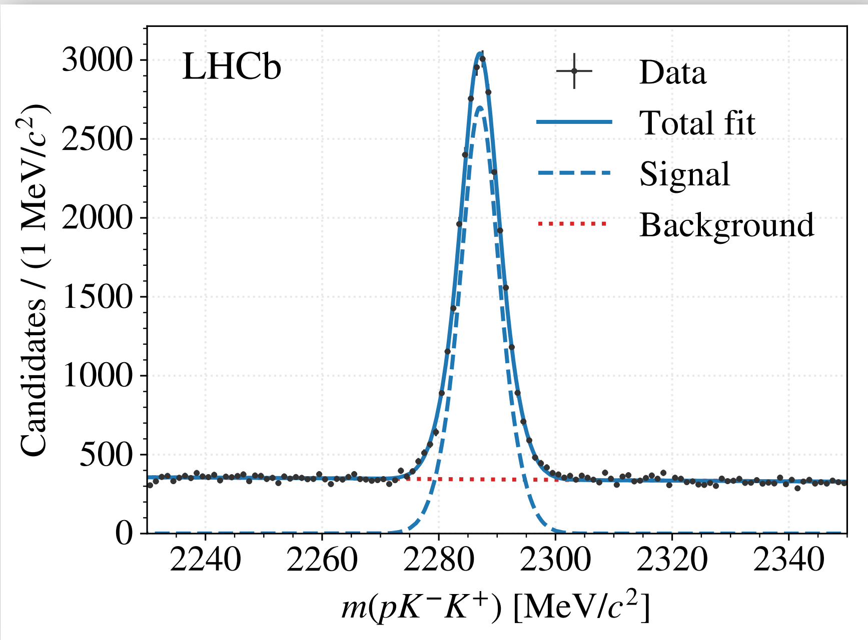


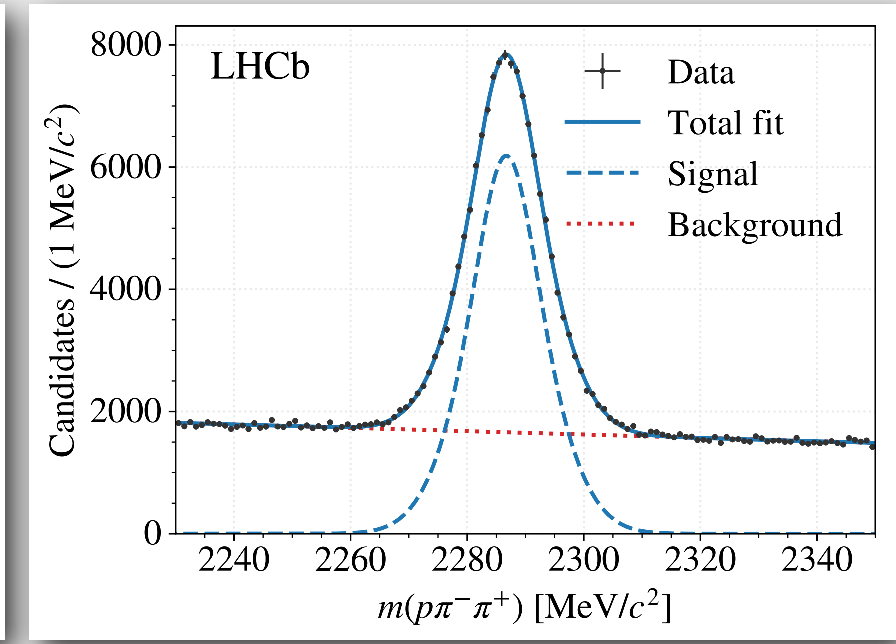
C.G.Wohl in PDG2014

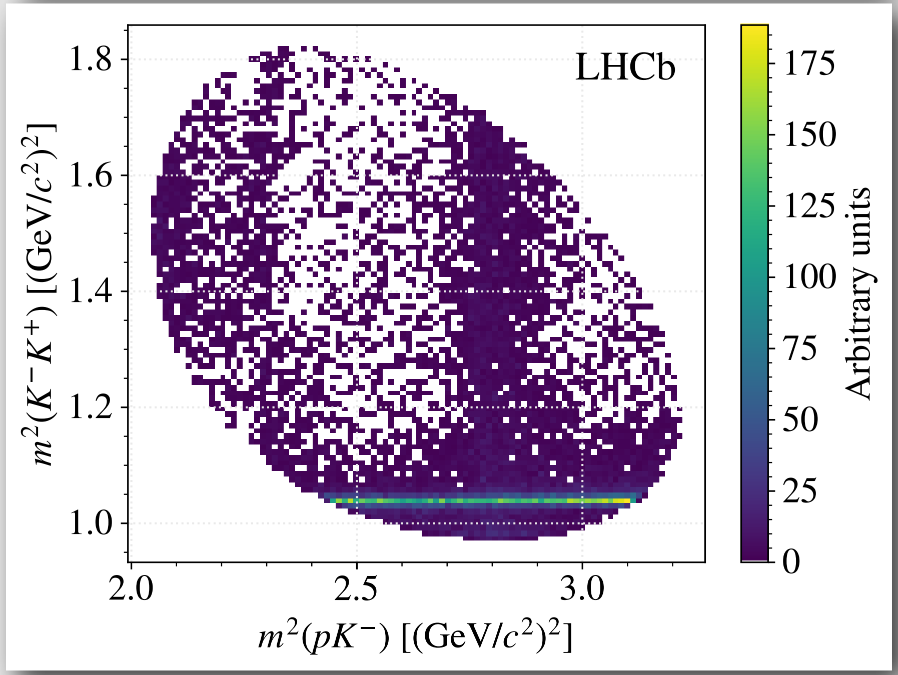
$\Lambda_c \to phh$

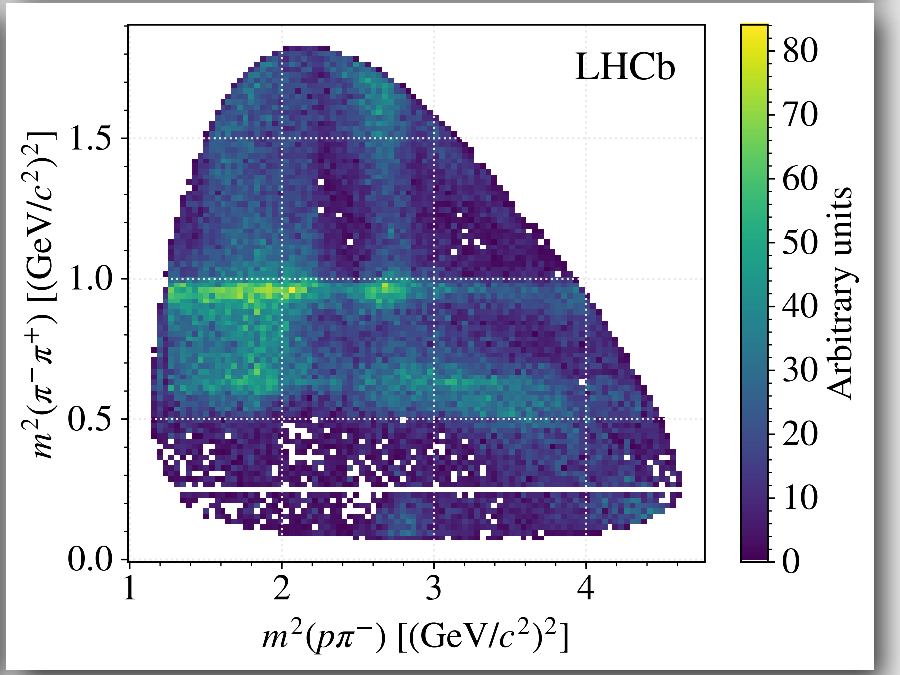
Phys. Rev. D97 (2018) 091101

- 2011+12 data ($3\ fb^{-1}$)
- Measure difference in CP asymmetries
  - ➡ Cancel systematics
  - ➡ Apply reweighting to improve cancellation



