CP violation & semileptonic decays in beauty and charm

LHCP June 8, 2018
Laurent Dufour, *on behalf of the ATLAS, CMS and LHCb collaborations*

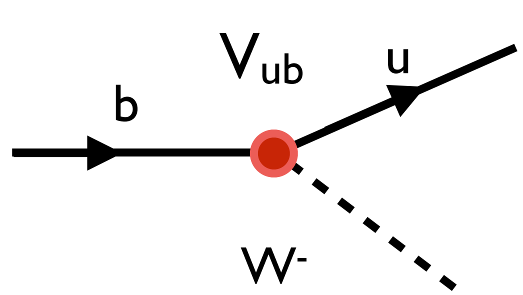
CP violation

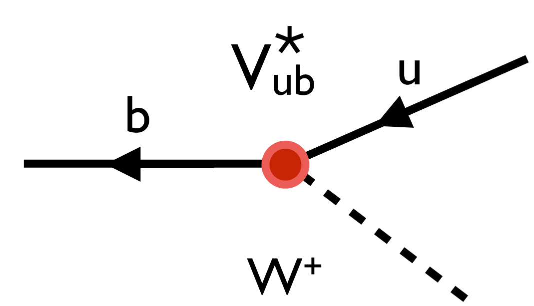
In the Standard Model: CP violation is only there in the **weak interaction**. The charged-current interaction for quarks is described by the **CKM matrix**

Wolfenstein parametrisation

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Complex: source of CP violation!



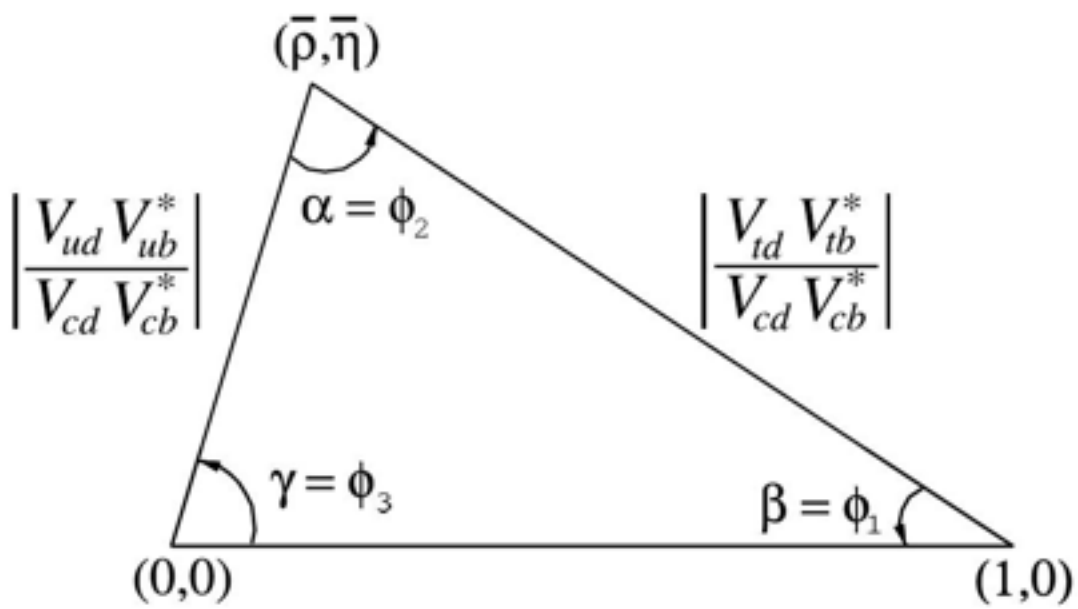


CP violation

Wolfenstein parametrisation

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

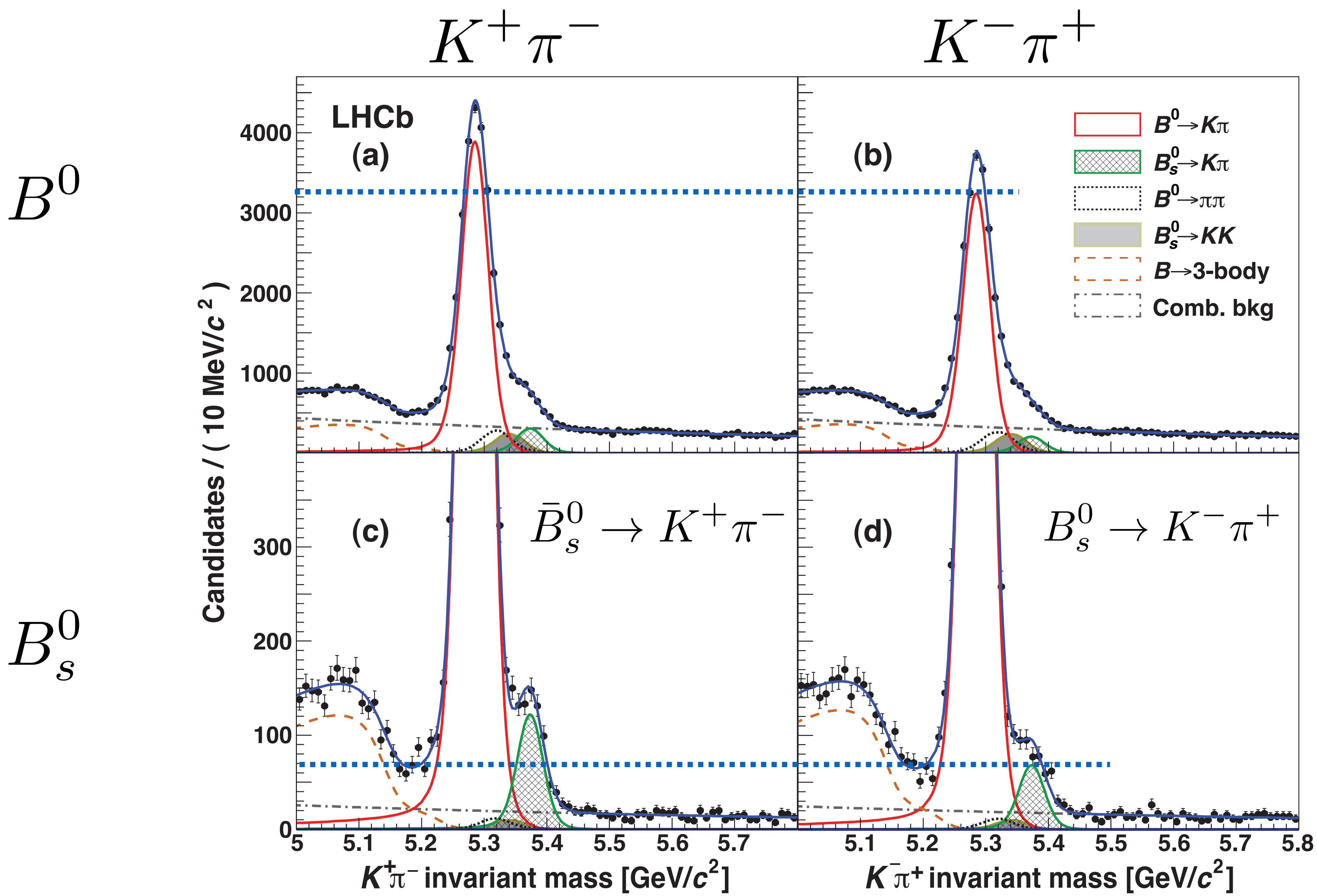
Unitarity $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ B^0 meson



Test the consistency of this triangle

[LHCB-PAPER-2011-029]

Example of CP violation



[LHCb-PAPER-2018-006]

LHCb Run-1 data set

$B_s \to K^- \pi^+$, $B^0 \to K^+ \pi^-$

$$A_{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$

$\bar{A}_{\bar{f}}$ Amplitude of $\bar{B}^0$ to $K^-\pi^+$

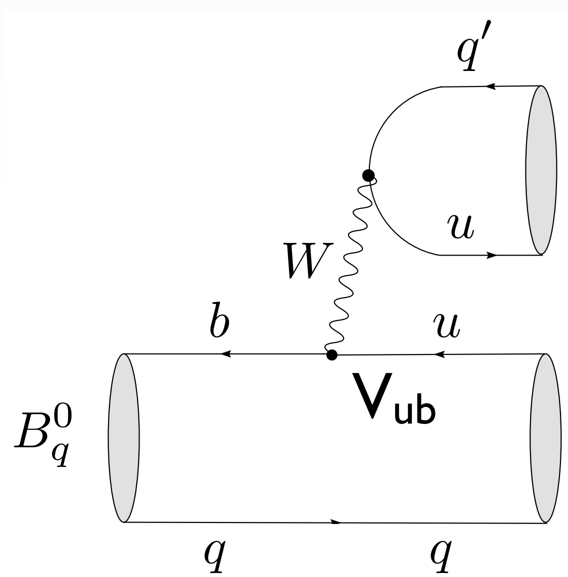
A_f Amplitude of B^0 to $K^+\pi^-$

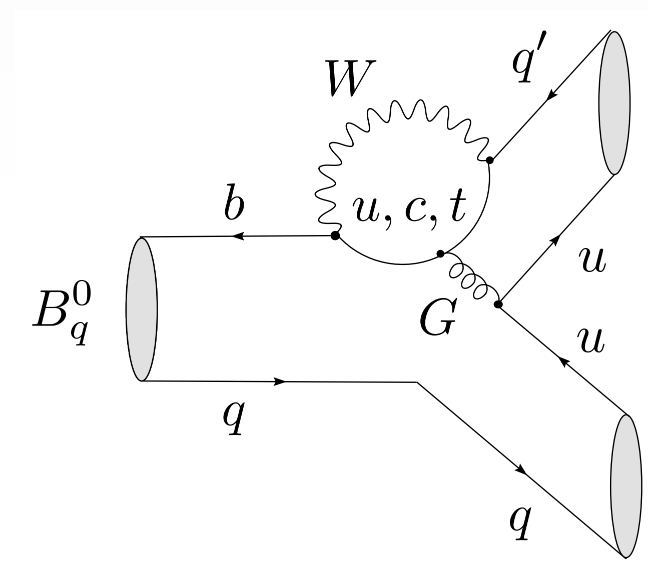
$B_s \to K^- \pi^+$, $B^0 \to K^+ \pi^-$

$$A_{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$

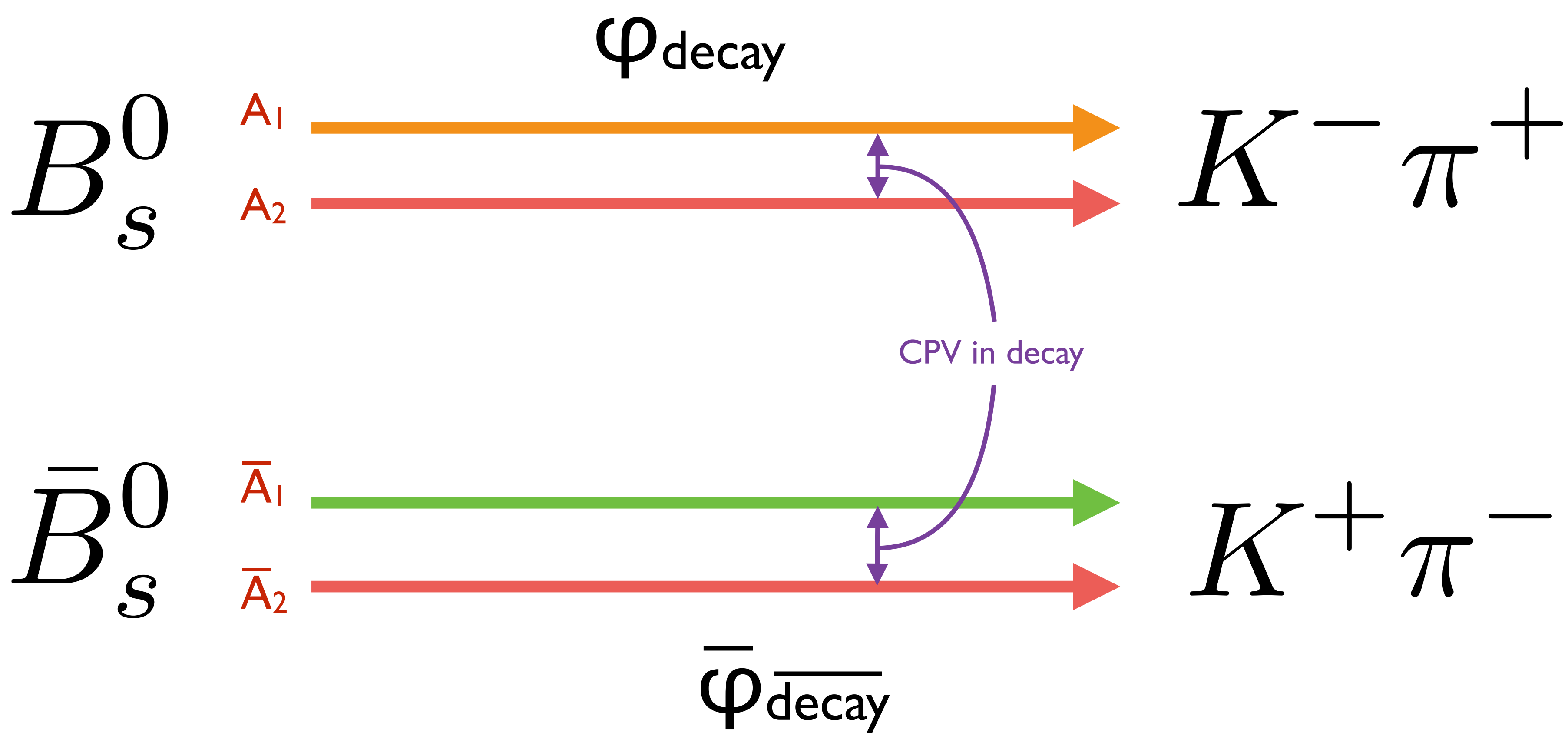
$\bar{A}_{\bar{f}}$ Amplitude of $\bar{B}^0$ to $K^- \pi^+$

A_f Amplitude of B^0 to $K^+ \pi^-$

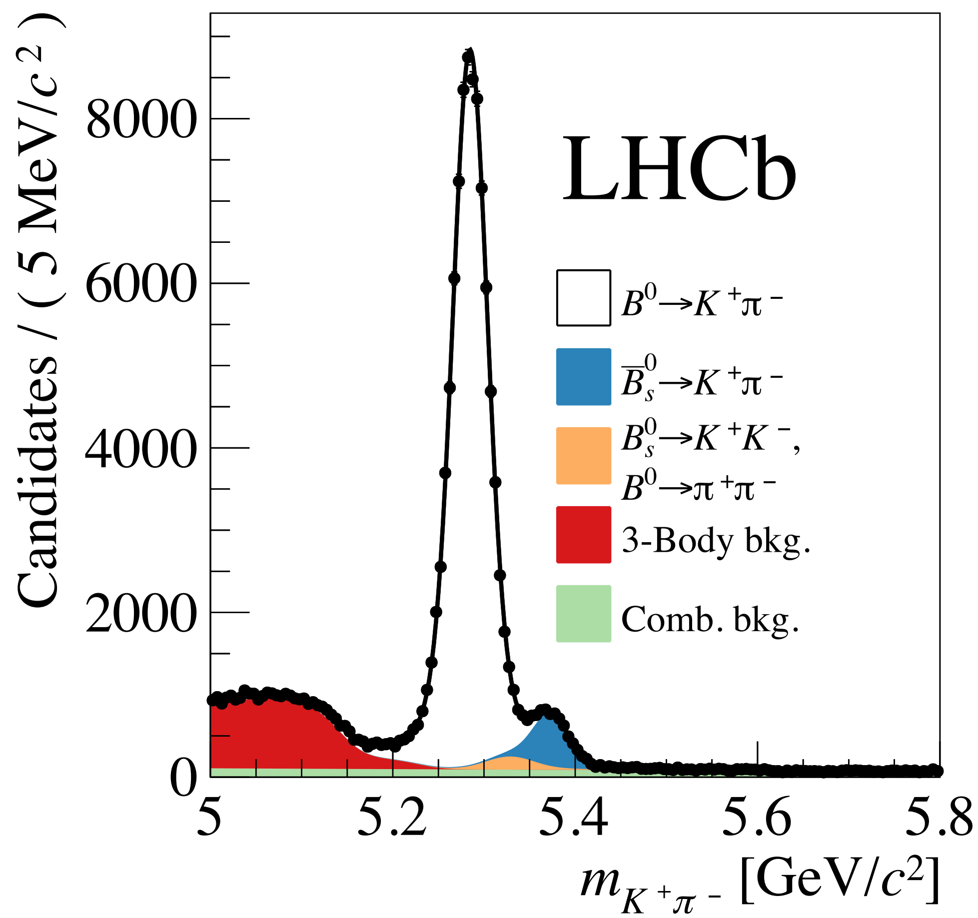




CP violation in decay



$B_s \to K^- \pi^+$, $B^0 \to K^+ \pi^-$



STRATEGY

Count the number of decays + correct for the production and instrumental asymmetry.

