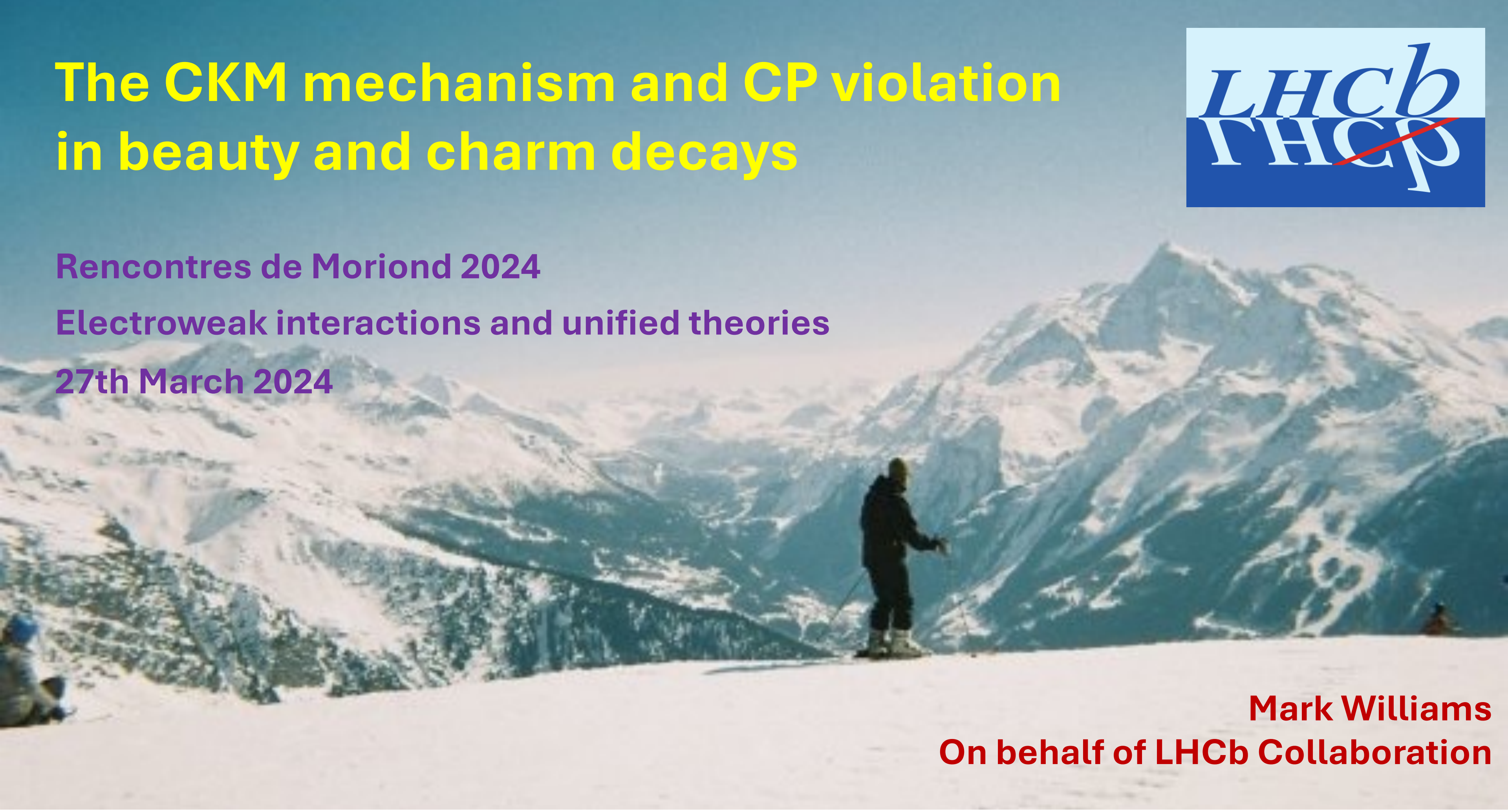
The CKM mechanism and CP violation in beauty and charm decays

Rencontres de Moriond 2024

Electroweak interactions and unified theories

27th March 2024



Mark Williams

On behalf of LHCb Collaboration

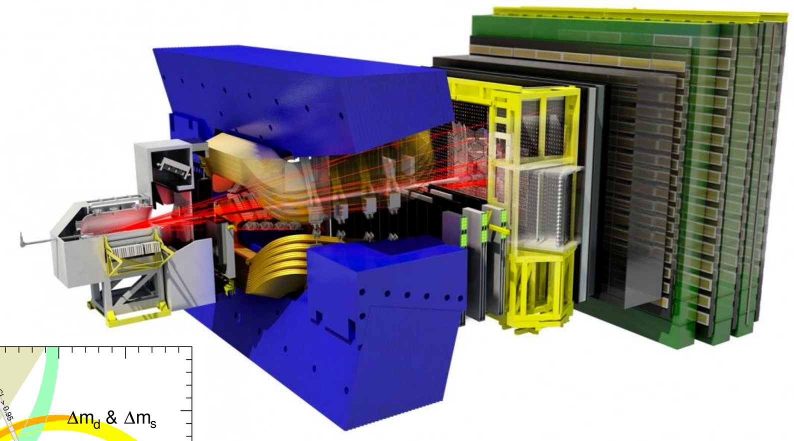
THE ROYAL SOCIETY

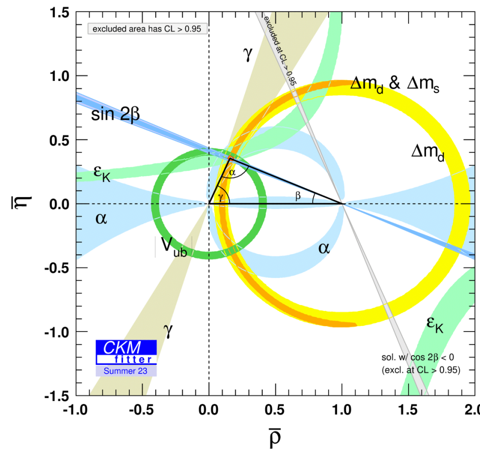
THE UNIVERSITY of EDINBURGH

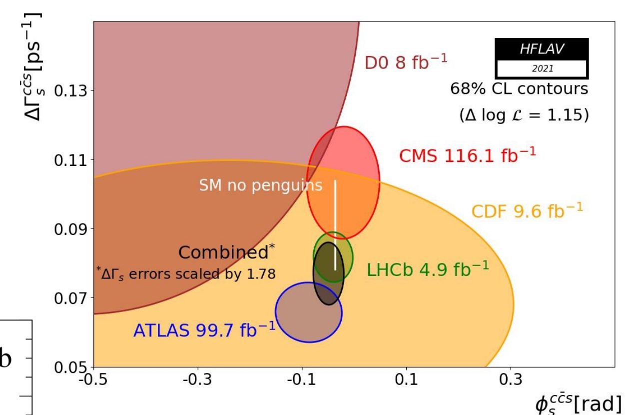
EDINBURGH PARTICLE PHYSICS EXPERIMENTS

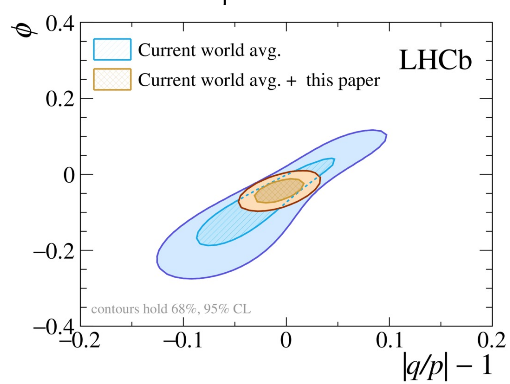
Introduction & Outline

- LHCb original detector now retired
  ⇒ huge success
  ⇒ unprecedented b and c sample
- Still many key measurements coming out
- Run 3 analyses ongoing
- Today focus on Run 1+2:
  - ➢ CKM angle γ
  - ➢ CPV in $B^0_{(s)}$ systems (time-dependent, time-integrated)
  - ➢ CPV in charm mesons









- Study of CP violation in $B^0_{(s)} \to DK^*(892)^0$ decays with $D \to K\pi(\pi\pi)$, $\pi\pi(\pi\pi)$, and KK final states (arXiv:2401.17934, submitted to JHEP - Fresh)
- A model-independent measurement of the CKM angle γ in partially reconstructed $B^\pm \to D^* h^\pm$ decays with $D \to K^0_S h^+ h^-$ ($h=\pi,K$)
  (arXiv: 2311.10434, JHEP 02 (2024) 118)
- Measurement of the CKM angle γ using the $B^\pm \to D^* h^\pm$ channels
  (arXiv: 2310.04277, JHEP 12 (2023) 013)
- Measurement of the CKM angle γ in the $B^0 \to DK^{*0}$ channel using self-conjugate $D \to K^0_S h^+ h^-$ decays (arXiv:2309.05514, Eur. Phys. J. C 84 (2024) 206)

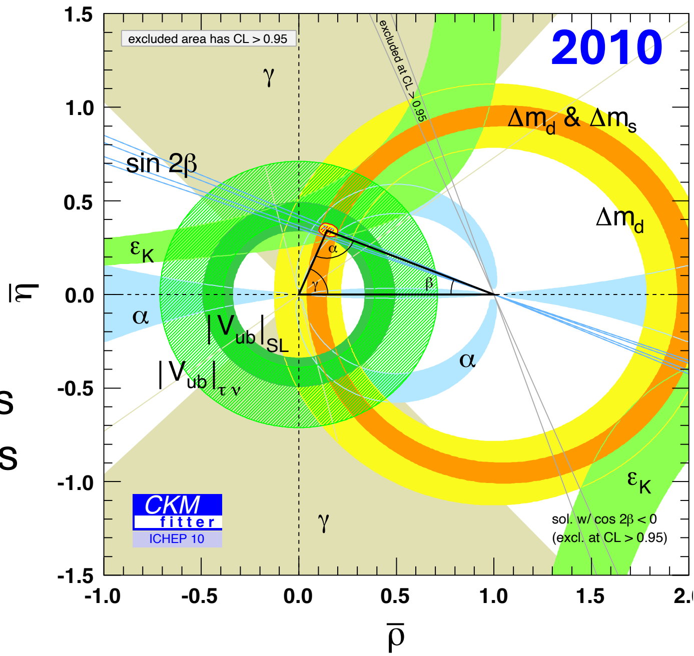
Part 1: CKM angle γ

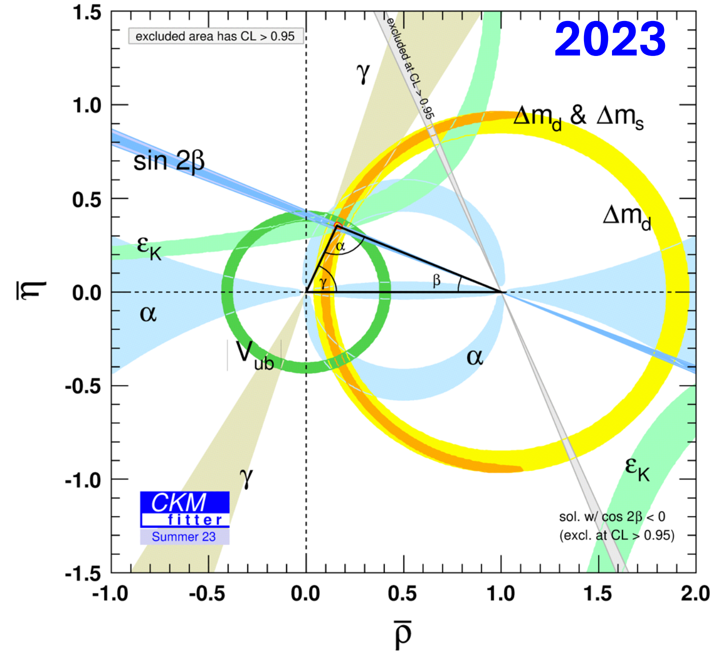
CKM angle γ

Already a major success of LHCb

Wide programme:

- B^0, B^0_s, B^+
- Different B decays
- Different D decays





$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

No top quarks – can measure at tree-level via interference of $b\to\bar{c}us$ ($\bar{u}cs$) decays

Measure in tree-level processes

γ = (66.2 ± 3.5)° ⇒ precise SM benchmark
(HFLAV)

Compare to indirect constraints (unitarity)

γ = (65.5 ± 1.3)° ⇒ sensitive to NP
(CKMFitter)

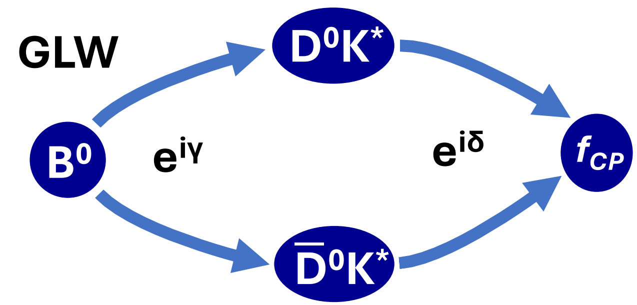
CPV in $B^0_{(s)} \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

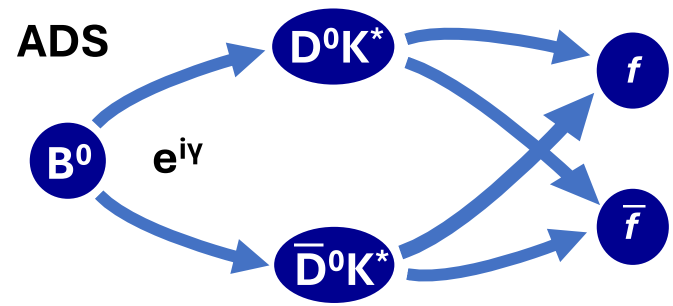
arXiv:2401.17934
(Submitted to JHEP)

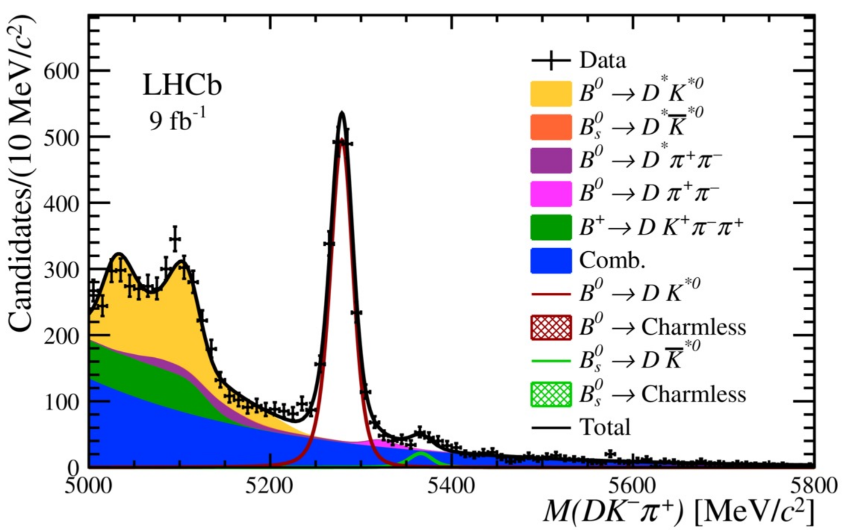
Use D decays to CP-eigenstate ($\pi^+\pi^-$, K^+K^-, $4\pi^\pm$) and via CF/DCS paths ($K^\mp\pi^\pm$, $K^-\pi^+\pi^+\pi^-$)

Interference ⇒ CP asymmetries ⇒ sensitive to γ

Full Run 1+2 sample ($9fb^{-1}$)







Example fit for $\bar{B}^0 \to \bar{K}^*(D \to K^-3\pi)$ channel
*⇒ 7 channels x 2 B flavours = **14 samples** fitted*

CPV in $B^0_{(s)} \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

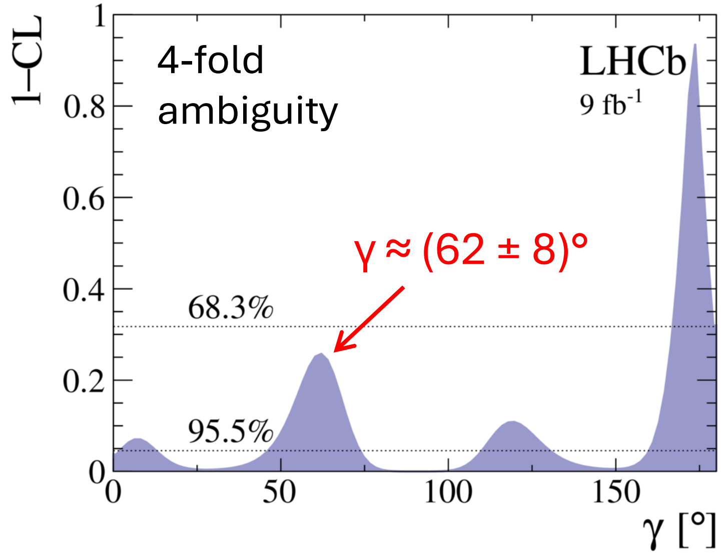
arXiv:2401.17934
(Submitted to JHEP)

Parameter	Value
$\mathcal{A}_{K\pi}$	$0.031 \pm 0.017 \pm 0.015$
$\mathcal{R}^+_{\pi K}$	$0.069 \pm 0.013 \pm 0.005$
$\mathcal{R}^-_{\pi K}$	$0.093 \pm 0.013 \pm 0.005$
$\mathcal{A}_{K\pi\pi\pi}$	$-0.012 \pm 0.018 \pm 0.016$
$\mathcal{R}^+_{\pi K\pi\pi}$	$0.060 \pm 0.014 \pm 0.006$
$\mathcal{R}^-_{\pi K\pi\pi}$	$0.038 \pm 0.014 \pm 0.006$
$\mathcal{R}^{KK}_{CP}$	$0.811 \pm 0.057 \pm 0.017$
$\mathcal{A}^{KK}_{CP}$	$-0.047 \pm 0.063 \pm 0.015$
$\mathcal{R}^{\pi\pi}_{CP}$	$1.104 \pm 0.111 \pm 0.026$
$\mathcal{A}^{\pi\pi}_{CP}$	$-0.034 \pm 0.094 \pm 0.016$
$\mathcal{R}^{4\pi}_{CP}$	$0.882 \pm 0.086 \pm 0.033$
$\mathcal{A}^{4\pi}_{CP}$	$0.021 \pm 0.087 \pm 0.016$

A: asymmetries
R: ratios of rates

$\Rightarrow$

60% more precise than previous best for CPV parameters (*still stat. limited*)