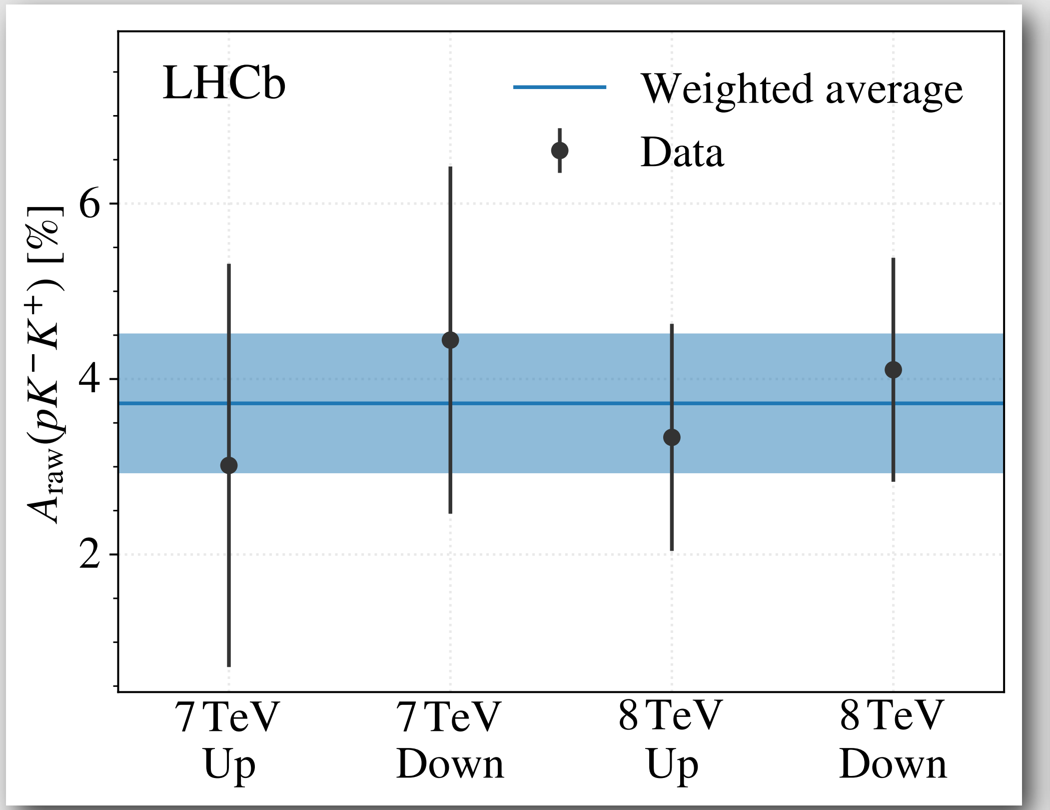


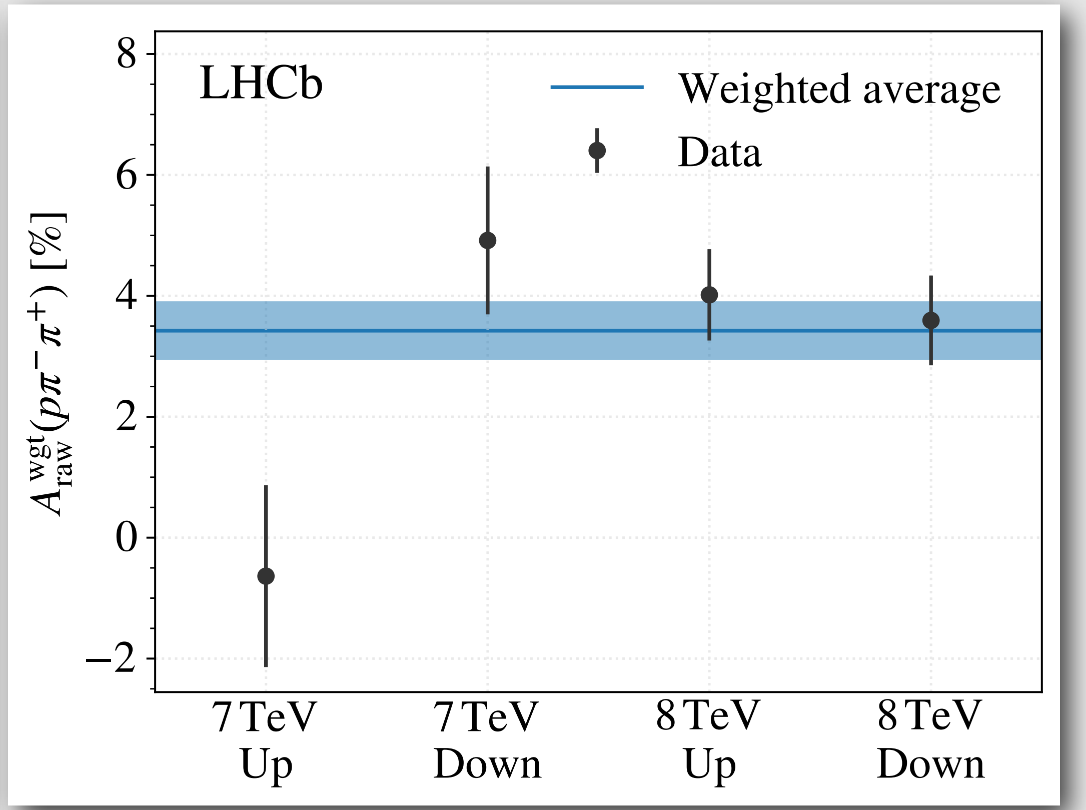


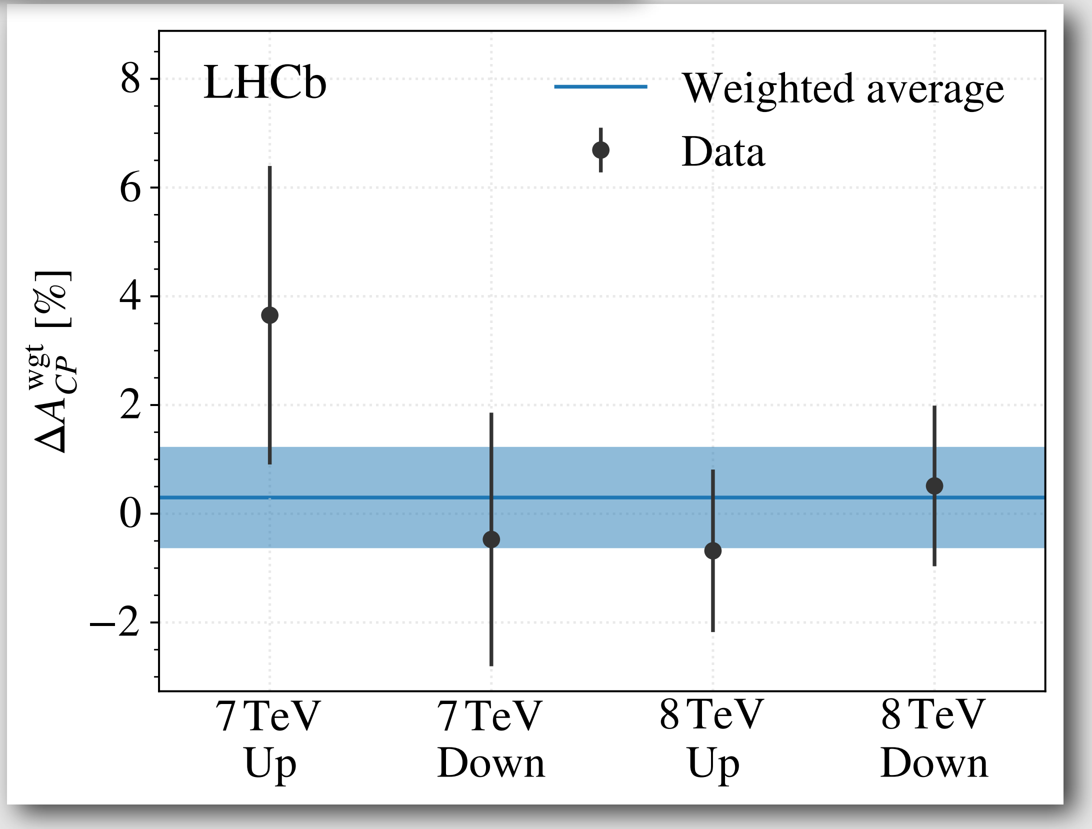


$\Lambda_c \to phh$ - II

Phys. Rev. D97 (2018) 091101







$$\Delta A_{CP}^{\rm wgt} = A_{CP}(pK^-K^+) - A_{CP}^{\rm wgt}(p\pi^-\pi^+) = (0.30 \pm 0.91 \pm 0.61)\,\%,$$

CPV in decays

- Summary so far
  - ➡ Multiple lines of attack
    - Sum rule test with $D^+ \to \pi^+\pi^0$
    - Testing large predictions with $D^0 \to K_S K_S$
    - Searching for CPV in rare four-body decays
    - First go at baryon CP violation $\Lambda_c \to phh$
  - ➡ All results in agreement with CP symmetry

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:

$|q/p| \neq 1$

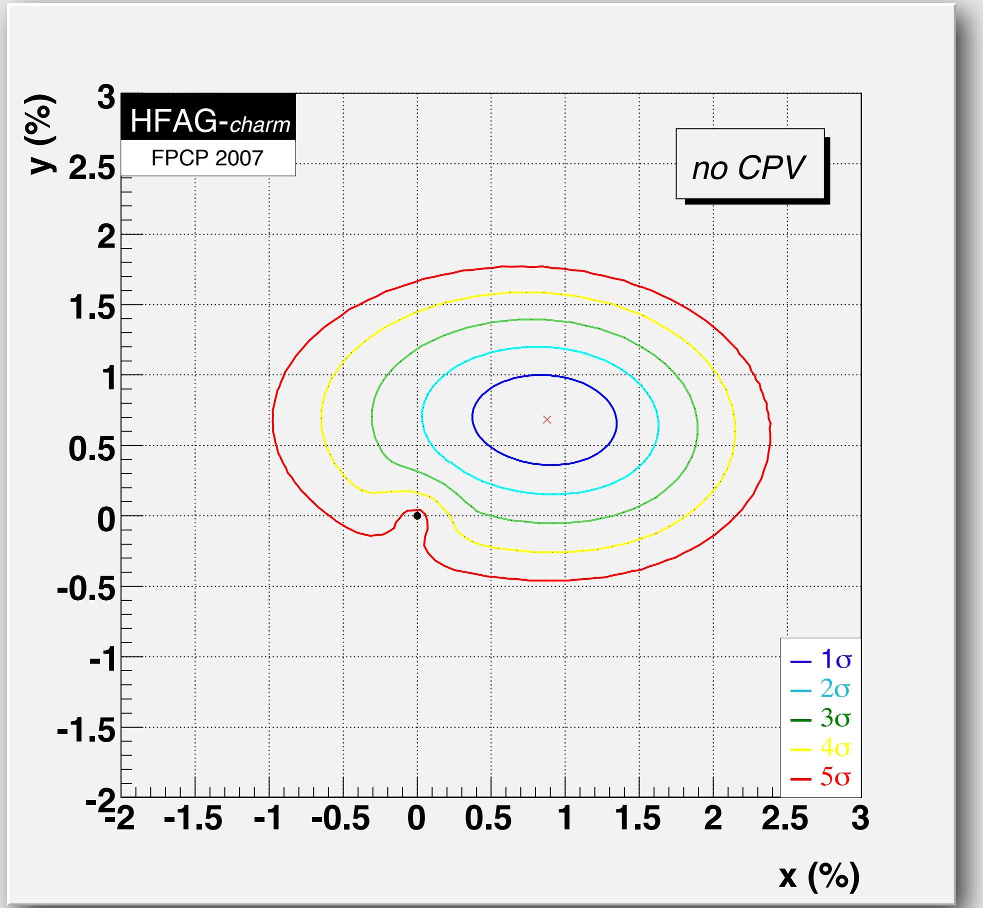
$\phi \equiv \arg(q/p) \neq 0, \pi$

Indirect CP violation:

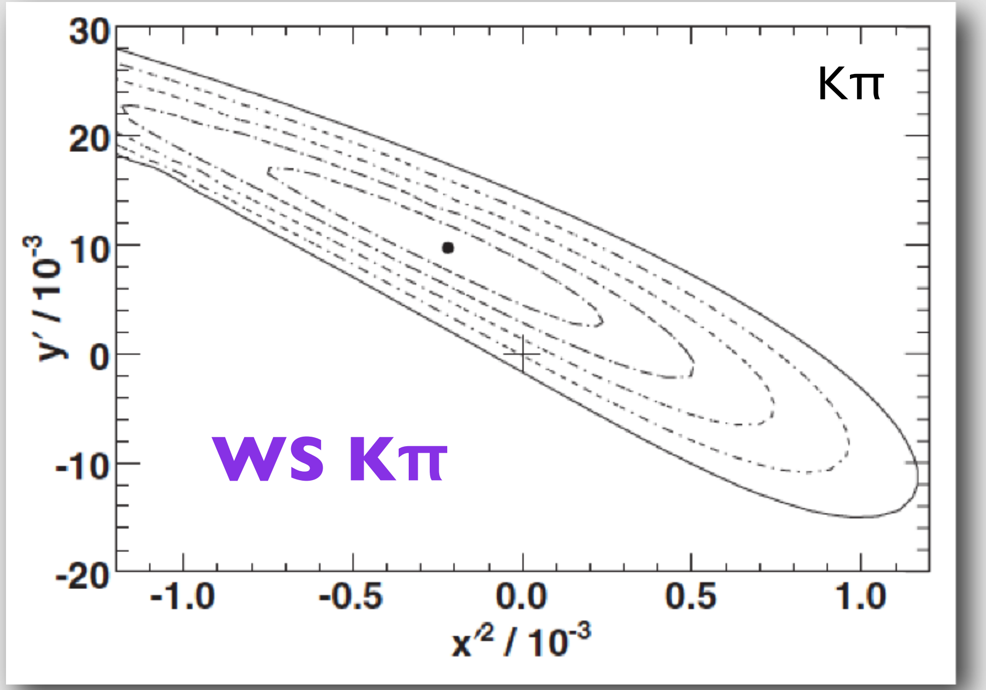
$$a_{CP}^{ind} = -a_m \, y \cos\phi - x \sin\phi$$

