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(ON BEHALF OF LHCB, ATLAS AND CMS COLLABORATIONS)

CP VIOLATION AND MIXING IN B AND CHARM DECAYS

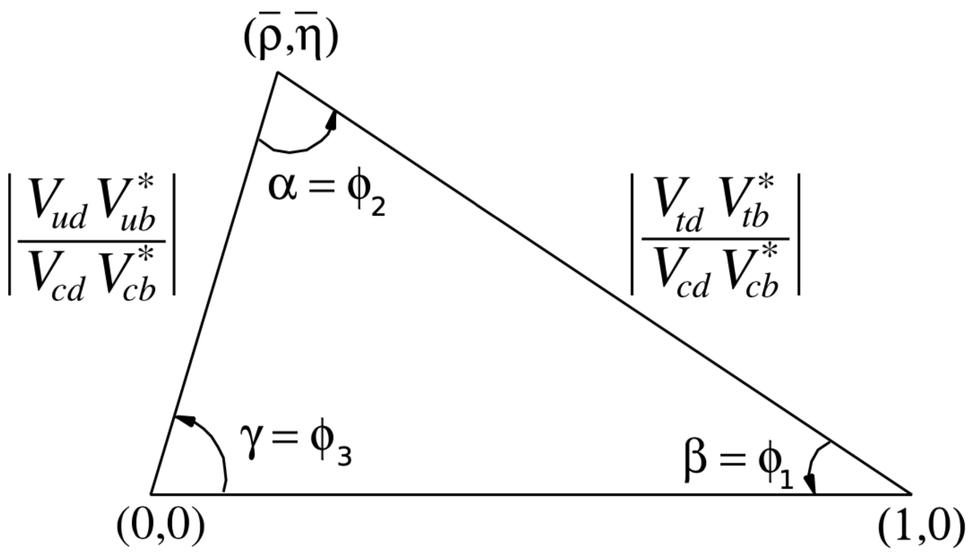
LHCP, 2022

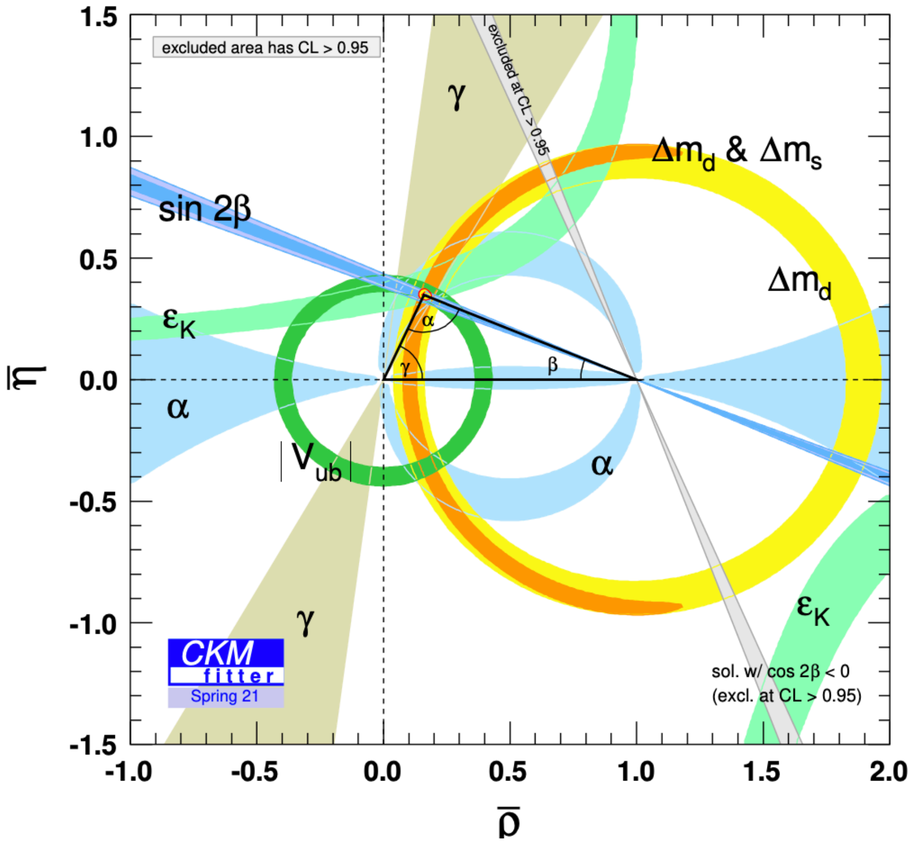
Outline

- γ angle measurement
  - LHCb combination [JHEP 12 (2021) 141]
  - $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ decays ****NEW***** [LHCb-PAPER-2022-017, preliminary]
- Effective lifetime measurement. ****NEW**** [PAPER-2022-010, preliminary]
  - $B_s^0 \to J/\psi\eta$
- ϕ_s measurement in CMS and ATLAS [Phys. Lett. B 816 (2021) 136188] [Eur. Phys. J. C 81 (2021) 342]
- CPV in B decays
  - CPV in B->3h across the Dalitz plane. [LHCb-PAPER-2021-049, LHCb-PAPER-2021-050, Preliminary]
  - $B^0 \to p\bar{p}K^+\pi^-$ [LHCb-PAPER-2022-003, Preliminary]
- CPV and mixing in charm decays:
  - CP asymmetry in Ds decays. [arXiv:2204.12228]
  - y_{cp} from 2-body decays. [LHCb-PAPER-2021-041] [arXiv:2202.09106]

Introduction

Cabibbo-Kobayashi-Maskawa unitary triangle





LHCb combination of γ angle

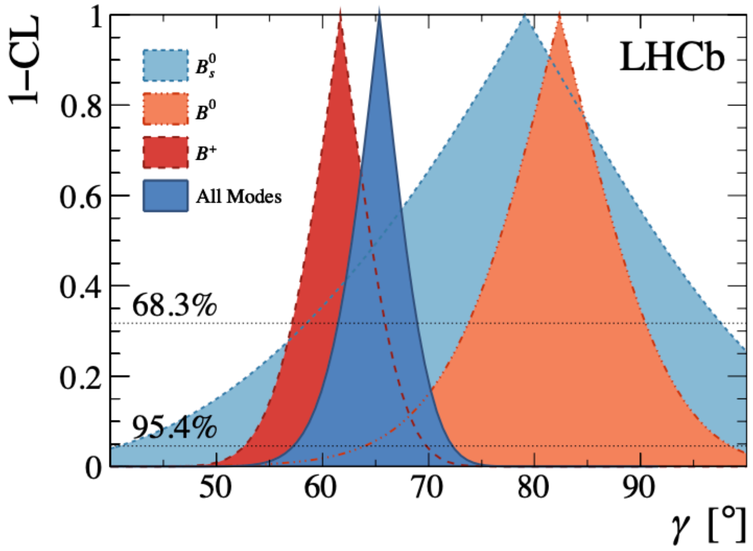
[JHEP 12 (2021) 141]

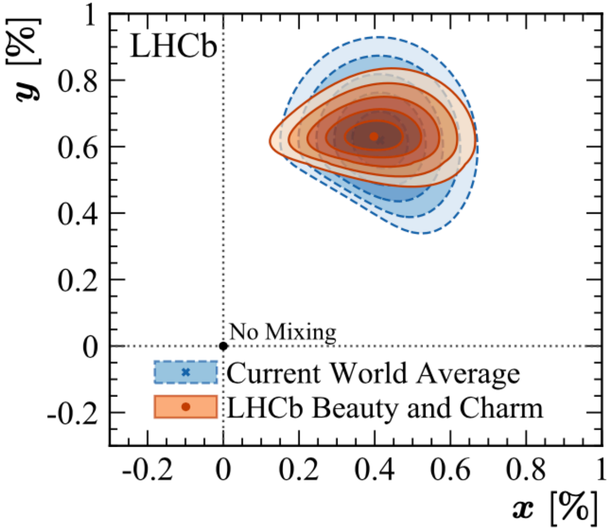
- LHCb measurements sensitive to γ and charm mixing are combined
- $\gamma = (65.4^{+3.8}_{-4.2})^\circ$
- Most precise by single experiment!
- Around 2σ tension between charged and neutral B mesons
- Excellent agreement with indirect results

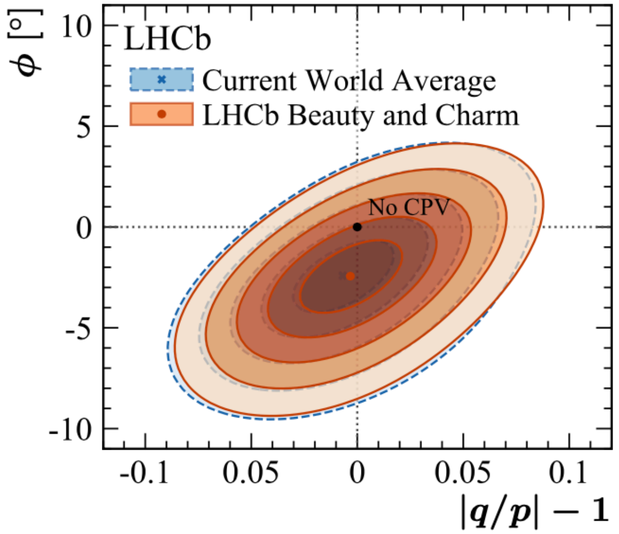
$\gamma = (65.8 \pm 2.2)^\circ$, $\gamma = (65.55^{+0.90}_{-2.65})^\circ$

UT Fit CKM fitter

- $x \equiv \Delta M/\Gamma = (0.400^{+0.052}_{-0.053})\%$
- $y \equiv \Delta\Gamma/2\Gamma = (0.630^{+0.033}_{-0.030})\ \%$ (factor of 2 improved!)
- $|q/p| = 0.997 \pm 0.016$ and $\phi = (-2.4 \pm 1.2)^\circ$







CKM angle γ in $B^{\pm} \to Dh^{\pm}$ decays

New [LHCb-PAPER-2022-017, preliminary]

- Decay $B^{\pm} \to DK^{\pm}$, $D \to K^{+}\pi^{-}\pi^{-}\pi^{+}$
- Large CP asymmetry measured in bins of D phase space

