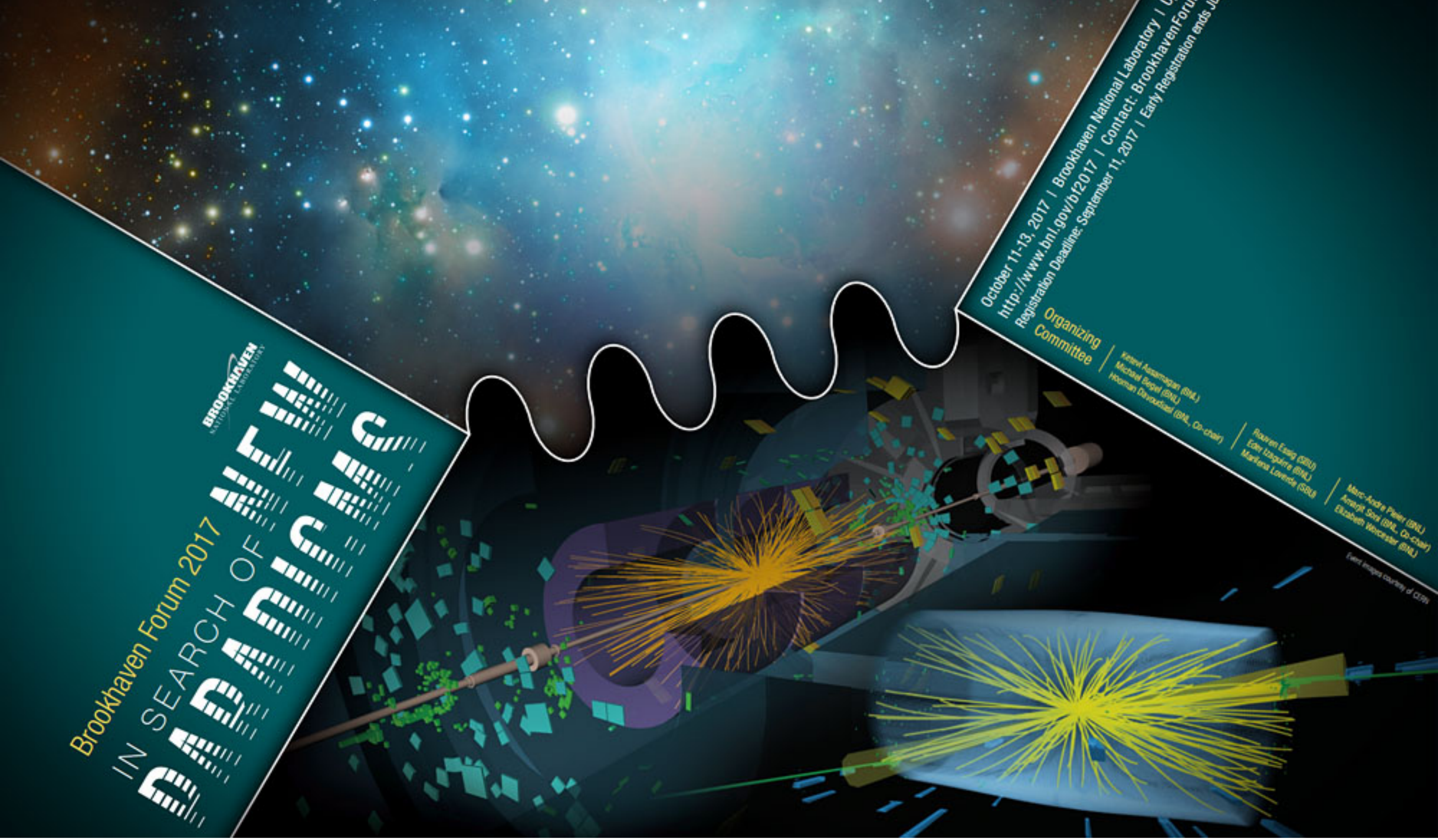
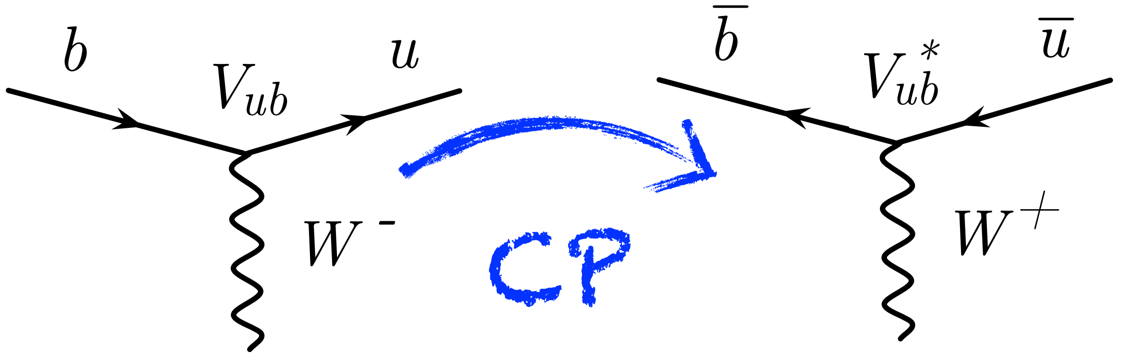


CP violation measurements in beauty and charm hadrons at LHCb

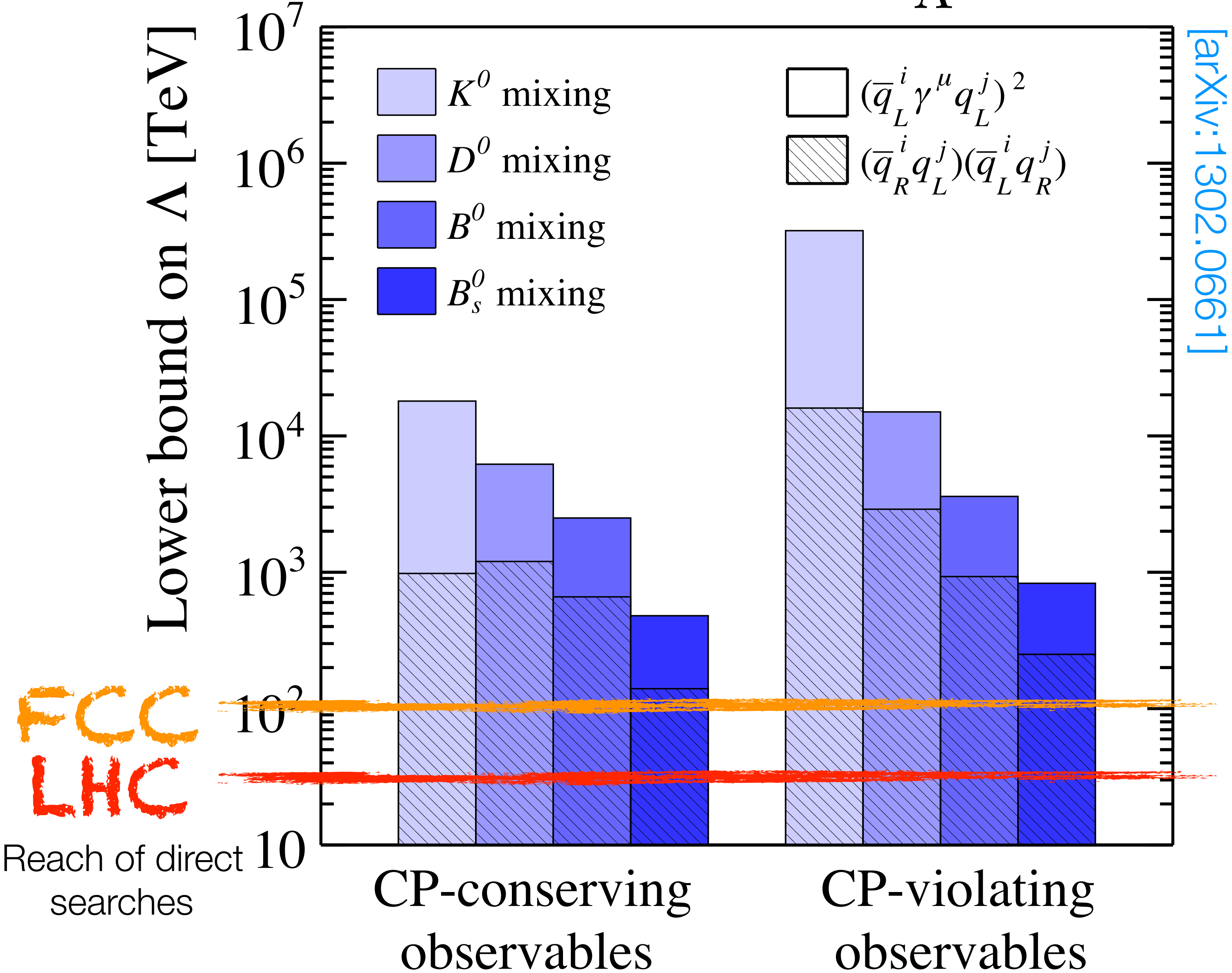
Angelo Di Canto on behalf of LHCb

CPV in the Standard Model (and beyond)

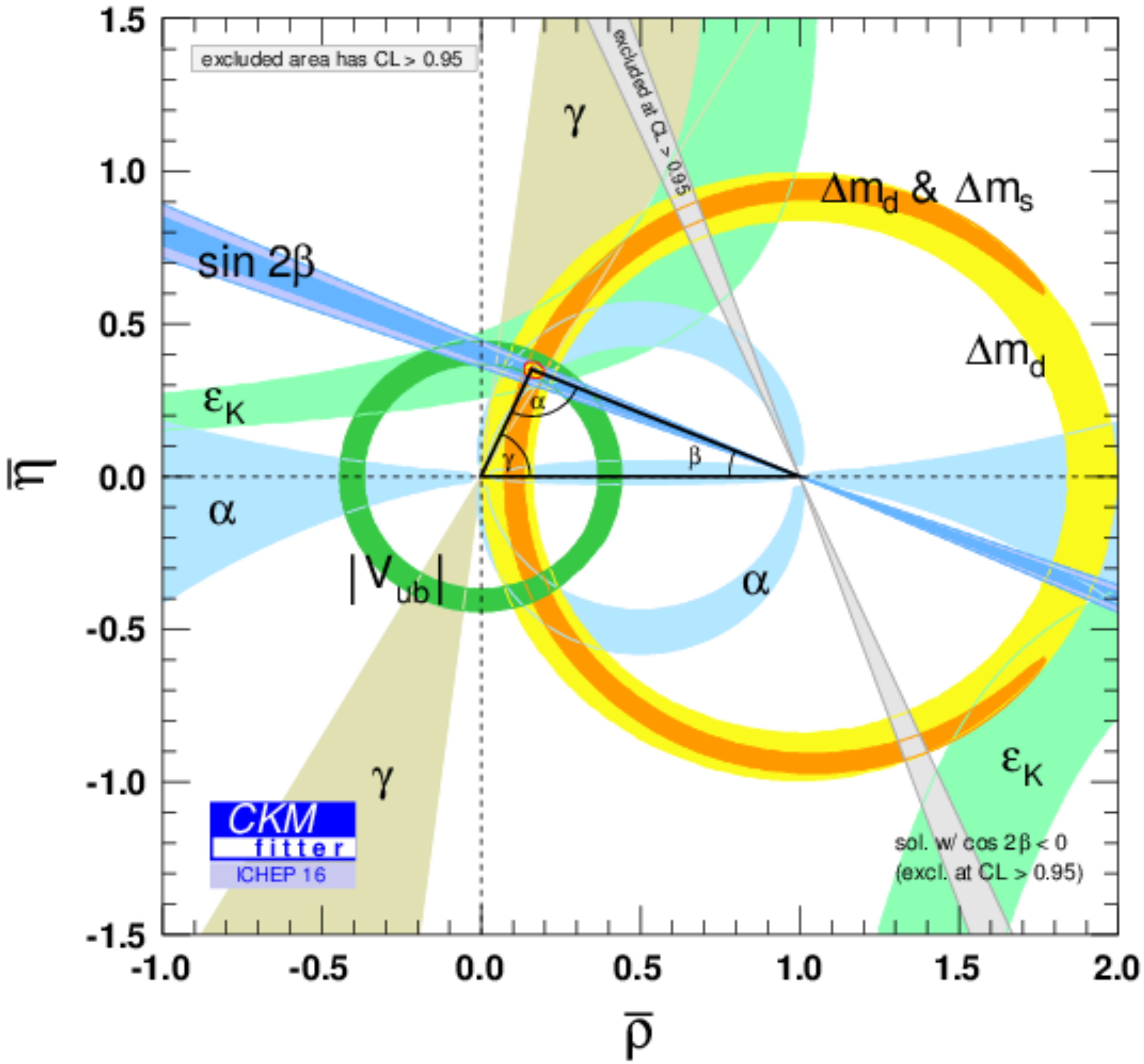
- The phase of the CKM matrix is the dominant source of CPV in the SM
- In extensions of the SM additional sources can arise from exchange of new particles (that may not be at directly accessible at the LHC)
- Decays of heavy-flavoured mesons are the best laboratory to test the CKM paradigm and look for new sources of CPV