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⇒

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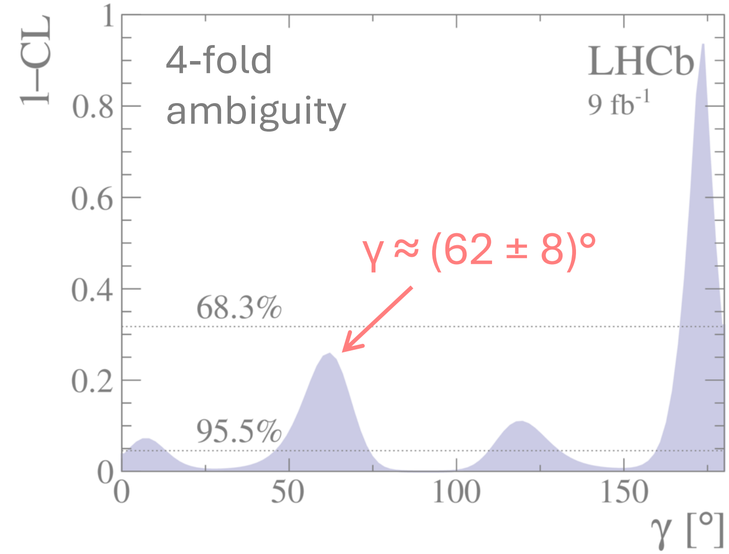
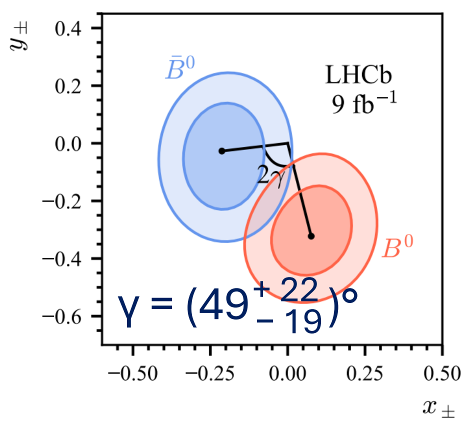
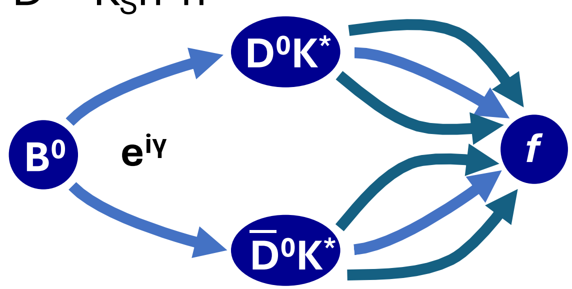
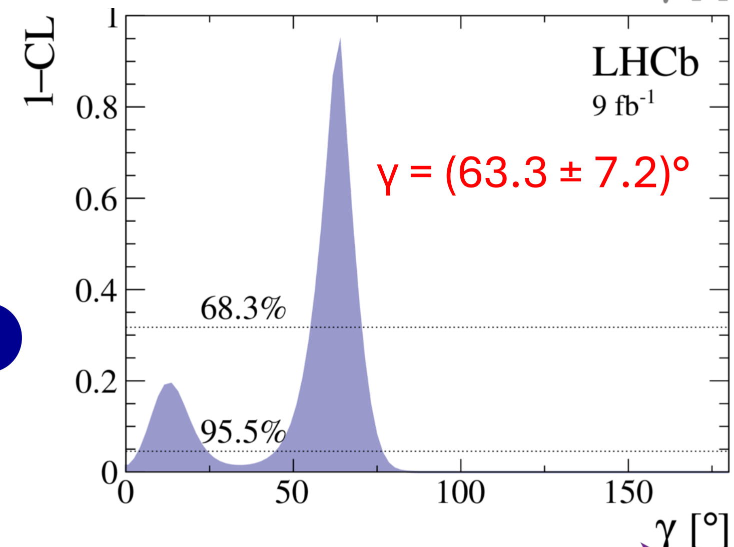


Combining with recent LHCb analysis of $B^0 \to DK^{*0}$ with $D \to K^0_S h^+h^-$ ⇒





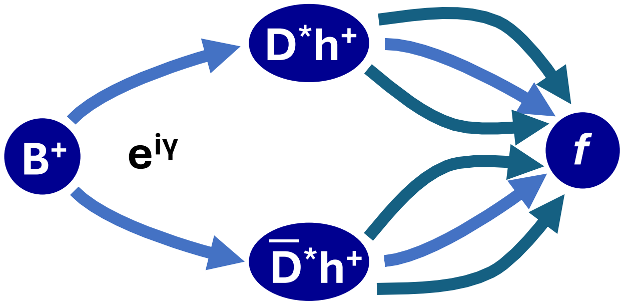
Eur.Phys.J.C 84 (2024) 2, 206 (arXiv:2309.05514)



$B^{\pm} \rightarrow D^{*} h^{\pm}$, $D \rightarrow K^0_S h^+ h^-$

Multibody final state with rich resonant structure
⇒ strong phases depend on Dalitz coordinates

Model-agnostic: use binned input from BESIII & CLEO
arXiv:2003.00091 arXiv:2007.07959 arXiv:1010.2817



Approach 1: Reconstruct $D^* \rightarrow D\pi^0$ and $D\gamma$
⇒ Better control of backgrounds

⇒ first time in LHCb & first with model-agnostic approach (Run 1+2)

JHEP 12 (2023) 013 (arXiv:2310.04277)

Approach 2: no π^0/γ reconstruction
⇒ Higher signal efficiency

⇒ update with full Run 1+2

JHEP 02 (2024) 118 (arXiv:2311.10434)

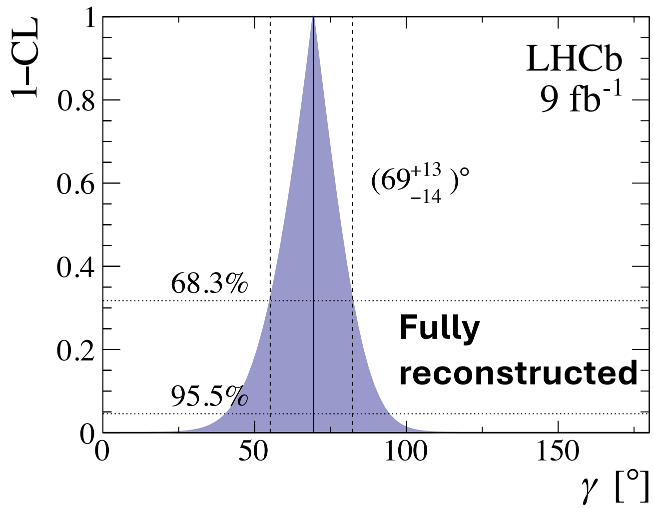
$B^\pm \to D^* h^\pm$, $D \to K^0_S h^+ h^-$

Single clear maximum

Statistically limited

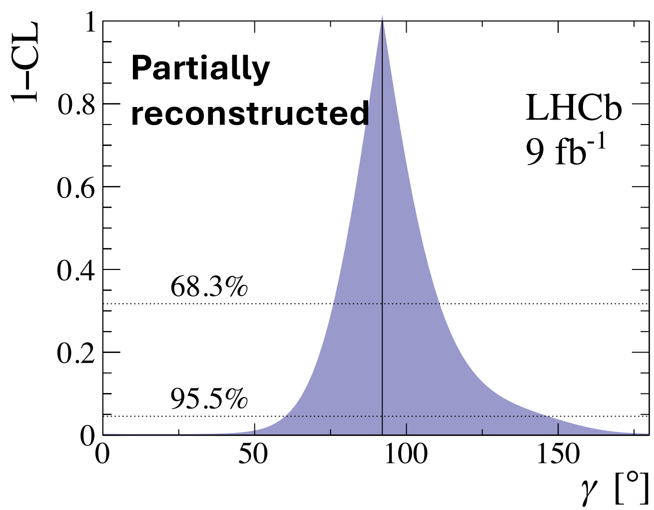
Outlook for γ

- Most benchmark channels completed with Run 1+2
- More data
  ⇒ more precision
- Investigating new channels for full exploitation in Run 3



arXiv:2310.04277 (JHEP 12 (2023) 013)

$$\begin{aligned} \gamma &= (69^{+13}_{-14})°, \\ r_B^{D^*K} &= 0.15 \pm 0.03, \\ r_B^{D^*\pi} &= 0.01 \pm 0.01, \\ \delta_B^{D^*K} &= (311 \pm 14)°, \\ \delta_B^{D^*\pi} &= (37 \pm 37)°. \end{aligned}$$



arXiv:2311.10434 (JHEP 02 (2024) 118)

$$\begin{aligned} \gamma &= (92^{+21}_{-17})°, \\ r_B^{D^*K} &= 0.080^{+0.022}_{-0.023}, \\ \delta_B^{D^*K} &= (310^{+15}_{-20})°, \\ r_B^{D^*\pi} &= 0.009^{+0.005}_{-0.007}, \\ \delta_B^{D^*\pi} &= (304^{+37}_{-38})°. \end{aligned}$$

- A measurement of $\Delta\Gamma_s$ (arXiv:2310.12649, Submitted to JHEP)
- Measurement of CP violation in $B^0 \to \psi(\to \ell^+\ell^-)K^0_S(\to \pi^+\pi^-)$ decays (arXiv:2309.09278, PRL 132 (2024) 021801)
- Improved measurement of CP violation parameters in $B^0_s \to J/\psi K^+K^-$ decays in the vicinity of the $\phi(1020)$ resonance (arXiv:2308.01468, PRL 132 (2024) 051802)
- Measurement of CP asymmetries and branching fraction ratios of B^- decays to two charm mesons (arXiv:2306.09945, JHEP 09 (2023) 202)
- Precision Measurement of CP Violation in the Penguin-Mediated Decay $B^0_s \to \phi\phi$ (arXiv:2304.06198, PRL 131 (2023) 171802)

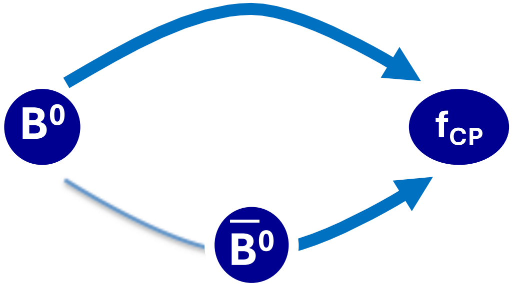
Part 2: CPV in $B^0_{(s)}$ decays

Time-dependent CPV in B^0 decays: β

PRL 132 (2024) 021801
(arXiv:2309.09728)

Full Run 2 analysis of benchmark channels: $J/\psi(\to\mu\mu,ee)K^0_S$ $\psi(2S)(\to\mu\mu)K^0_S$

~306k ~43k ~24k



$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\overline{B}^0(t)\to f) - \Gamma(B^0(t)\to f)}{\Gamma(\overline{B}^0(t)\to f) + \Gamma(B^0(t)\to f)} = \frac{S\sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

Time-dependent asymmetry

CPV parameters: C, S, $A_{\Delta\Gamma}$

$$S = \sin(2\beta + \Delta\phi_d + \Delta\phi_d{}^{\mathrm{NP}})$$

Time-dependent CPV in B^0 decays: β

PRL 132 (2024) 021801
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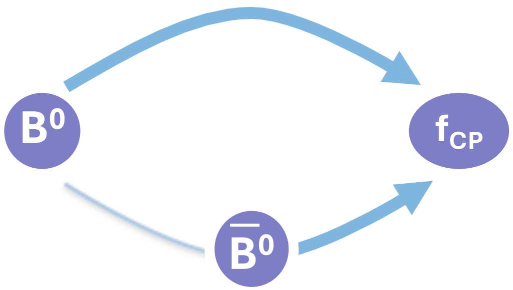

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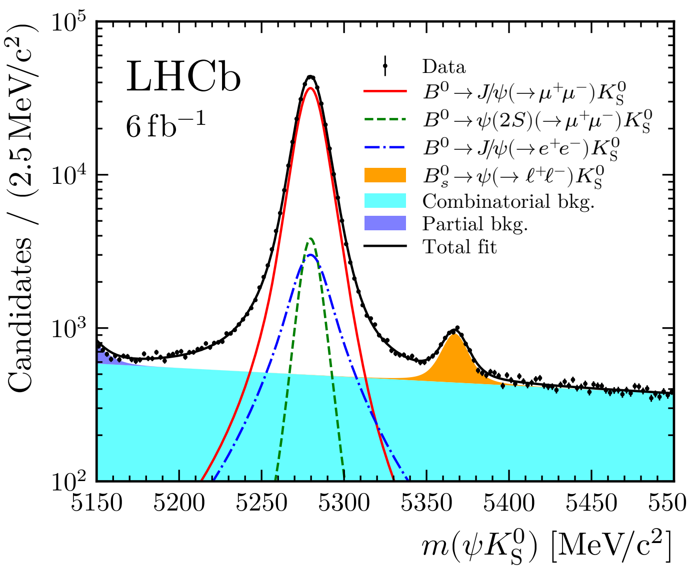
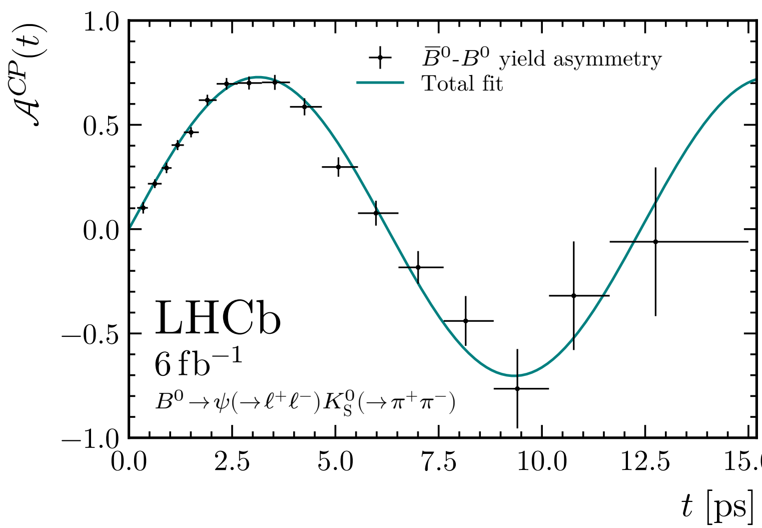




Most recent WA:
$\sin(2\beta) = 0.699 \pm 0.017$

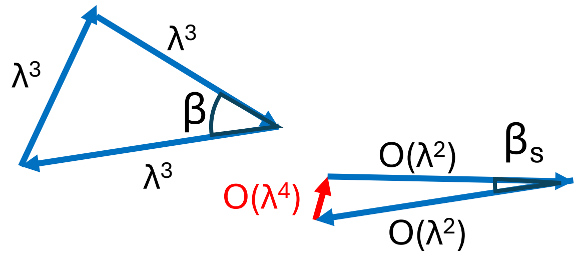
$$S_{\psi K^0_S} = 0.717 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$C_{\psi K^0_S} = 0.008 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})$$

World-best
(better precision than WA)

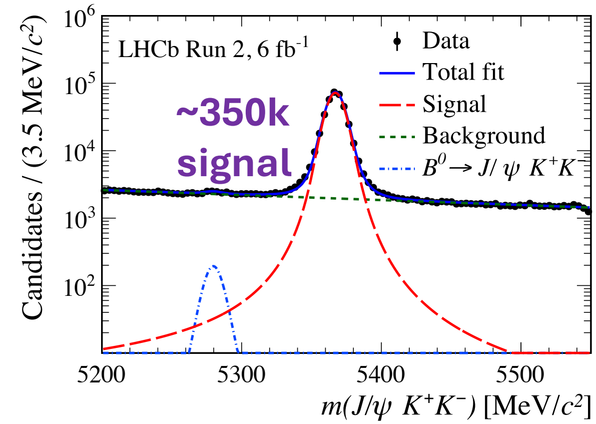
[PRL 132 (2024) 051802](#)
[(arXiv:2308.01468)](#)

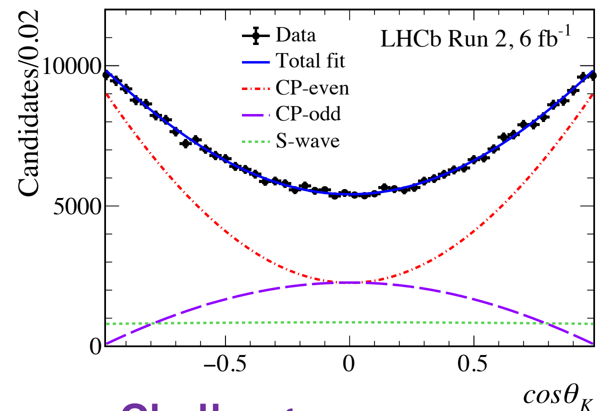
Time-dep. CPV in B_s^0 decays: ϕ_s

B_s^0 analogue of sin(2β)
⇒ suppressed from CKM
⇒ precisely constrained in SM



For $b \to c\bar{c}s$ measure phase $\phi_s \approx -2\beta_s$ = −0.0368(9) rad (SM)





Challenges:
- Flavour tagging
- Time acceptance
- Angular analysis

Time-dep. CPV in B_s^0 decays: ϕ_s

PRL 132 (2024) 051802
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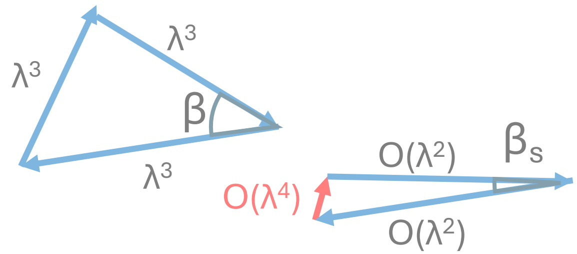

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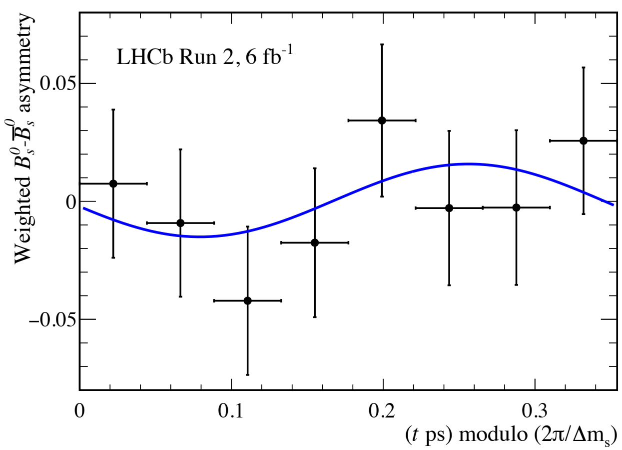
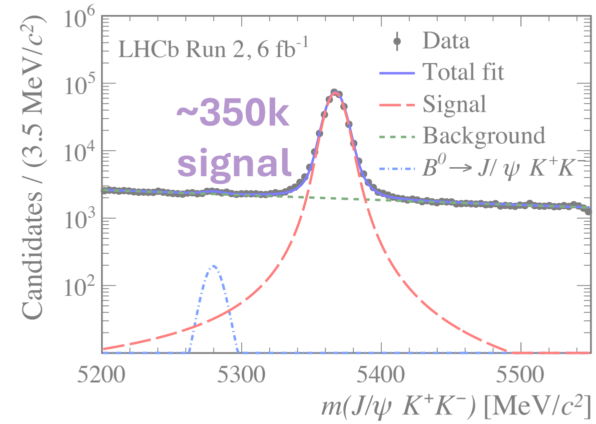
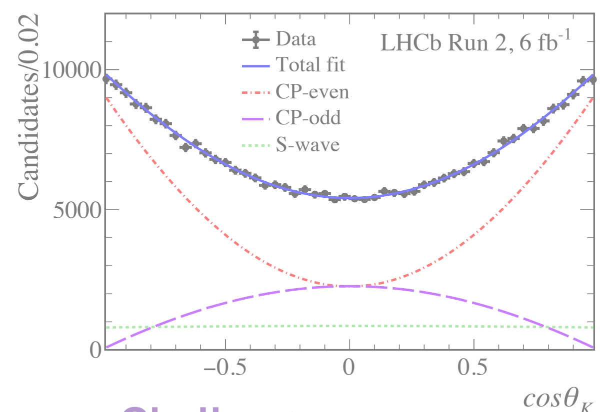