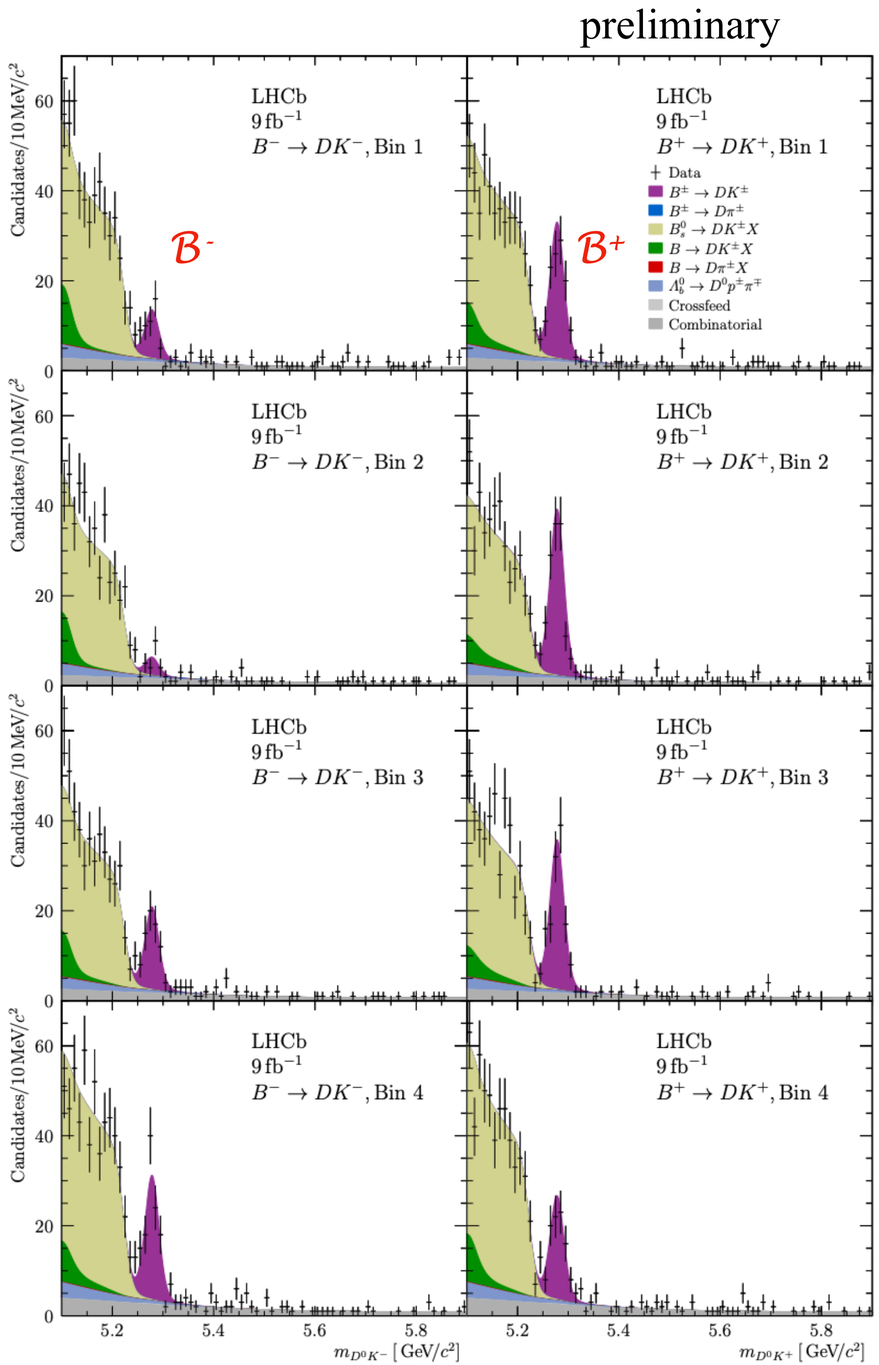
  D hadronic parameters from BESII, CLEO-c

- Run1/2: 9 fb^{-1}

$$\gamma = (54.8^{+6.0+0.6+6.7}_{-5.8-0.6+4.3})^{\circ}$$

the second most precise result in single D decay mode!

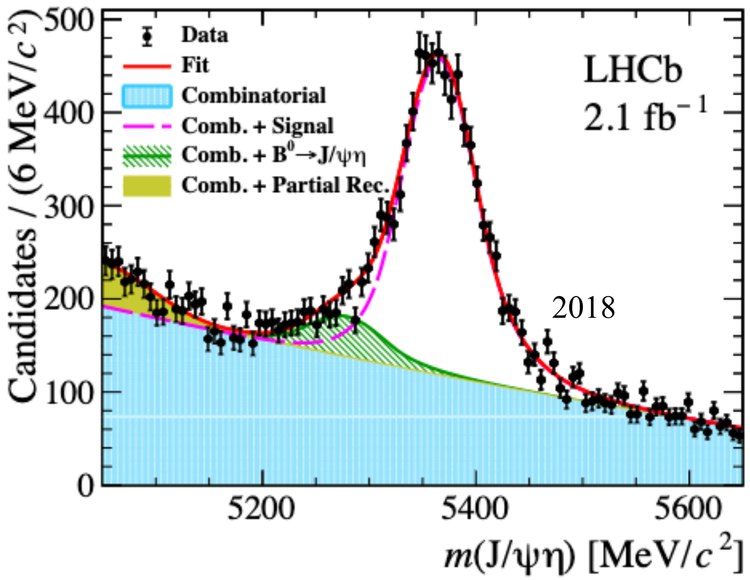
- Compatible results with LHCb combination

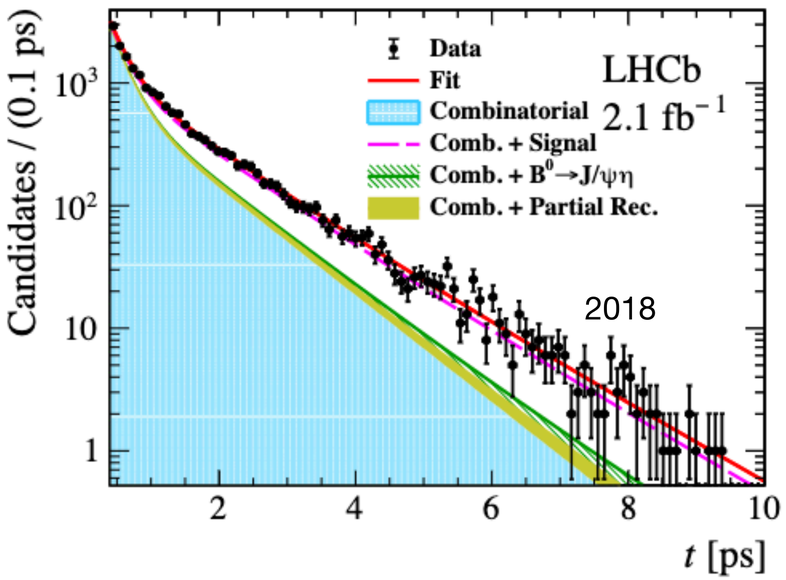


Effective lifetime in $B_S^0 \to J/\psi\eta$

New
[PAPER-2022-010, preliminary]

- The decay is CP-even in the limit of CP conservation effective lifetime $\tau_L = 1/\Gamma_L$
- Improving the precision is important for direct $\Delta\Gamma_s$ measurements, e.g. $B_s^0 \to J/\psi\phi$
- 2D ML fit to mass and decay time to obtain the effective lifetime.





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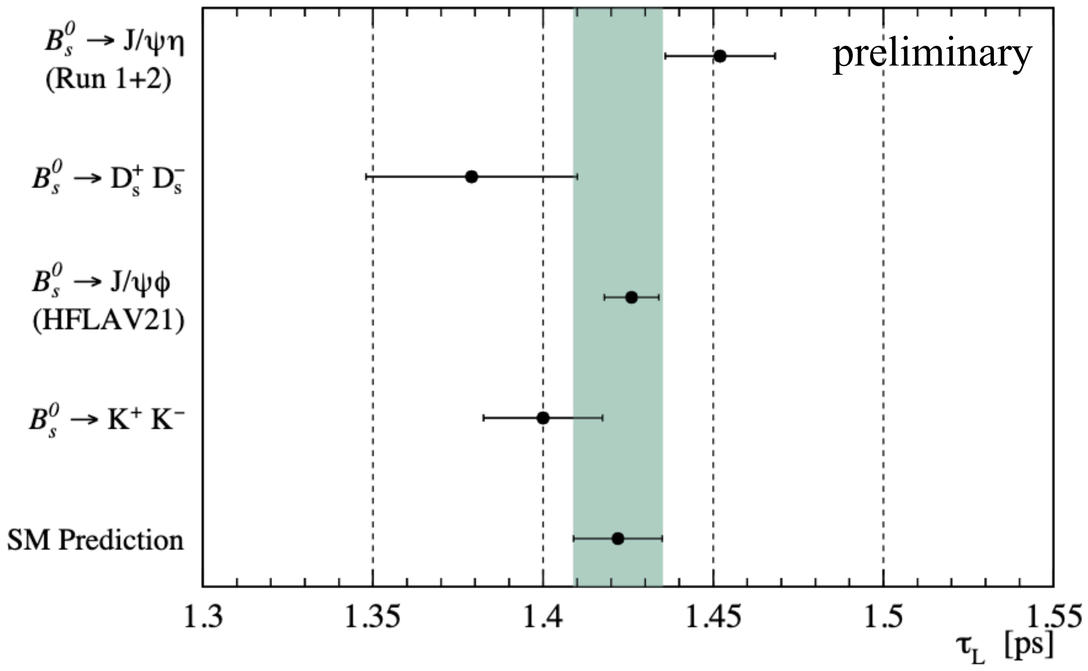
[PAPER-2022-010, preliminary]



Run2 result is factor of 2 more precise than Run 1!

$$\tau_L = 1.445 \pm 0.016 \pm 0.008\ ps$$

Combination of Run 1 and Run 2 result :

$$\tau_L = 1.452 \pm 0.014 \pm 0.007 \pm 0.002\ ps$$

ϕ_s measurement in CMS and ATLAS

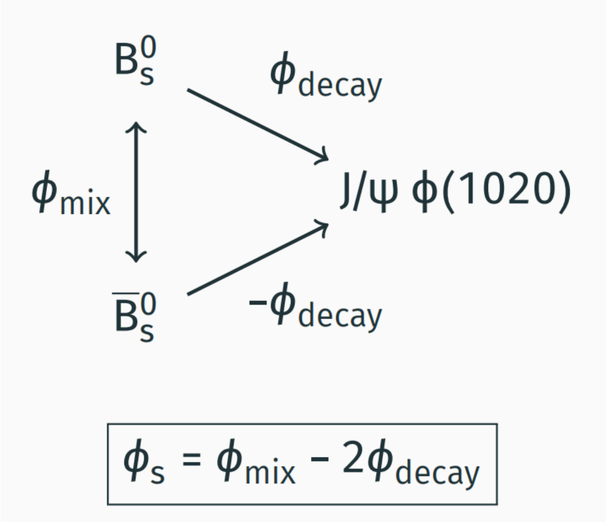
A Golden channel..

