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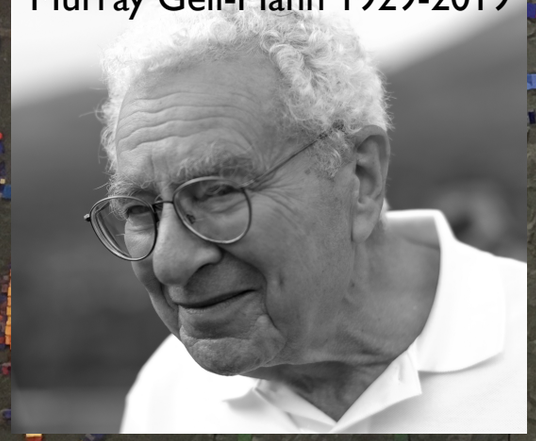
Quark CP violation

Marco Gersabeck (The University of Manchester)
on behalf of the LHCb collaboration
presenting also results from ATLAS, Belle and BESIII

Rencontre de Blois, Blois, 4 June 2019

Murray Gell-Mann 1929-2019



Enter antimatter

LETTERS TO THE EDITOR

[*The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, or to correspond with the writers of, rejected manuscripts intended for this or any other part of* NATURE. *No notice is taken of anonymous communications.*]

Potential Matter.—A Holiday Dream.

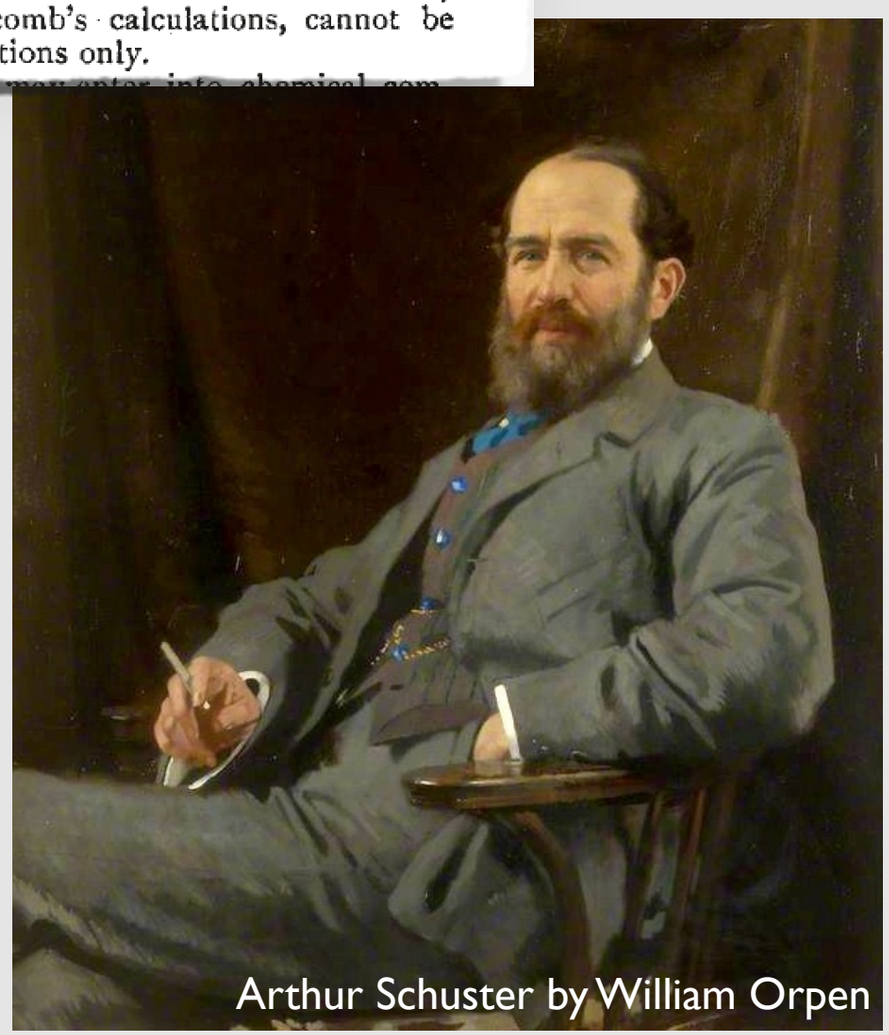
WHEN the year's work is over and all sense of responsibility has left us, who has not occasionally set his fancy free to dream

undistinguishable in fact from them until they are brought into each other's vicinity. If there is negative electricity, why not negative gold, as yellow and valuable as our own, with the same boiling point and identical spectral lines; different only in so far that if brought down to us it would rise up into space with an acceleration of 981. The fact that we are not acquainted with such matter does not prove its non-existence; for if it ever

incipient worlds which our telescopes have revealed to us. Astronomy, the oldest and yet most juvenile of sciences, may still have some surprises in store. May anti-matter be commended to its care! But I must stop—the holidays are nearing their end—the British Association is looming in the distance; we must return to sober science, and dreams must go to sleep till next year.

Do dreams ever come true? ARTHUR SCHUSTER.

tional velocity of our solar and of many stellar systems, which cannot be self-generated. Unless we threw our laws of dynamics overboard, or imagine the rotation to have been impressed by creation, we must conclude that some outside body or system of bodies is endowed with an equal and opposite angular momentum. What has become of that outside body, and how could it have parted company with our solar system, if attractive forces only were acting? Another unexplained fact is found in the large velocities of some of the fixed stars, which, according to Prof. Newcomb's calculations, cannot be explained by gravitational attractions only.



Arthur Schuster by William Orpen

CP violation

CP violation in decay

$$D^0 \longrightarrow K^-K^+$$

$$\overline{D}^0 \longrightarrow K^-K^+$$

Direct CP violation

→ depends on decay mode
→ independent of decay time

Interference

Indirect CP violation

→ independent of decay mode in SM
→ effect varies as function of decay time

CP violation in mixing

$$D^0 \longrightarrow \overline{D}^0 \longrightarrow D^0 \longrightarrow \overline{D}^0 \longrightarrow$$

CP violation

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Flavour physics:
Fast-tracking discoveries

- K^0-$\overline{K}^0$ mixing and smallness of $K^0 \rightarrow \mu^+\mu^-$

  ➡ GIM mechanism predicts charm quark in 1970

- Kaon CP violation (30+25 years ago)

  ➡ KM mechanism predicts bottom and top quarks in 1973

    - Charm & bottom quarks discovered: 1974+1977

- B^0-$\overline{B}^0$ oscillations discovered in 1987

  ➡ Requires $m_{top} > 50$ GeV to deactivate GIM cancellation

    - Top quark discovered: 1995

Flavour physics:
Fast-tracking discoveries

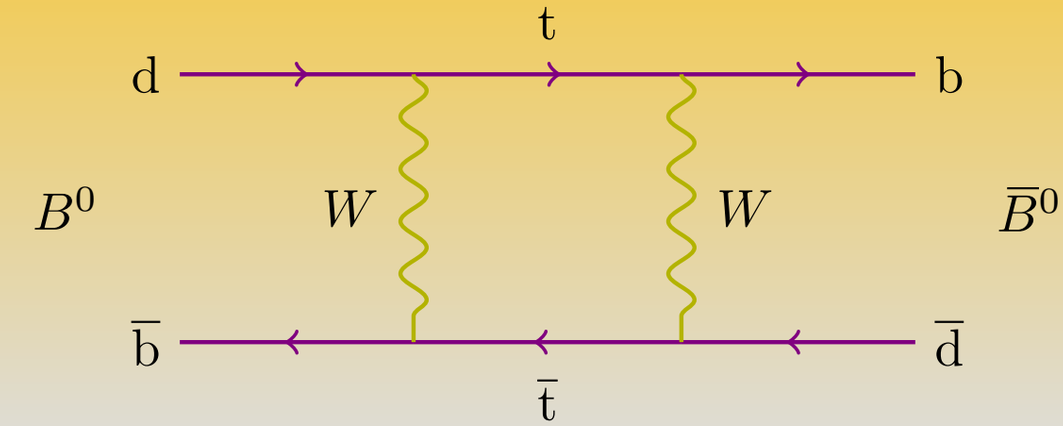
- K^0-$\overline{K}^0$ mixing

  ➡ GIM mech

- Kaon CP vio

  ➡ KM mech

Then: ARGUS, 10^5 $B\overline{B}$ decays, probing 0.1 TeV
Now: LHCb, 10^{11} $B\overline{B}$ decays, probing 100 TeV



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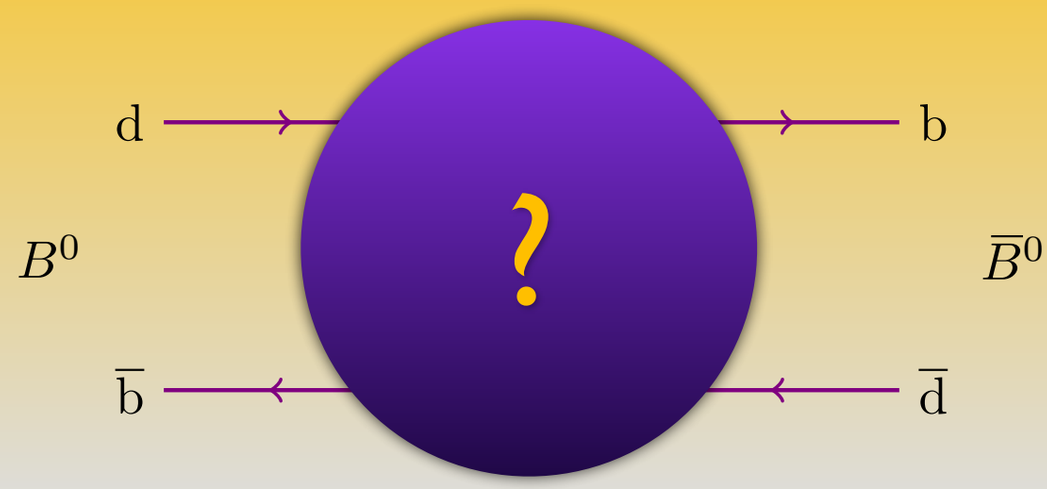

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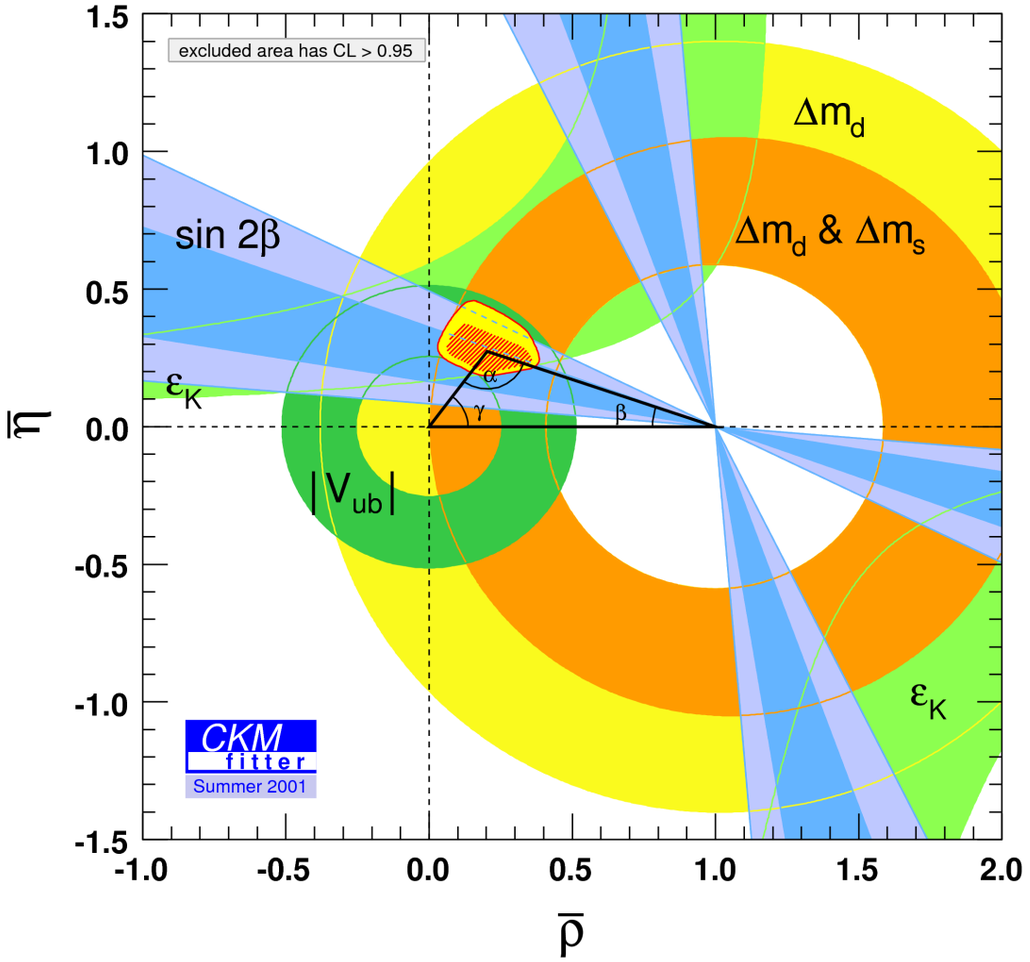
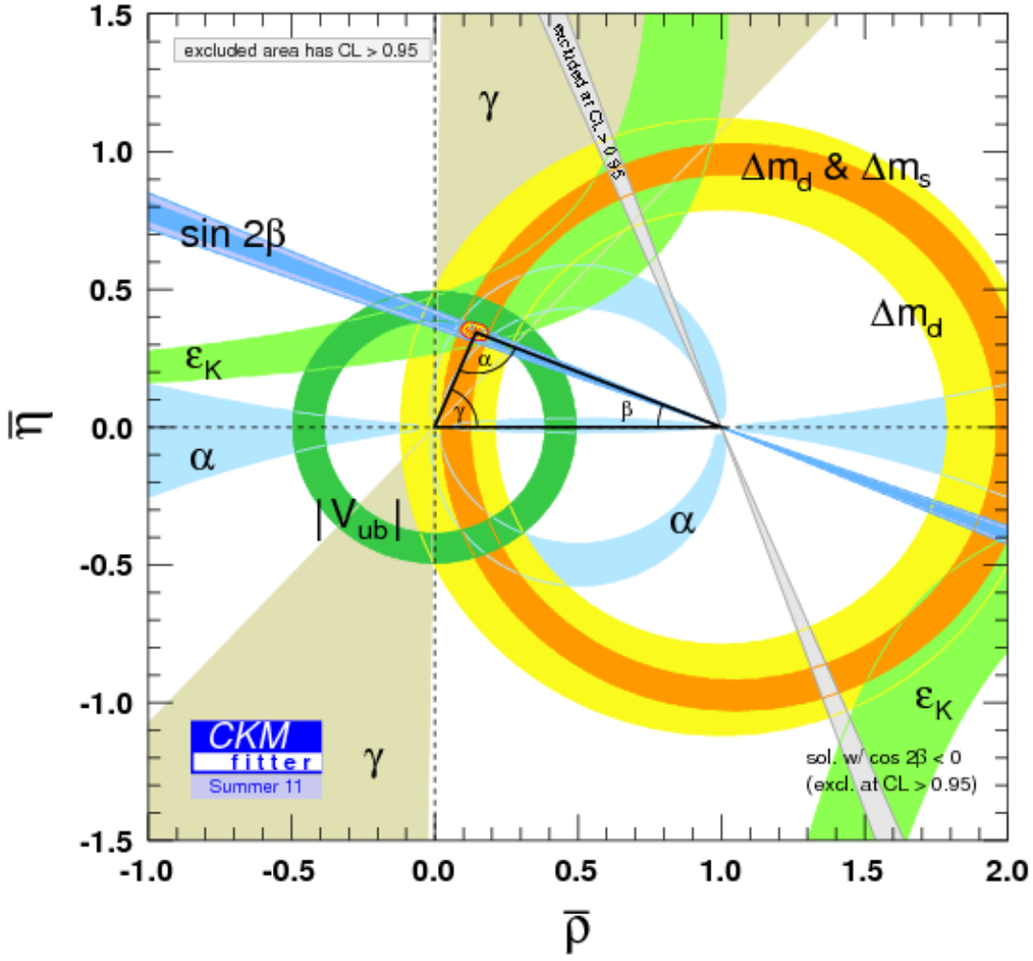
CKM and beyond

Summer 2001



Summer 2011



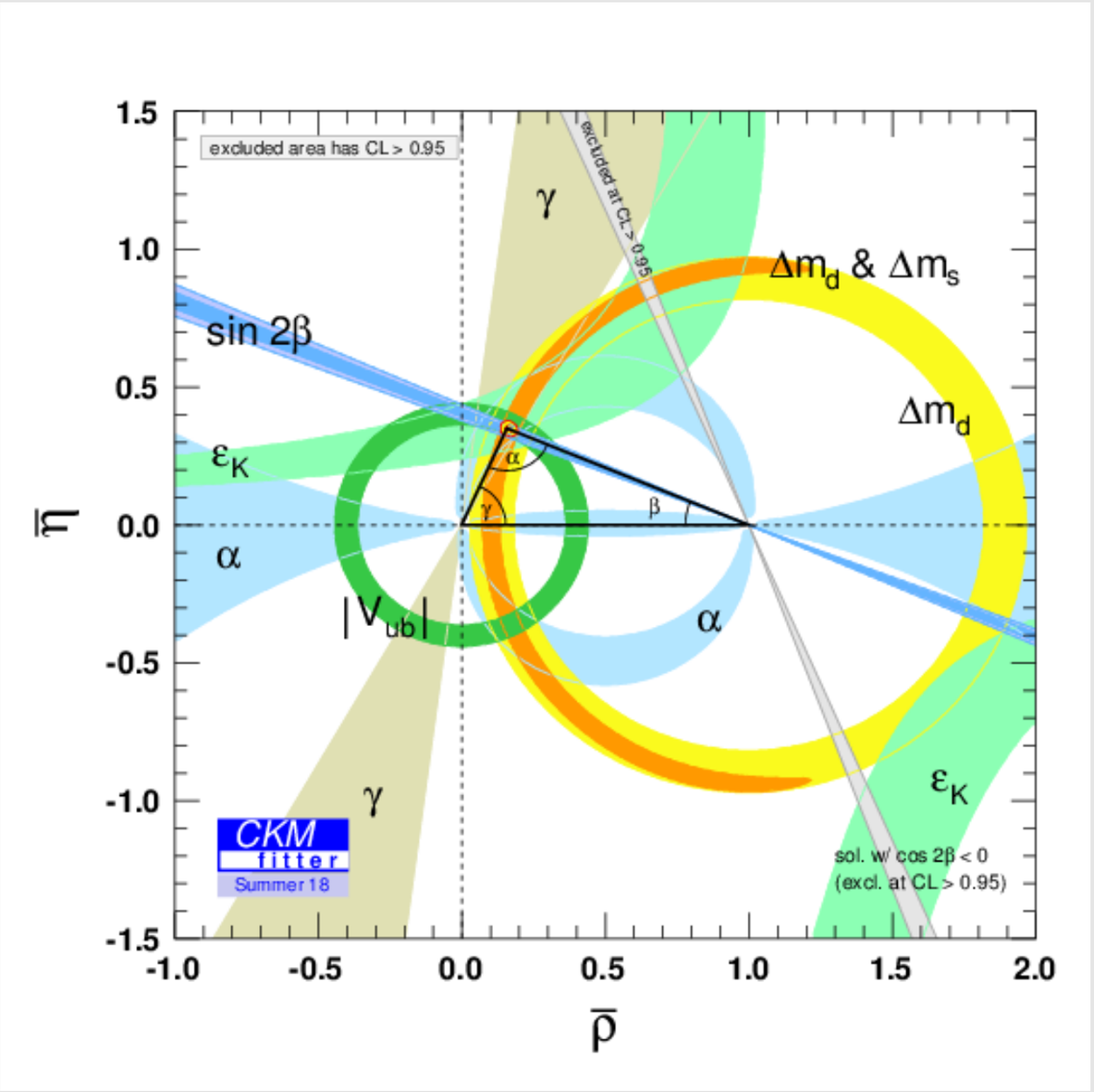
- A decade of precision measurements
- Huge success for BaBar and Belle

CKM today

- 2010-2020

➡ Enter LHCb

- Errors on apex reduced by factor of ~2-3
- Pushing with ever greater precision to find small inconsistencies



Ingredients

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Could

Charm's third time be the real charm?