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



Experimental status



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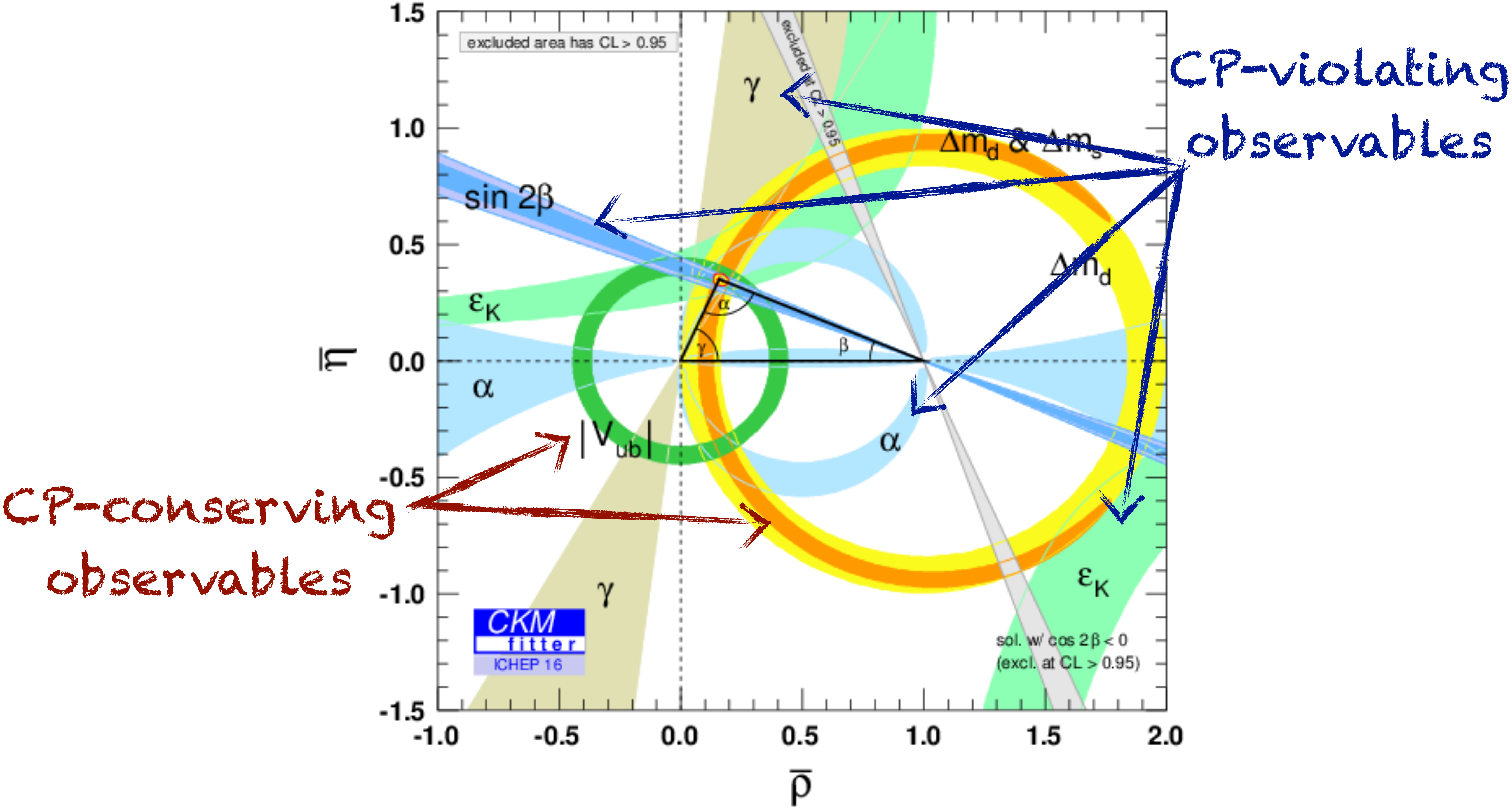
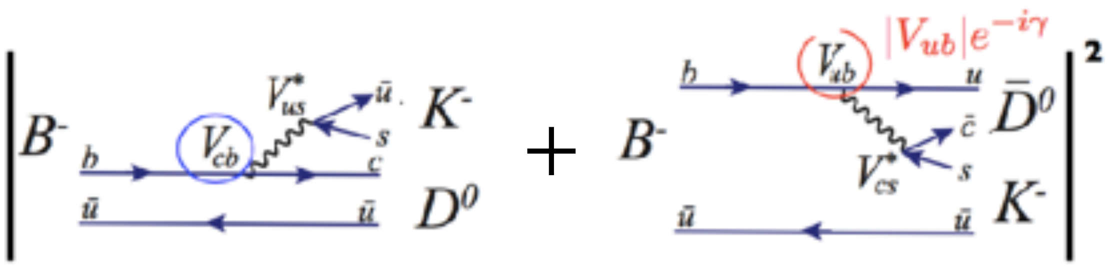


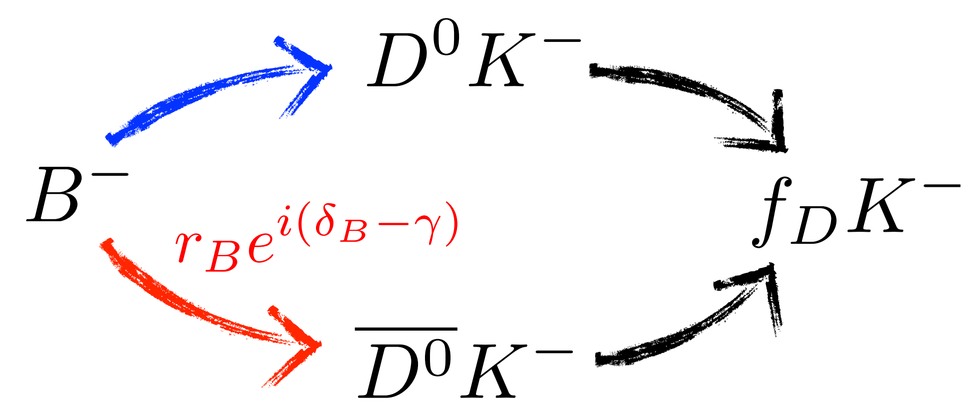
CKM angle γ

- The least constrained angle of the CKM matrix and only CPV parameter that can be measured from trees



$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \approx 76^\circ$$

- Negligibly small theory uncertainties [JHEP 01 (2014) 051]
  → powerful test of the SM



- Possible to combine several D final states to improve precision [PLB 253 (1991) 483, PLB 265 (1991) 172, PRL 78 (1997) 3257, PRD 68 (2003) 054018]

$f_D = K^+K^-, \pi^+\pi^-$	GLW
$K^\mp\pi^\pm$	ADS
$K_S\pi^+\pi^-$	GGSZ

[LHCb-CONF-2017-004]

LHCb combination

- Constraints from several decay modes (85 observables, 37 parameters) to find

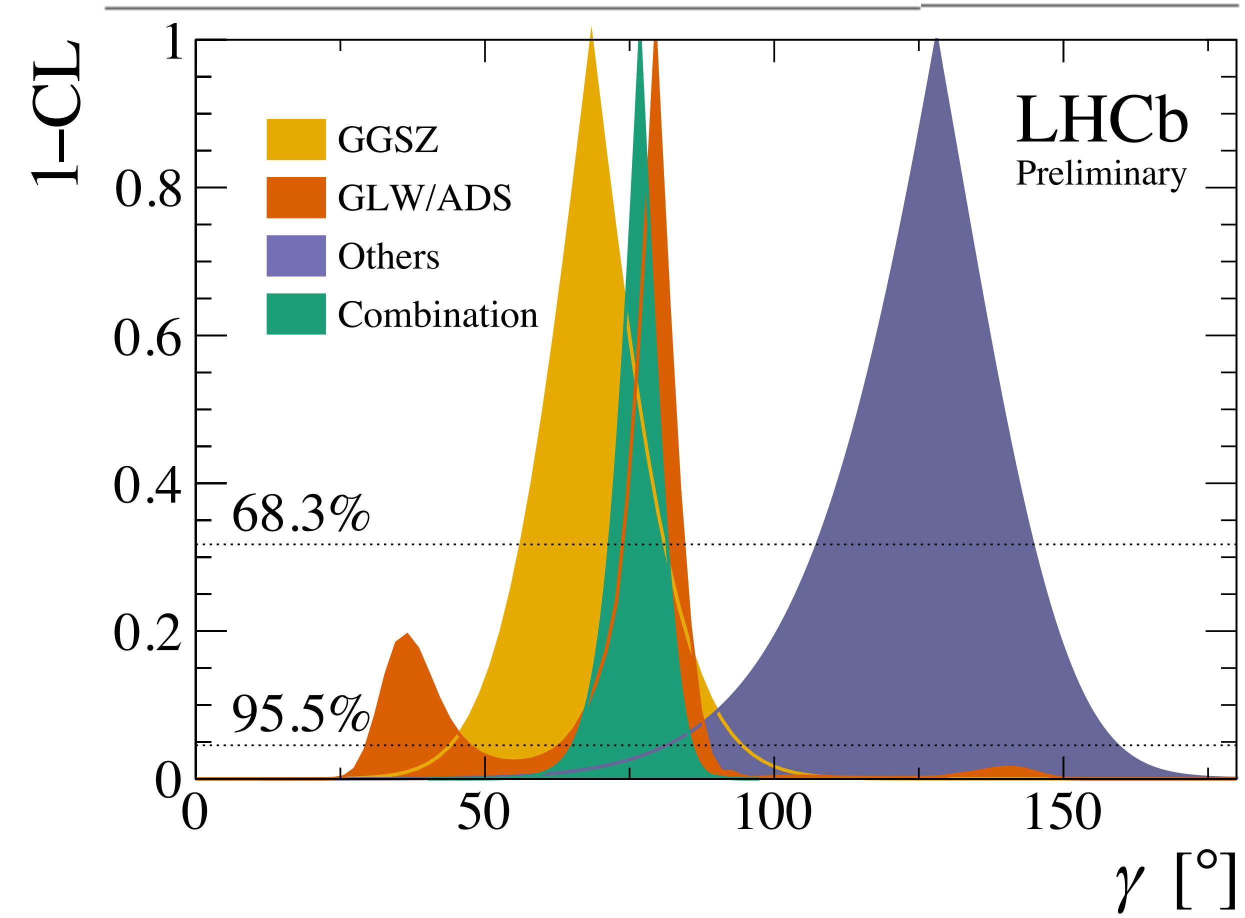
$$\gamma = (76.8^{+5.1}_{-5.7})^\circ$$

- To be compared with world average of [HFLAV]

$$\gamma = (76.2^{+4.7}_{-5.0})^\circ$$

- Soon many more results from Run 2
- Expect ~1°(0.4°) precision after LHCb phase-1(2) upgrade [EPJC 73 (2013) 2373, CERN-LHCC-2017-003]
- Belle 2 with 50/ab will be competitive with LHCb phase-1 upgrade