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

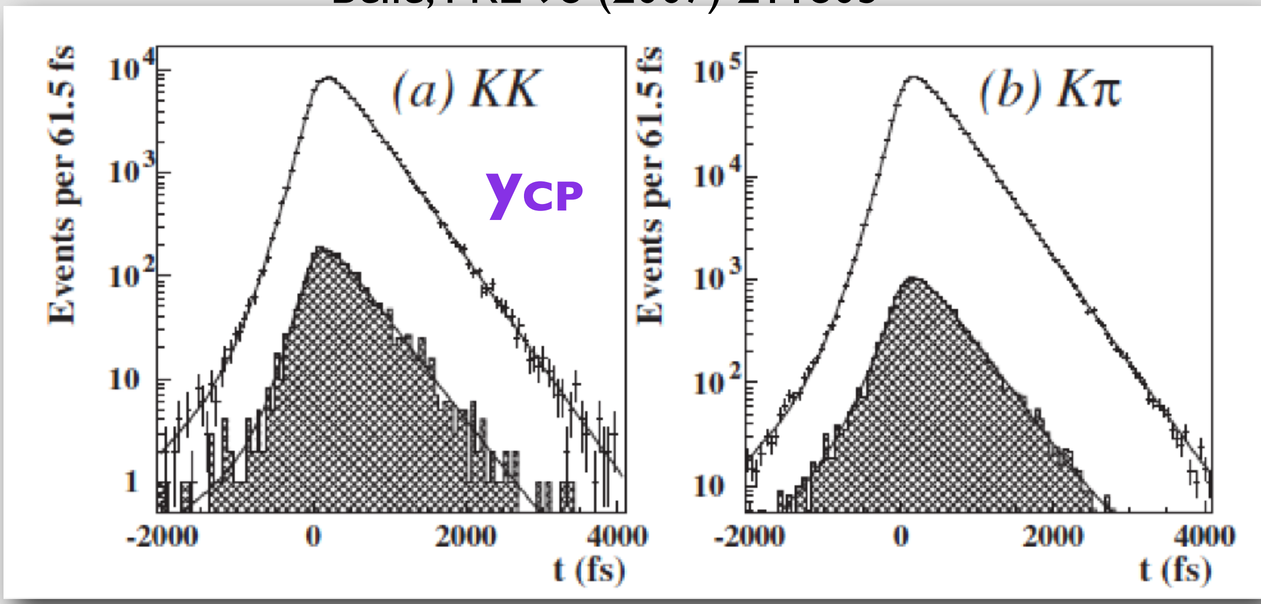
Mixing discovery



BABAR, PRL 98 (2007) 211802



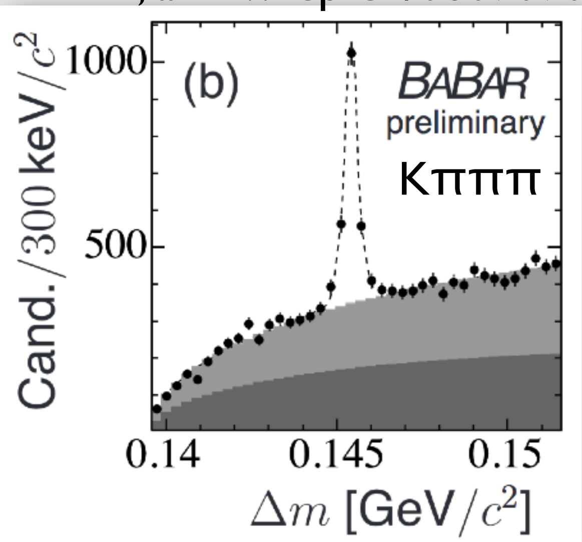
Belle, PRL 98 (2007) 211803

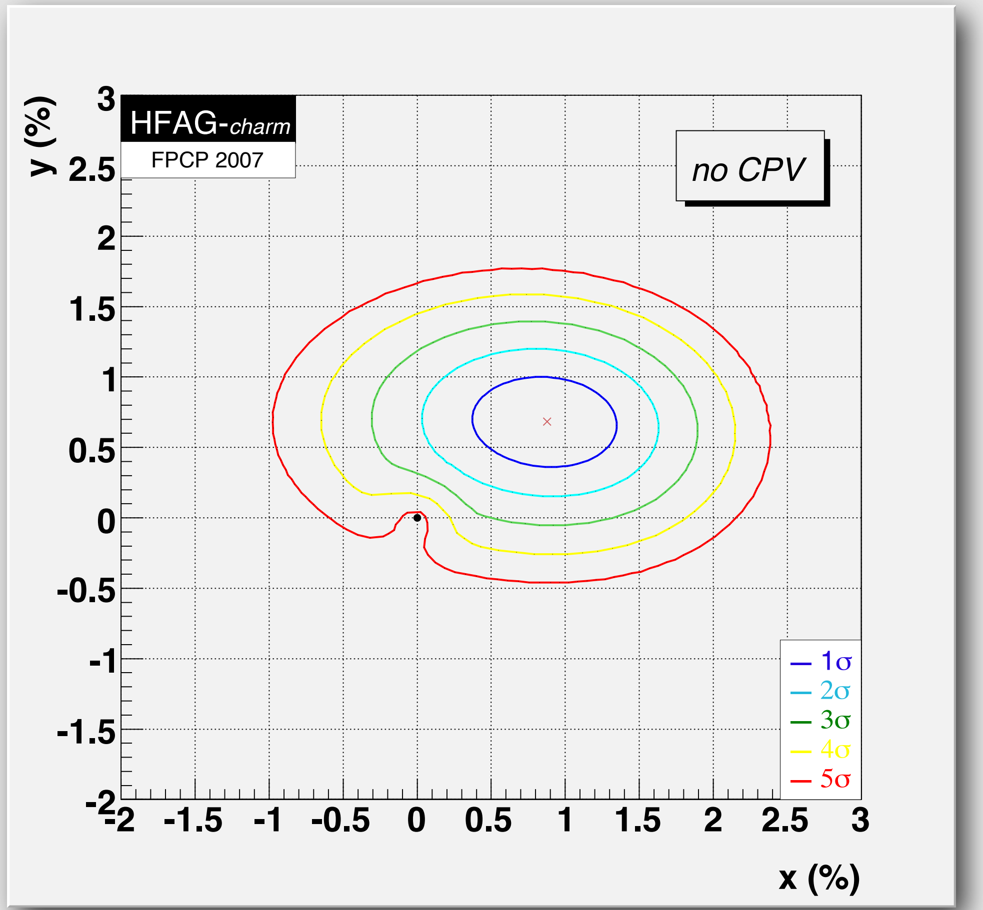


- Discovery through combination of measurements
- Mostly two-body

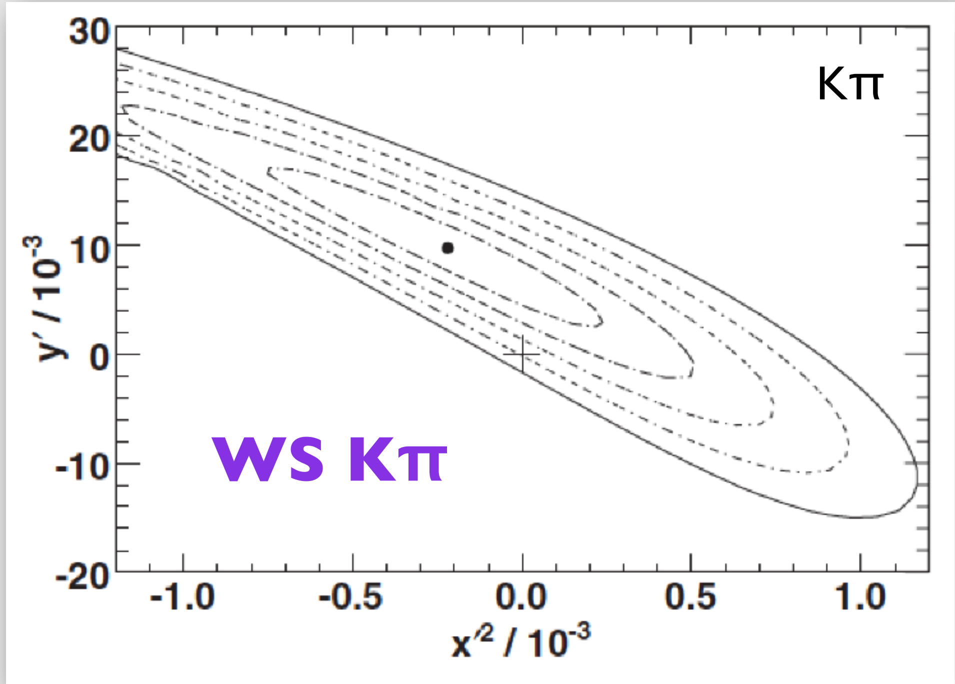
Mixing discovery

BABAR, arXiv:hep-ex/0607090

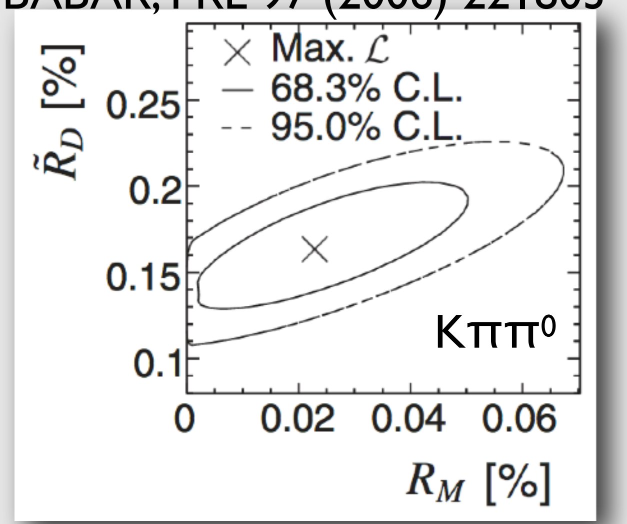




BABAR, PRL 98 (2007) 211802

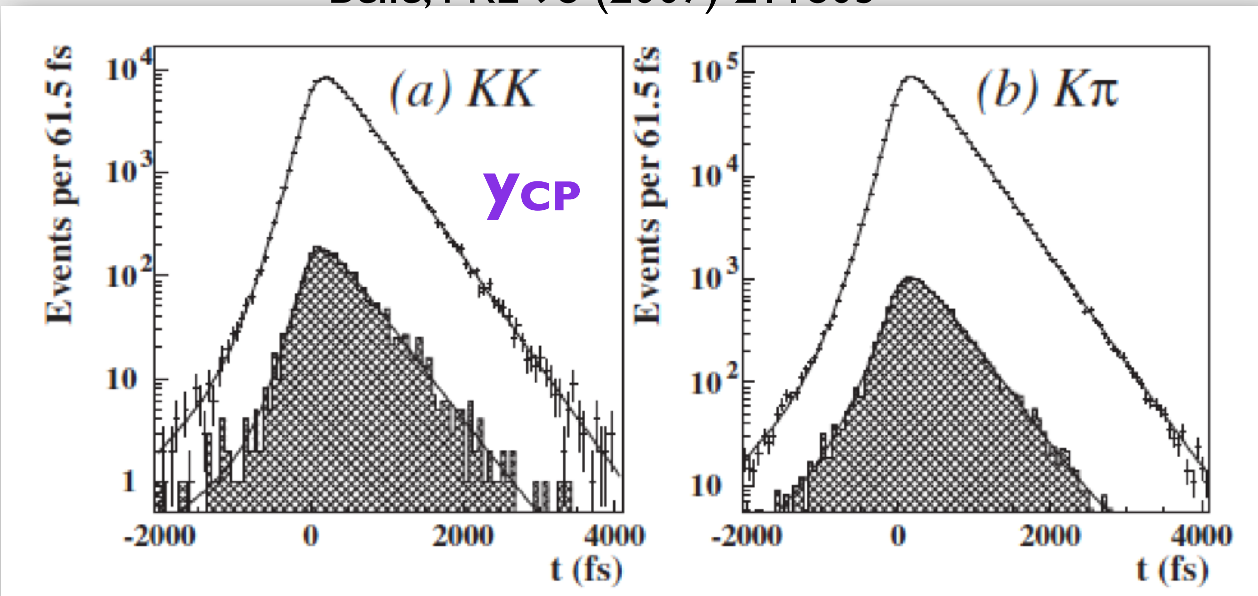


BABAR, PRL 97 (2006) 221803



- Discovery through combination of measurements
- Mostly two-body

Belle, PRL 98 (2007) 211803



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

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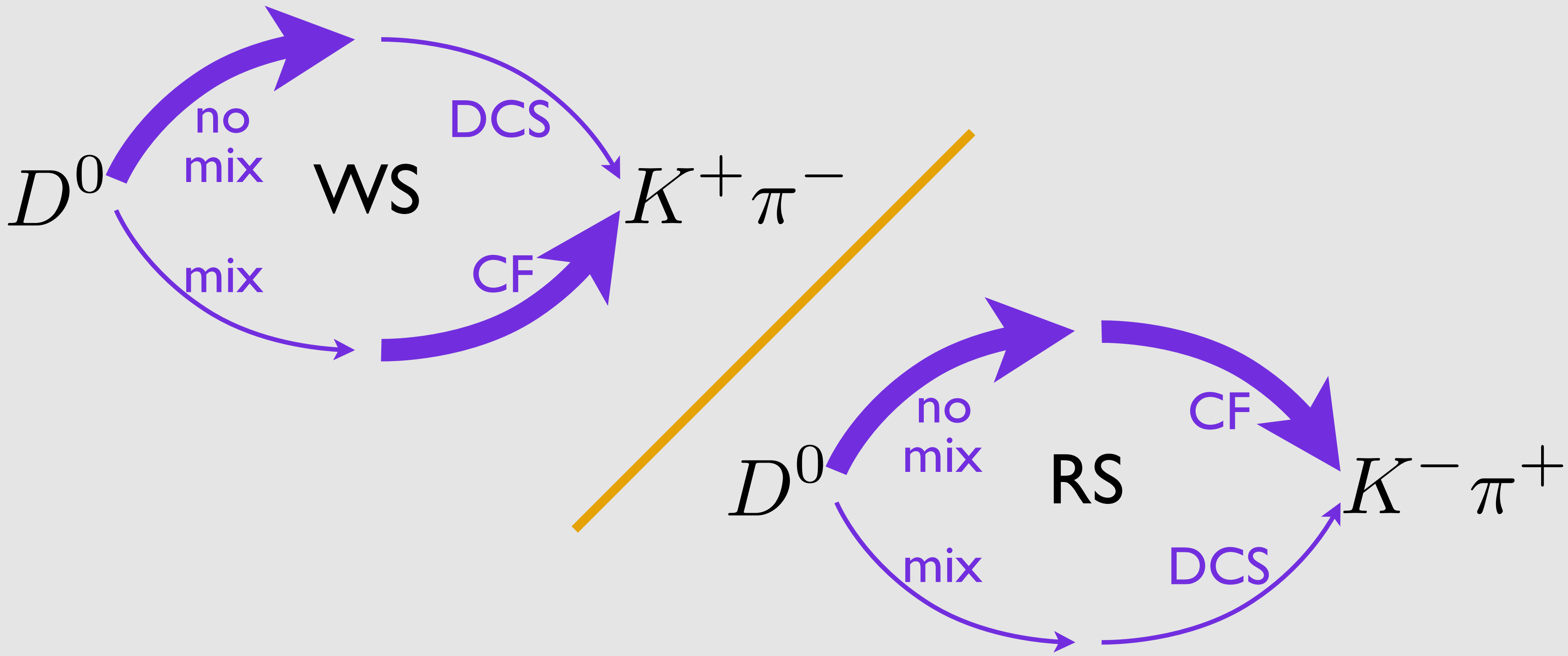
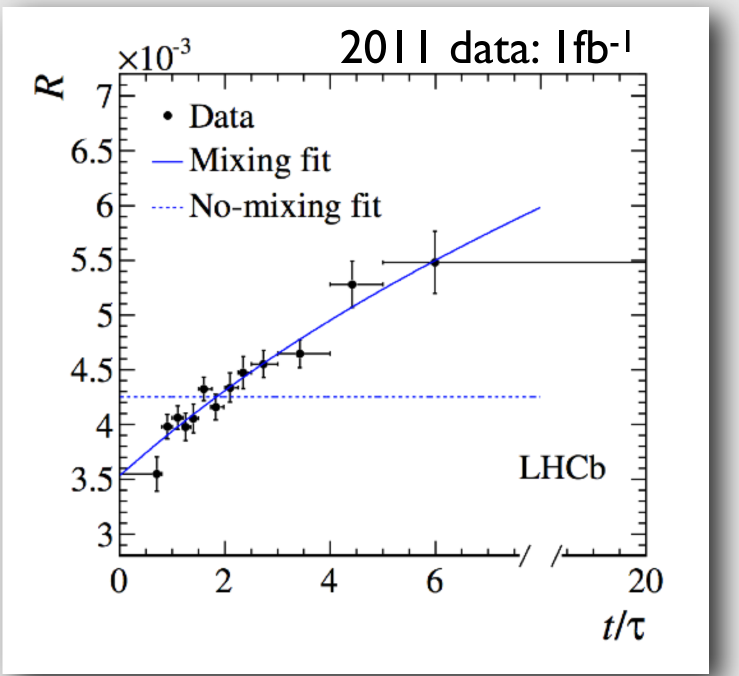