Parameter	Values		
ϕ_s [rad]	−0.039	±0.022	±0.006
$\lvert\lambda\rvert$	1.001	±0.011	±0.005
$\Gamma_s - \Gamma_d$ [ps^{-1}]	−0.0056	$^{+0.0013}_{-0.0015}$	±0.0014
$\Delta\Gamma_s$ [ps^{-1}]	0.0845	±0.0044	±0.0024
Δm_s [ps^{-1}]	17.743	±0.033	±0.009
$\lvert A_\perp\rvert^2$	0.2463	±0.0023	±0.0024
$\lvert A_0\rvert^2$	0.5179	±0.0017	±0.0032
$\delta_\perp - \delta_0$ [rad]	2.903	$^{+0.075}_{-0.074}$	±0.048
$\delta_\parallel - \delta_0$ [rad]	3.146	±0.061	±0.052





- Full Run 2 analysis of benchmark channel $J/\psi(\phi\to)K^+K^-$
- No evidence for CP asymmetry
- Most precise ϕ_s measurement, *still stat. limited*

Challenges:

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Time-dep. CPV in B_s^0 decays: ϕ_s

PRL 132 (2024) 051802
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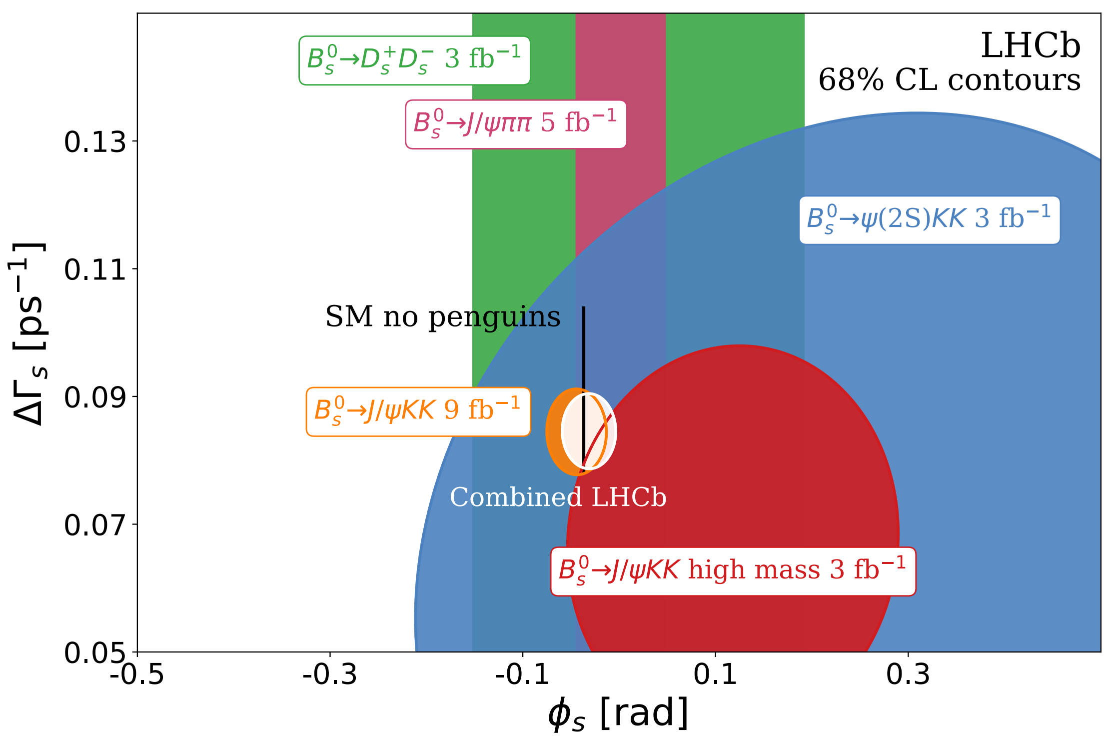
⇒ precisely co

For $b \to c\bar{c}s$ me

LHCb combination: $\phi_s = -0.031 \pm 0.018$ rad



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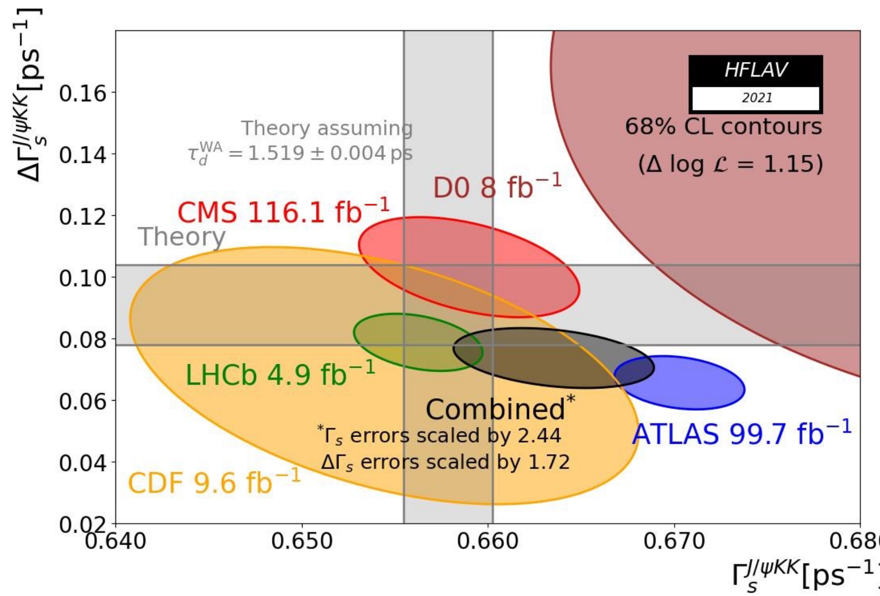
...s:
- ...r tagging
- Time acceptance
- Angular analysis

$\Delta\Gamma_s$ measurement

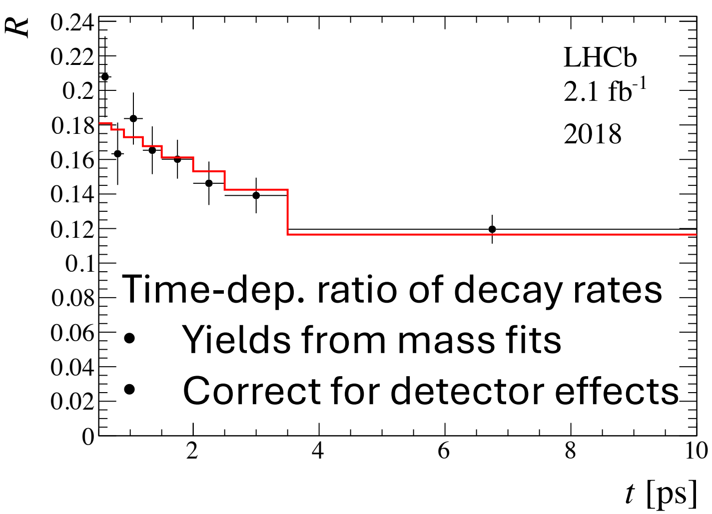
arXiv:2310.12649
(submitted to JHEP)

Disagreement between different (Γ_s, $\Delta\Gamma_s$) measurements in $J/\psi K^+K^-$ channel
⇒ Motivates independent checks



$B_s^0 \to J/\psi\pi^+\pi^-$ CP-odd ⇒ measure τ_H
$f_0(980)$ region

$B_s^0 \to J/\psi\eta'$ CP-even ⇒ measure τ_L
$\eta' \to \rho^0\gamma$



Time-dep. ratio of decay rates
- Yields from mass fits
- Correct for detector effects

Combine data-taking years (full Run 1+2)

LHCb $J/\psi\eta'$ and $J/\psi\pi^+\pi^-$:
$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009$ ps^{-1}

LHCb $J/\psi\phi$:
$0.0845 \pm 0.0044 \pm 0.0024$ ps^{-1}

- Measurement of D^0 mixing and search for CP violation with $D^0 \to K^+\pi^-$ decays
  (New for Moriond EW)
- Search for time-dependent CP violation in $D^0 \to \pi^+\pi^-\pi^0$ decays
  (New for Moriond EW)
- Search for CP violation in the phase space of $D^0 \to K^0_S K^\pm \pi^\mp$ decays with the energy test (arXiv:2310.19397, accepted by JHEP)
- Search for CP violation in the phase space of $D^0 \to \pi^-\pi^+\pi^0$ decays with the energy test (arXiv:2306.12746, JHEP 09 (2023) 129)

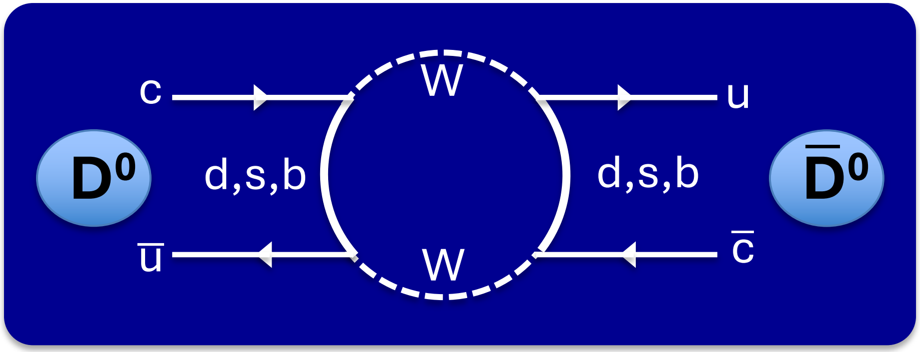
Part 3: Charm

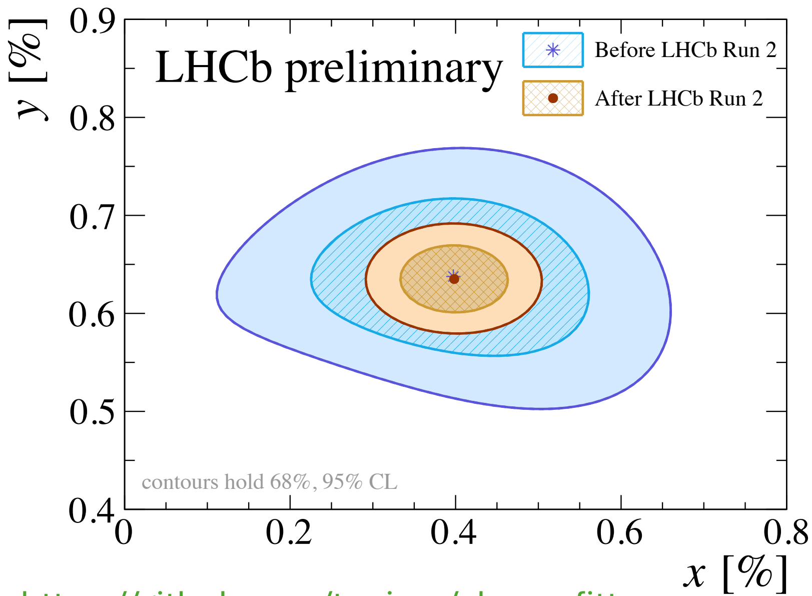
Mixing and CPV in charm

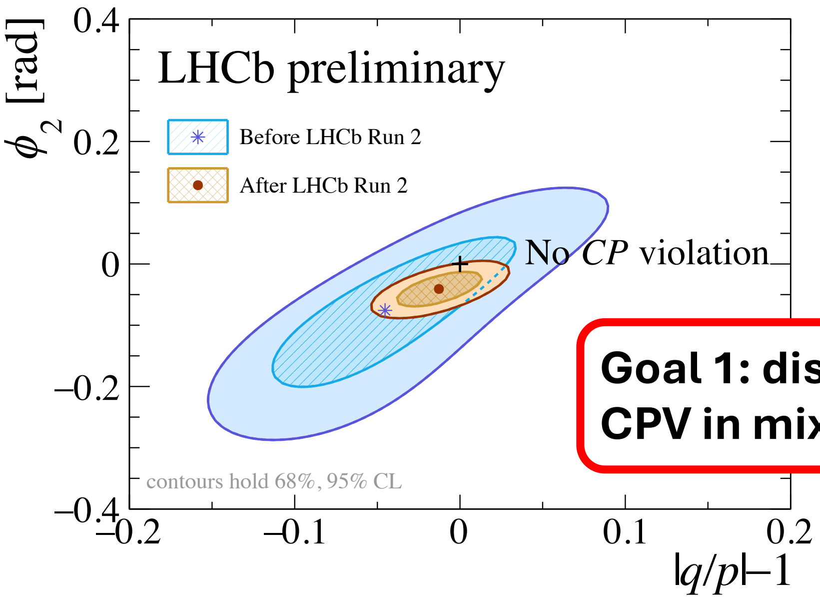
Short-distance mixing highly suppressed (CKM and GIM)

⇒ Mixing & CPV very small $x = \Delta m/\Gamma \ll 1$ $y = \Delta\Gamma/2\Gamma \ll 1$

⇒ Calculations challenging



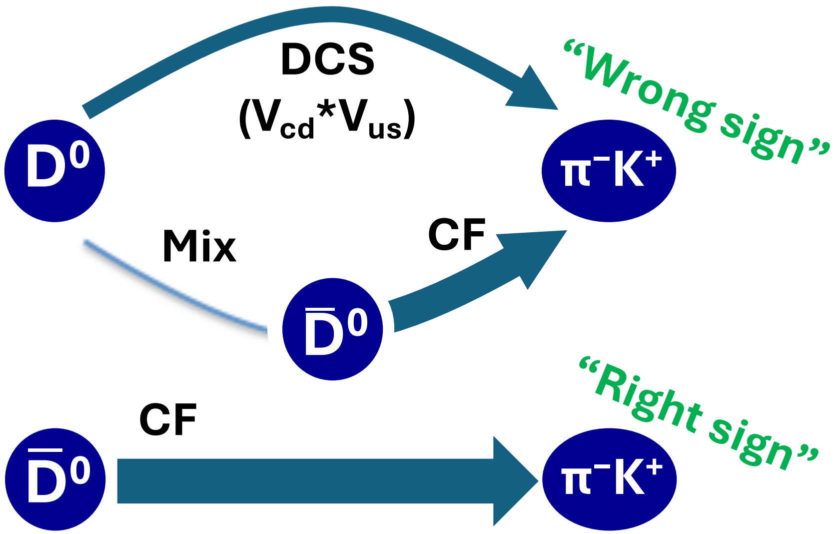




Goal 1: discover CPV in mixing

https://github.com/tpajero/charm-fitter

Mixing and CPV in charm: $D^0 \to K^+\pi^-$



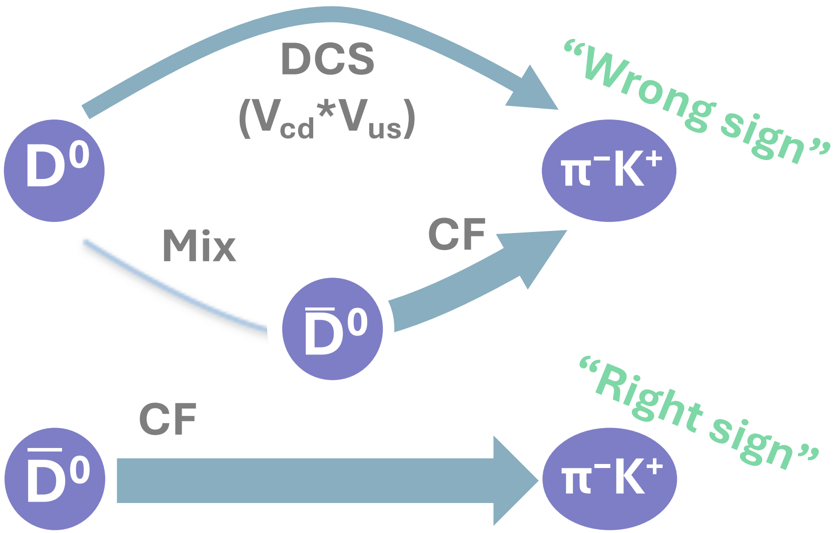
Discovery channel for charm mixing

Fit time-dependent ratio R(t):

$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\bar{D}^0(t) \to K^+\pi^-)}$$

$$R^-_{K\pi}(t) \equiv \frac{\Gamma(\bar{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$

Mixing and CPV in charm: $D^0 \to K^+\pi^-$



Discovery channel for charm mixing

Fit time-dependent ratio R(t):

$$R^{+}_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)}$$

$$R^{-}_{K\pi}(t) \equiv \frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$

CPV in decay

CPV in mixing

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\frac{t}{\tau_{D^0}} + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

DCS

Interference

Mixing

⇒ Probes CPV in mixing, $SU(3)_F$ breaking, rescattering effects & provides null test of SM.

Mixing and CPV in charm: $D^0 \to K^+\pi^-$

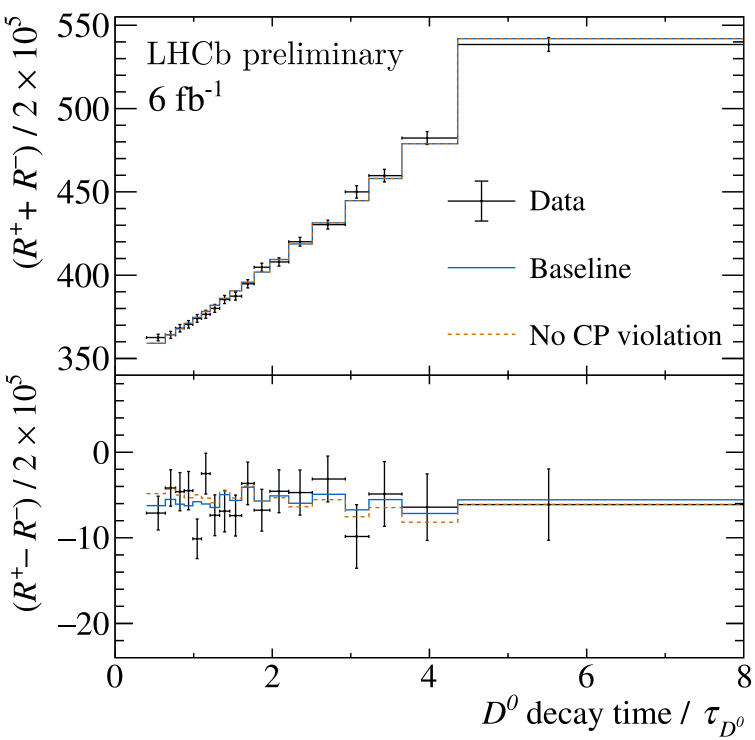
LHCb-PAPER-2024-008
(in preparation)

(NEW!)

Full Run 2 data sample. Production flavor tagged via $D^{*+} \to D^0\pi^+$ decays.

Experimental challenges:

- Backgrounds
- Nuisance asymmetries ⇒ determined with $D^0 \to K^+K^-$ control mode



Signal yields: 1.6M WS 412M RS

Parameters	
$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

First evidence of quadratic behaviour

No evidence of CPV

60% improvement in precision compared to previous best. Still statistically limited.