B decay	D decay	Method	Status since [JHEP 12 (2016) 087]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	Updated to Run 1 + 2 fb^{-1} Run 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	As before
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	New (Run 1 + 2fb^{-1} Run 2)
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	New (Run 1 + 2fb^{-1} Run 2)
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	TD	Updated to 3 fb^{-1} Run 1



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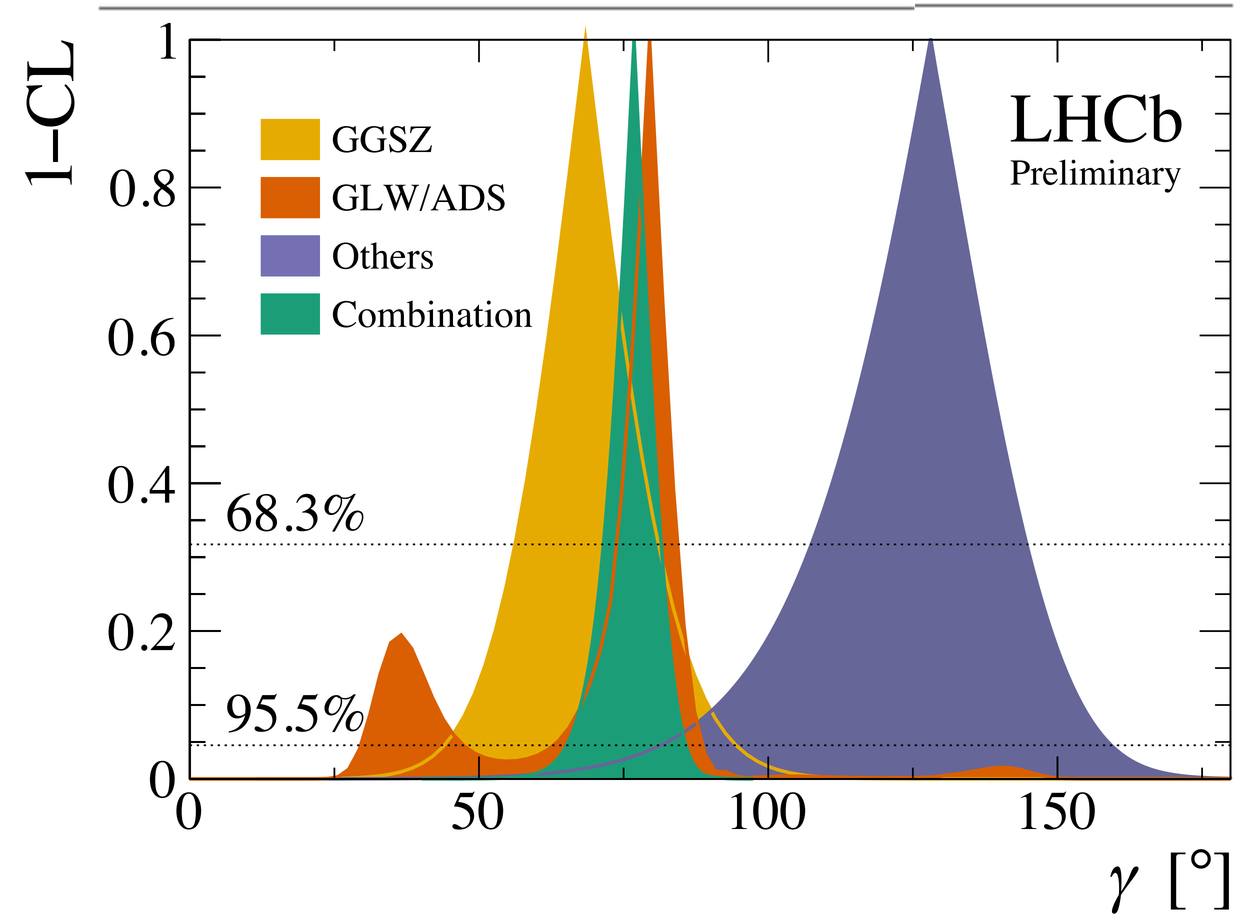


$B^{\pm}\to DK^{*\pm}$ in Run 1+2 data

NEW

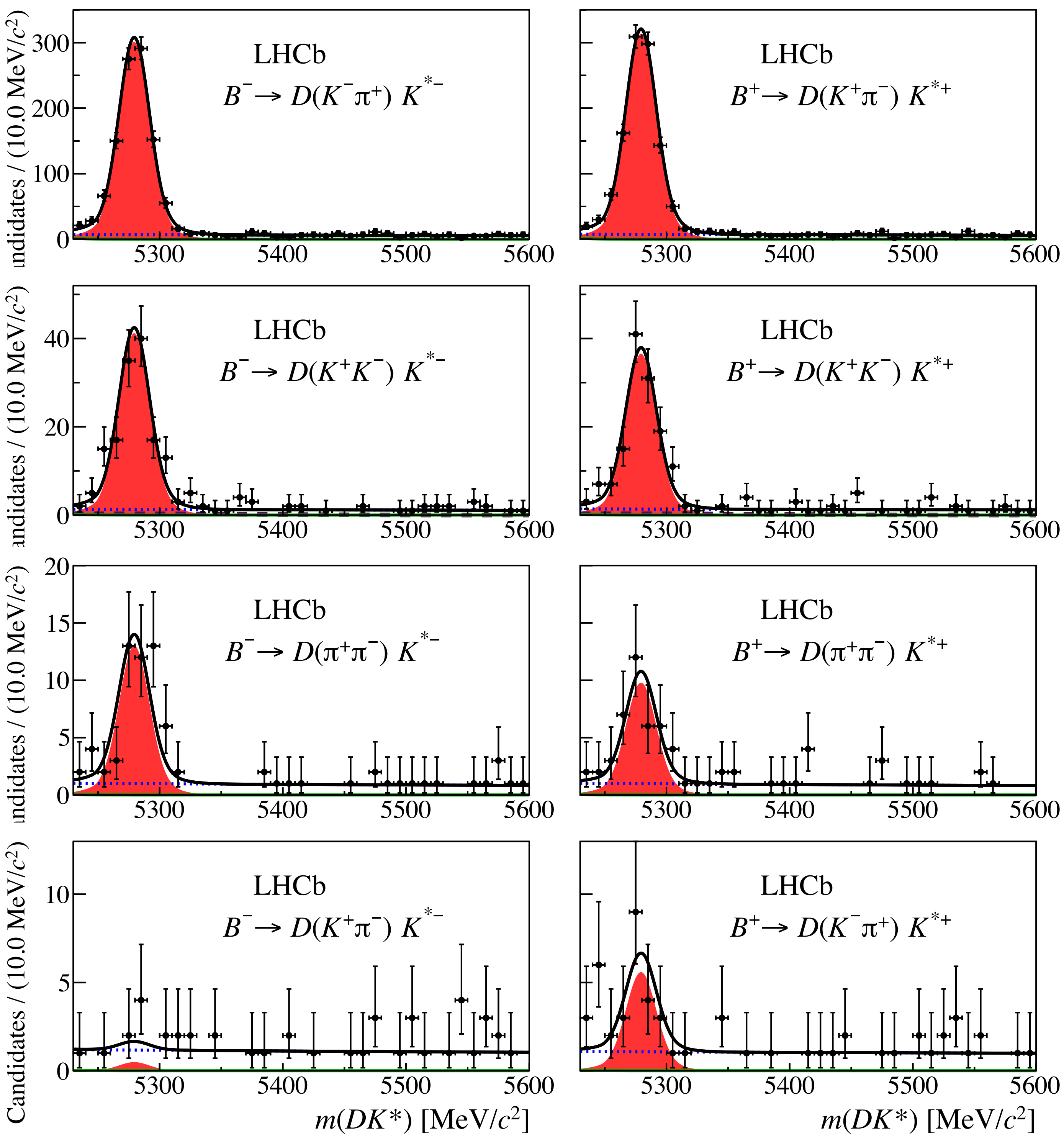
[LHCb-PAPER-2017-030]

- Uses 2- and 4-body D decays and $K^{*\pm}\to K_S\pi^{\pm}$ decays
- Constraints on r_B, δ_B and γ from measurement of ratio of rates and CP asymmetries

$$R_{CP+} = 1 + r_B^2 + 2r_B\cos\delta_B\cos\gamma$$
$$A_{CP+} = r_B\sin\delta_B\sin\gamma/R_{CP+}$$

- Results in the 2-body modes consistent and more precise than BaBar [PRD 80 (2009) 092001]

$$R_{CP+} = 1.18 \pm 0.08 \pm 0.01$$
$$A_{CP+} = 0.08 \pm 0.06 \pm 0.01$$
$$R_{ADS} = 0.011 \pm 0.004 \pm 0.001$$
$$A_{ADS} = -0.81 \pm 0.17 \pm 0.04$$



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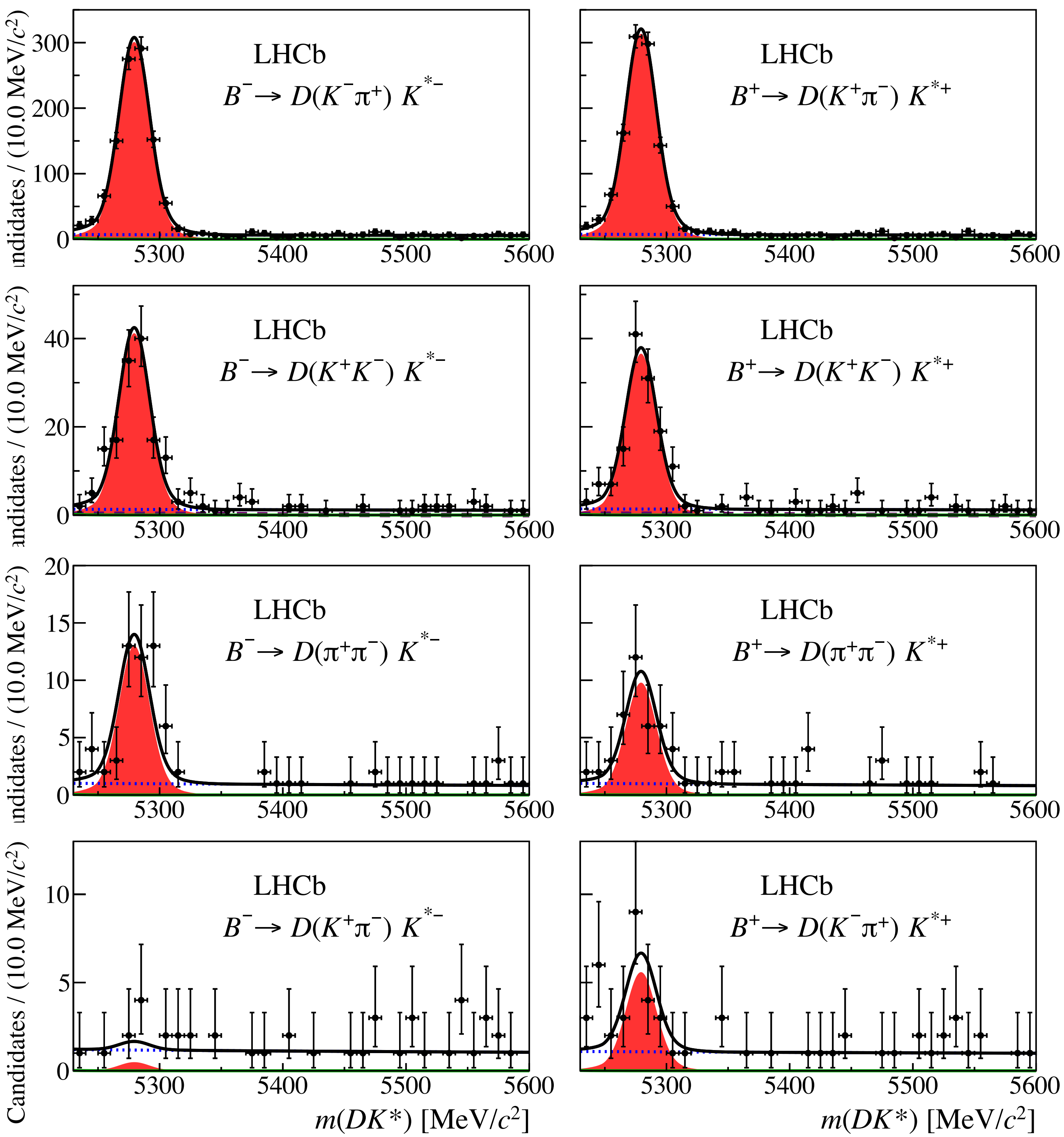
4.3σ evidence of suppressed ADS mode