Ikaros Bigi, arXiv:0902.3048 [hep-ph]

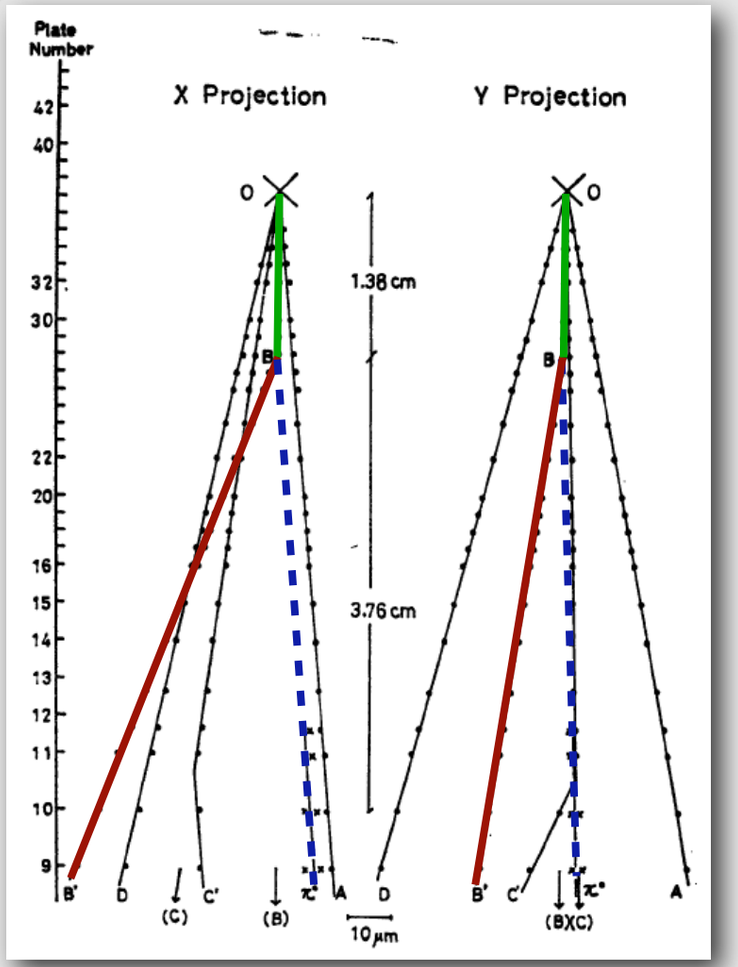
3 cheers to charm

1

Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*



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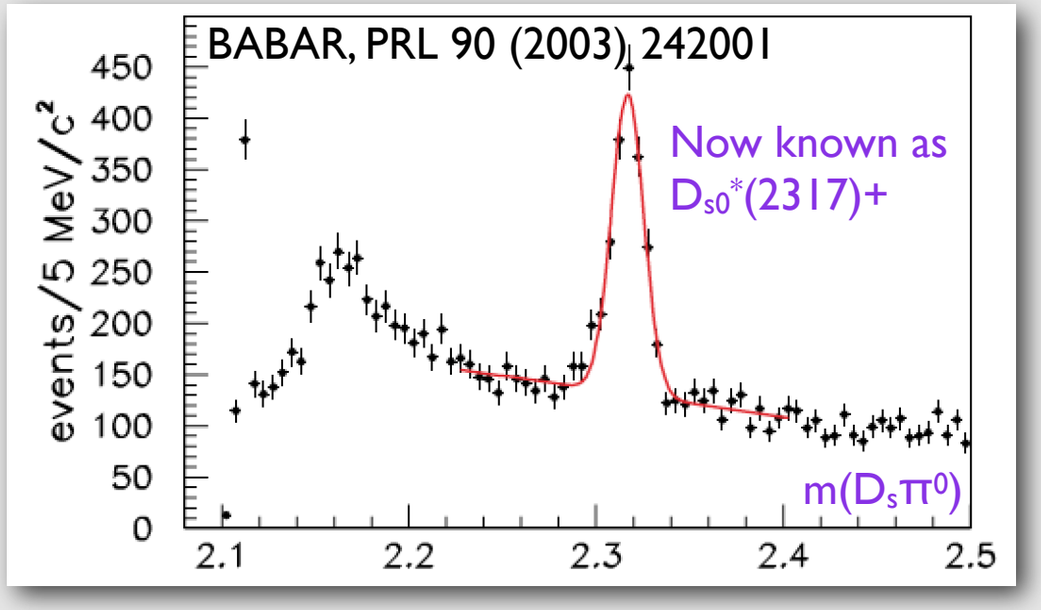

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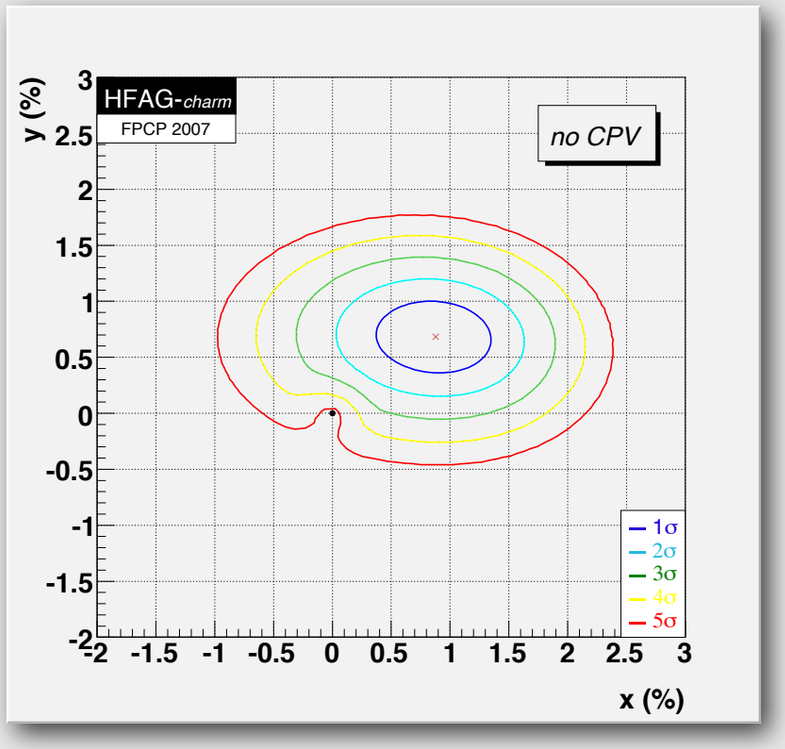
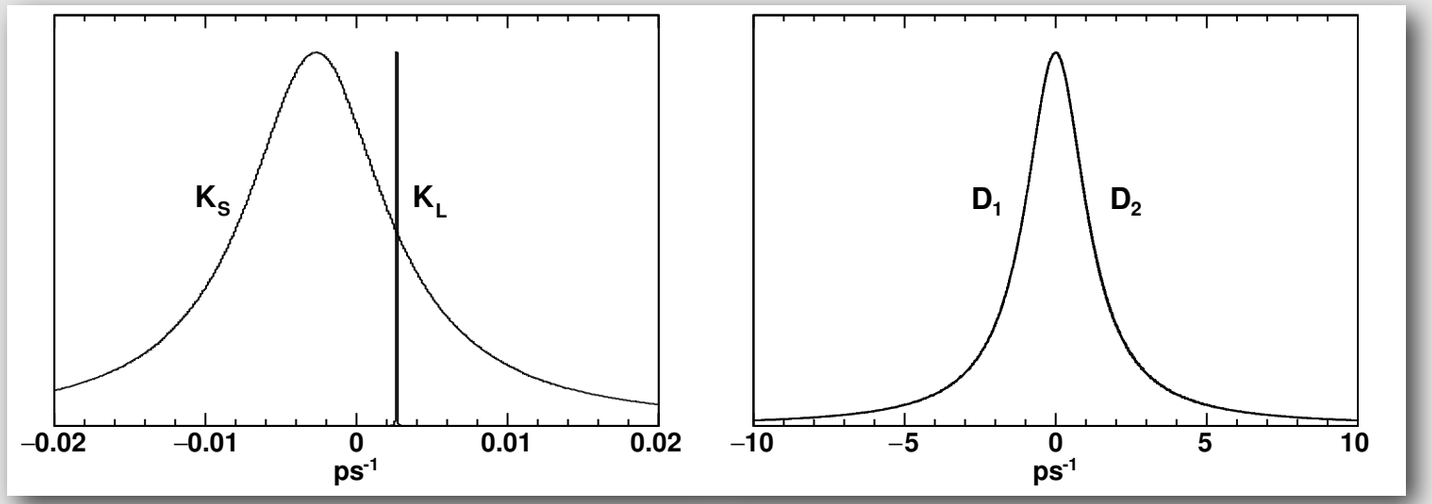


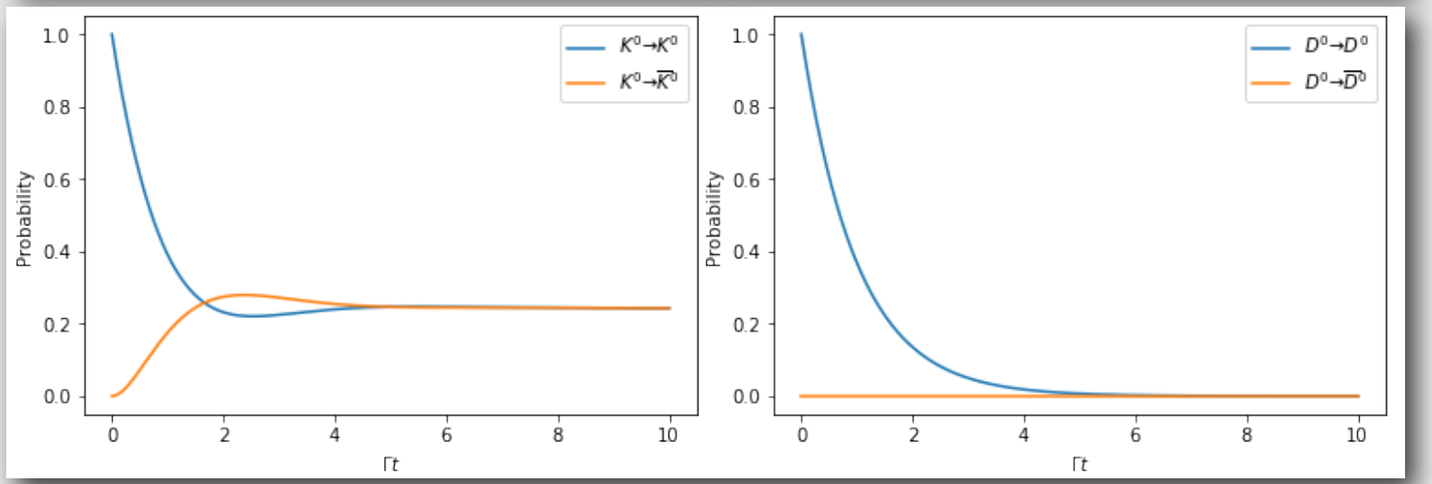
Mixing

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Hamiltonian eigenstates

Flavour eigenstates





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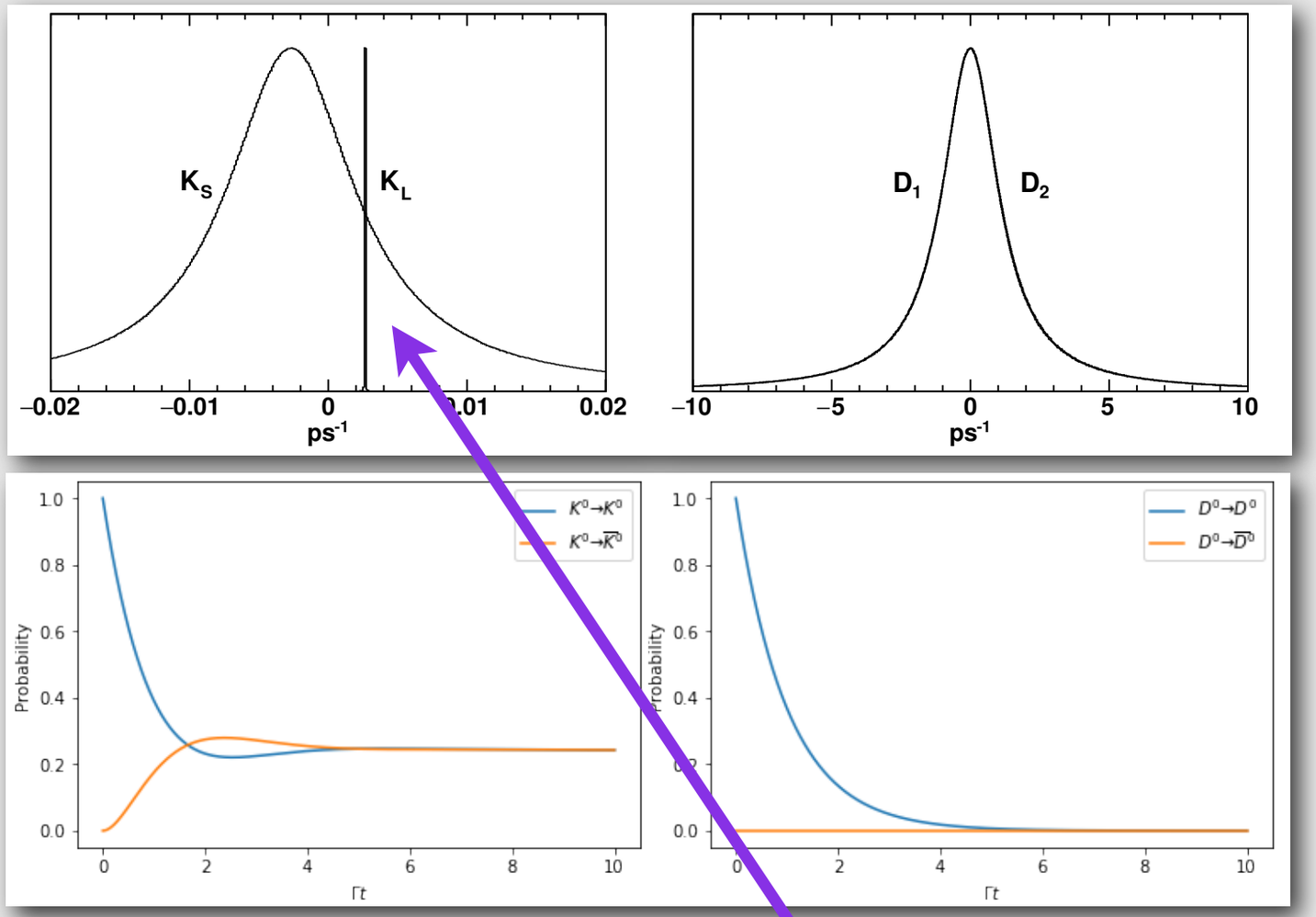

Mass difference → Oscillation

$$P(M^0 \to \overline{M}^0, t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))$$

$$\Delta m \equiv m_2 - m_1$$

$$x \equiv \Delta m/\Gamma$$

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Hamiltonian eigenstates

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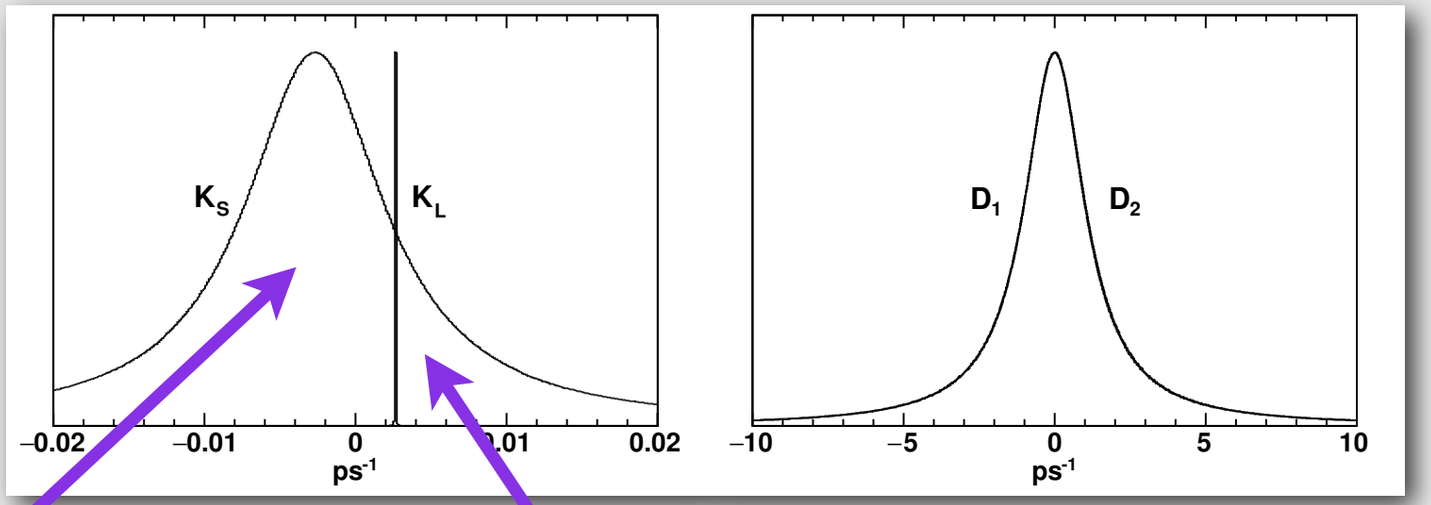

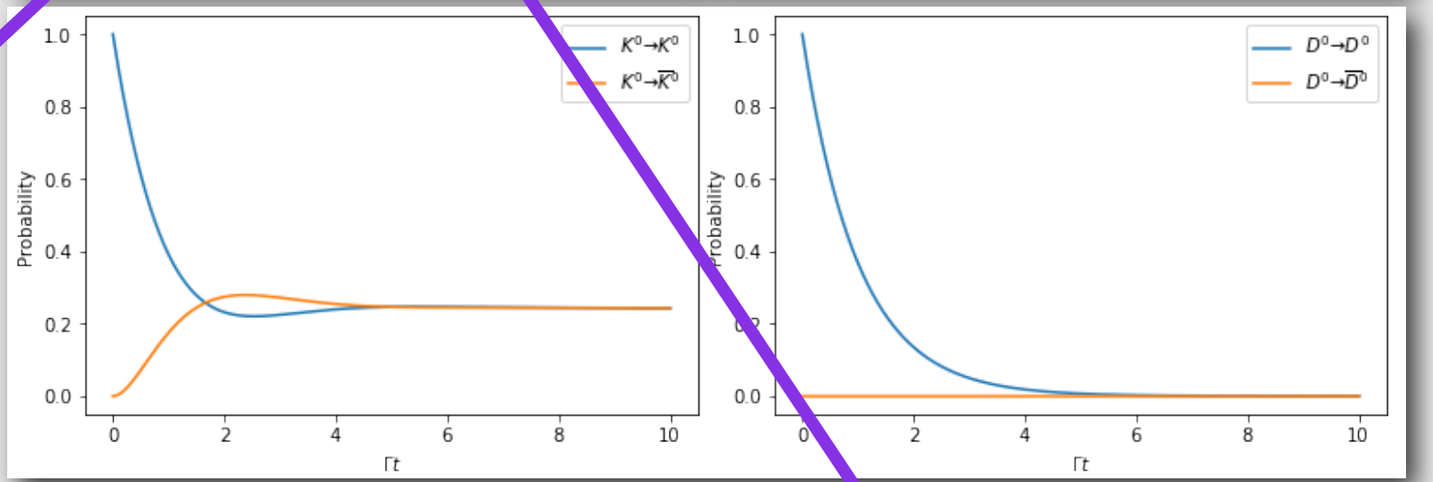

Width difference

→ Lifetime difference

$$\Delta\Gamma \equiv \Gamma_2 - \Gamma_1$$

$$y \equiv \Delta\Gamma/(2\Gamma)$$

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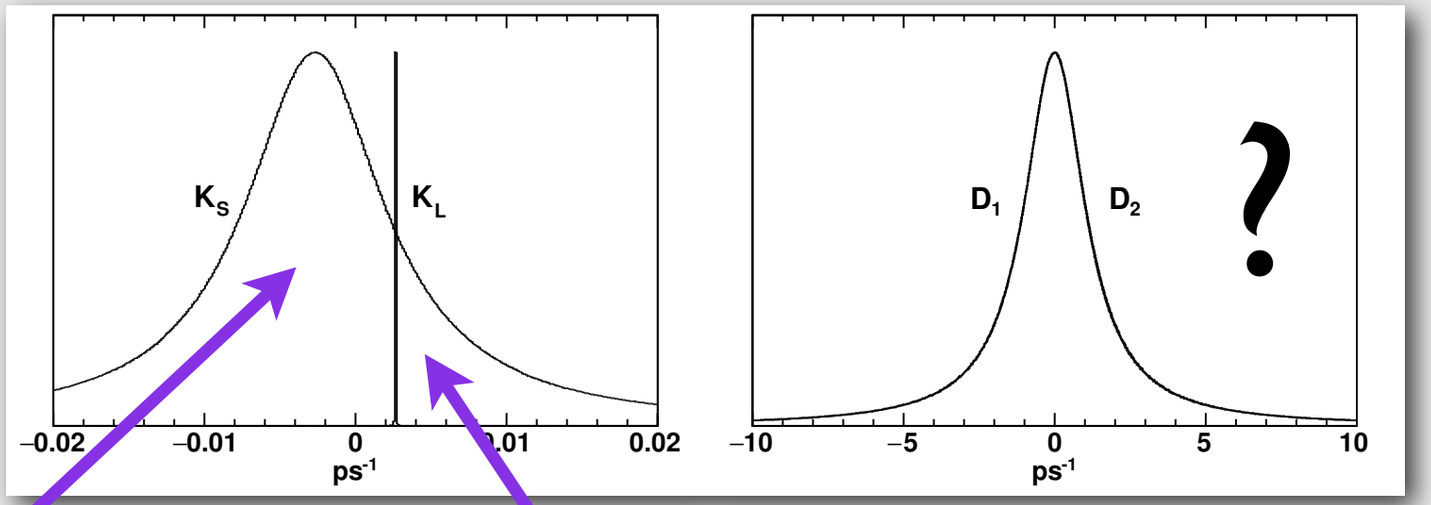