Mixing and CPV in charm: $D^0(t)\to\pi^+\pi^-\pi^0$ (NEW!)

Measure time-dependent CP asymmetry:

$$A_{CP}(f_{CP},t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\bar{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\bar{D}^0\to f_{CP}}(t)}$$

$$\approx a^{\rm dir}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}},$$

mixing-induced CPV ⇒ universal

Related to mixing and CPV parameters:

$$\Delta Y_{f_{CP}} \approx \frac{\eta_{f_{CP}}}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin(\phi) - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos(\phi)\right]$$

Mixing and CPV in charm: $D^0(t) \to \pi^+\pi^-\pi^0$ (NEW!)

Measure time-dependent CP asymmetry:

$$A_{CP}(f_{CP}, t) \equiv \frac{\Gamma_{D^0 \to f_{CP}}(t) - \Gamma_{\bar{D}^0 \to f_{CP}}(t)}{\Gamma_{D^0 \to f_{CP}}(t) + \Gamma_{\bar{D}^0 \to f_{CP}}(t)} \approx a^{\mathrm{dir}}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}},$$

Related to mixing and CPV parameters:

$$\Delta Y_{f_{CP}} \approx \frac{\eta_{f_{CP}}}{2} \left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right| \right) x \sin(\phi) - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right| \right) y \cos(\phi) \right]$$

mixing-induced CPV ⇒ universal

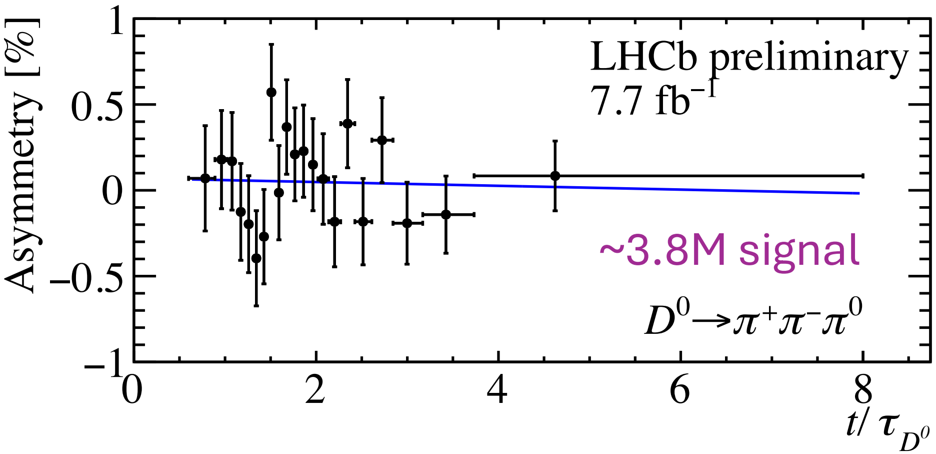
No evidence of CP violation:

$$\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$$

Validated with Kππ channel:

$$\Delta Y_{K\pi\pi} = (-1.7 \pm 1.8 \pm 3.5) \times 10^{-4}$$

See YSF talk from Niall Mchugh



LHCb-PAPER-2024-003 (in preparation)

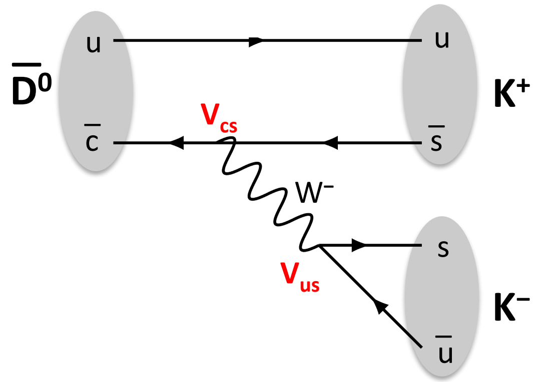
CPV in charm decay

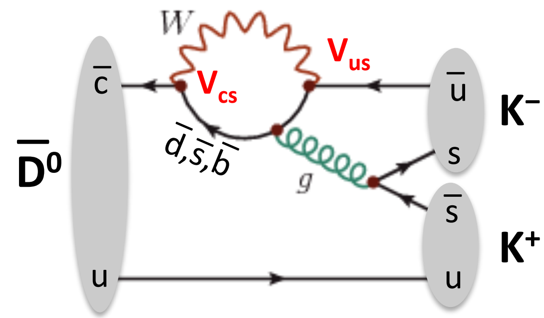
2019 discovery: Difference in CP asymmetries A_{CP} between $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$

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

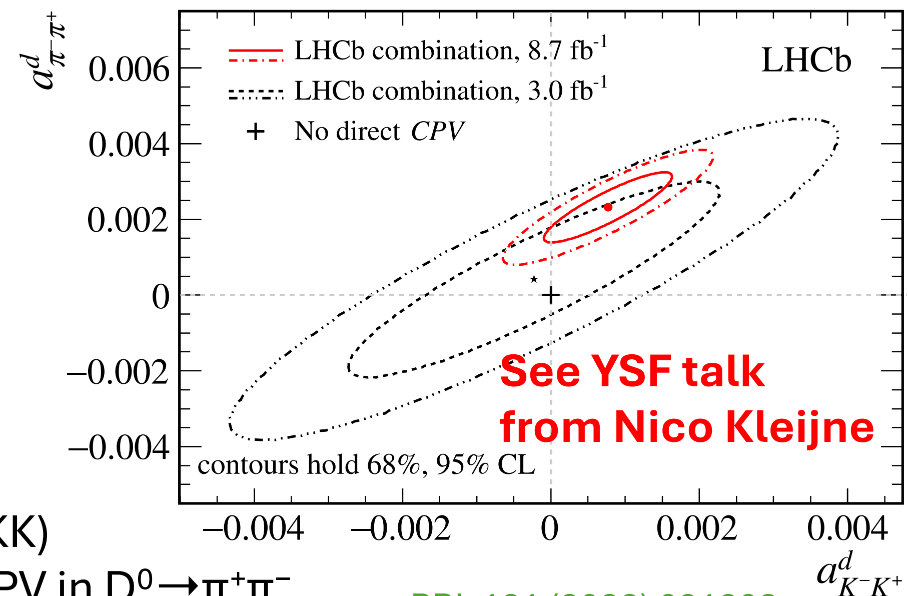
5.3σ from zero **SM or BSM?**

PRL 122 (2019) 211803
(arXiv:1903.08726)





Goal 2: confirm and characterize CPV in decay



2023 update of $A_{CP}(KK)$
⇒ 3σ evidence for CPV in $D^0 \to \pi^+\pi^-$

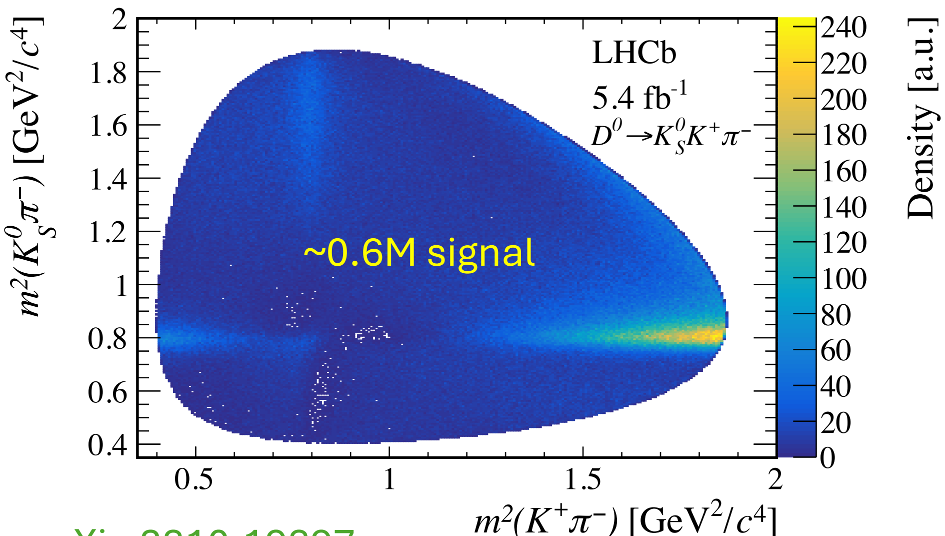
PRL 131 (2023) 091802
(arXiv:2209.03179)

CPV in charm decay

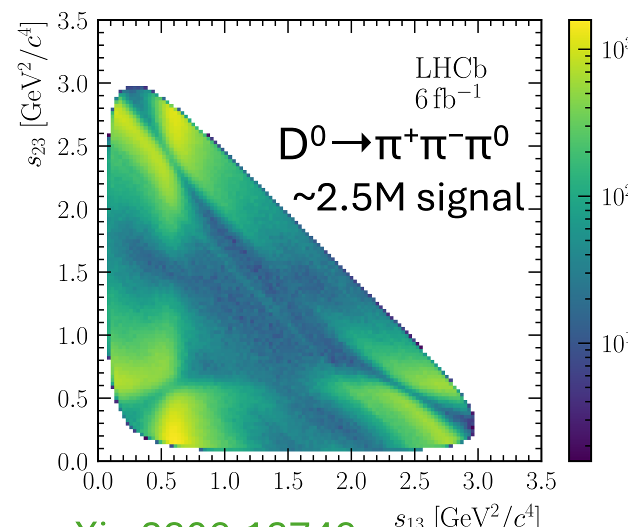
Next steps:

- Add new channels
- Search for **local** CPV in phase-space of multibody decays
  ⇒ Exploit different methods

Recent searches for local CPV with Energy Test method (Run 2) ⇒ No evidence in $D^0 \to K^0_S K^- \pi^+$ (*p*-value 0.70), $D^0 \to K^0_S K^+ \pi^-$ (0.66), $D^0 \to \pi^+\pi^-\pi^0$ (0.62).



arXiv:2310.19397
(accepted by JHEP)

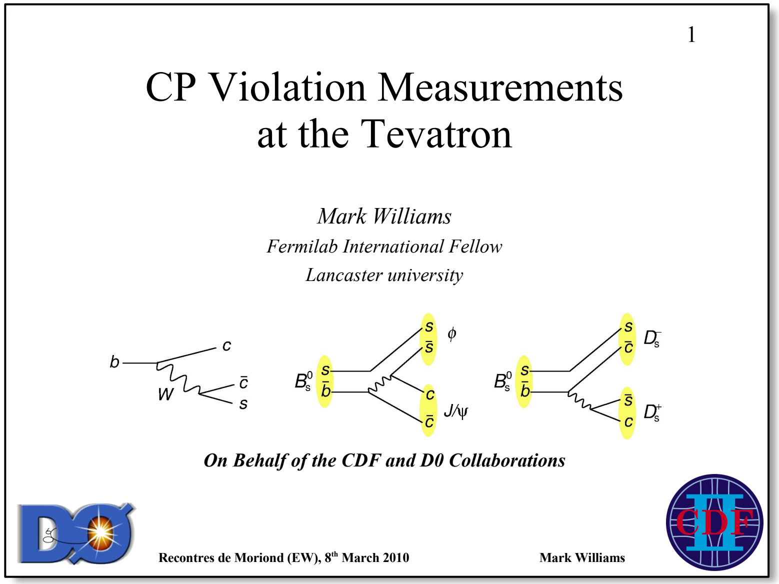


arXiv:2306.12746
(JHEP 09 (2023) 129)

Summary and Outlook

We've come a long way since the LHC started

(2010 Moriond EW CPV talk)

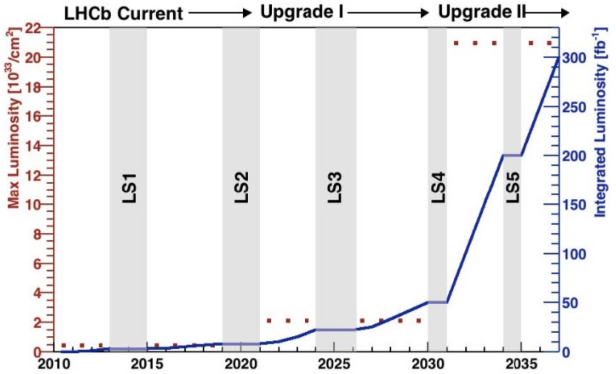


Many notable achievements with Run 1+2 data
+ we're not done yet

(2019 Moriond: discovery of charm CPV)

The future is bright!

(2030 Moriond: ???)



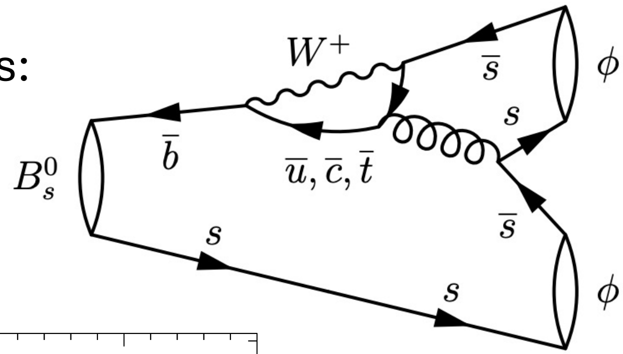
Extra slides

$B_s^0 \to \phi\phi$

PRL 131 (2023) 171802
arXiv:2304.06198

Compared to J/ψϕ analysis:

- Penguin dominated
- Charmless final state

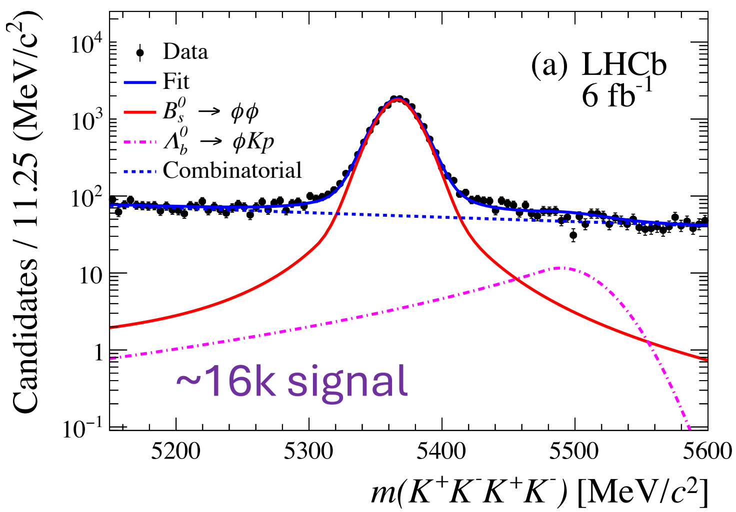


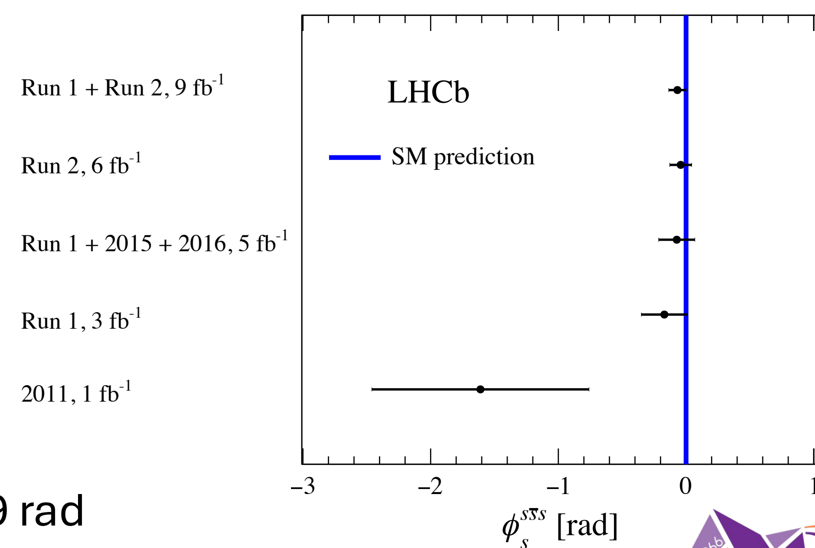
Measure weak phase $\phi_s^{s\bar{s}s}$

+ direct CPV parameter |λ|

in each polarization mode

Parameter	Result
$\phi_s^{s\bar{s}s}$ [rad]	$-0.042 \pm 0.075 \pm 0.009$
$\lvert\lambda\rvert$	$1.004 \pm 0.030 \pm 0.009$
$\lvert A_0\rvert^2$	$0.384 \pm 0.007 \pm 0.003$
$\lvert A_\perp\rvert^2$	$0.310 \pm 0.006 \pm 0.003$
$\delta_\parallel - \delta_0$ [rad]	$2.463 \pm 0.029 \pm 0.009$
$\delta_\perp - \delta_0$ [rad]	$2.769 \pm 0.105 \pm 0.011$





Full Run 2 sample

⇒ No CPV, agrees with SM

⇒ Consistent across polarization states

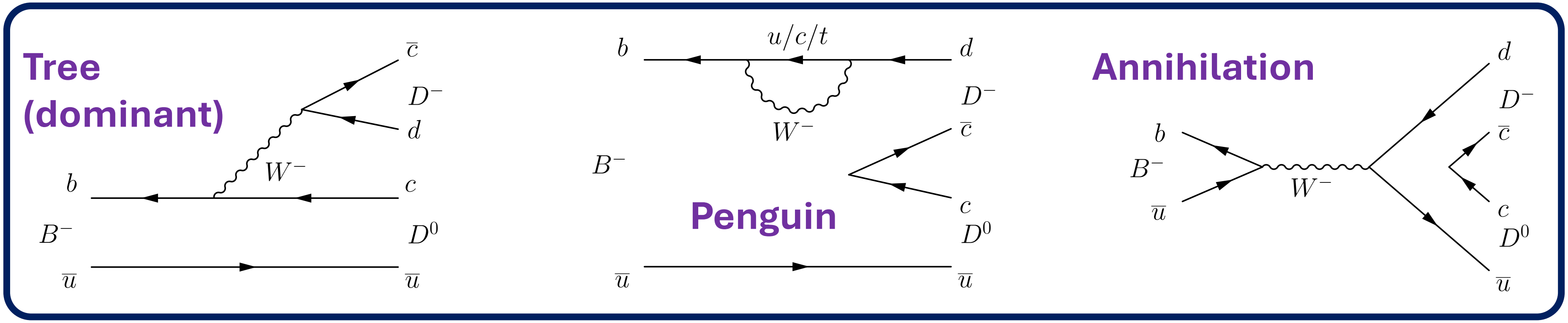
Combining with Run 1: $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad

$B^- \to D_{(s)}^{(*)-} D^{(*)0}$

JHEP 09 (2023) 202
arXiv:2306.09945

Measure time-integrated charge asymmetry of decay rates

$$\mathcal{A}^{CP} \equiv \frac{\Gamma(B^- \to D_{(s)}^{(*)-} D^{(*)0}) - \Gamma(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0})}{\Gamma(B^- \to D_{(s)}^{(*)-} D^{(*)0}) + \Gamma(B^+ \to D_{(s)}^{(*)+} \overline{D}^{(*)0})}$$



