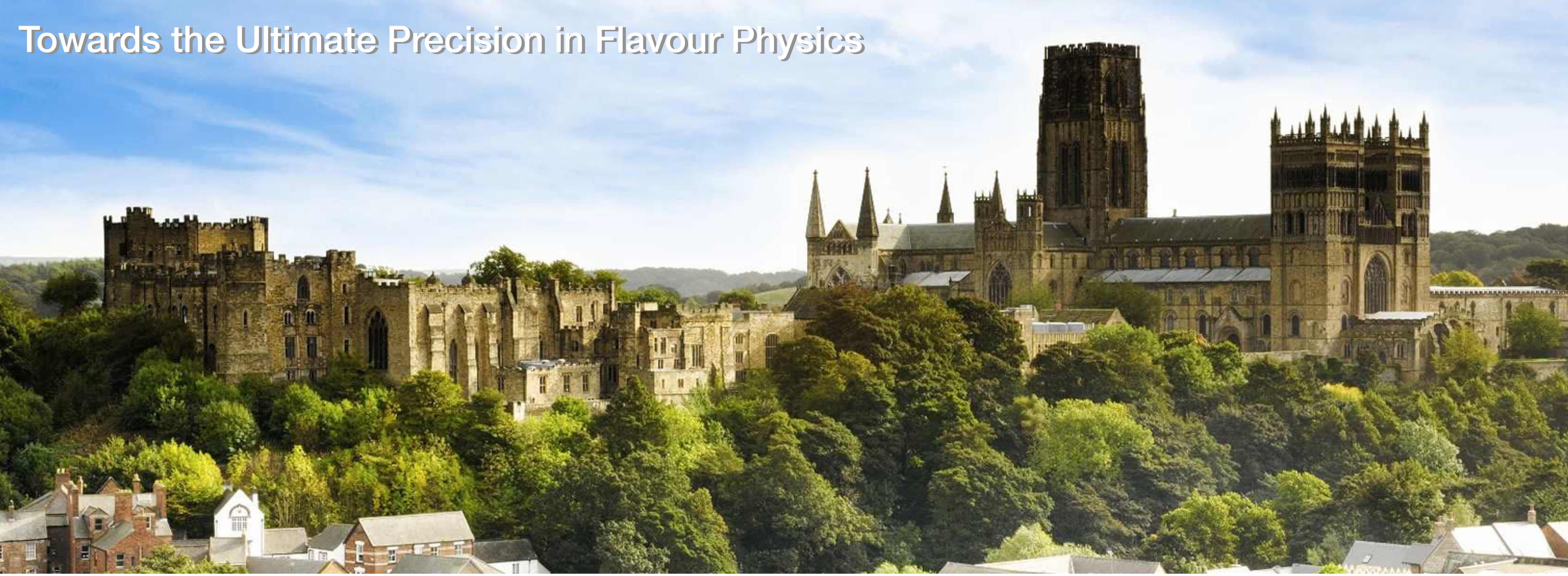


Direct and indirect CP violation in two-body charm decays

Angelo Di Canto

IPPP Durham, 2-4 April 2019

Finally two concurrent charm factories

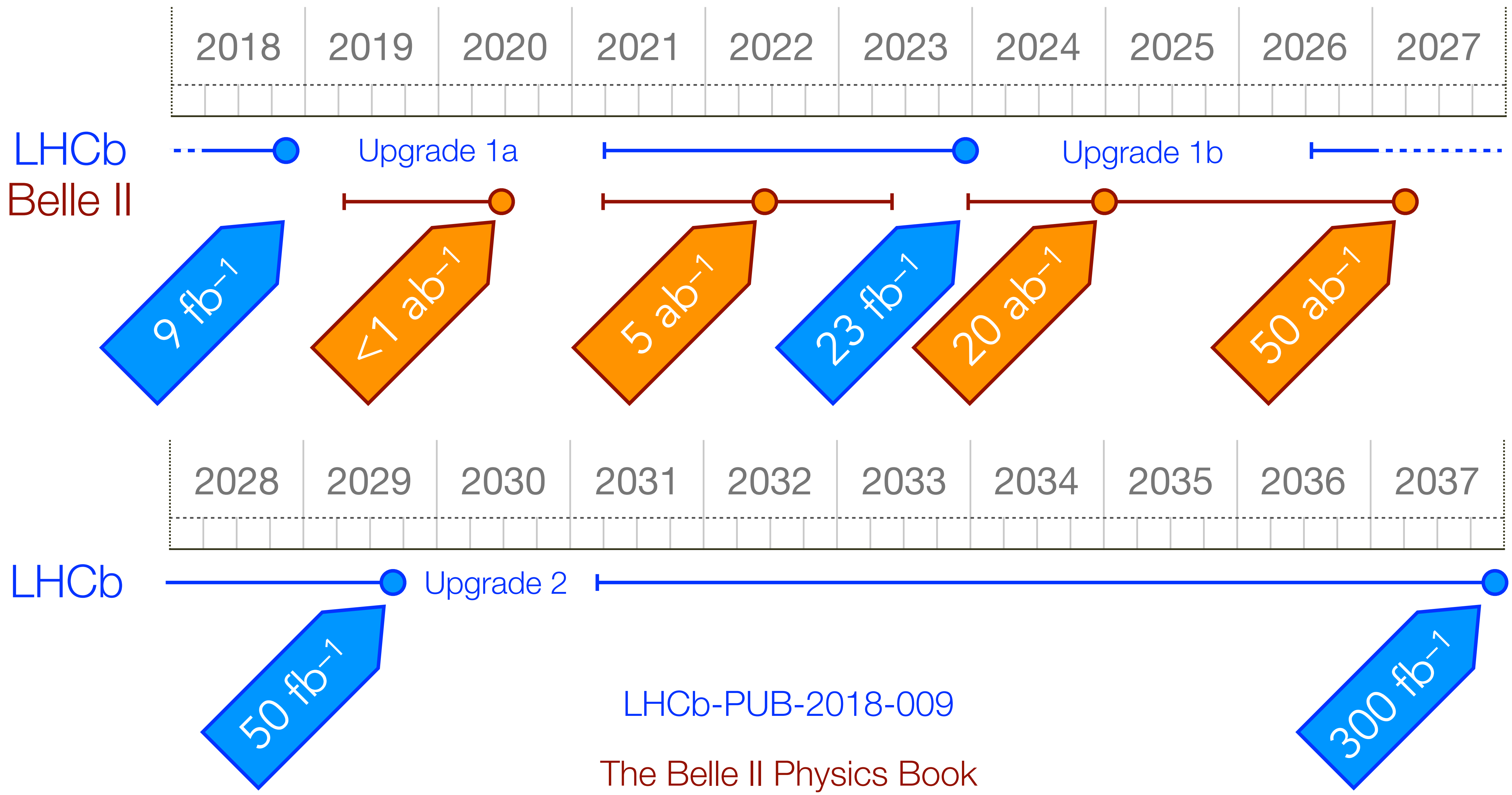
LHCb

- 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

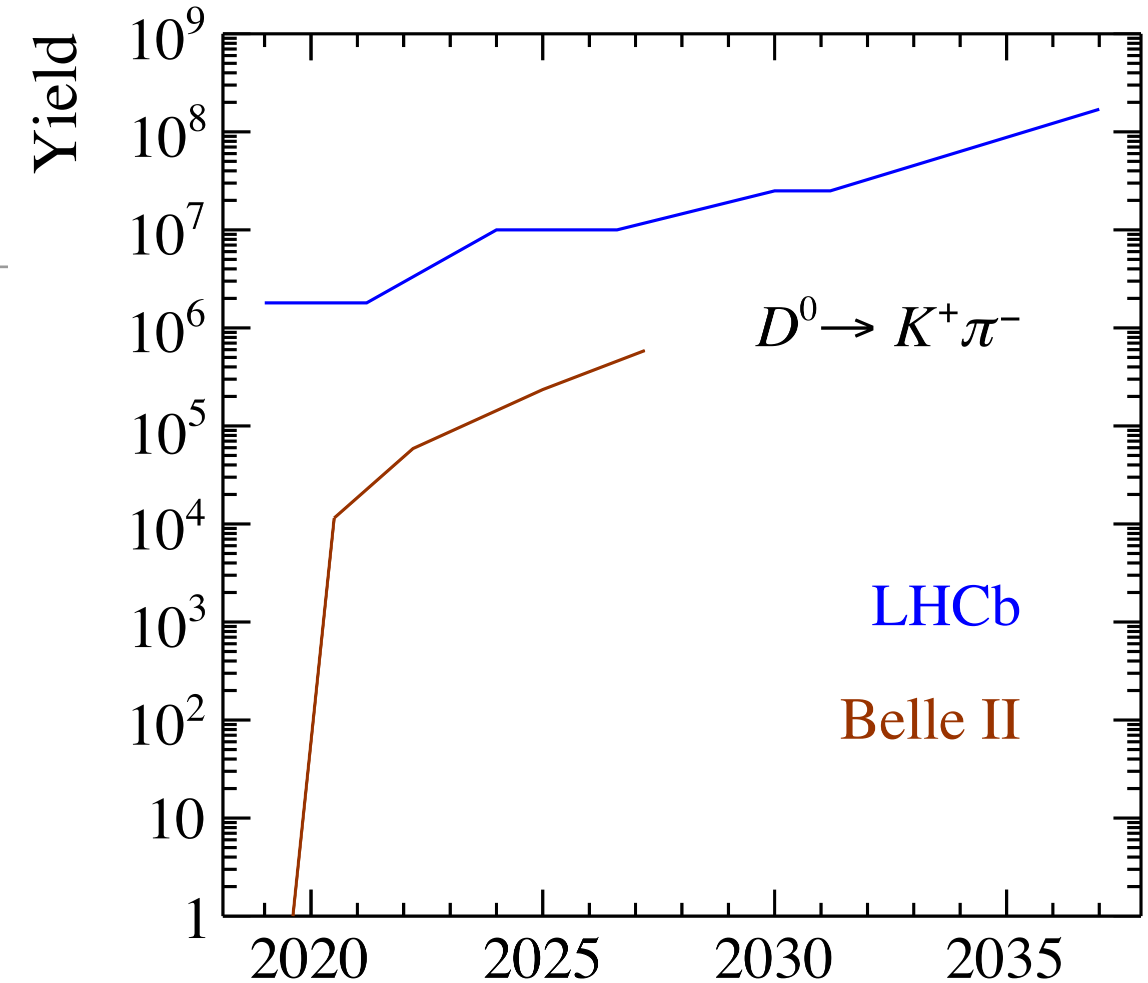


LHCb-PUB-2018-009

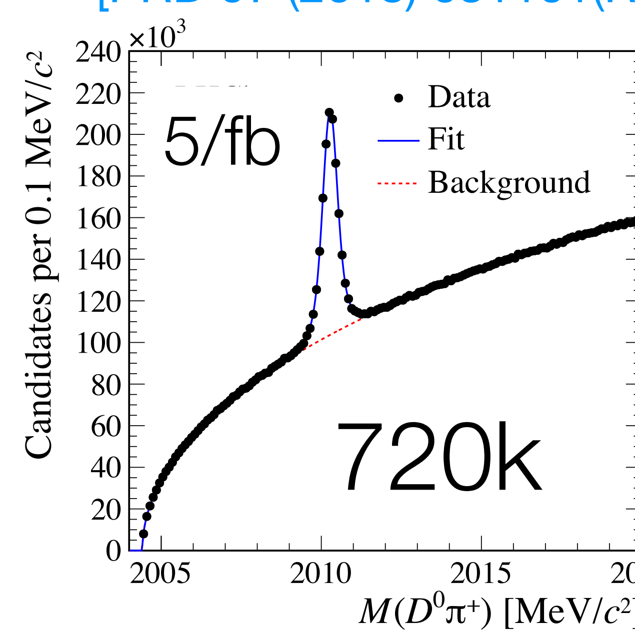
The Belle II Physics Book
(+ latest lumi projections)

Two-body decays

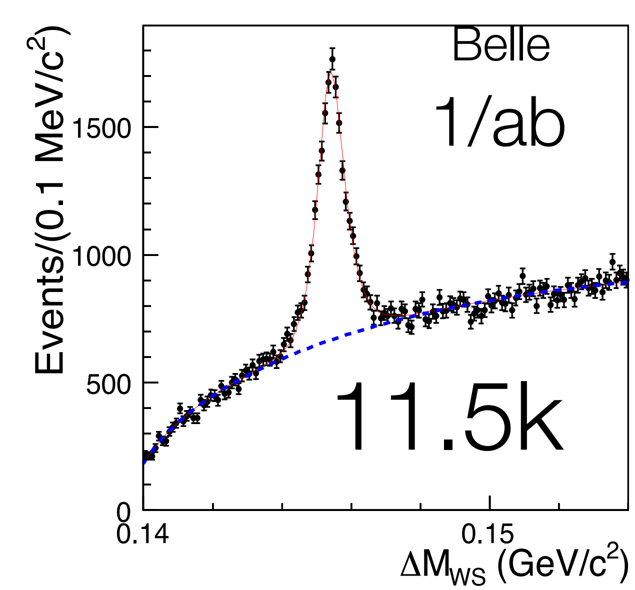
- Final states made of charged particles (including cases with one K_S) are by far dominated by LHCb — much larger yields, similar purities
  - Subject of **this talk**
- A crucial contribution from Belle II is expected on final state with neutrals
  - See **Marko's talk** later



[PRD 97 (2018) 031101(R)]



[PRL 112 (2014) 111801]



Direct CP violation

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

- Observed (raw) asymmetries suffer from instrumental and production effects

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

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

The CP asymmetry you want to measure

Detection asymmetry of tagging track (π^+ or μ^-)

Production asymmetry of parent hadron (D* or B)