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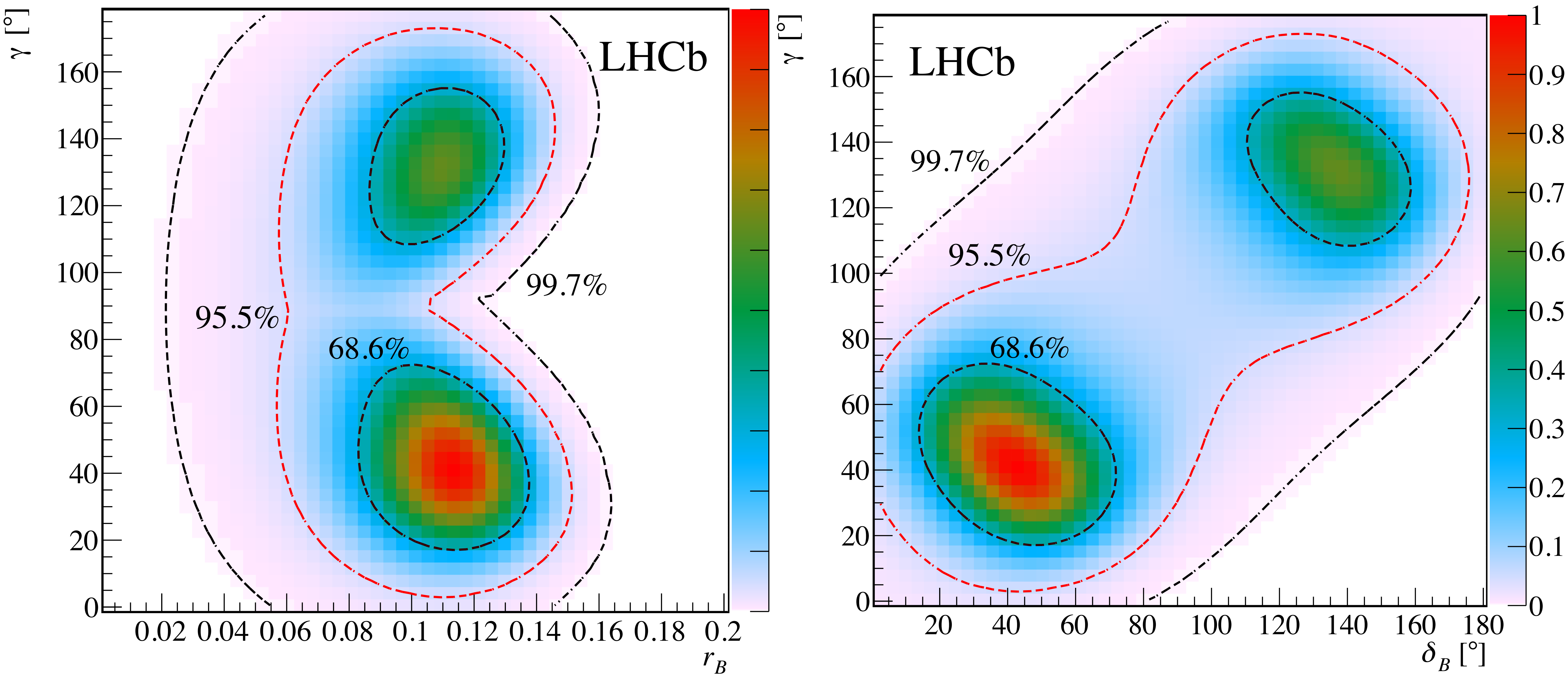
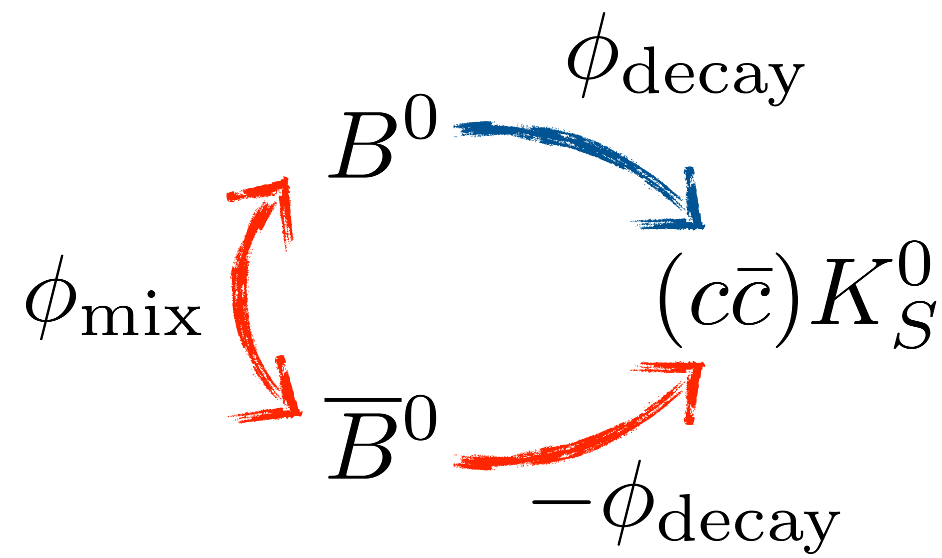
[LHCb-PAPER-2017-030]



CP violation in the B^0 system

- Interference between mixing and decay in $B^0 \to (c\bar{c})K_S$ is sensitive to the angle β

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \sim 22^\circ$$



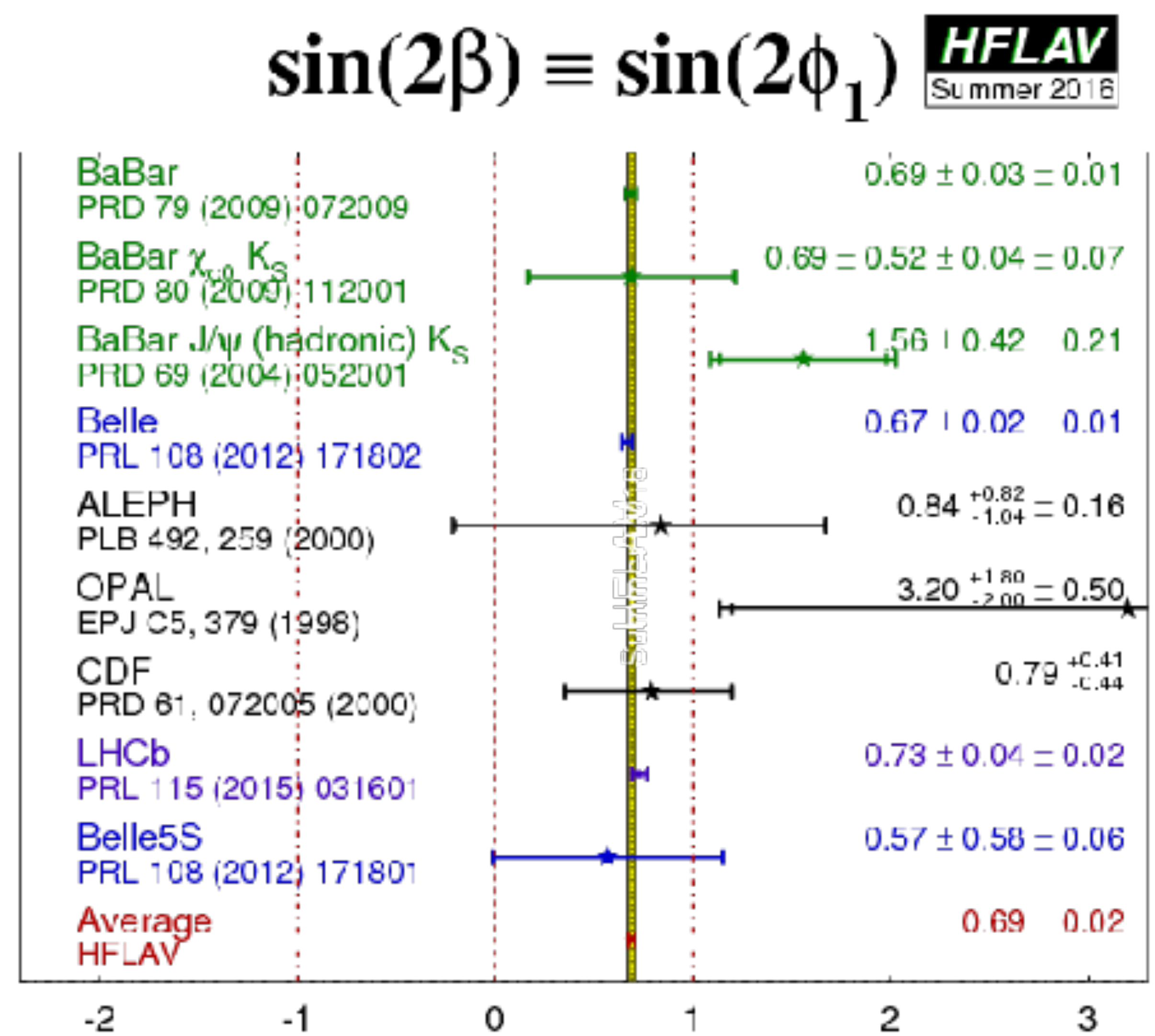
$$\phi = \phi_{\rm mix} - 2\phi_{\rm decay} \sim 2\beta$$

- The B-factories still dominate the world average [HFLAV]

$\beta = (21.9 \pm 0.7)^\circ$

but LHCb with Run 1 data is already pretty close

- LHCb is expected to reach 0.6° (0.2°) precision with Run 2 (phase-1 upgrade) [EPJC 73 (2013) 2373]



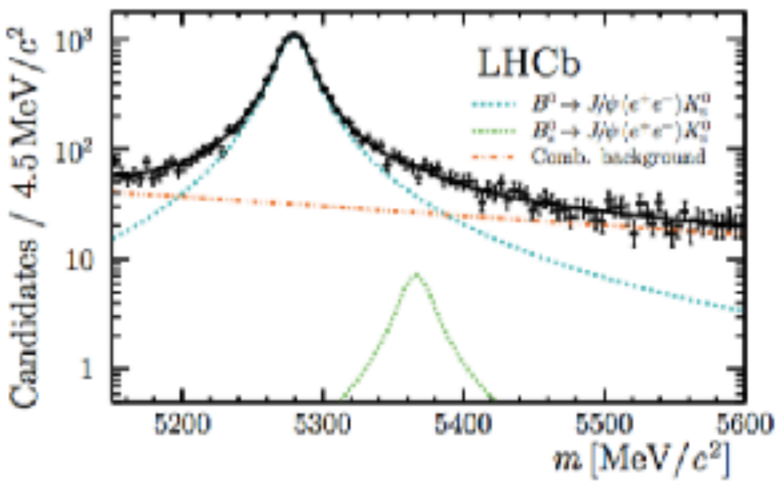
$\sin(2\beta)$ from $B^0 \to (c\bar{c})K_S$ decays