$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2+y'^2}{4}(\frac{t}{\tau})^2$$

- 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

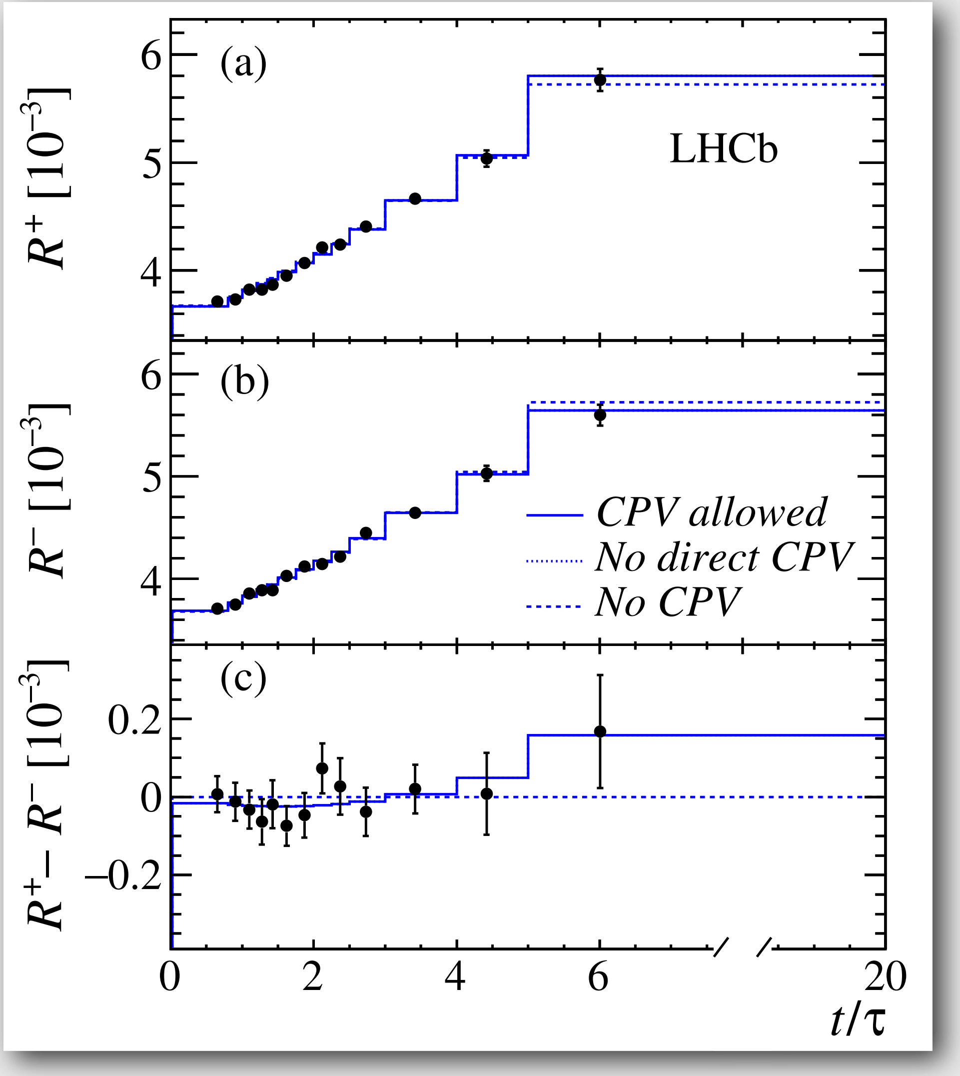


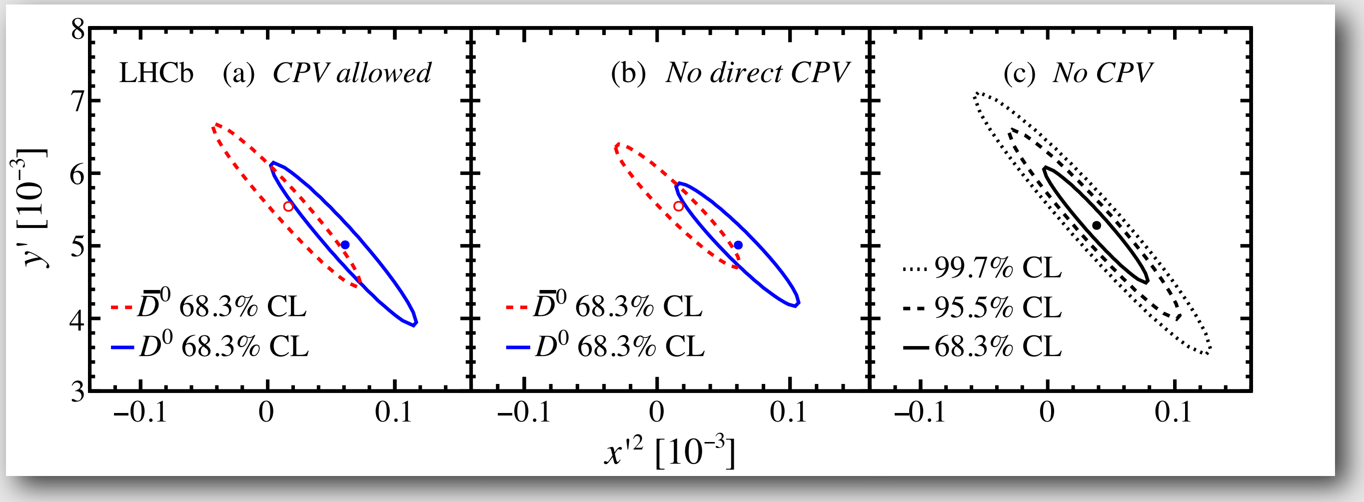
PRL 110 (2013) 101802

CPV in WS Kπ

PRD 97 (2018) 031101

- 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
- 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



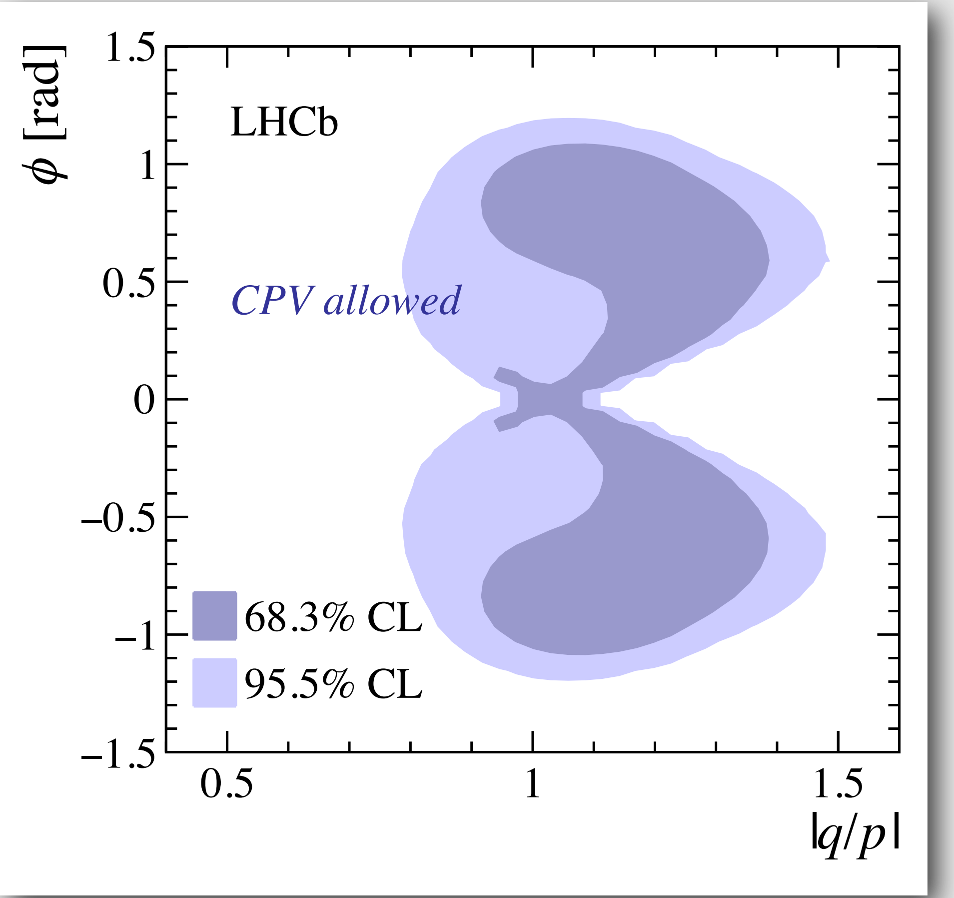


CPV in WS Kπ - II

- 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



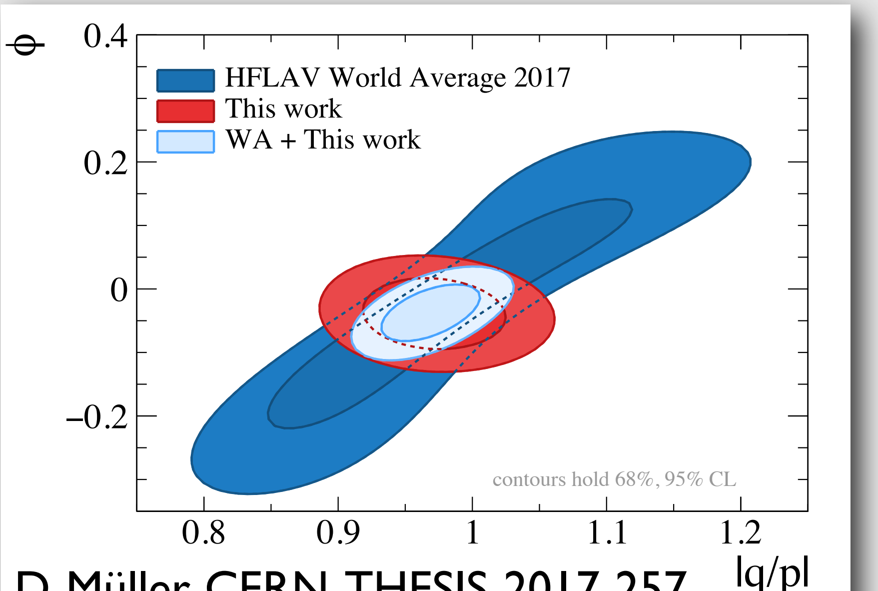
Multi-body decays

- Give access to full set of mixing and CP violation observables
  - ➡ In particular: sensitivity to x
  - ➡ Require amplitude models
    - ▸ Liaise with theory community on new techniques
  - ➡ Or quantum-correlated measurements
    - ▸ See Jim Libby's talk in this session

Realistically need both

- In last ten years time-dependent measurements almost only in $D^0 \rightarrow K_S \pi^+ \pi^-$
  - ➡ A missed opportunity?
  - ➡ Recent work by BABAR on $D^0 \rightarrow \pi^+ \pi^- \pi^0$
  - ➡ Surely something for Belle II
  - ➡ Very promising studies at LHCb

Potential of $D^0 \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$ at LHCb