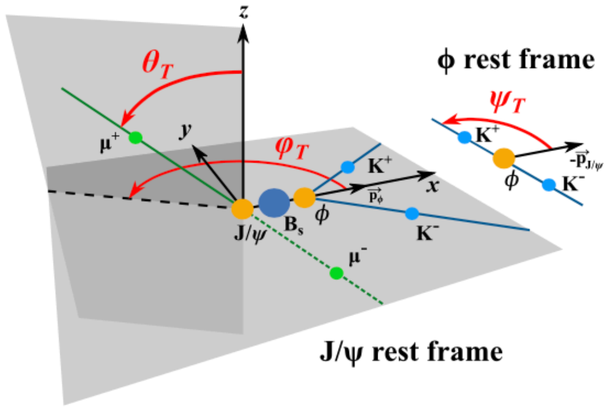
[Phys. Lett. B 816 (2021) 136188]

- $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ decay is studied at 13 TeV.
- It's a golden channel to measure ϕ_s

$$\phi_s = -2\beta_s = arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$$

- SM prediction: $\phi s \simeq -2\beta s = -36.96^{+0.72}_{-0.84}$ mrad [CKM fitter]
- New physics can modify the phase via the contribution of BSM particles to B_s mixing!
- Not a single CP state - an angular analysis needed to separate CP-odd and CP-even components in the final state
- A novel OS trigger to estimate the initial flavour of the B_s^0 meson in the production.
- Many additional observables measured : Γs , $\Delta\Gamma s$, $|\lambda| = (q/p)(\bar{A}_f/A_f)$,

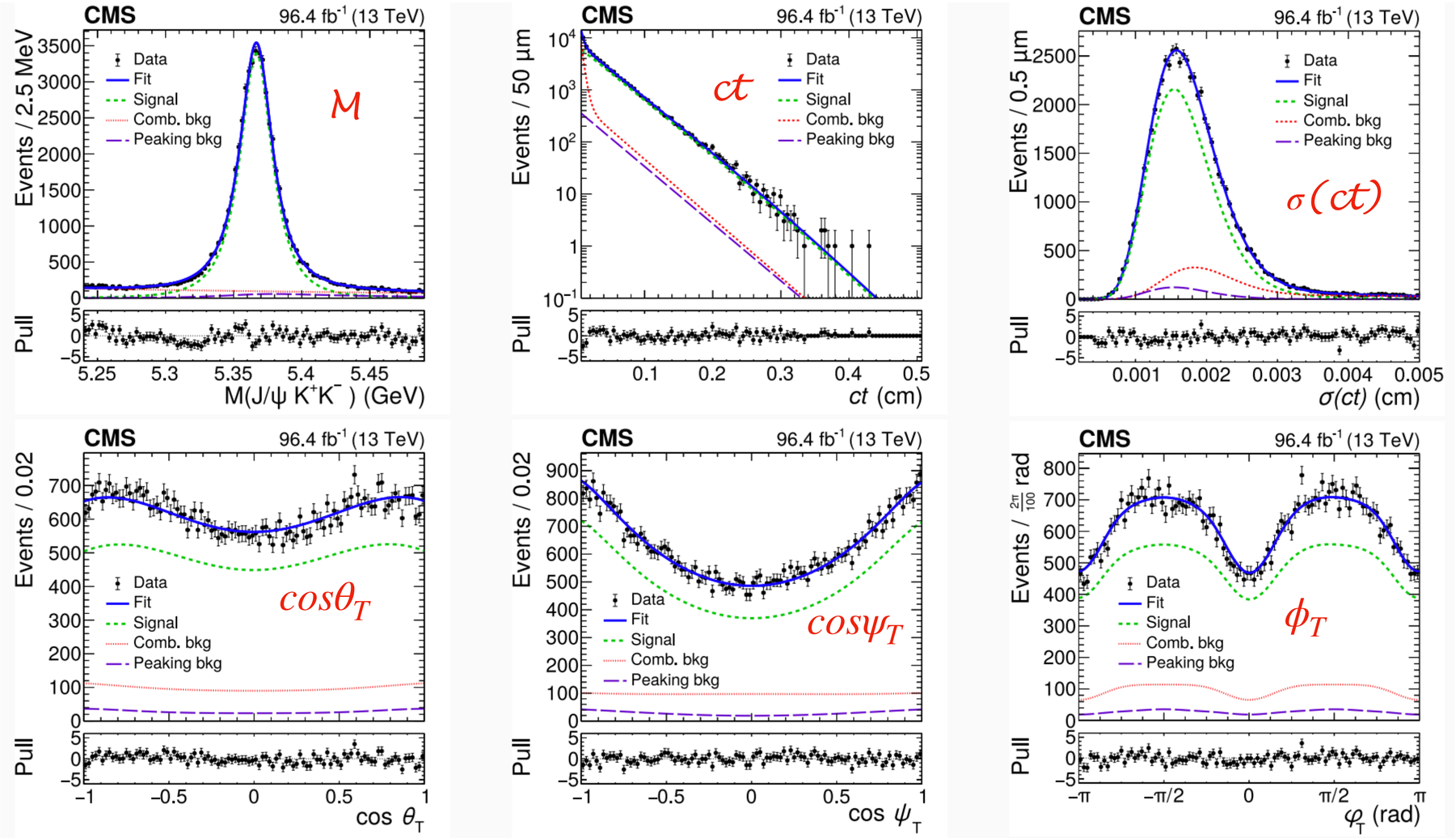




Fit Projections (CMS)

[Phys. Lett. B 816 (2021) 136188]

- Multi-dimensional fit



Results (CMS)

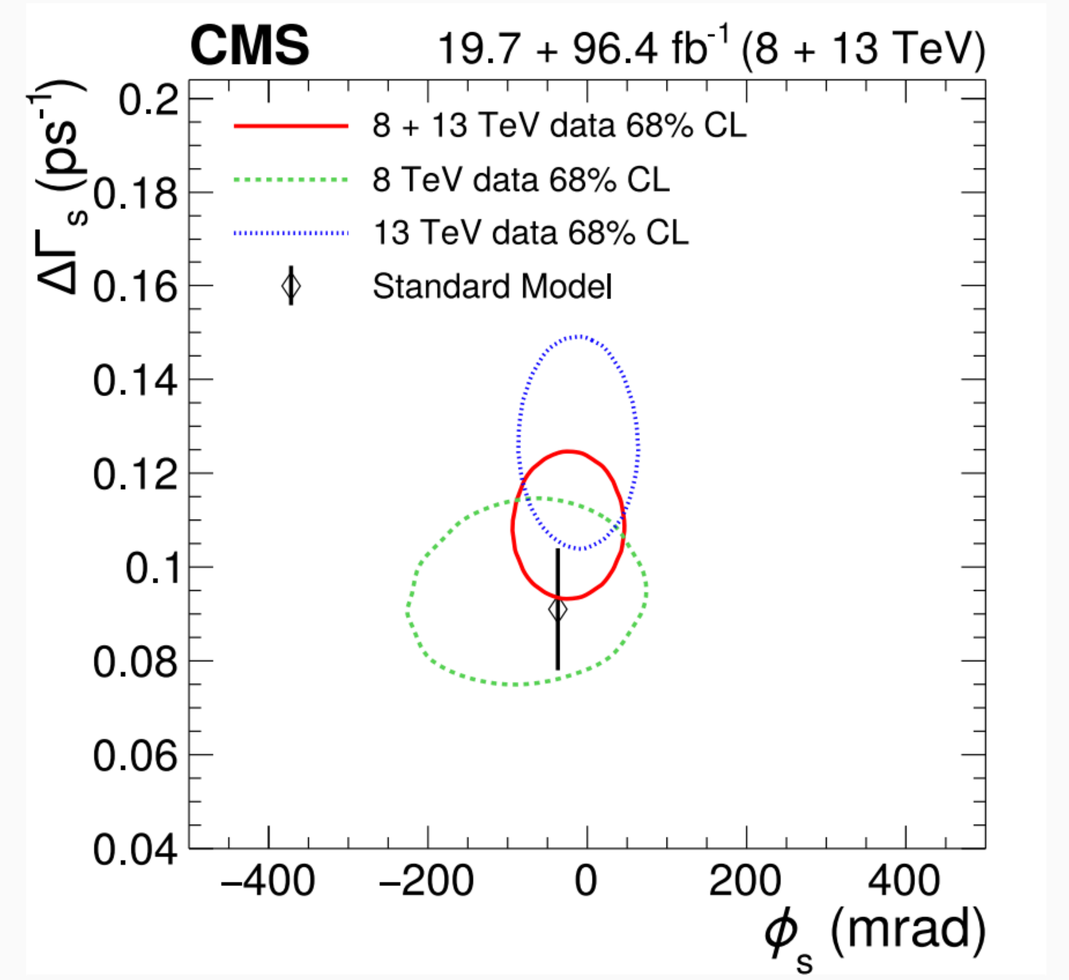
[Phys. Lett. B 816 (2021) 136188]

- Run 2 only (96.4 fb^{-1})
- $\phi_s = -11 \pm 50$ (stat) $\pm$ 10 (syst) mrad
- $\Delta\Gamma_s = 0.114 \pm 0.014$ (stat) $\pm$ 0.007 (syst) ps^{-1}

- Run 1 + Run 2 (116.1 fb^{-1})
- $\phi_s = -21 \pm 44$ (stat) $\pm$ 10 (syst) mrad
- $\Delta\Gamma_s = 0.1032 \pm 0.0095$ (stat) $\pm$ 0.0048 (syst) ps^{-1}
- Greatly improved ϕ_s due to statistics and the new tagging strategy in Run 2.