RESULT

$$A_{CP}^{B^0} = -0.084 \pm 0.004 \pm 0.003$$
$$A_{CP}^{B_s^0} = 0.213 \pm 0.015 \pm 0.007$$
$$\Delta = -0.11 \pm 0.04 \pm 0.03$$

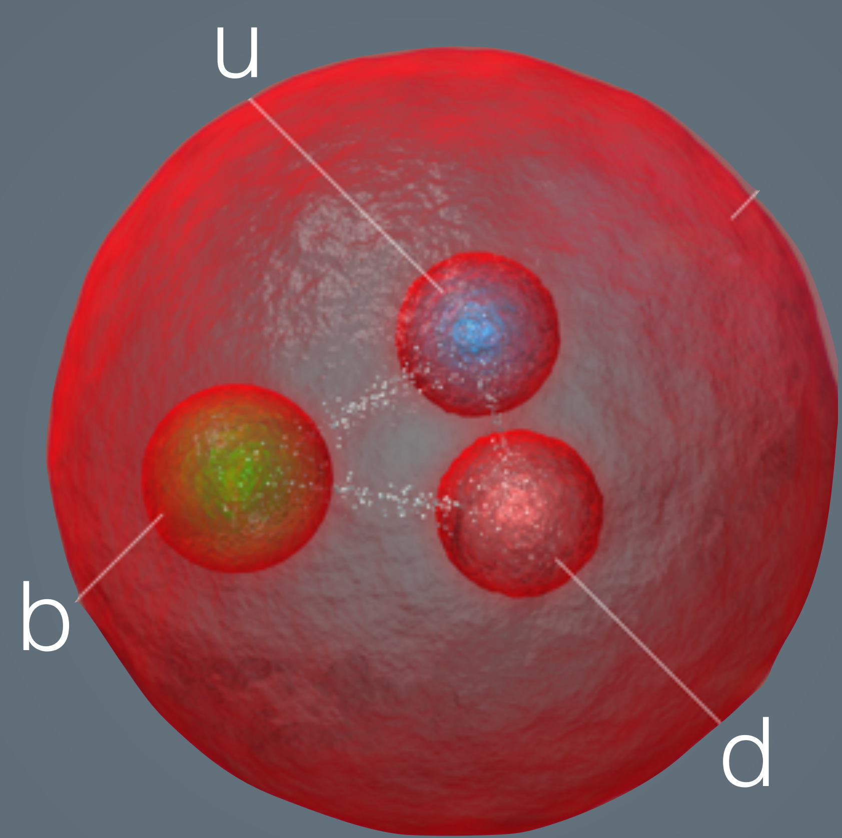
U-SPIN[1]

2.2σ

$$\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B_s^0}} + \frac{\mathcal{B}\left(B_s^0 \to \pi^+ K^-\right)}{\mathcal{B}\left(B^0 \to K^+\pi^-\right)} \frac{\tau_d}{\tau_s} = 0,$$

[1]: H.J. Lipkin, Phys. Lett. B621 (2005) 126

b baryons: Λ_b

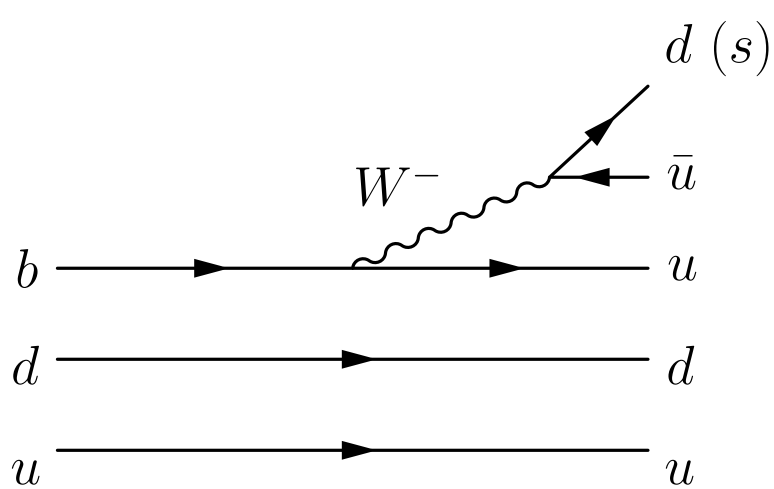


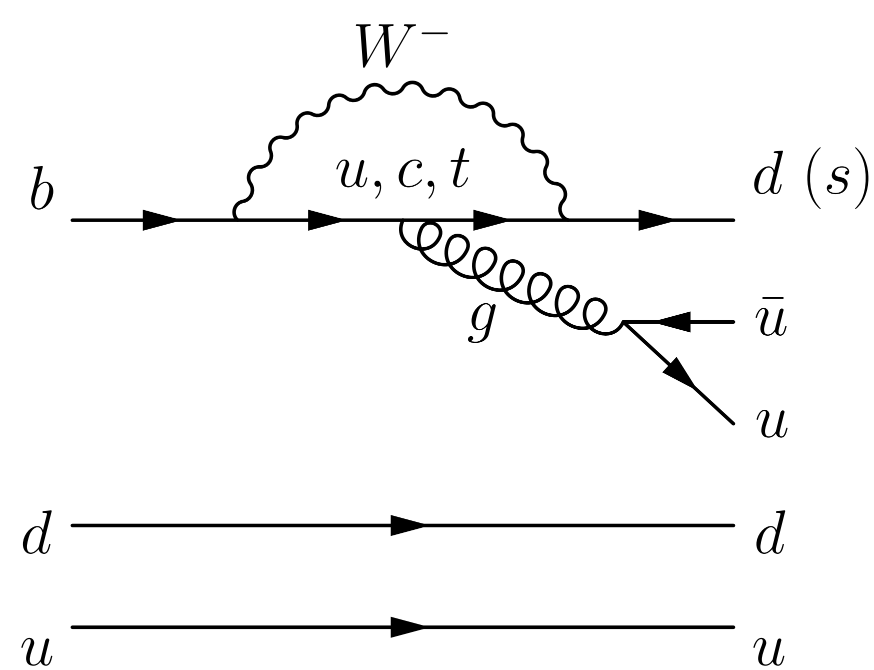
[LHCB-PAPER-2018-025 in prep]

LHCb Run-1 data set

$\Lambda_b \to pK$, $\Lambda_b \to p\pi$

Similar diagrams to $B_s \to K^- \pi^+$, $B^0 \to K^+ \pi^-$!





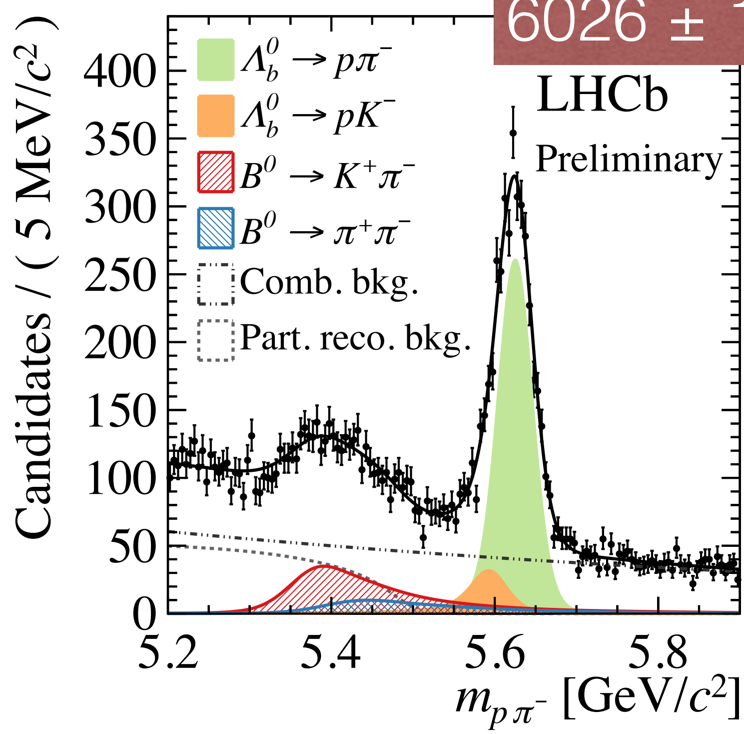
New

[LHCB-PAPER-2018-025 in prep]

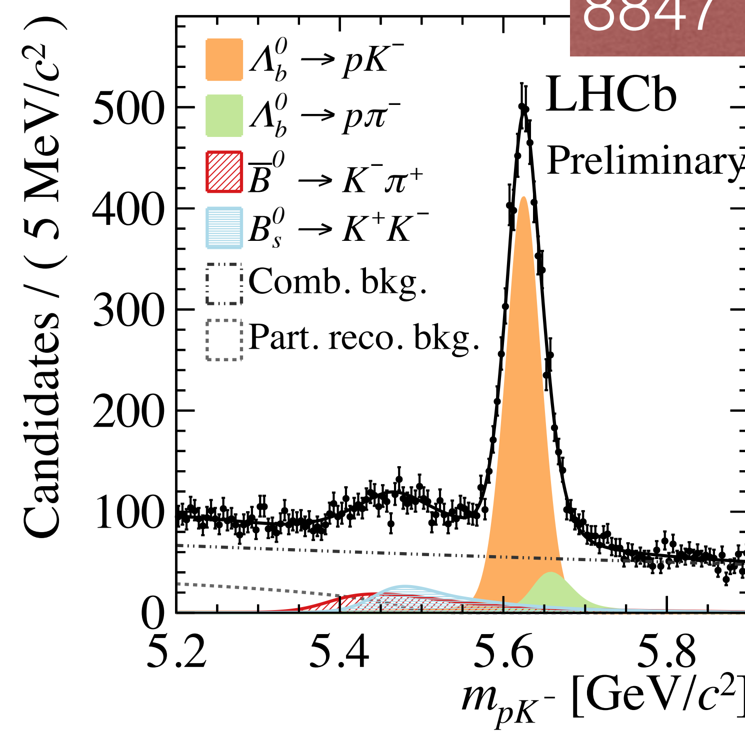
LHCb Run-I data set

$\Lambda_b \to pK$, $\Lambda_b \to p\pi$

6026 ± 105



8847 ± 125



RESULT

$$A_{CP}^{pK} = -0.020 \pm 0.013 \pm 0.019$$
$$A_{CP}^{p\pi} = -0.035 \pm 0.017 \pm 0.020$$

production + instr. asymmetries, correlated!

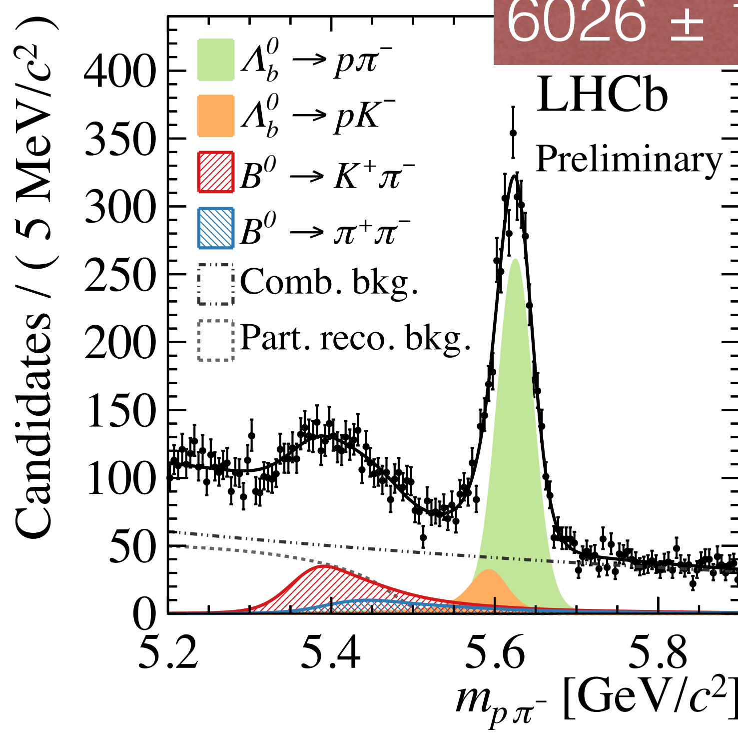
New

[LHCB-PAPER-2018-025 in prep]

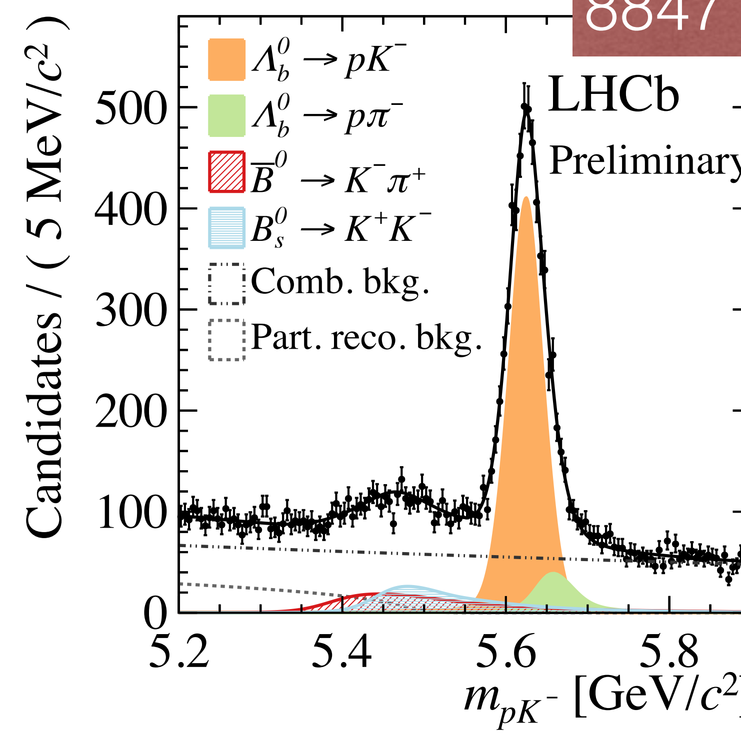
LHCb Run-1 data set

$\Lambda_b \to pK$, $\Lambda_b \to p\pi$

6026 ± 105



8847 ± 125



RESULT

$$A_{CP}^{pK} = -0.020 \pm 0.013 \pm 0.019$$

$$A_{CP}^{p\pi} = -0.035 \pm 0.017 \pm 0.020$$

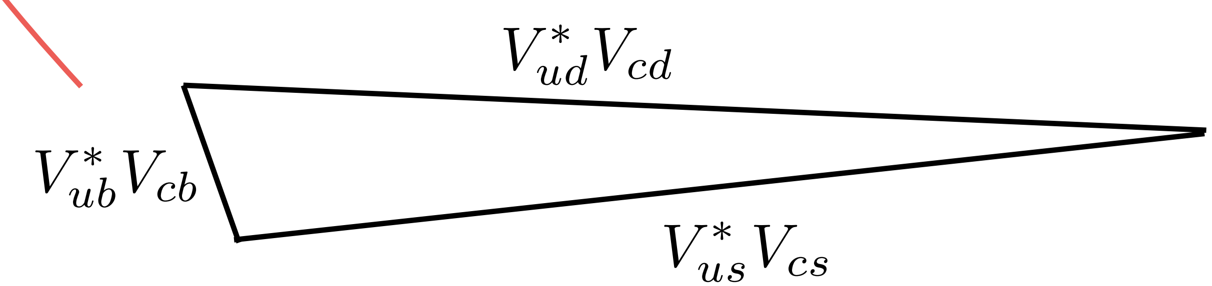
$$+0.013 \pm 0.021 \pm 0.013$$

production + instr. asymmetries, correlated!

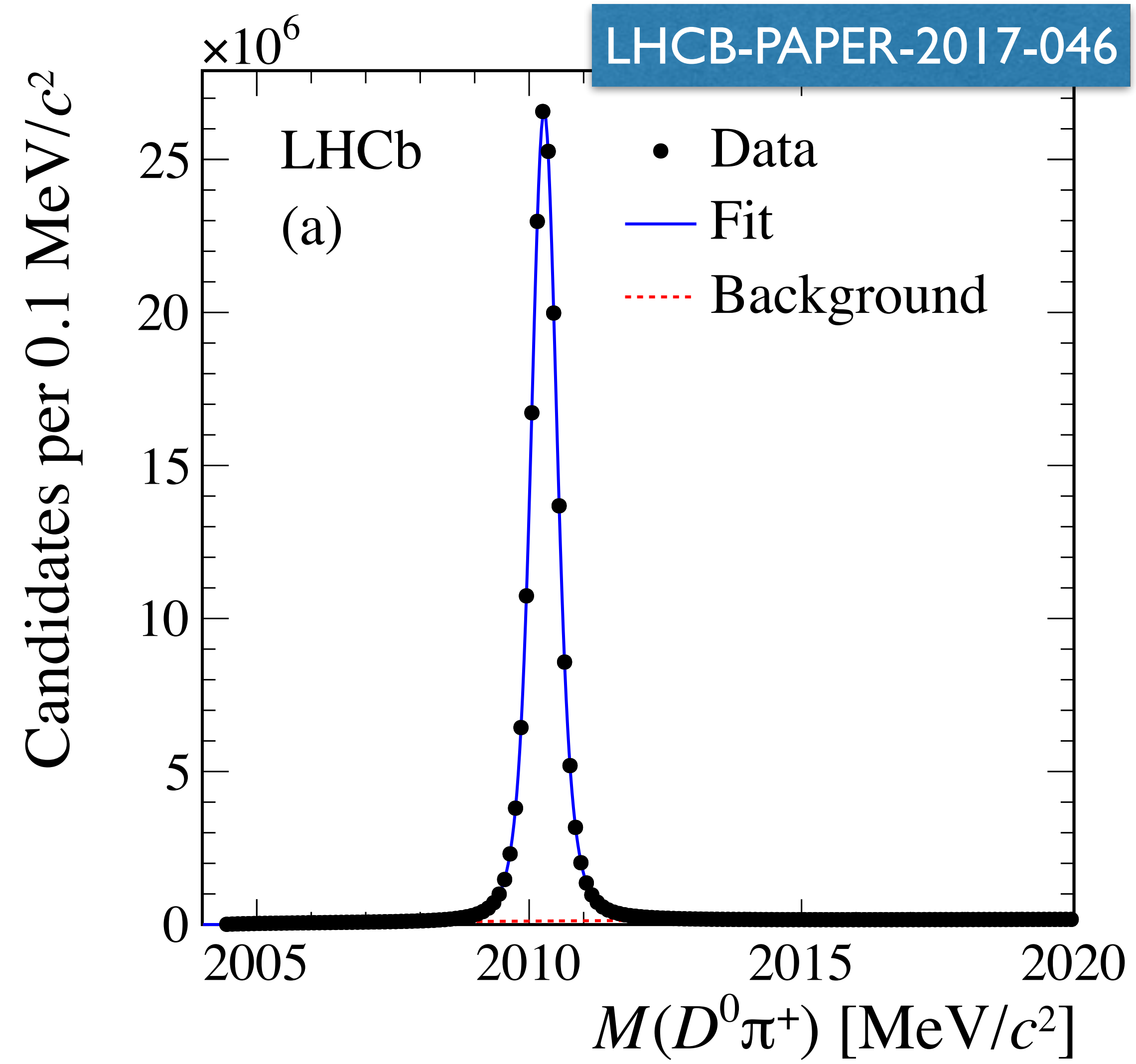
-

Direct CPV in charm

- Complicated calculations.
- Expectation: little CP violation.
- ✓ Enormous production at the LHC



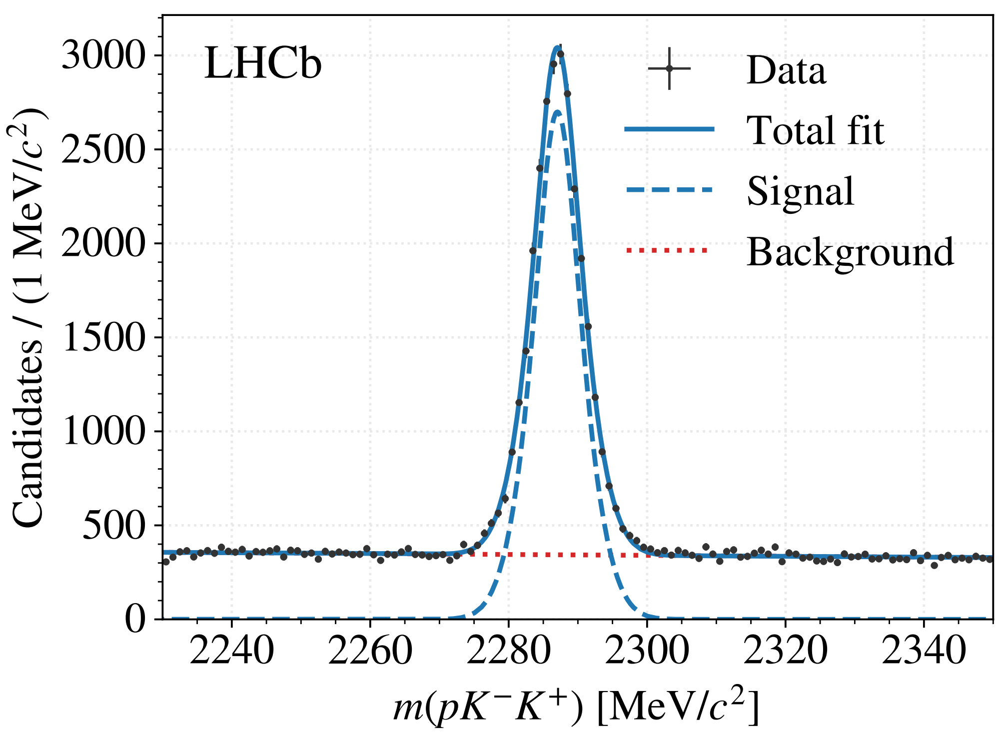
(not to scale)

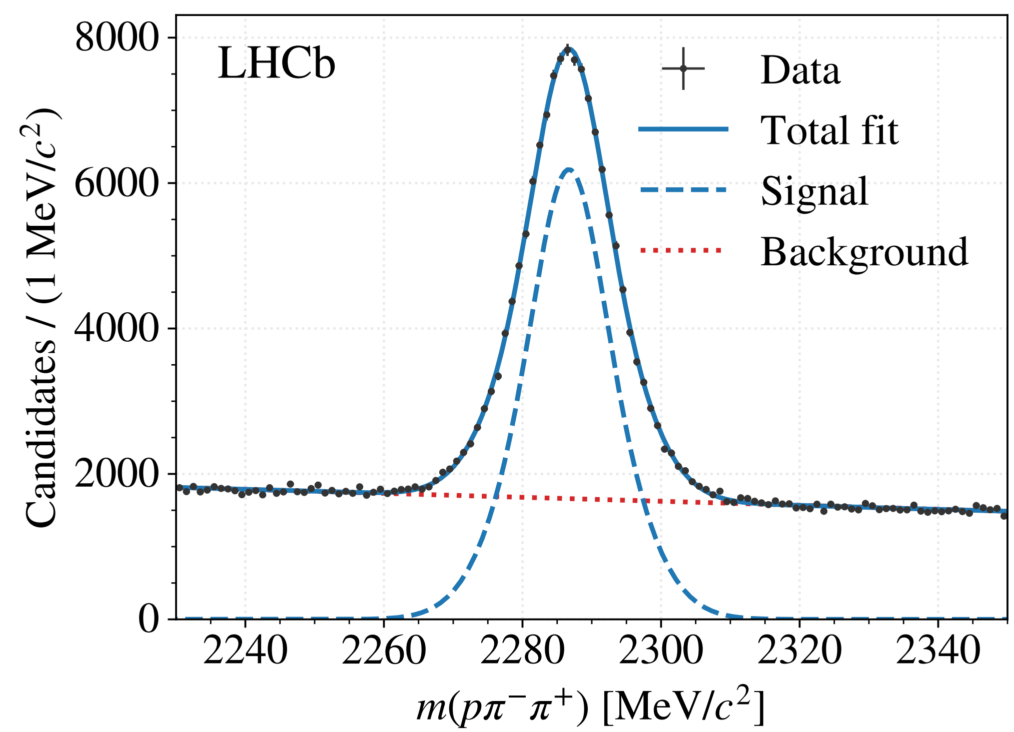


[LHCb-PAPER-2017-044]

LHCb Run-1 data set

ΔA_{CP} Λ_c^+





CPV in Cabibbo suppressed $\Lambda_c \rightarrow pKK$ and $\Lambda_c \rightarrow p\pi\pi$?