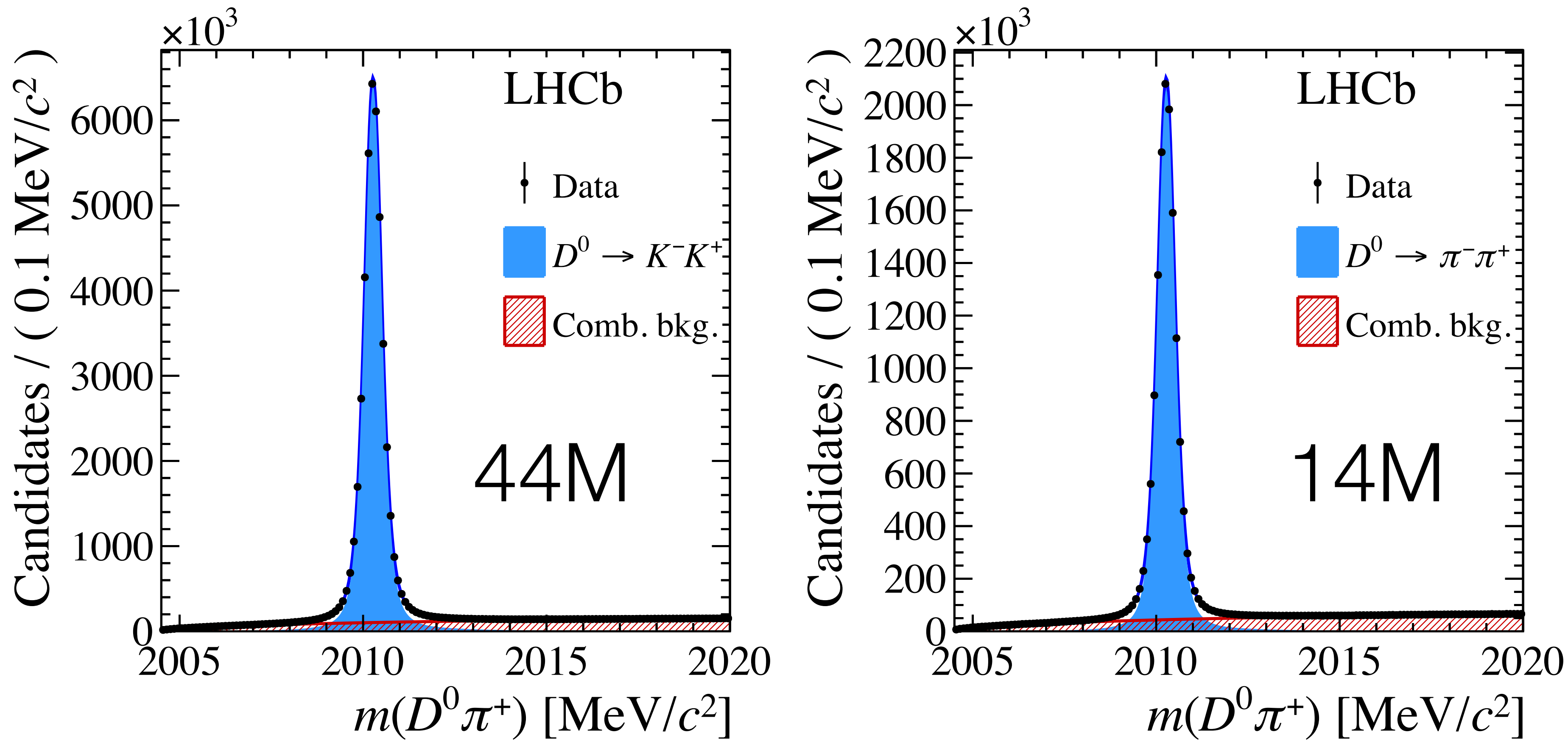
- Difference of raw asymmetries to cancel unwanted effects

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

- Similar strategy for most of other CP asymmetry measurements — one or more suitable additional modes are needed to remove detection/production asymmetries

Observation of CPV in charm

6/fb
Run 2

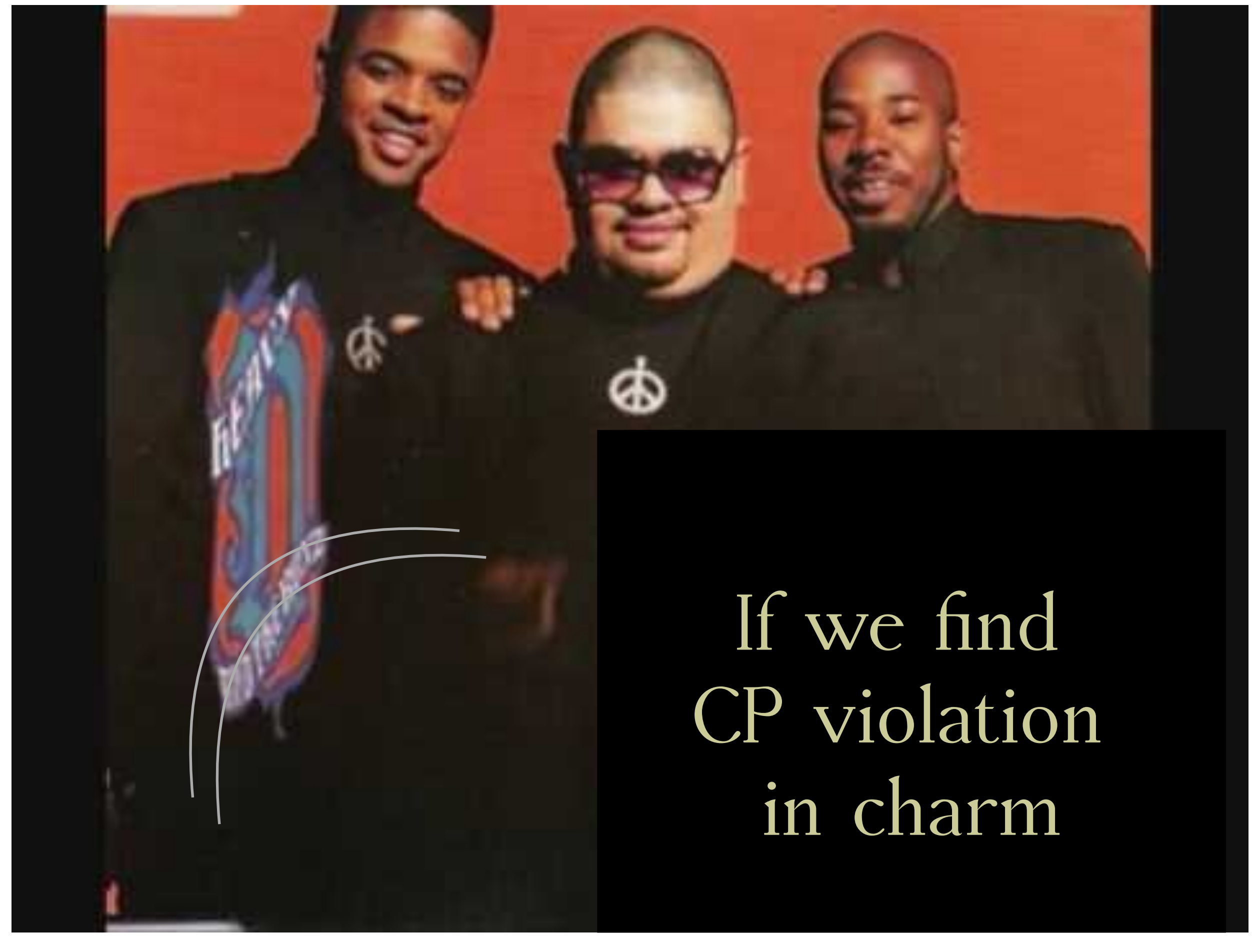


[arXiv:1903.08726]

- Combining with previous Run 1 result (for a total of 9/fb) and with independent sample of D^0 mesons from semileptonic B decays

$$\Delta A_{CP} = (-1.54 \pm 0.29)\times 10^{-3}$$

which is 5.3 standard deviations away from zero



… what are we gonna do with it?


it’s BSM!
it’s SM!