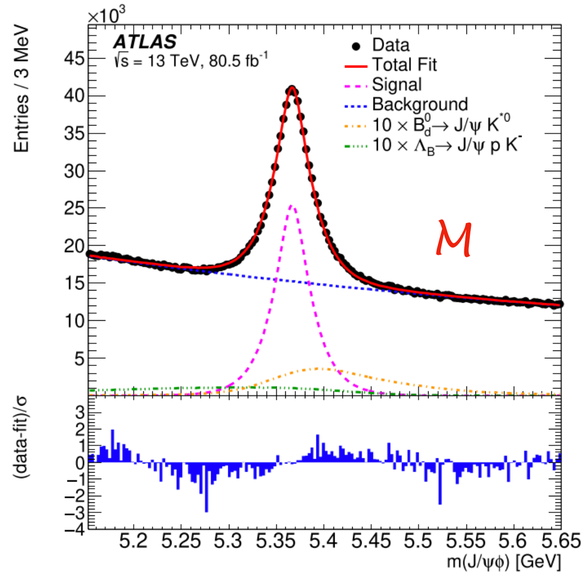
- Results are consistent with SM predictions.
- The first measurement by CMS of Δm_s and $|\lambda|$

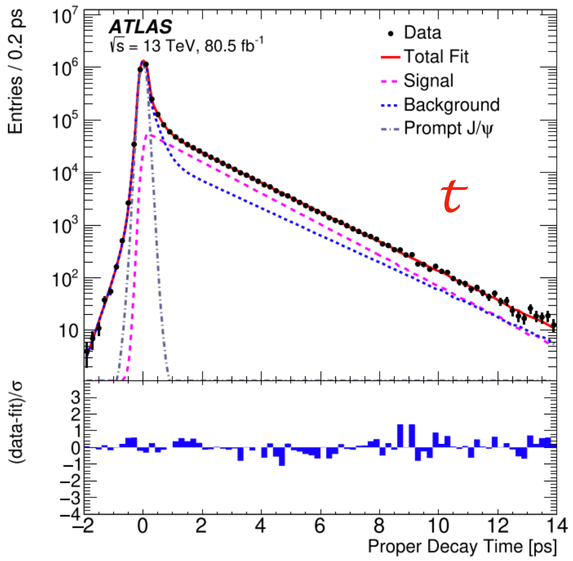
Combination of 8 TeV and 13 TeV

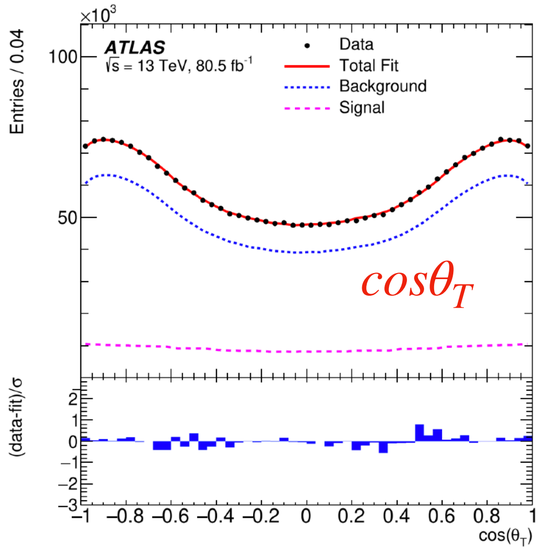


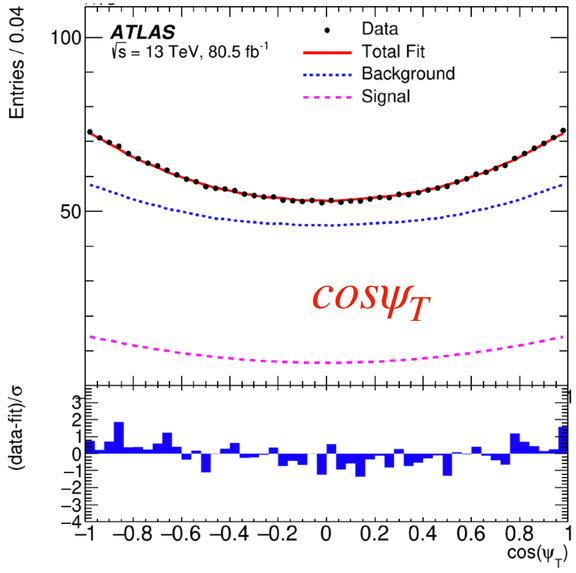
Fit Projections (ATLAS)

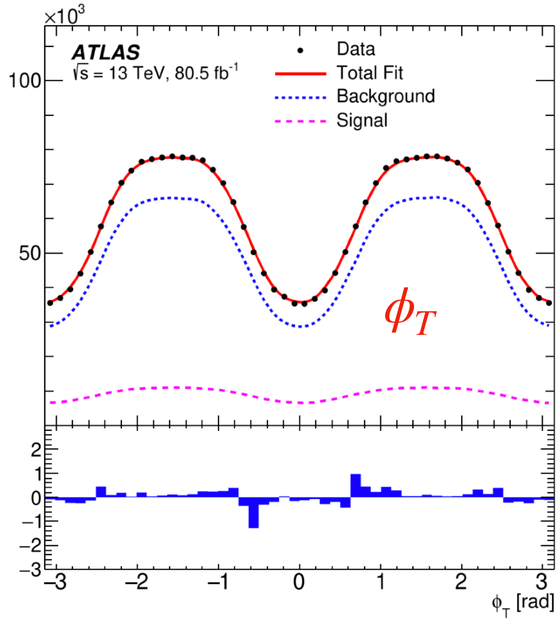
[Eur. Phys. J. C 81 (2021) 342]











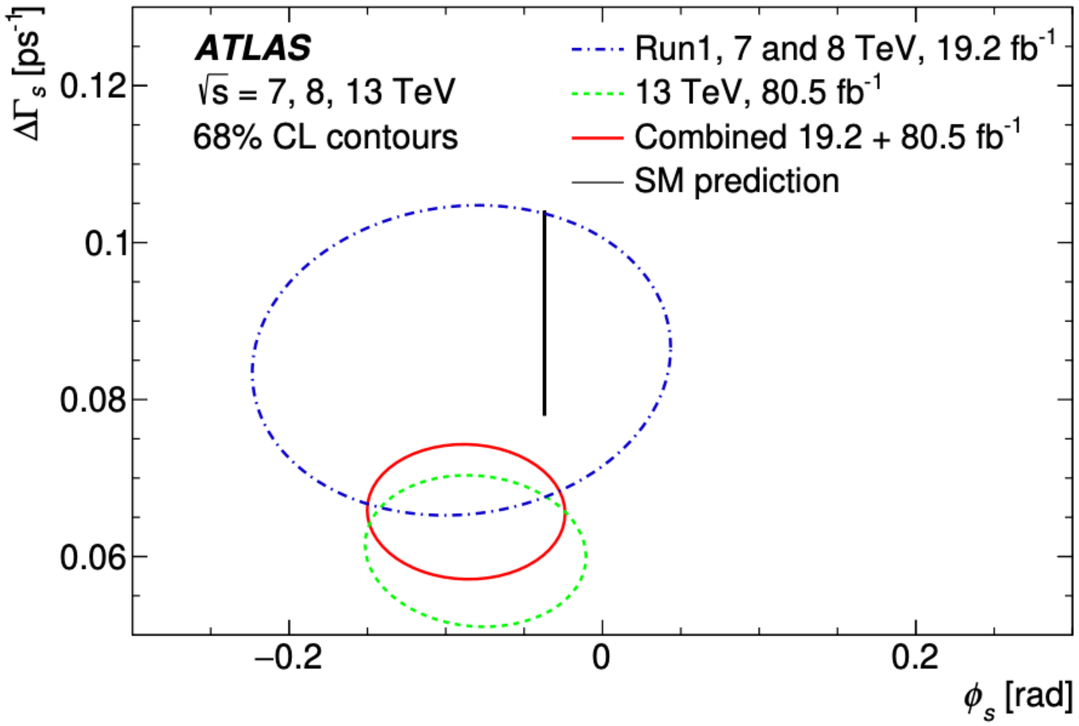
Results (ATLAS)

[Eur. Phys. J. C 81 (2021) 342]

- Run 2 only (80.5 fb^{-1})
- $\phi_s = -0.081 \pm 0.041$ (stat) $\pm$ 0.022 (syst) rad
- $\Delta\Gamma_s = 0.0607 \pm 0.047$ (stat) $\pm$ 0.0043 (syst) ps^{-1}