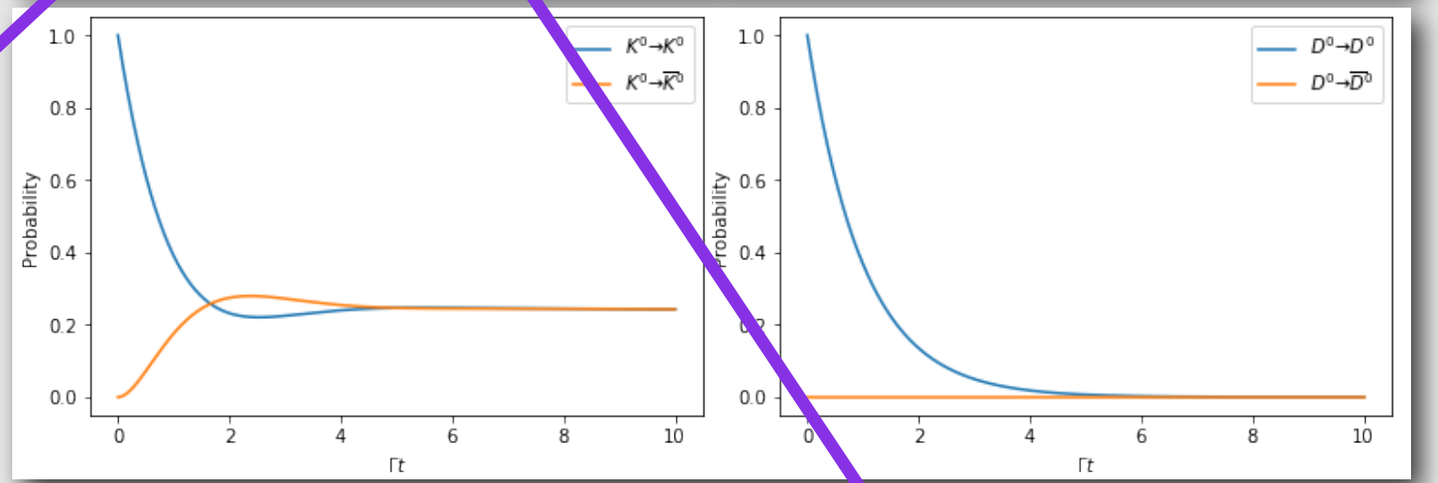

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→ Oscillation

$$\Delta m \equiv m_2 - m_1$$

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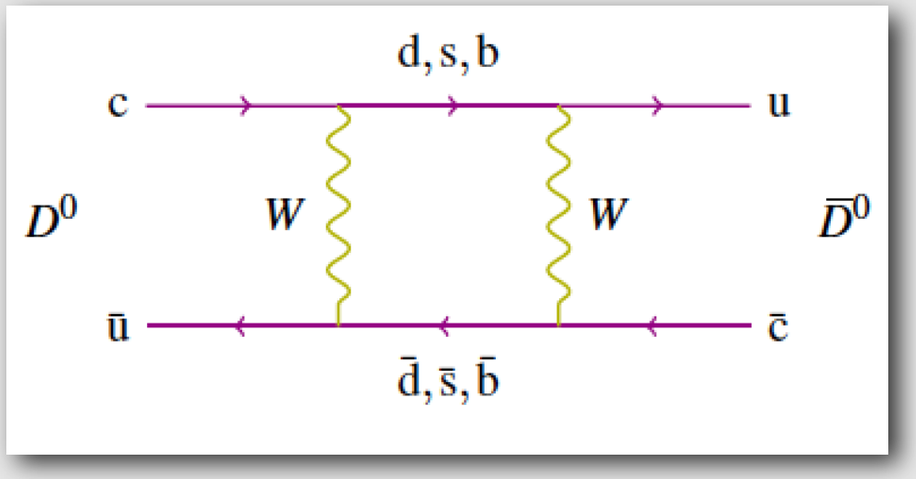
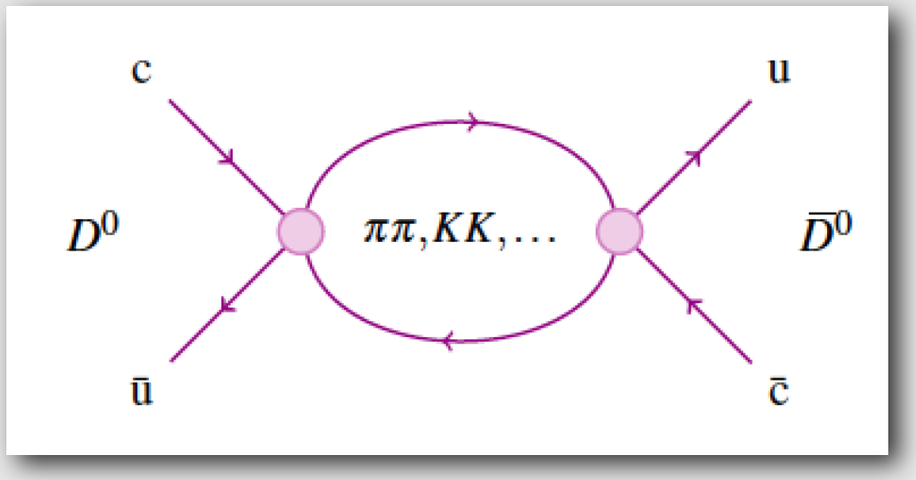
Charm: hardly a CKM triangle

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





D^0-$\bar{D}^0$ mixing

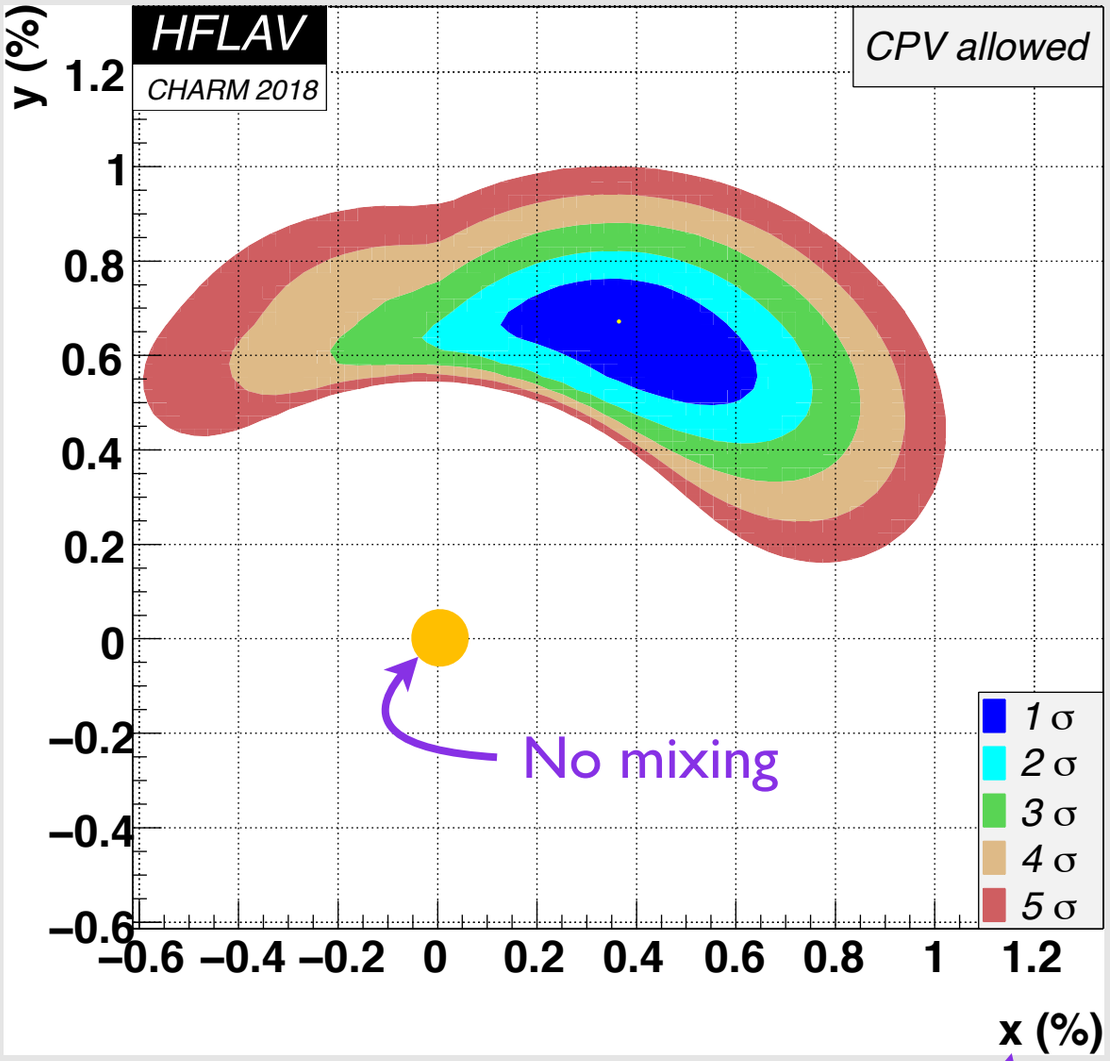
1000 TeV

Probing highest scales

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

Mixing nowadays

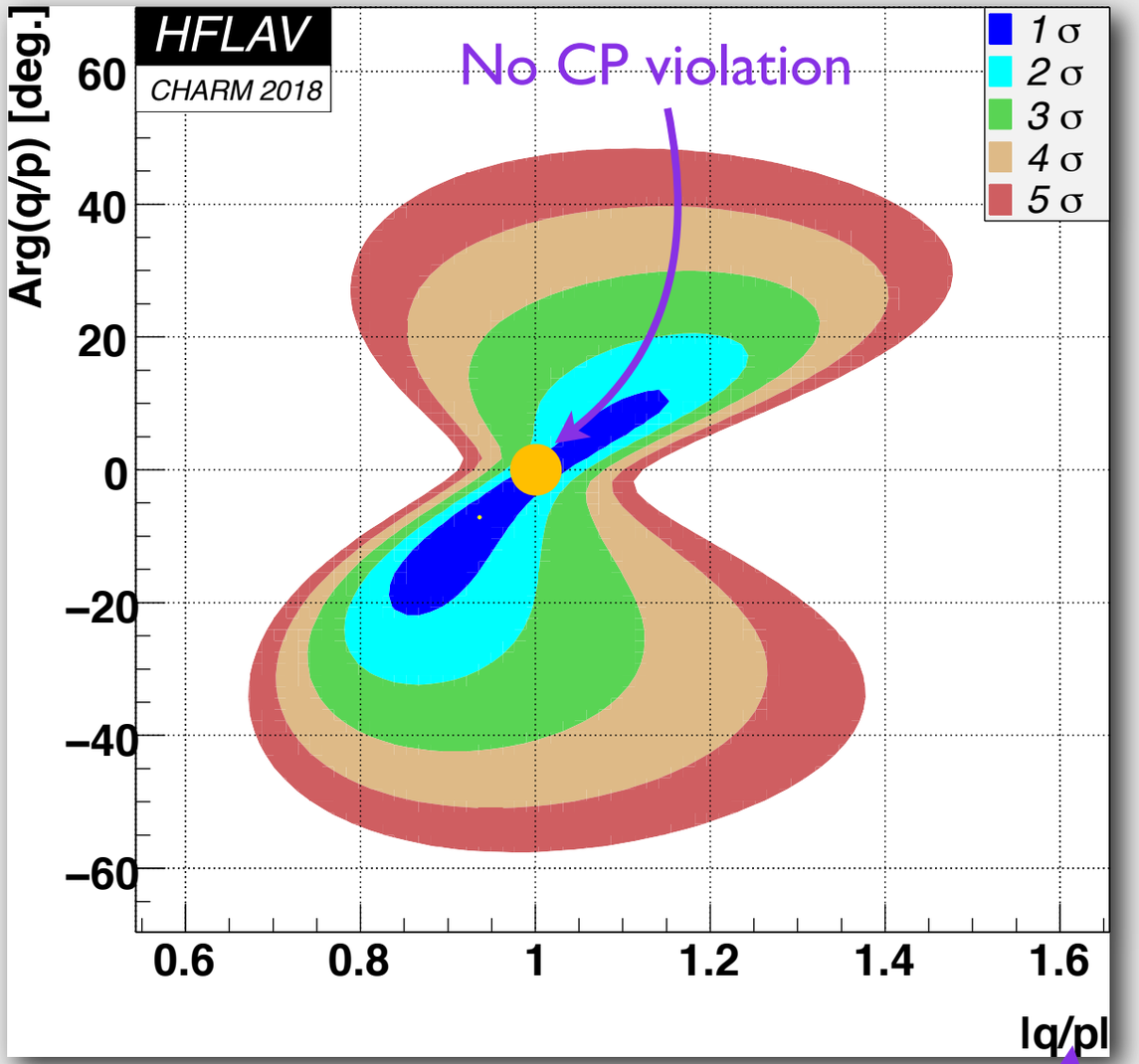
Width difference



Mass difference

- Mixing established
  - ➡ x≠0 still open question

CP violating weak phase



Asymmetry in mixing rate

- No sign of CP violation

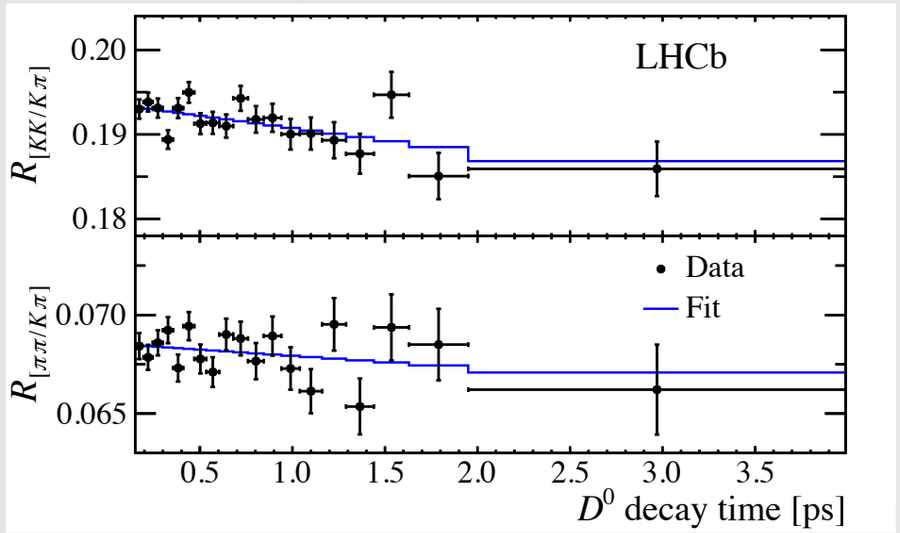
Mixing and indirect CPV

- y_{CP} measures effective lifetime of decays to CP eigenstate (here: K^+K^-, $\pi^+\pi^-$)

  ➡ Coincides with Hamiltonian eigenstate for CP symmetry

  - Measures $\Delta\Gamma$ or y

LHCb, Phys. Rev. Lett. 122 (2019) 011802

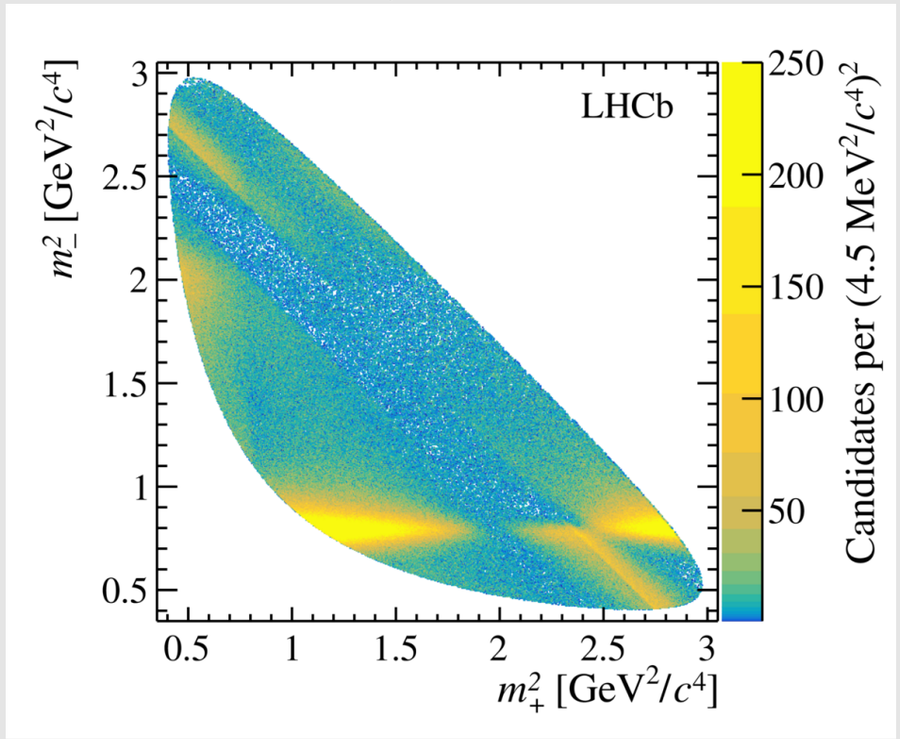


- $D^0 \to K_S\pi^+\pi^-$ requires time-dependent amplitude analysis

  ➡ Gives access to mixed and unmixed rates and strong phase differences

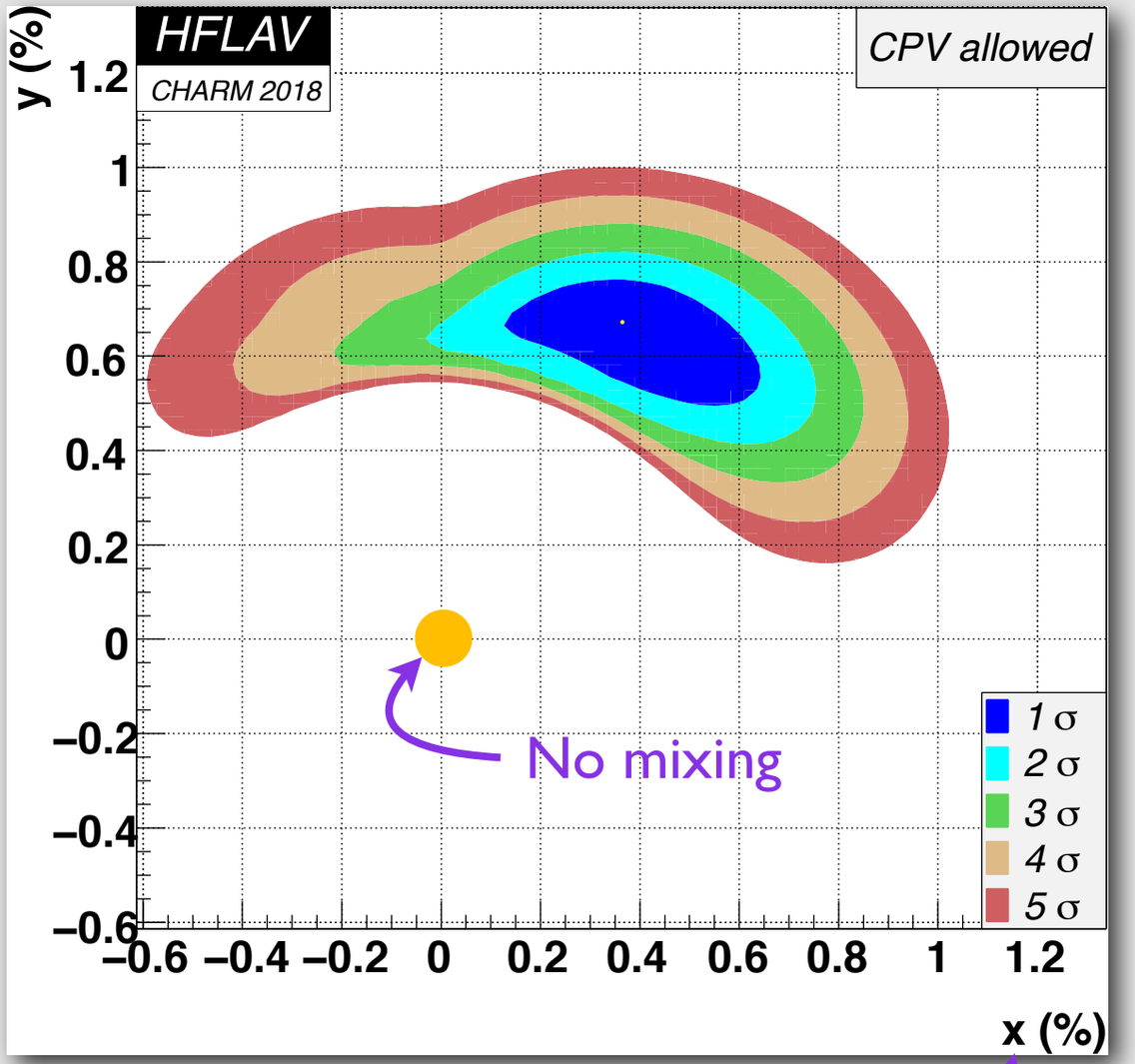
  - Measures individual mixing (x,y) and CPV parameters (|q/p|, ϕ)