Optimise for the *difference* only:

$$A_{CP}\left(\Lambda_c^+ \to pK^+K^-\right) - A_{CP}\left(\Lambda_c^+ \to p\pi^+\pi^-\right)$$

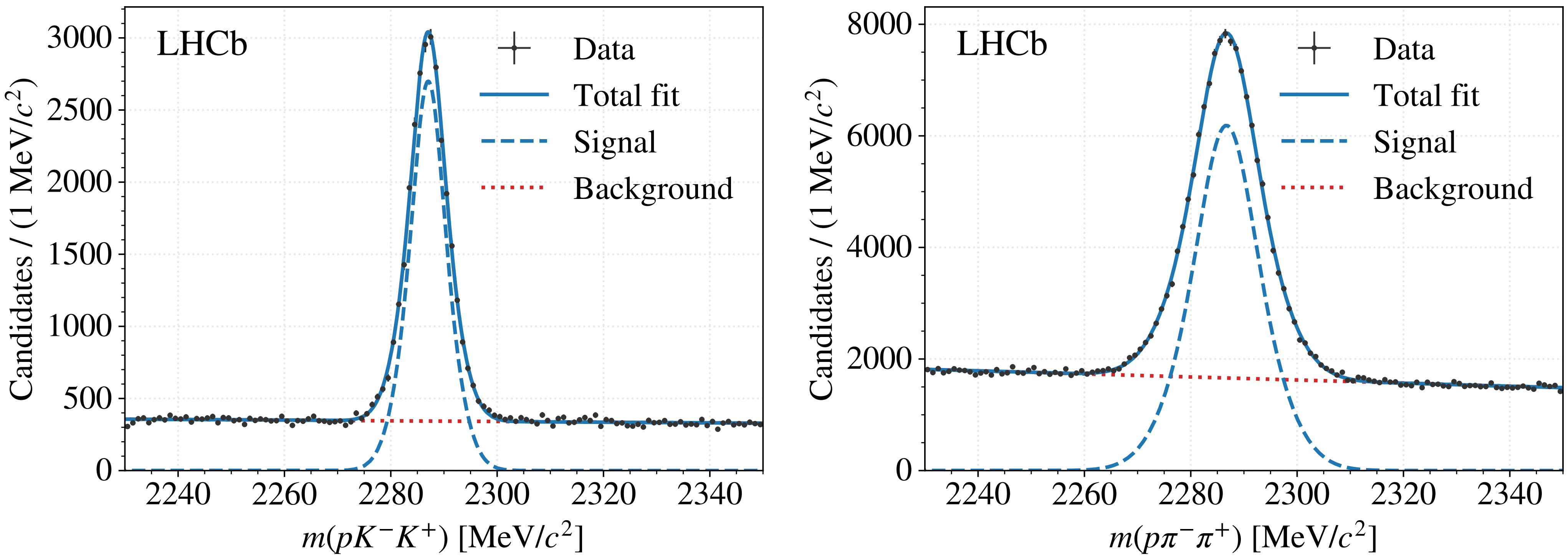
weighting procedure

STRATEGY

[LHCb-PAPER-2017-044]

LHCb Run-1 data set

ΔA_{CP} Λ_c^+



Details: Talk by A. Pearce, this afternoon

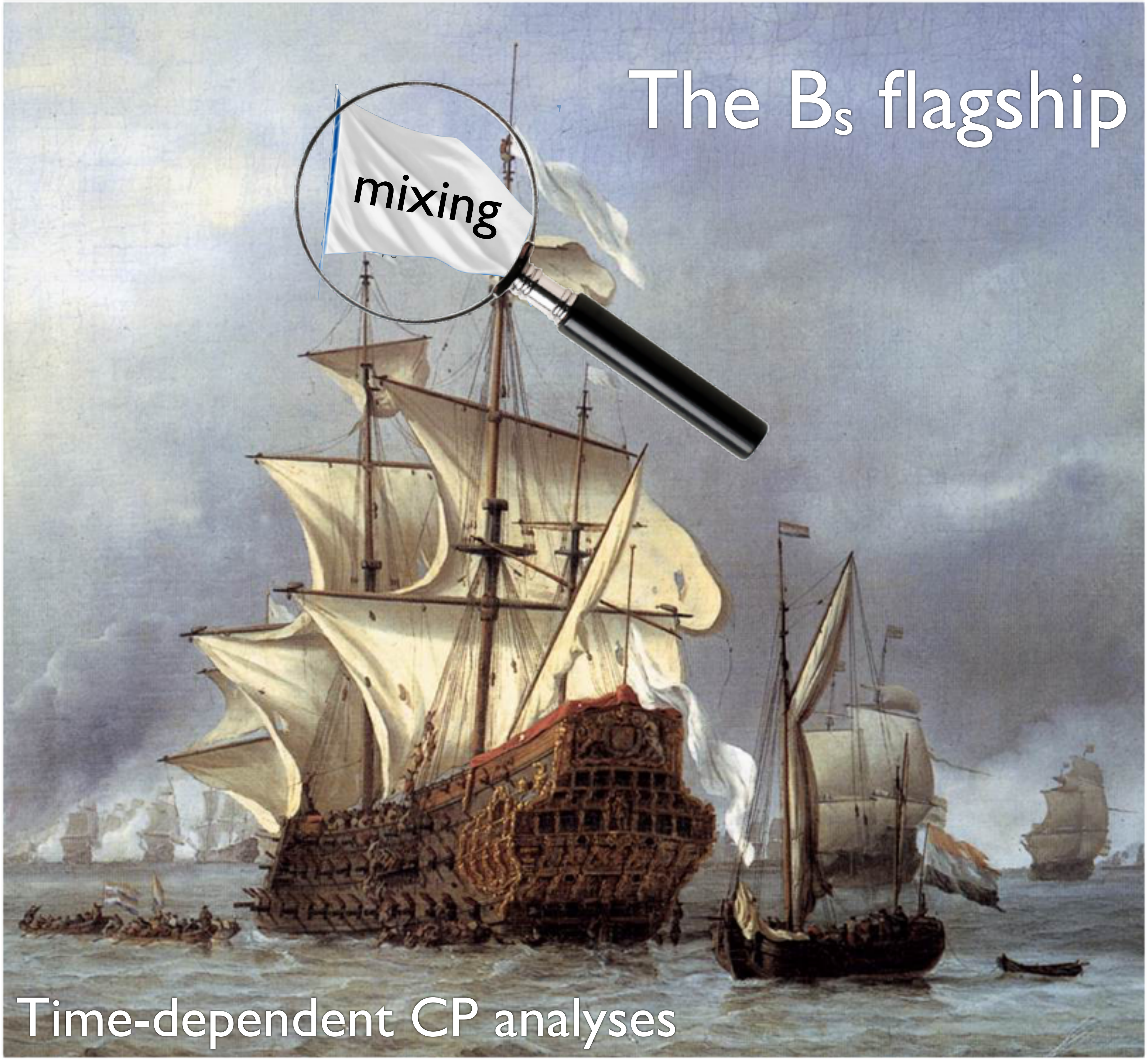
$$\Delta A_{CP}^{\text{wgt}} = (0.30 \pm 0.91 \pm 0.61)\%,$$

RESULT

The B_s flagship

Willem van de Velde the Elder

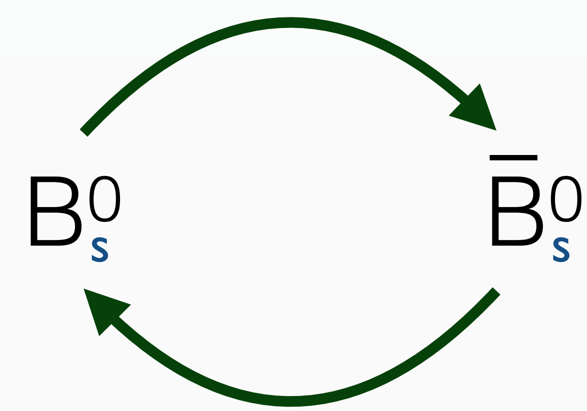
The B_s flagship



Time-dependent CP analyses

Willem van de Velde the Elder

Mixing



The mass eigenstates are mixtures of the flavour eigenstates

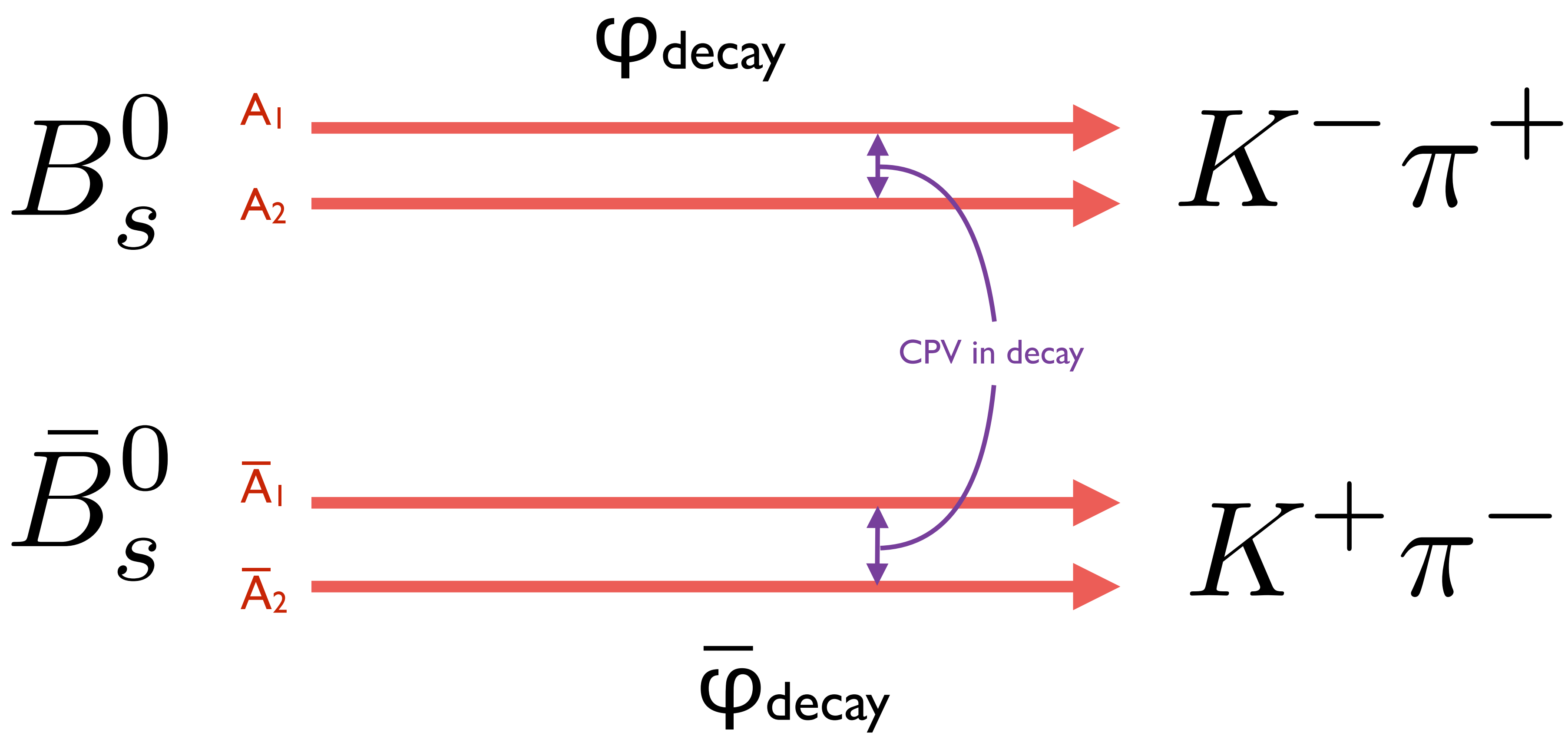
$$\langle B_s^0{}_{L,H}| = p\,\langle B_s^0| \mp q\,\langle \bar{B}_s^0|$$

Mass difference, Δm_s — Oscillation frequency

Decay width difference $\Delta\Gamma_s$ — Phase

Experimental evidence (~0.3%) + theoretical predictions:
CP eigenstates ~ mass eigenstates