SM predictions → PDG

Decay	Ref. [3]	Ref. [4]	Ref. [5]	Ref. [6]	Measured [8]
$B^- \to D_s^- D^0$	-0.28 ± 0.06	-	$-0.26^{+0.05}_{-0.04}$	-0.14 ± 0.25	-0.4 ± 0.7
$B^- \to D_s^{*-} D^0$	-0.065 ± 0.005	-	$-0.07^{+0.03}_{-0.02}$	-0.01 ± 0.10	-
$B^- \to D_s^- D^{*0}$	0.045 ± 0.015	-	$0.03^{+0.02}_{-0.02}$	0.08 ± 0.03	-
$B^- \to D^- D^0$	4.95 ± 1.08	$0.6^{+0.6}_{-0.1}$	$4.4^{+1.1}_{-0.4}$	-	1.6 ± 2.5
$B^- \to D^- D^{*0}$	-0.80 ± 0.35	$-0.5^{+0.1}_{-0.4}$	$-0.6^{+0.4}_{-0.2}$	-	13 ± 18
$B^- \to D^{*-} D^0$	1.19 ± 0.16	$0.1^{+0.6}_{-0.1}$	$1.2^{+0.4}_{-0.3}$	-	-6 ± 13
$B^- \to D^{*-} D^{*0}$	1.19 ± 0.16	$0.2^{+0.0}_{-0.1}$	$1.2^{+0.4}_{-0.3}$	-	-15 ± 11

(Kim, Wang, Yang) (Lu, Xiao, Wang, Li)
(Li, Wang, Sanda, Lu) (Xu, Wang)

Experimental input essential:

⇒ more precision

⇒ more channels

⇒ CP asymmetries & BR ratios

$B^- \to D_{(s)}^{(*)-} D^{(*)0}$

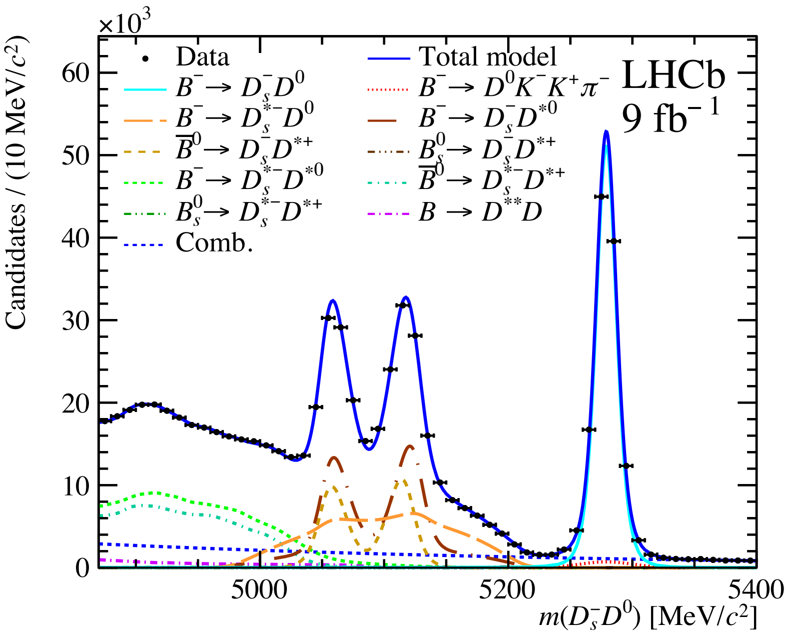
JHEP 09 (2023) 202
arXiv:2306.09945

$D^0 \to K^-\pi^+$ | $D^{*-} \to \overline{D}^0\pi^-$
$D^0 \to K^-\pi^+\pi^-\pi^+$ | $D_s^- \to K^-K^+\pi^-$
$D^- \to K^+\pi^-\pi^-$

Full Run 1+2 sample

- Raw yields from mass fits
- Correct for nuisance asymmetries

Missing neutrals from D_s^{*-} / D^{*0} decay



Results:

$$\mathcal{A}^{CP}(B^- \to D_s^- D^0) = (+0.5 \pm 0.2 \pm 0.5 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D_s^{*-} D^0) = (-0.5 \pm 1.1 \pm 1.0 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D_s^- D^{*0}) = (+1.1 \pm 0.8 \pm 0.6 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D^- D^0) = (+2.5 \pm 1.0 \pm 0.4 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D^- D^{*0}) = (-0.2 \pm 2.0 \pm 1.4 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D^{*-} D^0) = (+3.3 \pm 1.6 \pm 0.6 \pm 0.3)\%$$
$$\mathcal{A}^{CP}(B^- \to D^{*-} D^{*0}) = (+2.3 \pm 2.1 \pm 1.7 \pm 0.3)\%$$

(stat.) (syst.) (ext.)

⇒ No evidence of CP violation
⇒ Most precise measurements for all 7 channels (still stat. limited)

Extra: Wrong sign $D^0 \to K\pi$: formalism

$$R^{\pm}_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\frac{t}{\tau_{D^0}} + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

$$R_{K\pi} = \frac{1}{2}\left(\left|\frac{A_{\bar f}}{\bar A_{\bar f}}\right|^2 + \left|\frac{\bar A_f}{A_f}\right|^2\right),$$

$$A_{K\pi} = \frac{|A_{\bar f}/\bar A_{\bar f}|^2 - |\bar A_f/A_f|^2}{|A_{\bar f}/\bar A_{\bar f}|^2 + |\bar A_f/A_f|^2} \approx a^d_{\rm DCS},$$

Expect ~ O(10^{-5}) in SM – key null test

$$c_{K\pi} \approx y_{12}\cos\phi^\Gamma_f \cos\Delta_f + x_{12}\cos\phi^M_f \sin\Delta_f,$$

Mainly constrains $\Delta_f \Rightarrow$ improved knowledge of $SU(3)_F$ breaking

$$\Delta c_{K\pi} \approx x_{12}\sin\phi^M_f \cos\Delta_f - y_{12}\sin\phi^\Gamma_f \sin\Delta_f,$$

$$c'_{K\pi} \approx \frac{1}{4}\left(x^2_{12} + y^2_{12}\right),$$

$$\Delta c'_{K\pi} \approx \frac{1}{2}x_{12}y_{12}\sin(\phi^M_f - \phi^\Gamma_f).$$

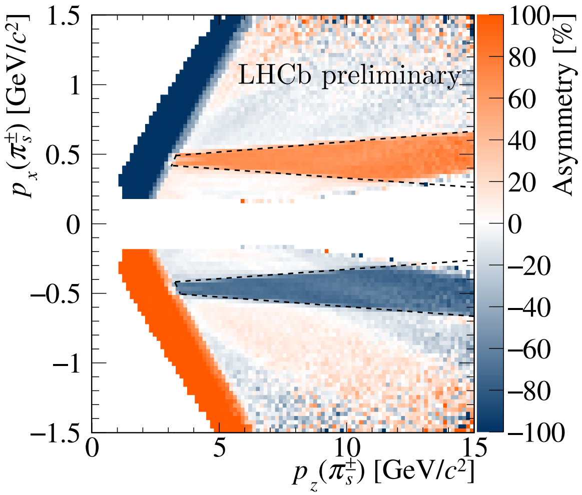
Probe mixing-induced CPV

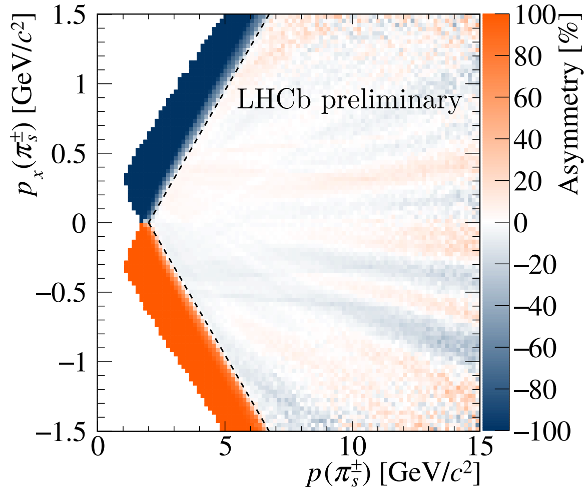
$$\phi^M_f - \Delta_f \equiv \arg(-M_{12}\,A_f/\bar A_f), \qquad \phi^M_f + \Delta_f \equiv \arg(-M_{12}\,A_{\bar f}/\bar A_{\bar f}),$$

$$\phi^\Gamma_f - \Delta_f \equiv \arg(-\Gamma_{12}\,A_f/\bar A_f), \qquad \phi^\Gamma_f + \Delta_f \equiv \arg(-\Gamma_{12}\,A_{\bar f}/\bar A_{\bar f}).$$

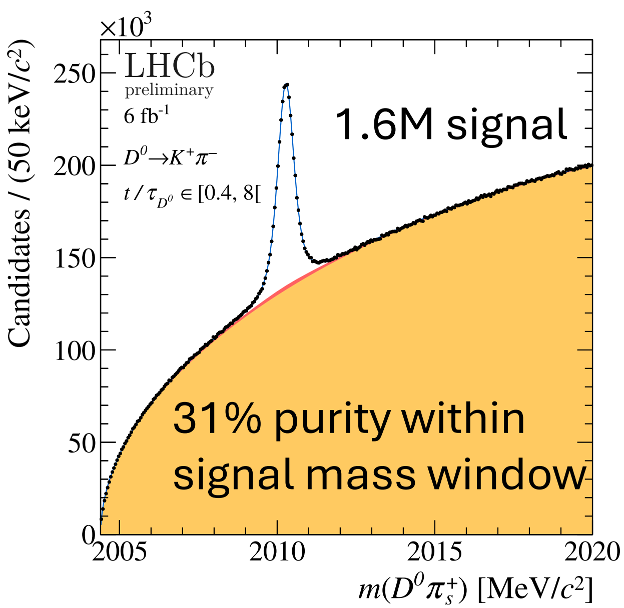
Extra: Wrong sign $D^0 \rightarrow K\pi$: selection

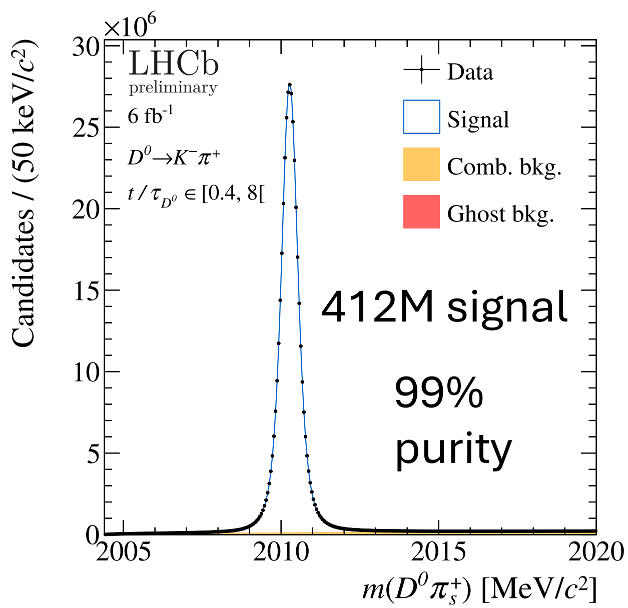
LHCb-PAPER-2024-008
(in preparation)





‘Fiducial selection’ removes candidates from detector regions with large instrumental charge asymmetries
(plots for RS candidates)

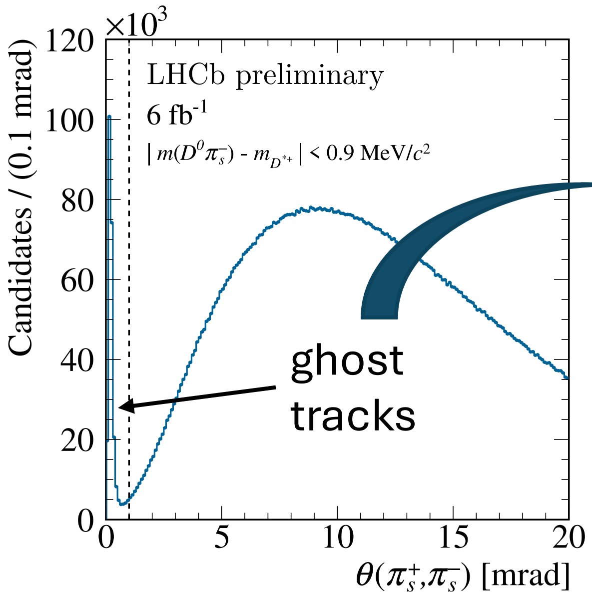


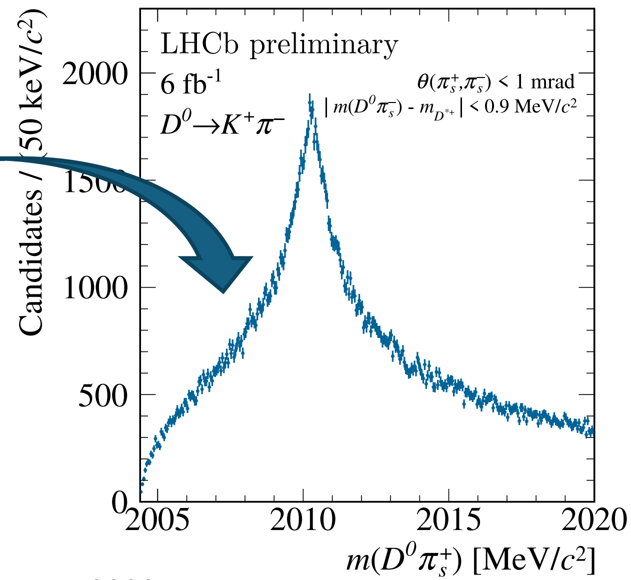


$m(D^0\pi)$ distribution for WS and RS samples after all selections.

Fits to this variable used to subtract BG from R(t)

Extra: Wrong sign $D^0 \to K\pi$: backgrounds

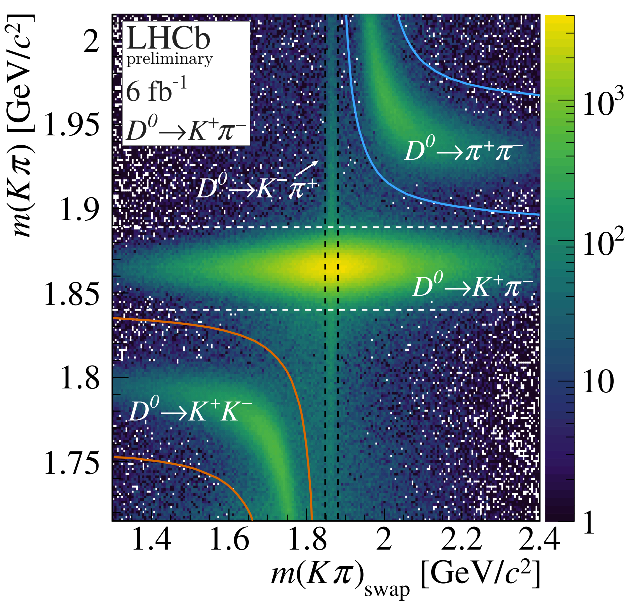


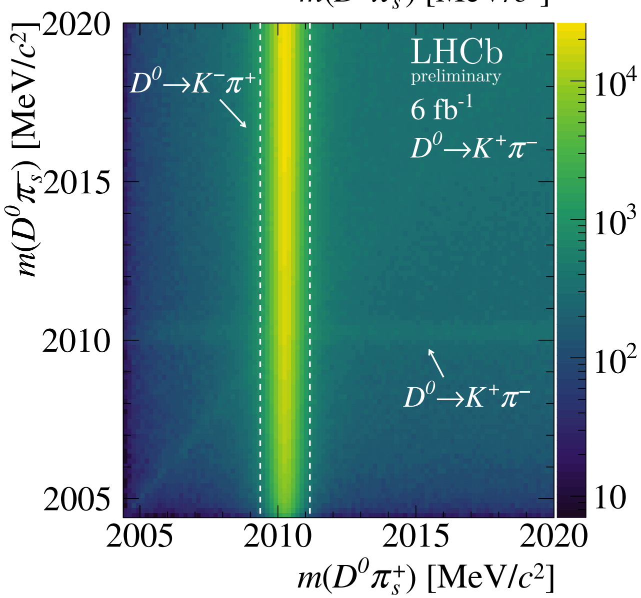


'Ghost' tracks from random hits give problematic BG.

Suppressed with fiducial and track-quality cuts.

Modelled with data-driven approach.



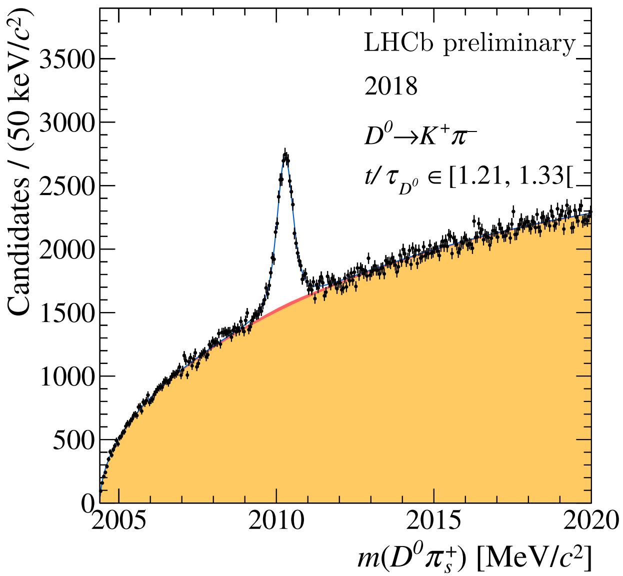


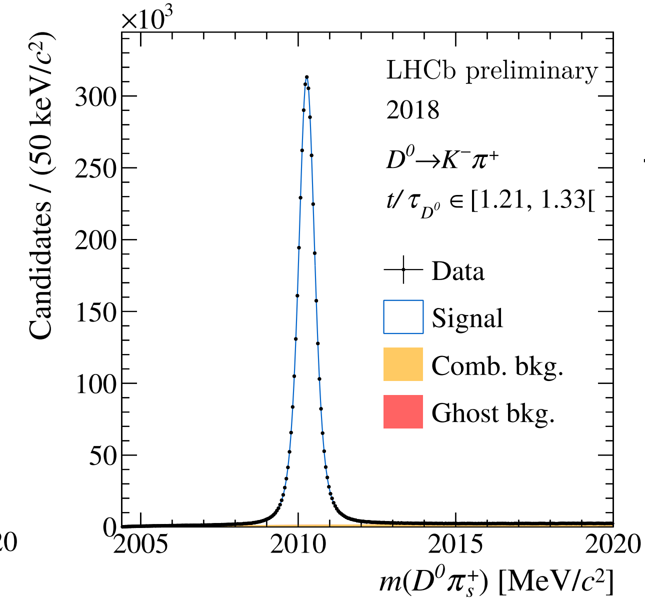
Left: misID backgrounds in WS sample

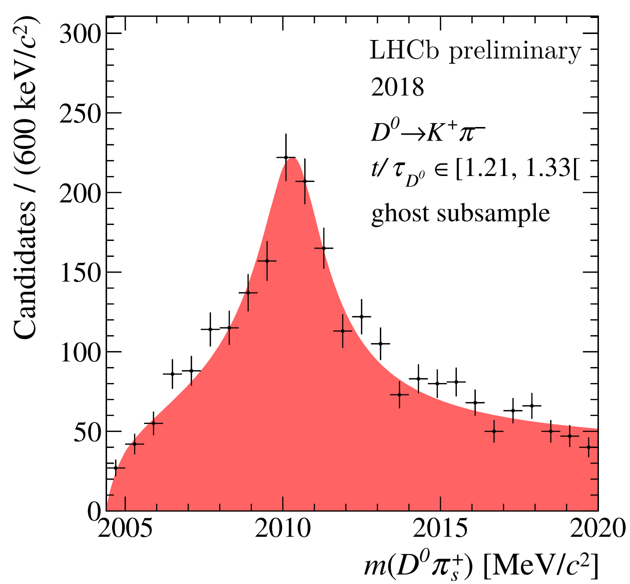
Right: WS-RS cross-talk

LHCb-PAPER-2024-008 (in preparation)

