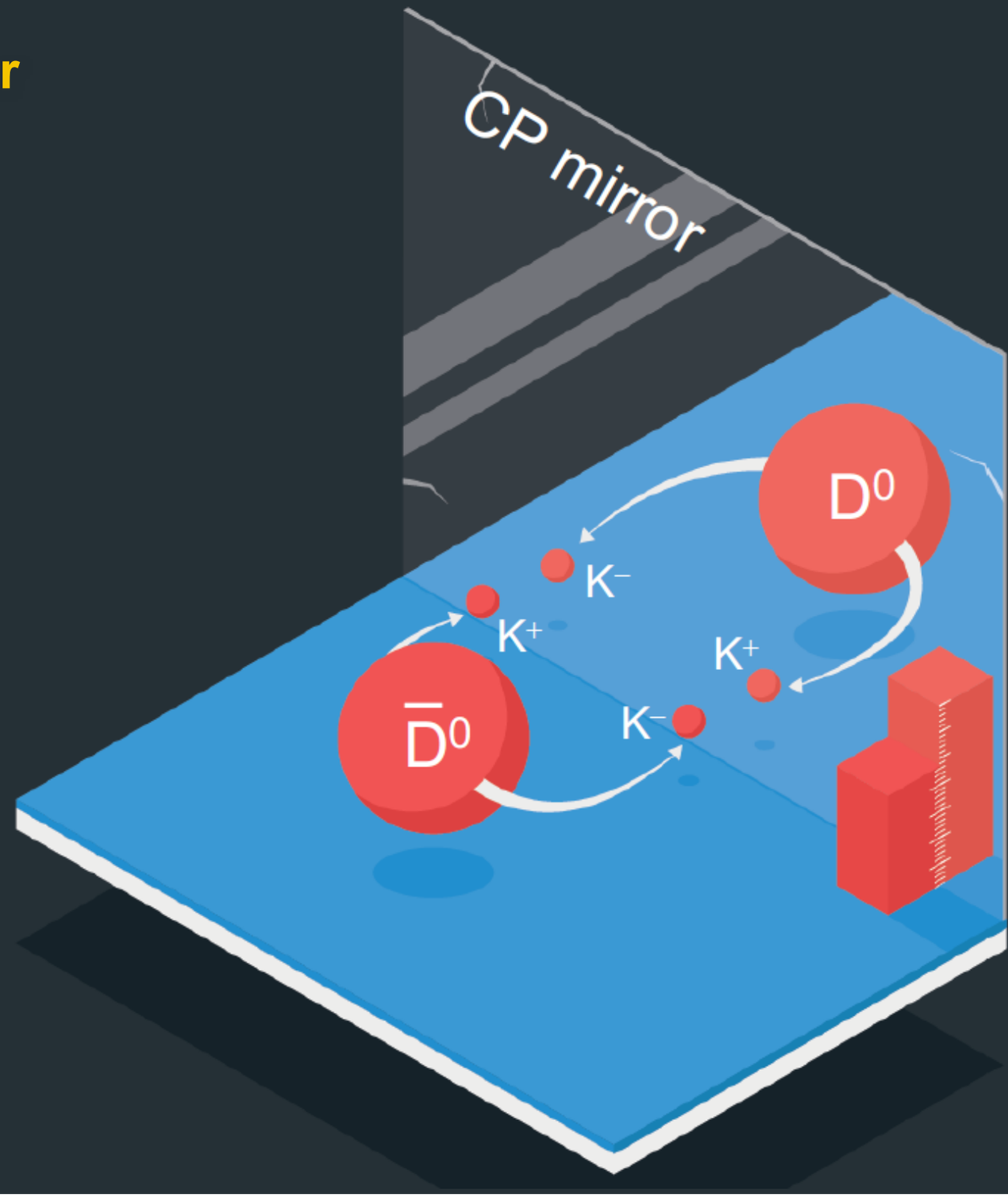
2019 Lattice X Intensity Frontier

September 23–25, 2019
Brookhaven National Laboratory, Upton NY



Charm *CP* violation

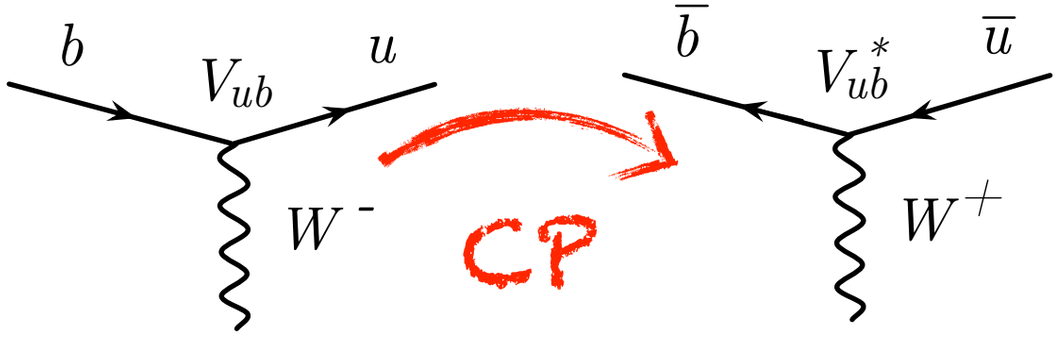
Experimental status and prospects

Angelo Di Canto

BROOKHAVEN NATIONAL LABORATORY

CP violation in the standard model

- Irreducible phase of the Cabibbo-Kobayashi-Maskawa matrix describing the charged currents of quarks



- Potentially large effects in transitions involving the third generation

- Highly suppressed for charm, which has small couplings to the third generation

$$V \approx \begin{array}{c} \\ \\ \\ \end{array}\begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\varphi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\varphi} & -\lambda^2 & 1 \end{pmatrix} \end{array} \begin{array}{c} \\ u \\ c \\ t \end{array}$$

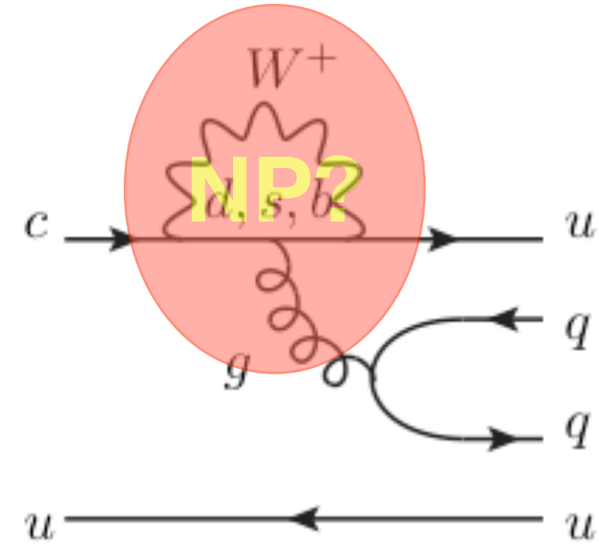
$$\lambda \approx 0.22$$

Why shall we bother about charm?

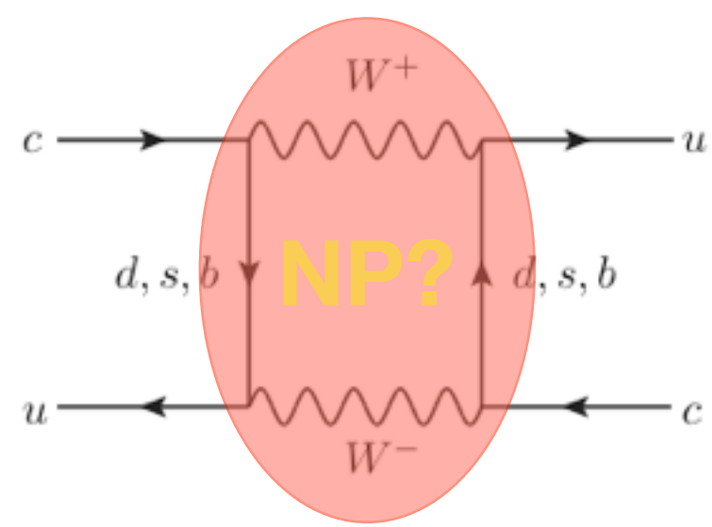
Discovery tool, standard model effects are ~10^{-3} or smaller, potential room for new physics to show up

Unique, gives sensitivity to new physics coupling to up-type quarks (complementary to *K* and $B_{(s)}$ decays)

Challenging, need O(1-100M) yields and control over systematic uncertainties. Predictions are difficult, not a precision probe



$\Delta C=1$



$\Delta C=2$

Finally two concurrent charm factories

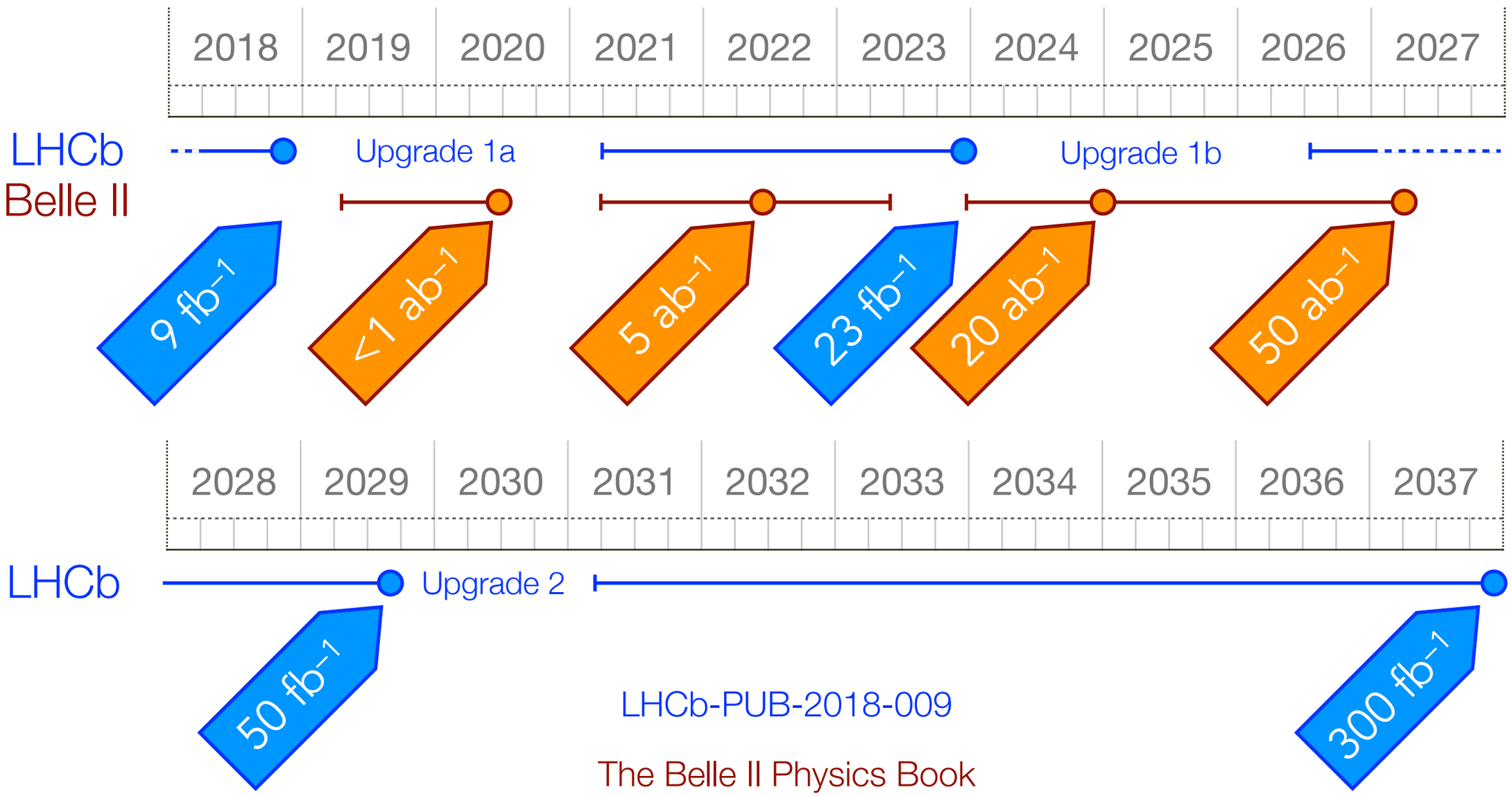
LHCb

- Huge advantage in production rate, but also large backgrounds — stringent online selections
- Superior decay-time resolution and access to larger decay times
- …but tricky efficiency effects (*e.g.* decay-time acceptance)