LHCb, arXiv:1903.08726



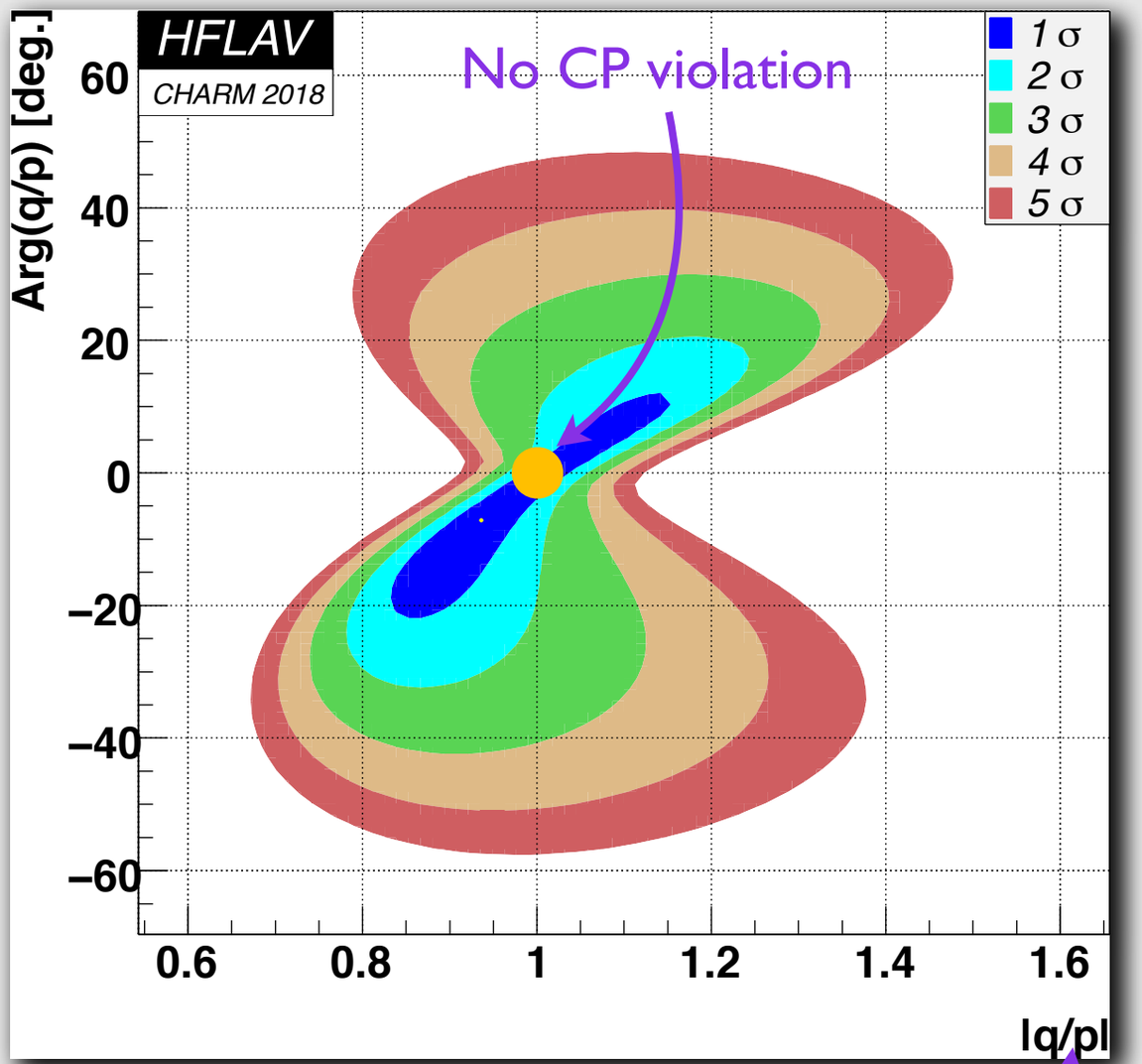
Mixing nowadays

Width difference



Mass difference

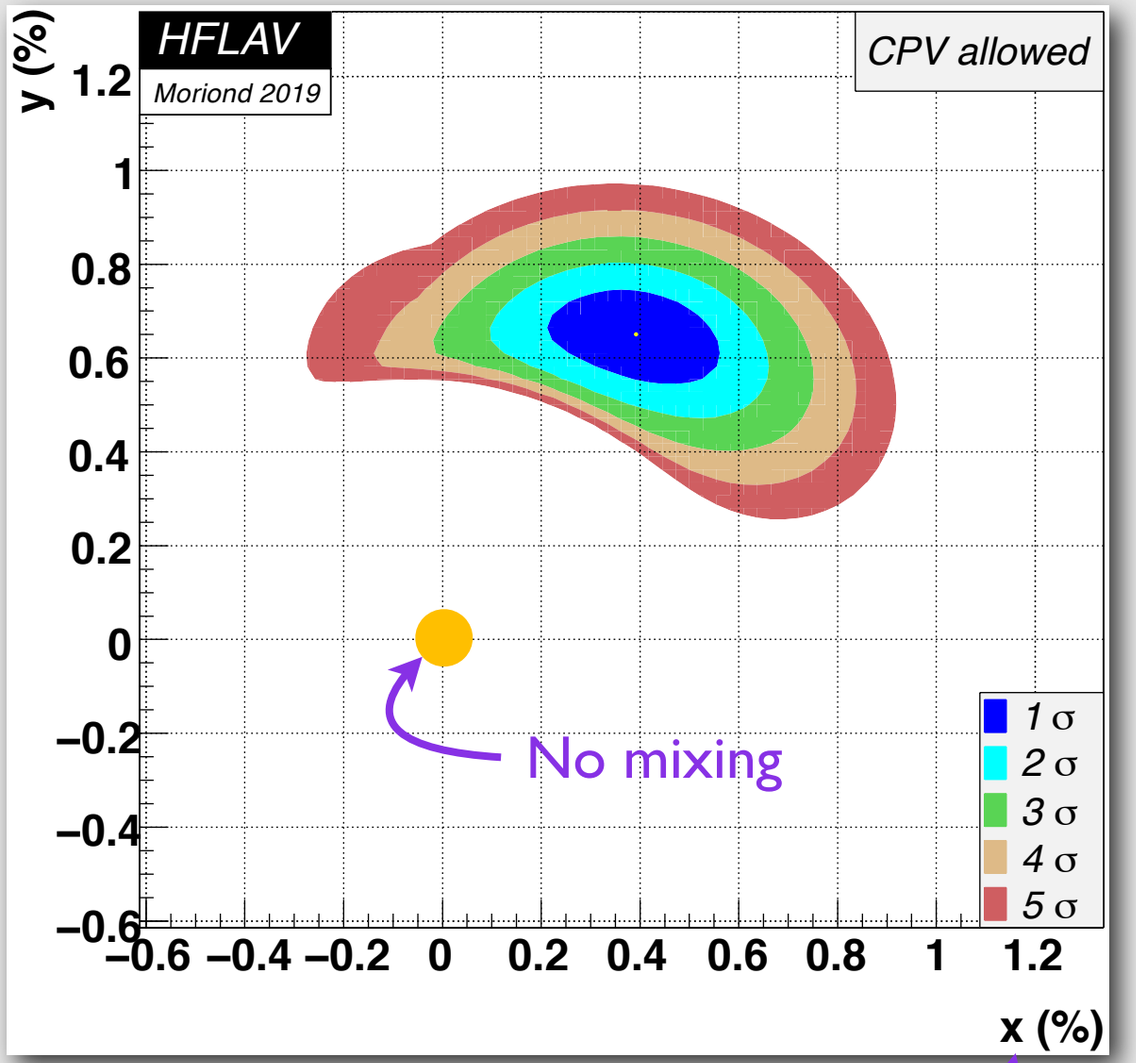
CP violating weak phase



Asymmetry in mixing rate

Mixing nowadays

Width difference



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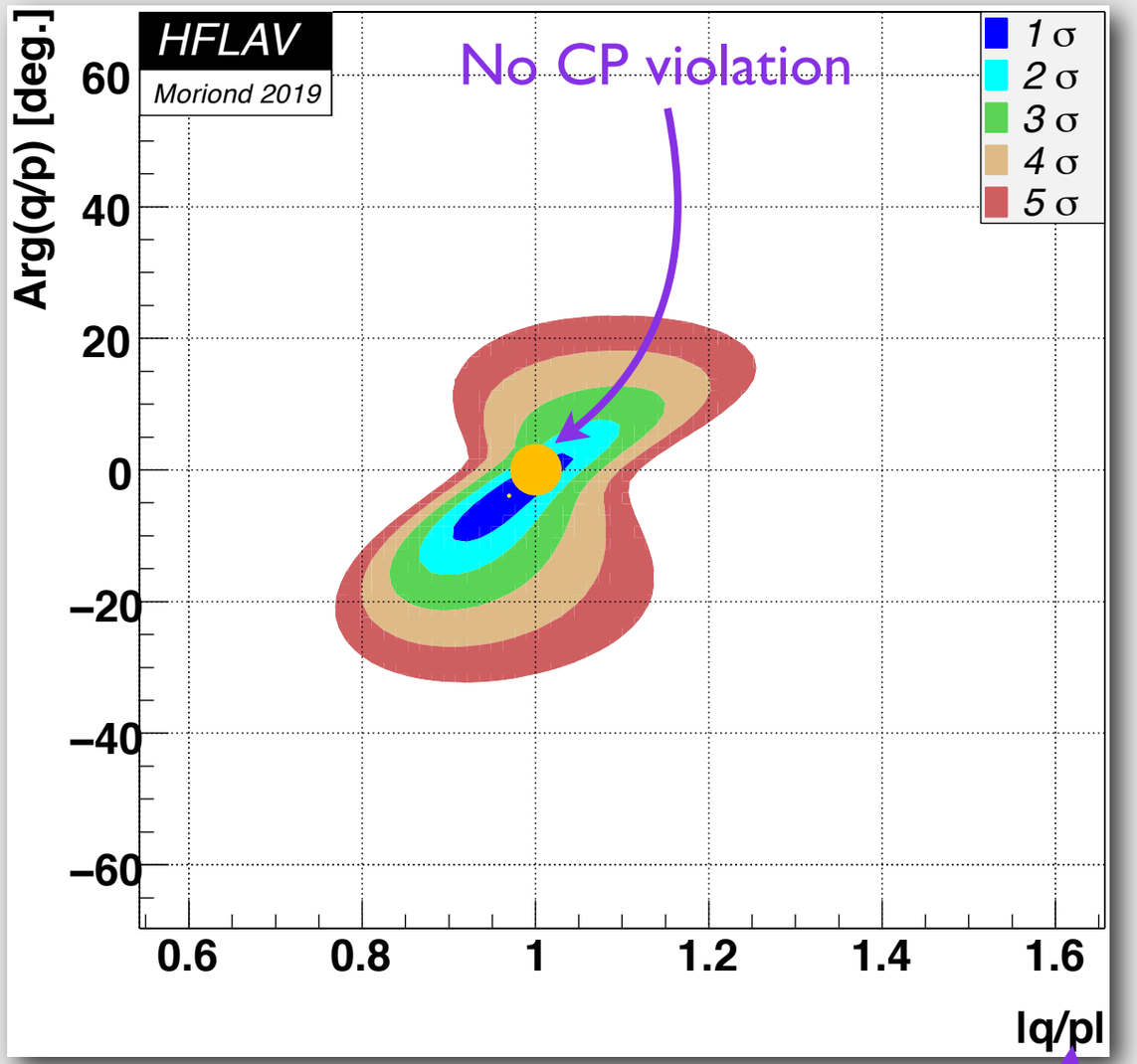

Asymmetry in mixing rate

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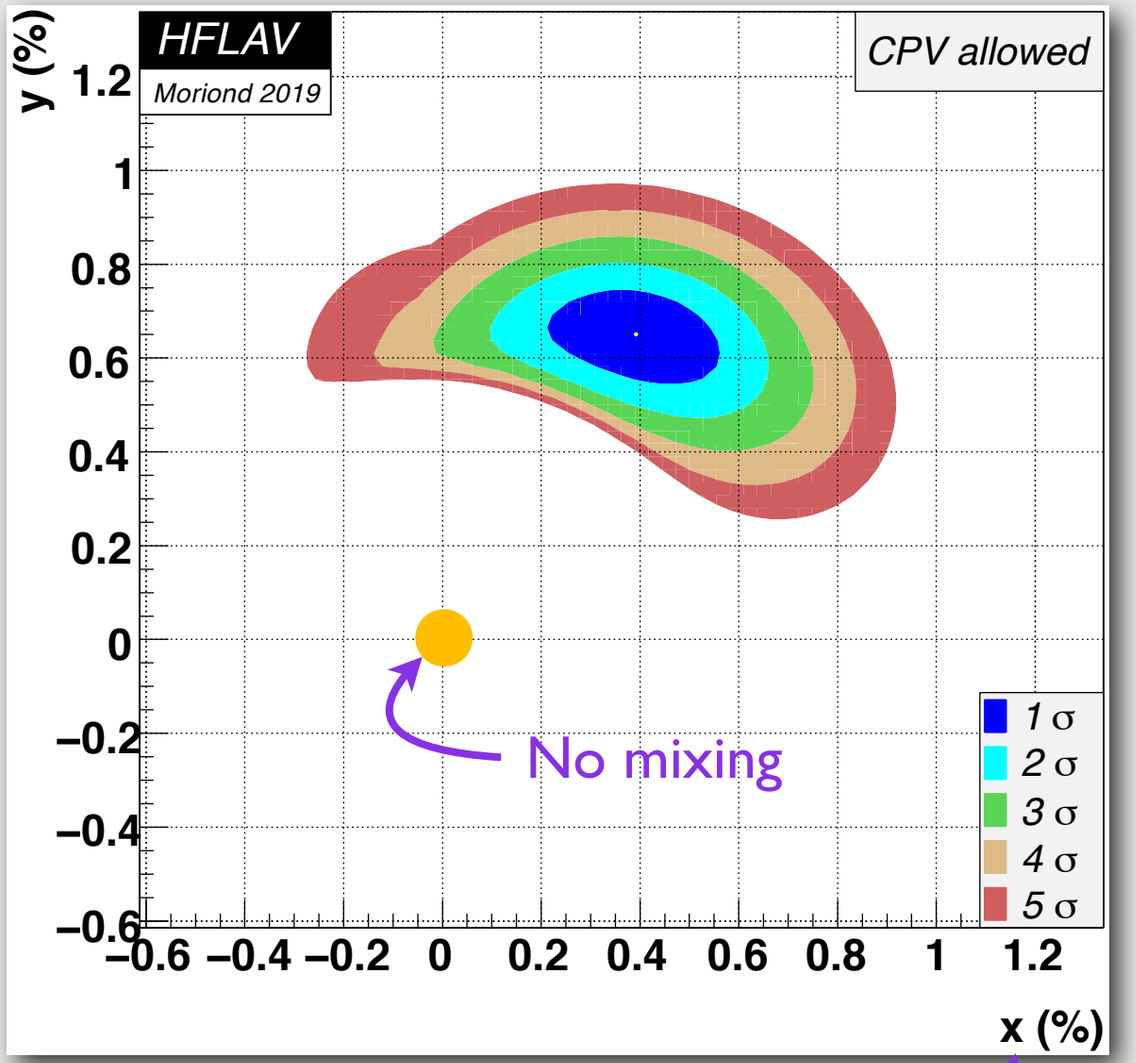

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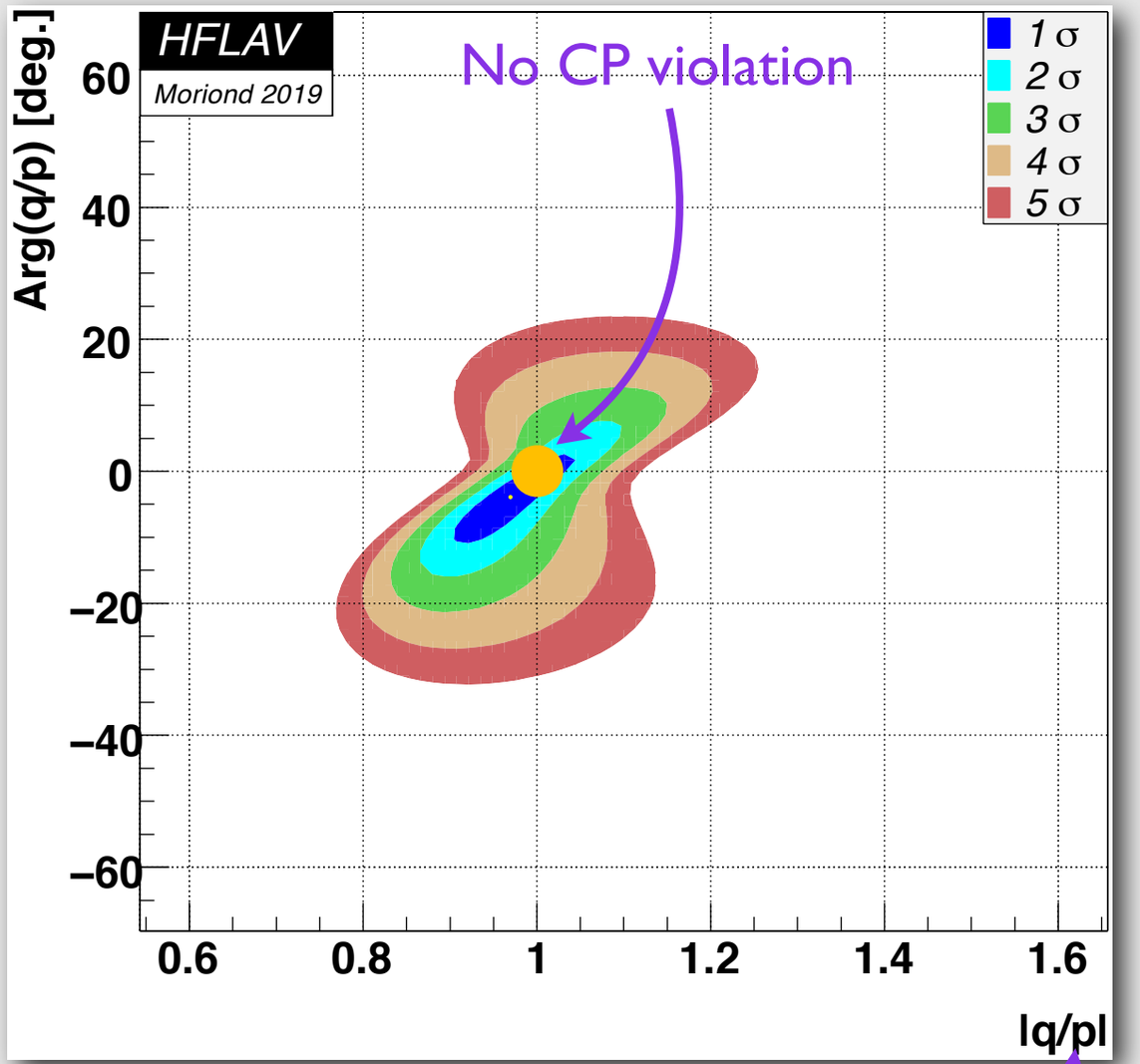
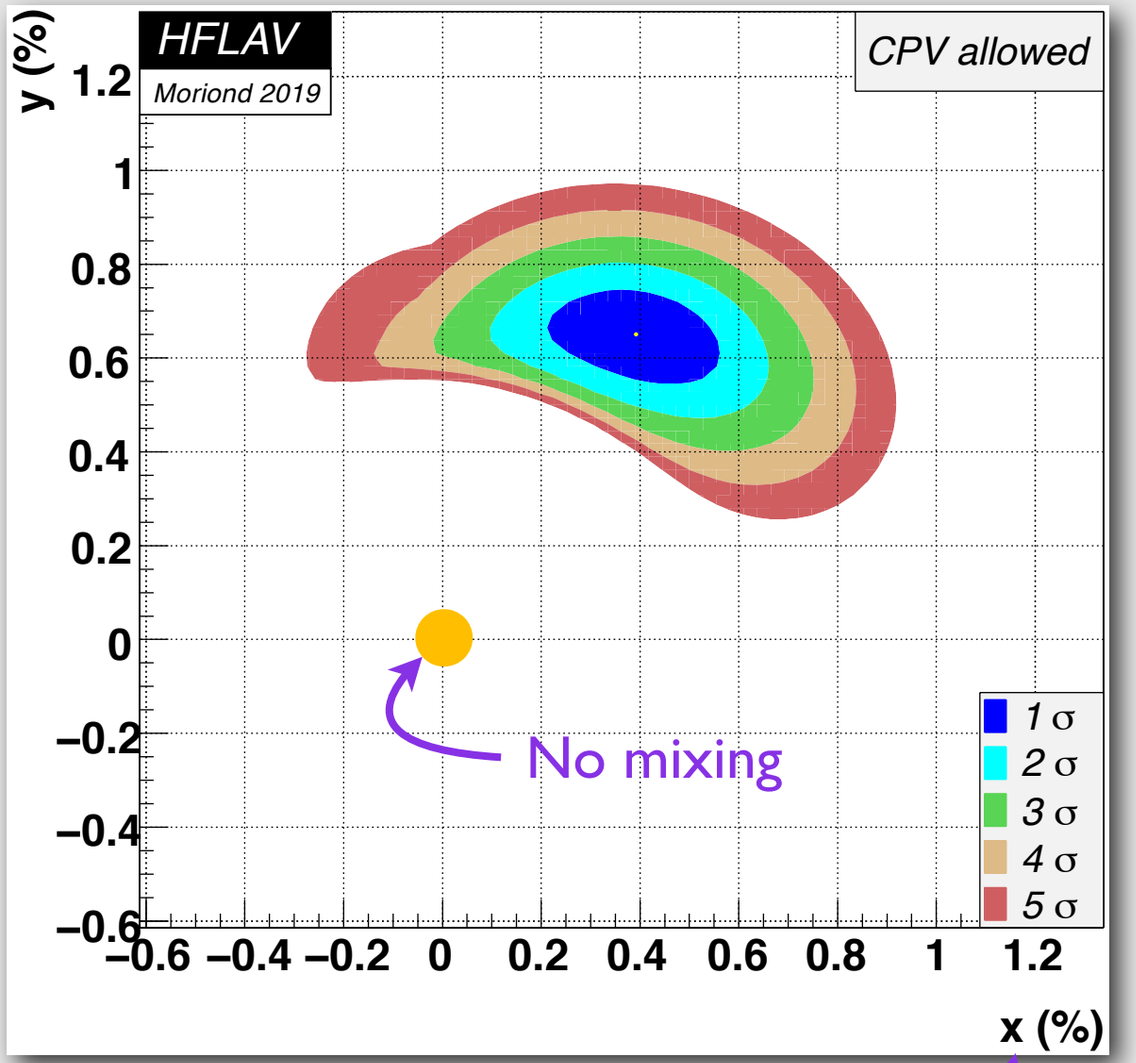