Extra: Wrong sign $D^0 \to K\pi$: example fits





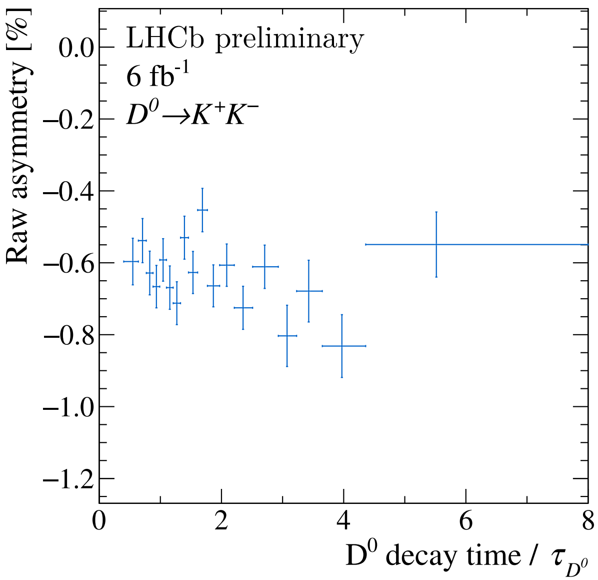


Example set of simultaneous fits in single decay-time bin

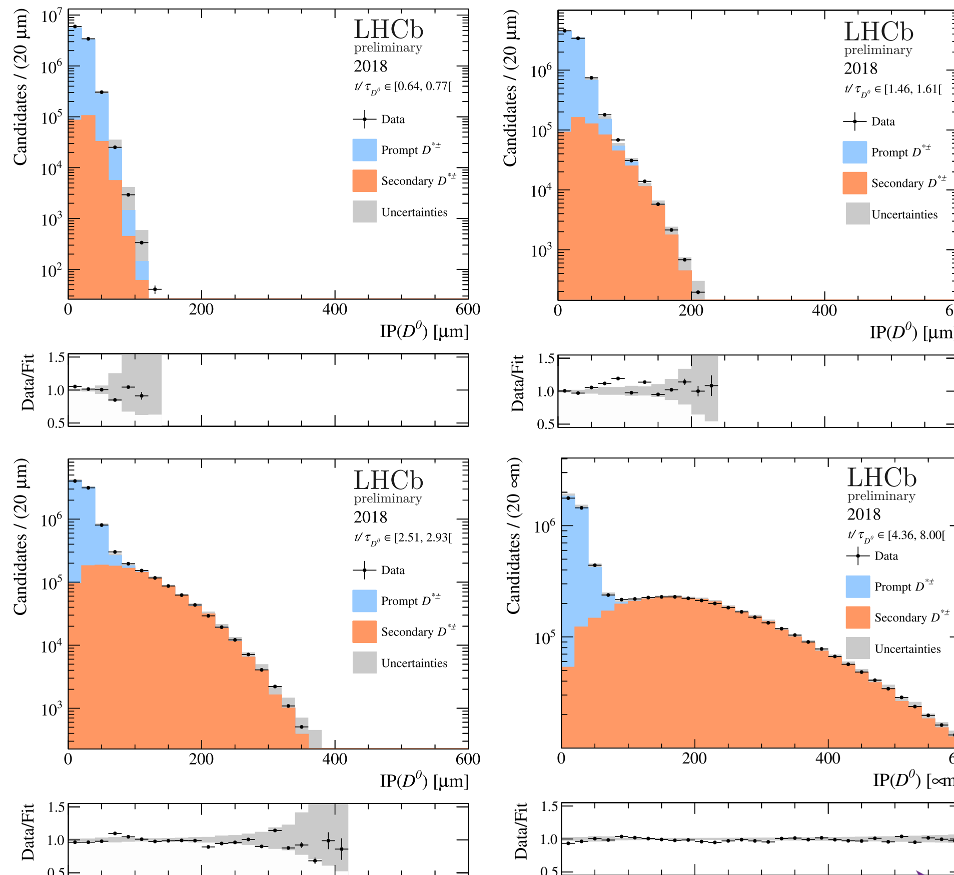
- RS
- WS
- Ghost control-sample

LHCb-PAPER-2024-008
(in preparation)

Extra: Wrong sign $D^0 \to K\pi$: corrections



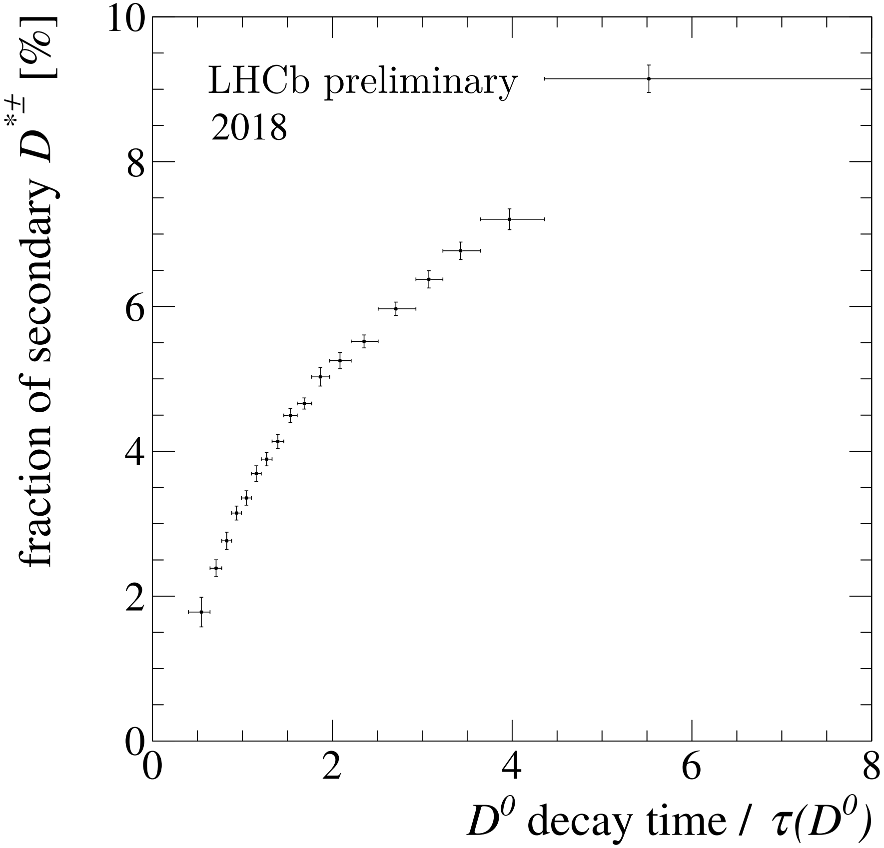
Instrumental asymmetries determined from $D^0 \to K^+K^-$ control mode

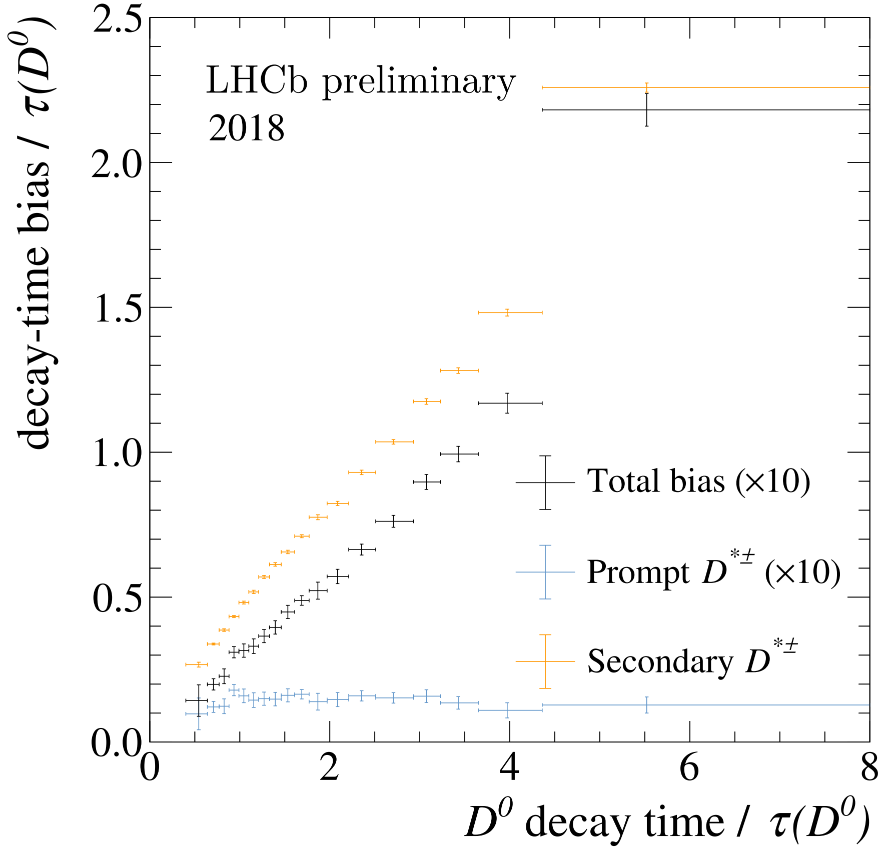


Fits to IP used to statistically disentangle prompt and secondary charm – mitigates and accounts for residual decay time bias.

LHCb-PAPER-2024-008 (in preparation)

Extra: Wrong sign $D^0 \to K\pi$: decay-time bias





Left: Secondary contamination depends on decay time.

Right: Decay time bias from secondary background

LHCb-PAPER-2024-008 (in preparation)

Extra: Wrong sign $D^0 \to K\pi$: results

Parameters		Correlations					
		$R_{K\pi}$	$c_{K\pi}$	$c'_{K\pi}$	$A_{K\pi}$	$\Delta c_{K\pi}$	$\Delta c'_{K\pi}$
$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$	100.0	-92.4	80.0	0.9	-0.8	0.1
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$		100.0	-94.1	-1.4	1.4	-0.7
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$			100.0	0.7	-0.7	0.1
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$				100.0	-91.5	79.4
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$					100.0	-94.1
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$						100.0

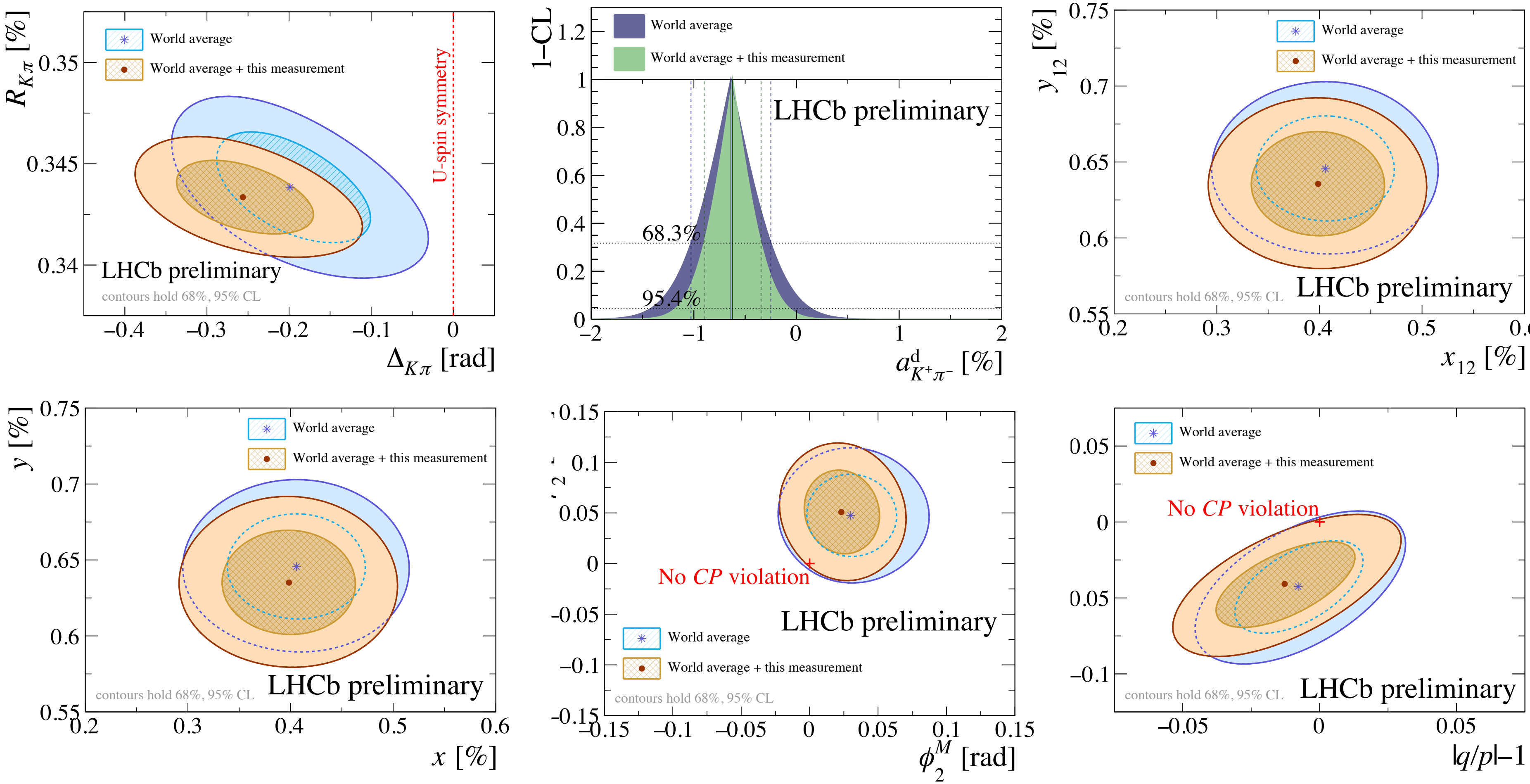
Run 2 measurement and correlations

Source	$R_{K\pi}$ $[10^{-5}]$	$c_{K\pi}$ $[10^{-4}]$	$c'_{K\pi}$ $[10^{-6}]$	$A_{K\pi}$ $[10^{-3}]$	$\Delta c_{K\pi}$ $[10^{-4}]$	$\Delta c'_{K\pi}$ $[10^{-6}]$
Mass mismodeling	0.5	0.8	0.9	1.4	0.8	0.8
Ghost soft pions	0.4	0.8	0.8	1.1	0.8	1.1
Instrumental asymmetry	–	–	–	1.2	0.7	0.7
a^d_{KK} external input	–	–	–	1.1	–	–
ΔY external input	–	–	–	–	0.1	0.1
Doubly misidentified background	0.1	0.1	0.1	–	–	–
Common removal	0.2	–	–	–	–	–
Decay-time bias	0.1	0.2	0.1	0.1	–	–
m_{D^0}/τ_{D^0} external input	–	0.1	0.1	–	–	–
Total systematic uncertainty	0.7	1.1	1.2	2.4	1.3	1.4
Statistical uncertainty	1.9	3.3	3.5	5.5	3.3	3.5
Total uncertainty	2.0	3.5	3.7	6.0	3.6	3.8

Breakdown of uncertainties: Statistically limited for all parameters

LHCb-PAPER-2024-008 (in preparation)

Extra: Wrong sign $D^0 \to K\pi$: impact



Impact of measurement on charm mixing and CPV parameters

LHCb-PAPER-2024-008
(in preparation)

Extra: Time-dep. CPV in $D^0(t)\to\pi^+\pi^-\pi^0$

Measure time-dependent CP asymmetry:

$$A_{CP}(f_{CP},t) \equiv \frac{\Gamma_{D^0\to f_{CP}}(t) - \Gamma_{\bar{D}^0\to f_{CP}}(t)}{\Gamma_{D^0\to f_{CP}}(t) + \Gamma_{\bar{D}^0\to f_{CP}}(t)} \approx a^{\text{dir}}_{f_{CP}} + \Delta Y_{f_{CP}} \frac{t}{\tau_{D^0}},$$

CPV in decay (ignore)

mixing-induced CPV ⇒ universal (up to CP eigenvalue sign $\eta_{f_{CP}}$)

Related to mixing and CPV parameters:

$$\Delta Y_{f_{CP}} \approx \frac{\eta_{f_{CP}}}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin(\phi) - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos(\phi)\right]$$

For multibody decay, different intermediate resonances can have different CP eigenvalues
⇒ Integrating over phase-space can dilute sensitivity:

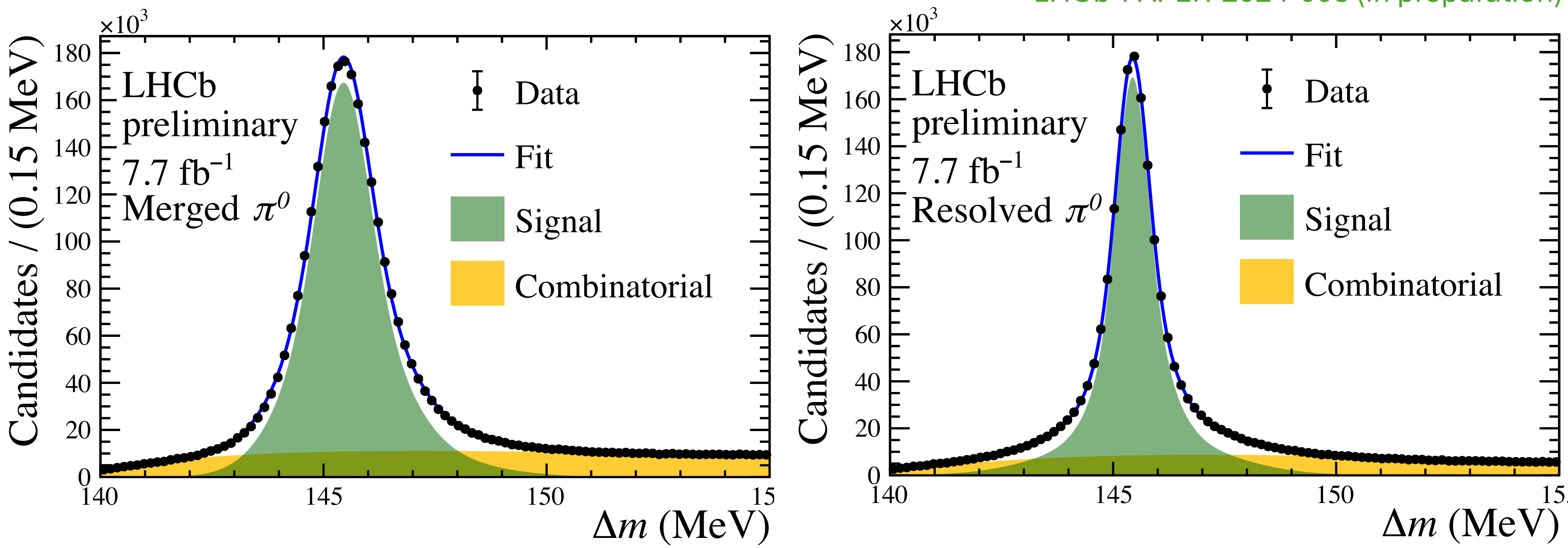
$$\Delta Y^{\text{eff}}_f = |2F^f_+ - 1|\Delta Y,$$