Belle II

- Cleaner environment allows for more generous selections — milder efficiency effects
- Better reconstruction of final states with neutrals/invisible particles
- Much easier separation between promptly produced charm and secondary (from-*B*) decays

Prospects of data collection



LHCb-PUB-2018-009

The Belle II Physics Book
(+ latest lumi projections)

The rule of thumb

$1\ fb^{-1} \sim 1\ ab^{-1}$

@ LHCb @ Belle II

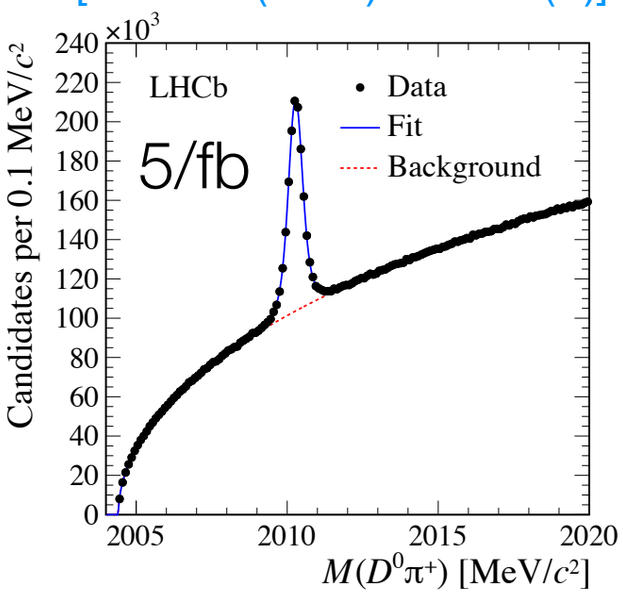
The rule of thumb

$$\cancel{1\ \mathrm{fb}^{-1}\ @\ \mathrm{LHCb} \sim 1\ \mathrm{ab}^{-1}\ @\ \mathrm{Belle\ II}}$$

does not hold for charm

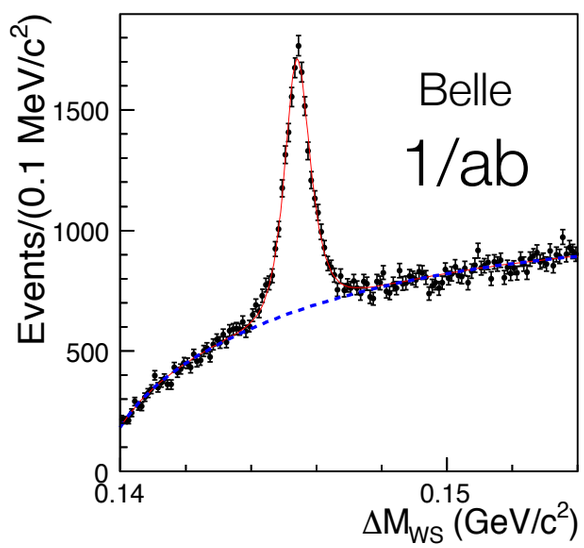
The rule of thumb

[PRD 97 (2018) 031101(R)]



$N/\mathcal{L}$~150k

[PRL 112 (2014) 111801]

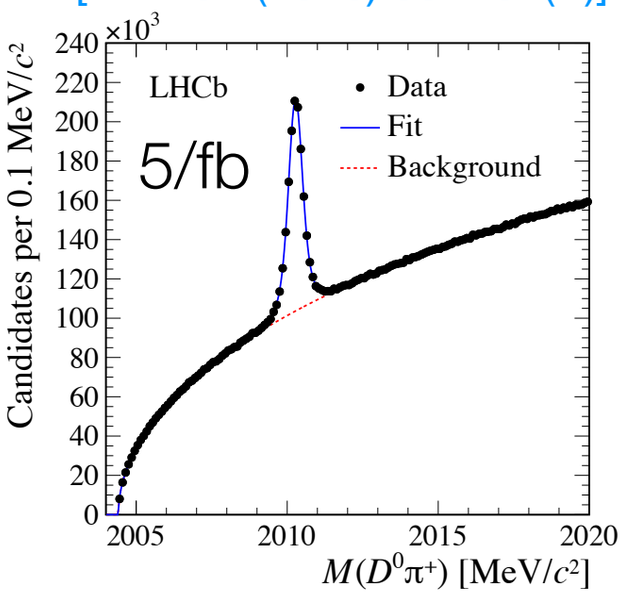


$N/\mathcal{L}$~10k

$$D^{*+} \to D^0(\to K^+\pi^-)\pi^+$$

The rule of thumb

[PRD 97 (2018) 031101(R)]



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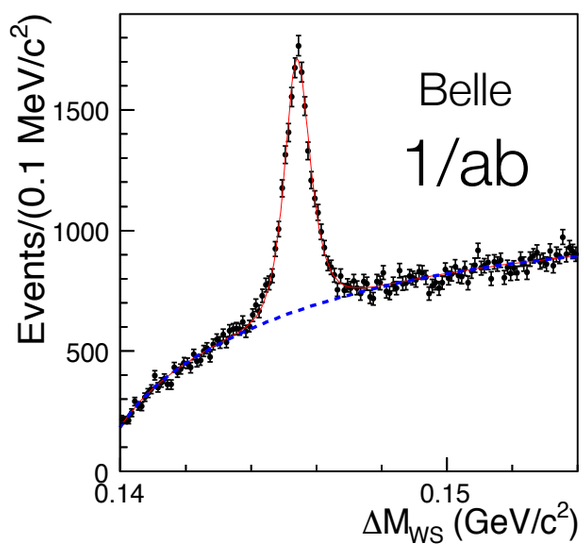
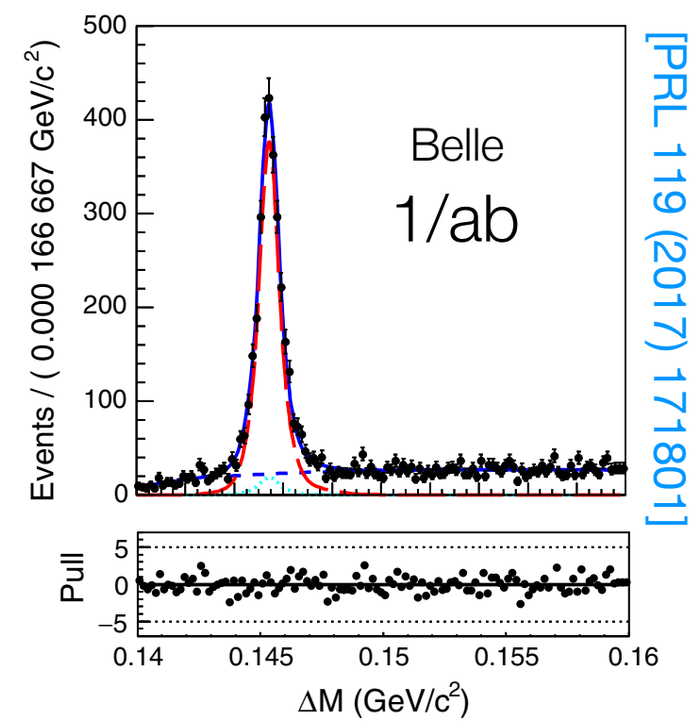


$N/\mathcal{L}$~10k

$D^{*+} \to D^0(\to K^+\pi^-)\pi^+$

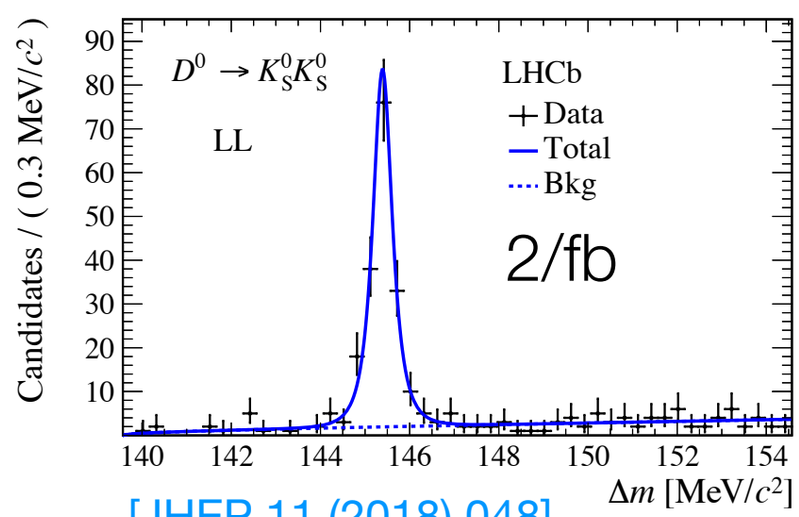
$N/\mathcal{L}$~5.4k



[PRL 119 (2017) 171801]

$N/\mathcal{L}$~0.5k

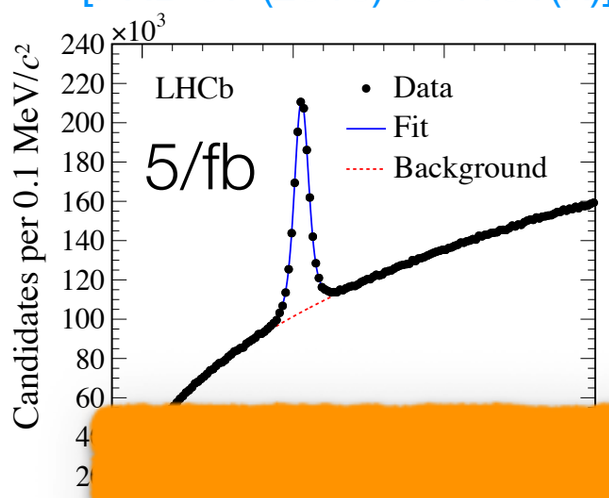
$D^{*+} \to D^0(\to K_S K_S)\pi^+$



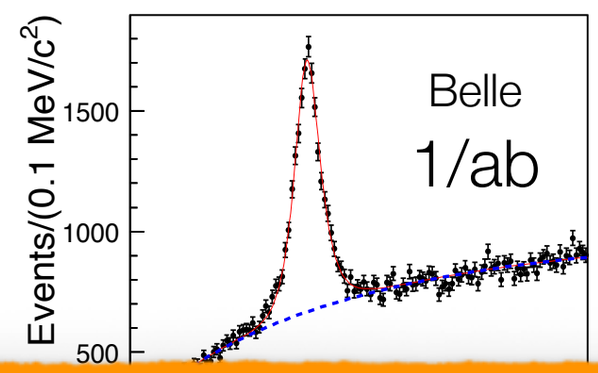
[JHEP 11 (2018) 048]