CP violation in decay



CP violation in decay+mixing

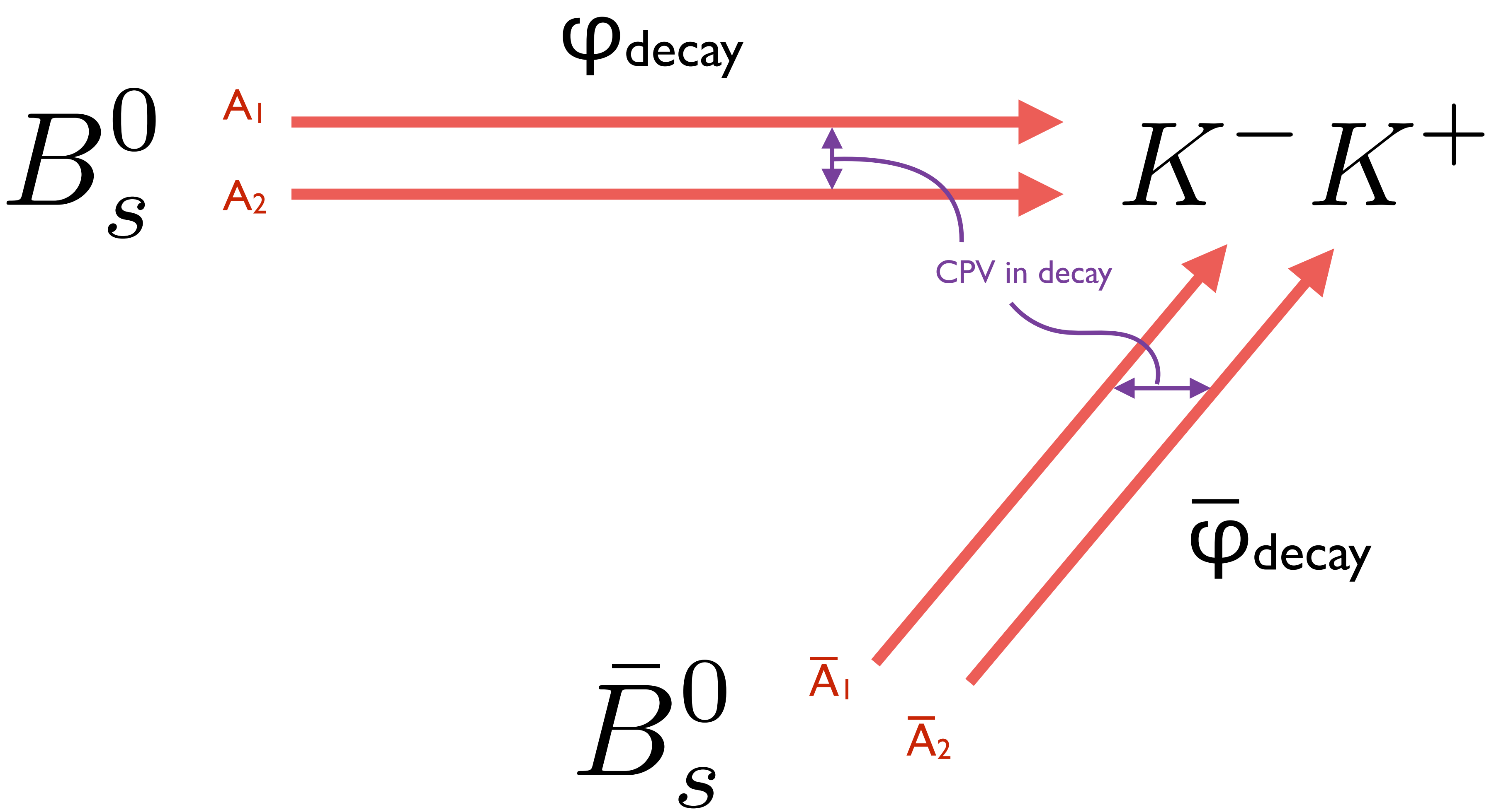


Illustration by Matthew Kenzie

CP violation in decay+mixing

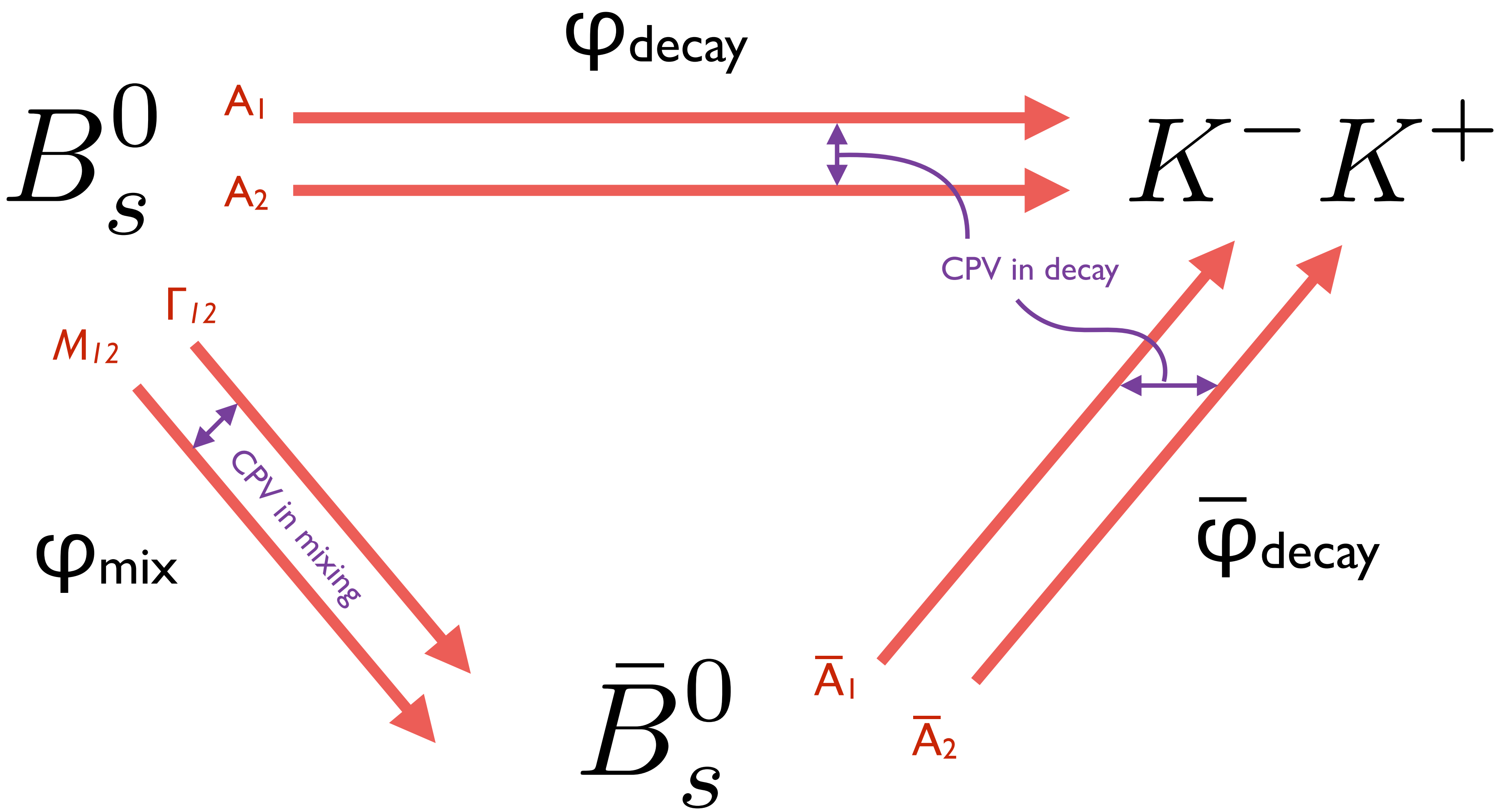
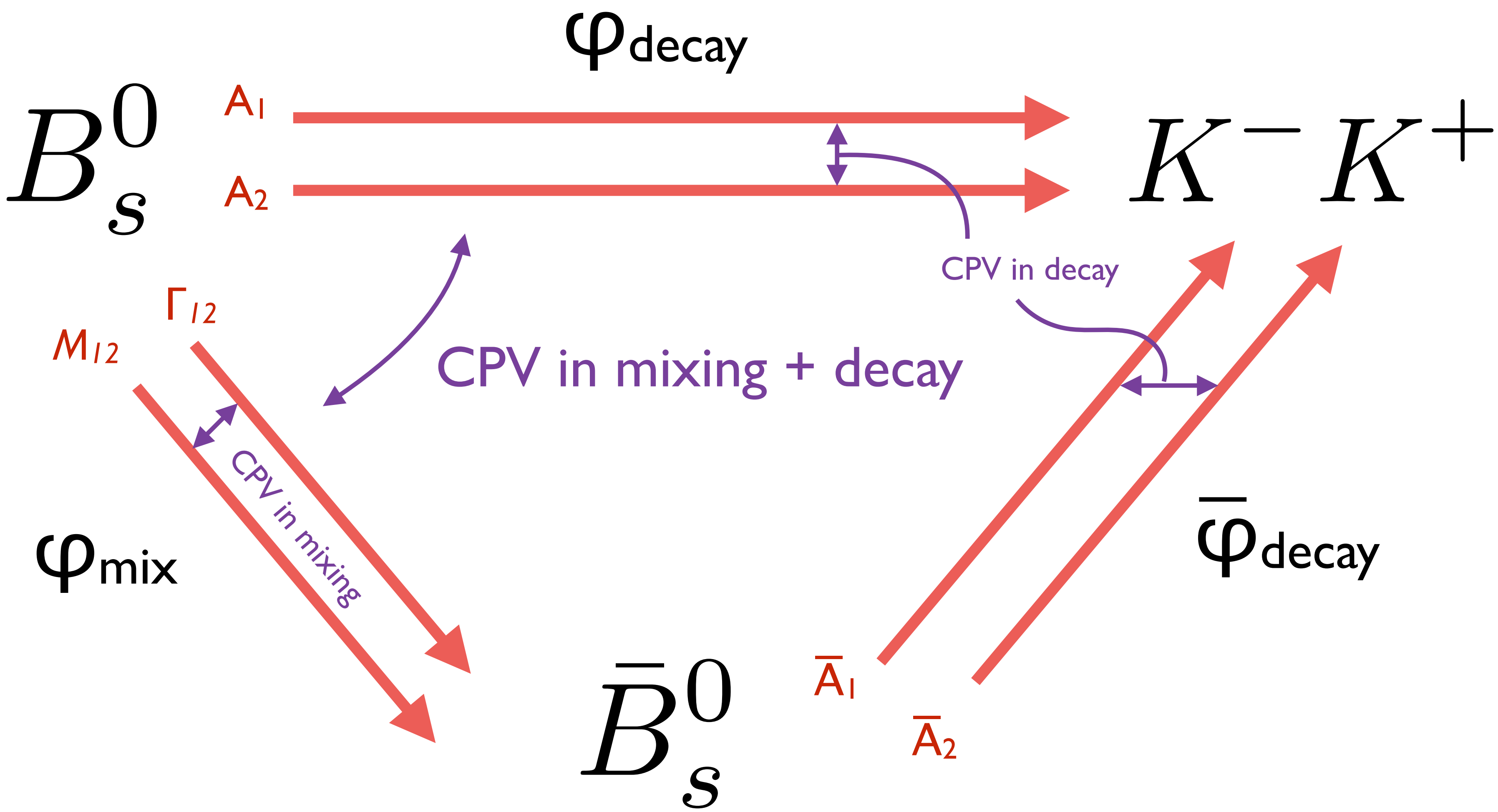


Illustration by Matthew Kenzie

CP violation in decay+mixing



$$A_{CP}(t) = \frac{\Gamma_{B^0_{(s)}\to f}(t) - \Gamma_{\bar{B}^0_{(s)}\to f}(t)}{\Gamma_{B^0_{(s)}\to f}(t) + \Gamma_{\bar{B}^0_{(s)}\to f}(t)}$$

Illustration by Matthew Kenzie

Time-dependent CP asymmetry

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f\cos(\Delta m_{d,s}t) + S_f\sin(\Delta m_{d,s}t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right)}$$

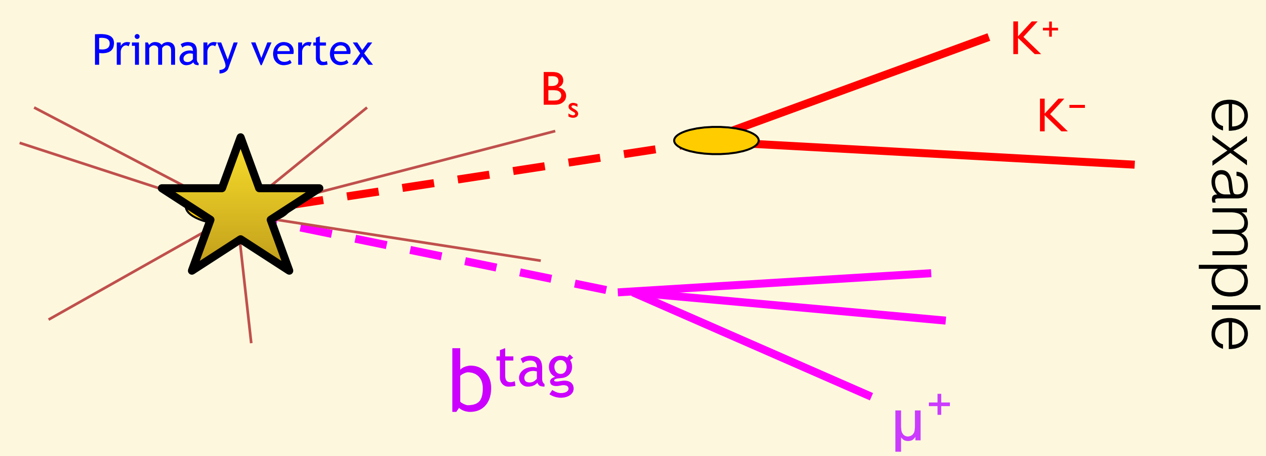
Observables

CPV decay	C_f
CPV interference	S_f
CPV in ΔΓ	$A_f^{\Delta\Gamma}$

(Assumed: |q/p|~1)

Requirements

1 Knowing the flavour at production.



2 Excellent proper-time resolution, *O*(50fs)

[LHCb-PAPER-2018-006]

LHCb Run-I data set

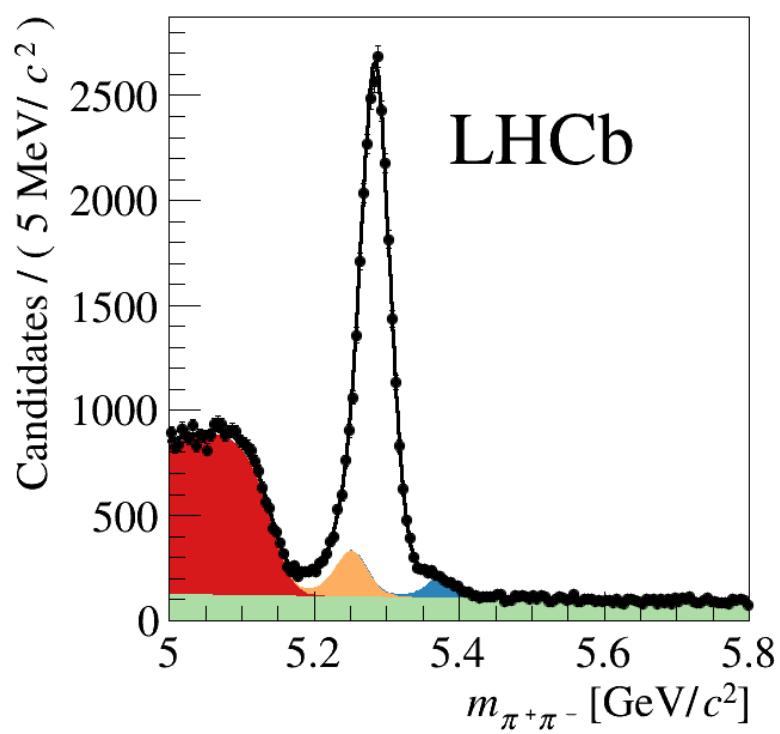
$B^0 \to \pi^+\pi^-$ results

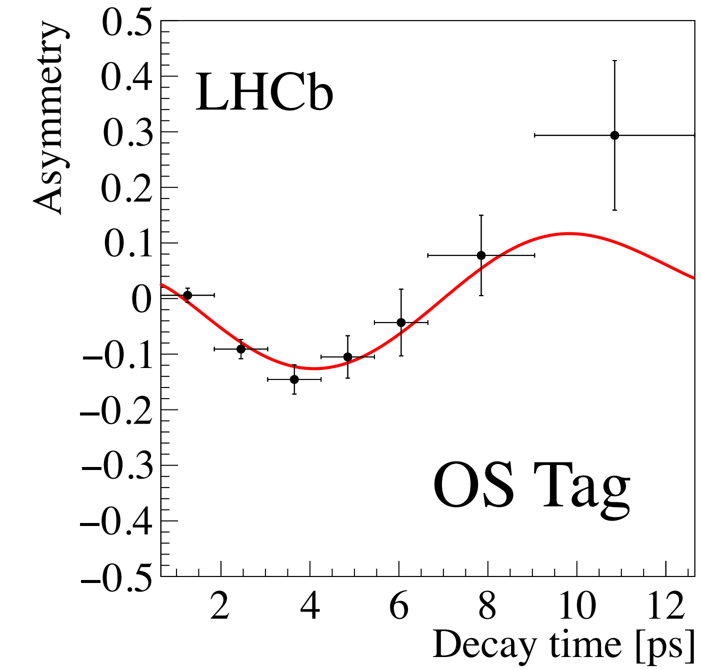
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cancelto{1}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right)}}$$

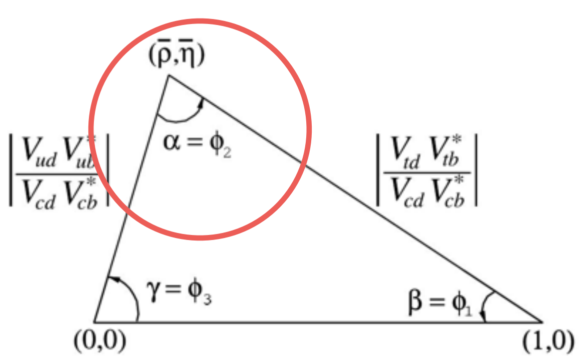
Fitted observables

CPV decay C_f

CPV interference S_f







$$\boxed{\begin{array}{lcrrr} C_{\pi^+\pi^-} & = & -0.34 & \pm 0.06 & \pm 0.01, \\ S_{\pi^+\pi^-} & = & -0.63 & \pm 0.05 & \pm 0.01, \end{array}}$$

[LHCb-PAPER-2018-006]

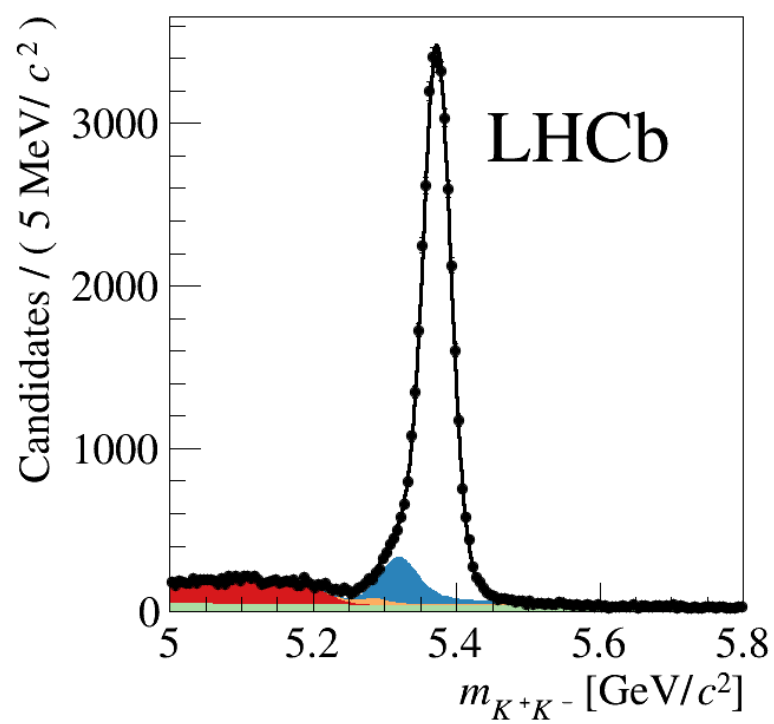
LHCb Run-1 data set

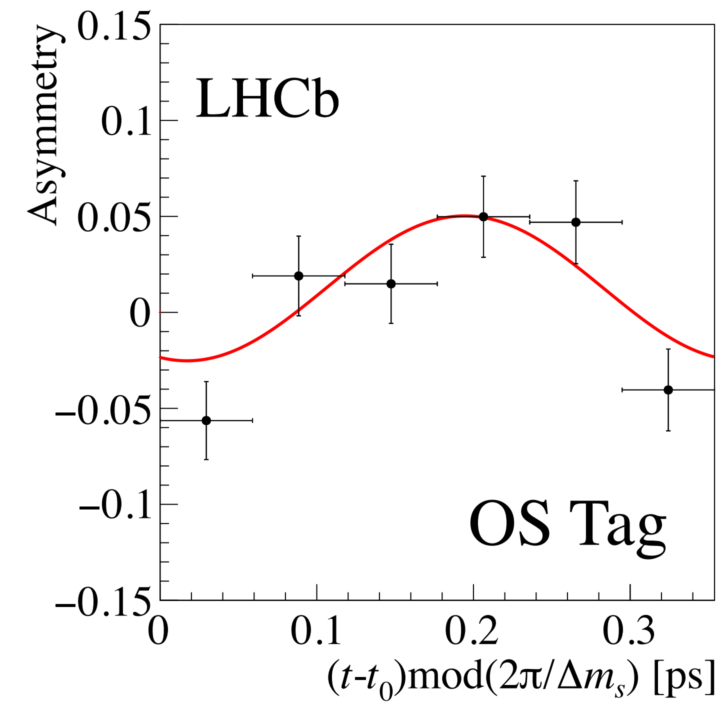
$B_s \rightarrow K^+K^-$ results

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right)}$$

Fitted observables

CPV decay	C_f
CPV interference	S_f
CPV in ΔΓ	$A_f^{\Delta\Gamma}$





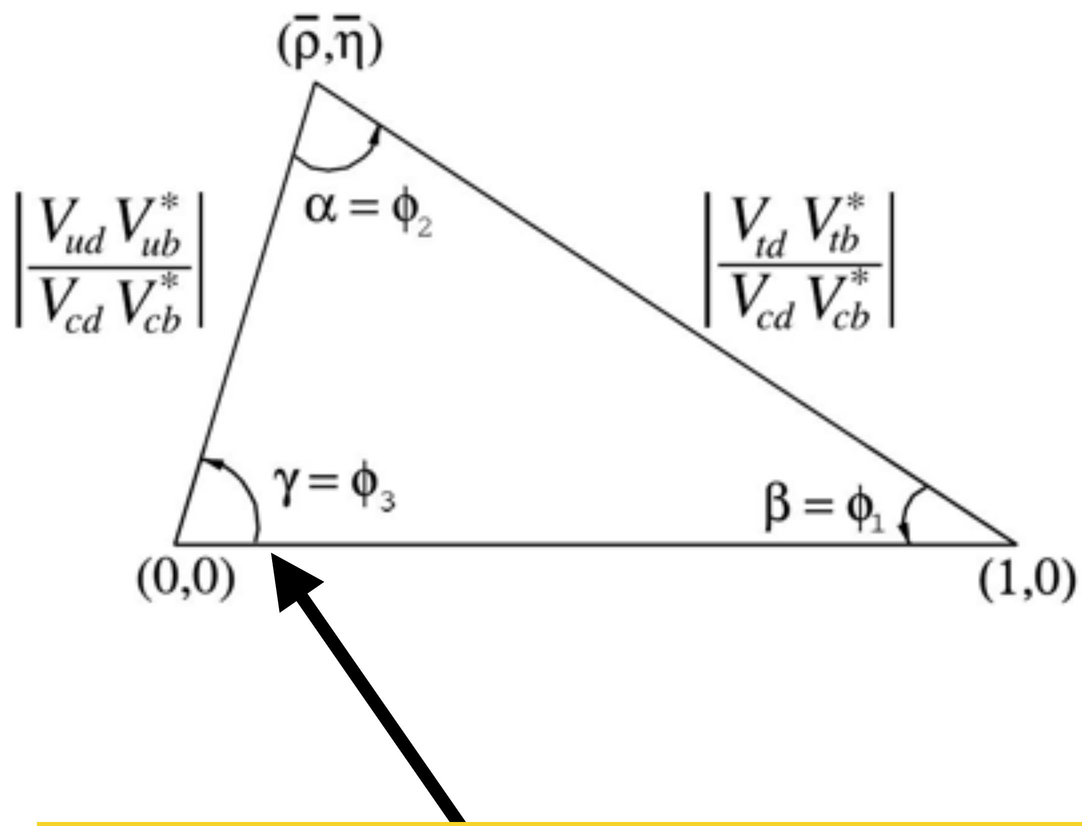
$$\begin{aligned} C_{K^+K^-} &= 0.20 \pm 0.06 \pm 0.02 \\ S_{K^+K^-} &= 0.18 \pm 0.06 \pm 0.02 \\ A^{\Delta\Gamma}_{K^+K^-} &= -0.79 \pm 0.07 \pm 0.10 \end{aligned}$$