Understand its origin

- Measure CP asymmetries in many flavor-SU(3) related two-body decays — Belle II role will be crucial (final states with neutrals)

- Individual CP asymmetries rely on ability to determine the production and detection asymmetry with Cabibbo-favored decays where CPV is assumed to be negligible

- *e.g.* $A_{CP}(D^0 \to h^+h^-)$ is measured at LHCb (3/fb) using $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K_S\pi^+$ decays [PLB 767 (2017) 177]

$$A_{CP}(D^0 \to K^+K^-) = (1.4 \pm 1.5 \pm 1.0)\times10^{-3}$$
$$A_{CP}(D^0 \to \pi^+\pi^-) = (2.4 \pm 1.5 \pm 1.1)\times10^{-3}$$

- Latest HFLAV average for the direct CP asymmetries is ($A_{CP} \approx a_{CP}^{dir} + a_{CP}^{ind} \langle t/\tau \rangle$)

$$a_{CP}^{dir}(D^0 \to K^+K^-) = (-0.9 \pm 1.6)\times10^{-3}$$
$$a_{CP}^{dir}(D^0 \to \pi^+\pi^-) = (0.6 \pm 1.6)\times10^{-3}$$

The key: control detection asymmetries

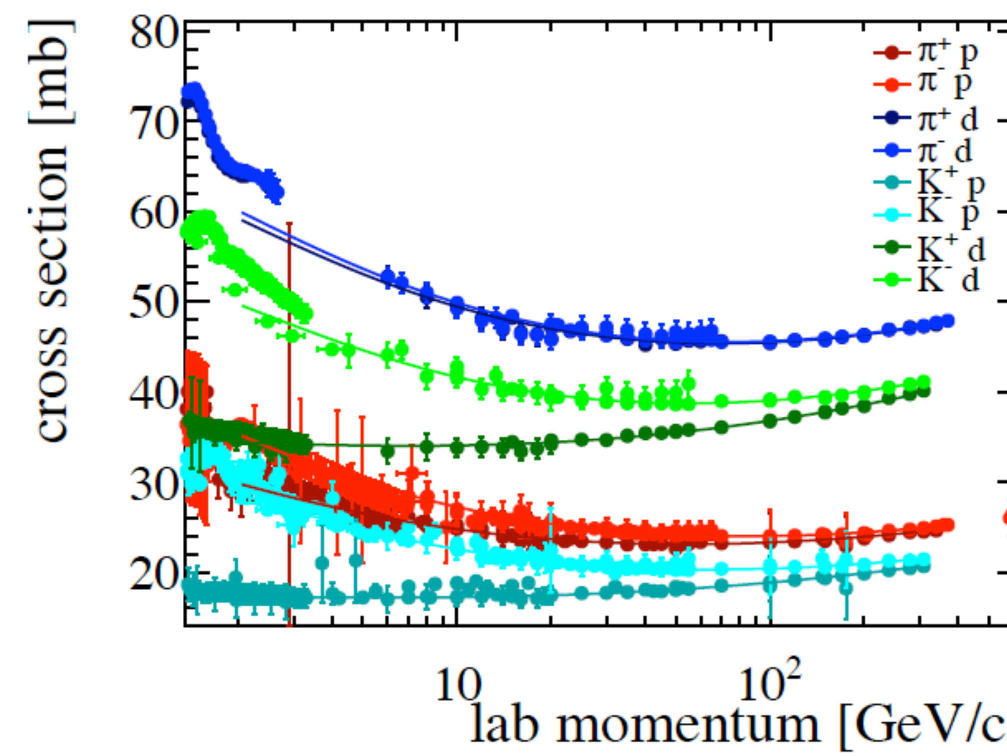
- Detector layout and/or differences in interaction cross section result in different reconstruction efficiencies for positively and negatively charged particles

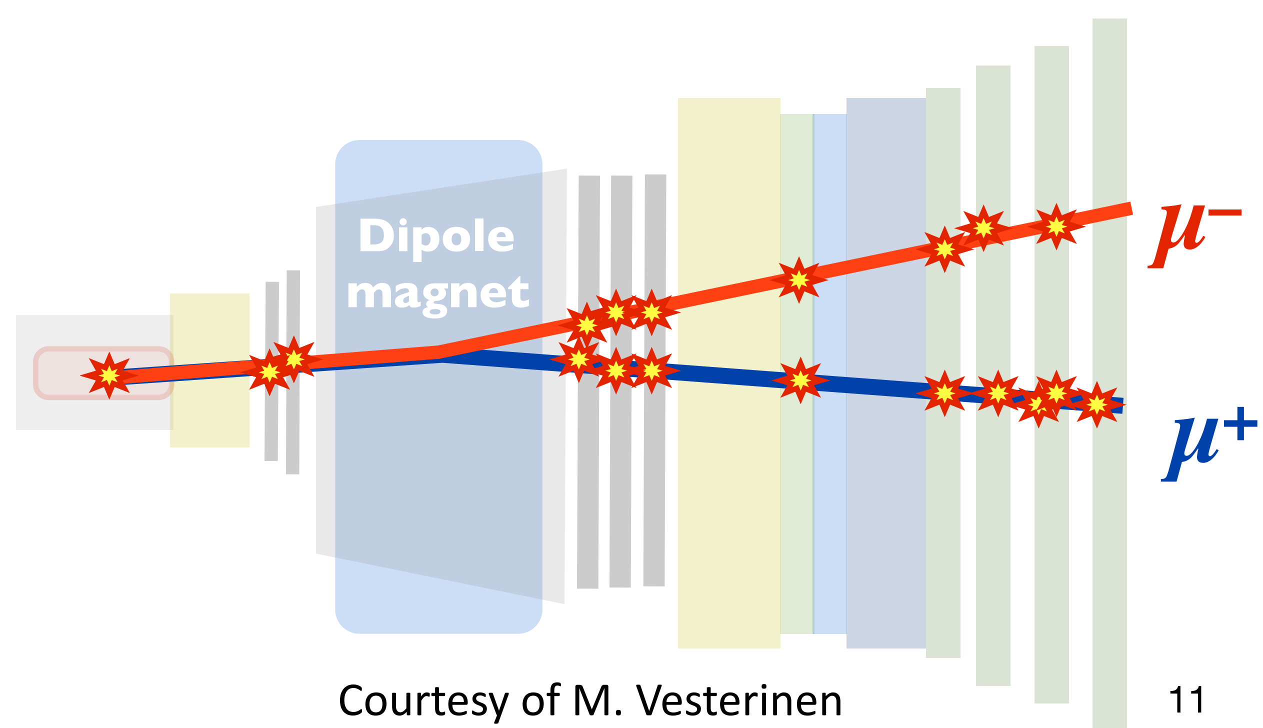
$$A_D(f) = \frac{\varepsilon(f) - \varepsilon(\bar{f})}{\varepsilon(f) + \varepsilon(\bar{f})}$$