The rule of thumb

[PRD 97 (2018) 031101(R)]



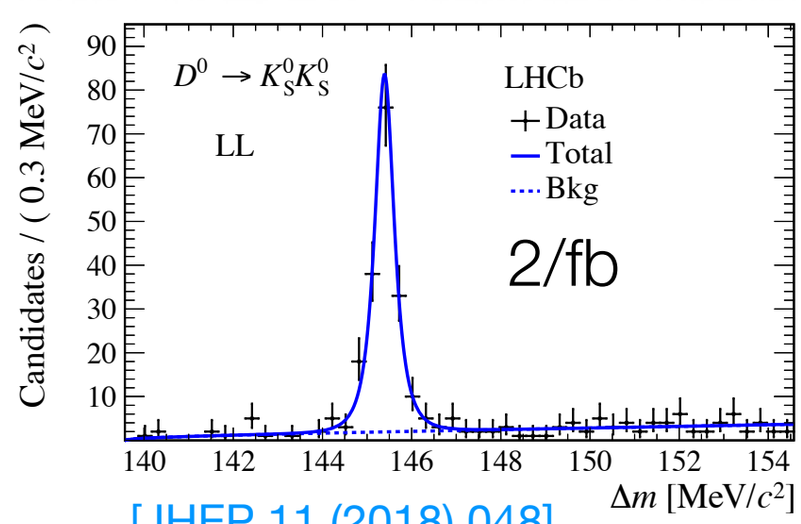
[PRL 112 (2014) 111801]



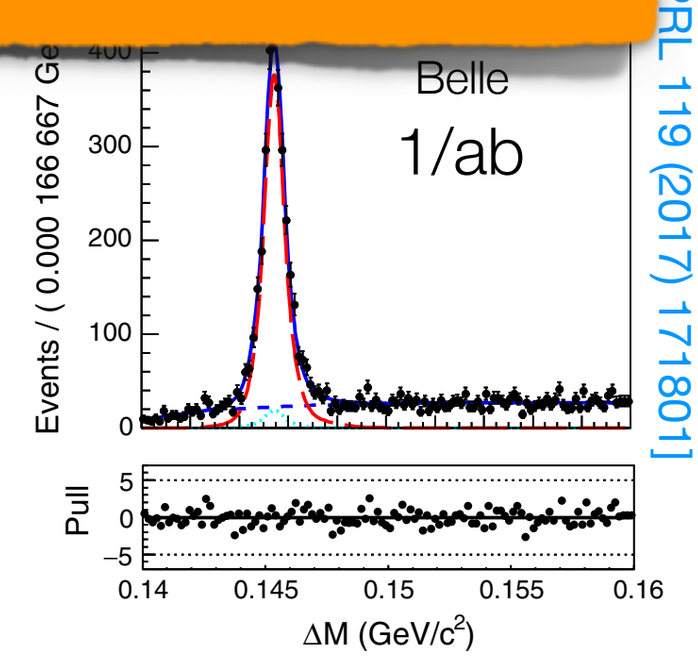
$D^{*+} \to D^0(\to K^+\pi^-)\pi^+$

COMPLEMENTARITY

$D^{*+} \to D^0(\to K_S K_S)\pi^+$



[JHEP 11 (2018) 048]



[PRL 119 (2017) 171801]

Direct *CP* violation

CP asymmetries with $D^0 \to h^+h^-$ decays

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

CP asymmetries with $D^0 \to h^+h^-$ decays

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$$\frac{N(D^0 \to h^+h^-) - N(\bar{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\bar{D}^0 \to h^+h^-)}$$

$$A(h^+h^-) = A_{CP}(h^+h^-) + A_D + A_P$$

The *CP* asymmetry we want to measure

Detection asymmetry of tagging particle (π^+ or μ^-) — D^0 final state does not contribute being charge symmetric

Production asymmetry of parent hadron (D^{*+} or $\bar{B}$)

CP asymmetries with $D^0 \to h^+h^-$ decays

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$$\frac{N(D^0 \to h^+h^-) - N(\bar{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\bar{D}^0 \to h^+h^-)}$$

$$A(h^+h^-) = A_{CP}(h^+h^-) + A_D + A_P$$

The *CP* asymmetry we want to measure

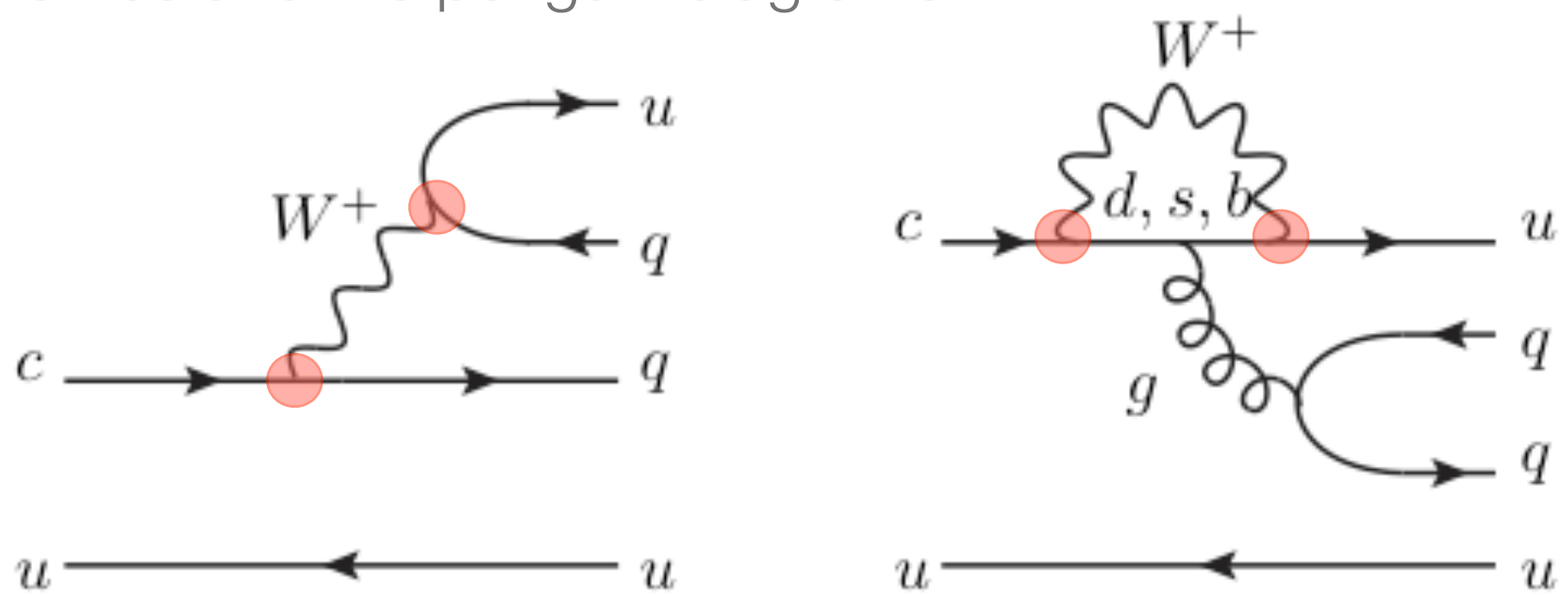
Detection asymmetry of tagging particle (π^+ or μ^-) — D^0 final state does not contribute being charge symmetric

Production asymmetry of parent hadron (D^{*+} or $\bar{B}$)

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = A(K^+K^-) - A(\pi^+\pi^-)$$

Naive expectation

- In the standard model, *CP* violation in $D^0 \to h^+h^-$ is generated by the interference between the tree and the penguin diagrams



$$|A_{CP}| \sim r_{CKM} = \mathrm{Im}(V_{ub}V_{cb}^*/V_{uq}V_{cq}^*) \approx 6.5\times10^{-4}$$

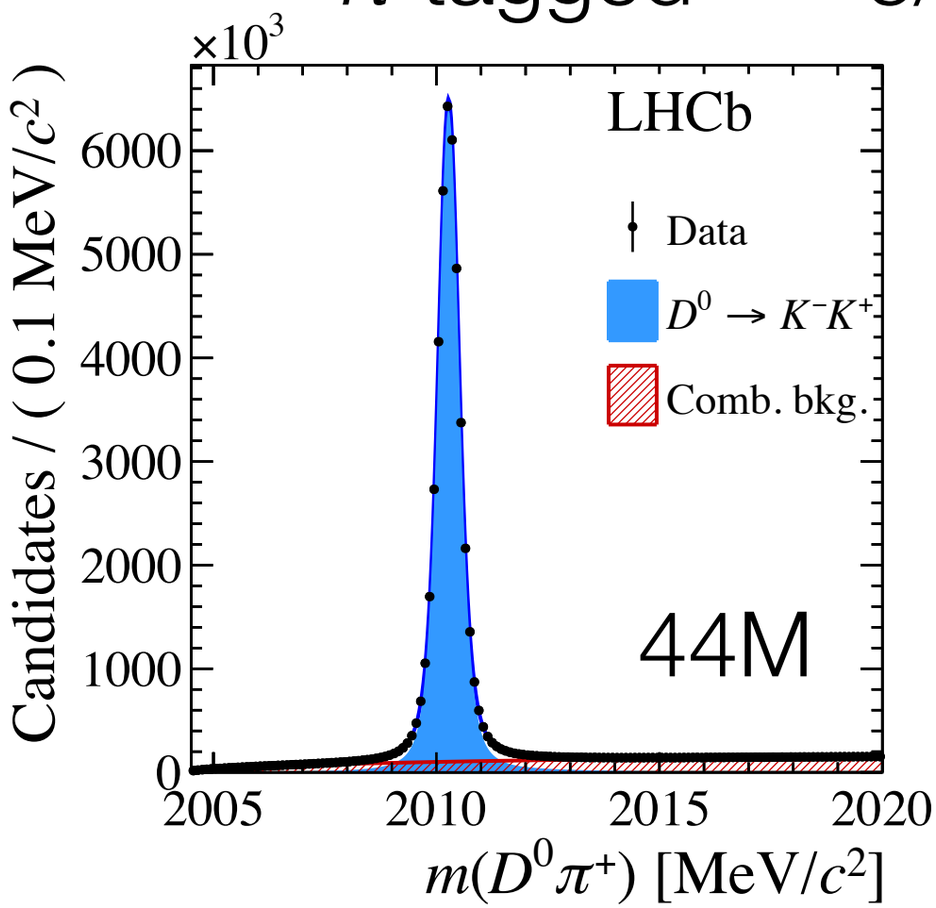
- In the limit of SU(3)/U-spin symmetry, $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$ have same magnitude and opposite signs $\Longrightarrow |\Delta A_{CP}| \approx 13\times10^{-4}$