Asymmetry in mixing rate

- Evidence for x>0

Mixing nowadays

Width difference



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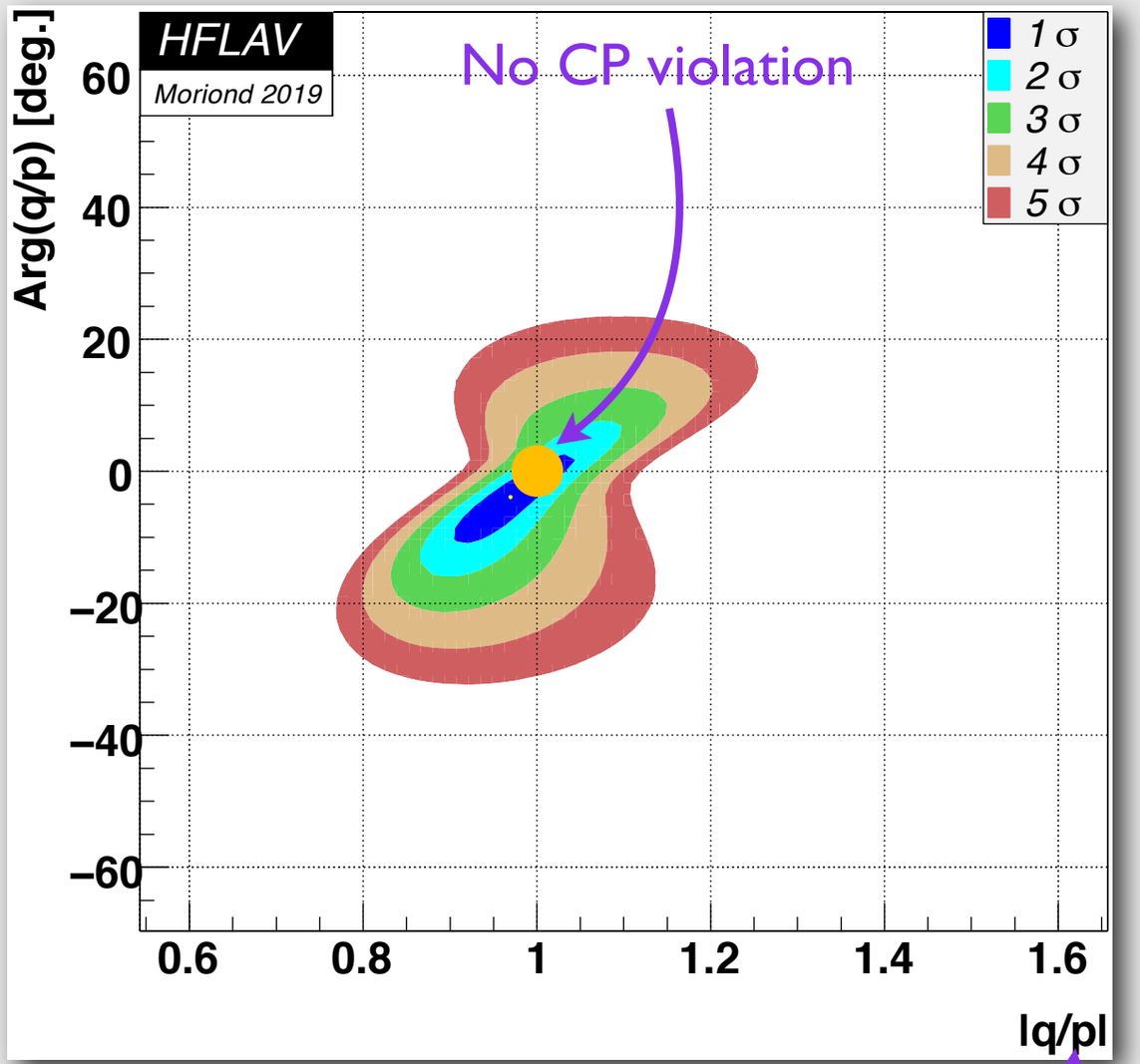
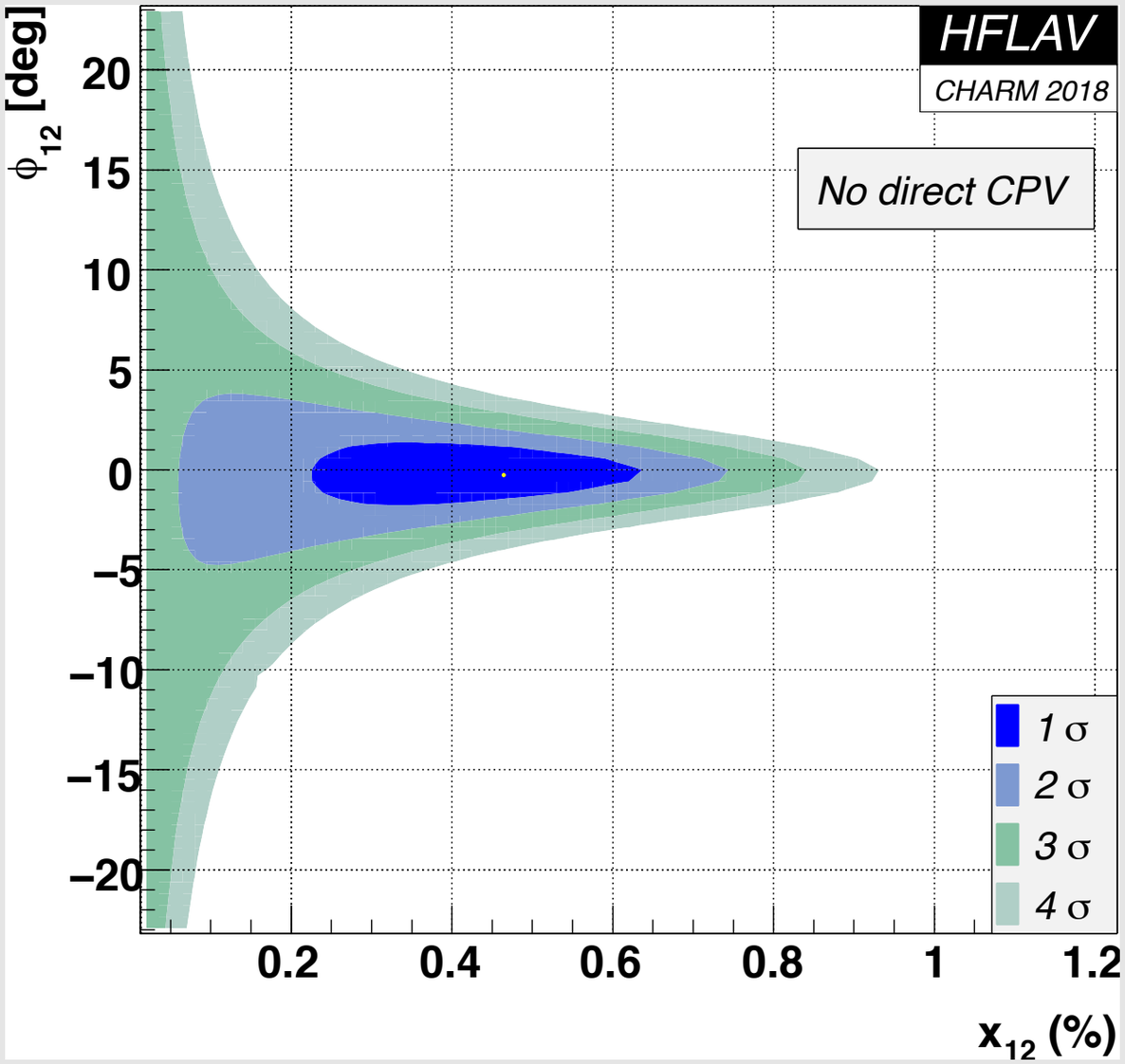
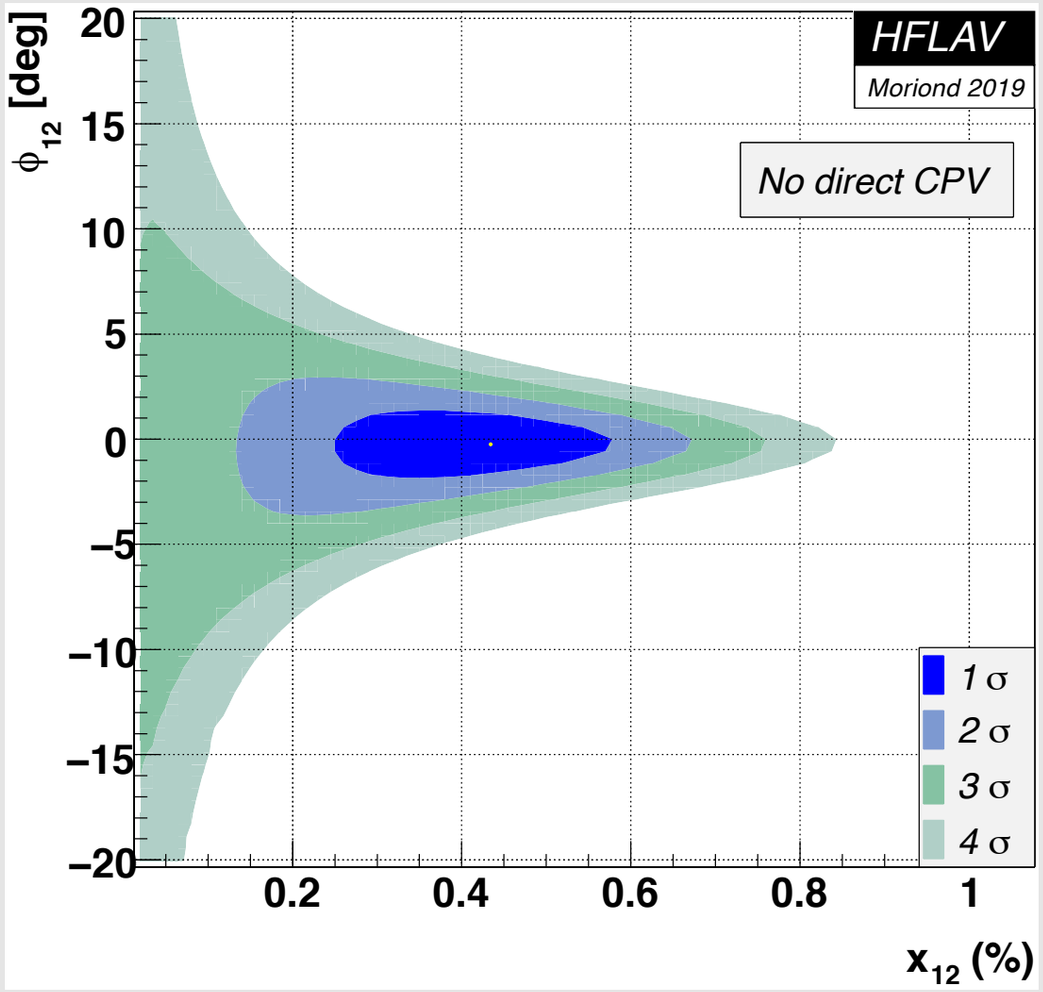


Asymmetry in mixing rate

- Still no sign of CP violation

CPV constraints

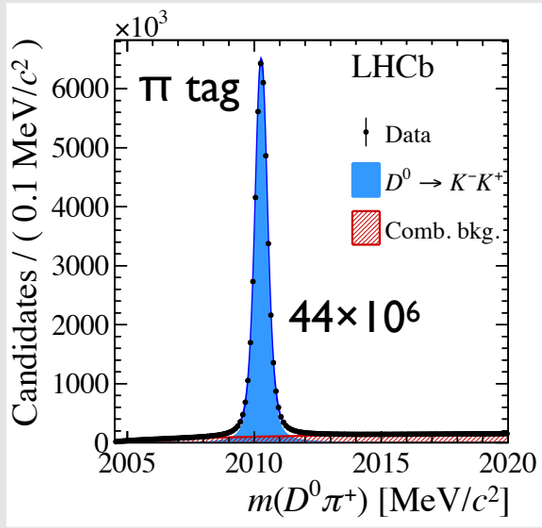


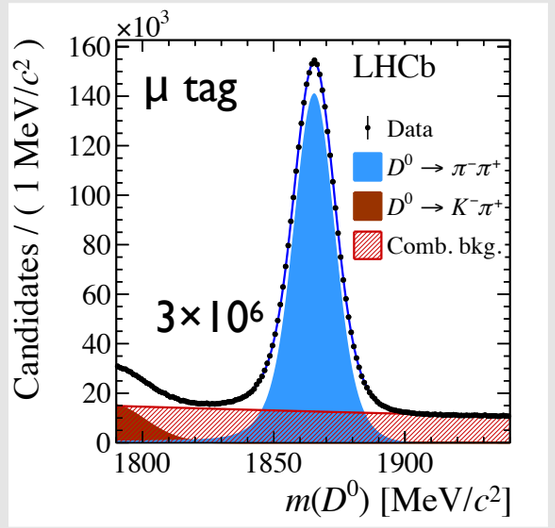


- Assume no direct CPV in doubly Cabibbo-suppressed decay
  - ➡ Can reduce parameter set to three
  - ➡ Improved precision on x leads to much better constraint on CPV phase

ΔA_{CP}

LHCb, Phys. Rev. Lett. 122 (2019) 211803

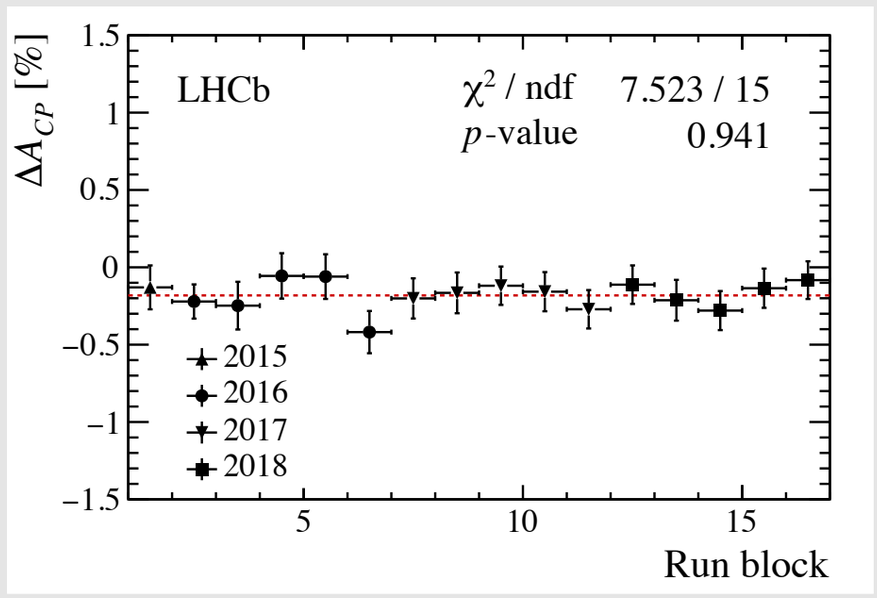




- Measure difference in time-integrated CP asymmetry between K^+K^- and $\pi^+\pi^-$ decays

  ➡ Expect improved sensitivity due to sign flip in CKM structure and cancellation of systematic uncertainties

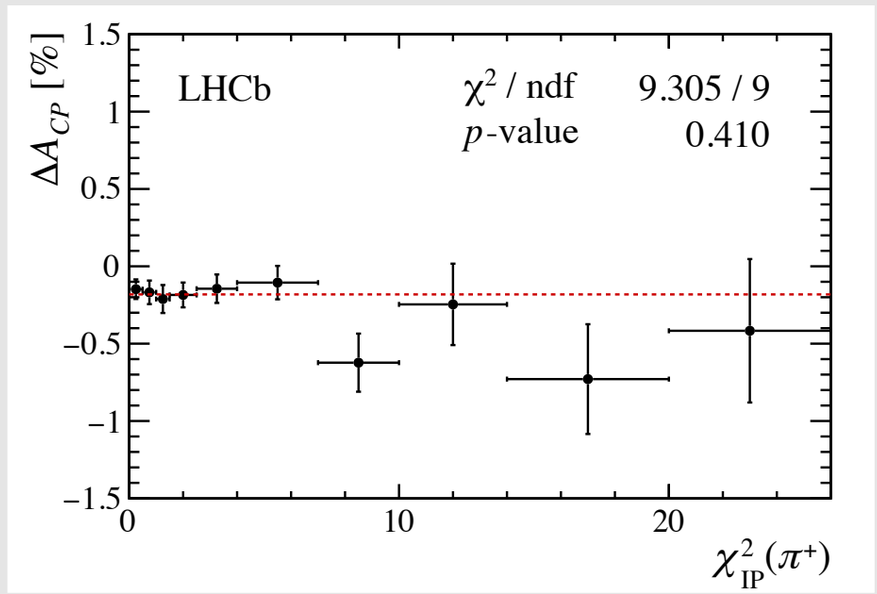
  - $V_{us} \sim -V_{cd}$



- Full Run 1+2 result (9 fb^{-1}) determined from prompt charm (π tag) and charm from B decays (μ tag)

  ➡ $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

- First observation of CPV in charm decays



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In detail

A. Ukleja, Tu 17:50

LHCb, Phys. Rev. Lett. 122 (2019) 211803

Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B fractions	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5

- New analysis based on Run 2 data, corresponds to 6 fb^{-1}
- Systematic uncertainties sub-dominant and determined by data-driven methods

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$

Theory perspective*

$$\Delta A_{CP}^{\text{Exp.}} = (-15.6 \pm 2.9) \times 10^{-4}$$

Physics Letters B 774 (2017) 235–242

$$\left|\Delta a_{CP}^{dir}\right| < 0.020 \pm 0.003\%$$

Direct CP asymmetry in $D \to \pi^-\pi^+$ and $D \to K^-K^+$ in QCD-based approach

Alexander Khodjamirian [a], Alexey A. Petrov [a,b,c,*]

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[b] Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA
[c] Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48196, USA

BSM!

The Emergence of the $\Delta U = 0$ Rule in Charm Physics

SM

Yuval Grossman* and Stefan Schacht†

D… of Physics, LEPP, Cornell University, Ithaca, NY 14853, USA

"in SM requires mild non-perturbative enhancement due to rescattering amplitudes"

ΔA_{CP} within the Standard Model and beyond

Mikael Chala, Alexander Lenz, Aleksey V. Rusov and Jakub Scholtz

BSM!

$$|\Delta A_{CP}^{\text{SM}}| \leq 3 \times 10^{-4}$$

Z'?

Implications on the first observation of charm CPV at LHCb

Hsiang-nan Li[1*], Cai-Dian Lü[2†], Fu-Sheng Yu[3‡]

[1] *Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*

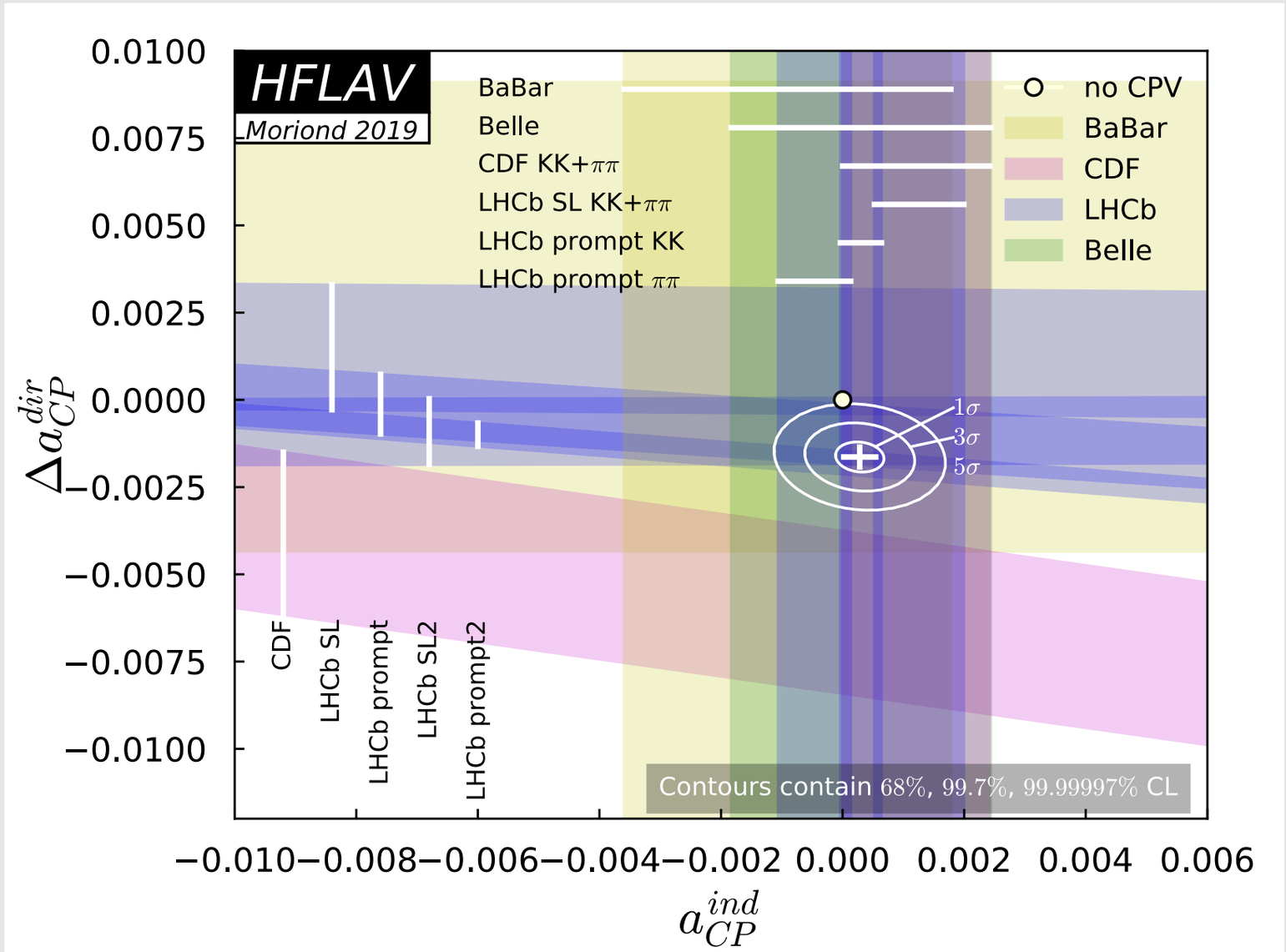
Lanzhou 730000, People's Republic of China

SM

$$\Delta A_{CP}^{\text{SM}} = (-0.57 \sim -1.87) \times 10^{-3}$$

*a brief snapshot that cannot do justice to the amount of work done here

CP violated in charm



- Direct CPV in charm
- No hint for indirect CPV
- SM or BSM?