D. Müller, CERN-THESIS-2017-257

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

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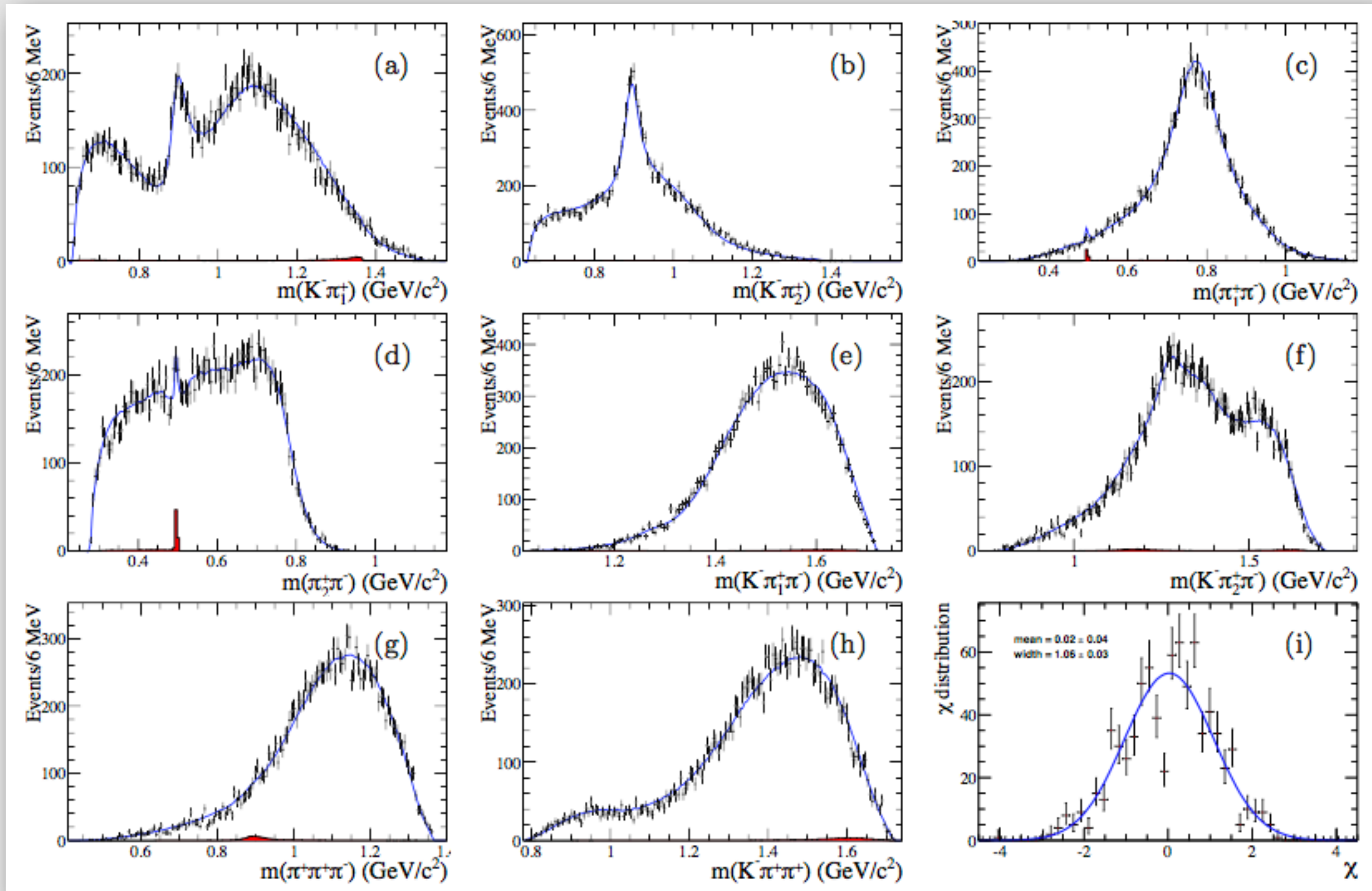

PRD 95 (2017) 072010

Amplitude	ϕ_i	Fit fraction (%)
$D^0[S] \to \bar{K}^*\rho^0$	$2.35 \pm 0.06 \pm 0.18$	$6.5 \pm 0.5 \pm 0.8$
$D^0[P] \to \bar{K}^*\rho^0$	$-2.25 \pm 0.08 \pm 0.15$	$2.3 \pm 0.2 \pm 0.1$
$D^0[D] \to \bar{K}^*\rho^0$	$2.49 \pm 0.06 \pm 0.11$	$7.9 \pm 0.4 \pm 0.7$
$D^0 \to K^- a_1^+(1260),\ a_1^+(1260)[S] \to \rho^0\pi^+$	0(fixed)	$53.2 \pm 2.8 \pm 4.0$
$D^0 \to K^- a_1^+(1260),\ a_1^+(1260)[D] \to \rho^0\pi^+$	$-2.11 \pm 0.15 \pm 0.21$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[S] \to \bar{K}^{*0}\pi^-$	$1.48 \pm 0.21 \pm 0.24$	$0.1 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[D] \to \bar{K}^{*0}\pi^-$	$3.00 \pm 0.09 \pm 0.15$	$0.7 \pm 0.2 \pm 0.2$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270) \to K^-\rho^0$	$-2.46 \pm 0.06 \pm 0.21$	$3.4 \pm 0.3 \pm 0.5$
$D^0 \to (\rho^0 K^-)_A\pi^+,\ (\rho^0 K^-)_A[D] \to K^-\rho^0$	$-0.43 \pm 0.09 \pm 0.12$	$1.1 \pm 0.2 \pm 0.3$
$D^0 \to (K^-\rho^0)_P\pi^+$	$-0.14 \pm 0.11 \pm 0.10$	$7.4 \pm 1.6 \pm 5.7$
$D^0 \to (K^-\pi^+)_{S-wave}\rho^0$	$-2.45 \pm 0.19 \pm 0.47$	$2.0 \pm 0.7 \pm 1.9$
$D^0 \to (K^-\rho^0)_V\pi^+$	$-1.34 \pm 0.12 \pm 0.09$	$0.4 \pm 0.1 \pm 0.1$
$D^0 \to (\bar{K}^{*0}\pi^-)_P\pi^+$	$-2.09 \pm 0.12 \pm 0.22$	$2.4 \pm 0.5 \pm 0.5$
$D^0 \to \bar{K}^{*0}(\pi^+\pi^-)_S$	$-0.17 \pm 0.11 \pm 0.12$	$2.6 \pm 0.6 \pm 0.6$
$D^0 \to (\bar{K}^{*0}\pi^-)_V\pi^+$	$-2.13 \pm 0.10 \pm 0.11$	$0.8 \pm 0.1 \pm 0.1$
$D^0 \to ((K^-\pi^+)_{S-wave}\pi^-)_A\pi^+$	$-1.36 \pm 0.08 \pm 0.37$	$5.6 \pm 0.9 \pm 2.7$
$D^0 \to K^-((\pi^+\pi^-)_S\pi^+)_A$	$-2.23 \pm 0.08 \pm 0.22$	$13.1 \pm 1.9 \pm 2.2$
$D^0 \to (K^-\pi^+)_{S-wave}(\pi^+\pi^-)_S$	$-1.40 \pm 0.04 \pm 0.22$	$16.3 \pm 0.5 \pm 0.6$
$D^0[S] \to (K^-\pi^+)_V(\pi^+\pi^-)_V$	$1.59 \pm 0.13 \pm 0.41$	$5.4 \pm 1.2 \pm 1.9$
$D^0 \to (K^-\pi^+)_{S-wave}(\pi^+\pi^-)_V$	$-0.16 \pm 0.17 \pm 0.43$	$1.9 \pm 0.6 \pm 1.2$
$D^0 \to (K^-\pi^+)_V(\pi^+\pi^-)_S$	$2.58 \pm 0.08 \pm 0.25$	$2.9 \pm 0.5 \pm 1.7$
$D^0 \to (K^-\pi^+)_T(\pi^+\pi^-)_S$	$-2.92 \pm 0.14 \pm 0.12$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to (K^-\pi^+)_{S-wave}(\pi^+\pi^-)_T$	$2.45 \pm 0.12 \pm 0.37$	$0.5 \pm 0.1 \pm 0.1$

- Based on 16000 RS candidates (99.4% purity)
  - ➡ Double-tagged sample via $\bar{D}^0 \to K\pi$ decays
- First study of this decay in this millennium
- Paving the way for time-dependent amplitude analysis

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

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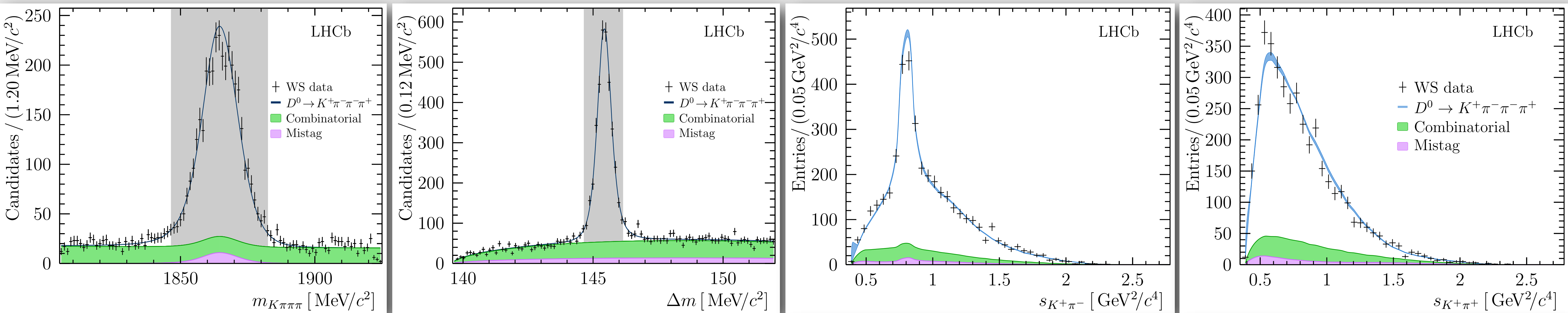
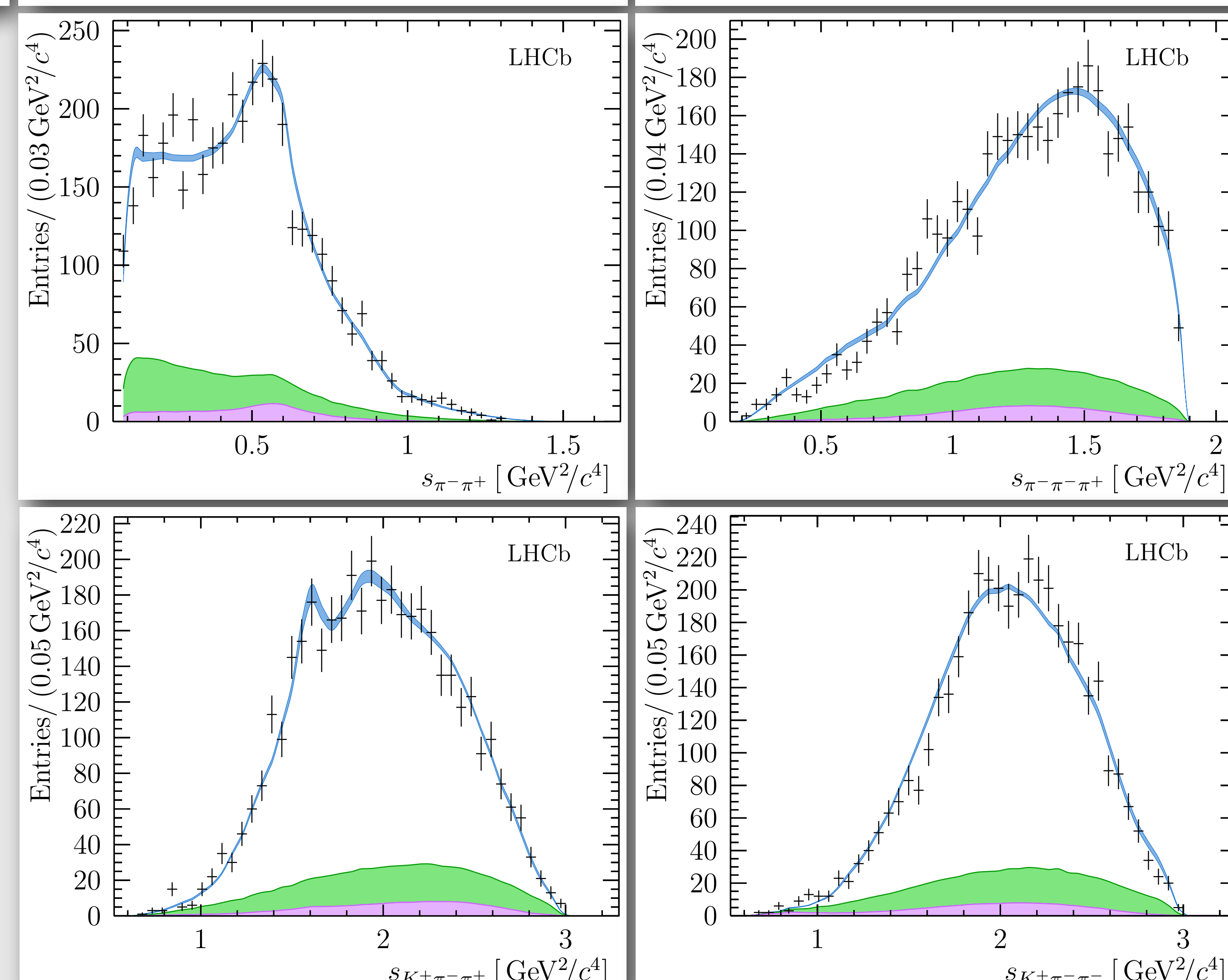
EPJ C78 (2018) 443



- 2011+12 data (3 fb^{-1})
- Based on 2500 WS events (82.4% purity)
  - ➡ Suppressed by factor of ~300
  - ➡ Input to time-dependent analysis
- Also measured RS model with ~900k events (99.6% purity)
  - ➡ Broadly similar but some disagreement on NR contribution