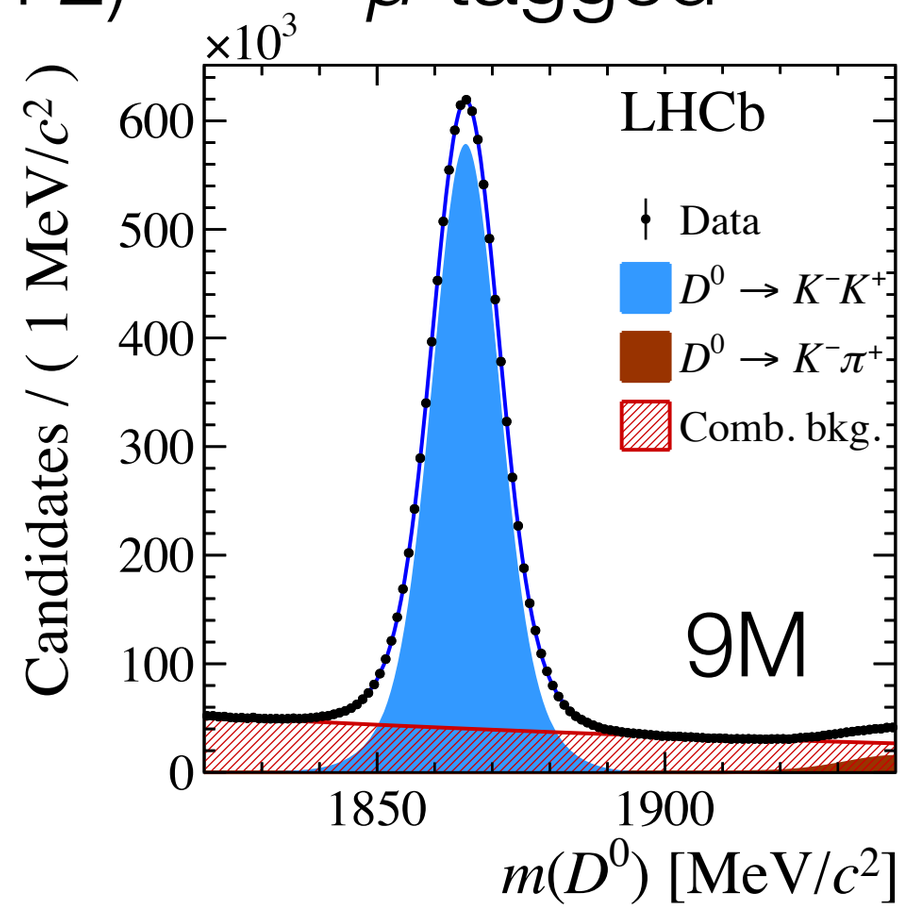
- In addition to be robust against experimental biases, ΔA_{CP} provides enhanced sensitivity to *CP* violation

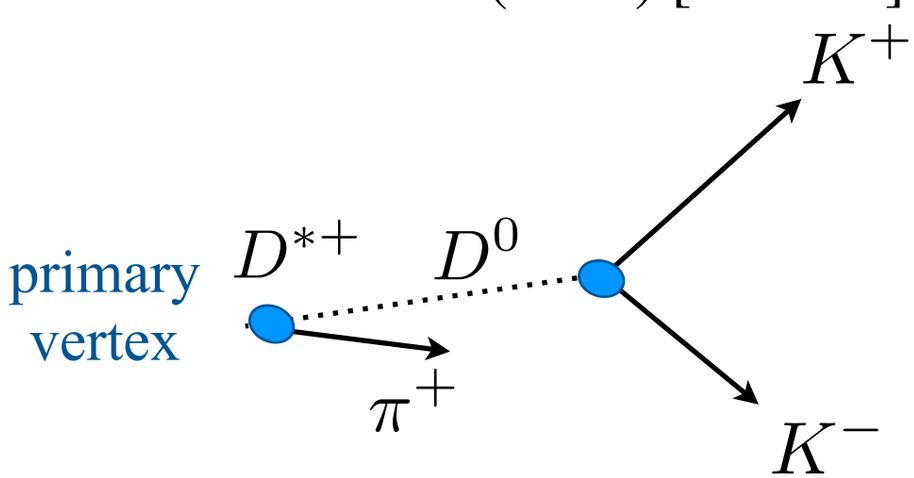
$D^0 \to h^+h^-$ decays at LHCb

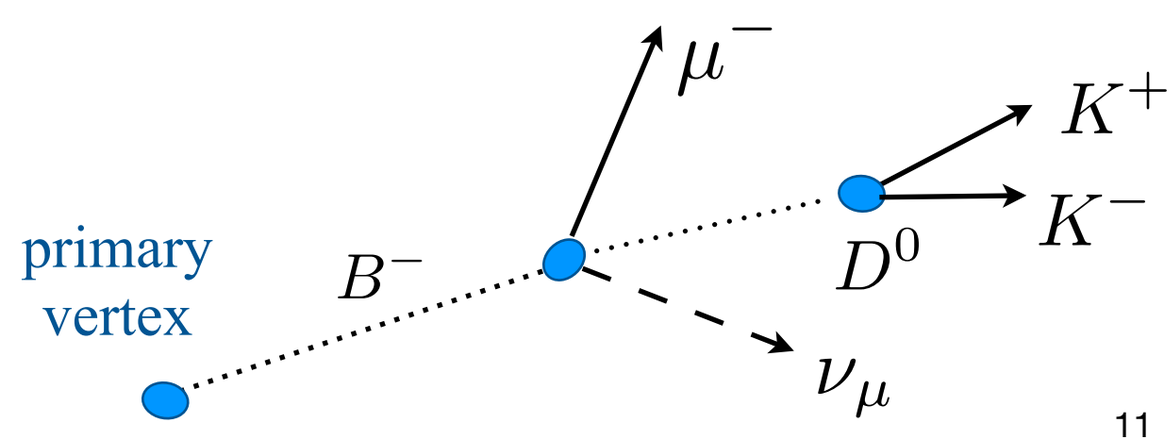
[PRL 122 (2019) 211803]

π tagged 6/fb (Run 2) μ tagged









Results

[PRL 122 (2019) 211803]

ΔA_{CP} [10^{-4}]		
-18.2 ± 3.2 (stat) ± 0.9 (syst)		π tagged (Run 2)
-9 ± 8 (stat) ± 5 (syst)		μ tagged (Run 2)

Results

[PRL 122 (2019) 211803]

ΔA_{CP} [10^{-4}]		
-18.2 ± 3.2 (stat) ± 0.9 (syst)		π tagged (Run 2)
-9 ± 8 (stat) ± 5 (syst)		μ tagged (Run 2)
-10 ± 8 (stat) ± 3 (syst)		π tagged (Run 1) [PRL 116 (2016) 191601]
-14 ± 16 (stat) ± 8 (syst)		μ tagged (Run 1) [JHEP 07 (2014) 041]

Results

[PRL 122 (2019) 211803]

ΔA_{CP} [10^{-4}]		
-18.2 ± 3.2 (stat) ± 0.9 (syst)		π tagged (Run 2)
-9 ± 8 (stat) ± 5 (syst)		μ tagged (Run 2)
-10 ± 8 (stat) ± 3 (syst)		π tagged (Run 1) [PRL 116 (2016) 191601]
-14 ± 16 (stat) ± 8 (syst)		μ tagged (Run 1) [JHEP 07 (2014) 041]
-15.4 ± 2.9 (stat+syst)		combined

5.3σ deviation from zero

first observation of *CP* violation in charm

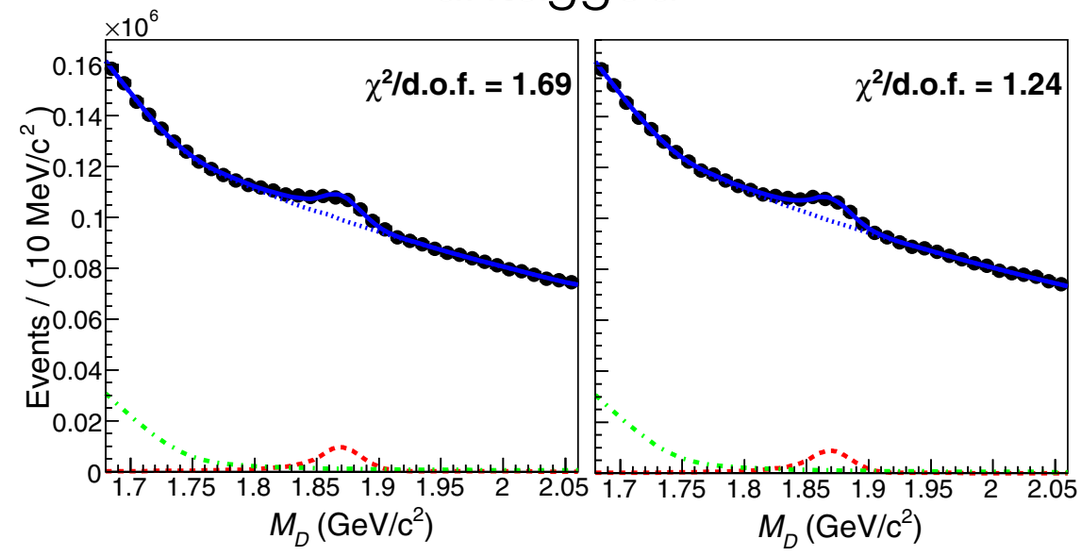
Now what?

- Measured value is in the ballpark of the standard model value
- Difficult to say if new physics is at play. Need better control of the QCD effects
- Experimentally look for *CP* violation in radiative decays, test isospin sum rules and SU(3) related modes
- Huge program of measurements, where Belle II role with neutrals will be crucial
- Can we expect any progress on the theory (LQCD) side?