  ➡ Open question for now
- Need theoretical advances and more measurements

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More two-body asymmetries

E. Gersabeck, Tu 17:30

- New LHCb measurement of Cabibbo-suppressed $D_{(s)}^+$ decays at $\sqrt{s}$ = 13 TeV

➡ Combination with Run 1 results yields

$$\mathcal{A}_{CP}(D_s^+ \to K_S^0\pi^+) = (\ \ 1.6 \ \pm 1.7 \ \pm 0.5\ ) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to K_S^0 K^+) = (-0.04 \pm 0.61 \pm 0.45) \times 10^{-3},$$
$$\mathcal{A}_{CP}(D^+ \to \phi\pi^+) = (\ \ 0.03 \pm 0.40 \pm 0.29) \times 10^{-3},$$

LHCb, arXiv:1903.01150

- BESIII analysed related Cabibbo-favoured decays in 3.2 fb^{-1} at $\sqrt{s}$ = 4.2 GeV

$$A_{\rm CP}(D_s^\pm \to K_S^0 K^\pm) = (0.6 \pm 2.8_{\rm stat.} \pm 0.6_{\rm syst.})\%$$
$$A_{\rm CP}(D_s^\pm \to K_L^0 K^\pm) = (-1.1 \pm 2.6_{\rm stat.} \pm 0.6_{\rm syst.})\%$$

BESIII, arXiv:1903.04164

Multibody asymmetries

- 4-body decays offer many options
  - ➡ Phase-space integrated asymmetries
  - ➡ P-even amplitude asymmetries
  - ➡ P-odd asymmetries (triple products)
- Several analyses fail to find CPV
  - ➡ $D^0 \to K^+K^-\pi^+\pi^-$ Belle, Phys. Rev. D 99 (2019) 011104(R); LHCb, JHEP 02 (2019) 126
  - ➡ $D^0 \to K^+K^-\mu^+\mu^-$ LHCb, Phys. Rev. Lett. 121 (2018) 091801

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From charm to beauty

Ingredients

Charmless b-decays

- Loop contributions omnipresent
- Plenty of room for BSM contributions to enter
- Multi-body decays have rich resonance structure

➡ Expect to see large CP asymmetries

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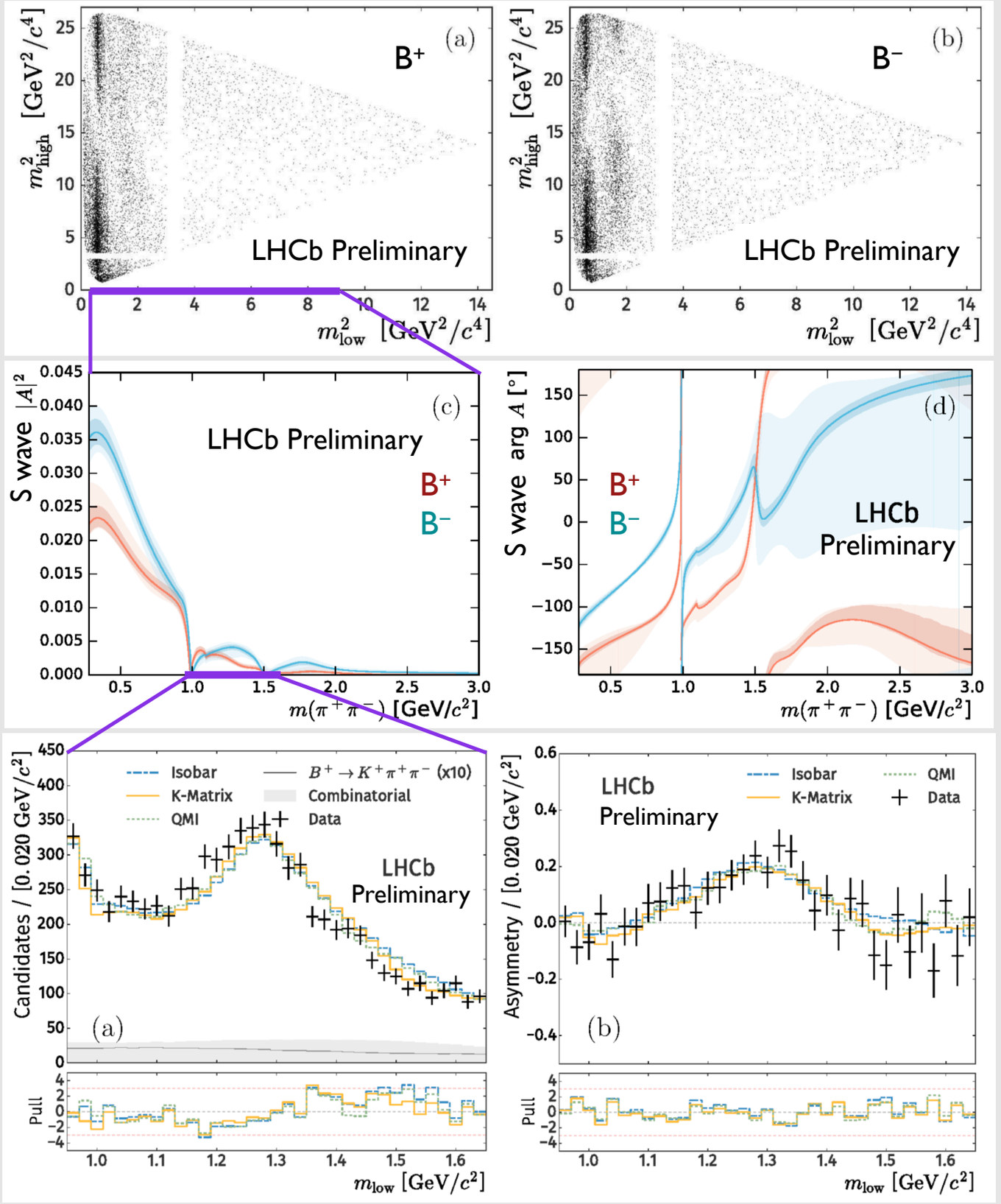
$B^{\pm} \to \pi^+\pi^-\pi^{\pm}$

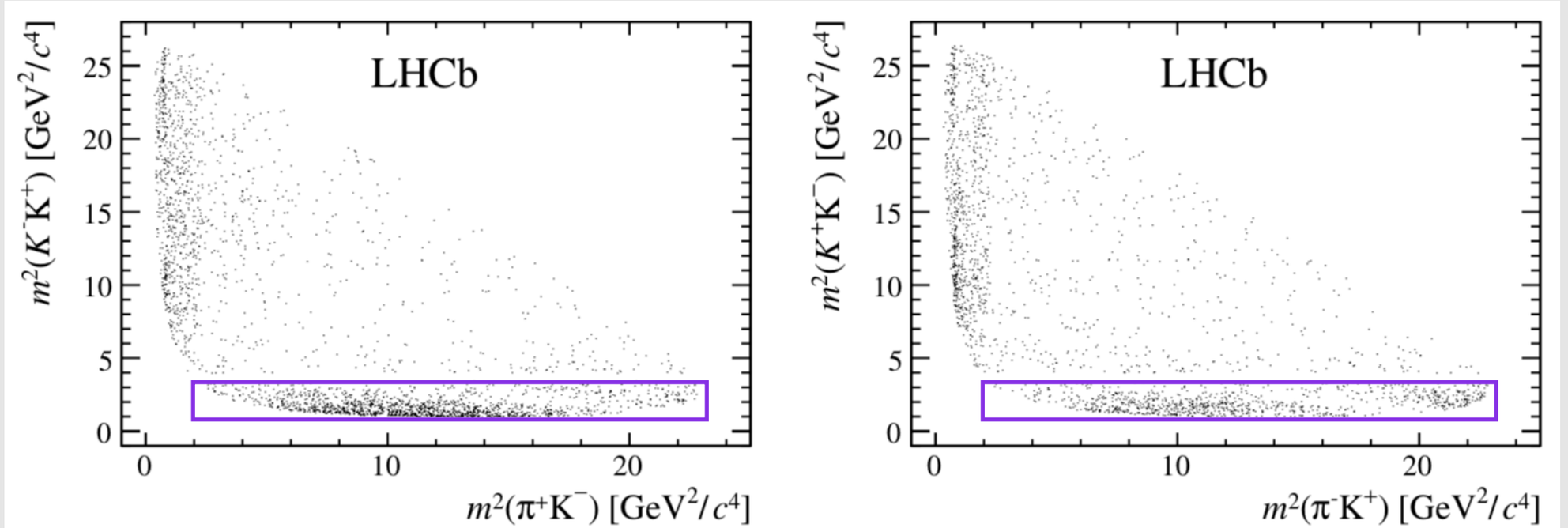
LHCb Preliminary
LHCb-PAPER-2019-017,
LHCb-PAPER-2019-018

- Amplitude analysis and CP asymmetry measurement in Dalitz plot
  - ➡ Rich resonance structure
  - ➡ Three approaches to modelling S wave
    - ▸ Including re-scattering and resonances
  - ➡ Large amplitude and phase differences between B^+ and B^- observed
  - ➡ ~40% asymmetry observed in $f_2(1270)$ resonance
    - ▸ First-ever CPV in tensor

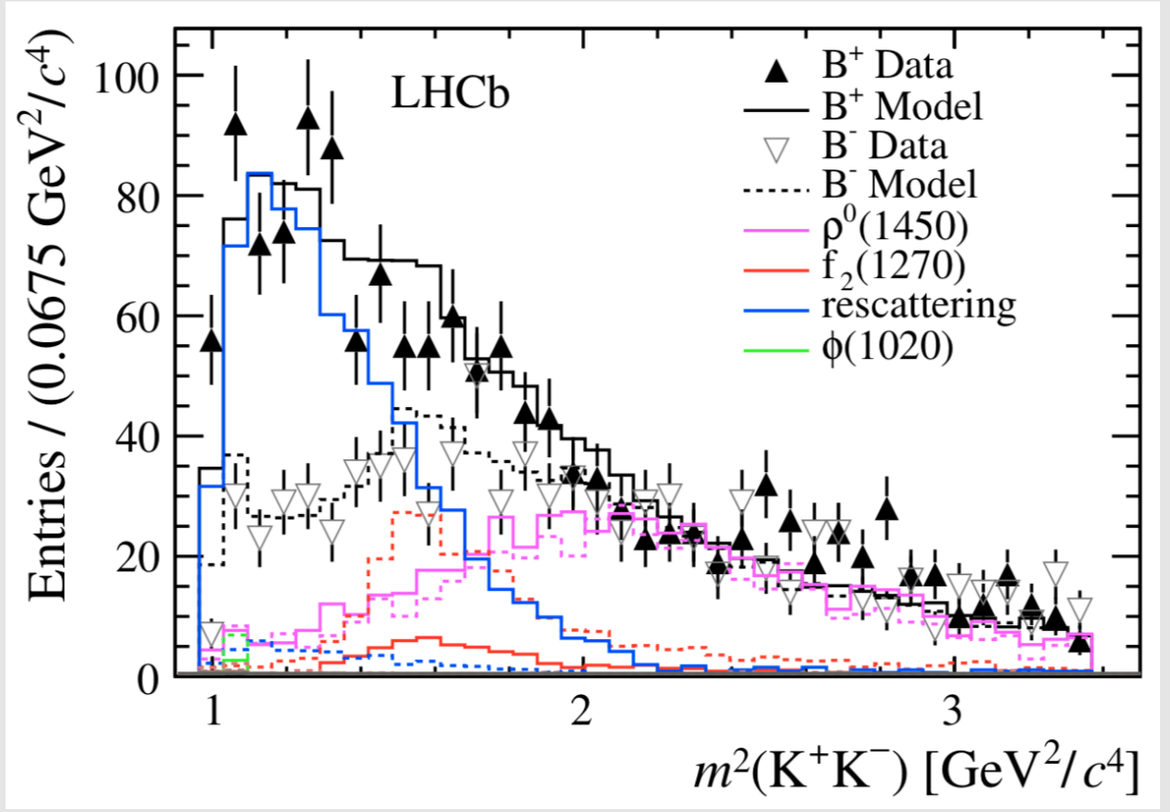


$B^{\pm} \to K^+K^-\pi^{\pm}$

LHCb, arXiv:1905.09244



- Amplitude analysis and CP asymmetry measurement in Dalitz plot
  - ➡ Significant rescattering contribution at low KK masses
  - ➡ Predominantly for B^+
  - ➡ Huge asymmetry in this component: $(-66\pm4\pm2)\%$

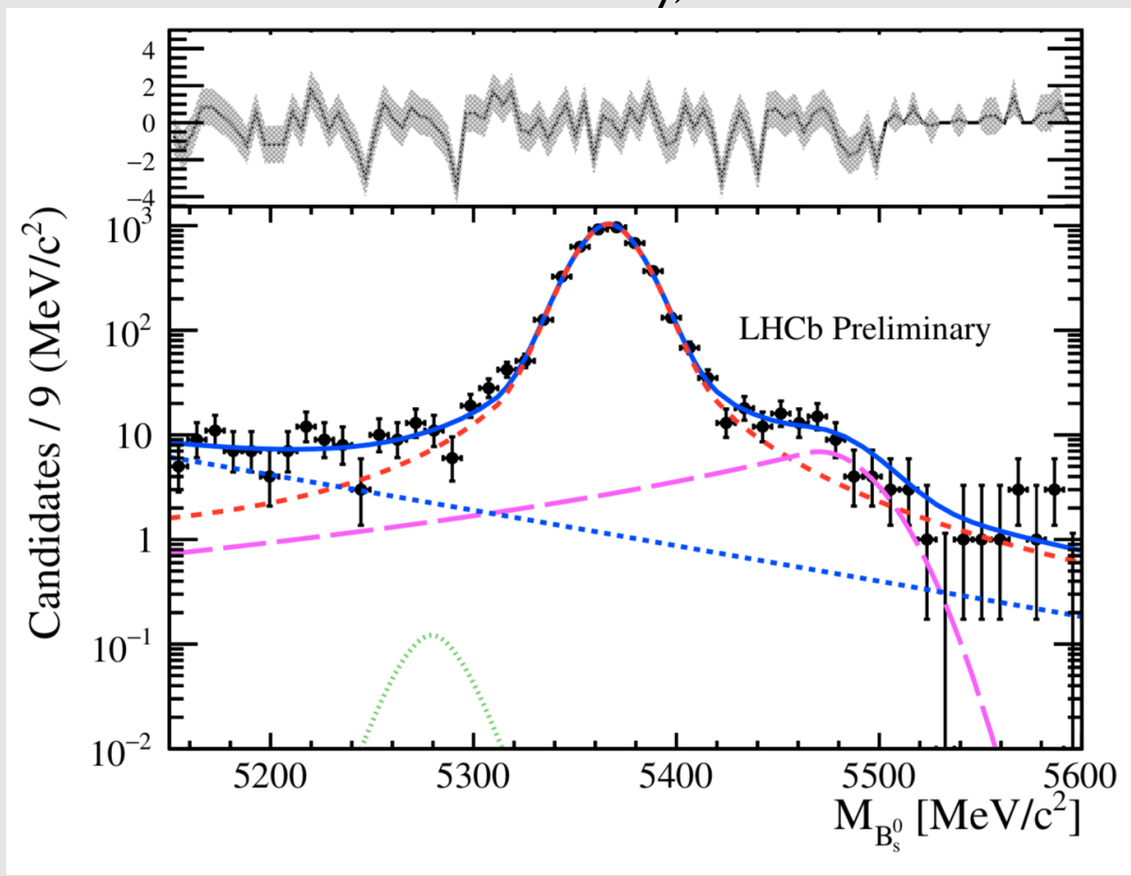


$B_s \to \phi\phi$

A. Ukleja, Tu 17:50

- Time-dependent CP and triple-product asymmetries
  - ➡ New analysis of 2015+16 data (2 fb^{-1}), combined with Run 1 analysis (3 fb^{-1})
  - ➡ No CPV in $b \to s\bar{s}s$ transitions
  - ➡ Triple product asymmetries in variables U and V

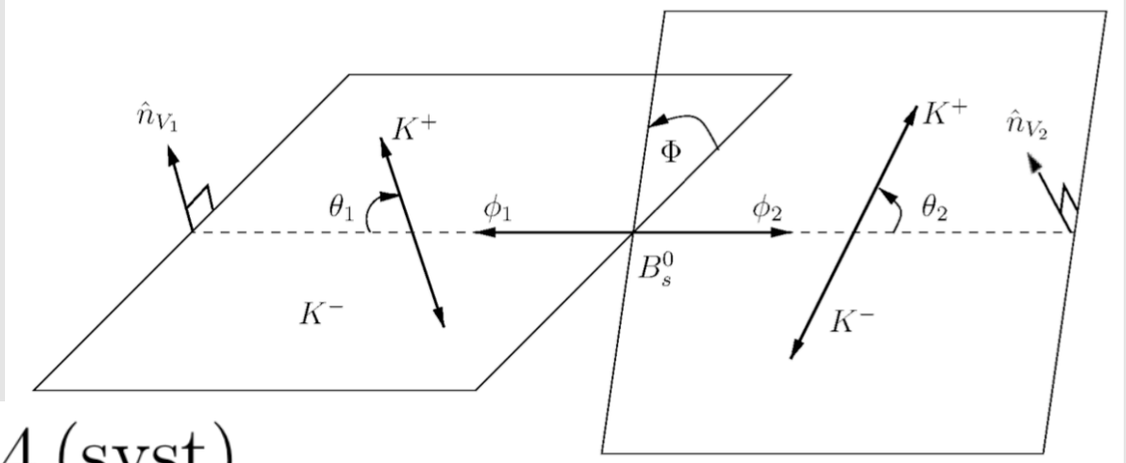
LHCb Preliminary, LHCb-PAPER-2019-019



$$U \equiv \sin\Phi\cos\Phi$$

$$V \equiv \sin(\pm\Phi)$$

$$+\text{ sign if } \cos\theta_1 \cos\theta_2 \geq 0$$



$$A_U = -0.003 \pm 0.011\,(\text{stat}) \pm 0.004\,(\text{syst})$$
$$A_V = -0.014 \pm 0.011\,(\text{stat}) \pm 0.004\,(\text{syst})$$

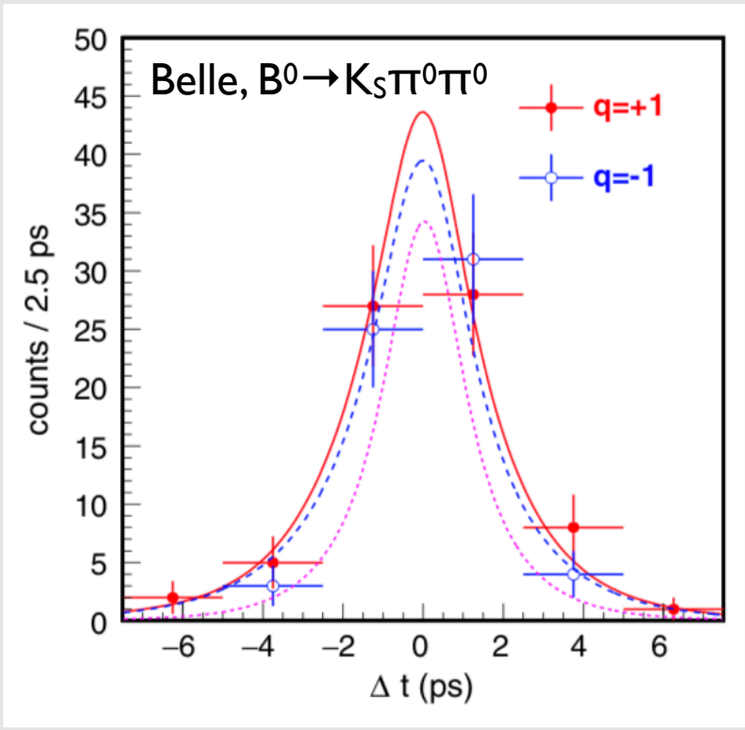
In other news

- Phase-space integrated/two-body analyses

➡ $\Lambda_b \to pK/p\pi$: LHCb, Phys. Lett. B784 (2018) 124
no asymmetries, also in difference

➡ $B^\pm \to K_S K_S K^\pm$: Belle, Phys. Rev. D 99 (2019) 011102(R)
no asymmetry found ($b \to s/d$ loops)

➡ $B^0 \to K_S \pi^0 \pi^0$: Belle, Phys. Rev. D 99 (2019) 031102(R)
large asymmetry, measures $\sin(2\beta_{eff})$