For This decay mode, dominant resonances are CP-even ($\rho\pi$) so dilution is very small effect:

$$F^{\pi\pi\pi}_+ = 0.973 \pm 0.017$$

Extra: Time-dep. CPV in $D^0(t) \to \pi^+\pi^-\pi^0$

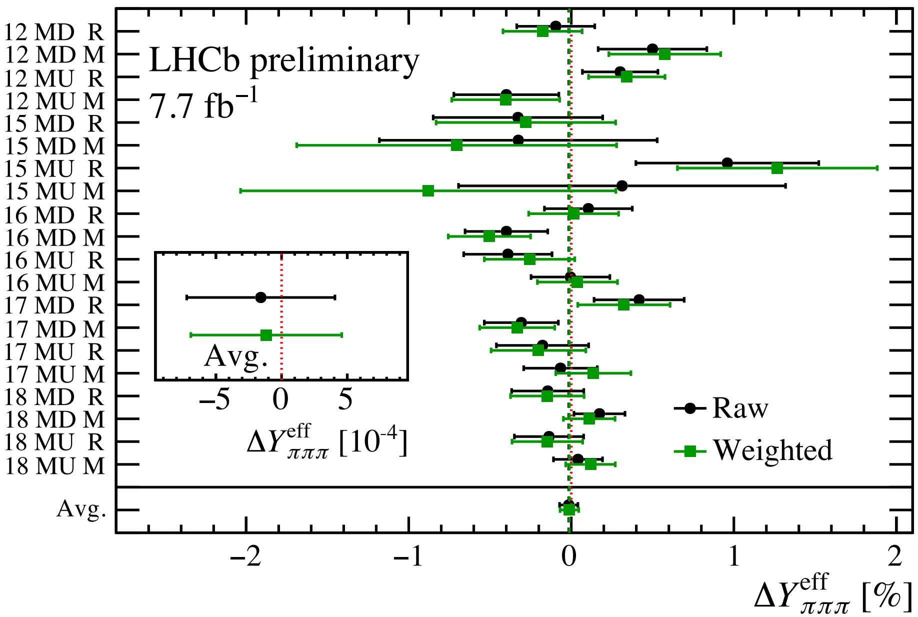
LHCb-PAPER-2024-003 (in preparation)

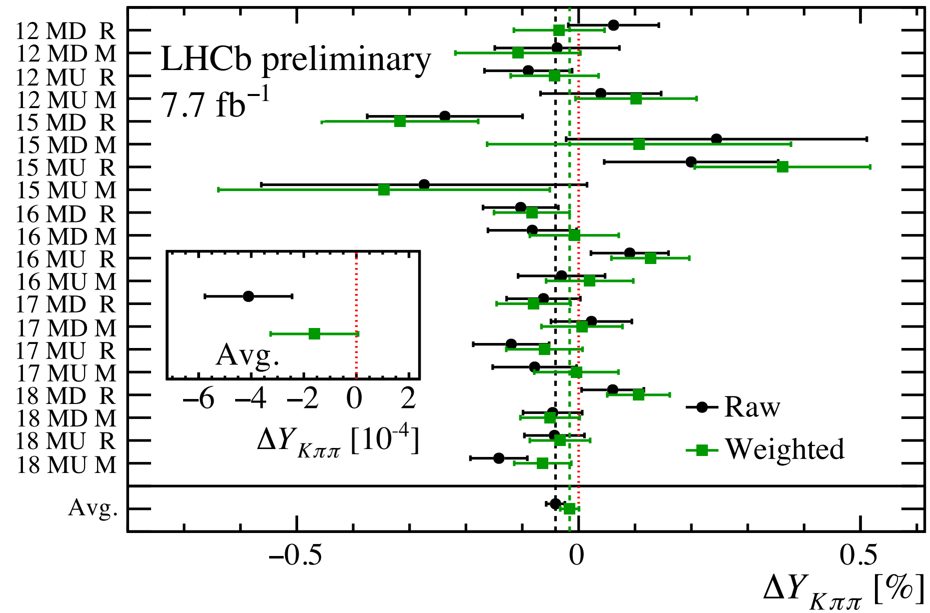


$\Delta m \equiv m(D^*) - m(D^0)$ distributions for signal channel, for *merged* and *resolved* γγ

Extra: Time-dep. CPV in $D^0(t)\to\pi^+\pi^-\pi^0$

LHCb-PAPER-2024-003 (in preparation)



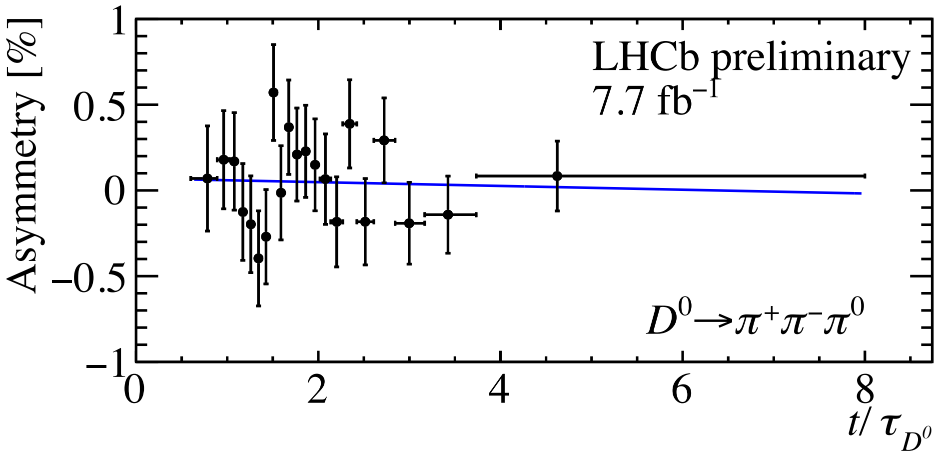


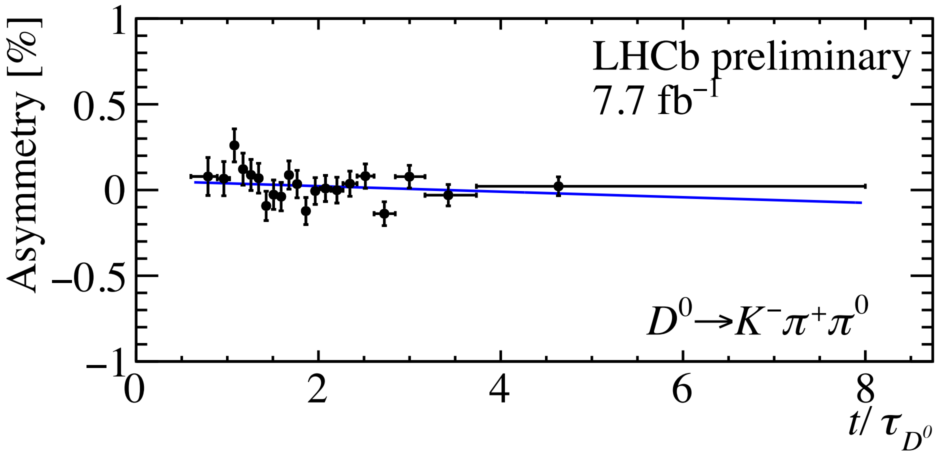
Measurements of $\Delta Y_{\pi\pi\pi}$ in different subsamples of the data, and average, before and after applying kinematic weighting correction for nuisance asymmetries.

Shown for both signal (left) and control (right) channels.

Extra: Time-dep. CPV in $D^0(t)\to\pi^+\pi^-\pi^0$

LHCb-PAPER-2024-003 (in preparation)



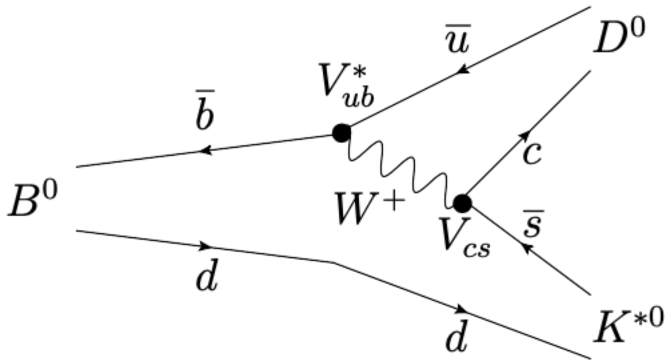


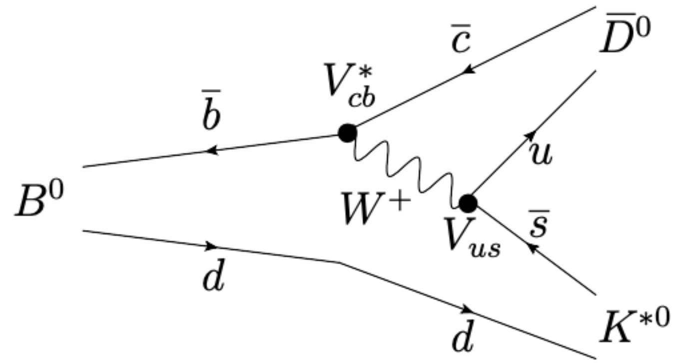
Time-dependent CP asymmetry for all subsamples combined ⇒ slope gives ΔY^{eff}

Shown for both signal (left) and control (right) channels.

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

arXiv:2401.17934
(Submitted to JHEP)





Experimental observables:

CF/DCS (ADS):

$$\mathcal{R}^+_{\pi K(\pi\pi)} \equiv \frac{\Gamma\left(B^0 \to D\left[\pi K(\pi\pi)\right] K^{*0}\right)}{\Gamma\left(B^0 \to D\left[K\pi(\pi\pi)\right] K^{*0}\right)} \quad \text{and} \quad \mathcal{R}^-_{\pi K(\pi\pi)} \equiv \frac{\Gamma\left(\overline{B}^0 \to D\left[\pi K(\pi\pi)\right] \overline{K}^{*0}\right)}{\Gamma\left(\overline{B}^0 \to D\left[K\pi(\pi\pi)\right] \overline{K}^{*0}\right)}$$

$$\mathcal{A}_{K\pi} \equiv \frac{\Gamma\left(\overline{B}^0 \to D[K\pi(\pi\pi)]\overline{K}^{*0}\right) - \Gamma\left(B^0 \to D[K\pi(\pi\pi)]K^{*0}\right)}{\Gamma\left(\overline{B}^0 \to D[K\pi(\pi\pi)]\overline{K}^{*0}\right) + \Gamma\left(B^0 \to D[K\pi(\pi\pi)]K^{*0}\right)}$$

CP-eigenstates (GLW):

$$\mathcal{R}^{hh(\pi\pi)}_{CP} \equiv \frac{\Gamma(\overline{B}^0 \to D[hh(\pi\pi)]\overline{K}^{*0}) + \Gamma(B^0 \to D[hh(\pi\pi)]K^{*0})}{\Gamma(\overline{B}^0 \to D[K\pi(\pi\pi)]\overline{K}^{*0}) + \Gamma(B^0 \to D[K\pi(\pi\pi)]K^{*0})} \times \frac{\mathcal{B}(D^0 \to K\pi(\pi\pi))}{\mathcal{B}(D^0 \to hh(\pi\pi))}$$

$$\mathcal{A}^{hh(\pi\pi)}_{CP} \equiv \frac{\Gamma\left(\overline{B}^0 \to D[hh(\pi\pi)]\overline{K}^{*0}\right) - \Gamma\left(B^0 \to D[hh(\pi\pi)]K^{*0}\right)}{\Gamma\left(\overline{B}^0 \to D[hh(\pi\pi)]\overline{K}^{*0}\right) + \Gamma\left(B^0 \to D[hh(\pi\pi)]K^{*0}\right)}$$

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

arXiv:2401.17934
(Submitted to JHEP)

Interpret measurements in terms of (γ, r^{DK^*}, δ^{DK^*}) with external inputs:

- Coherence factor κ_{B0} (dilution of interference effects from non-K* decays
- Hadronic D decay parameters r_D^X, δ_D^X, κ_D (for ADS)
- CP-even fractions F_+ (for GLW)

$$\mathcal{A}_{CP}^{hh(\pi\pi)} = \frac{2\kappa_{B^0} r_{B^0}^{DK^*}\left(2F_+^{hh(\pi\pi)}-1\right)\sin\left(\delta_{B^0}^{DK^*}\right)\sin(\gamma)}{1+\left(r_{B^0}^{DK^*}\right)^2+2\kappa_{B^0}\cos\left(\delta_{B^0}^{DK^*}\right)\cos(\gamma)},$$

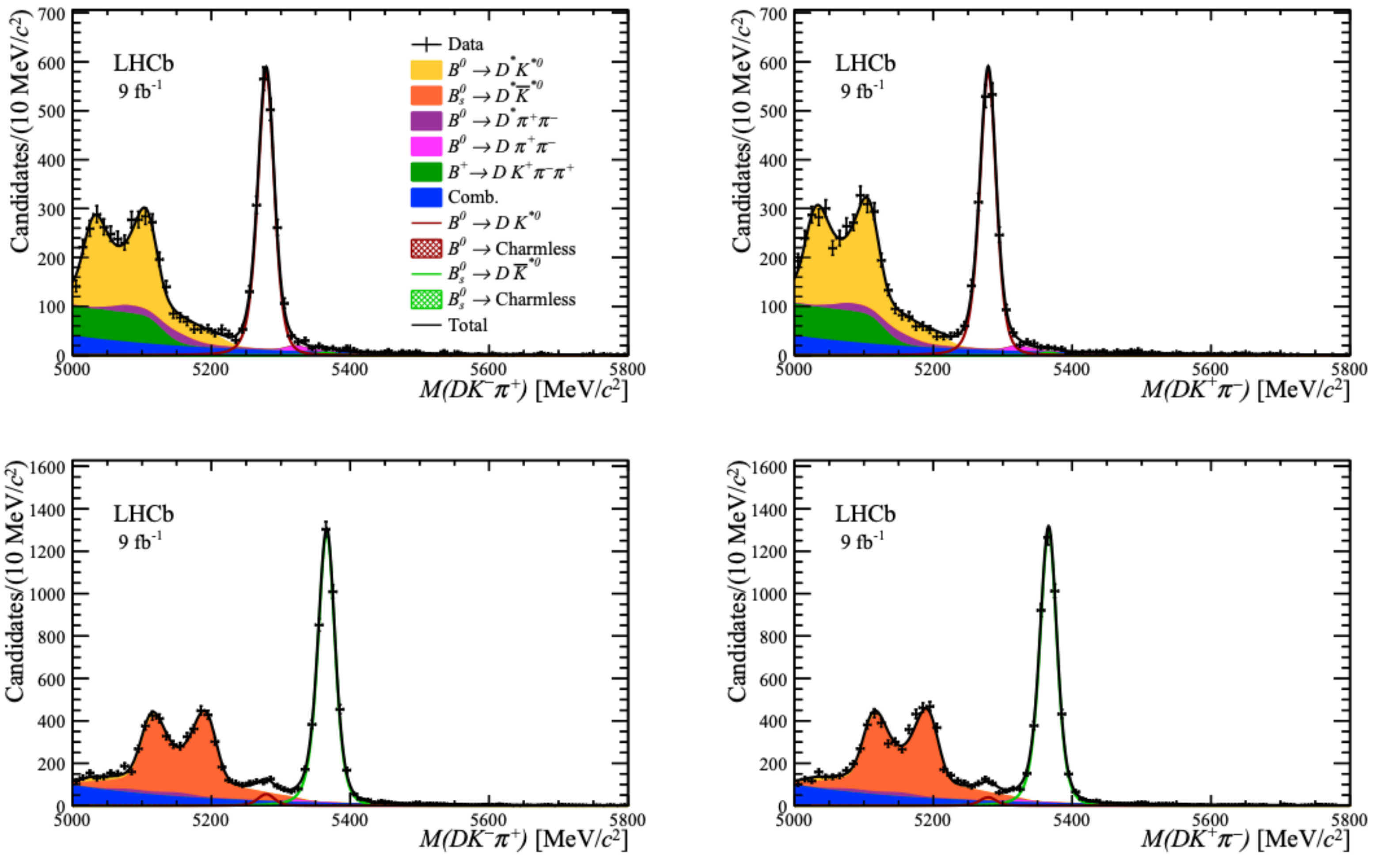
$$\mathcal{R}_{CP}^{hh(\pi\pi)} = \frac{1+\left(r_{B^0}^{DK^*}\right)^2+2\kappa_{B^0} r_{B^0}^{DK^*}\left(2F_+^{hh(\pi\pi)}-1\right)\cos\left(\delta_{B^0}^{DK^*}\right)\cos(\gamma)}{1+\left(r_{B^0}^{DK^*}\right)^2\left(r_D^{K\pi\pi\pi}\right)^2+2\kappa_{B^0} r_{B^0}^{DK^*} r_D^{K\pi\pi\pi}\kappa_D^{K\pi\pi\pi}\cos\left(\delta_{B^0}^{DK^*}-\delta_D^{K\pi\pi\pi}\right)\cos(\gamma)}$$

$$\mathcal{R}_{\pi K(\pi\pi)}^{\pm} = \frac{\left(r_{B^0}^{DK^*}\right)^2+\left(r_D^{K\pi(\pi\pi)}\right)^2+2\kappa_{B^0} r_{B^0}^{DK^*} r_D^{K\pi(\pi\pi)}\kappa_D^{K\pi(\pi\pi)}\cos\left(\delta_{B^0}^{DK^*}+\delta_D^{K\pi(\pi\pi)}\pm\gamma\right)}{1+\left(r_{B^0}^{DK^*}\right)^2\left(r_D^{K\pi(\pi\pi)}\right)^2+2\kappa_{B^0} r_{B^0}^{DK^*} r_D^{K\pi(\pi\pi)}\kappa_D^{K\pi(\pi\pi)}\cos\left(\delta_{B^0}^{DK^*}-\delta_D^{K\pi(\pi\pi)}\pm\gamma\right)}$$

$$\mathcal{A}_{K\pi(\pi\pi)} = \frac{2\kappa_{B^0}\kappa_D^{K\pi(\pi\pi)} r_D^{K\pi(\pi\pi)}\sin\left(\delta_{B^0}^{DK^*}-\delta_D^{K\pi(\pi\pi)}\right)\sin(\gamma)}{1+\left(r_{B^0}^{DK^*}\right)^2\left(r_D^{K\pi(\pi\pi)}\right)^2+2\kappa_{B^0}\kappa_D^{K\pi(\pi\pi)} r_D^{K\pi(\pi\pi)}\cos\left(\delta_{B^0}^{DK^*}-\delta_D^{K\pi(\pi\pi)}\right)\cos(\gamma)}$$