CP violation in $D^+ \to \pi^+\pi^0$ decays

- In the standard model ΔA_{CP} comes from ΔU=0 transitions
- *CP* violation in ΔU=1, *e.g.* in $D^+ \to \pi^+\pi^0$, would unambiguously be new physics
- Current best measurement from Belle (1/ab)

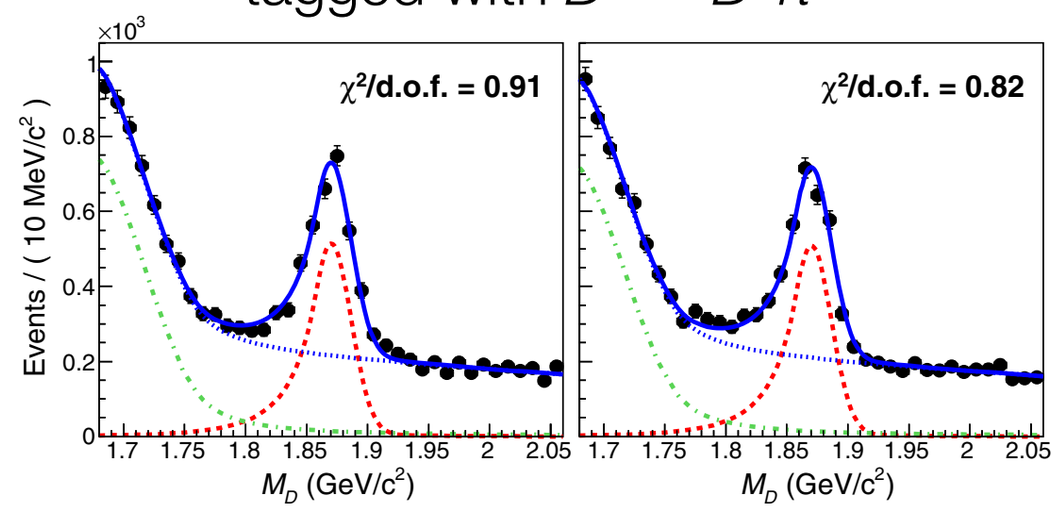
untagged



$$A_{CP} = (2.3 \pm 1.2 \pm 0.2)\%$$

- D^{*+} tagging crucial in suppressing the background
- Similar performances expected for Belle II. Sensitivity with 50/ab ~0.17%, maybe possible at LHCb but difficult

tagged with $D^{*+} \to D^+\pi^0$



[PRD 97 (2018) 011101(R)]

Prospects for direct *CP* violation

Decay mode	Current best sensitivity (stat + syst) [10^{-3}]		LHCb 300/fb (stat only) [10^{-3}]	Belle II 50/ab (stat+syst) [10^{-3}]
ΔA_{CP}	0.29	LHCb (9/fb)	0.03	0.6
$D^0 \to K^+K^-$	1.8	LHCb (3/fb)	0.07	0.3
$D^0 \to \pi^+\pi^-$	1.8	LHCb (3/fb)	0.07	0.5
$D^0 \to \pi^0\pi^0$	6.5	Belle (1/ab)	(?)	0.9
$D^0 \to K^+\pi^-$	9.1	LHCb (5/fb)	0.5	(4.0)
$D^0 \to K_S K_S$	15	Belle (1/ab)	2.8	2.1
$D_s \to K_S\pi^+$	18	LHCb (6.8/fb)	0.32	2.9
$D^+ \to K_S K^+$	0.76	LHCb (6.8/fb)	0.12	0.4
$D^0 \to \phi\gamma$	66	Belle (1/ab)	(?)	10
$D^0 \to \rho^0\gamma$	150	Belle (1/ab)	(?)	20
$D^+ \to \phi\pi^+$	0.49	LHCb (4.8/fb)	0.06	0.4
$D^+ \to \pi^0\pi^+$	13	Belle (1/ab)	(?)	1.7