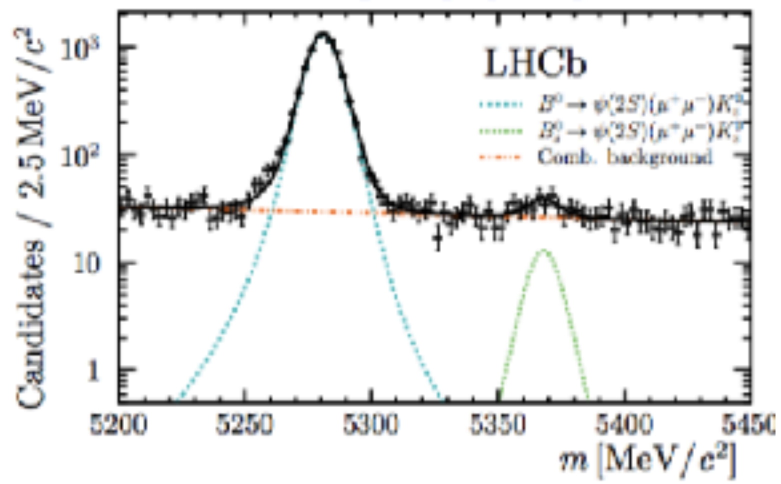
NEW

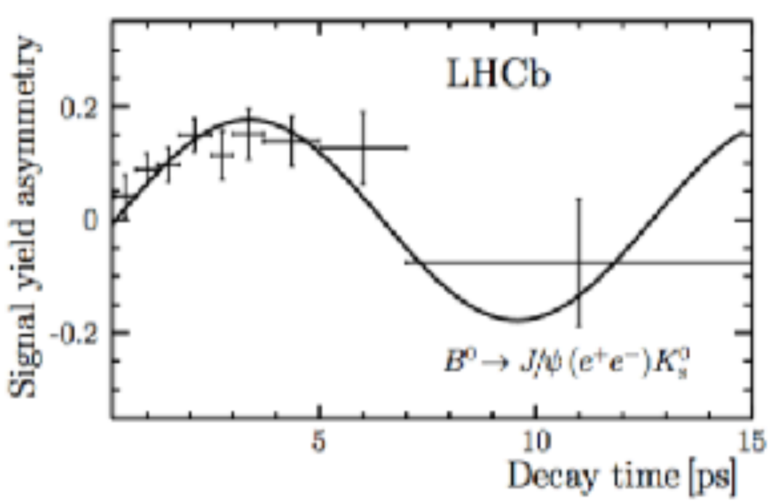
[LHCb-PAPER-2017-029]

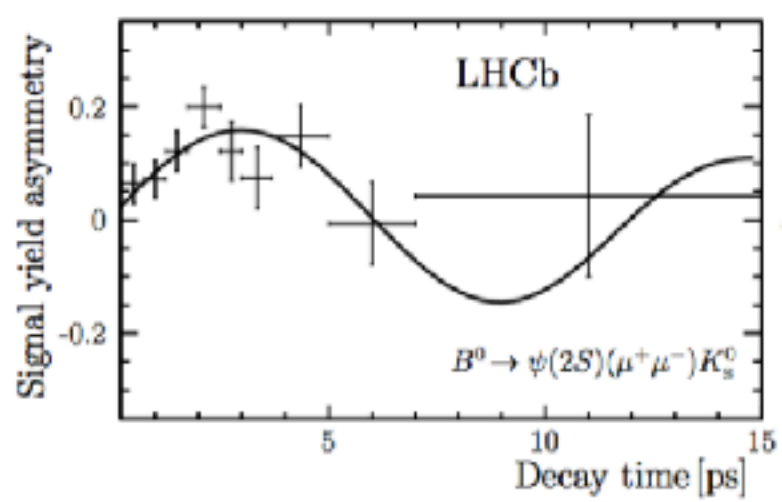
- Additional channels from Run 1 data

$B \to J/\psi(ee)K_S$ **$B \to \psi(2S)(\mu\mu)K_S$**



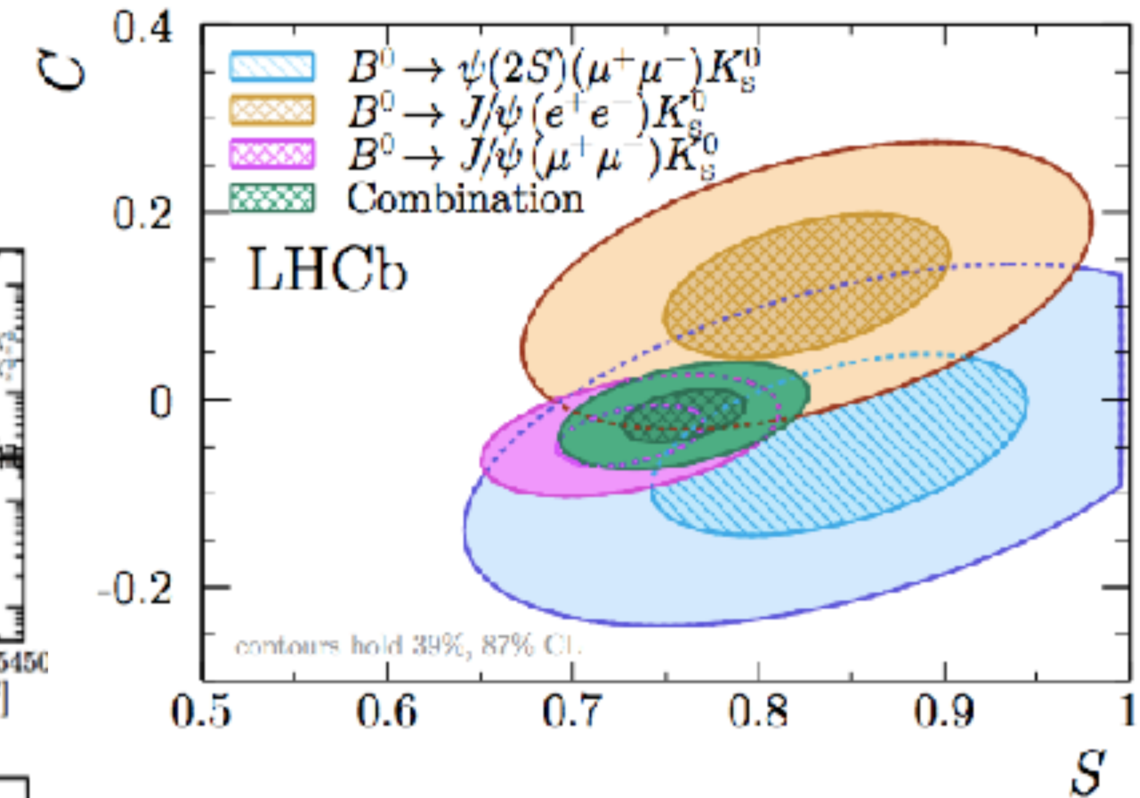






$$A_{CP}(t) = S\sin(\Delta m t) - C\cos(\Delta m t)$$

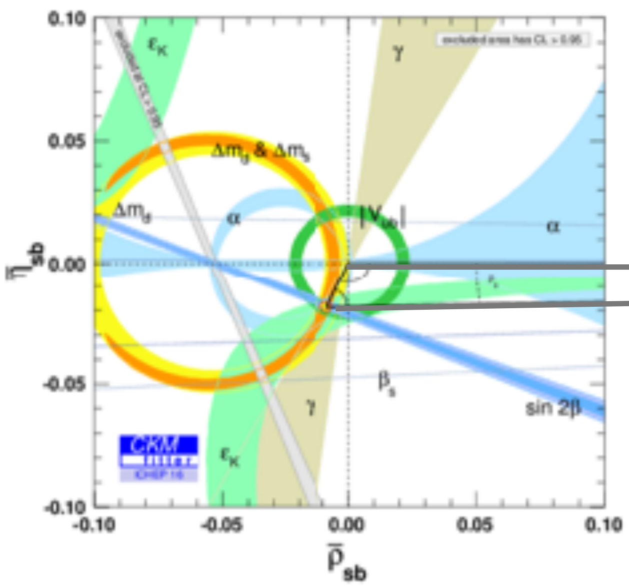
$$S \approx \sin(2\beta)$$



$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$
$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$

- About 20% improvement in precision wrt previous result [PRL 115 (2015) 031601]

CP violation in the B_s system



$$\beta_s = \arg\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right) \sim 1^\circ$$

- Golden channel is $B_s \to J/\psi\phi$, but additional sensitivity comes from other $b \to c\bar{c}s$ transitions

- Pioneering measurements from Tevatron have now been improved by more than a factor 10 by LHCb (+ Atlas and CMS)

LHCb:

- $J/\psi\phi$ [PRL114, 041801 (2015)]
- $J/\psi K^+K^-$ [arXiv:1704.08217 (2017)]
- $J/\psi\pi^+\pi^-$ [Phys. Lett. B736, (2014) 186]
- $\psi(2S)\phi$ [Phys. Lett. B762 (2016) 253-262]
- $D_s^+D_s^-$ [PRL113, 211801 (2014)]

CMS:

- $J/\psi\phi$ [Phys. Lett. B 757 (2016) 97]

ATLAS:

- $J/\psi\phi$ [JHEP 08 (2016) 147]

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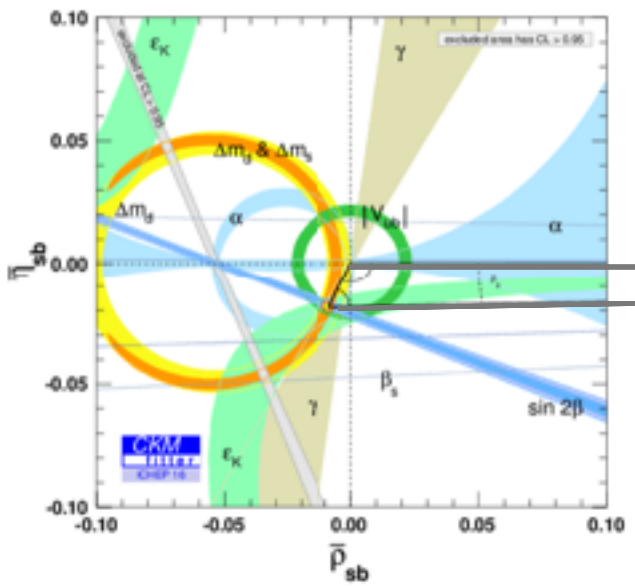

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CMS:

- $J/\psi\phi$ [Phys. Lett. B 757 (2016) 97]