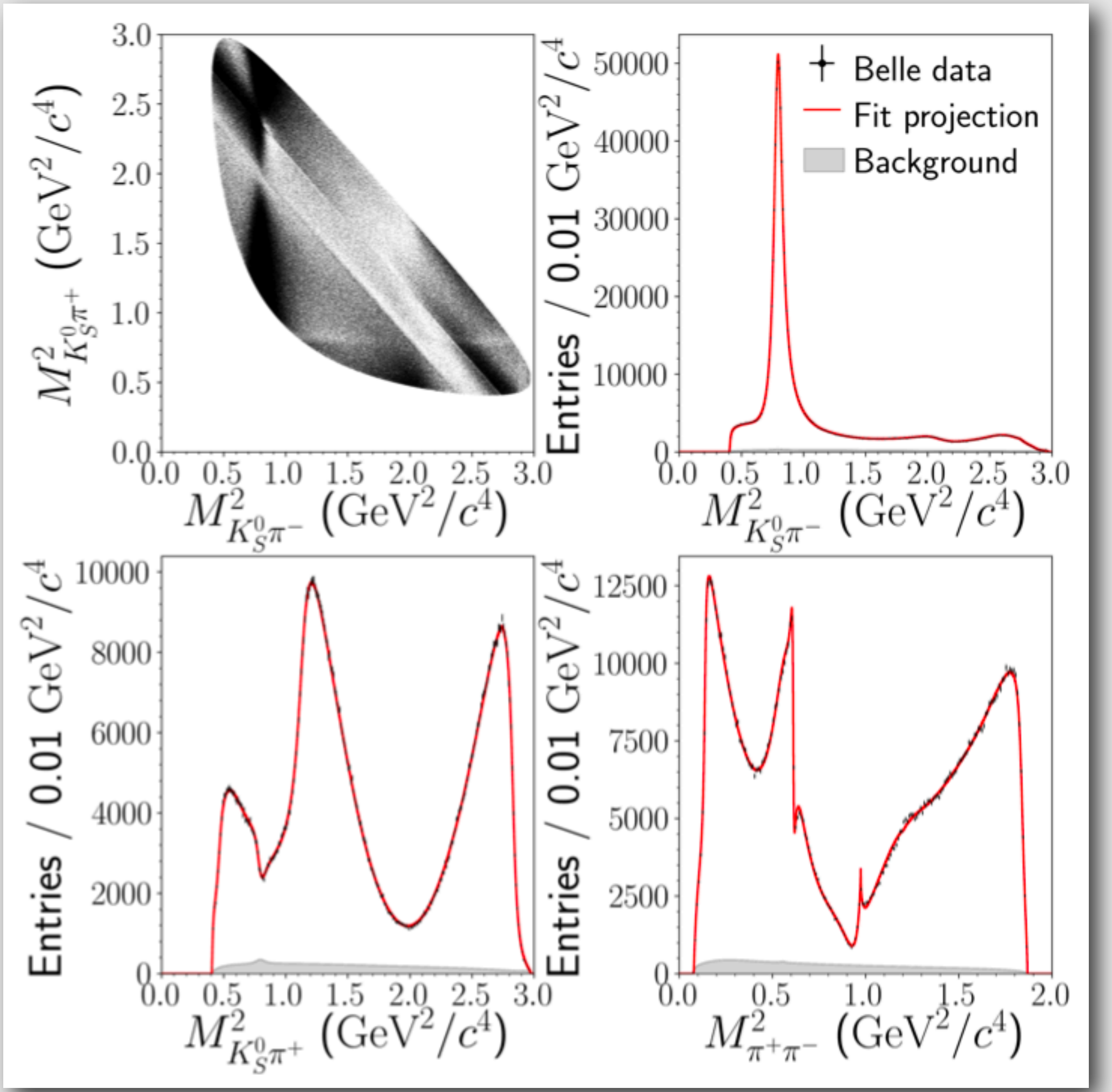


The golden mode

arXiv:1804.06152
arXiv:1804.06153

- Joint BaBar and Belle amplitude analysis of $D^0 \rightarrow K_S \pi\pi$
- 1.2M candidates
- Prime candidate to perform time-dependent analysis to measure x

➡ Feasible both for Belle II and LHCb



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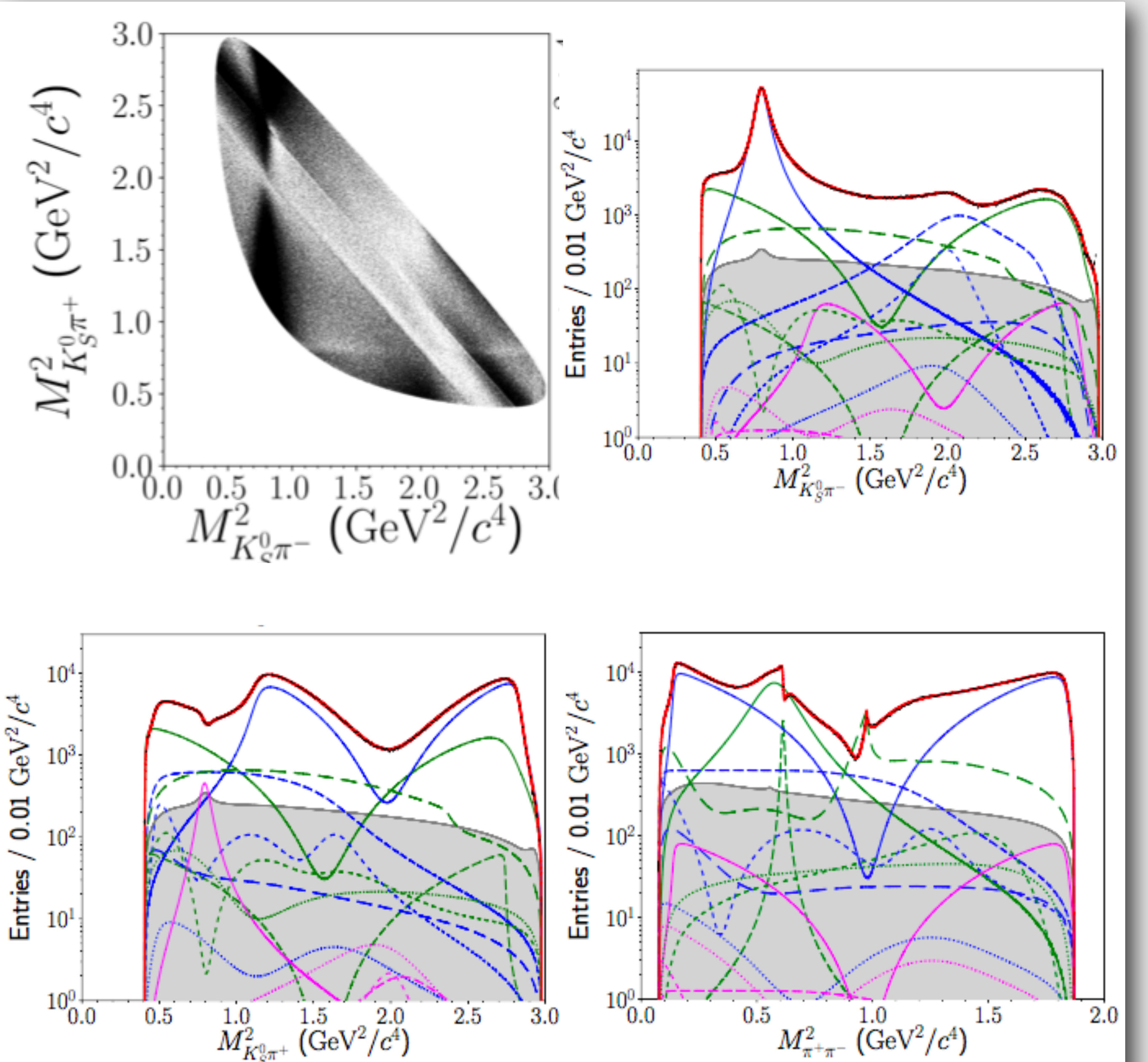
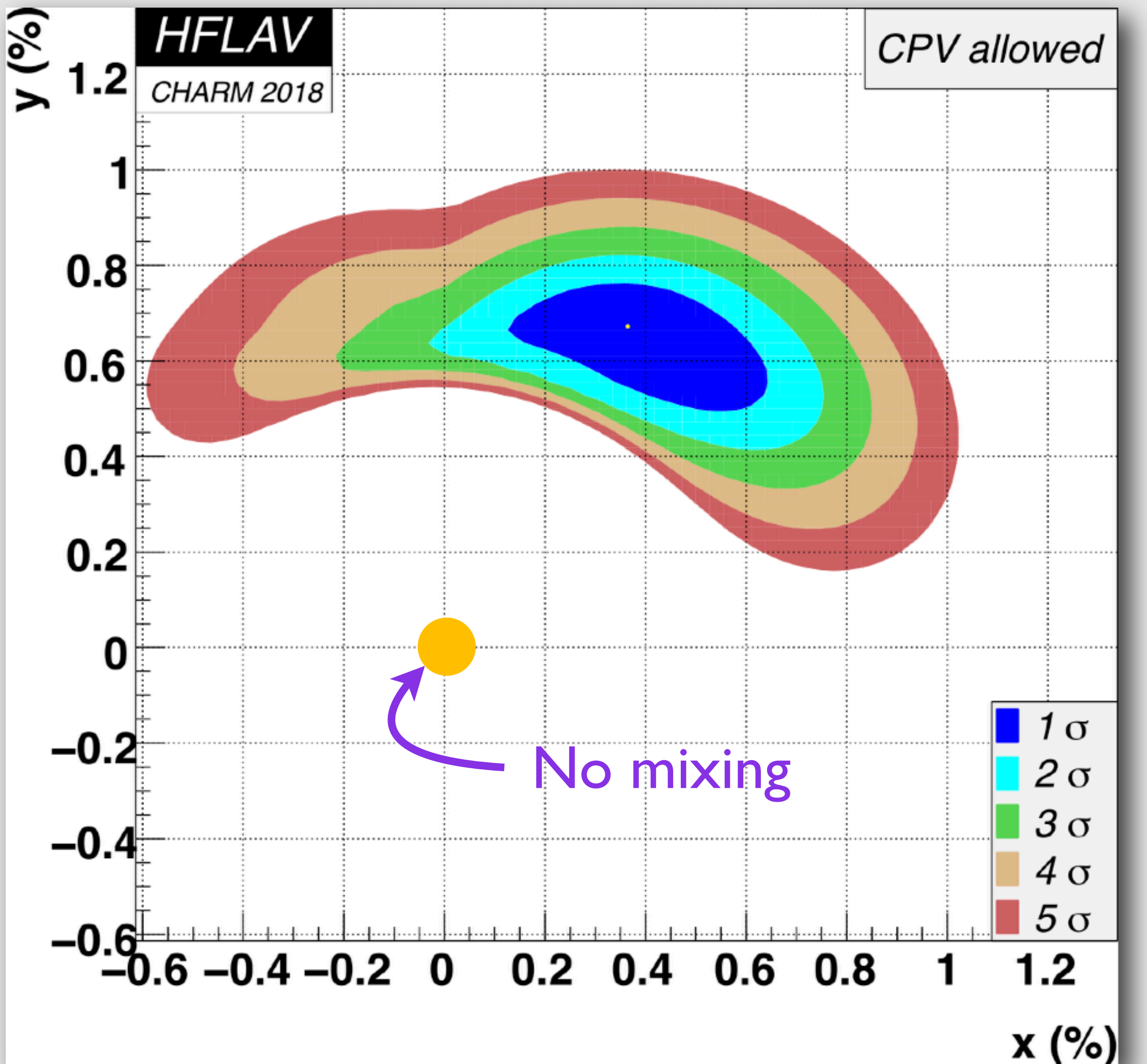