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

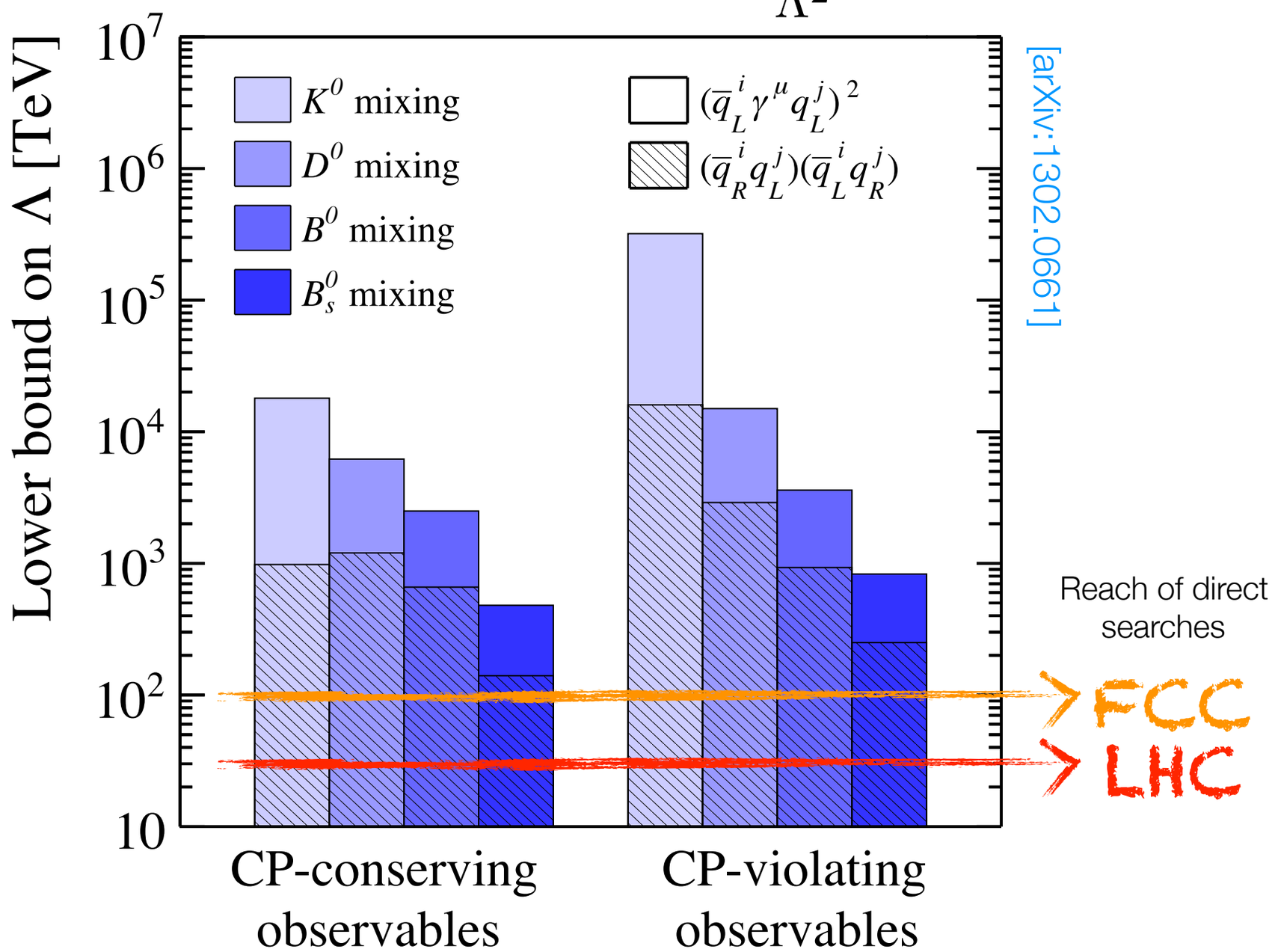
$$x = (m_1 - m_2)/\Gamma$$

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

Mixing-induced *CP* violation

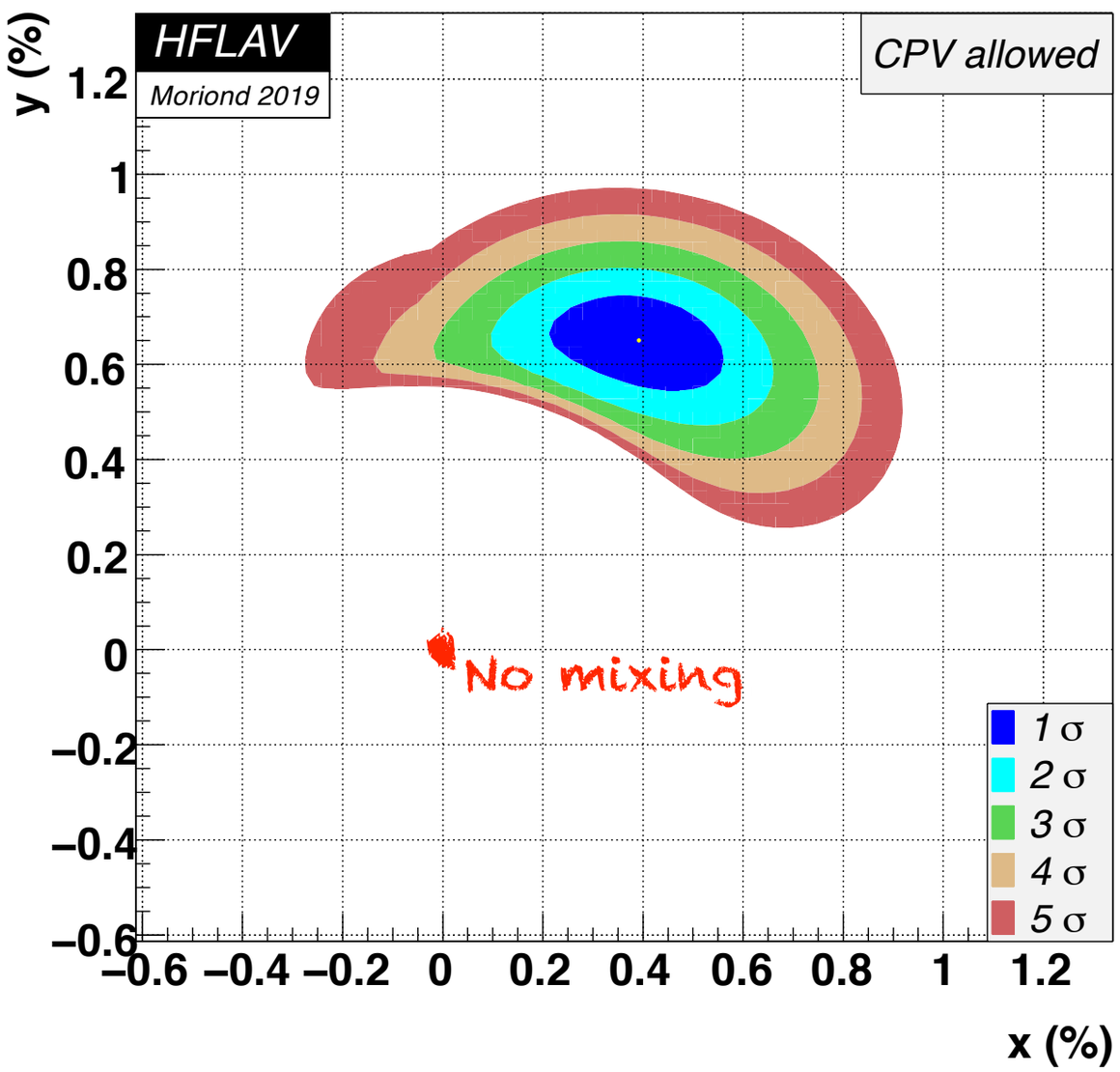
Impressive reach

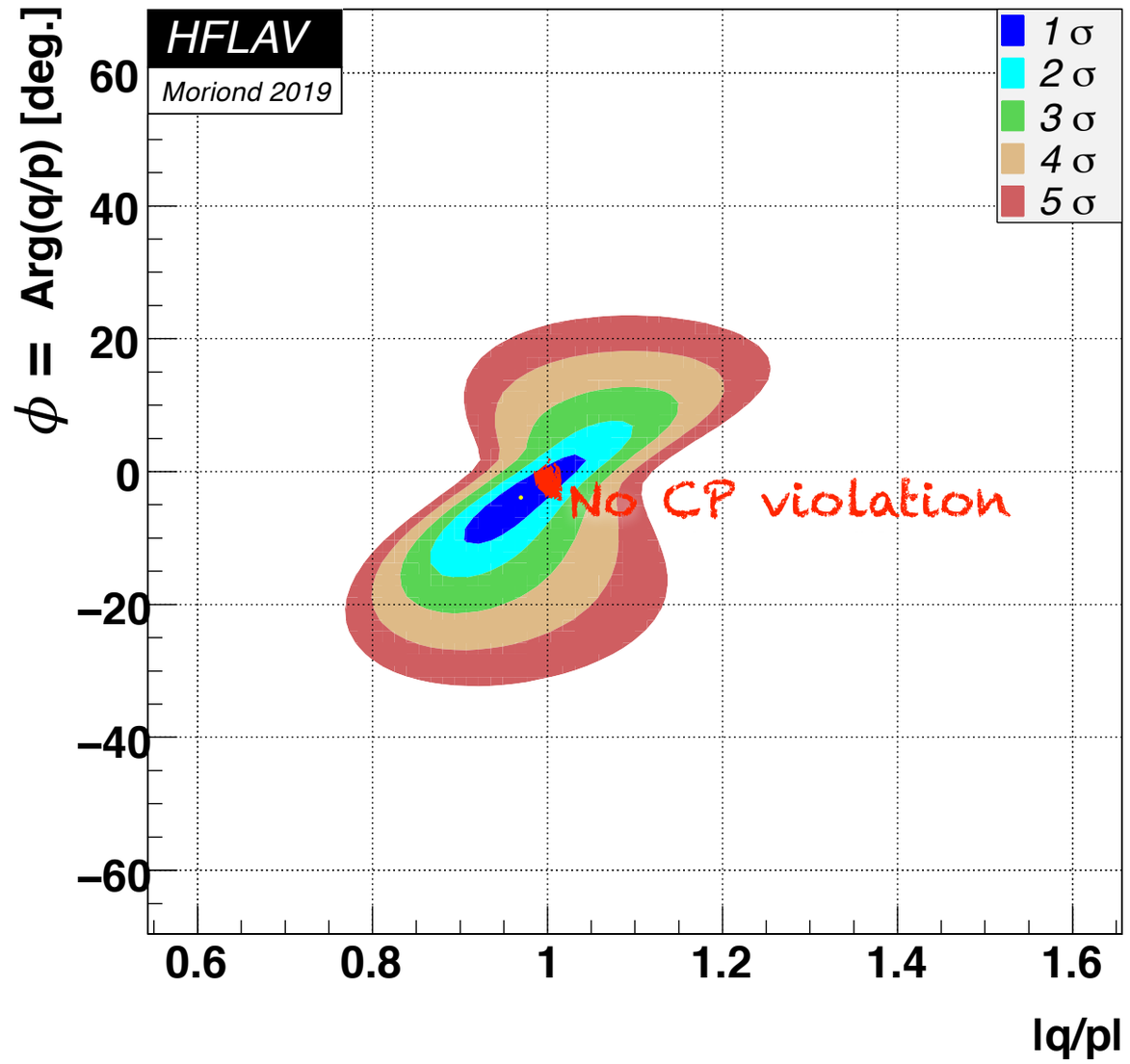
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{O}_{\Delta F=2}$$



[arXiv:1302.0661]

Experimental status





$$x = (3.9\ ^{+1.1}_{-1.2}) \times 10^{-3}$$

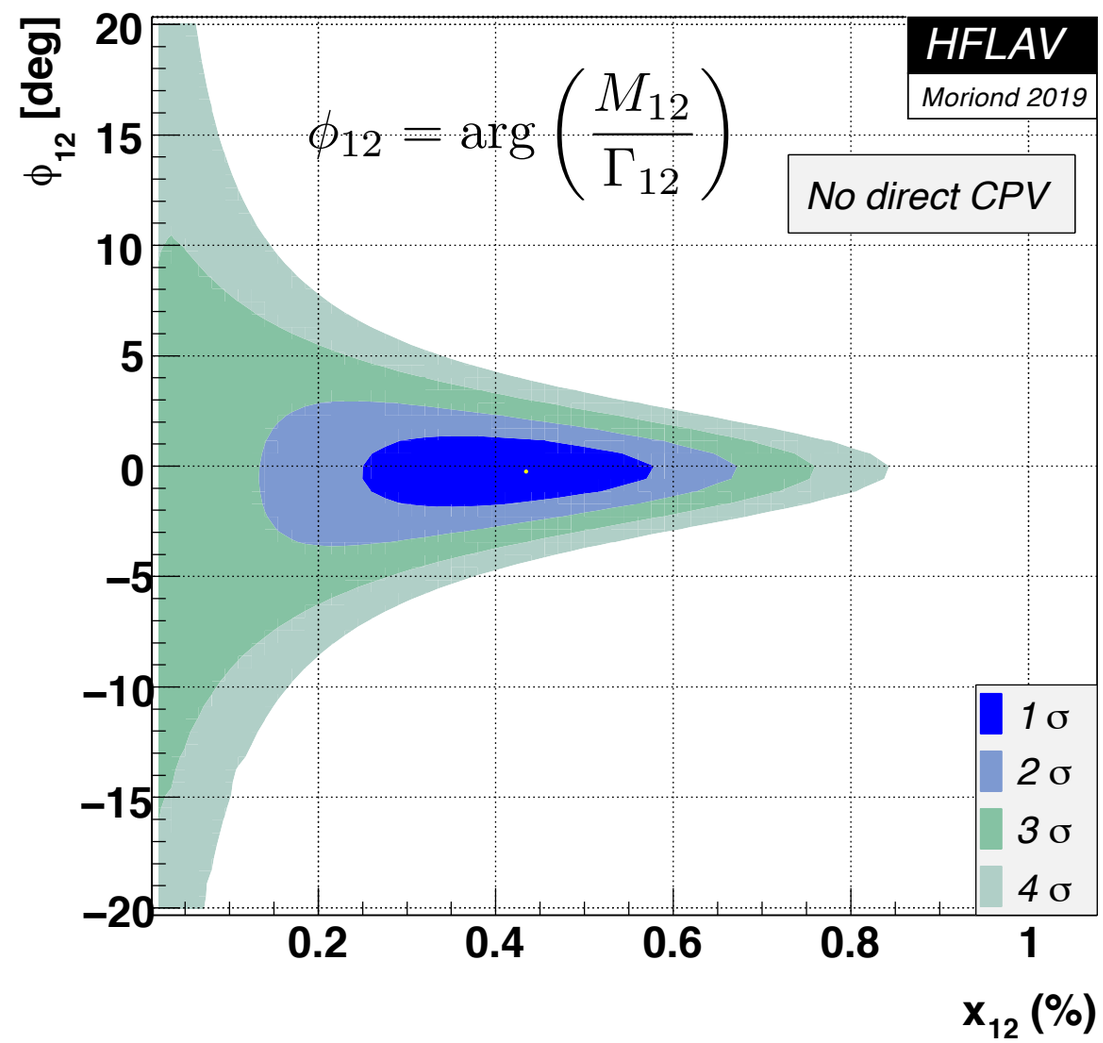
$$y = (6.51\,^{+0.63}_{-0.69}) \times 10^{-3}$$

$$|q/p| = 0.969\,^{+0.050}_{-0.045}$$

$$\phi = (-3.9\,^{+4.5}_{-4.6})^{\circ}$$

Theory expectation

- Charm mixing is long-distance dominated. Impossible to calculate (?)
- *CP* violation in ΔC=2 transitions expected at order $r_{CKM}/\varepsilon \approx 2\times10^{-3} \sim 1/8^{o}$ (for a nominal U-spin breaking ε~30%)
- Experimental sensitivity limited by the knowledge of $x_{12} \approx x$
  - Available mixing measurements are mostly based on decays to two-body final states, which are primarily sensitive to *y*
  - Need more measurements with multi-body final states



$$\phi_{12} = (-0.25\,^{+0.99}_{-0.96})^{\circ}$$

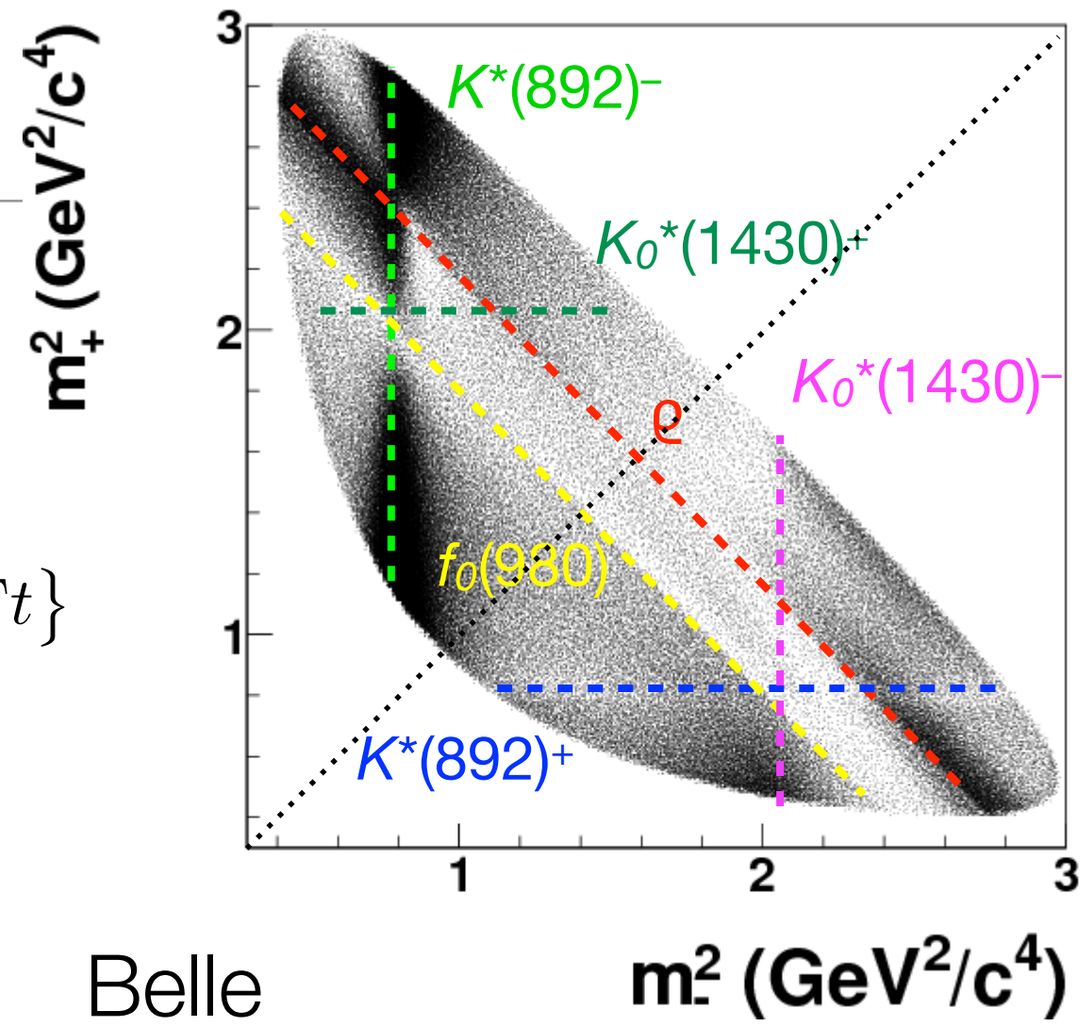
Mixing with $D^0 \to K_S \pi^+ \pi^-$

- Multiple interfering amplitudes enhance the sensitivity to mixing

$$\mathcal{P}_{D^0} \propto e^{-\Gamma t}\{|\mathcal{A}_{D^0}|^2 - \mathrm{Re}[\mathcal{A}^*_{D^0}\mathcal{A}_{\overline{D}^0}(y+ix)]\Gamma t\}$$