- Some detection asymmetries can be largely reduced when averaging data collected with opposite magnet polarities — not enough for high-precision measurements

- More in Mika's talk later

Chin. Phys. C 38 (2014) 090001





Courtesy of M. Vesterinen

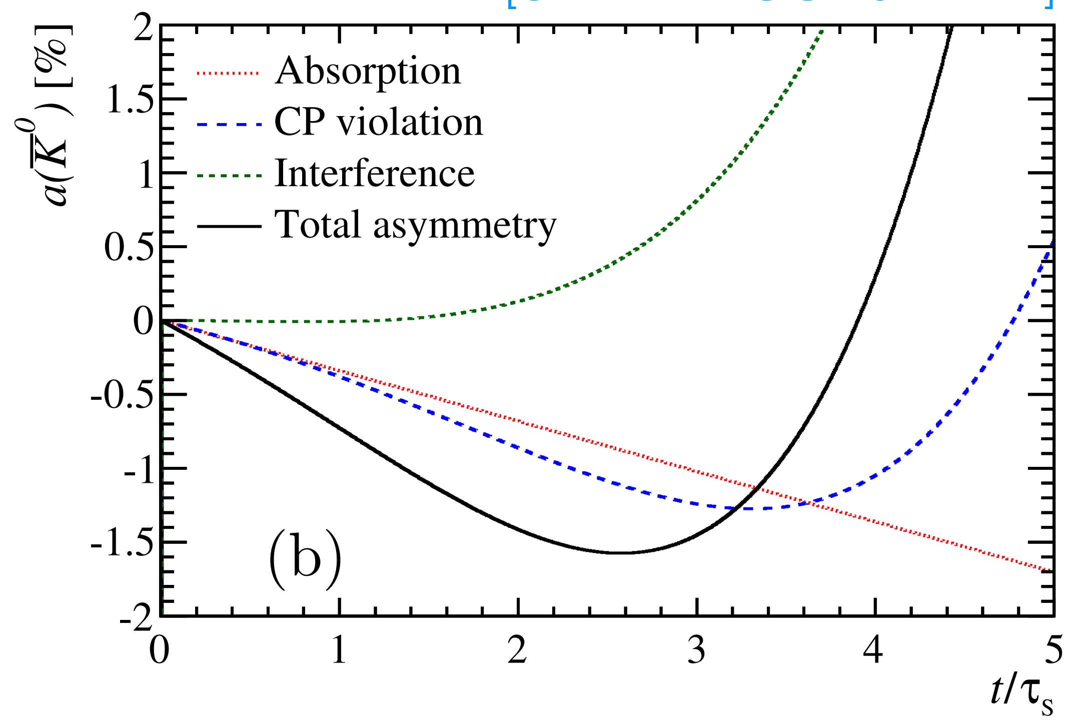
Neutral kaons asymmetry

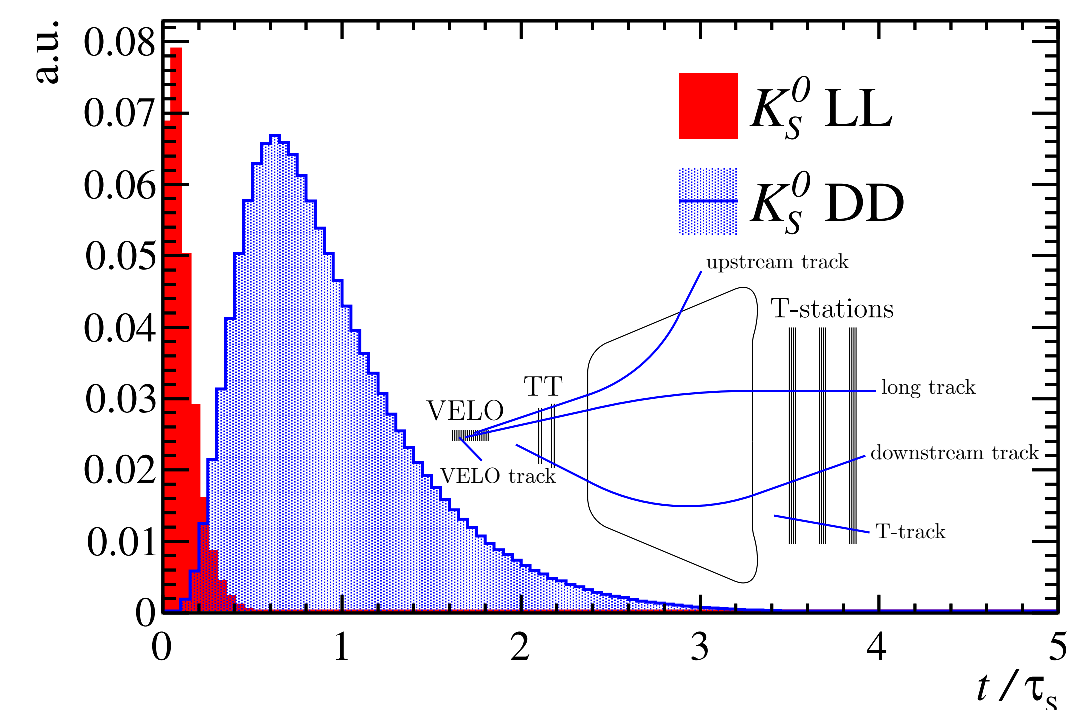
[CERN-THESIS-2014-274]

- Neutral kaons violates CP and their mixing can be affected by material interactions (*i.e.* regeneration of K_S in K_L beams)
- Both effects lead to tiny detection asymmetries when using K_S that decay in the VELO (LL)

$$A(K_S\ \mathrm{LL}) = (-0.73 \pm 0.05)\times10^{-3}$$
$$A(K_S\ \mathrm{DD}) = (-6.2 \pm 0.3)\times10^{-3}$$

- Uncertainty limited by the knowledge of the detector material — if not under control, may impact the ultimate precision
- CP asymmetries with one K_S mesons in the final state are currently limited to LL candidates (~1/3 of reconstructed decays)