First evidence
Combined: 4σ

[LHCb-PAPER-2018-006]

$B_s \to K^+K^-$: γ

Can be used to constrain γ (using U-spin symmetry) [1,2],
anticipating update with new results



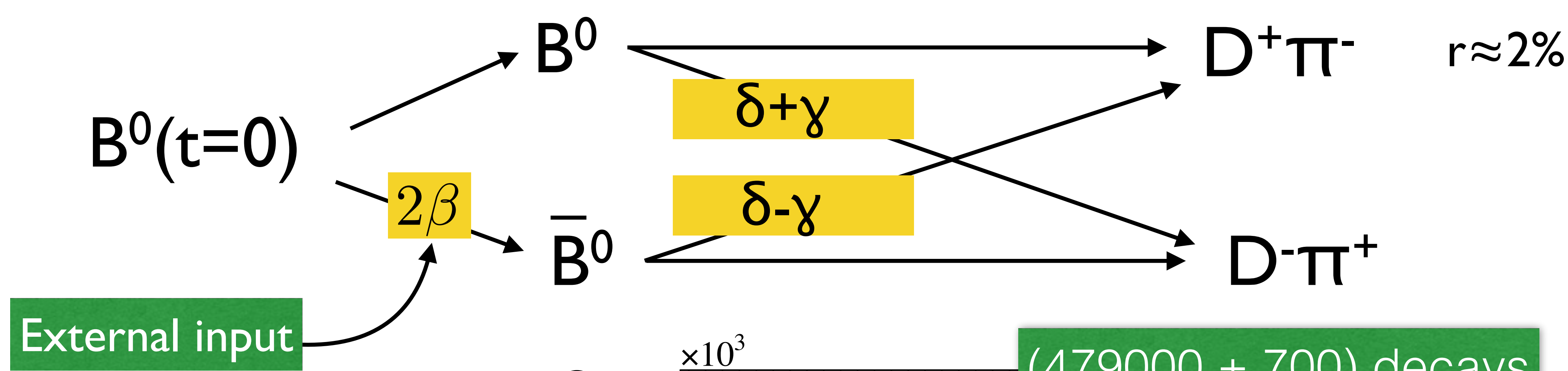
Theory very clean: $\delta\gamma/\gamma < O(10^{-7})$[3]
Experimentally: least well known (just)

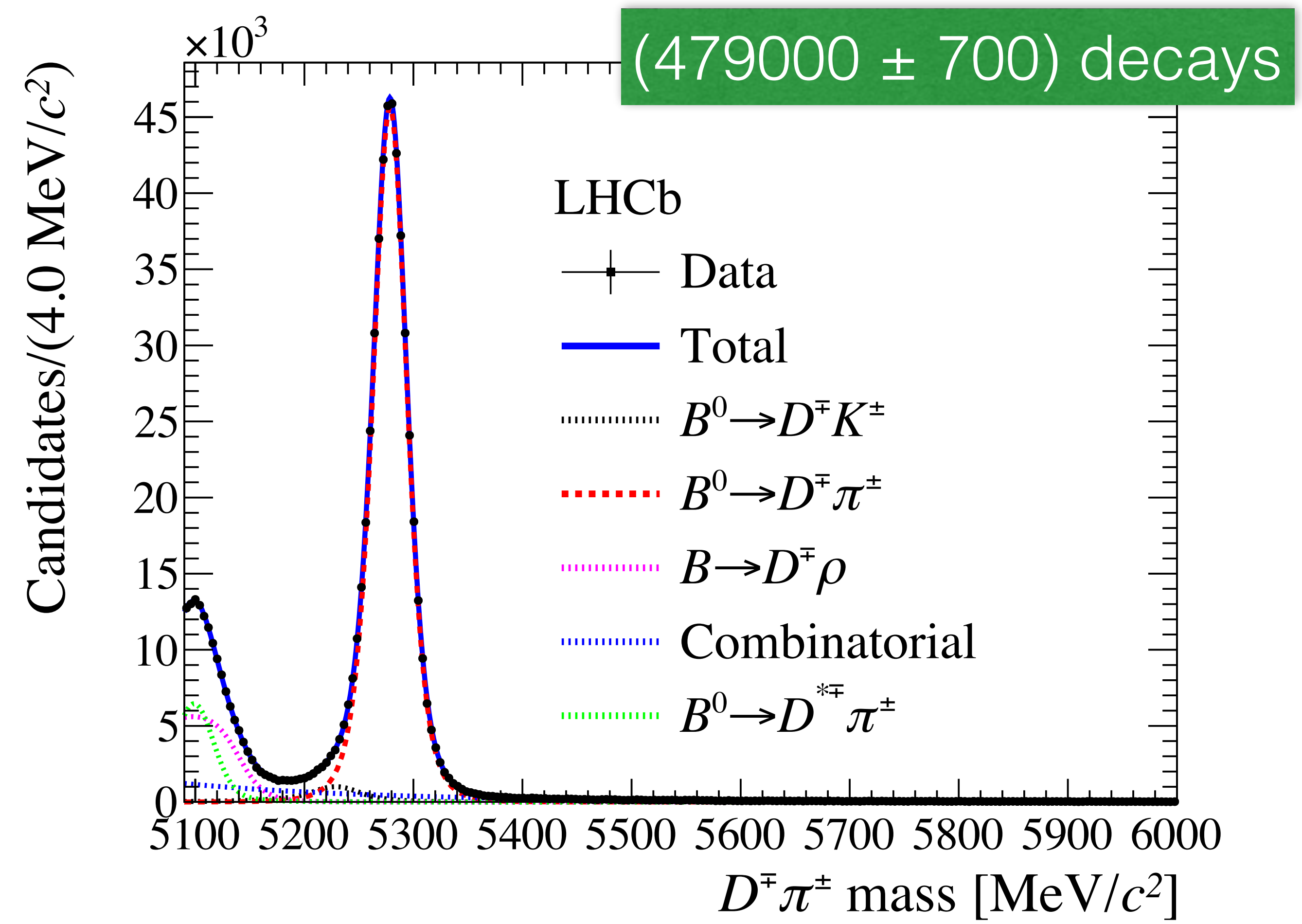
[1]: R. Fleischer, Phys. Lett. B 459 (1999) 306 (concept)
[2]: LHCb-PAPER-2014-045 (application)
[3]: Brod, Zupan, JHEP 1401 (2014) 051

[LHCb-PAPER-2018-009]

LHCb Run-1 data set

Direct γ measurement: $B^0 \rightarrow D^+\pi^-$





Fitted observables

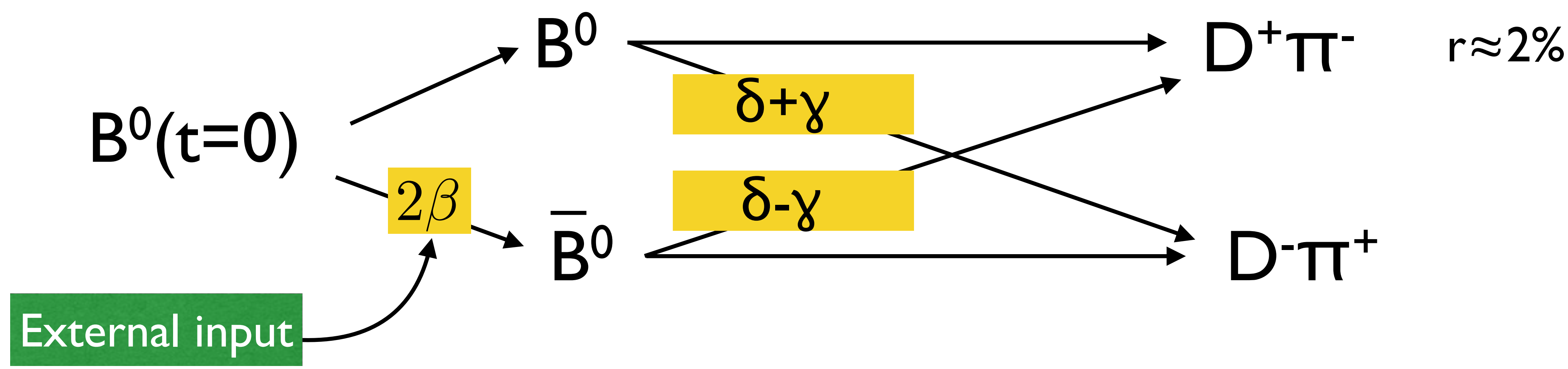
CPV interference $B \rightarrow D^- \pi^+$ — S_f

CPV interference $B \rightarrow D^+ \pi^-$ — $S_{\bar{f}}$

[LHCb-PAPER-2018-009]

LHCb Run-I data set

Direct γ measurement: $B^0 \rightarrow D^+\pi^-$

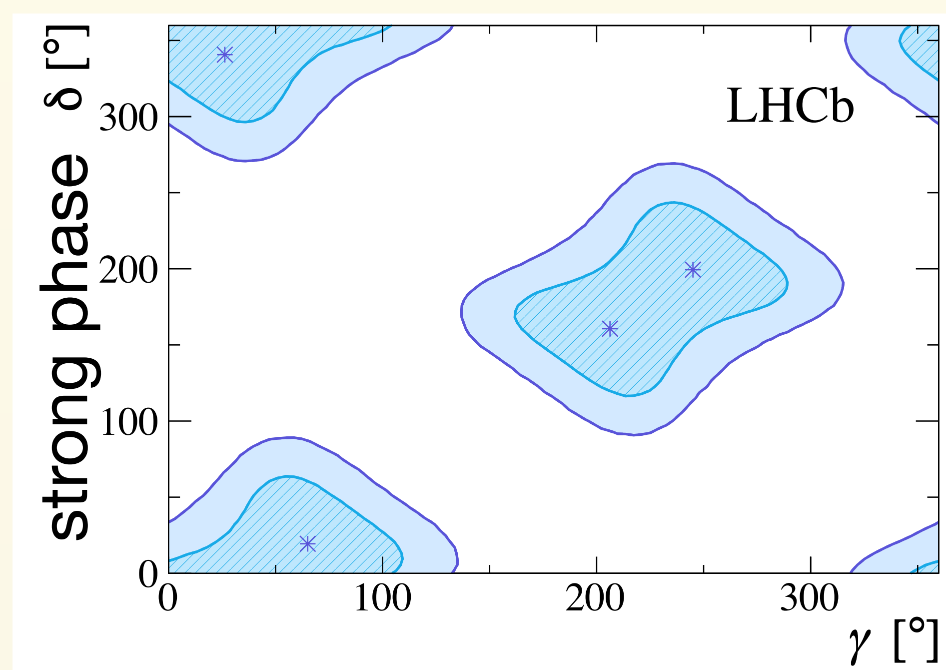


Fitted observables

CPV interference $B \rightarrow D^- \pi^+$ S_f

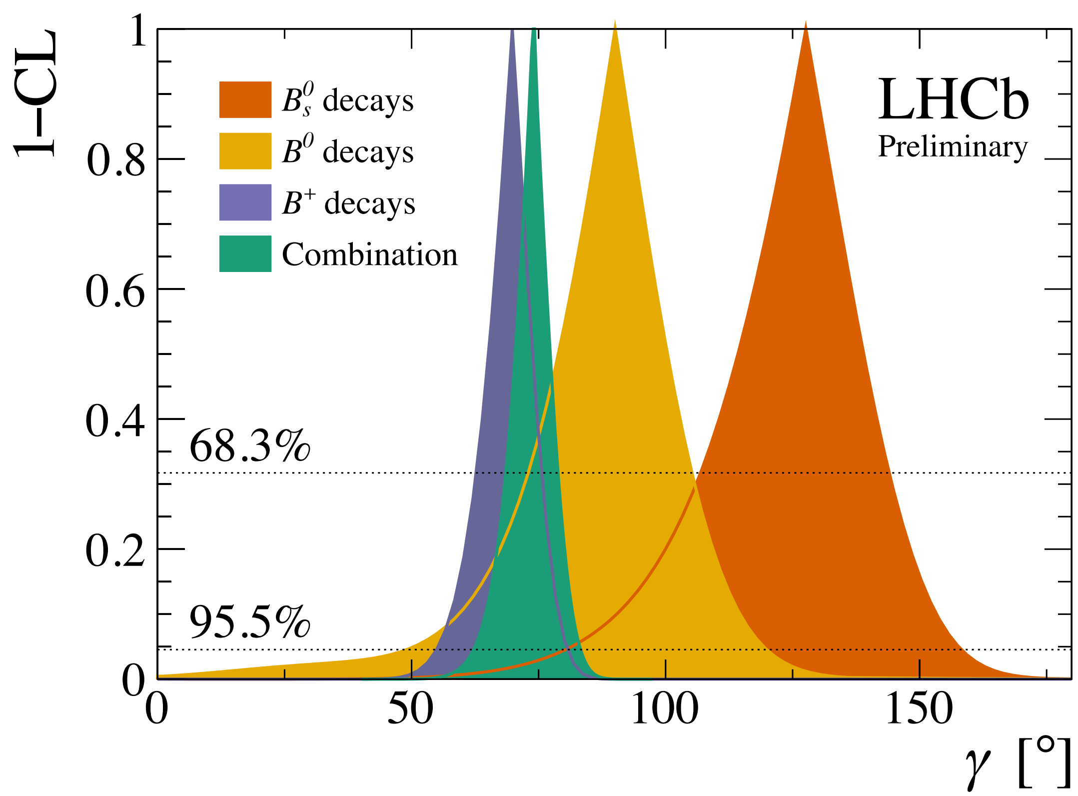
CPV interference $B \rightarrow D^+ \pi^-$ $S_{\bar{f}}$

Result



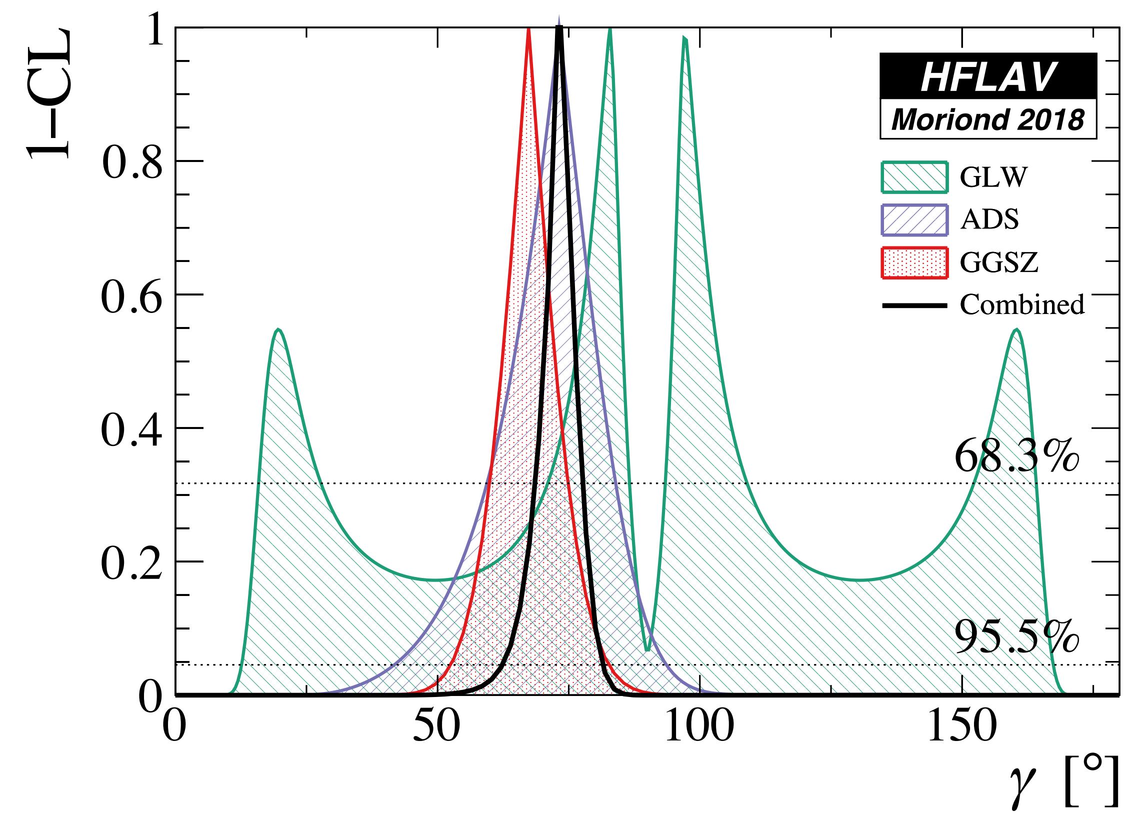
Status of gamma measurements

$\gamma = (74.0^{+5.0}_{-5.8})^\circ$



[LHCB-CONF-2018-002]

$\gamma = (73.5^{+4.2}_{-5.1})^\circ$

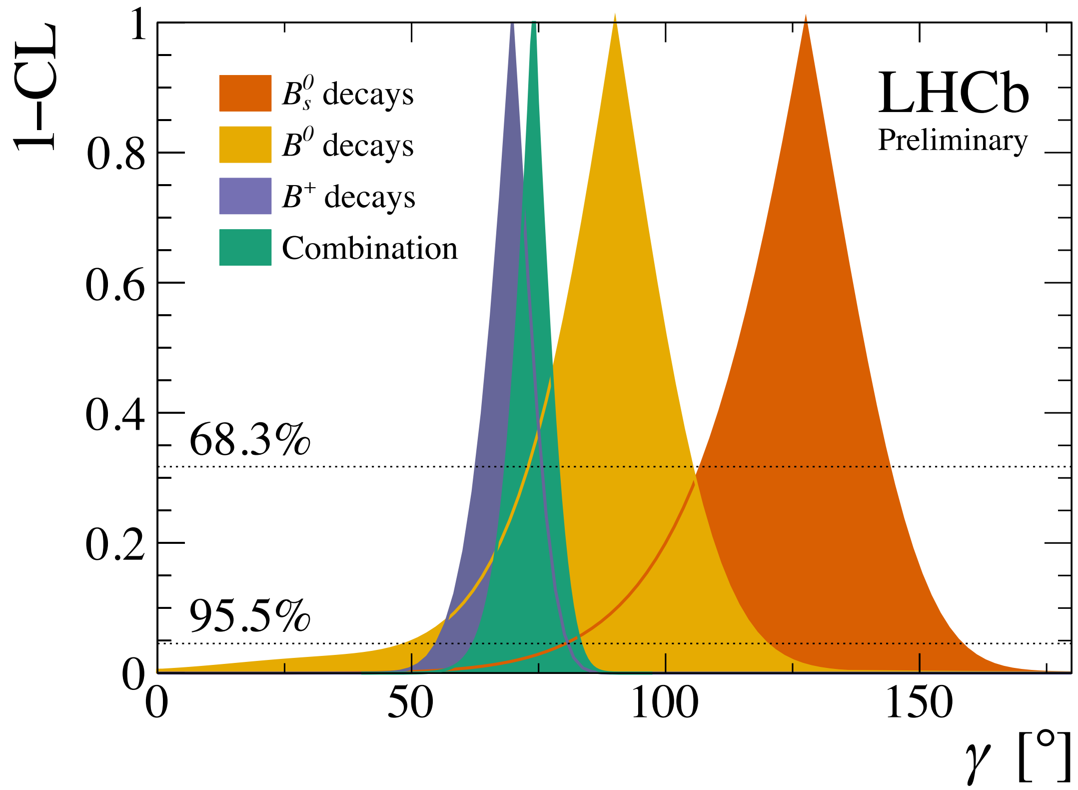


[HFLAV group]