- Requires a time-dependent Dalitz-plot analysis
- Pioneered by CLEO in 2005, then followed by *B* factories with larger yields
- Belle 1/ab result has been for long the best determination of *x* available

[PRD 89 (2014) 091103]

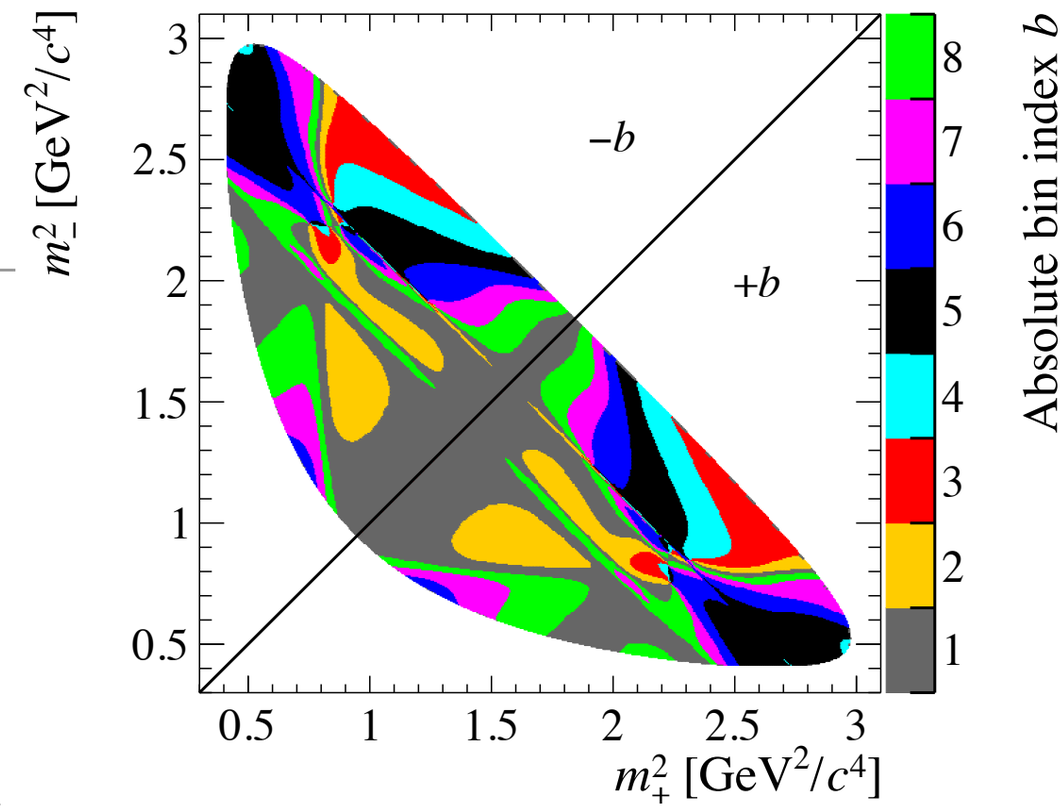


Belle

Fit type	Parameter	Fit result
No CPV	$x(\%)$	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$
	$\lvert q/p\rvert$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

Bin-flip method

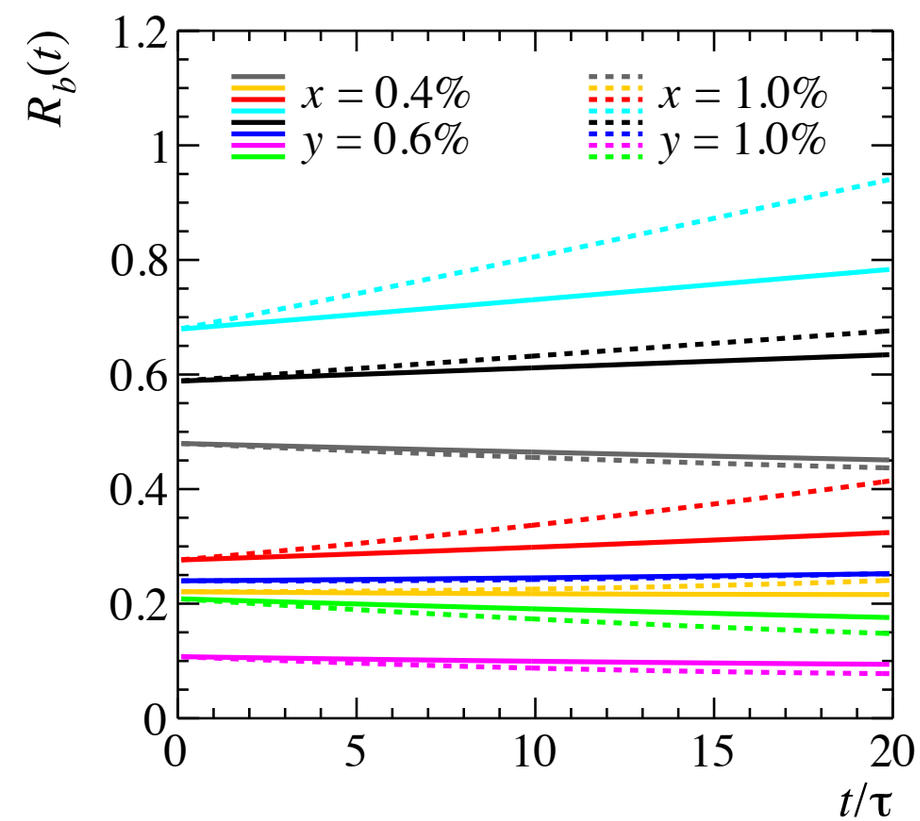
[PRD 99 (2019) 012007]



- Bin the Dalitz-plot to avoid amplitude model
- Ratio of events in bin $-b$ to events in bin b to suppress effects due to non-uniform efficiency variations (assuming *CP* symmetry)

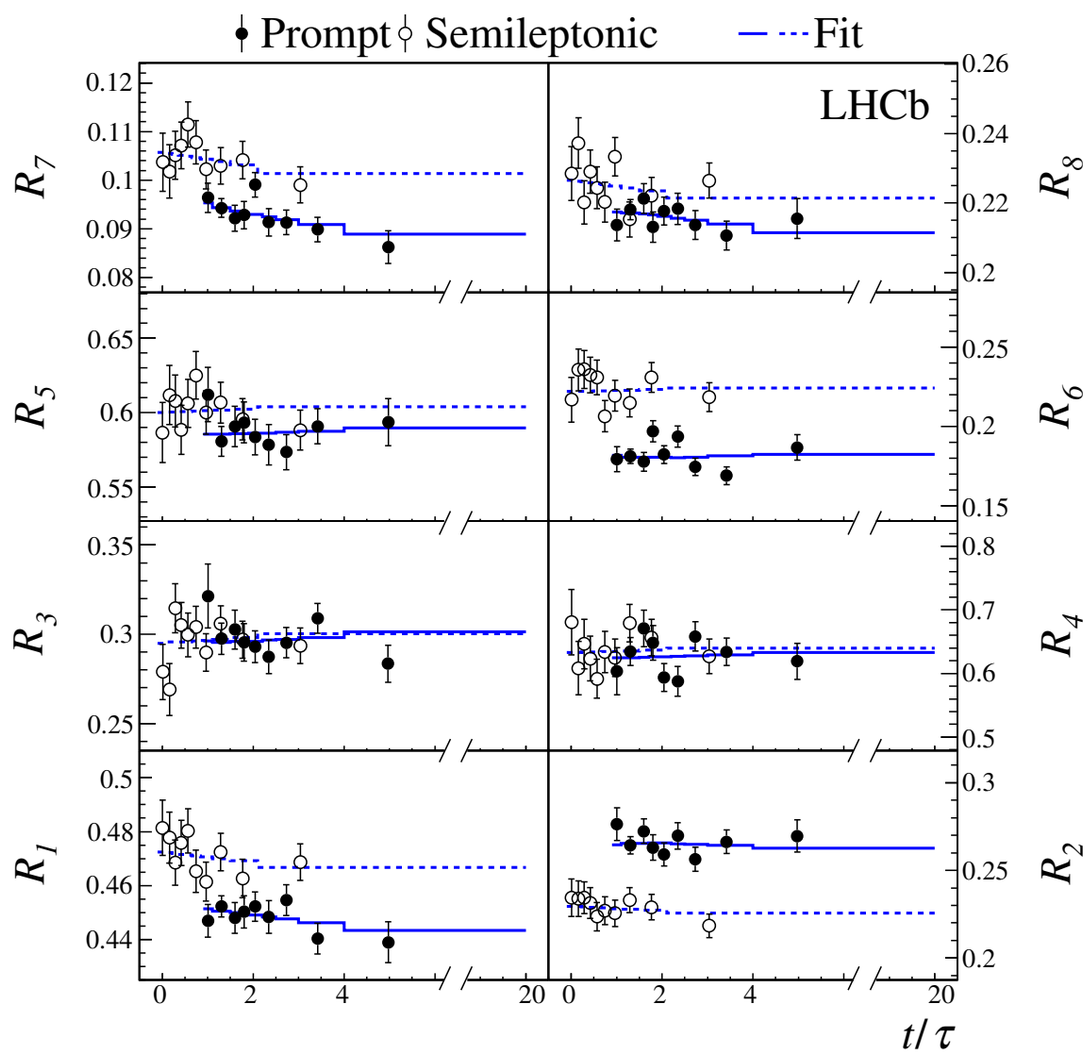
$$R_b \approx r_b - \sqrt{r_b}\left[(1-r_b)c_b\, y - (1+r_b)s_b\, x\right]\Gamma t$$