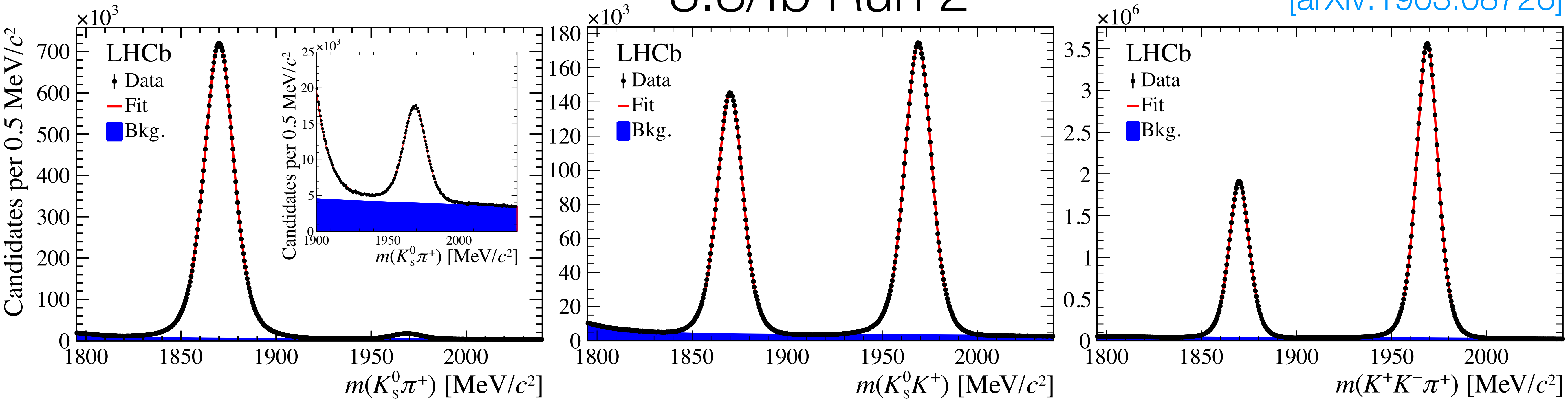




Example of other two-body modes

3.8/fb Run 2

[arXiv:1903.08726]



30.5M 0.6M 5.1M 6.5M 53.3M 107M

- Combined with Run 1 results yield

$$A_{CP}(D_s \to K_S\pi^+) = (1.6 \pm 1.7 \pm 0.5)\times 10^{-3}$$
$$A_{CP}(D^+ \to K_S K^+) = (-0.04 \pm 0.61 \pm 0.45)\times 10^{-3}$$
$$A_{CP}(D^+ \to \phi\pi^+) = (0.03 \pm 0.40 \pm 0.29)\times 10^{-3}$$

(the neutral kaon asymmetry is subtracted)

Overview of the possible reach

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
$D^0 \to K^+\pi^-$	9.1	LHCb (5/fb)	0.5	(4.0)
$D^0 \to K_S K_S$	15	Belle (1/ab)	2.8	2.3
$D_s \to K_S \pi^+$	18	LHCb (6.8/fb)	0.32	2.9
$D^+ \to K_S K^+$	0.76	LHCb (6.8/fb)	0.12	0.4
$D^0 \to K_S \bar{K}^{*0}$	3.0	LHCb (3/fb)	(0.06)	(?)
$D^0 \to K_S K^{*0}$	4.0	LHCb (3/fb)	(0.08)	(?)
$D^+ \to \phi\pi^+$	0.49	LHCb (4.8/fb)	0.06	0.4

Values in parentheses are my own (unofficial) projections

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

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

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

Mixing and indirect CP violation

Mixing with two-body modes

- Mostly sensitive to the normalised width difference — need multi-body decays to precisely measure x (see Jolanta's talk tomorrow)
- $D^0 \to K^+\pi^-$
  - Requires independent measurement of the strong-phase difference between $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^+\pi^-$ to access x and y
  - Gives direct access to $|q/p|$ and ϕ
- $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
  - Cannot directly access any of the underlying parameters, but with independent determination of (x,y) can provide tight bounds on $(|q/p|, \phi)$

[PRD 97 (2018) 031101(R)]

Mixing and CPV with $D^0 \to K^+\pi^-$

$$R(t) = \frac{\Gamma(D^0 \to K^+\pi^-|t)}{\Gamma(D^0 \to K^-\pi^+|t)} \approx R_D + \sqrt{R_D}y'\left(\frac{t}{\tau}\right) + \frac{x'^2+y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

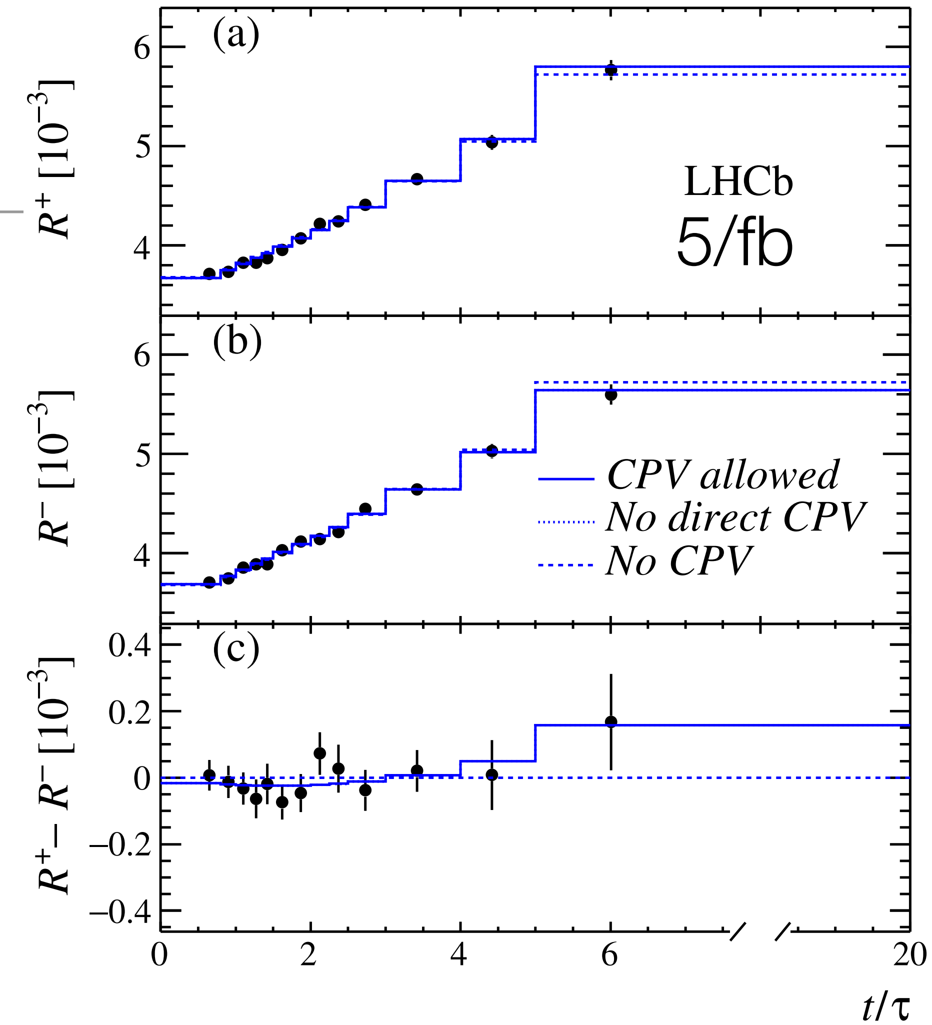
- The latest result from LHCb (5/fb) measures