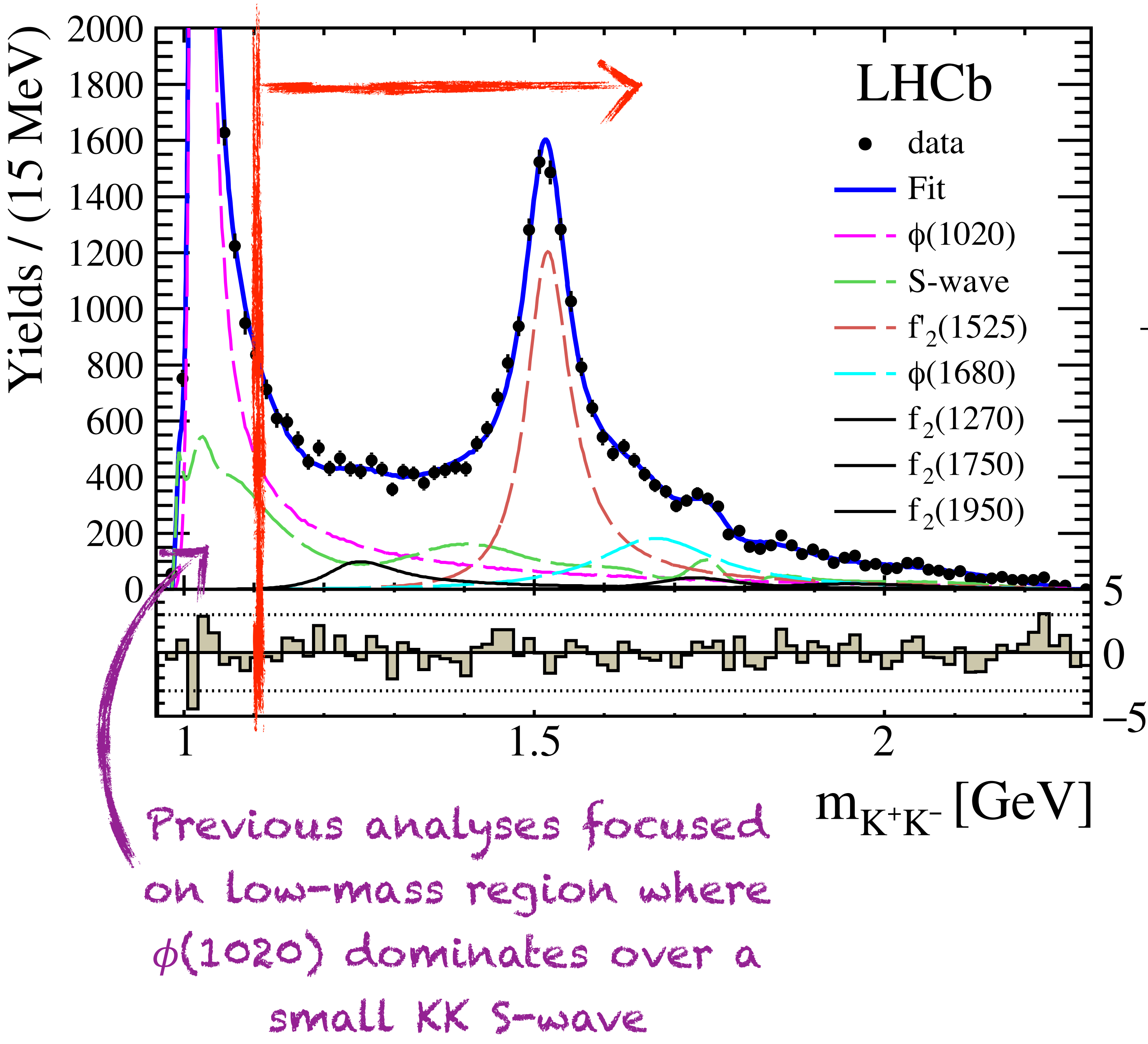
ATLAS:

- $J/\psi\phi$ [JHEP 08 (2016) 147]

$\phi_s = -2\beta_s$ using $B_s \to J/\psi KK$ decays

[JHEP 08 (2017) 037]

- Fully exploit Run 1 data by analysing the full *m(KK)* spectrum of $B_s \to J/\psi KK$ decays



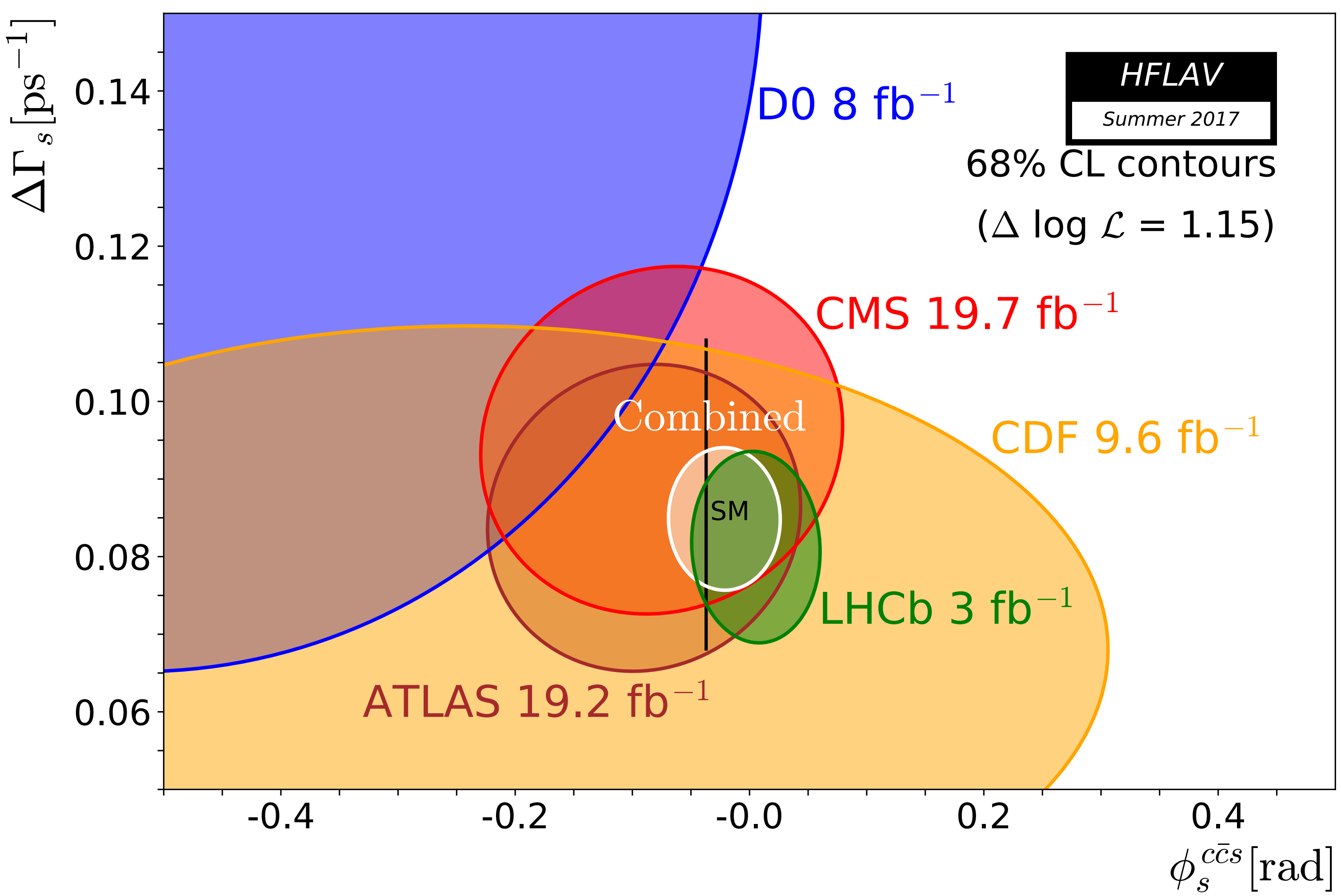
Flavor-tagged, time-dependent amplitude fit to separate the various CP-odd/even components

Parameter	Value
Γ_s [ps^{-1}]	$0.650 \pm 0.006 \pm 0.004$
$\Delta\Gamma_s$ [ps^{-1}]	$0.066 \pm 0.018 \pm 0.010$
ϕ_s [mrad]	$119 \pm 107 \pm 34$
$\vert\lambda\vert$	$0.994 \pm 0.018 \pm 0.006$

New LHCb average (including $J/\psi\phi$ *and* $J/\psi\pi\pi$)

$$\phi_s = (1 \pm 37)\mathrm{mrad}$$

Experimental status for ϕ_s



$$\phi_s = (-21 \pm 31)\,\mathrm{mrad}$$

- Still far from the SM uncertainty (~1 mrad) → plenty of room for new physics
- Sensitivity with LHCb phase-1(2) upgrade is expected to be ~9(3) mrad [EPJC 73 (2013) 2373, CERN-LHCC-2017-003]

What about the charm triangle?

$$\beta_c = \arg\left(-\frac{V_{cd}V_{ud}^*}{V_{cs}V_{us}^*}\right) \sim 0.03^\circ$$

NB: not in scale, the real angle is much smaller

- CPV practically absent in the SM (charm transitions almost completely decoupled from the third generation)
- Ideal place to look for new physics (especially if couples preferentially to up-type quarks)
- Very challenging: requires huge samples and control of systematic uncertainties below the 0.1% level

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

[PRL 118 (2017) 261803]

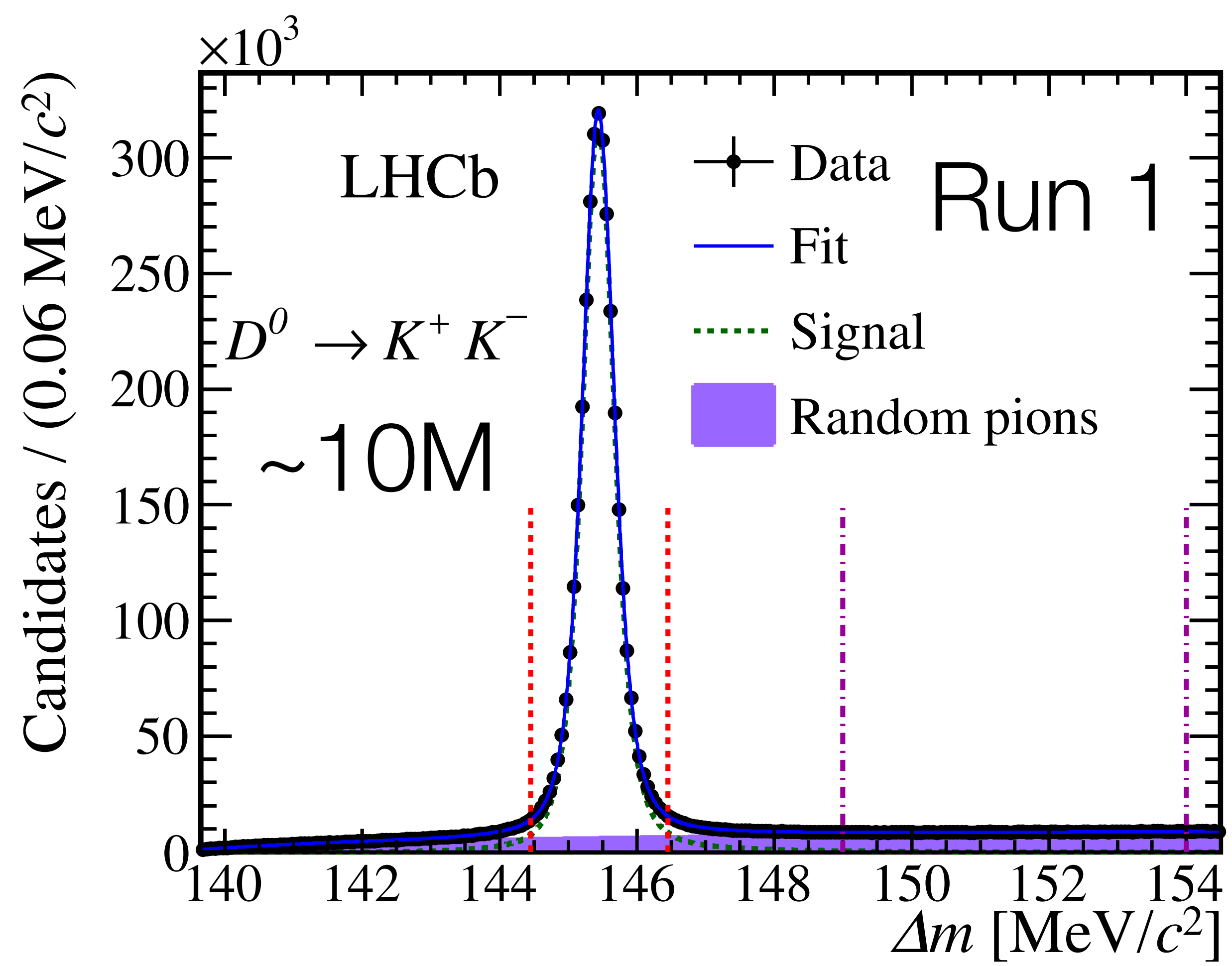
- Time-dependent asymmetry between D^0 and $\bar{D}^0$ to CP-even final states

$$A(t) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\bar{D}^0 \to h^+h^-)} \approx A_{CP} - A_{\Gamma}\frac{t}{\tau_D}$$

- Linear term due to CPV in interference between mixing and decay: $A_{\Gamma} \approx -x \sin\phi_D$