Indirect: $(65.3^{+1.0}_{-2.5})^\circ$ (~2σ) [CKMFitter]

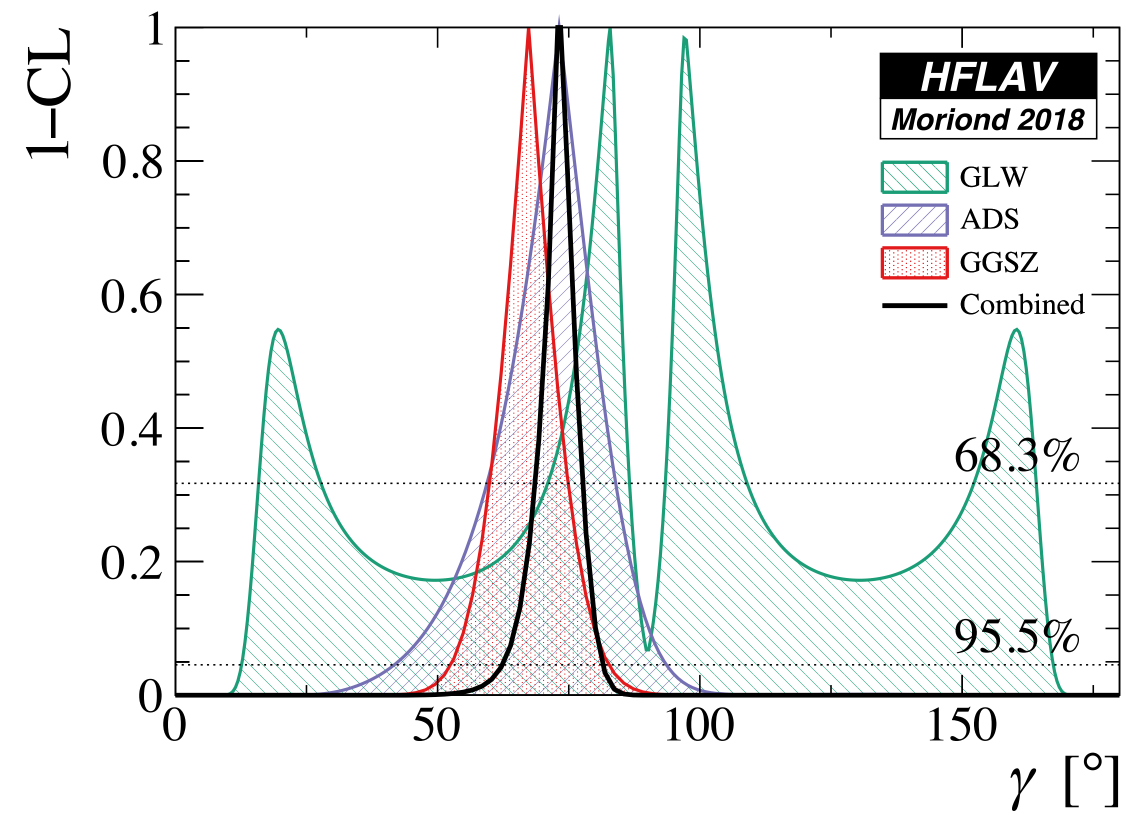
Status of gamma measurements

$\gamma = (74.0^{+5.0}_{-5.8})^\circ$



[LHCB-CONF-2018-002]

$\gamma = (73.5^{+4.2}_{-5.1})^\circ$



[HFLAV group]

New results: talk by Susan Haines

LHCb-PAPER-2018-017 LHCb run 2 $B^\pm \to D^0K^\pm$

LHCb-PAPER-2018-009 LHCb run 1 $B^0 \to D^+\pi^-$

$B_s \to J/\Psi\, K^- K^+$

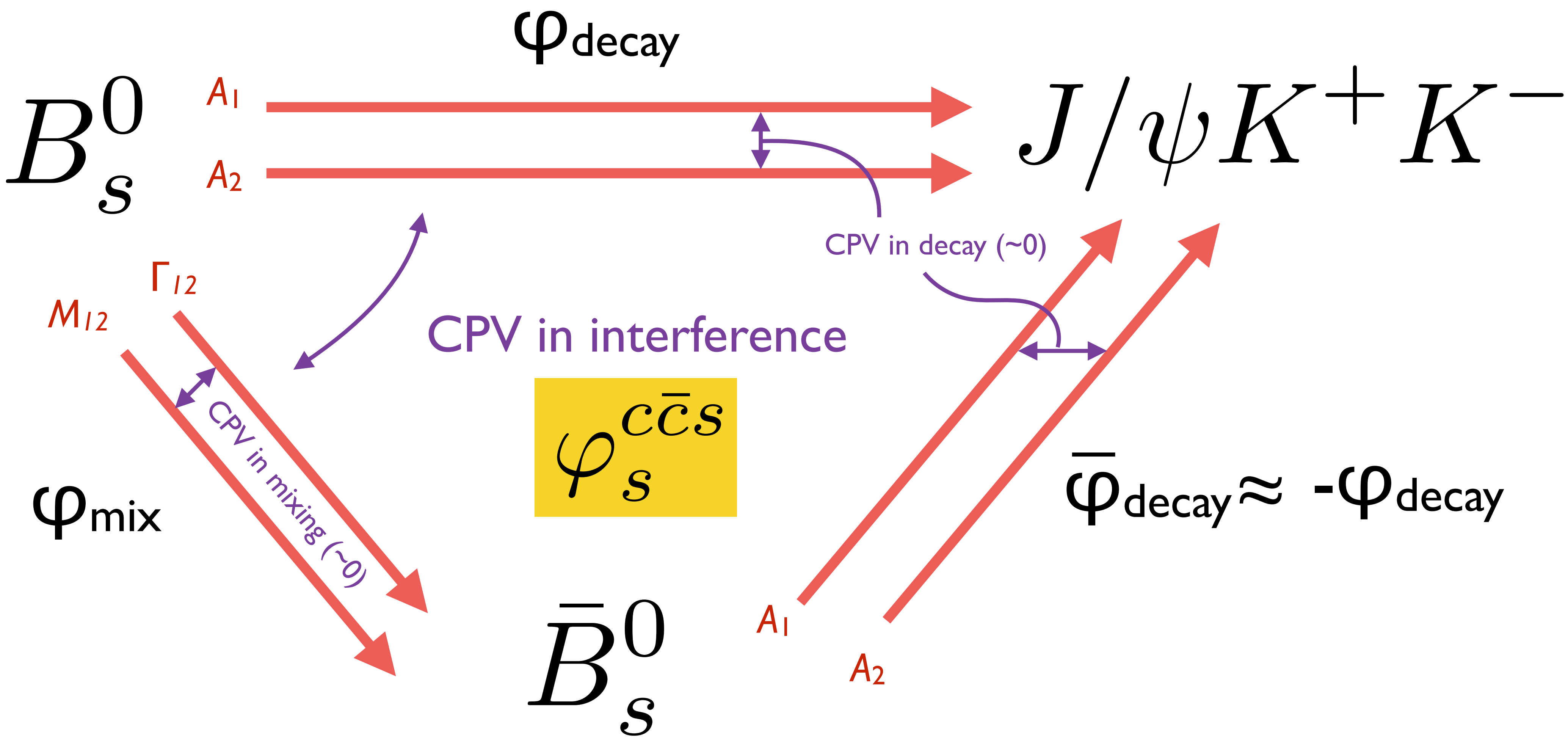
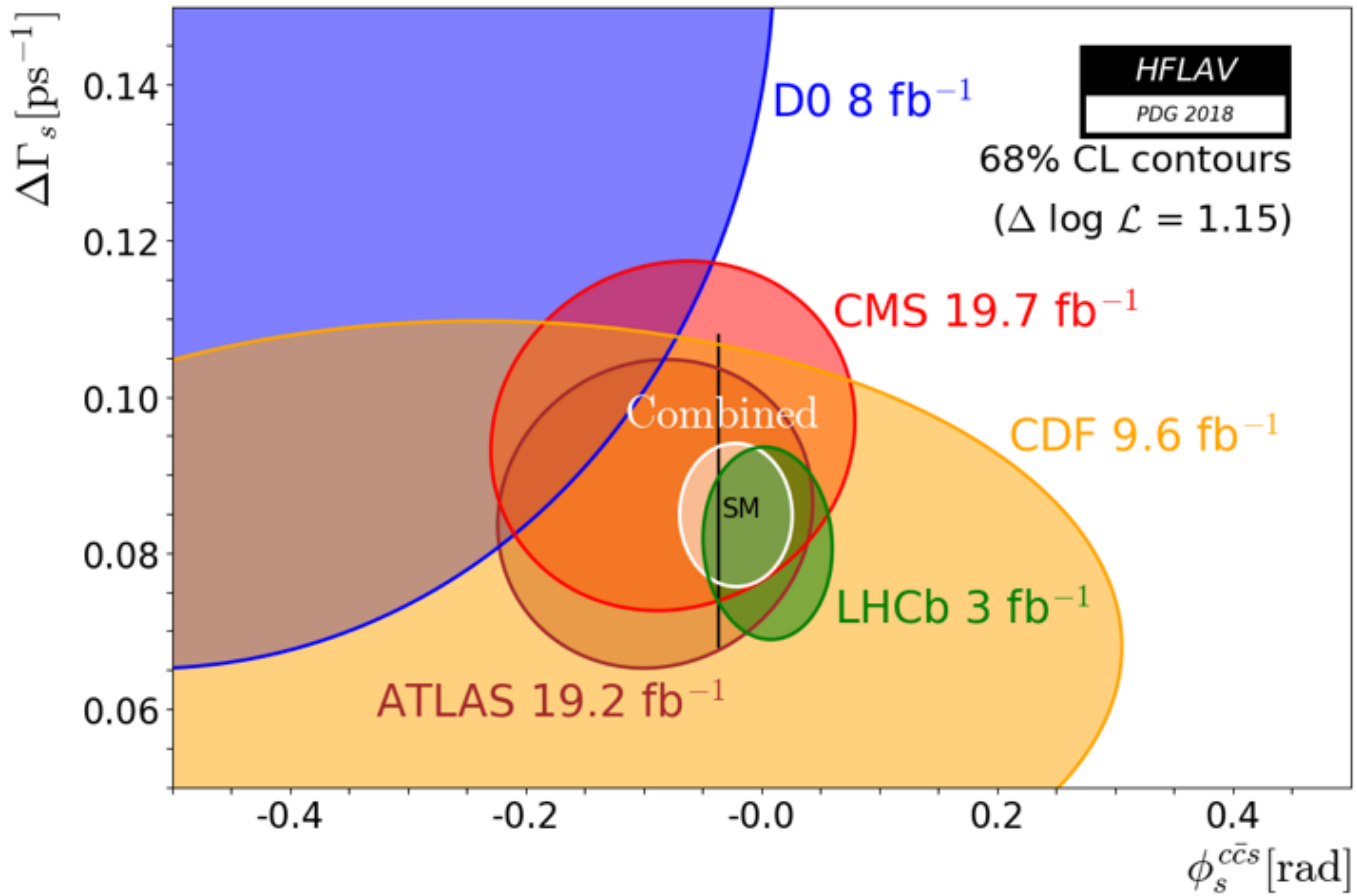


Illustration by Matthew Kenzie

[LHCb-PAPER-2017-008] (LHCb) [JHEP 08 (2016) 147] (ATLAS) [PLB 757 (2016) 97] (CMS)

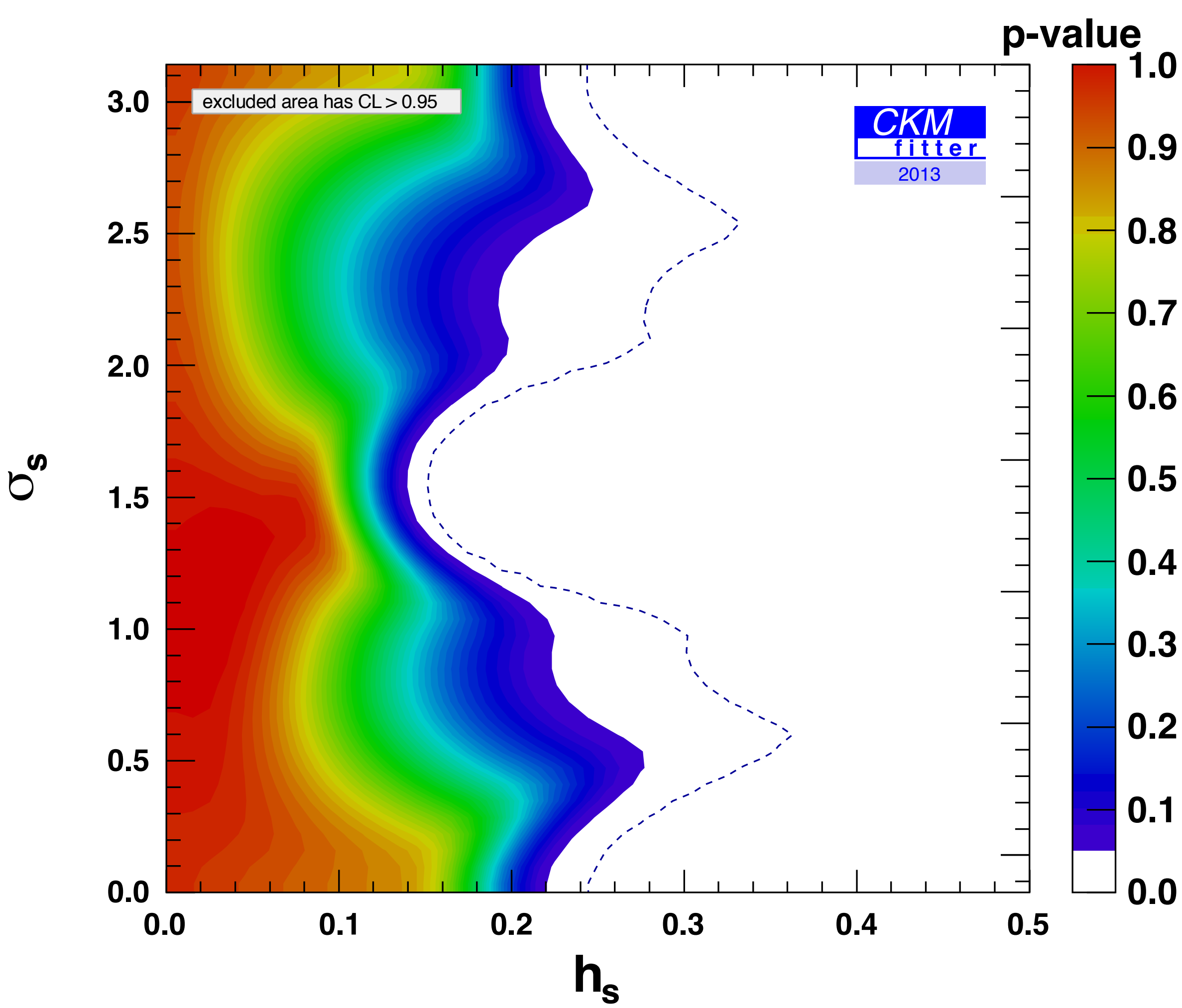
Current averages



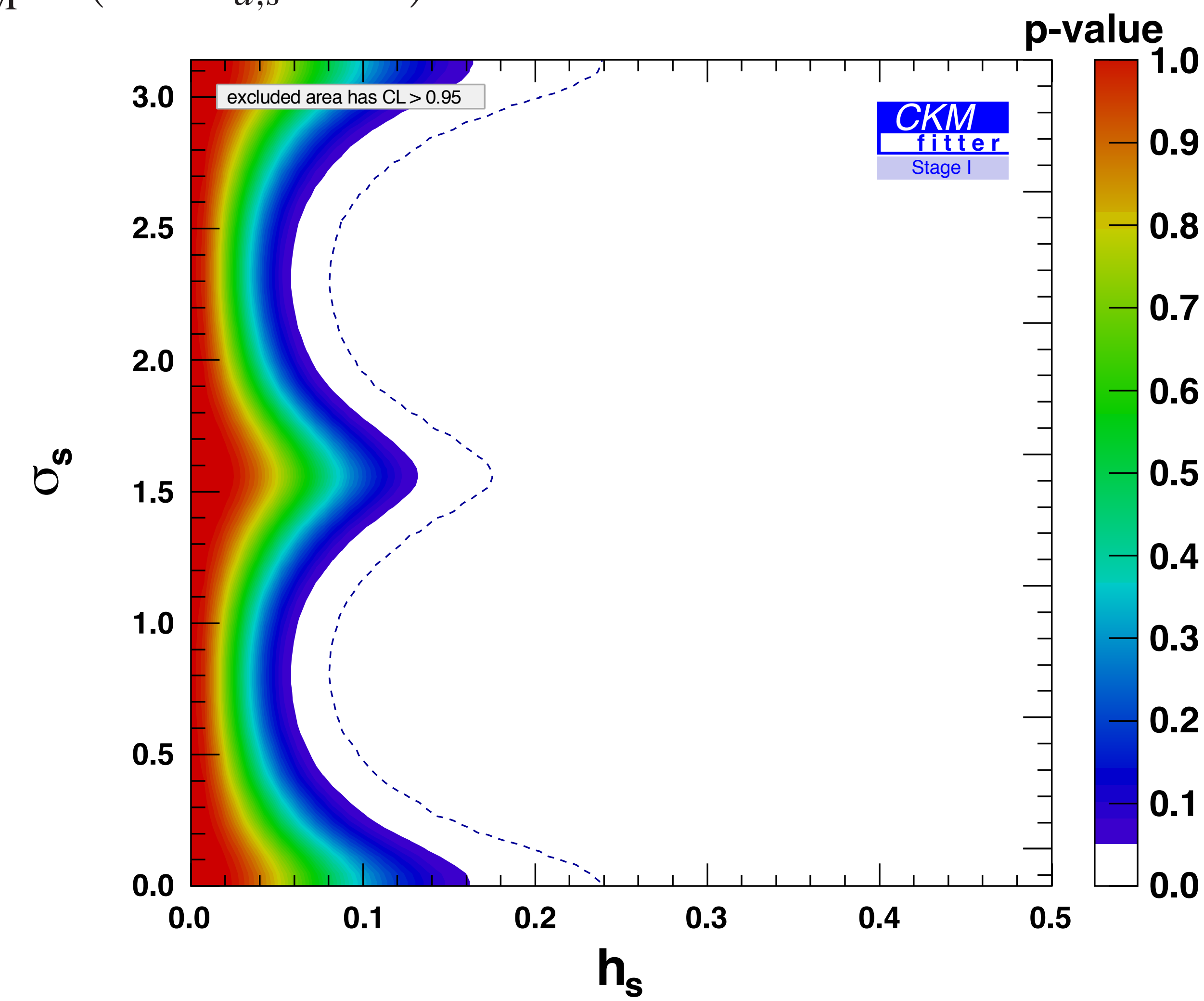
J. Charles, S. Descotes-Genon, Z. Ligeti, S. Monteil, M. Papucci, and K. Trabelsi
[Phys. Rev. D 89, 033016 (2014)]

Impact of mixing analyses

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\mathrm{SM}} \times (1 + h_{d,s} e^{2i\sigma_{d,s}}).$$