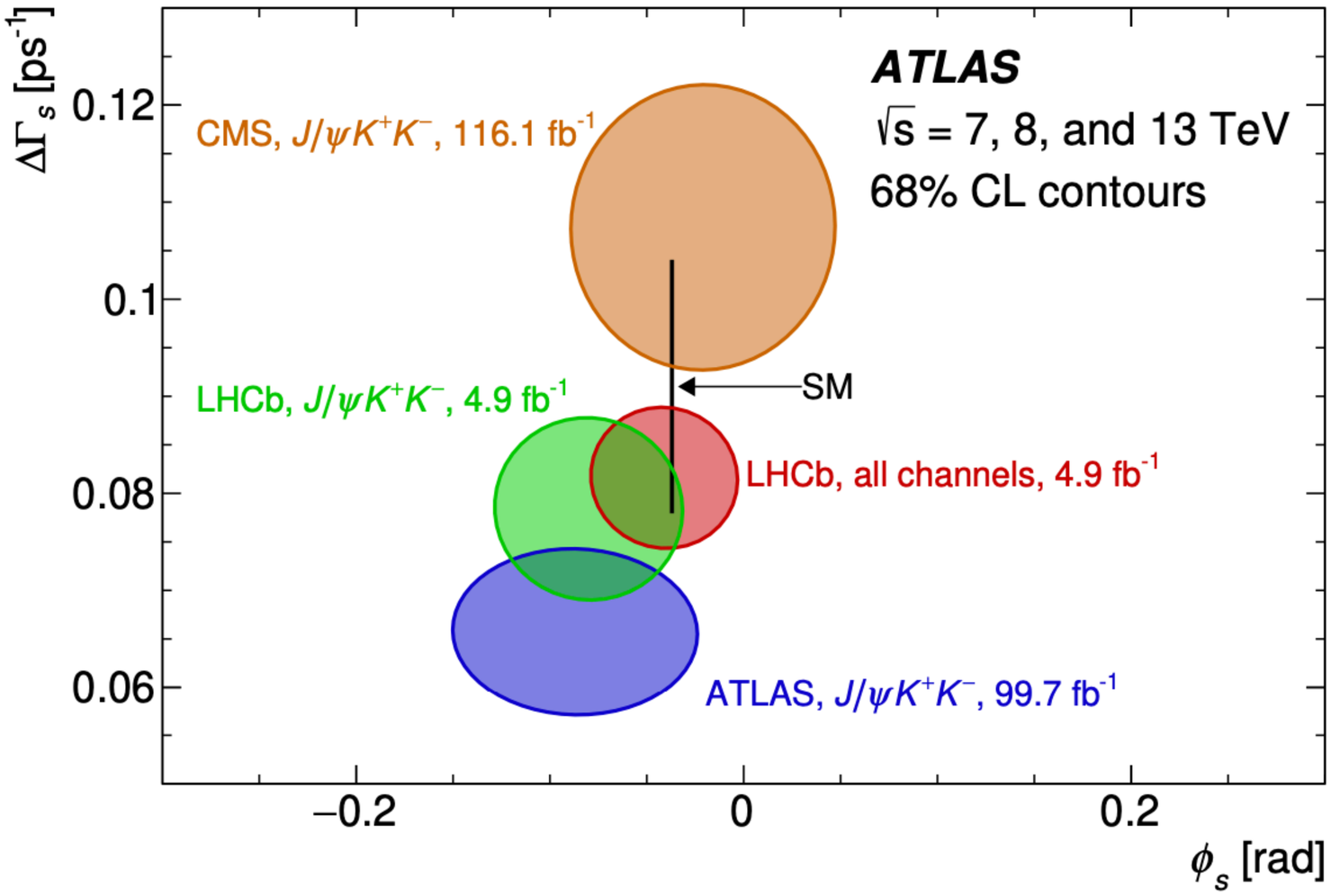
- Run 1 + Run 2 (99.7 fb^{-1})
- $\phi_s = -0.087 \pm 0.036$ (stat) $\pm$ 0.021 (syst) mrad
- $\Delta\Gamma_s = 0.0657 \pm 0.0043$ (stat) $\pm$ 0.0037 (syst) ps^{-1}

Combination of 7, 8 TeV and 13 TeV



Overview of the results

[Eur. Phys. J. C 81 (2021) 342]



Direct CP violation 3-body B+ decays

[LHCb-PAPER-2021-049]

- The raw asymmetry is obtained from simultaneous UML fit to $B^{\pm}$ invariant mass distributions.

- The acceptance-corrected raw asymmetry is defined:

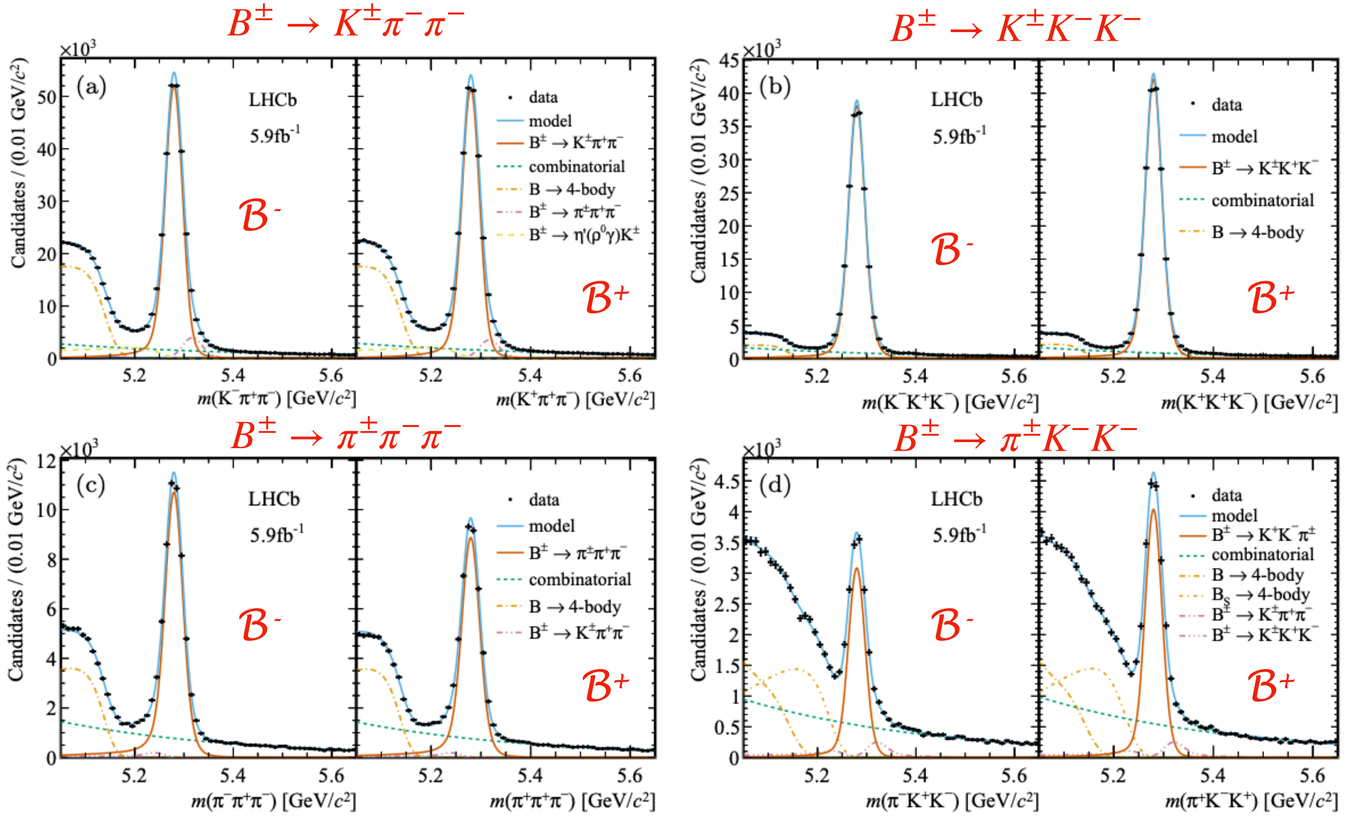
$$A_{\rm raw}^{\rm acc} \equiv \frac{N_{B^-}^{\rm acc} - N_{B^+}^{\rm acc}}{N_{B^-}^{\rm acc} + N_{B^+}^{\rm acc}} = \frac{(N_{B^-}/R) - N_{B^+}}{(N_{B^-}/R) + N_{B^+}}, \quad R = \frac{\varepsilon^{det}(B^-)}{\varepsilon^{det}(B^+)}$$

(physical) CP asymmetry →

$$A_{CP} = \frac{A_{raw}^{acc} - A_P}{1 - A_{raw}^{acc} A_P}$$

- AP is the production asymmetry and obtained from $B^{\pm} \to J/\psi K^{\pm}$ as a control channel.

$$A_P = A_{raw}^{acc}(B^{\pm} \to J/\psi K^{\pm}) - A_{CP}(B^{\pm} \to J/\psi K^{\pm})$$