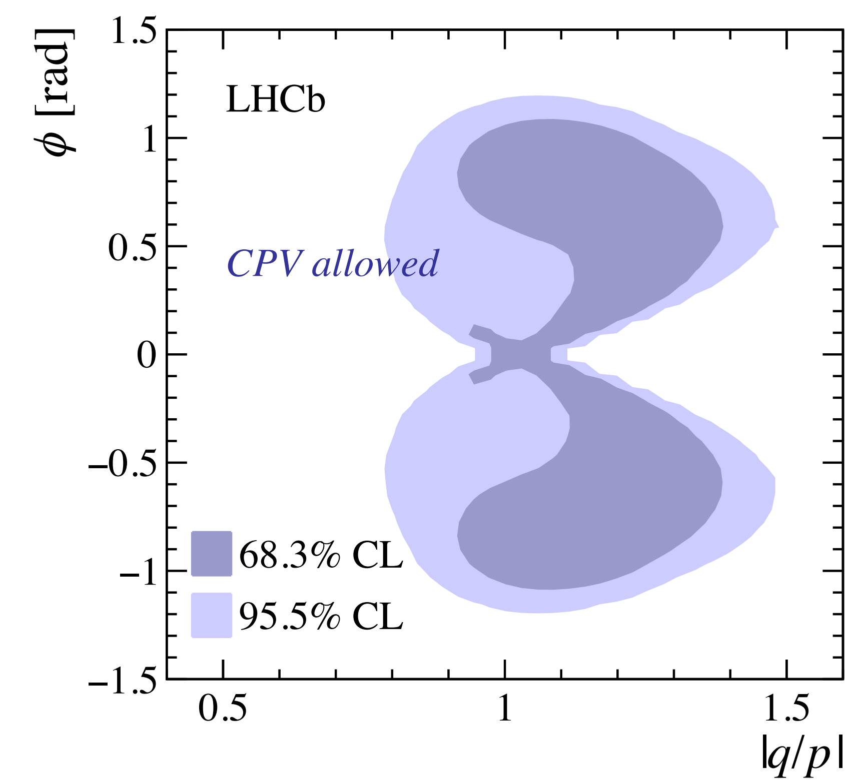
$$x'^2 = (3.9 \pm 2.7)\times 10^{-5}$$
$$y' = (5.28 \pm 0.52)\times 10^{-3}$$

and provides stringent bounds on direct CPV in DCS decays and CPV in mixing

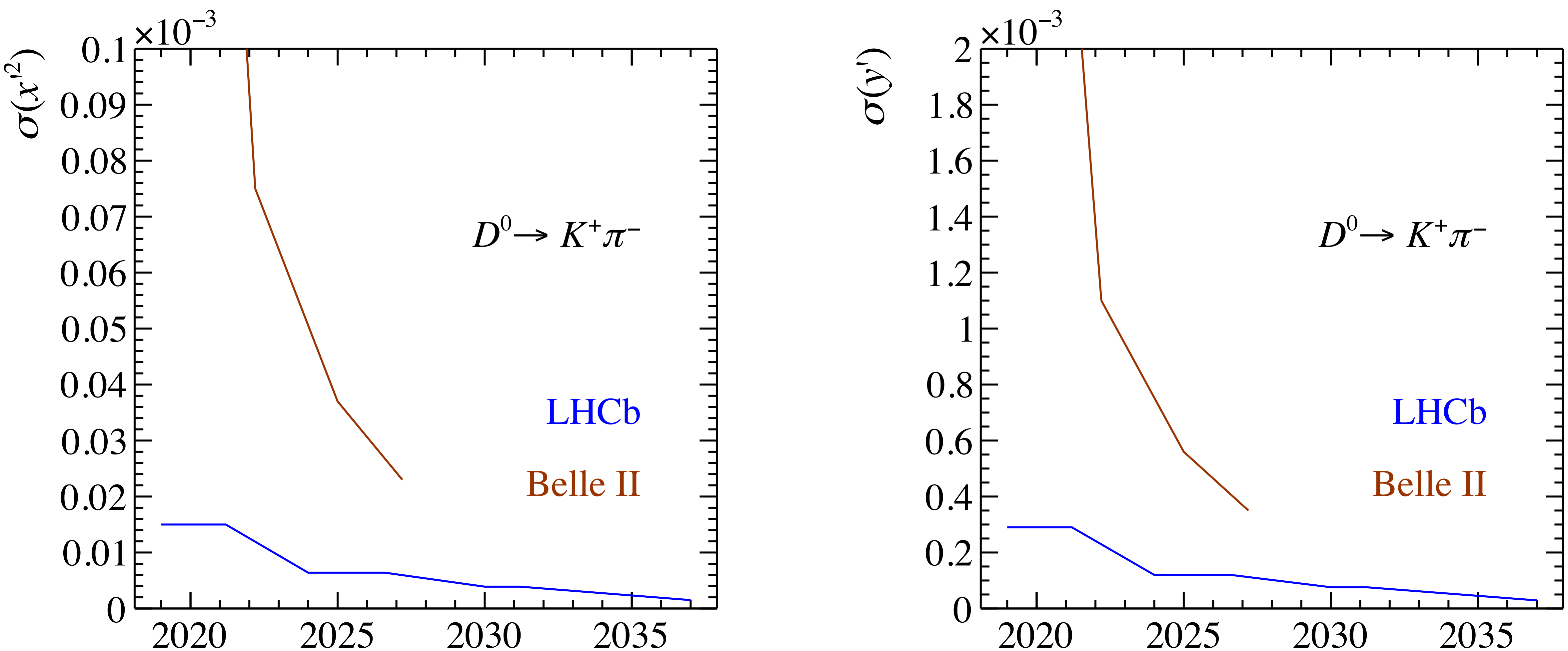
$$1.00 < |q/p| < 1.35 \text{ @ } 68\% \text{ CL}$$

- Dominant systematic (<50% of the statistical uncertainty) is due to contamination of charm from *b*-hadron decays





Mixing and CPV with $D^0 \to K^+\pi^-$: prospects



- Precision on $|q/p|$ and ϕ expected to be ~1% (~1 degree) with 300/fb
- Systematic uncertainties estimated using control samples of data — measurement expected to remain dominated by statistics

Indirect CPV in $D^0 \to h^+h^-$ decays

[PRL 118 (2017) 261803]