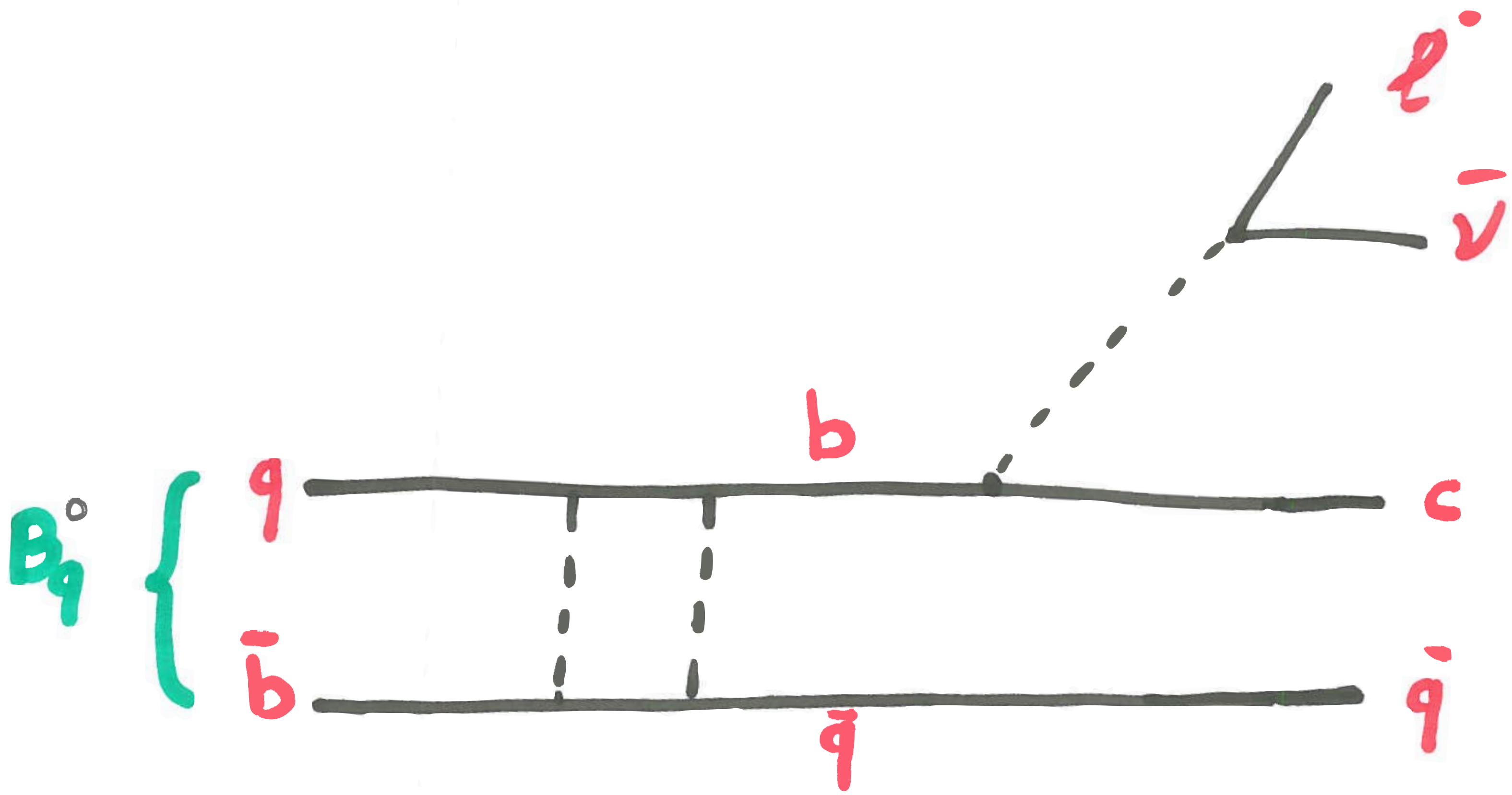
Status in 2013



~ end of Run 2

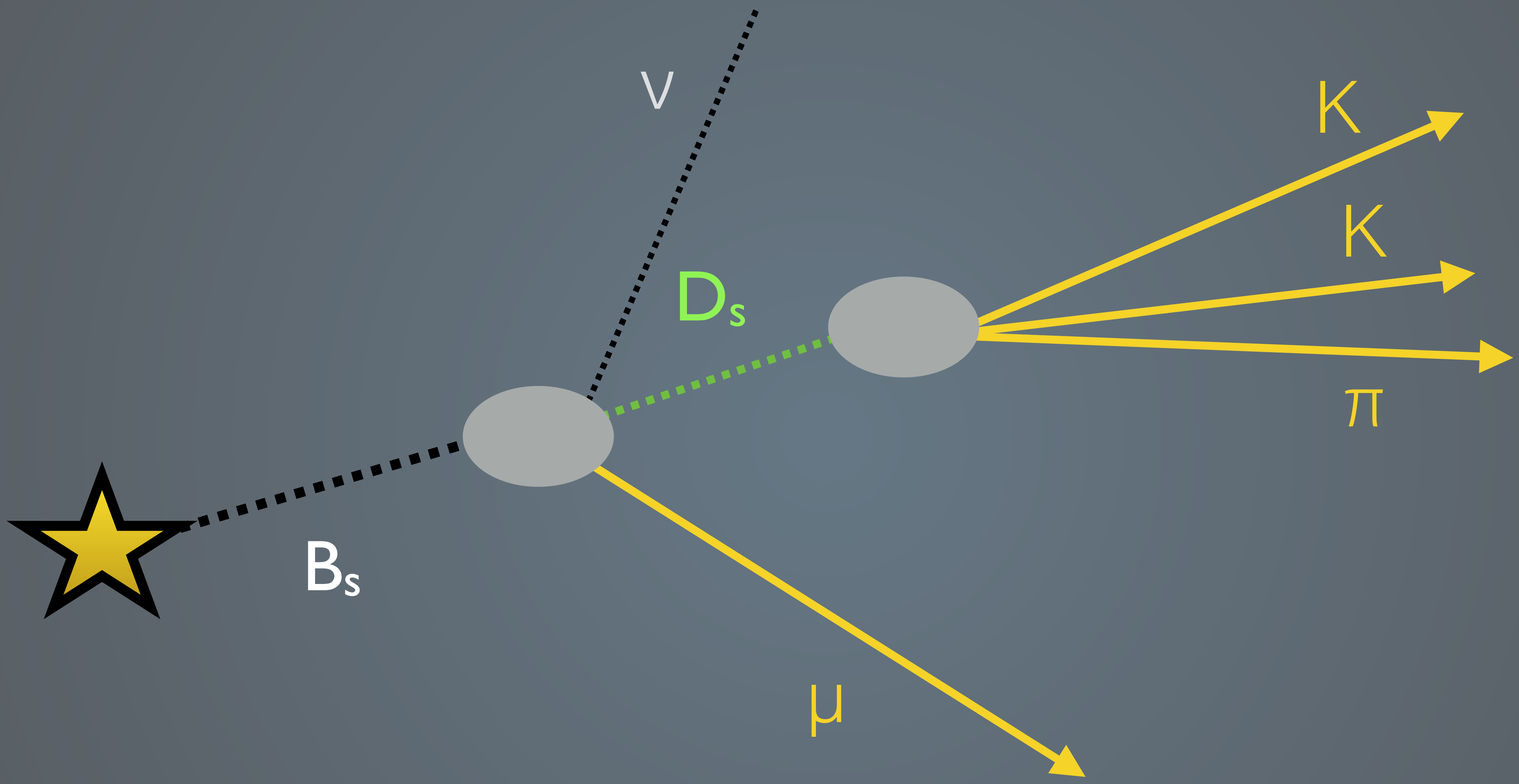
Looking forward to Run-2 updates!

Semileptonic decays



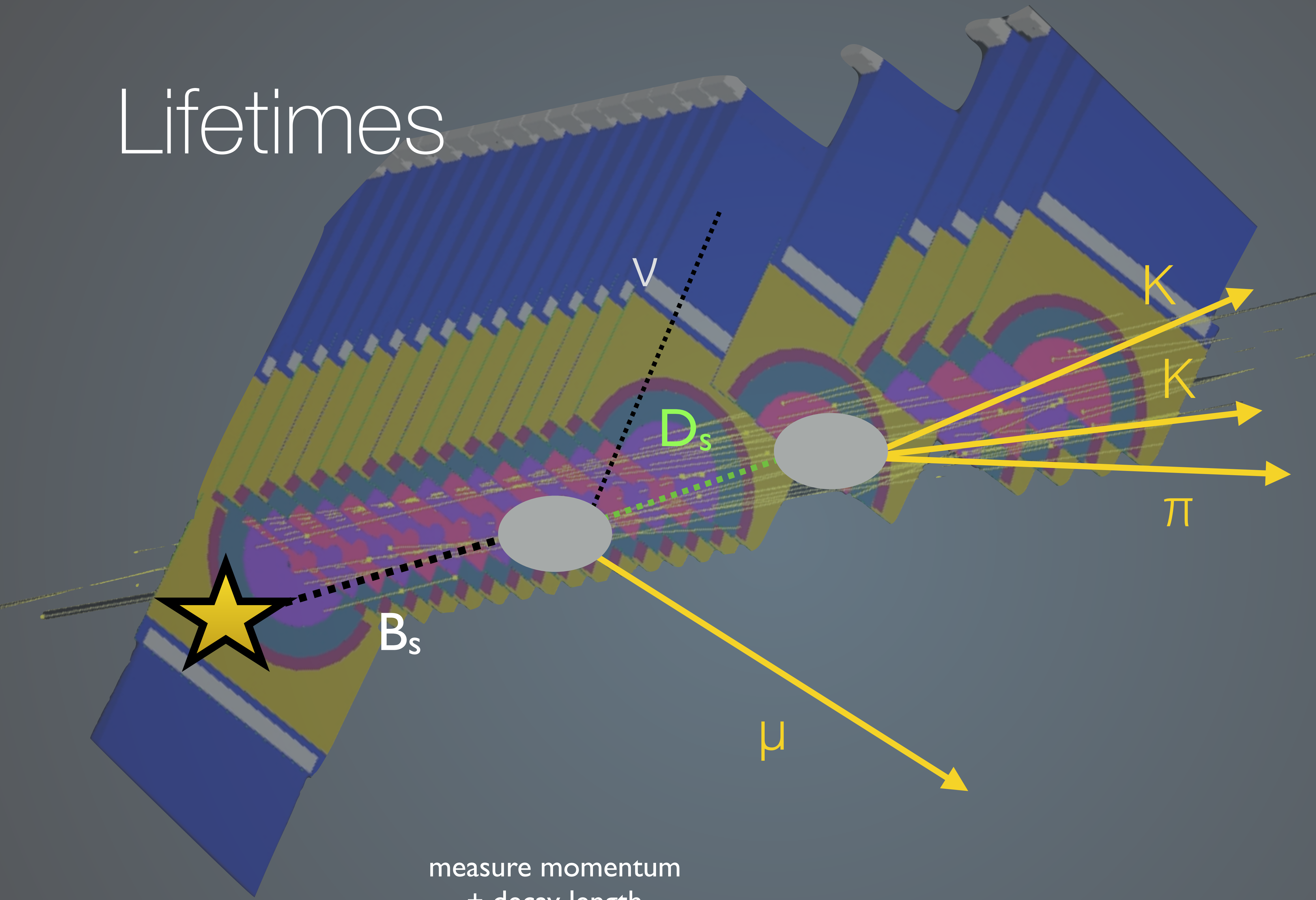
- ✔ Large branching ratios
- ✘ Technically challenging: partially reconstructed

Lifetimes



measure momentum
+ decay length

Lifetimes



measure momentum
+ decay length

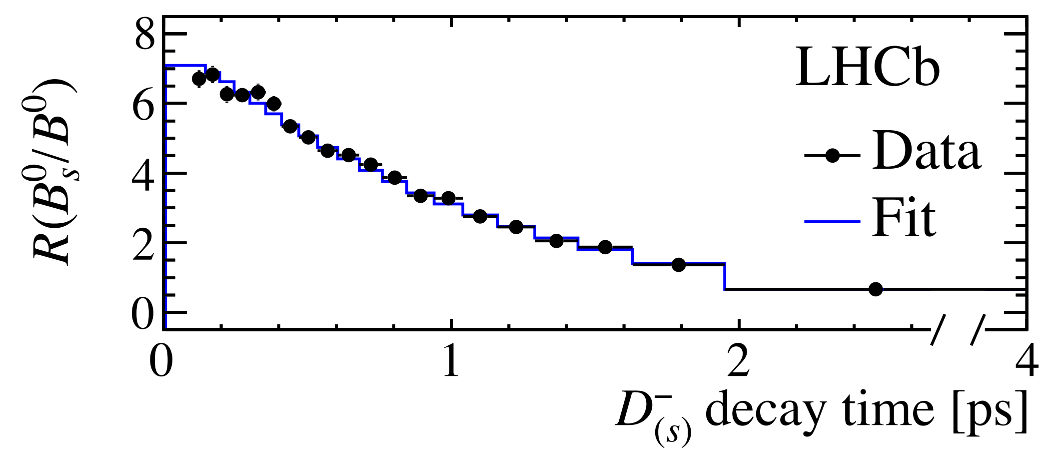
LHCB-PAPER-2017-004

LHCb Run-1 data set

Measurement of D_s & B_s lifetimes

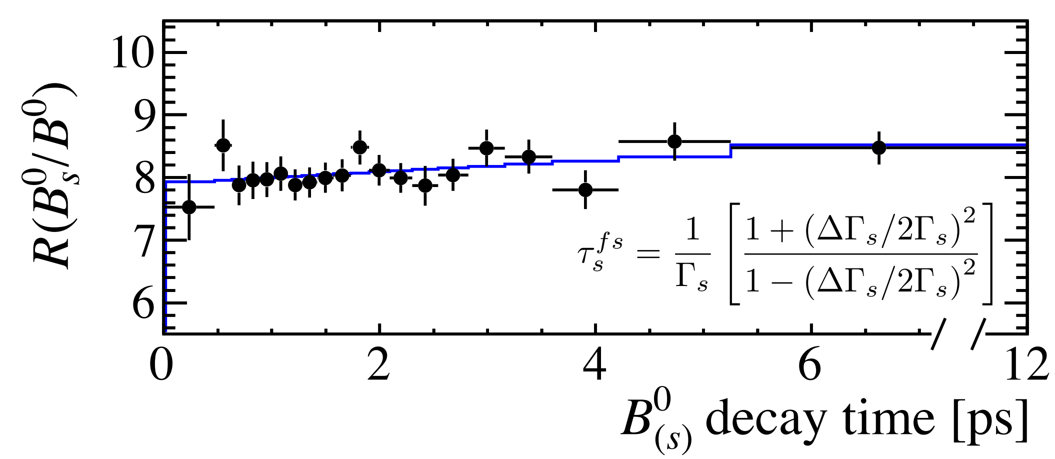
Use B_s and B^0 semileptonic decays, *to the same final state particles*:

$B_{(s)} \to D_{(s)}(\to KK\pi)\,\mu\,\nu$



Decay time acceptance: Measure ratio of lifetimes for B_s/B^0 and D_s/D^+.

Use world-average for the denominator.



Most precise single measurements

$\tau(D^-_s) = 0.5064 \pm 0.0030 \pm 0.0017 \pm 0.0017$ ps

$\tau(B^0_s) = 1.547 \pm 0.013 \pm 0.010 \pm 0.004$ ps

Measuring lifetimes with semileptonic decays is competitive!

New

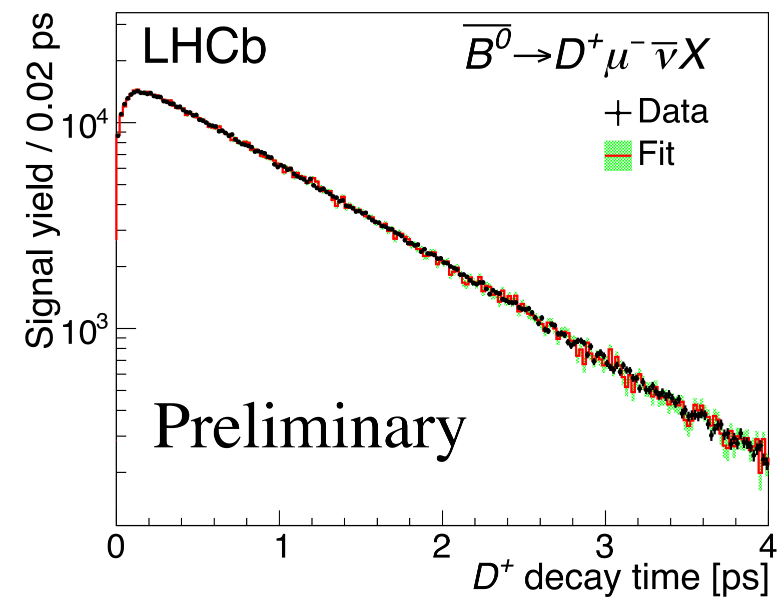
[LHCB-PAPER-2018-028 in prep]

LHCb Run-1 data set

Lifetime of Ω_c

Try to do a similar procedure for Ω_c baryons: current relative uncertainty on Ω_c lifetime is 17%[1]. Measure:

$$r_{\Omega_c^0} \equiv \frac{\tau_{\Omega_c^0}}{\tau_{D^+}},$$



Using semileptonic decays:

$$B \to D^+ \mu \nu X \qquad \Omega_b \to \Omega_c^0 \mu \nu X$$

$D^+ \to K\pi\pi$ $\qquad$ $\Omega_c^0 \to pKK\pi$

$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$

$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs},$$

RESULT

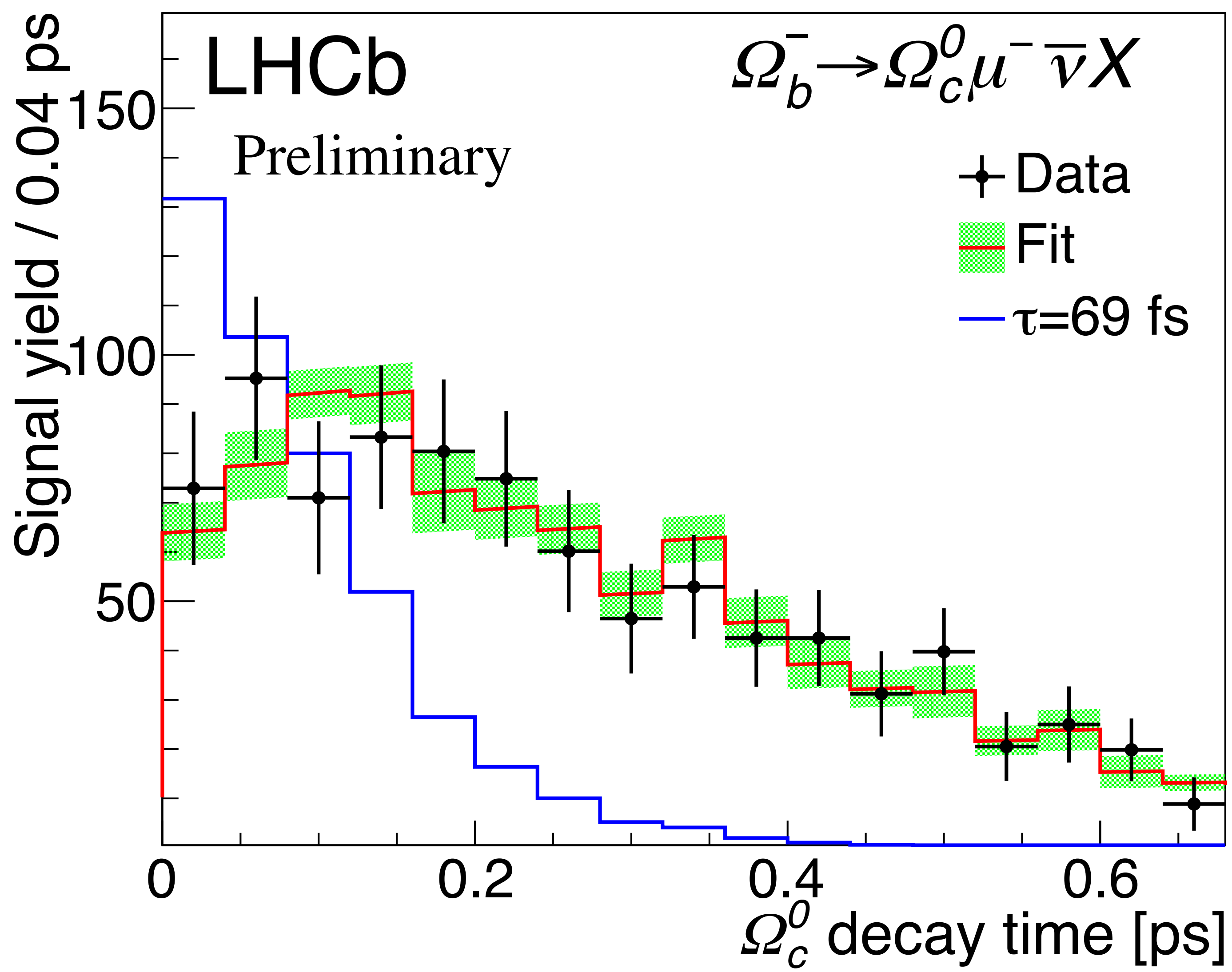
[1]: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