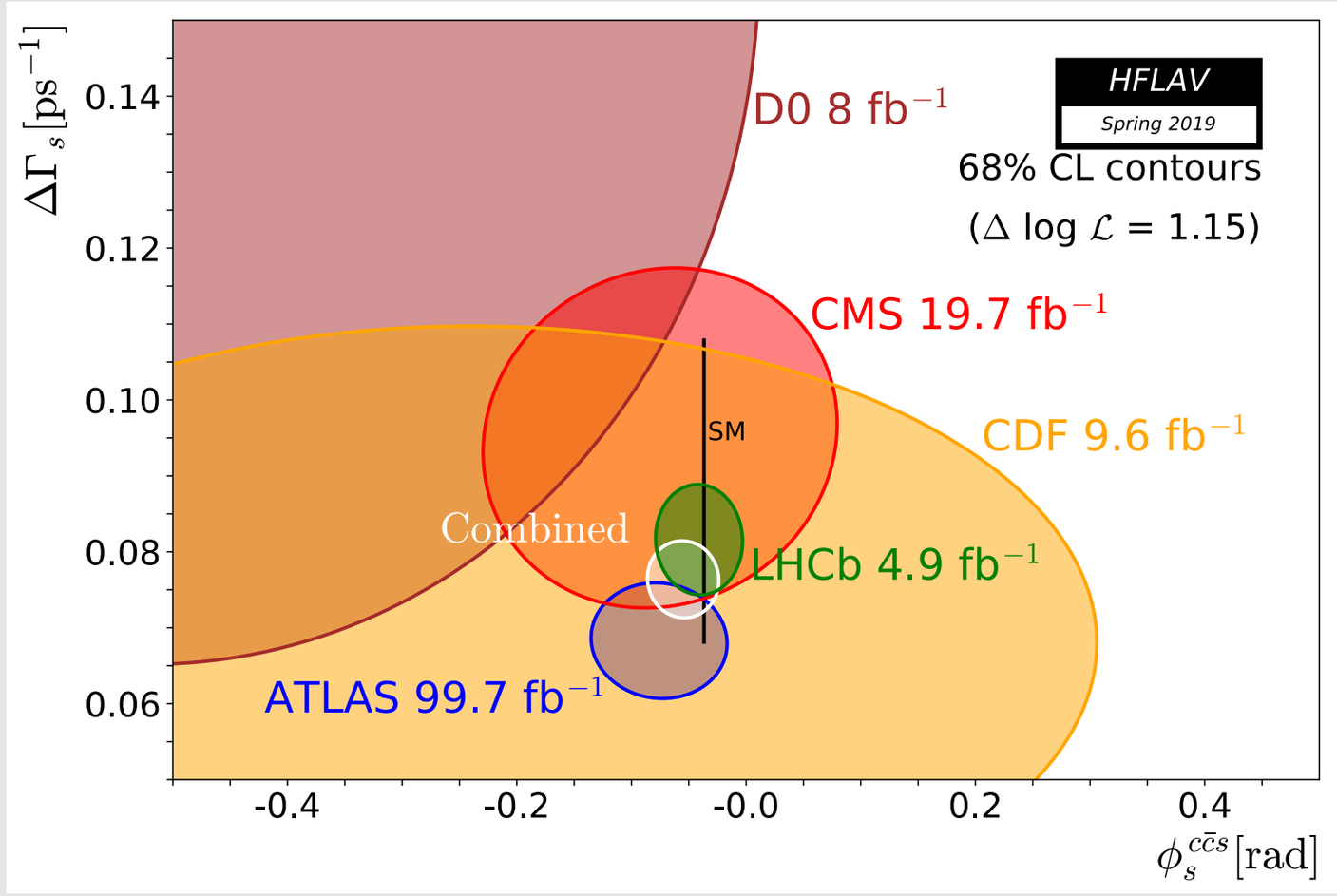
Ingredients

+

CP violation in B_s

A. Ukleja, Tu 17:50

- ATLAS 2011-17
  - ➡ J/ψϕ (prel.) (ATLAS-CONF-2019-009)
- LHCb 2011-16
  - ➡ J/ψKK (prel.) (LHCb-PAPER-2019-013)
  - ➡ J/ψππ (arXiv:1903.05530)



- Both main players have more data to analyse
- Some tension on absolute B_s lifetime
- Great agreement with theory on $\Delta\Gamma_s$
- ϕ_s starts to deviate from 0, but in perfect agreement with SM

Ingredients

Radiative

- Belle

  ➡ Measurements of isospin asymmetry and difference of direct CP asymmetries in charged and neutral inclusive $B \to X_s\gamma$ decays

$$\Delta A_{CP} = (+3.69 \pm 2.65 \pm 0.76)\%,$$ Belle, Phys. Rev. D 99 (2019) 032012

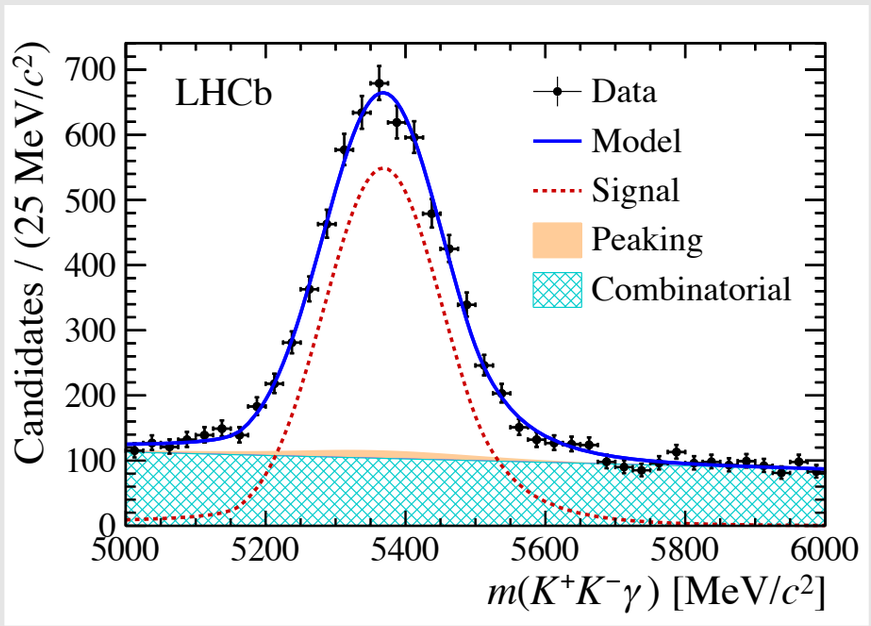
- LHCb

  ➡ First measurement of CP asymmetries in $B_s \to \phi\gamma$ decays (Run I, 3 fb^{-1})

  ➡ Completes initial LHCb core physics programme measurements

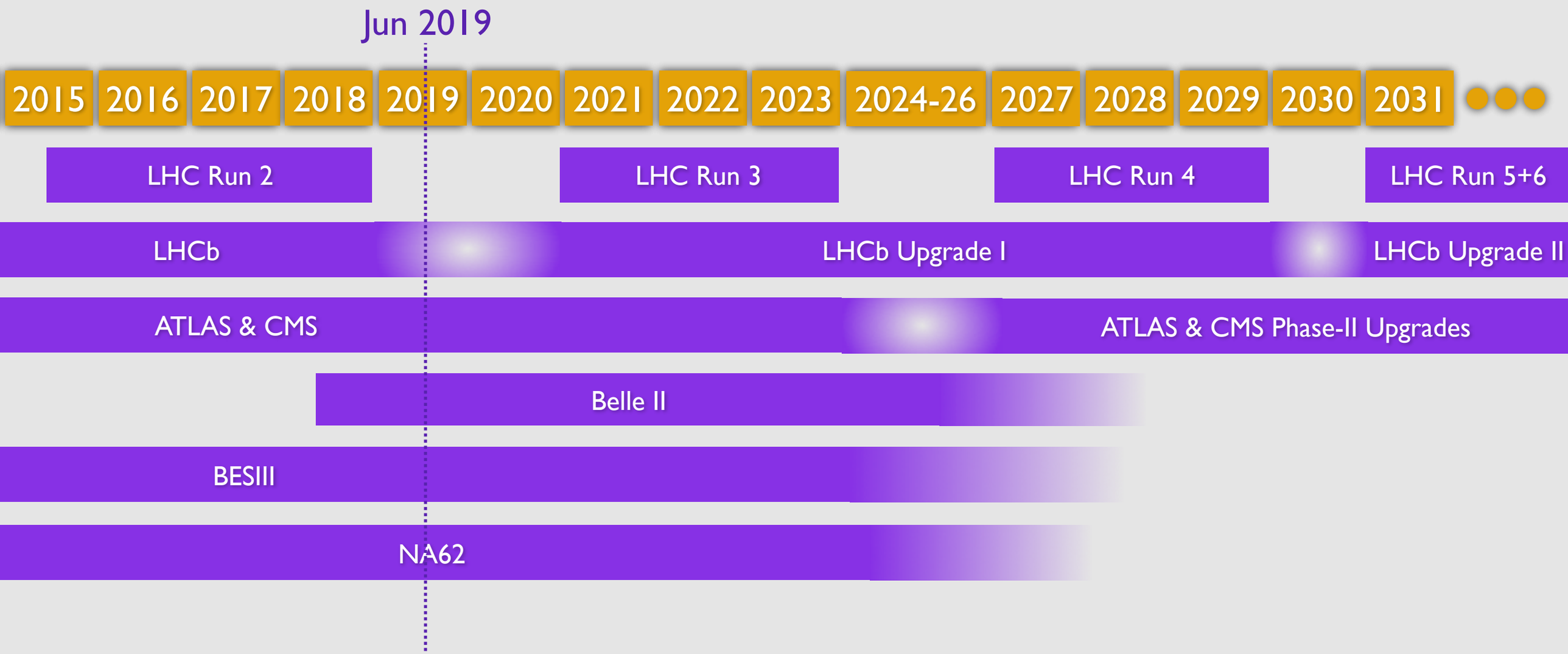
LHCb, arXiv:1905.06284

$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11,$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11,$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67^{+0.37}_{-0.41} \pm 0.17,$$



Ingredients

A flavourful decade

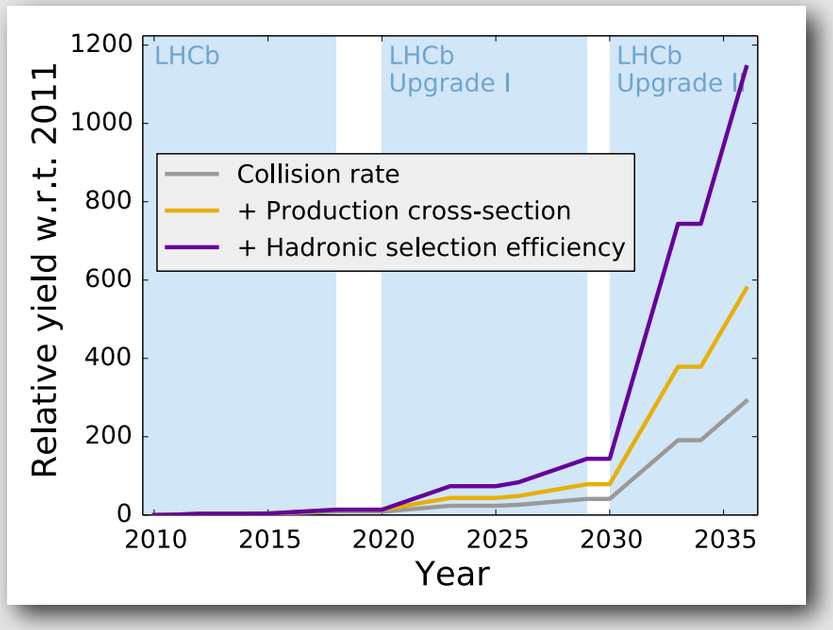


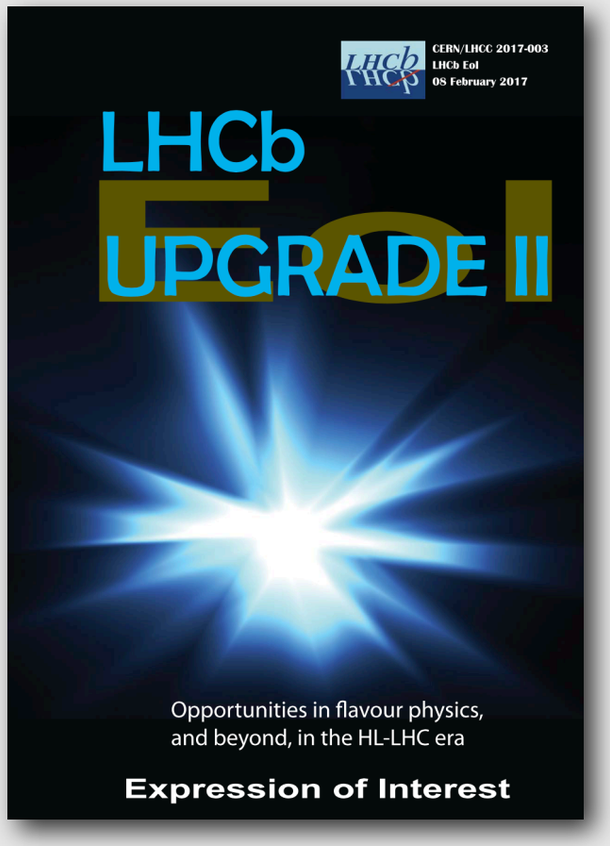
- Plus lots of activity on charged lepton flavour

➡ MEG, mu3e, mu2e, COMET, g-2, …

LHCb Upgrades

- LHCb has more than delivered on its promises
  - ➡ Detector now disassembled
  - ➡ Upgrade construction underway
- Will require much more data to
  - ➡ Shed light on existing anomalies
  - ➡ Challenge SM level in many areas
- LHCb largely unrivalled in charm and B_s, B_c, b-baryons (ATLAS+CMS will contribute to ϕ_s)
- LHCb Upgrade I will deliver real-time flavour physics
  - ➡ Novel detector and data acquisition will pave the way for Upgrade II
    - The ultimate frontier in flavour physics





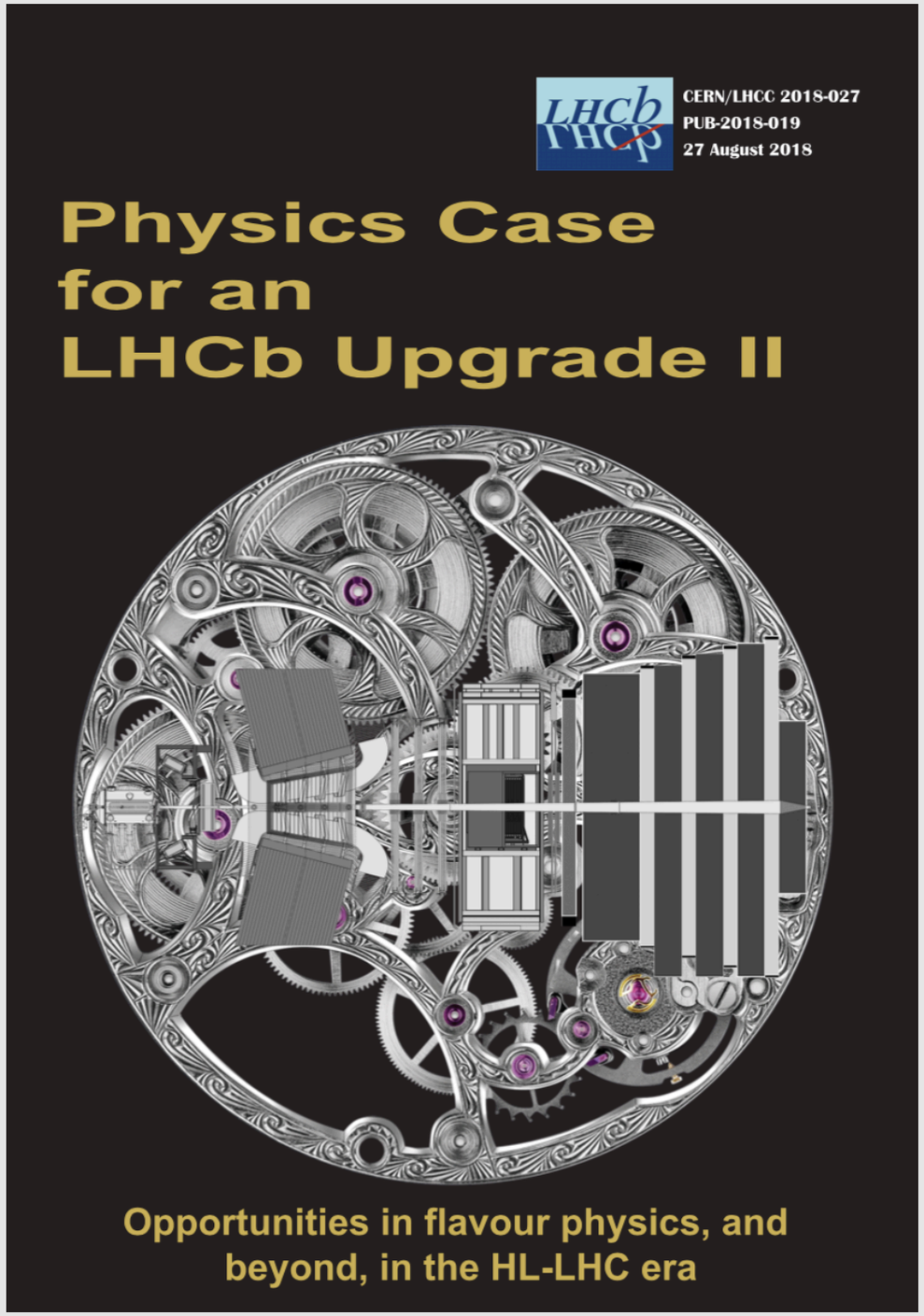
The ultimate frontier

$\pm 33.0 \times 10^{-4}$	± 5.4	± 49	$\pm 28.0 \times 10^{-5}$	LHCb Current
$\pm 10.0 \times 10^{-4}$	± 1.5 (Belle II) ± 1.5 (ATLAS/CMS)	± 14	$\pm 35.0 \times 10^{-5}$ (Belle II) $\pm 4.3 \times 10^{-5}$ (ATLAS/CMS)	LHCb 2025
$\pm 3.0 \times 10^{-4}$	± 0.35	± 6 ± 4	$\pm 1.0 \times 10^{-5}$	HL-LHC
a^s_{sl}	γ [°]	ϕ_s [mrad]	A_Γ	

- LHCb Upgrade II will challenge even tiniest SM predictions

  ➡ Uniquely wide range of measurements

- Sensitive to mass scales many orders of magnitude beyond the reach of direct measurements



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Conclusions

- CP violation is a versatile tool
  - ➡ Precision measurements of SM
  - ➡ Discovery tool for BSM physics
- Plenty of new results across the board
  - ➡ Charm CPV discovered in two-body D^0 decays
  - ➡ Huge asymmetries observed in several charmless B decays
  - ➡ Improved precision on ϕ_s
  - ➡ Major steps forward on inclusive and exclusive radiative $b \to s\gamma$ decays
- Huge potential for future measurements with much increases precision
  - ➡ Belle II and LHCb Upgrade I will lead the way
  - ➡ Ultimate precision requires LHCb Upgrade II

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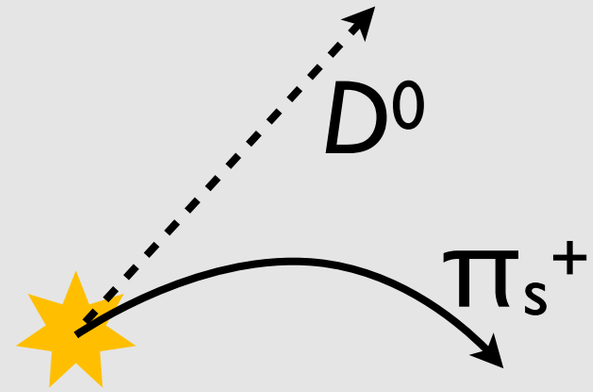
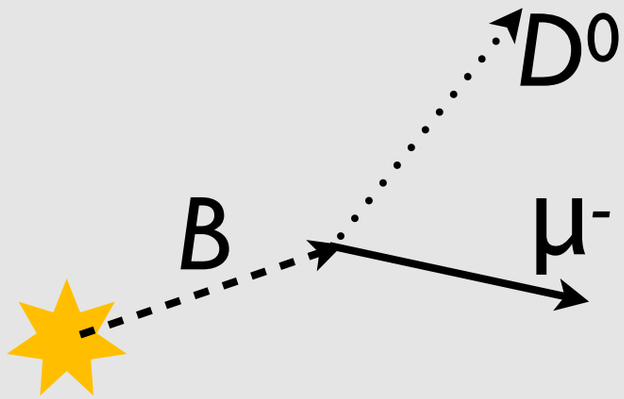
Backup