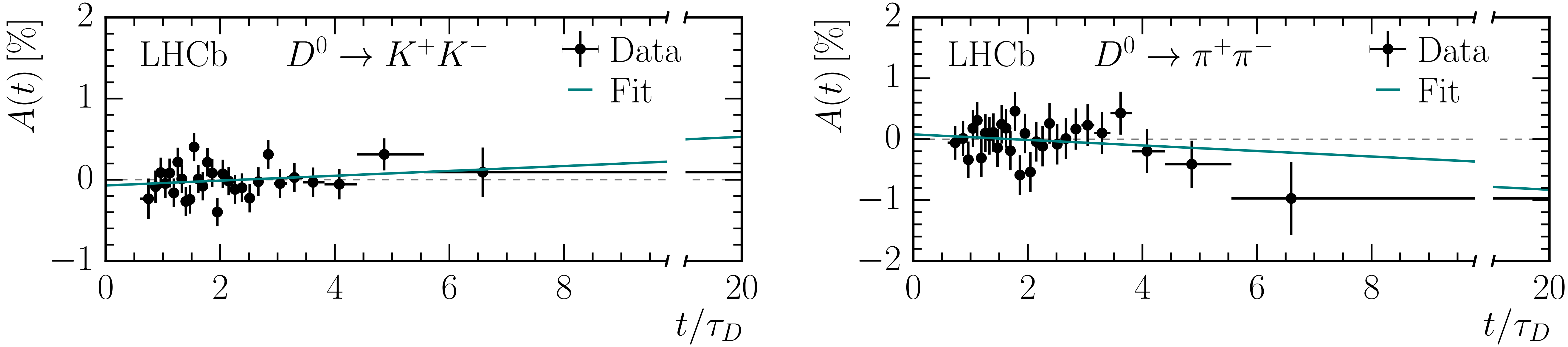
- Identify flavour at production with $D^{*+} \to D^0\pi^+$ decays

- Two different analysis methods return consistent results



Results

[PRL 118 (2017) 261803]

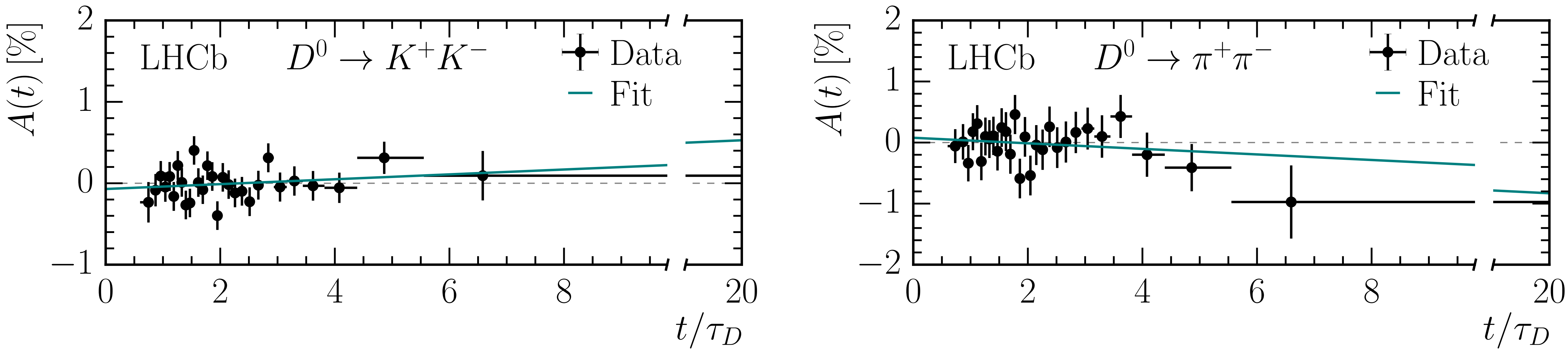


$$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10)\times 10^{-3}$$

$$A_\Gamma(\pi^+\pi^-) = (+0.46 \pm 0.58 \pm 0.12)\times 10^{-3}$$

Results

[PRL 118 (2017) 261803]



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- Combining the two final states

$$A_\Gamma = (-0.13 \pm 0.28 \pm 0.10)\times10^{-3}$$

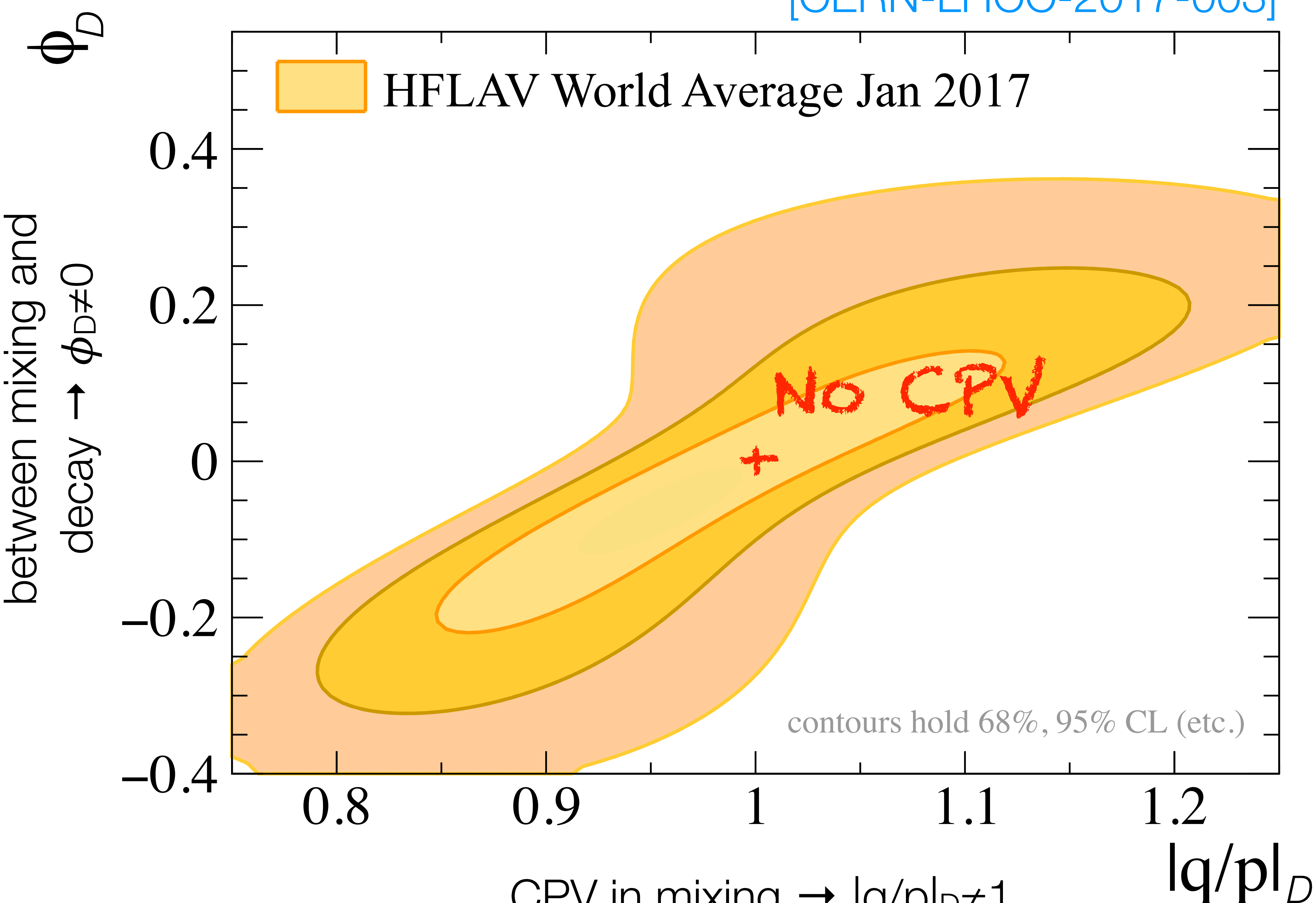
- And with the result based on $B \to D^0\mu^-X$ decays [JHEP 04 (2015) 043]

$$A_\Gamma = (-0.29 \pm 0.28)\times10^{-3}$$

- Consistent with CP symmetry. World's most precise measurement to date (Belle 2 would need to collect 50/ab to reach this precision)

Global fit to all charm mixing+CPV data

[CERN-LHCC-2017-003]

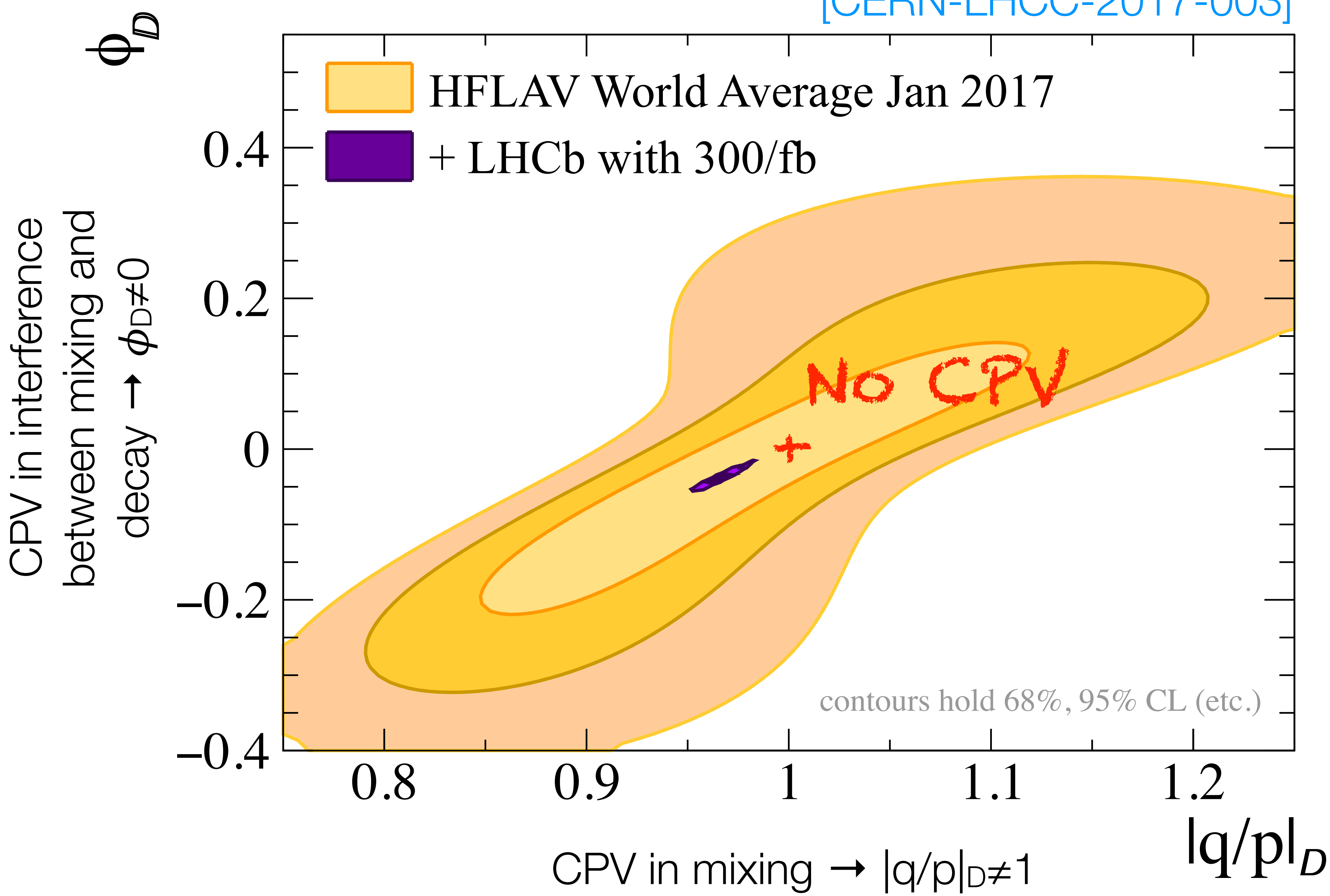


CPV in interference between mixing and decay → $\phi_D \neq 0$

CPV in mixing → $|q/p|_D \neq 1$

Global fit to all charm mixing+CPV data

[CERN-LHCC-2017-003]