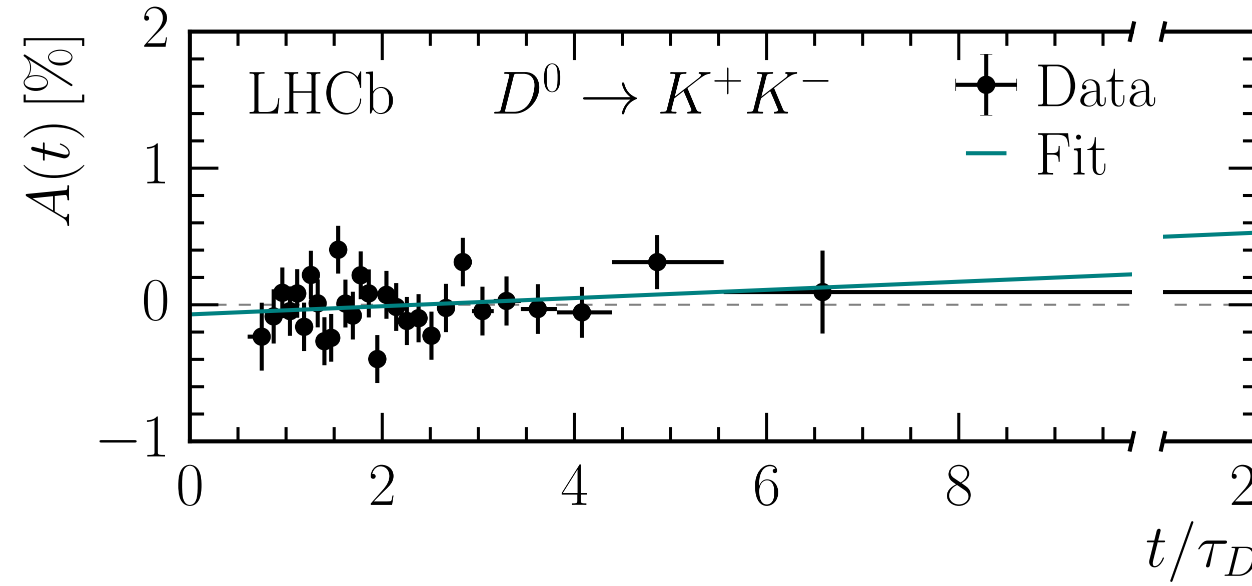
- Time-dependent asymmetry between D^0 and $\bar{D}^0$ to CP-even final states: linear term is $-A_\Gamma \approx x \sin\phi$

- Combining K^+K^- and $\pi^+\pi^-$ modes in 3/fb of LHCb data yields

$$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10)\times 10^{-3}$$

- Huge samples of $D^0 \to K^-\pi^+$ decays used to control time-dependent detector-induced asymmetries

- No official projections from Belle II (but yields scale as for $D^0 \to K^+\pi^-$), hence Belle II with 50/ab will not reach LHCb precision with 9/fb



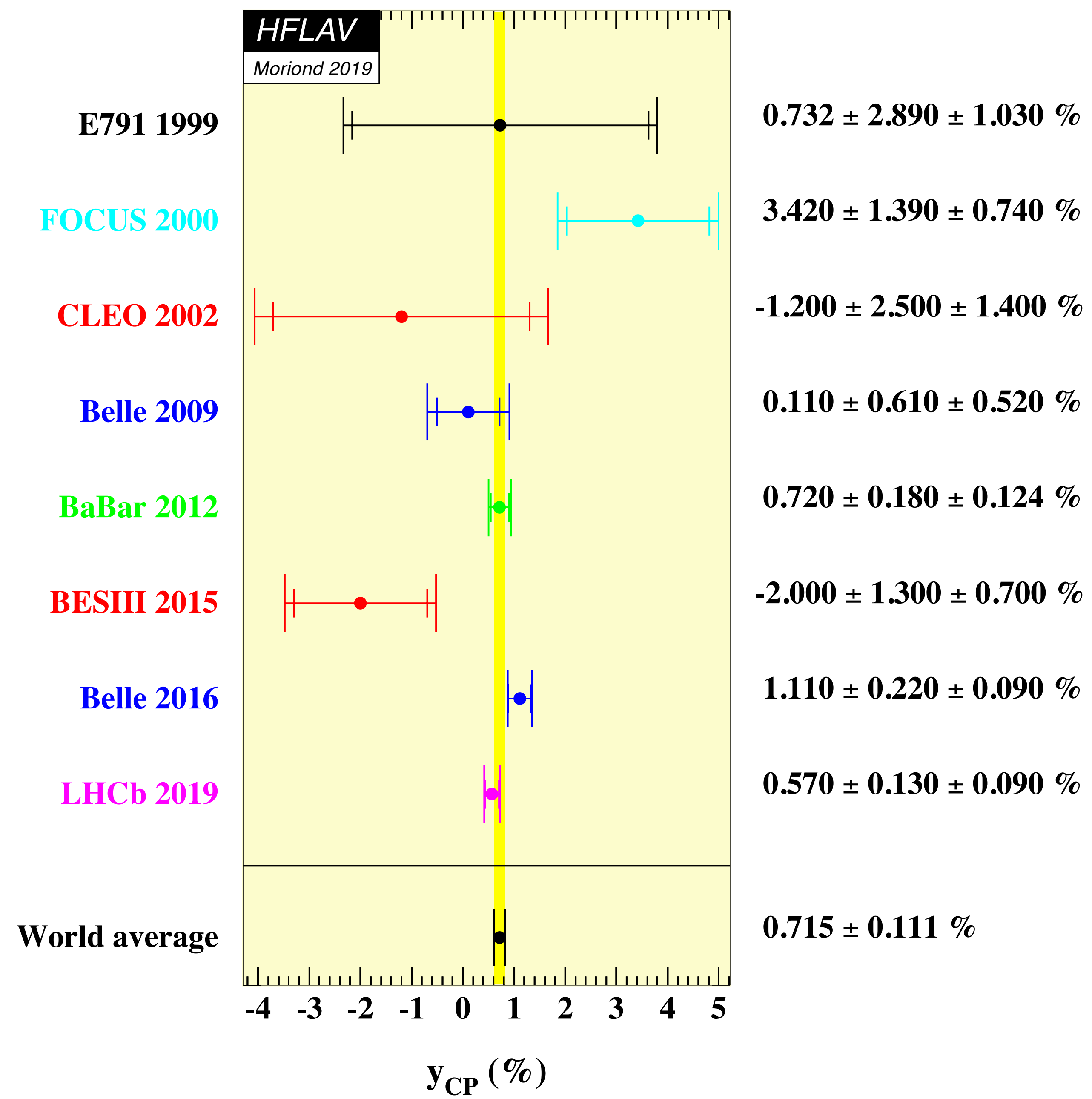
LHCb	K^+K^-		$\pi^+\pi^-$	
	Yield [10^9]	$\sigma(A_\Gamma)$ [10^{-5}]	Yield [10^9]	$\sigma(A_\Gamma)$ [10^{-5}]
9/fb	0.06	13	0.02	24
50/fb	0.79	3.5	0.24	6.5
300/fb	5.3	1.4	1.6	2.5

What about y_{CP}?

- Effective lifetime of decays to CP-even final state (relative to CP-mixed)

$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(h^+h^-)} - 1$$

- Most precise measurement from LHCb (3/fb) using D^0 from semileptonic B decays [PRL 122 (2019) 011802]
- No official projections available — would require nontrivial assumptions on systematics
- Could be a measurement where LHCb and Belle II can compete



Summary


The future can be bright…
but getting there it’s quite
a challenge