Flavour tagging

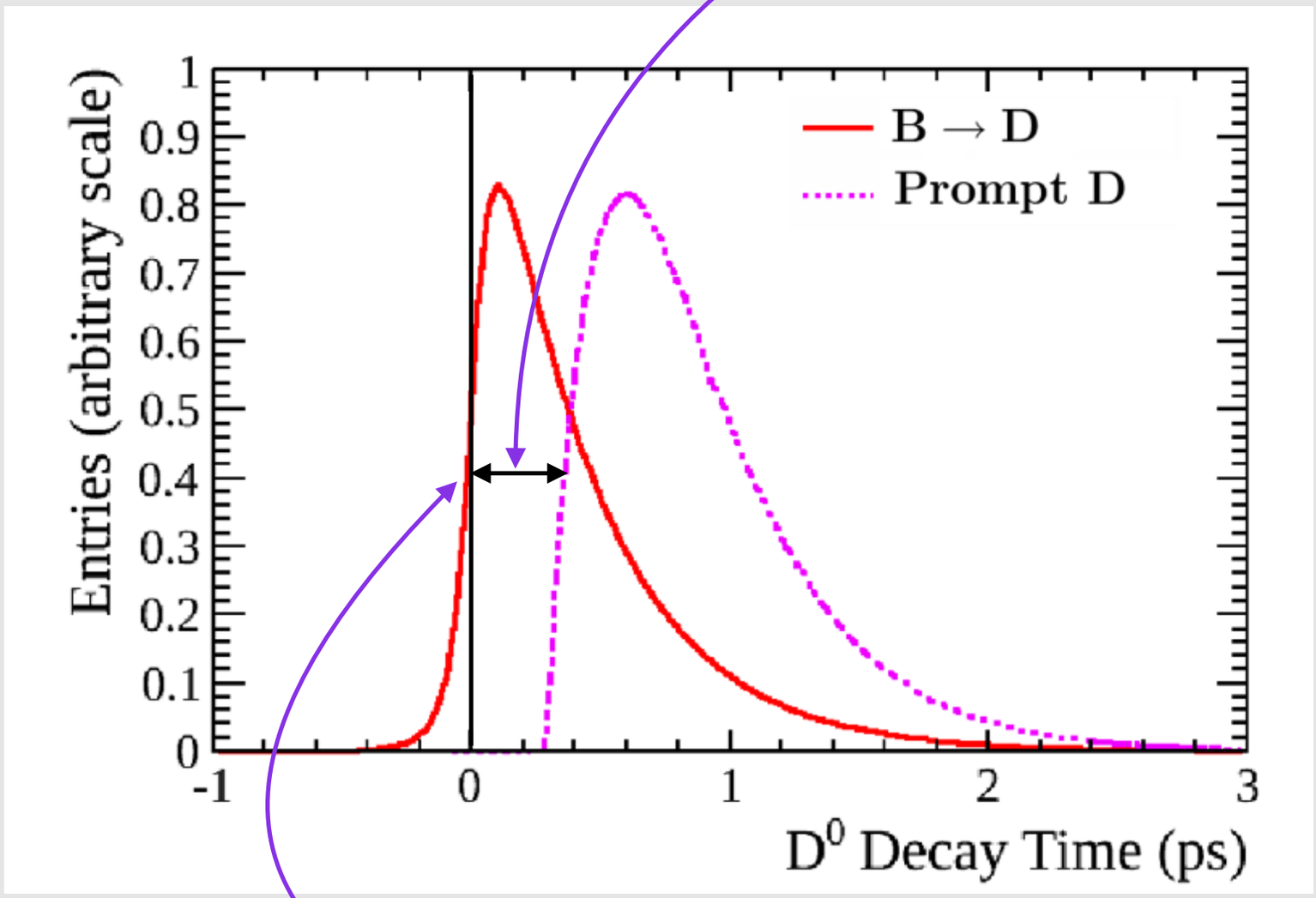
- Prompt D*-tagged
  - ➡ Larger yields
  - ➡ Background from D-from-B
- Muon-tagged
  - ➡ Smaller yields (somewhat)
  - ➡ Larger level of combinatorial background
  - ➡ Independent systematic uncertainties
- Doubly-tagged
  - ➡ The best of both worlds
  - ➡ Smallest samples

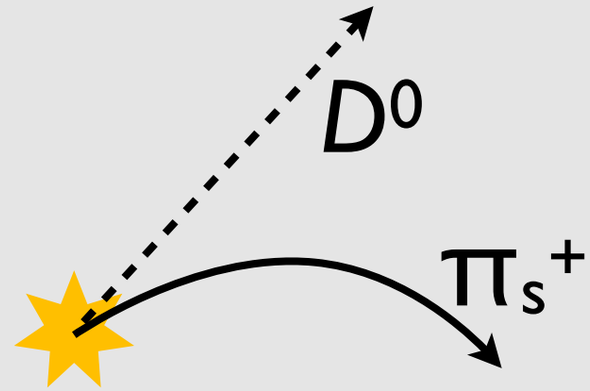


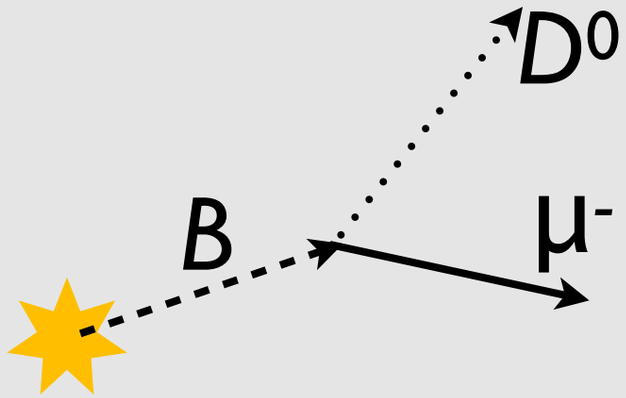


Flavour tagging and decay times

Cannot reconstruct D^0 decays close to **primary** vertex







Can reconstruct D^0 decays close to **displaced B** vertex

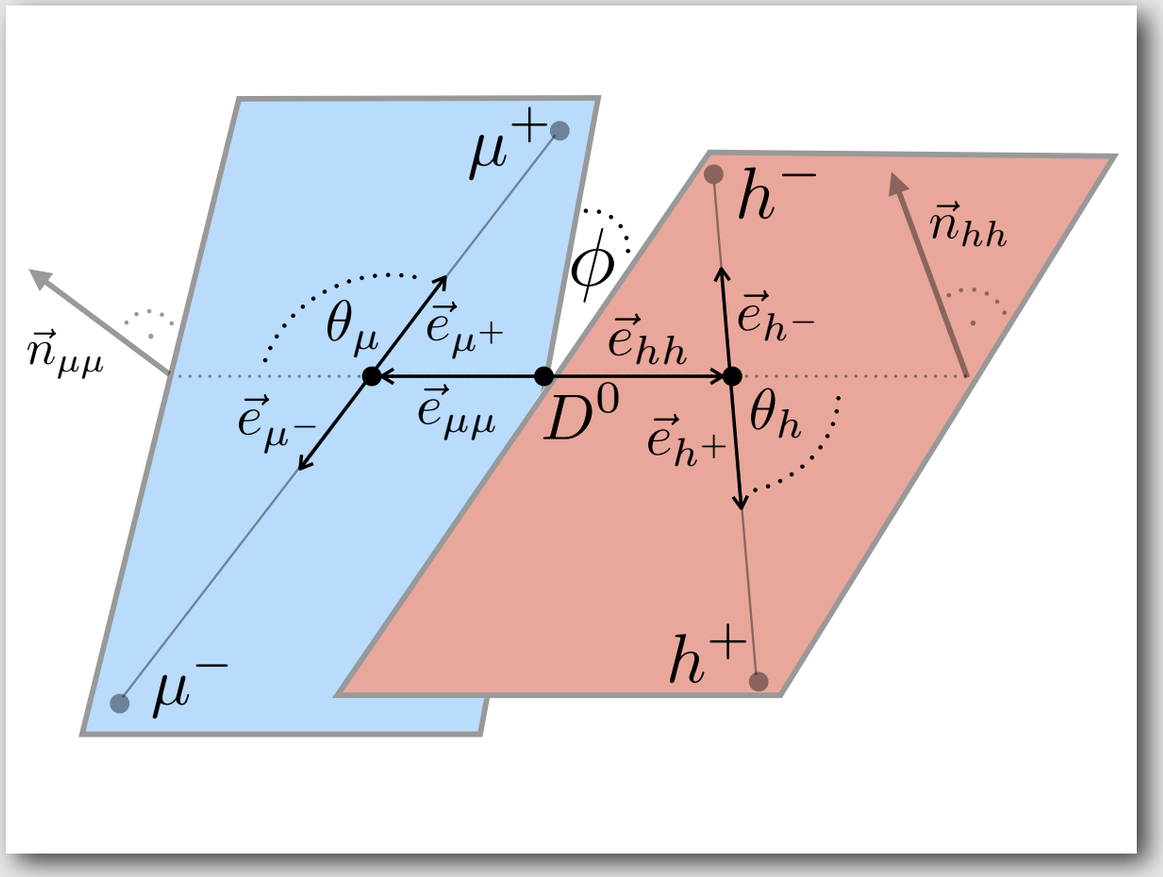
$D^0 \to hh\mu\mu$

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

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

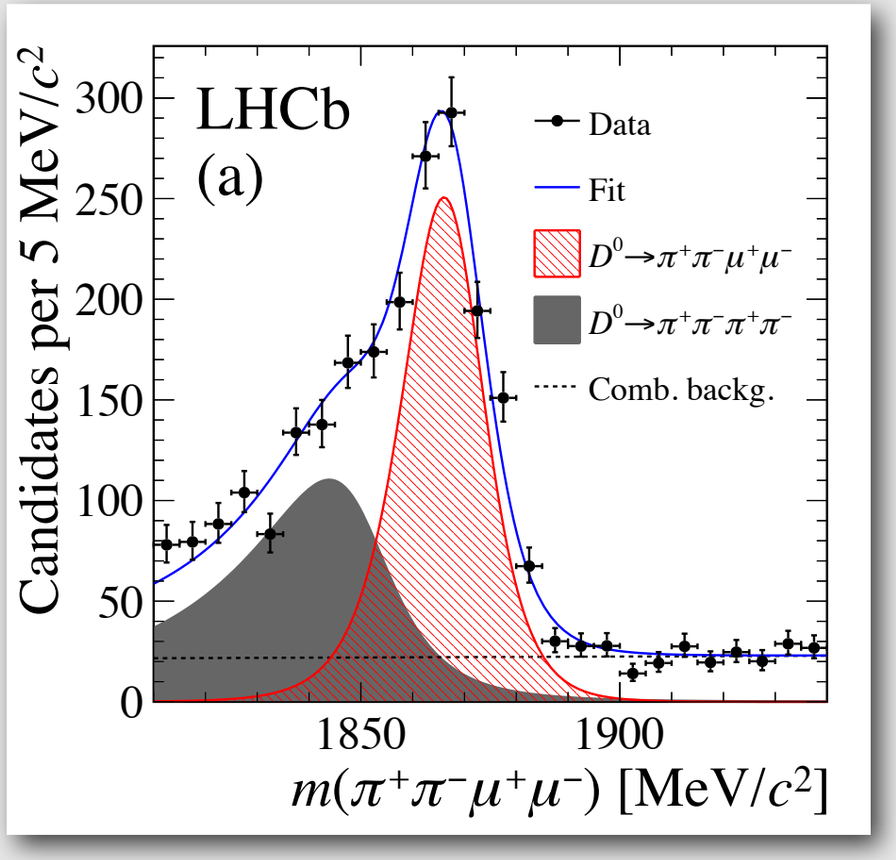
$$A_{2\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)},$$

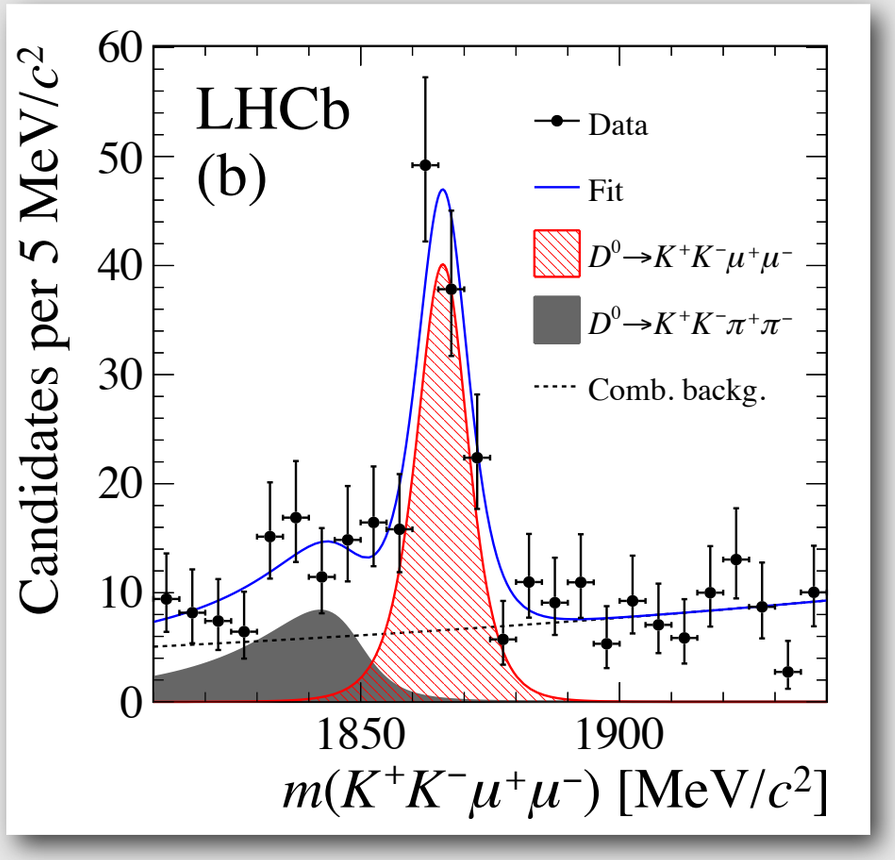
$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)},$$



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

LHCb, Phys. Rev. Lett. 121 (2018) 091801

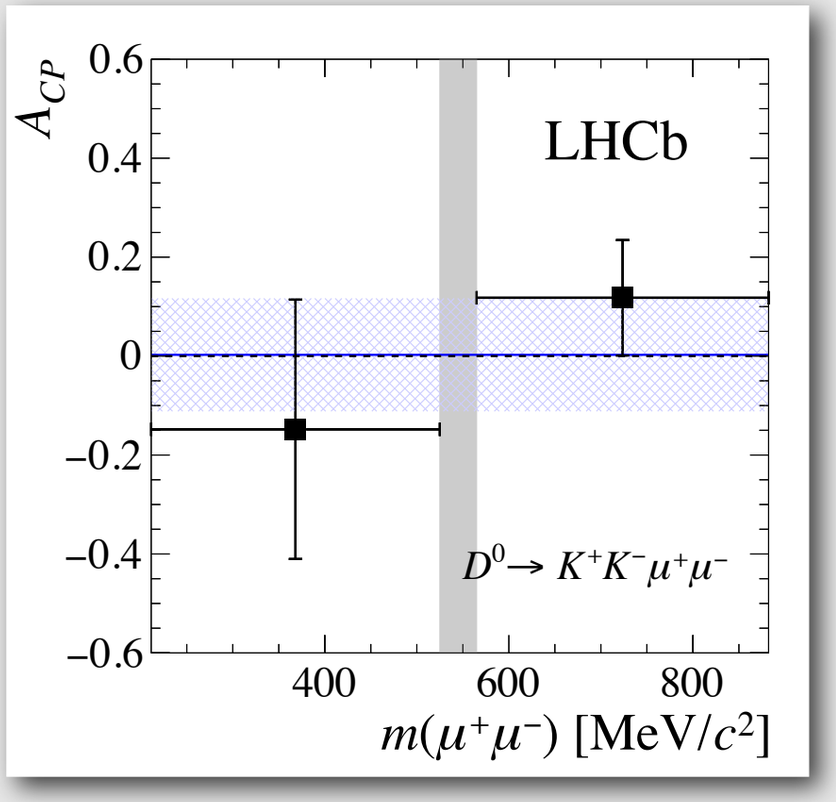


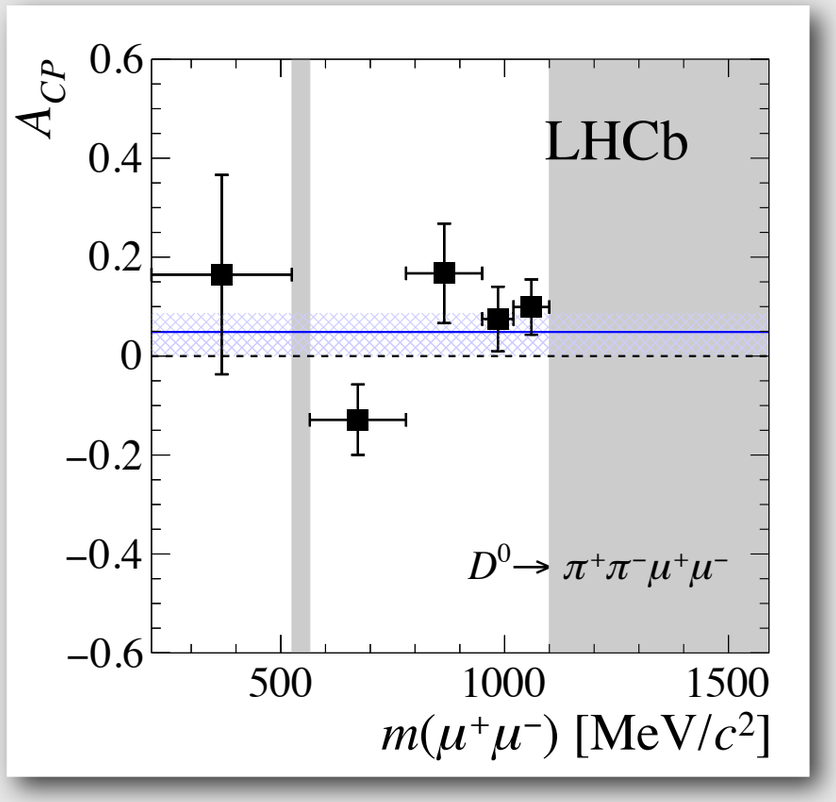


- LHCb 2011-16 data (5 fb^{-1})
- Includes significant signal in low-mass region (<525 MeV/c^2)
- A_{CP} normalised to $D^0 \to K^+K^-$

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

LHCb, Phys. Rev. Lett. 121 (2018) 091801





$m(\mu^+\mu^-)$ [MeV/c^2]	Efficiency-weighted yields Signal	Misid. back.	Comb. back.	Signal asymmetries $A_{\rm FB}$ [%]	$A_{2\phi}$ [%]	$A_{\mathcal{C}_P}$ [%]
			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	$0 \pm 11 \pm 2$	$9 \pm 11 \pm 1$	$0 \pm 11 \pm 2$

$B^{\pm} \to \pi^+\pi^-\pi^{\pm}$

LHCb Preliminary
LHCb-PAPER-2019-017,
LHCb-PAPER-2019-018

Contribution	Fit fraction (%)	A_{CP} (10^{-2})	B^+ phase (°)	B^- phase (°)
Isobar Model				
$\rho(770)^0$	$55.5 \pm 0.6 \pm 1.7$	$+0.7 \pm 1.1 \pm 2.2$	—	—
$\omega(782)$	$0.50 \pm 0.03 \pm 0.05$	$-4.8 \pm 6.4 \pm 9.4$	$-19 \pm 6 \pm 1$	$+8 \pm 16 \pm 1$
$f_2(1270)$	$9.0 \pm 0.3 \pm 1.4$	$+46.8 \pm 5.5 \pm 5.8$	$+5 \pm 3 \pm 12$	$+53 \pm 2 \pm 12$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 1.5$	$-12.9 \pm 6.4 \pm 29.7$	$+127 \pm 4 \pm 21$	$+154 \pm 4 \pm 6$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.2$	$-80.1 \pm 11.7 \pm 22.9$	$-26 \pm 7 \pm 14$	$-47 \pm 18 \pm 25$
S-wave	$25.4 \pm 0.5 \pm 1.3$	$+14.4 \pm 1.8 \pm 3.3$	—	—
rescatt	$1.4 \pm 0.1 \pm 0.4$	$+44.7 \pm 9.0 \pm 16.6$	$-35 \pm 6 \pm 10$	$-4 \pm 4 \pm 25$
σ	$25.2 \pm 0.6 \pm 1.1$	$+16.0 \pm 2.0 \pm 3.2$	$+115 \pm 2 \pm 14$	$+179 \pm 1 \pm 95$
K-Matrix				
$\rho(770)^0$	$56.5 \pm 0.7 \pm 3.4$	$+4.2 \pm 1.5 \pm 6.4$	—	—
$\omega(782)$	$0.47 \pm 0.04 \pm 0.03$	$-6.2 \pm 8.4 \pm 9.8$	$-15 \pm 6 \pm 4$	$+8 \pm 7 \pm 4$
$f_2(1270)$	$9.3 \pm 0.4 \pm 2.5$	$+42.8 \pm 4.1 \pm 9.1$	$+19 \pm 4 \pm 18$	$+80 \pm 3 \pm 17$
$\rho(1450)^0$	$10.5 \pm 0.7 \pm 4.6$	$+9.0 \pm 6.0 \pm 47.0$	$+155 \pm 5 \pm 29$	$-166 \pm 4 \pm 51$
$\rho_3(1690)^0$	$1.5 \pm 0.1 \pm 0.4$	$-35.7 \pm 10.8 \pm 36.9$	$+19 \pm 8 \pm 34$	$+5 \pm 8 \pm 46$
S-wave	$25.7 \pm 0.6 \pm 3.0$	$+15.8 \pm 2.6 \pm 7.2$	—	—
QMI				
$\rho(770)^0$	$54.8 \pm 1.0 \pm 2.2$	$+4.4 \pm 1.7 \pm 2.8$	—	—
$\omega(782)$	$0.57 \pm 0.10 \pm 0.17$	$-7.9 \pm 16.5 \pm 15.8$	$-25 \pm 6 \pm 27$	$-2 \pm 7 \pm 11$
$f_2(1270)$	$9.6 \pm 0.4 \pm 4.0$	$+37.6 \pm 4.4 \pm 8.0$	$+13 \pm 5 \pm 21$	$+68 \pm 3 \pm 66$
$\rho(1450)^0$	$7.4 \pm 0.5 \pm 4.0$	$-15.5 \pm 7.3 \pm 35.2$	$+147 \pm 7 \pm 152$	$-175 \pm 5 \pm 171$
$\rho_3(1690)^0$	$1.0 \pm 0.1 \pm 0.5$	$-93.2 \pm 6.8 \pm 38.9$	$+8 \pm 10 \pm 24$	$+36 \pm 26 \pm 46$
S-wave	$26.8 \pm 0.7 \pm 2.2$	$+15.0 \pm 2.7 \pm 8.1$	—	—