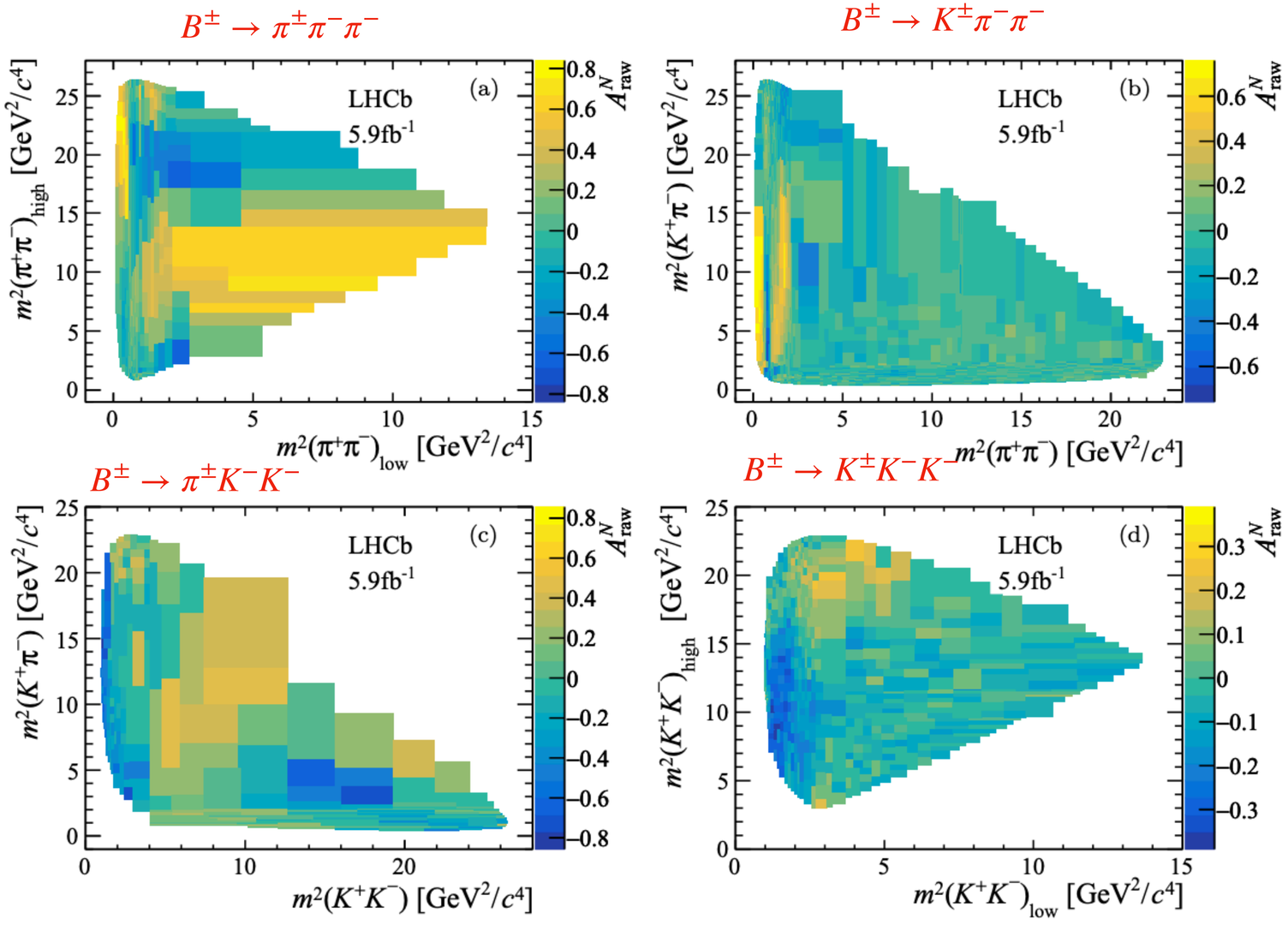


$$A_{CP}(B^{\pm} \to K^{\pm}\pi^+\pi^-) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003,$$
$$A_{CP}(B^{\pm} \to K^{\pm}K^+K^-) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003,$$
$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^+\pi^-) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003,$$
$$A_{CP}(B^{\pm} \to \pi^{\pm}K^+K^-) = -0.114 \pm 0.007 \pm 0.003 \pm 0.003,$$

Direct CP violation 3-body B+ decays

[LHCb-PAPER-2021-049]

- A_{CP} in bins of the Dalitz plots.
- Adaptive binning to have similar number of events in each bin.
- A rich pattern of large and localised asymmetries observed in $\pi\pi \to KK$ scattering region ($1\ \mathrm{GeV}^2/c^4 < m^2 < 2.25\ \mathrm{GeV}^2/c^4$)



Direct CP violation in charged B → PV decays

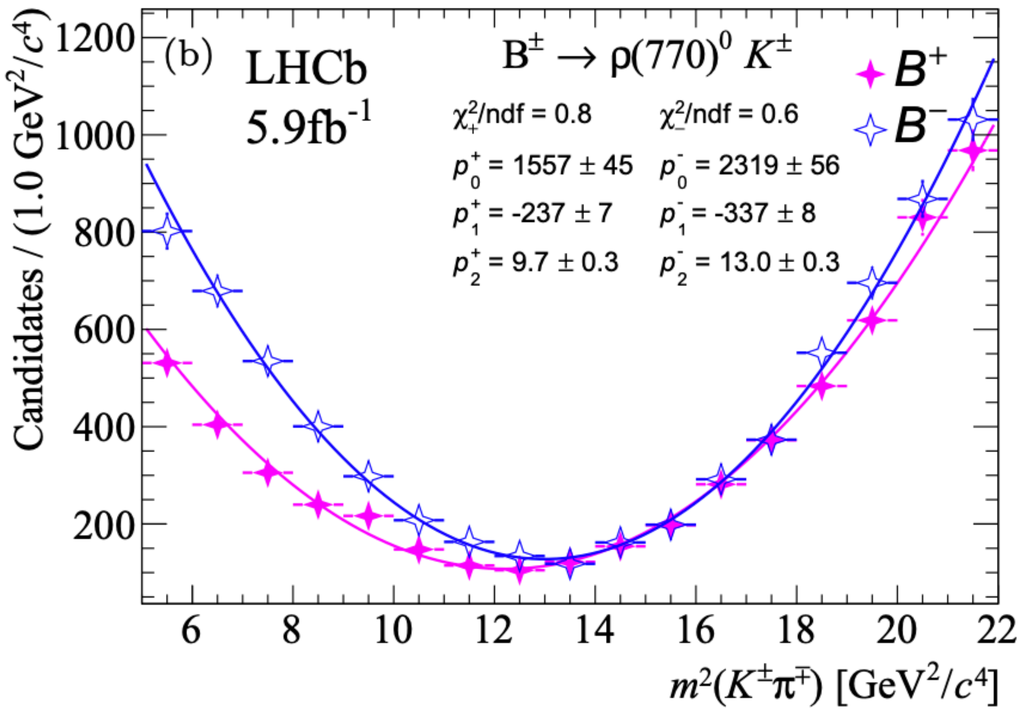
[LHCb-PAPER-2021-050]

- The B —> PV quasi-two-body decays of $B \to R(\to h_1^- h_2^+)h_3^+$ where R is the resonance
  - $s_{\parallel} = m^2(h_1^- h_2^+)$ vs $s_{\perp} = m^2(h_1^- h_3^+)$
- For the low mass and narrow resonances :

$$|M_{\pm}|^2 = p_0^{\pm} + p_1^{\pm} cos\theta(m_V, s_{\perp}) + p_2^{\pm} cos^2\theta(m_V, s_{\perp})$$

($p_{0,1,2}^{\pm}$ polynomial coefficients, θ helicity angle)

- CP asymmetry given in the B → PV decay is a function of $p_2^{\pm}$:
  - $A_{CP}^V = \dfrac{p_2^- - p_2^+}{p_2^- + p_2^+}$

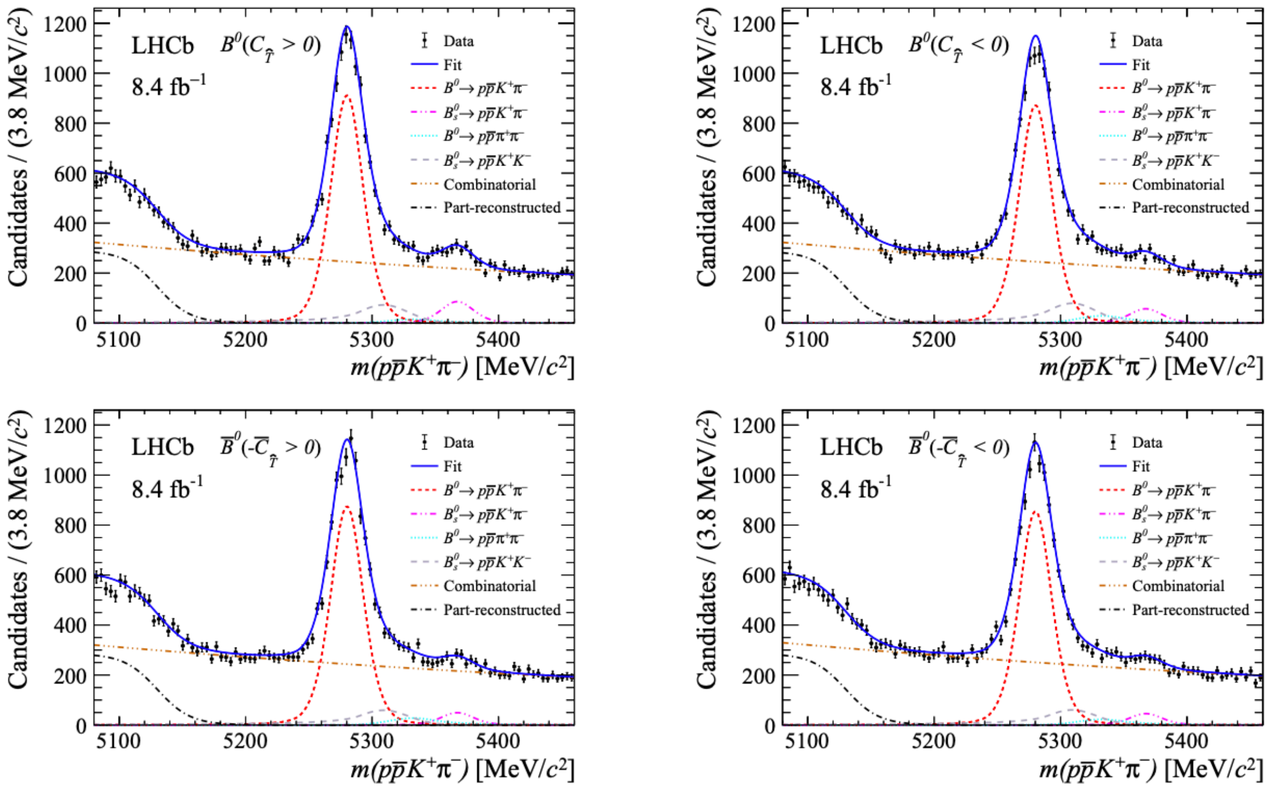


A large CP asymmetry is found in $B^{\pm} \to \rho(770)^0(\to \pi^+\pi^-)K^{\pm}$ decays
A_{CP} = = +0.150 ± 0.019 ± 0.011

CPV in $B^0 \to p\bar{p}K^+\pi^-$ decays

[LHCb-PAPER-2022-003]

- CPV in triple product asymmetries
  - in the region of $M(p\bar{p}) < 2.85$ GeV/c2 (Charmonium resonances excluded)
- The triple products are defined:
  - $C_{\hat{T}} = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^-} \times \vec{p}_p)$ and $\bar{C}_{\hat{T}} = \vec{p}_{K^-} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\bar{p}})$
- Under the CP transformation:
  - $$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$
    $$\bar{A}_{\hat{T}} = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$$
- CP-violating observables are :
  - $$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}}) \quad a_P^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$$



$$a_P^{\hat{T}\text{-odd}} = (1.49 \pm 0.85 \pm 0.08)\%,$$

$$a_{CP}^{\hat{T}\text{-odd}} = (0.51 \pm 0.85 \pm 0.08)\%,$$

Significant P-asymmetries found in the low M($p\bar{p}$) (5.8σ), no CP violation observed!