New

[LHCB-PAPER-2018-028 in prep]

LHCb Run-1 data set

Lifetime of Ω_c

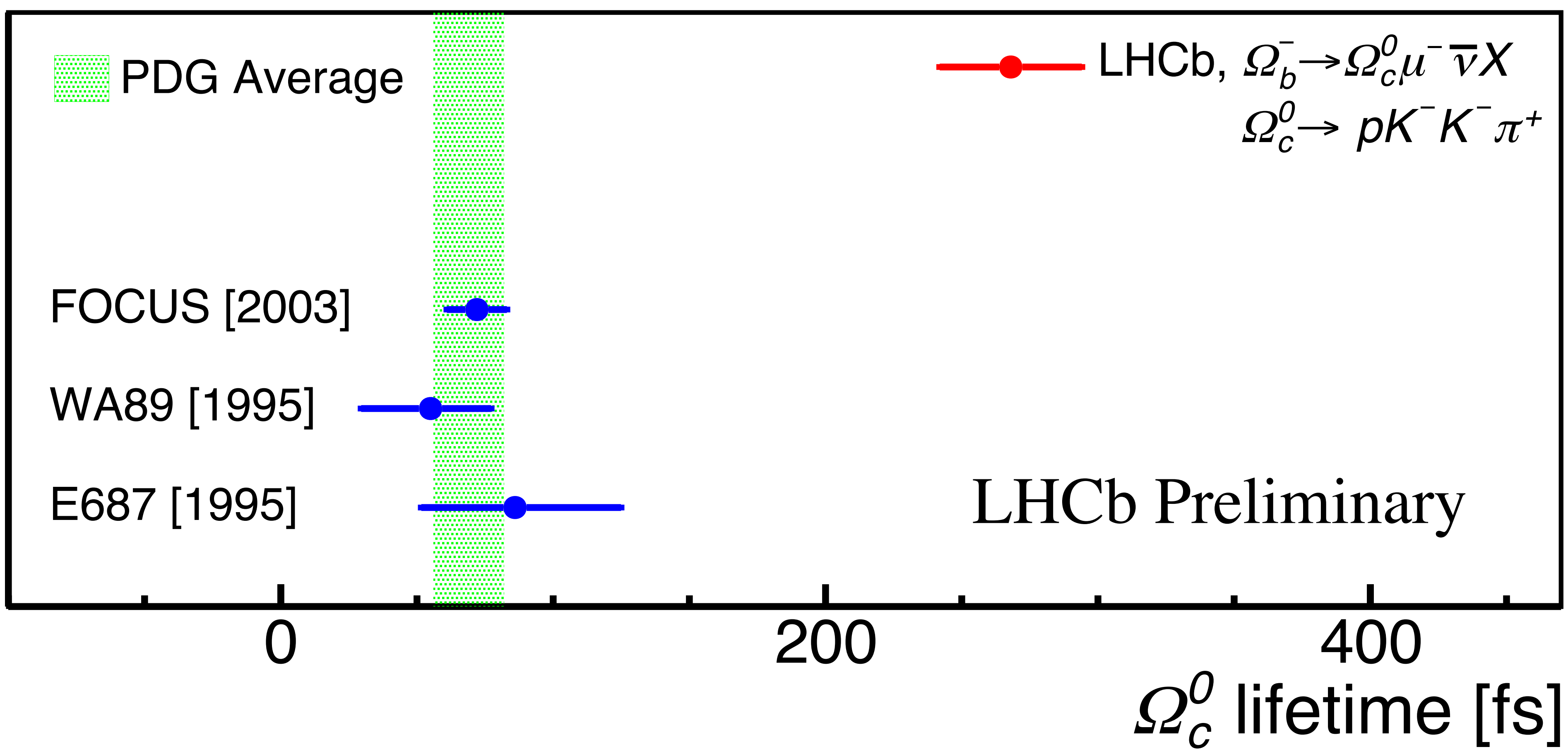


New

[LHCB-PAPER-2018-028 in prep]

LHCb Run-1 data set

Lifetime of Ω_c



New

[LHCB-PAPER-2018-028 in prep]

LHCb Run-1 data set

Lifetime of Ω_c

Expected hierarchy (Pauli interference)[1]:

$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$$

This measurement:

$$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$$

[1]: Browder, Honscheid, Pedrini, arXiv:hep-ph/9606354v2 (for example)

Conclusion

Seen that the domain of time-integrated CPV has been extended to **Λ_b**.
Time-dependent CPV: closing in on the CKM angle **gamma** and shown the strongest evidence for time-dependent CPV in B_s mesons (**$B_s \rightarrow KK$**).

The technique of using semileptonic decays for **lifetime** proved useful, this time with striking results for the **Ω_c^0 baryon**.

Eagerly awaiting the Run-2 results!

CP violation & semileptonic decays in beauty and charm

LHCP June 8, 2018

Laurent Dufour, *on behalf of the ATLAS, CMS and LHCb collaborations*

Backup slides

Systematics lifetime analysis Ds/Bs

	$\sigma[\Delta(D)]$ [ps^{-1}]	$\sigma[\Delta(B)]$ [ps^{-1}]
Fit bias	0.0004	0.0009
Decay model of $B_s^0 \to D_s^{*-}\mu^+\nu$	0.0005	0.0025
Sample composition	0.0007	0.0005
$f_s/f_d(p_T)$	0.0018	0.0028
Decay-time acceptance	0.0049	0.0004
Decay-time resolution	0.0039	0.0004
Feed-down from B_c^+ decays	–	0.0010
Total systematic	0.0065	0.0041
Statistical	0.0117	0.0053

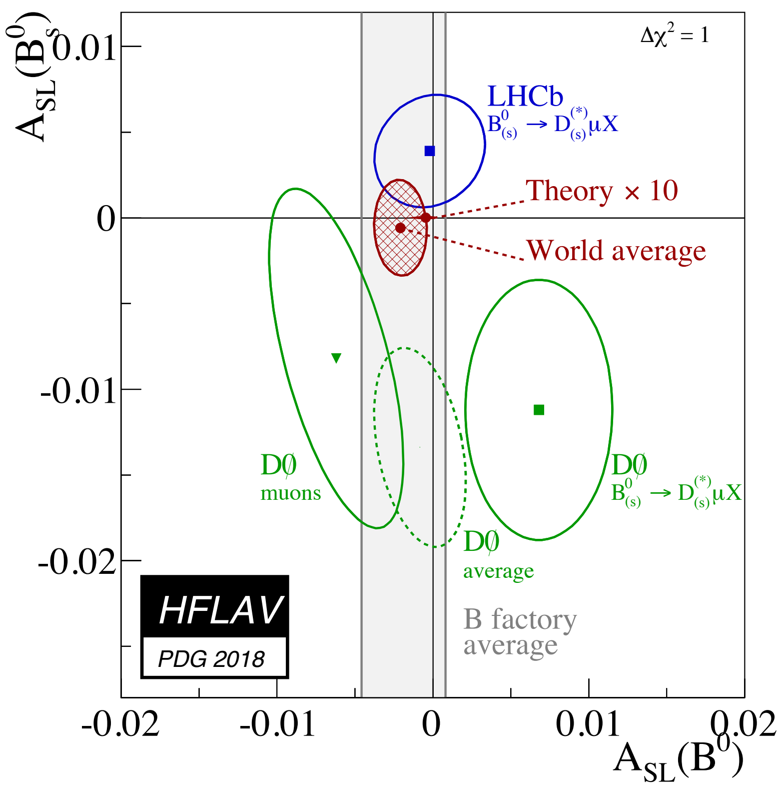
Systematics lifetime analysis Ω_c

Table 1: Summary of systematic uncertainties on the lifetime ratio, $r_{\Omega_c^0}$, in units of 10^{-4}.

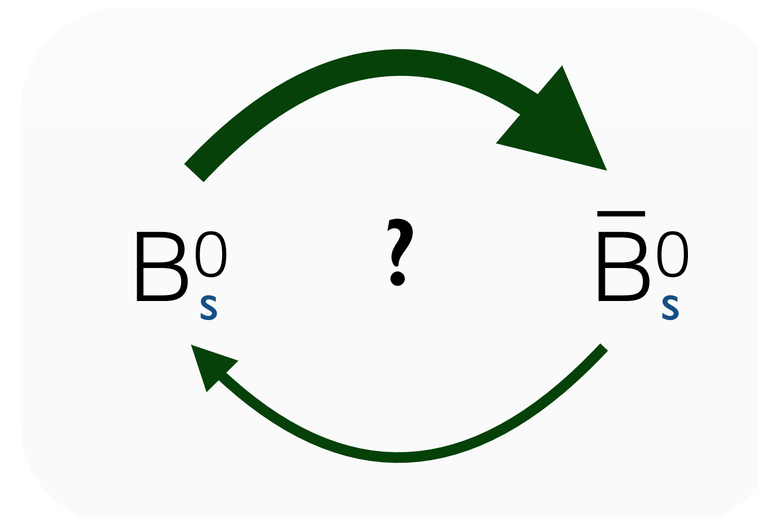
Source	$r_{\Omega_c^0}$
Decay time acceptance	13
Ω_b^- prod. spectrum	3
Ω_b^- lifetime	4
Decay time resolution	3
Background subtraction	18
$H_c(\tau^-, D)$, random μ^-	8
Simulated sample size	98
Total systematic	101
Statistical uncertainty	230

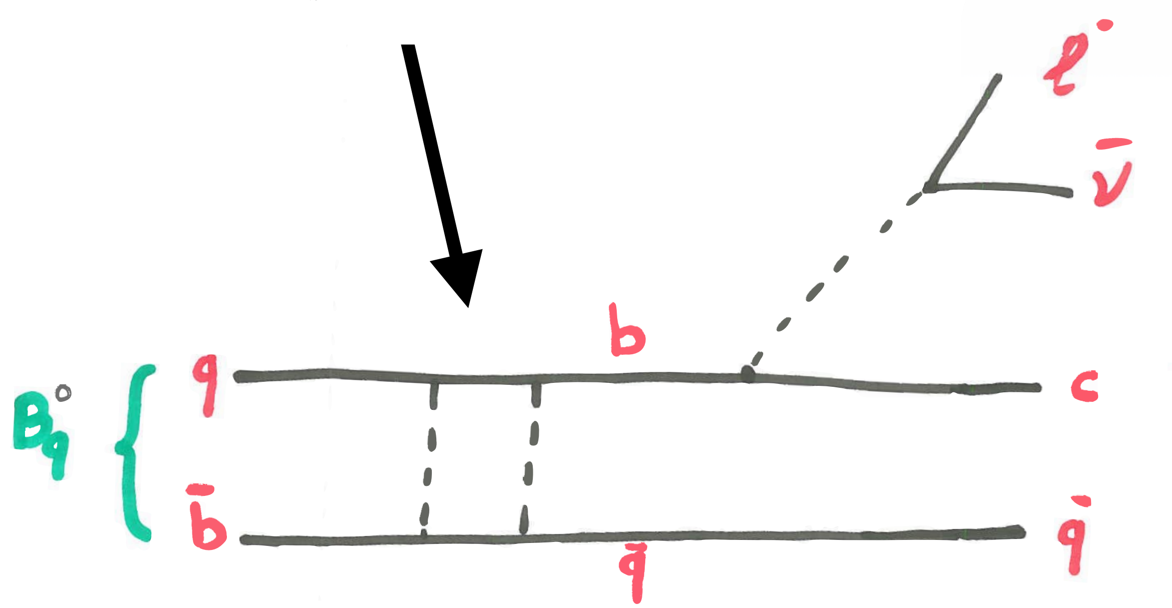
[LHCB-PAPER-2016-013]

Semileptonic decays



Are the mixing probabilities the same for B and $\overline{B}$?

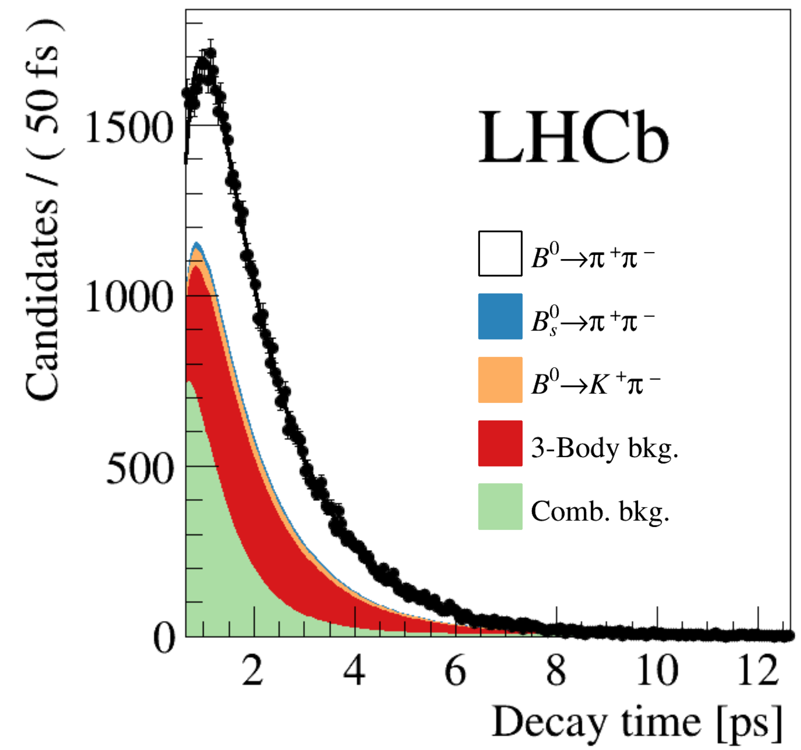


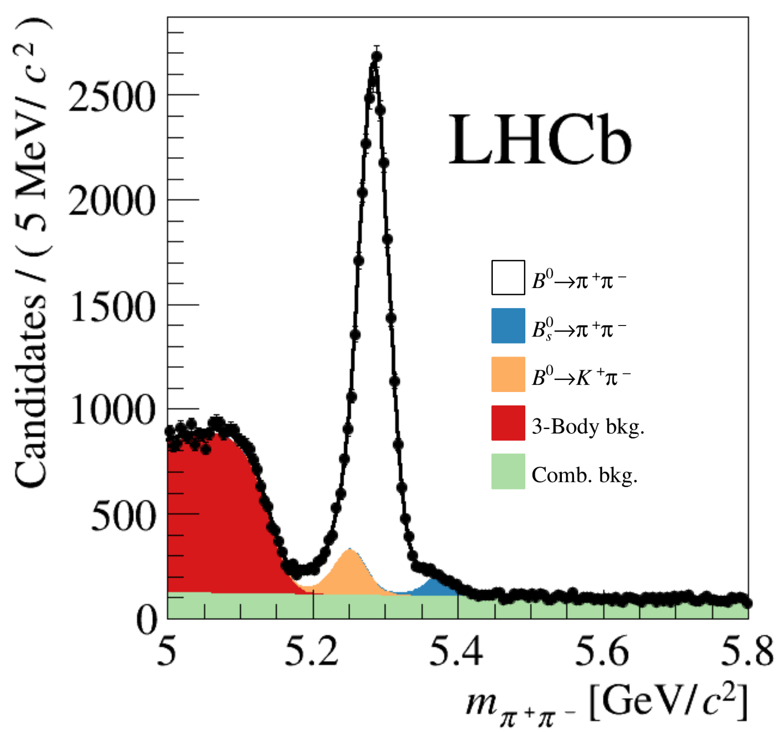


[LHCb-PAPER-2018-006]

$B_s \to KK$, $B^0 \to \pi\pi$

1 Fit the decay time distribution (split by flavour tag), using all components: access to $\Gamma(B_s \to f)$





2 Use the mass resolution to select the correct decay.

All phis measurements

Table 1: Direct experimental measurements of $\phi_s^{c\bar{c}s}$, $\Delta\Gamma_s$ and Γ_s using $B_s^0 \to J/\psi\,\phi$, $J/\psi\,K^+K^-$, $\psi(2S)\phi$, $J/\psi\,\pi^+\pi^-$ and $D_s^+D_s^-$ decays. Only the solution with $\Delta\Gamma_s > 0$ is shown, since the two-fold ambiguity has been resolved in Ref. [1]. The first error is due to statistics, the second one to systematics. The last line gives our average.

Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\,\phi$	$9.6\,\mathrm{fb}^{-1}$	$[-0.60,\ +0.12]$, 68% CL	$+0.068 \pm 0.026 \pm 0.009$	[2]
D0	$J/\psi\,\phi$	$8.0\,\mathrm{fb}^{-1}$	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[3]
ATLAS	$J/\psi\,\phi$	$4.9\,\mathrm{fb}^{-1}$	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	[4]
ATLAS	$J/\psi\,\phi$	$14.3\,\mathrm{fb}^{-1}$	$-0.110 \pm 0.082 \pm 0.042$	$+0.101 \pm 0.013 \pm 0.007$	[5]
ATLAS	above 2 combined		$-0.090 \pm 0.078 \pm 0.041$	$+0.085 \pm 0.011 \pm 0.007$	[5]
CMS	$J/\psi\,\phi$	$19.7\,\mathrm{fb}^{-1}$	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	[6]
LHCb	$J/\psi\,K^+K^-$	$3.0\,\mathrm{fb}^{-1}$	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0032$	[7]
LHCb	$J/\psi\,\pi^+\pi^-$	$3.0\,\mathrm{fb}^{-1}$	$+0.070 \pm 0.068 \pm 0.008$	—	[8]
LHCb	$J/\psi\,K^+K^{-\,a}$	$3.0\,\mathrm{fb}^{-1}$	$+0.119 \pm 0.107 \pm 0.034$	$+0.066 \pm 0.018 \pm 0.010$	[9]
LHCb	above 3 combined		$+0.001 \pm 0.037(\mathrm{tot})$	$+0.0813 \pm 0.0073 \pm 0.0036$	[9]
LHCb	$\psi(2S)\phi$	$3.0\,\mathrm{fb}^{-1}$	$+0.23^{+0.29}_{-0.28} \pm 0.02$	$+0.066^{+0.41}_{-0.44} \pm 0.007$	[10]
LHCb	$D_s^+D_s^-$	$3.0\,\mathrm{fb}^{-1}$	$+0.02 \pm 0.17 \pm 0.02$	—	[11]
All combined			-0.021 ± 0.031	$+0.085 \pm 0.006$	

[a] $m(K^+K^-) > 1.05\ \mathrm{GeV}/c^2$.