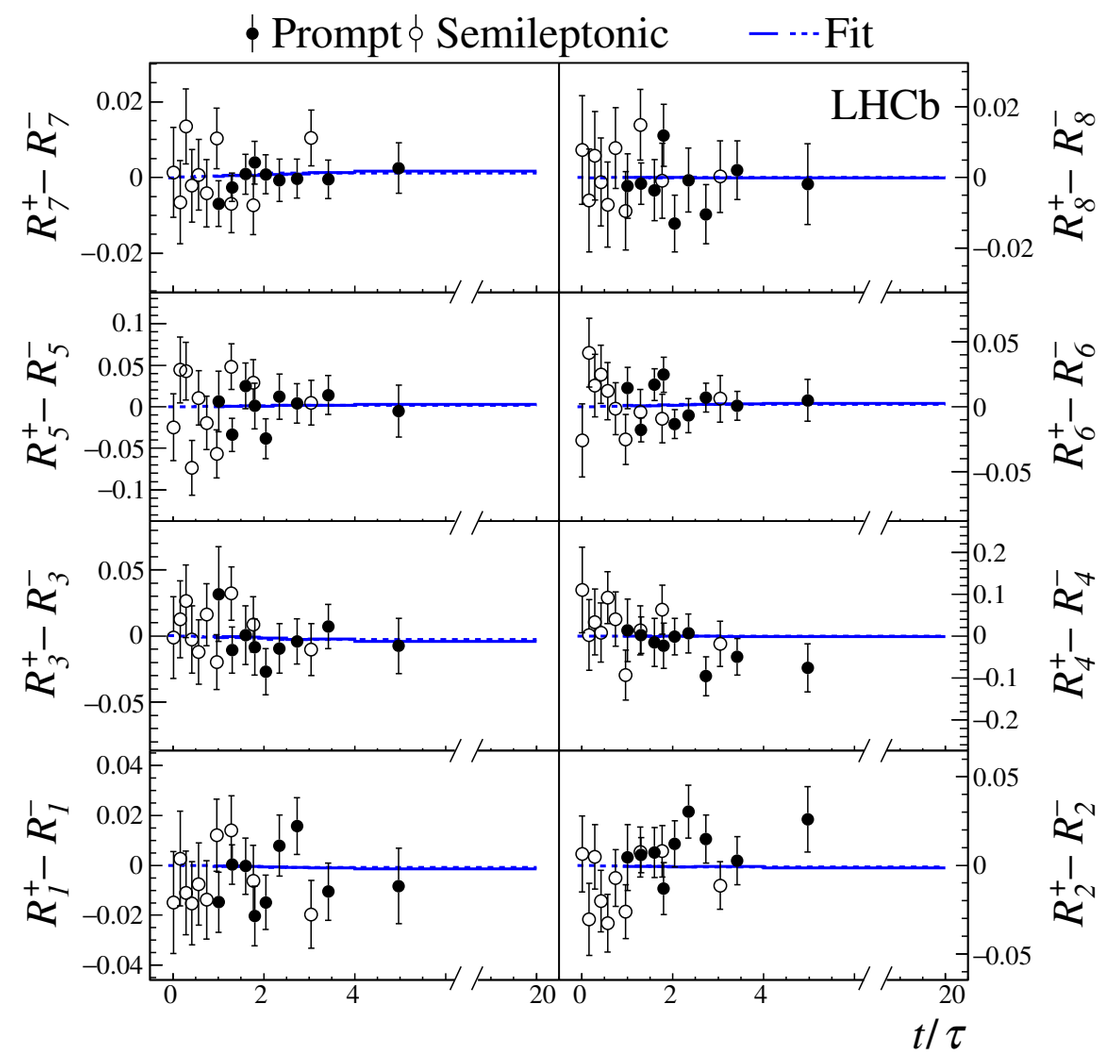
- Constrain hadronic parameters (c_b, s_b) using measurements with quantum-correlated $D^0\bar{D}^0$ pairs, *i.e.* at CLEO/BESIII
- Mixing parameters from simultaneous fit to all bins. Split in D^0 and $\bar{D}^0$ to access also indirect *CP* violation
- Model-independent and completely data driven



Bin-flip $D^0 \to K_S \pi^+ \pi^-$ at LHCb

[PRL 122 (2019) 231802]





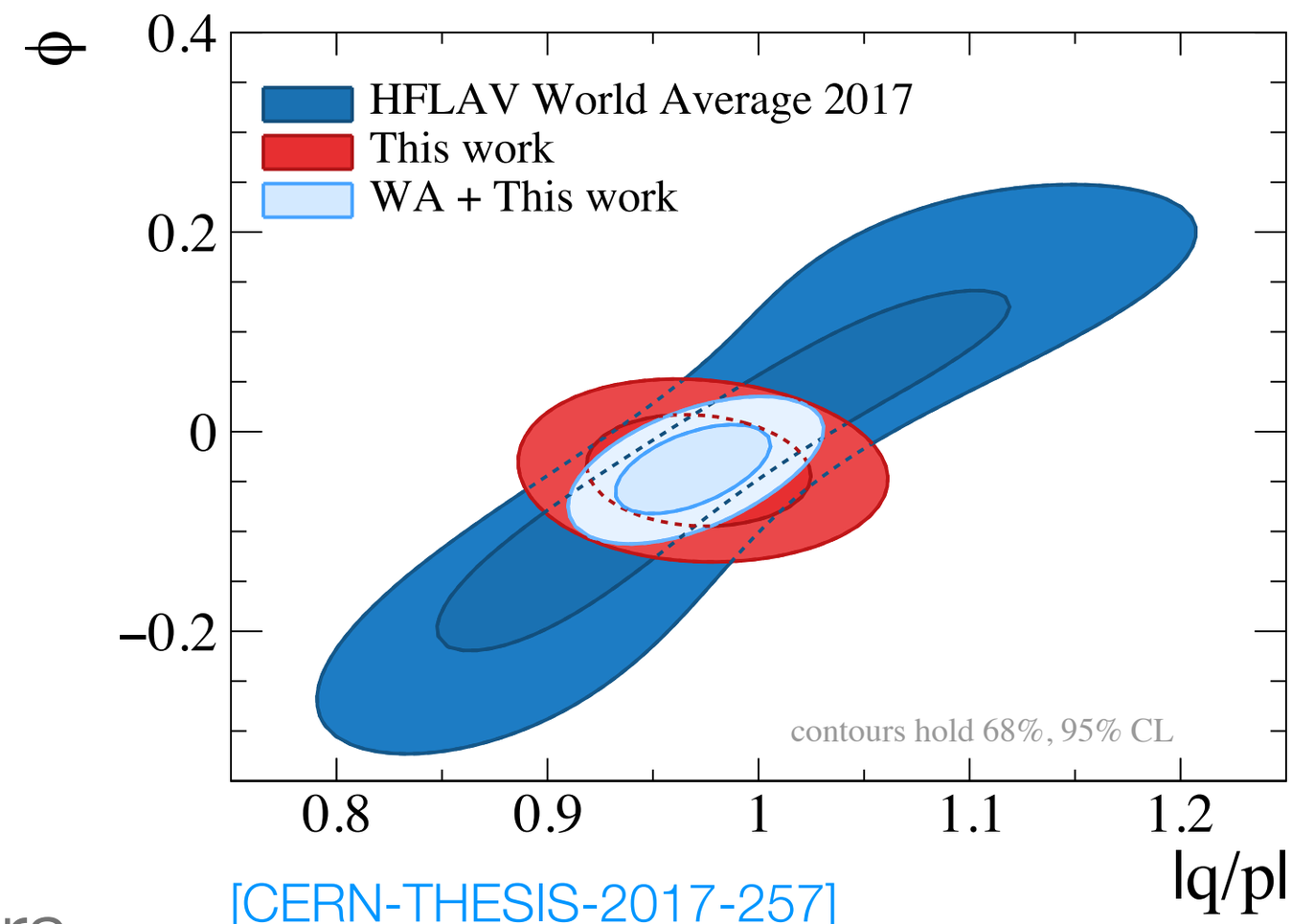
Parameter	Value	95.5% CL interval
x $[10^{-2}]$	$0.27^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
y $[10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p \rvert$	$1.05^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

Other multibody modes

- Lots of other promising final states not yet explored/fully exploited experimentally:
  e.g. $D^0 \to K^+\pi^-\pi^0$,
  $D^0 \to K^+\pi^-\pi^+\pi^-$,
  $D^0 \to K_S\pi^+\pi^-\pi^0$,
  …

- Model-independent analyses would have to rely on BESIII measurements of the strong-phase parameters

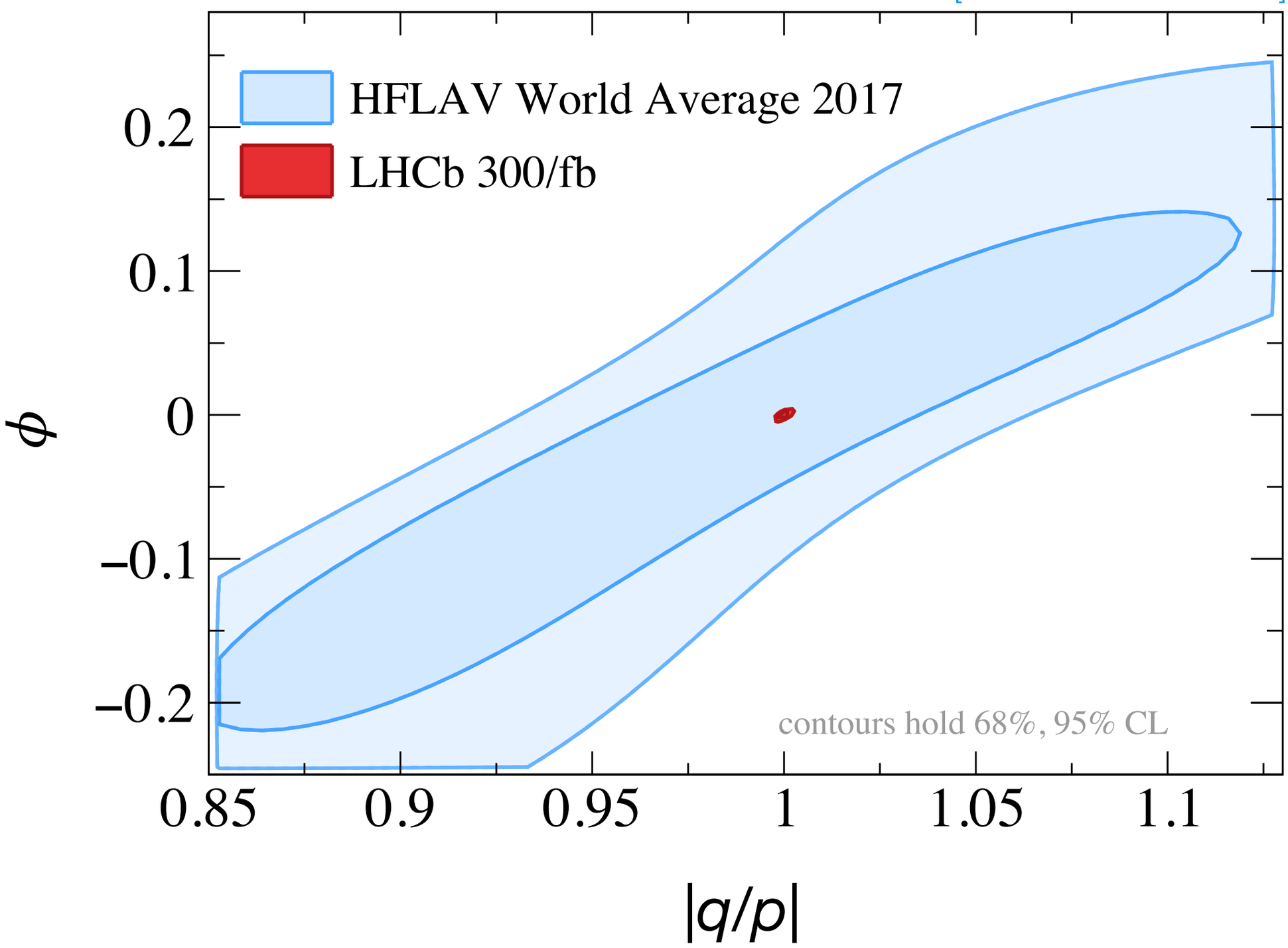
Potential of $D^0 \to K^+\pi^-\pi^+\pi^-$ @ LHCb



[CERN-THESIS-2017-257]

Prospects for mixing-induced *CP* violation

[LHCb-PUB-2018-009]



Summary

- Observed (direct) *CP* violation in charm decays
  - Measured asymmetry seems consistent with standard model, although predictions suffer from large uncertainties due to strong-interaction effects
  - Additional searches for *CP* violation in different decay modes can help to clarify the picture, together with improved theory calculations
- Yet no signs for mixing-induced *CP* violation. Precision still ~10× larger than naive standard model expectation, so plenty of room for new physics
- Huge experimental progress expected in the next decade(s) at LHCb and Belle II (with valuable inputs from BESIII). Can theory (LQCD) catch up?