Conclusions

- Flavour/CP violation plays a key role in unravelling what lies beyond the SM, providing access to energy scales and couplings unaccessible at the energy frontier
- LHCb is the ideal place where to study flavour/CP violation
  - Many measurements (based on Run 1 data only) have already exceeded those from the B-factories and the Tevatron
    - Could not cover many other interesting results (e.g. evidence of CPV in beauty baryons [Nature Physics 13 (2017) 391], search for strong CPV [PLB 764 (2017) 233], …)
  - All consistent with SM expectations and limited by statistics
  - Need to exploit Run 2 data and be prepared for the upgrades

Backup

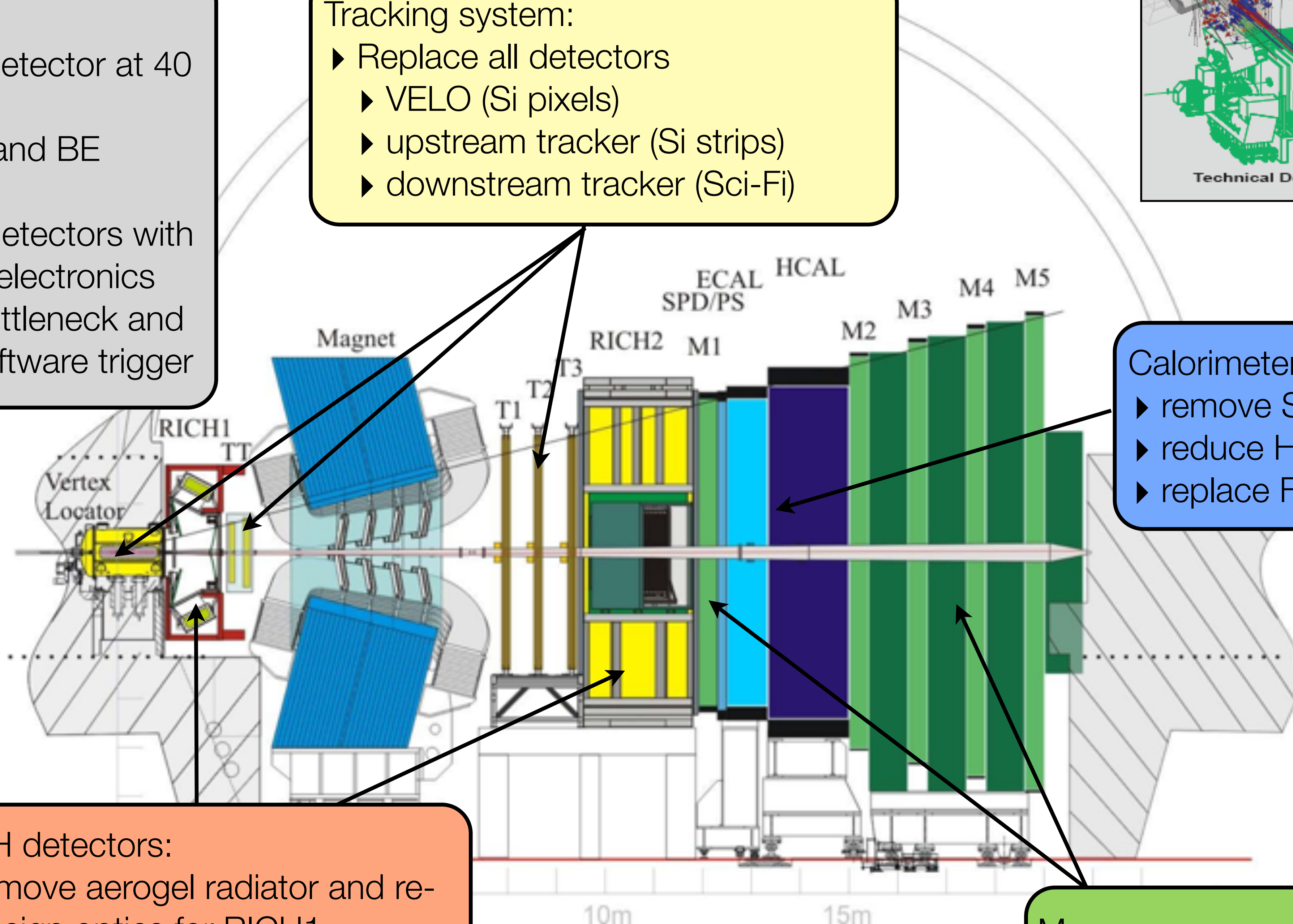
Letter of Intent for the LHCb Upgrade
CERN-LHCC-2011-001

Framework TDR for the LHCb Upgrade
CERN-LHCC-2012-007

LHCb phase-1 upgrade

Trigger & DAQ:
- read-out full detector at 40 MHz
  - replace FE and BE electronics
  - replace all detectors with embedded electronics
- remove L0 bottleneck and have an all software trigger

Tracking system:
- Replace all detectors
  - VELO (Si pixels)
  - upstream tracker (Si strips)
  - downstream tracker (Sci-Fi)



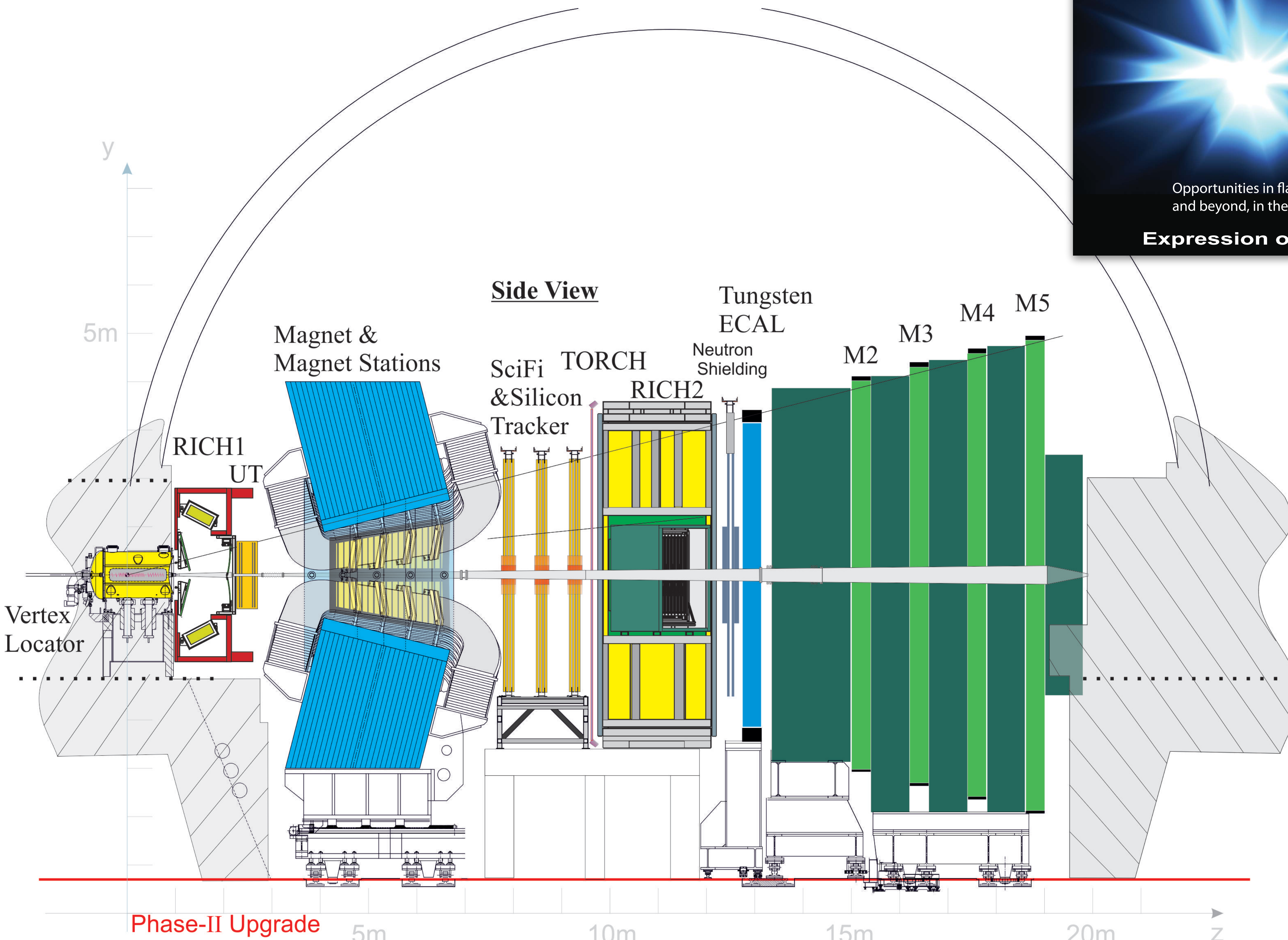
Calorimeters:
- remove SPD & PS
- reduce HV & PMT gain
- replace FE electronics

RICH detectors:
- remove aerogel radiator and re-design optics for RICH1
- replace photo-detectors

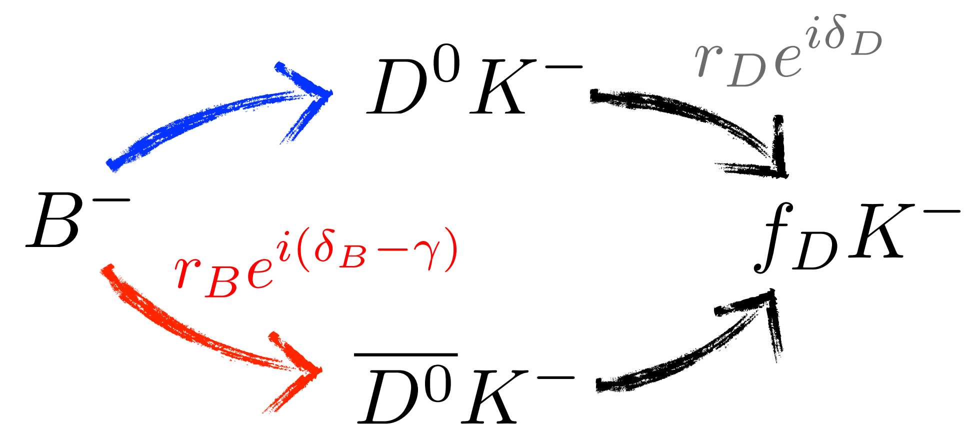
Muons:
- remove M1
- replace FE electronics

LHCb phase-2 upgrade

[CERN-LHCC-2017-003]



CP observables in $B^{\pm}\rightarrow DK^{\pm}$



- Gronau-London-Wyler uses (quasi-)CP-even final states

$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{CP+} = \frac{1}{R_{CP+}} 2r_B(2F_+ - 1)\sin(\delta_B)\sin(\gamma)$$

$$\frac{N(B\rightarrow[KK]_D K)\times\Gamma(D\rightarrow K\pi)}{N(B\rightarrow[K\pi]_D K)\times\Gamma(D\rightarrow KK)} = R_{CP+} = 1 + r_B^2 + 2r_B(2F_+ - 1)\cos(\delta_B)\cos(\gamma)$$

- Atwood-Dunietz-Soni uses DCS mode

$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{ADS} = \frac{1}{R_{ADS}} 2r_B r_D \sin(\delta_B + \delta_D)\sin(\gamma)$$

$$\frac{N(B^{\pm}\rightarrow[\pi^{\pm}K^{\mp}]_D K^{\pm})}{N(B^{\pm}\rightarrow[K^{\pm}\pi^{\mp}]_D K^{\pm})} = R_{ADS} = r_B^2 + r_D^2 + 2r_B r_D\cos(\delta_B + \delta_D)\cos(\gamma)$$