Individual fit contributions

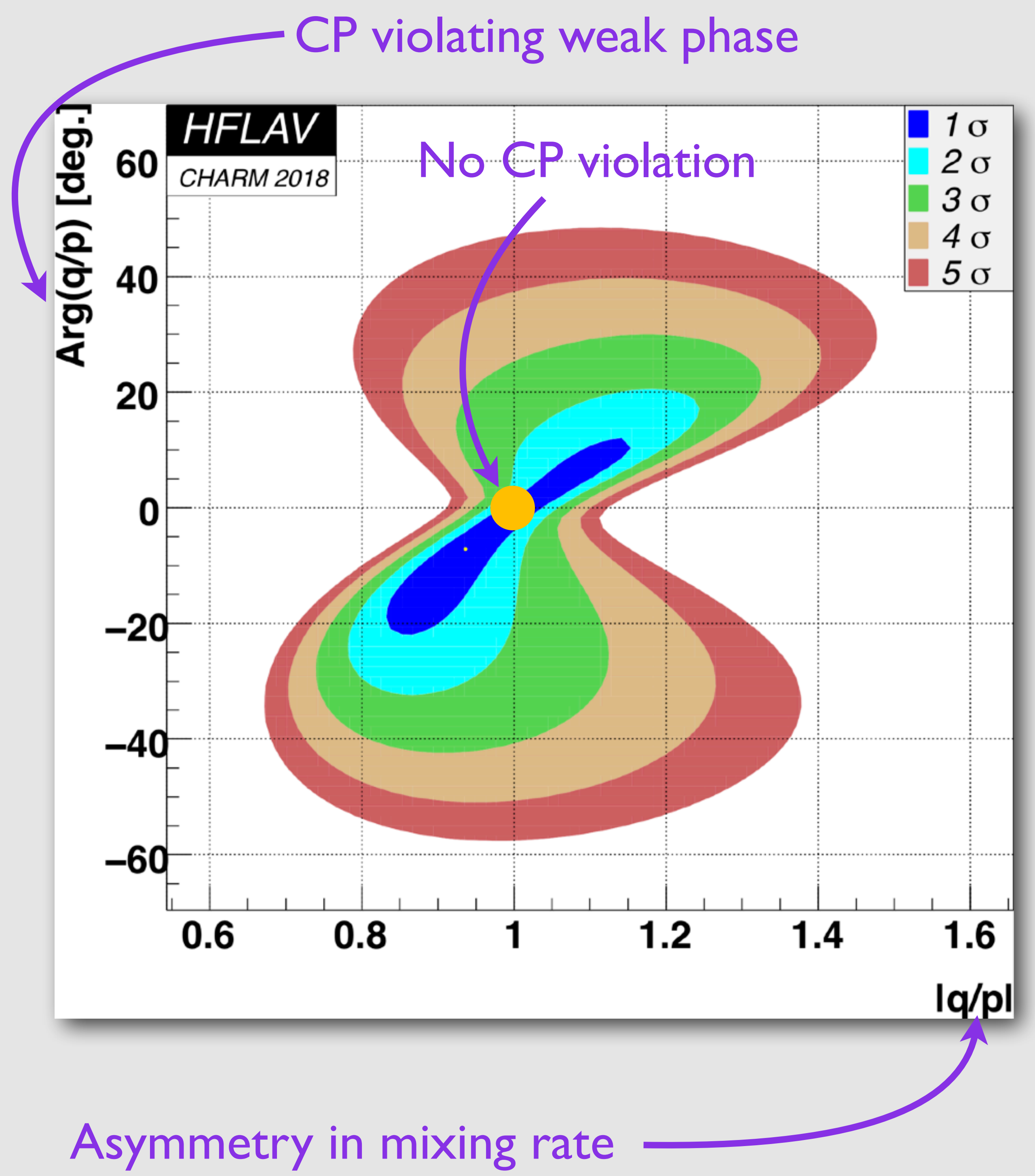
Mixing nowadays



- Mixing established
  - ➡ $x \neq 0$ still open question

CP violation overview

- No sign of CP violation
  …yet



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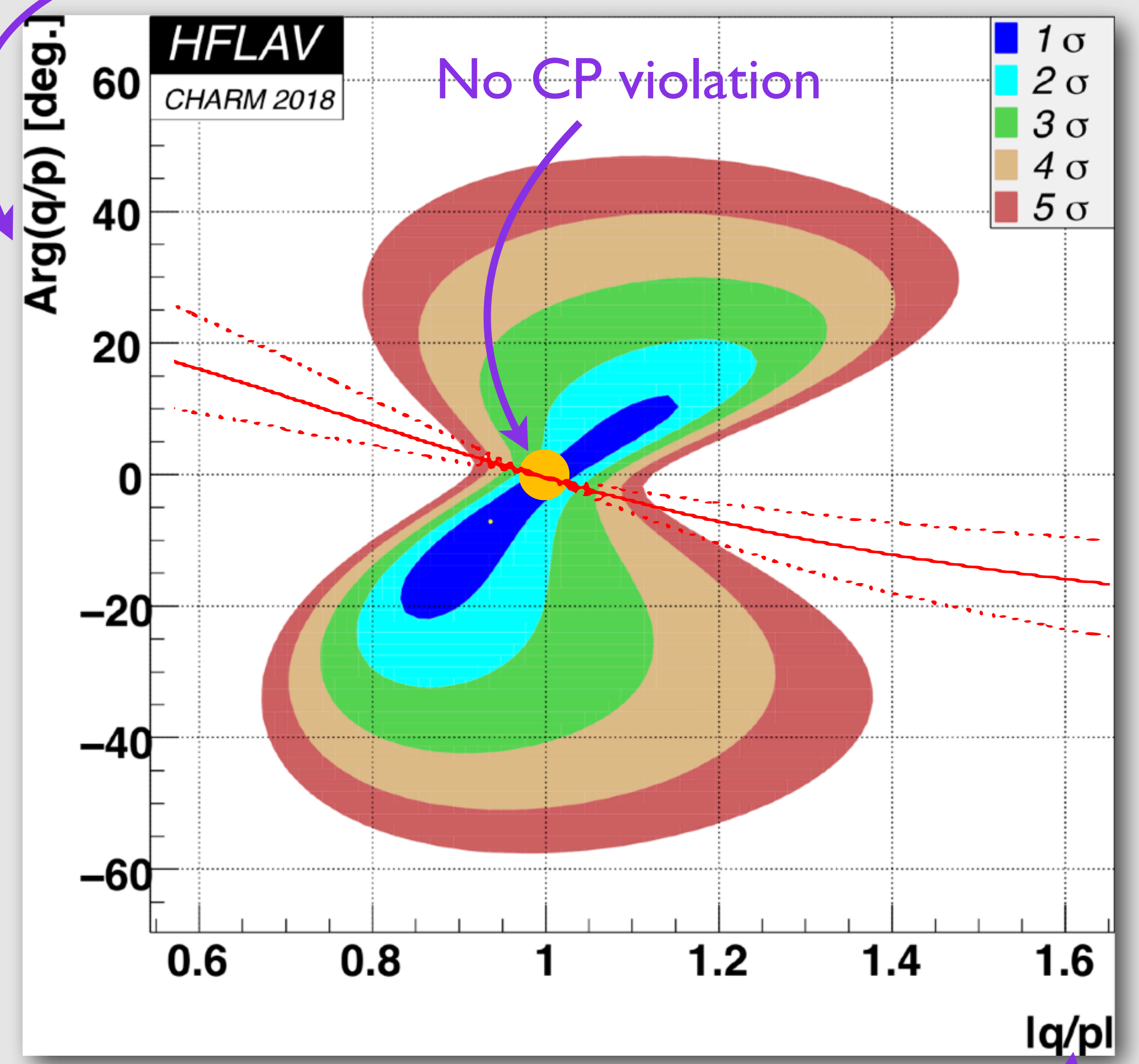
Can we do better?

- 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}, Φ_{12}
- Current sensitivity already very good
  - ➡ $\sigma(\Phi_{12}) = 1.7°$

CP violating weak phase



Asymmetry in mixing rate

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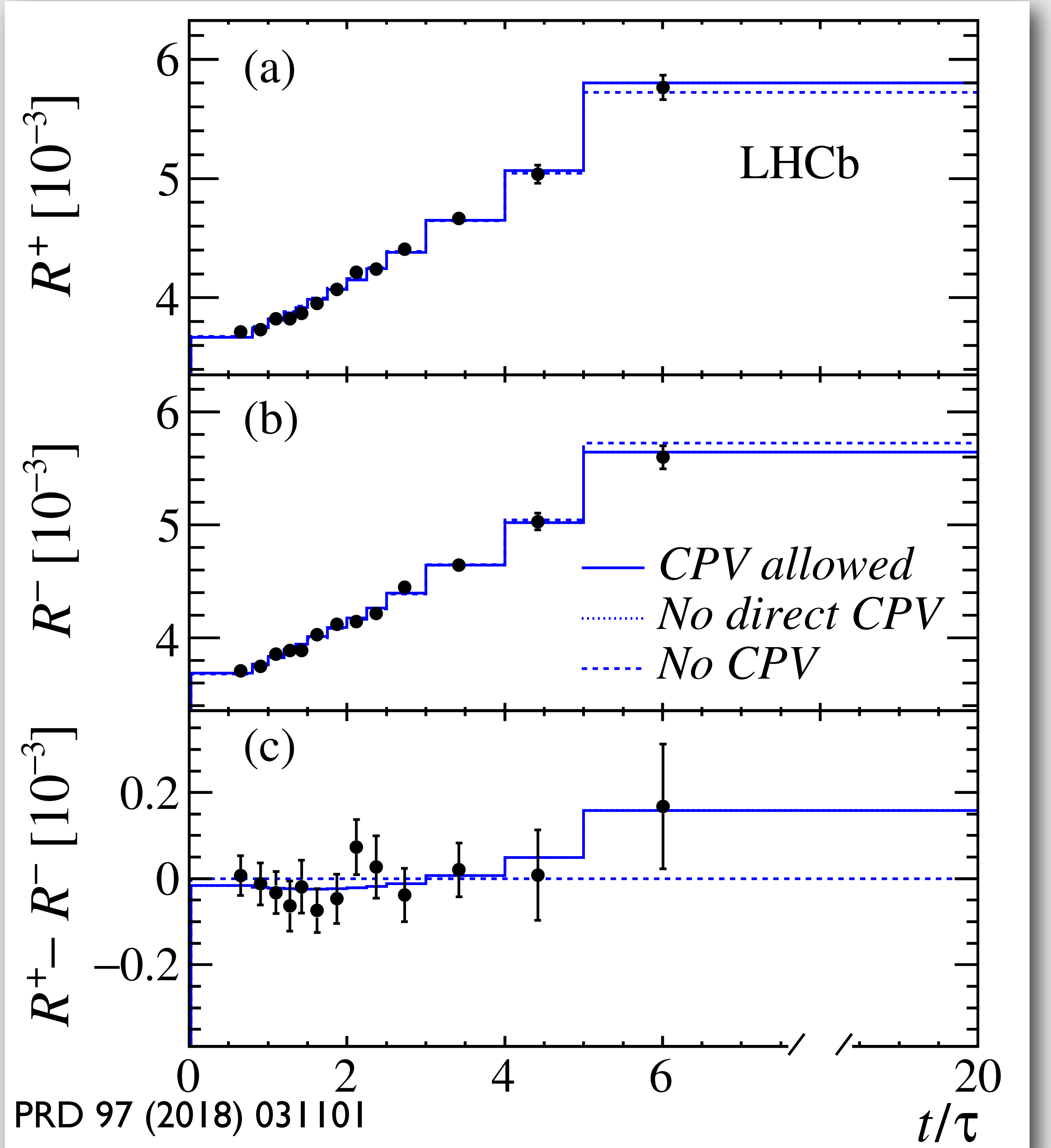

PRD 97 (2018) 031101

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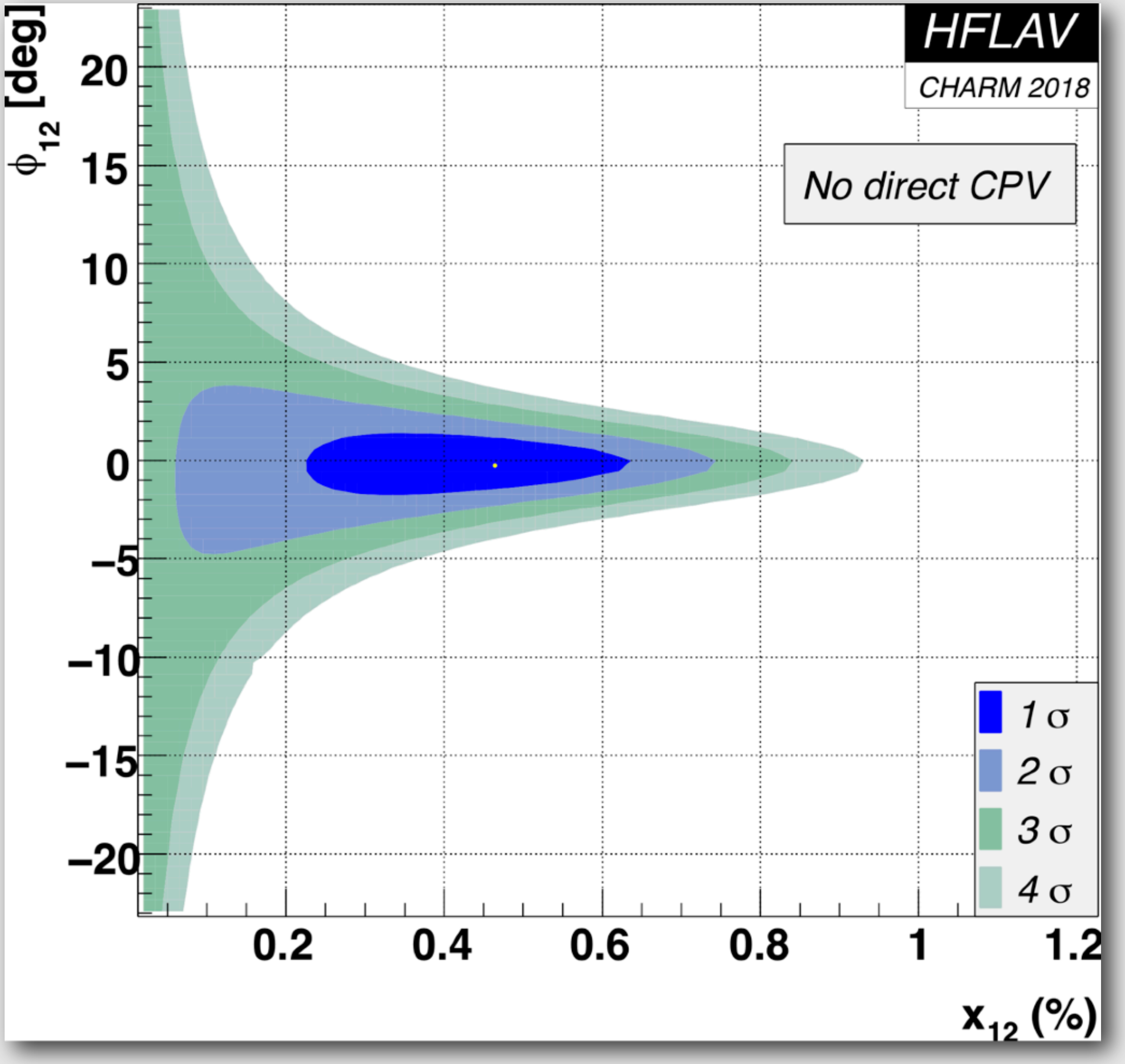