CPV and mixing in charm decays

Charm Mixing

- Neutral charm meson oscillates through its antiparticle known as $D^0 - \bar{D}^0$ mixing.

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

- Oscillations can be defined by two dimensionless parameters:

$$x \equiv \frac{(m_1 - m_2)}{\Gamma} \qquad y \equiv \frac{(\Gamma_1 - \Gamma_2)}{2\Gamma} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

ave. decay width

- Final state particles $D^0 \to f$ is measured via effective decay widths:

$$y^f_{CP} = \frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{2\Gamma} - 1\,. \qquad y^f_{CP} \approx y$$

in absence of CP violation

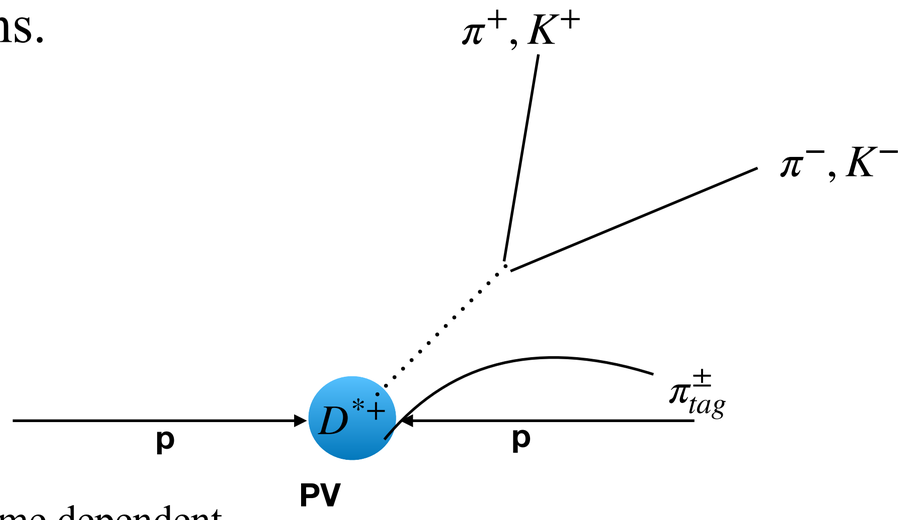
$y_{CP} - y_{CP}^{K\pi}$ in 2-body D^0 decays

[arXiv:2202.09106]

- Uses $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^+\pi^-$ as a proxy in decay widths.

$$\frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{\hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\bar{D}^0 \to K^+\pi^-)} - 1 \approx y_{CP}^{f} - y_{CP}^{K\pi} .$$

- Run2 : (6 fb^{-1})
- D^0 candidates selected from $D^{*+} \to D^0\pi^+_{tag}$



$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-(y_{CP}^{f} - y_{CP}^{K\pi})\, t/\tau_{D^0}} \frac{\varepsilon(f,t)}{\varepsilon(K^-\pi^+, t)}$$

time dependent efficiencies : $\varepsilon(f,t) = \varepsilon_{sel} \times \varepsilon_{det}$

$y_{CP} - y_{CP}^{K\pi}$ in 2-body D^0 decays

[arXiv:2202.09106]

- Uses $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^+\pi^-$ as a proxy in decay widths.

$$\frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{\hat{\Gamma}(D^0 \to K^-\pi^+) + \hat{\Gamma}(\bar{D}^0 \to K^+\pi^-)} - 1 \approx y_{CP}^{f} - y_{CP}^{K\pi} .$$

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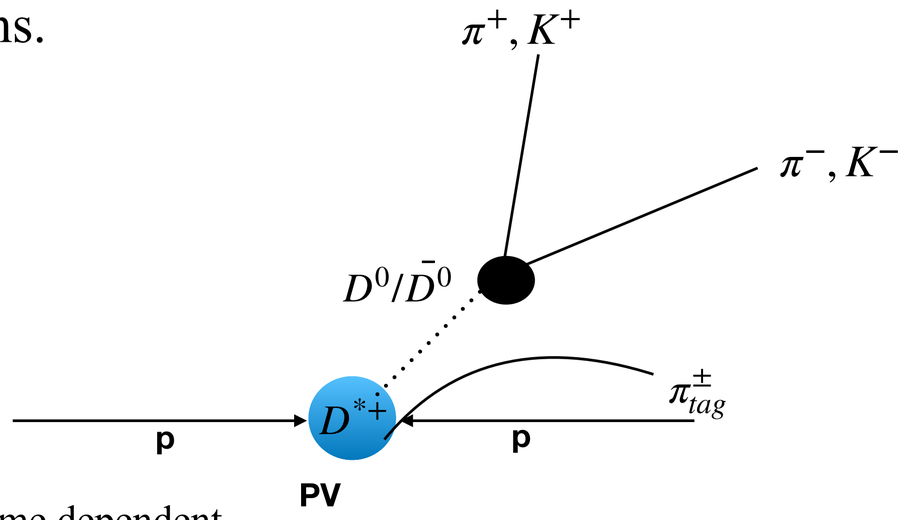

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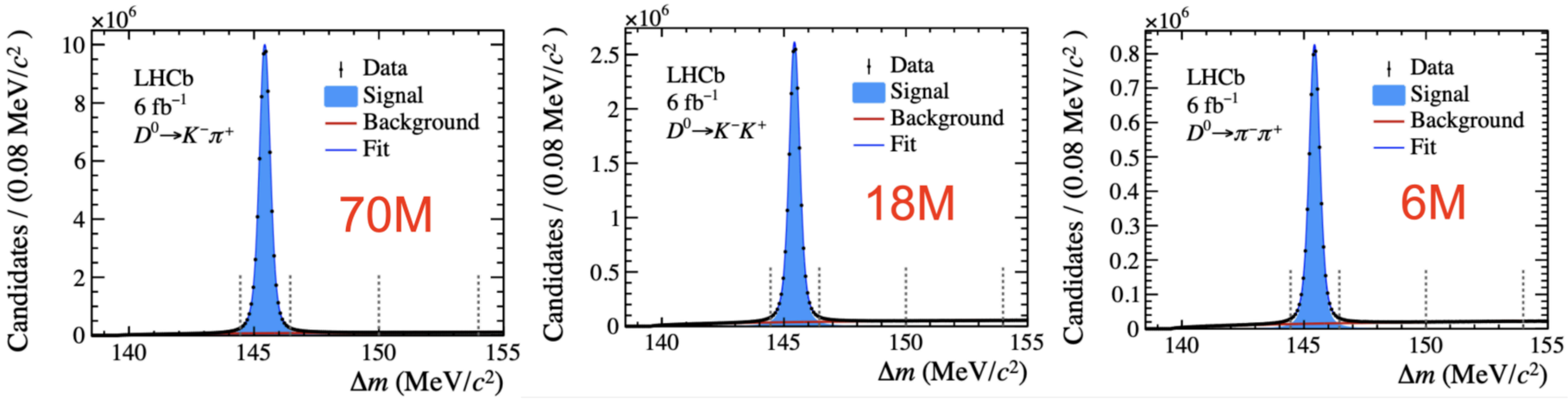
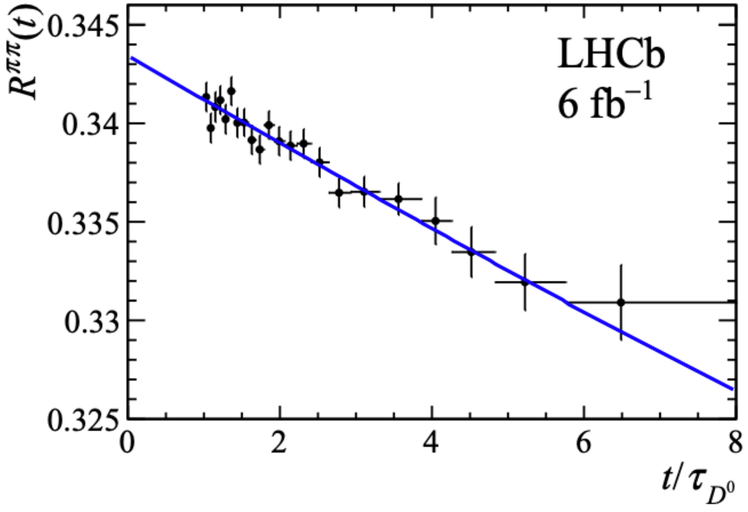
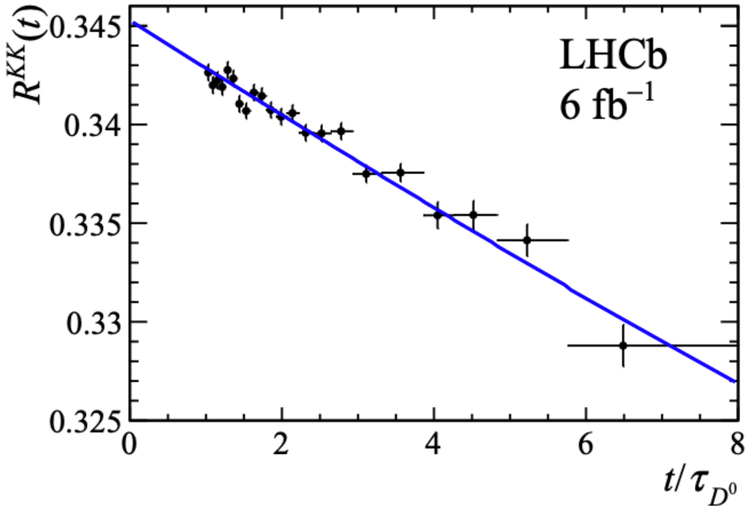


Fit to $\Delta M = m(h^-h^+\pi^+_{tag}) - m(h^-h^+)$

Results

[arXiv:2202.09106]





$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$

$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$

Assuming that all systematic uncertainties are fully correlated, the combination of the results:

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

- 4 times more precise than World Average !