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Future directions

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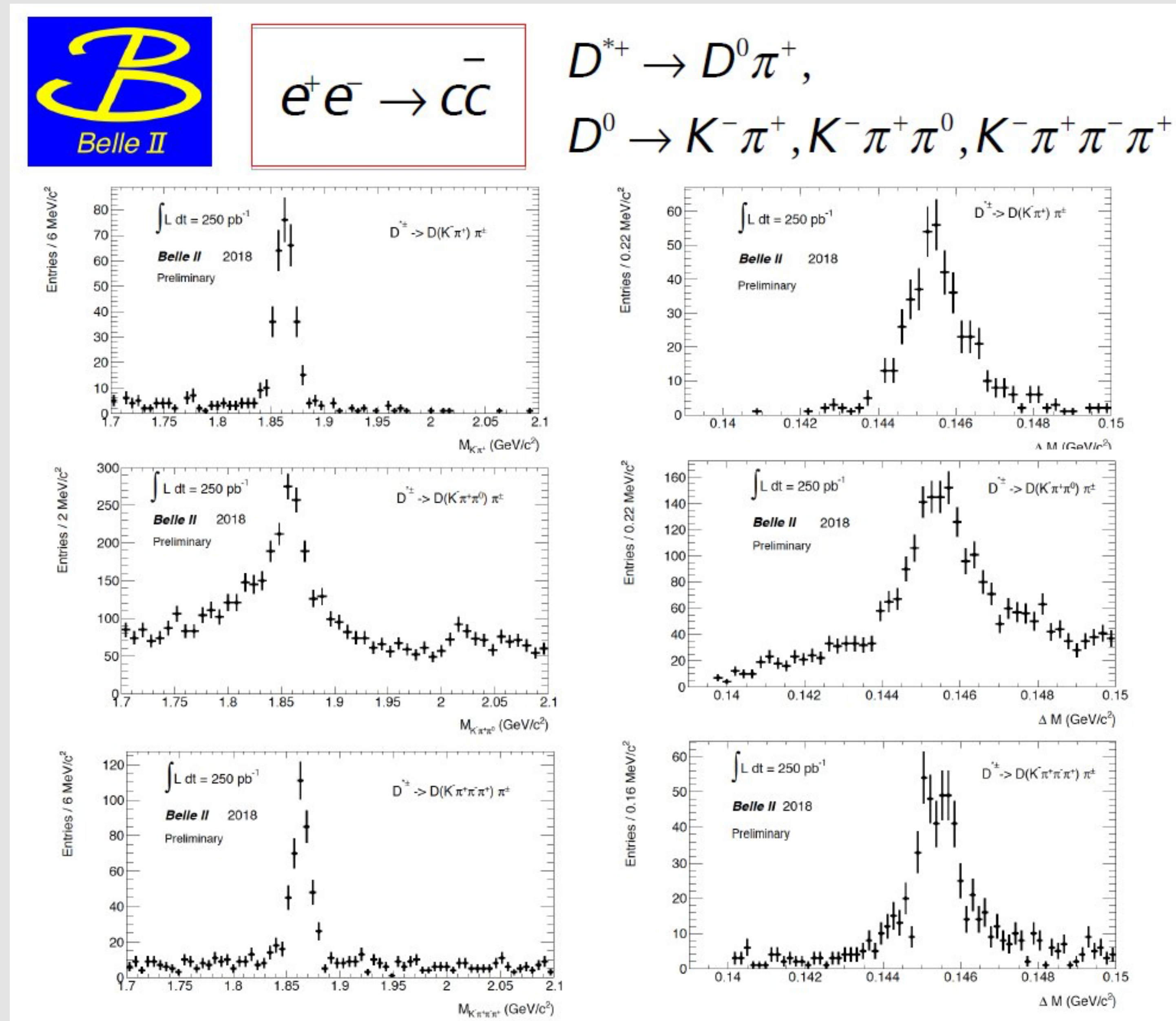
Challenges

- 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

Belle II

See talk by T. Browder

- First charm signals seen at Belle II
- LHCb sensitivity on charged two-body decays not in reach
- Can exploit strengths with neutral final-state particles
- Multi-body decays may benefit from lower backgrounds



https://twitter.com/belle2collab/status/1013652963099721729

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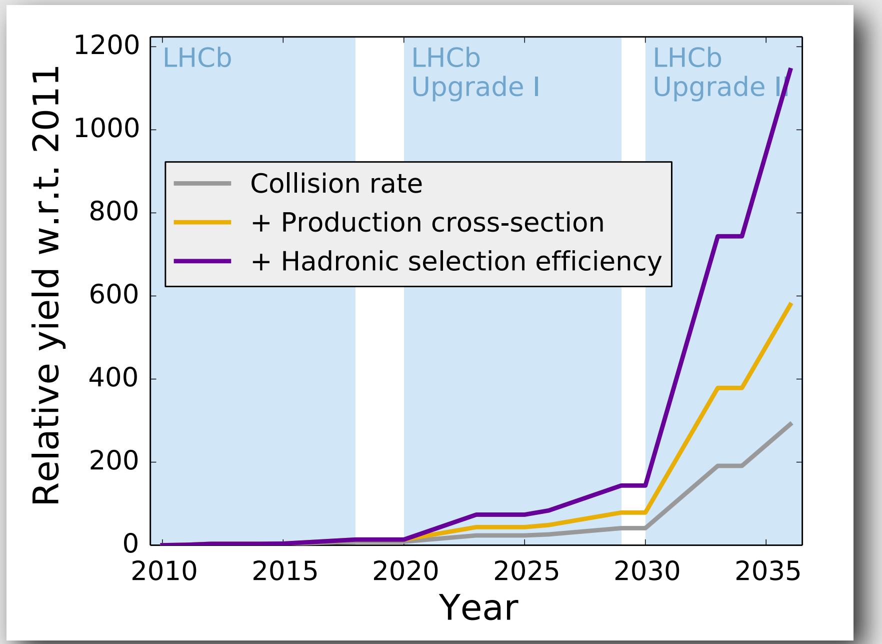
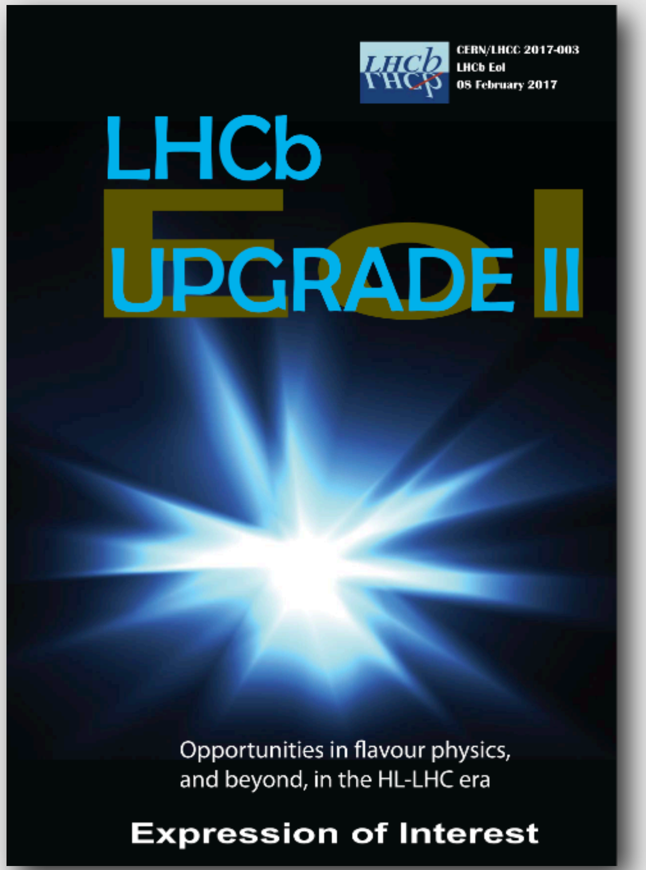
LHCb Upgrades

See talk by T. Szumlak

- LHCb Upgrade I in construction
- Will collect very high-rate real-time calibrated data
  - ➡ Huge potential for charm
- Need to dig a lot deeper to reach SM-level precision
  - ➡ LHCb Upgrade II
- LHCb is the best bet for charm for the foreseeable future
  - ➡ Best shot at BSM physics in the up-quark sector





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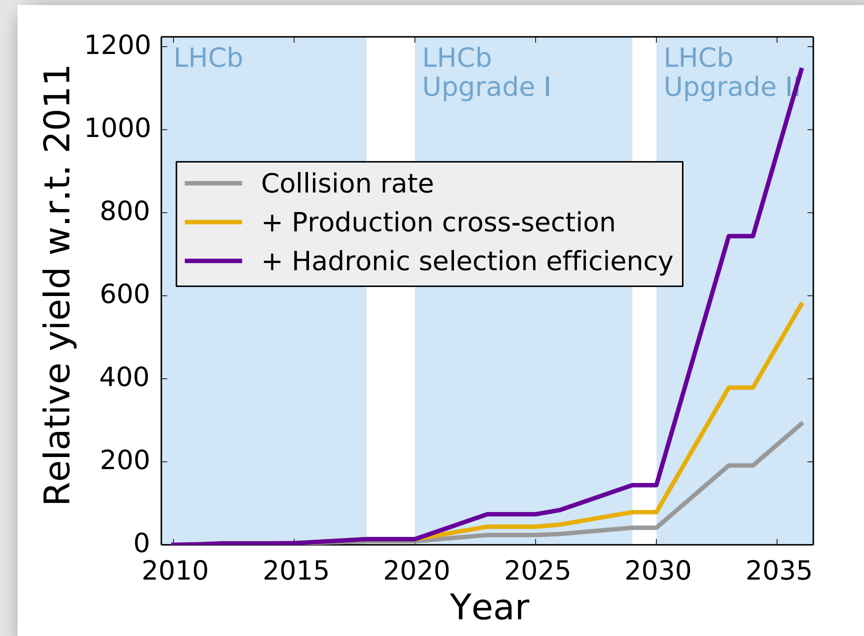

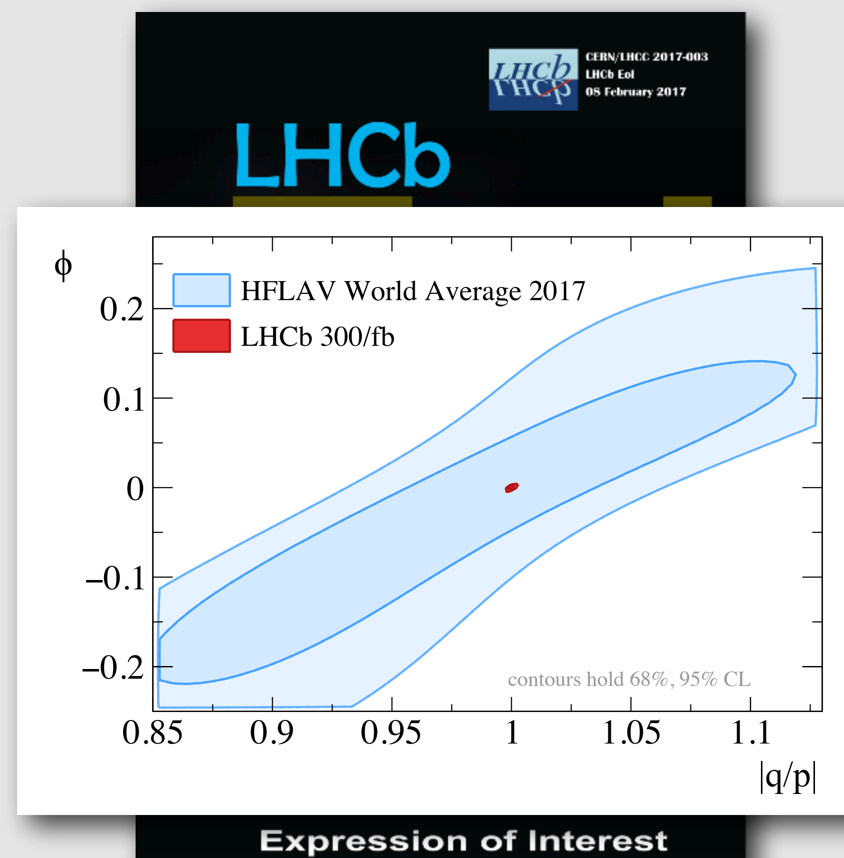

Conclusion

- Several new measurements of direct CP violation
  - ➡ $D^+ \to \pi^+\pi^0$
  - ➡ $D^0 \to K_S K_S$
  - ➡ $D^0 \to hh\mu\mu$
  - ➡ $\Lambda_c \to phh$
- Fewer news on indirect CP violation
  - ➡ New WS Kπ measurement
  - ➡ New amplitude analyses
    - Should be followed by time-dependent analyses
- Belle II starting and LHCb undergoing upgrade starting in a few months time
  - ➡ Significant increase in charm samples over the coming years
  - ➡ Need to stay in for the long haul (LHCb Upgrade II) to reach tiny CPV predictions