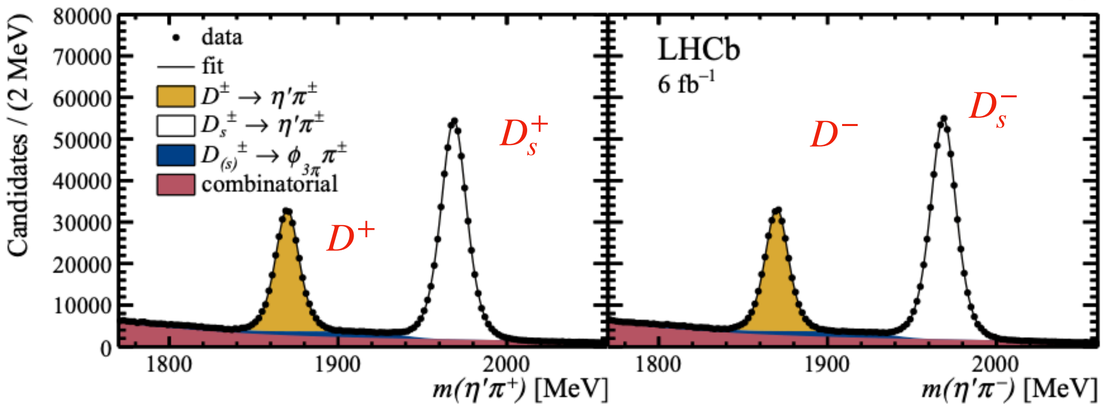
CP asymmetry in $D^+_{(s)} \to \eta^{(\prime)}\pi^+$ decays

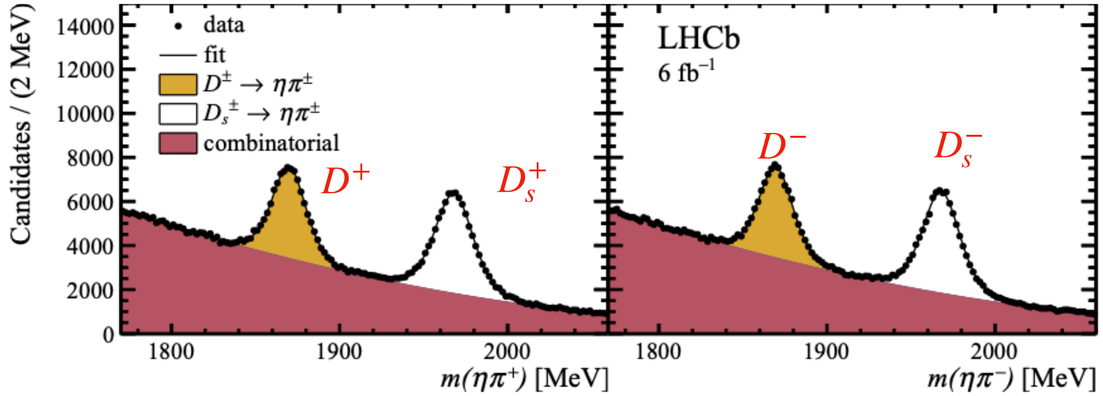
[arXiv:2204.12228]

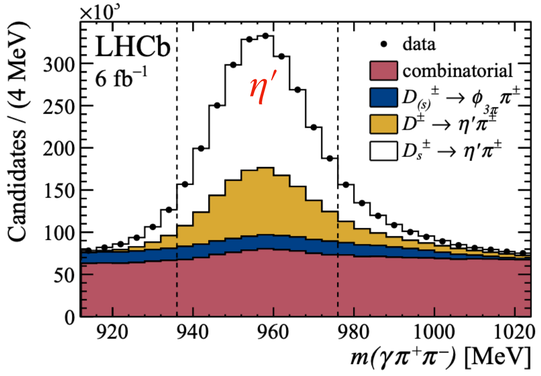
- CP asymmetry obtained from simultaneous, binned, extended ML fit to $m(\eta^{(\prime)}\pi^+)$, in bins of $m(\gamma\pi^+\pi^-)$
- Detection and production asymmetries subtracted using control channel : $D^+_{(s)} \to \phi\pi^+$
- Run2: 5.6 fb^{-1}

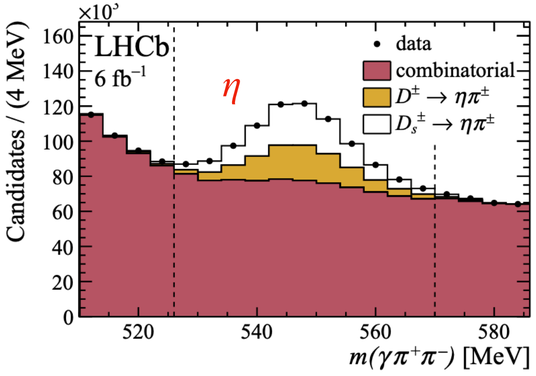
$$\mathcal{A}^{CP}(D^+ \to \eta\pi^+) = (0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta\pi^+) = (0.32 \pm 0.51 \pm 0.12)\%,$$
$$\mathcal{A}^{CP}(D^+ \to \eta'\pi^+) = (0.49 \pm 0.18 \pm 0.06 \pm 0.05)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta'\pi^+) = (0.01 \pm 0.12 \pm 0.08)\%,$$

- most precise measurements up to date!
- No CP violation effect is observed!









Summary

- LHC delivers many interesting results on the CPV in B and charm decays!
- With the new data that will be collected from this year, many more is on the way with more precision!
- Stay tuned!

BACKUP

CMS Run 2 results

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0026
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0049
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0045
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.05
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048

ATLAS Run 2 results

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_{\parallel}(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0046
$\delta_\perp - \delta_S$ [rad]	−0.25	0.05	0.04
Solution (a)			
$\delta_\perp$ [rad]	3.12	0.11	0.06
$\delta_\parallel$ [rad]	3.35	0.05	0.09
Solution (b)			
$\delta_\perp$ [rad]	2.91	0.11	0.06
$\delta_\parallel$ [rad]	2.94	0.05	0.09

CP asymmetry in $D^+_{(s)} \to \eta^{(\prime)}\pi^+$ decays

CP asymmetry is defined as:

experimentally

$$\mathcal{A}^{CP}(D^+_{(s)} \to f^+) \equiv \frac{\Gamma(D^+_{(s)} \to f^+) - \Gamma(D^-_{(s)} \to f^-)}{\Gamma(D^+_{(s)} \to f^+) + \Gamma(D^-_{(s)} \to f^-)}, \qquad \mathcal{A}^{\rm raw}(D^+_{(s)} \to f^+) \equiv \frac{N(D^+_{(s)} \to f^+) - N(D^-_{(s)} \to f^-)}{N(D^+_{(s)} \to f^+) + N(D^-_{(s)} \to f^-)}.$$

approximately

$$\mathcal{A}^{\rm raw}(D^+_{(s)} \to f^+) \approx \mathcal{A}^{CP}(D^+_{(s)} \to f^+) + \mathcal{A}^{\rm prod}(D^+_{(s)}) + \mathcal{A}^{\rm det}(f^+),$$

production asym detection asym

$$A^{det} = \frac{\varepsilon(f^+) - \varepsilon(f^-)}{\varepsilon(f^+) + \varepsilon(f^-)}$$

Same A^{prod} and A^{det} with control samples $D^+_s \to \phi\pi^+$ and $D^+ \to \phi\pi^+$

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$$\mathcal{A}^{\rm raw}(D^+ \to \eta^{(\prime)}\pi^+) - \mathcal{A}^{\rm raw}(D^+ \to \phi\pi^+) = \mathcal{A}^{CP}(D^+ \to \eta^{(\prime)}\pi^+) - \mathcal{A}^{CP}(D^+ \to \phi\pi^+),$$

external input as = (0.005 ± 0.051)%

$$\mathcal{A}^{\rm raw}(D^+_s \to \eta^{(\prime)}\pi^+) - \mathcal{A}^{\rm raw}(D^+_s \to \phi\pi^+) = \mathcal{A}^{CP}(D^+_s \to \eta^{(\prime)}\pi^+).$$

Simultaneous determination of γ angle

- Results from the charm and beauty sectors are combined
- Many inputs from LHCb charm analyses are included in the combination for the first time!
- Additional external constraints used on the hadronic parameters and coherence factors in B and D decays.
- Frequentist approach with 151 observables to determine 52 parameters

B decay	D decay	Ref.	Dataset	Status since Ref. [17]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[21]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[22]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[23]	Run 1&2	**Updated**
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[24]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[24]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[25]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[26]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[26]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[27]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[28]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[29]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[30]	Run 1&2	**New**
D decay	Observable(s)	Ref.	Dataset	Status since Ref. [17]
$D^0 \to h^+h^-$	ΔA_{CP}	[31–33]	Run 1&2	**New**
$D^0 \to h^+h^-$	y_{CP}	[34]	Run 1	**New**
$D^0 \to h^+h^-$	ΔY	[35–38]	Run 1&2	**New**
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[39]	Run 1	**New**
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[40]	Run 1&2(*)	**New**
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[41]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[42]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[43]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[44]	Run 2	**New**

Fit Model (CMS)

Event pdf: $P = N_{sig}P_{sig} + N_{bkg}P_{bkg} + N_{peak}P_{peak}$

$$P_{sig} = \epsilon(ct)\,\epsilon(\Theta)\,[\mathcal{F}(\Theta, ct, \alpha) \otimes G(ct, \sigma_{ct})]\,P_{sig}(m_{B_s^0})P_{sig}(\sigma_{ct})\,P_{sig}(\xi)$$

- $\epsilon(ct)\,\epsilon(\Theta)$: efficiency functions
- $\mathcal{F}(\Theta, ct, \alpha)$: differential decay rate
- $G(ct, \sigma_{ct})$: gaussian resolution model
- $P_{sig}(m_{B_s^0})$: signal mass pdf
- $P_{sig}(\sigma_{ct})$: signal σ_{ct} pdf
- $P_{sig}(\xi)$: tag distribution