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

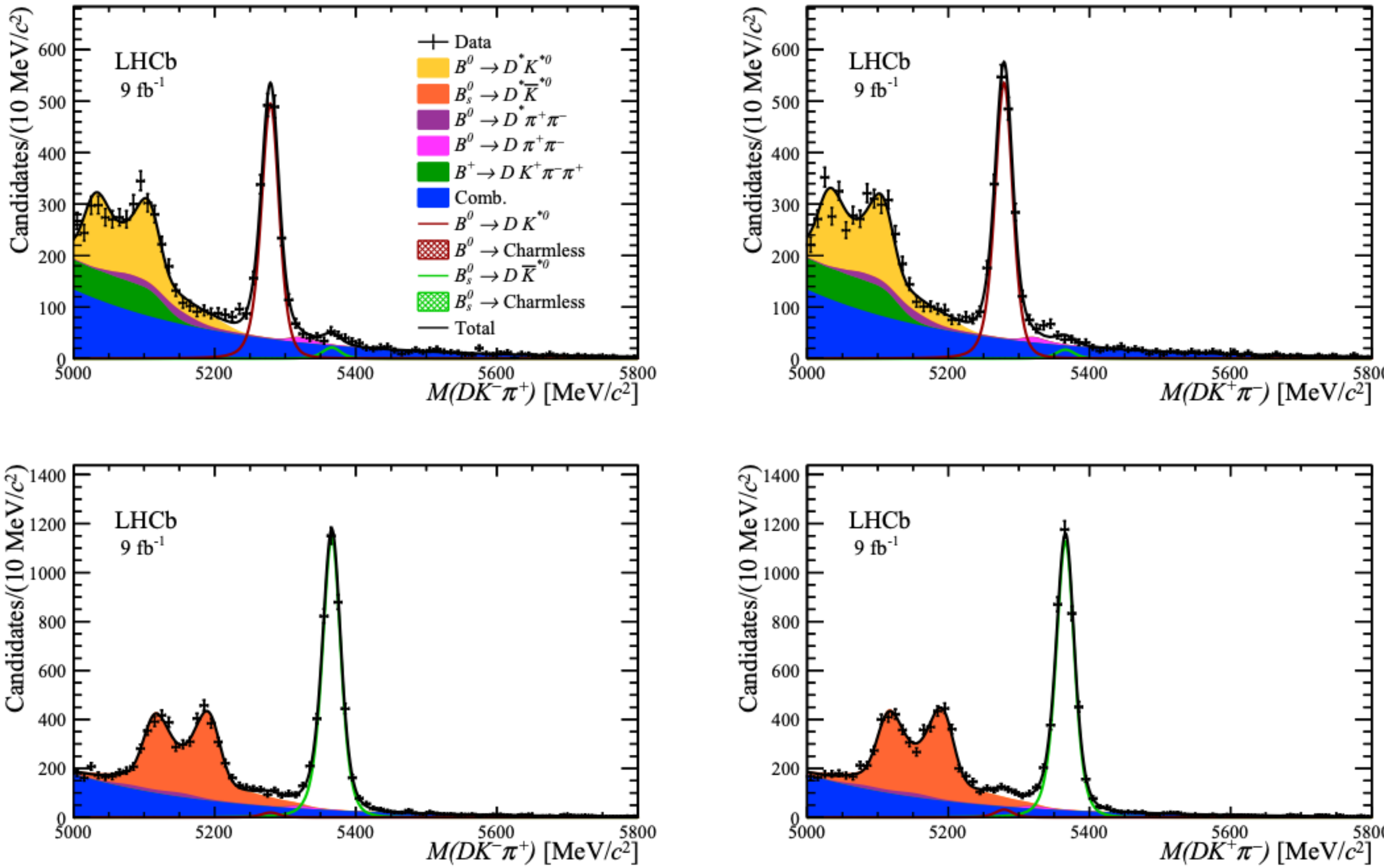
[arXiv:2401.17934](https://arxiv.org/abs/2401.17934)
(Submitted to JHEP)



Mass fits: D→Kπ for CF and CDS modes, for $\overline{B}{}^0$ (left) and B^0 (right) decays

Extra: CPV in $B^0 \to \overset{(—)}{D}{}^0 K^*(892)^0$ decays

arXiv:2401.17934
(Submitted to JHEP)



Mass fits: D→K3π for CF and DCS modes, for $\overline{B}{}^0$ (left) and B^0 (right) decays

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

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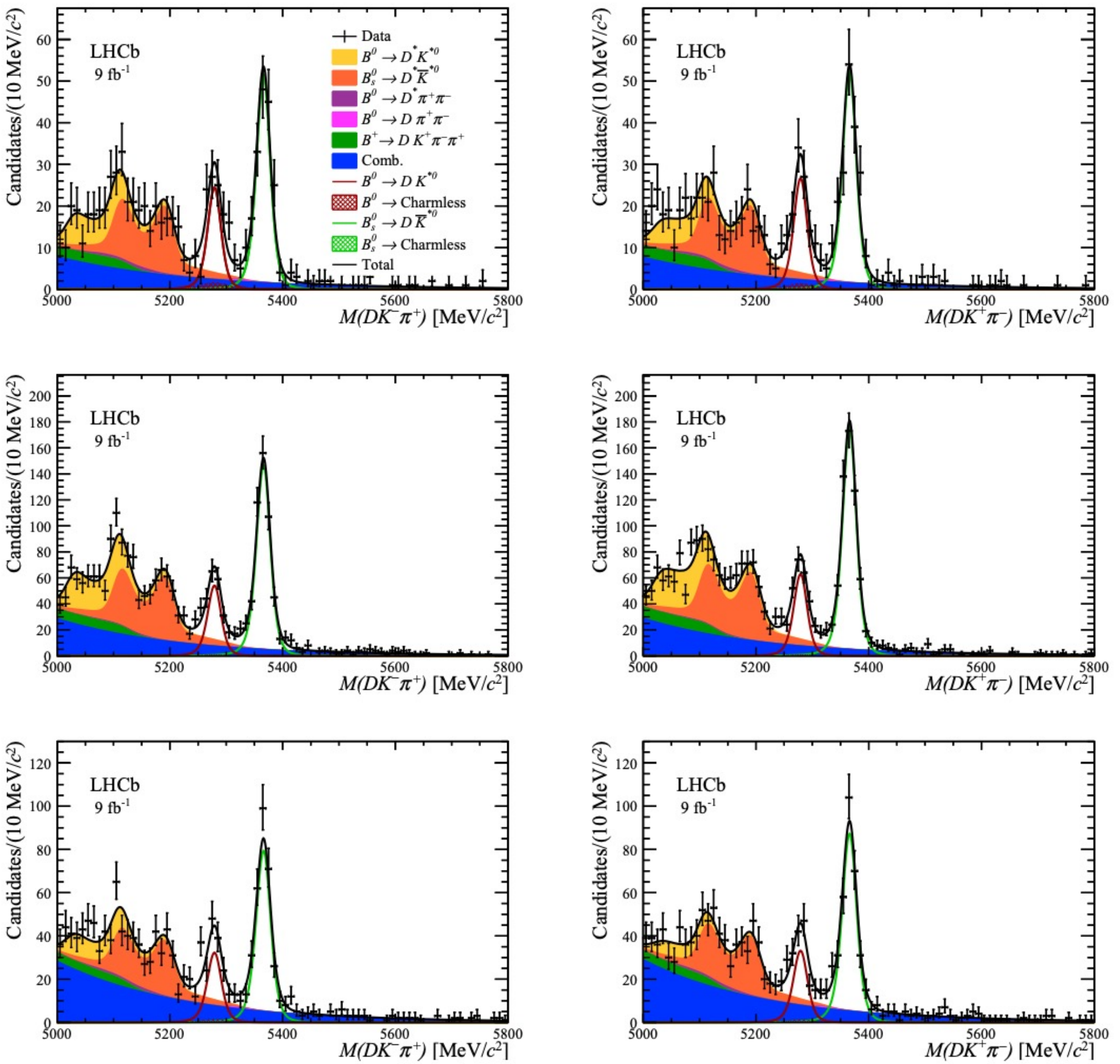
(Submitted to JHEP)



Mass fits:

- $D \to \pi\pi$ (top)
- $D \to KK$ (middle),
- $D \to \pi\pi\pi\pi$ (bottom)

for $\overline{B}{}^0$ (left) and B^0 (right) decays

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

[arXiv:2401.17934](https://arxiv.org/abs/2401.17934)
(Submitted to JHEP)

Measured observables in B^0 (left) and B^0_s (right) channels

Parameter	Value
$\mathcal{A}_{K\pi}$	$0.031 \pm 0.017 \pm 0.015$
$\mathcal{R}^+_{\pi K}$	$0.069 \pm 0.013 \pm 0.005$
$\mathcal{R}^-_{\pi K}$	$0.093 \pm 0.013 \pm 0.005$
$\mathcal{A}_{K\pi\pi\pi}$	$-0.012 \pm 0.018 \pm 0.016$
$\mathcal{R}^+_{\pi K\pi\pi}$	$0.060 \pm 0.014 \pm 0.006$
$\mathcal{R}^-_{\pi K\pi\pi}$	$0.038 \pm 0.014 \pm 0.006$
$\mathcal{R}^{KK}_{CP}$	$0.811 \pm 0.057 \pm 0.017$
$\mathcal{A}^{KK}_{CP}$	$-0.047 \pm 0.063 \pm 0.015$
$\mathcal{R}^{\pi\pi}_{CP}$	$1.104 \pm 0.111 \pm 0.026$
$\mathcal{A}^{\pi\pi}_{CP}$	$-0.034 \pm 0.094 \pm 0.016$
$\mathcal{R}^{4\pi}_{CP}$	$0.882 \pm 0.086 \pm 0.033$
$\mathcal{A}^{4\pi}_{CP}$	$0.021 \pm 0.087 \pm 0.016$

Parameter	Value
$\mathcal{A}_{s,\pi K}$	$-0.009 \pm 0.011 \pm 0.020$
$\mathcal{R}^+_{s,K\pi}$	$0.004 \pm 0.002 \pm 0.006$
$\mathcal{R}^-_{s,K\pi}$	$0.004 \pm 0.002 \pm 0.006$
$\mathcal{A}_{s,\pi K\pi\pi}$	$-0.029 \pm 0.012 \pm 0.021$
$\mathcal{R}^+_{s,K\pi\pi\pi}$	$0.019 \pm 0.004 \pm 0.007$
$\mathcal{R}^-_{s,K\pi\pi\pi}$	$0.015 \pm 0.004 \pm 0.007$
$\mathcal{R}^{s,KK}_{CP}$	$1.000 \pm 0.034 \pm 0.016$
$\mathcal{A}^{s,KK}_{CP}$	$0.062 \pm 0.032 \pm 0.021$
$\mathcal{R}^{s,\pi\pi}_{CP}$	$0.996 \pm 0.057 \pm 0.023$
$\mathcal{A}^{s,\pi\pi}_{CP}$	$-0.001 \pm 0.056 \pm 0.021$
$\mathcal{R}^{s,4\pi}_{CP}$	$1.010 \pm 0.048 \pm 0.033$
$\mathcal{A}^{s,4\pi}_{CP}$	$0.017 \pm 0.044 \pm 0.022$

3σ evidence for interference
in KK mode (R < 1)

No evidence for interference
(R ≈ 1)

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

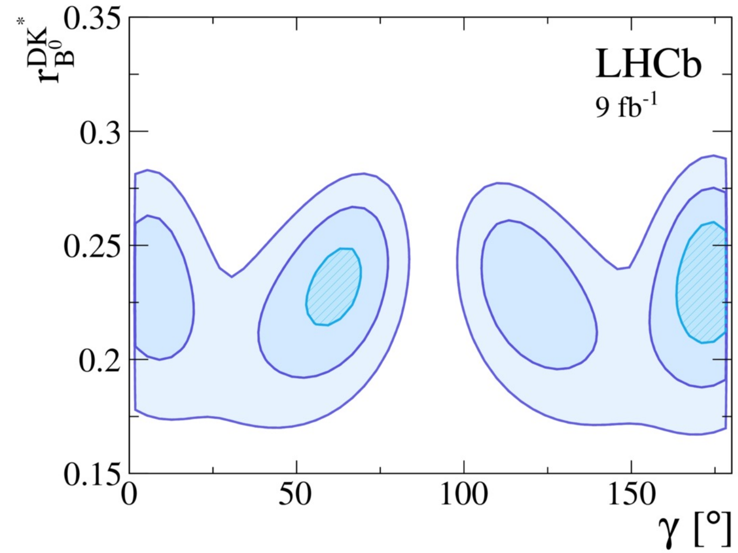
arXiv:2401.17934
(Submitted to JHEP)

	$\mathcal{A}_{K\pi}$	$\mathcal{R}^{+}_{\pi K}$	$\mathcal{R}^{-}_{\pi K}$	$\mathcal{R}^{\pi\pi}_{CP}$	$\mathcal{A}^{\pi\pi}_{CP}$	$\mathcal{R}^{KK}_{CP}$	$\mathcal{A}^{KK}_{CP}$	$\mathcal{A}_{K\pi\pi\pi}$	$R^{+}_{\pi K\pi\pi}$	$\mathcal{R}^{-}_{\pi K\pi\pi}$	$\mathcal{R}^{4\pi}_{CP}$	$\mathcal{A}^{4\pi}_{CP}$
A_{prod}	0.009	0.001	0.001	0.002	0.009	–	0.009	0.009	0.001	0.001	–	0.009
$A_{K\pi}$	0.009	0.001	0.001	0.001	0.006	0.001	0.006	0.009	0.001	0.001	0.001	0.006
PID	0.008	0.004	0.004	0.012	0.010	0.010	0.010	0.010	0.004	0.004	0.017	0.011
Fit PDFs	–	0.003	0.003	–	–	–	–	–	0.003	0.003	–	–
Charmless Asymmetries	–	–	–	0.011	0.005	–	–	–	0.001	0.001	–	–
Combinatorial Asymmetries	–	0.002	0.002	–	0.002	–	0.001	–	0.004	0.004	–	0.001
Input Branching Fractions	–	–	–	0.020	–	0.013	–	–	–	–	0.028	–
Total systematic	0.015	0.005	0.005	0.026	0.016	0.017	0.015	0.016	0.006	0.006	0.033	0.016
Statistical	0.017	0.013	0.013	0.110	0.103	0.057	0.064	0.018	0.014	0.014	0.084	0.088

Measurements generally limited by sample size
Largest systematic uncertainties from nuisance asymmetries and PID efficiency

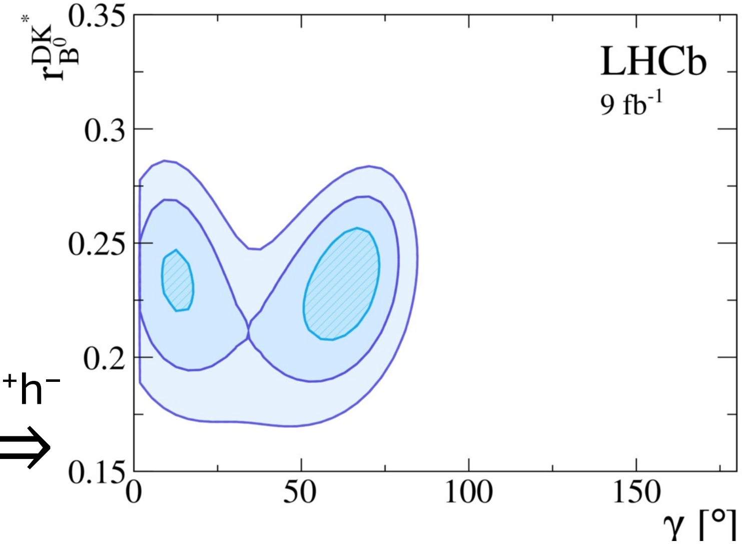
Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

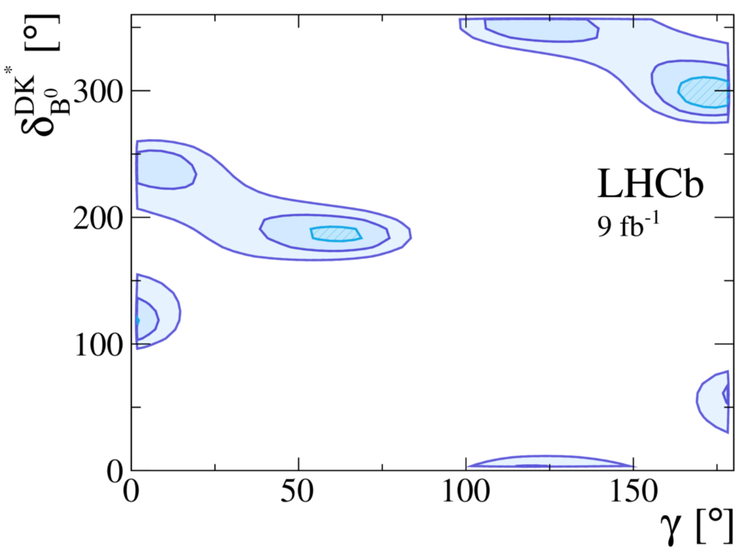
arXiv:2401.17934
(Submitted to JHEP)



⇐ Just this analysis

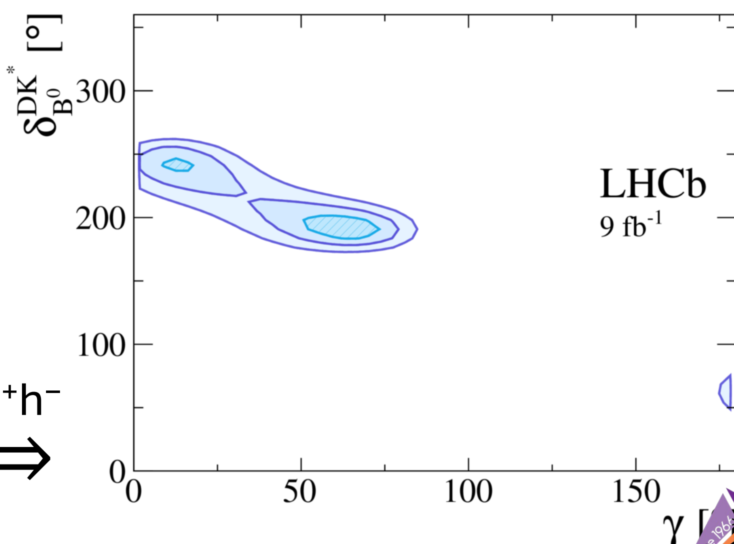
+ combine with $D \to K^0_S h^+ h^-$ ⇒





⇐ Just this analysis

+ combine with $D \to K^0_S h^+ h^-$ ⇒



Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

Eur.Phys.J.C 84 (2024) 2, 206
(arXiv:2309.05514)

Yields in bin *i* of Dalitz plot:

$$N_i(B^0) = h^{B^0}\left[F_{-i} + (x_+^2 + y_+^2)F_i + 2\kappa\sqrt{F_iF_{-i}}(x_+c_i - y_+s_i)\right]$$
$$N_i(\bar{B}^0) = h^{\bar{B}^0}\left[F_i + (x_-^2 + y_-^2)F_{-i} + 2\kappa\sqrt{F_iF_{-i}}(x_-c_i + y_-s_i)\right]$$

⇒ sensitive to γ:

$$x_\pm \equiv r_{B^0}\cos(\delta_{B^0} \pm \gamma)$$
$$y_\pm \equiv r_{B^0}\sin(\delta_{B^0} \pm \gamma)$$

Where:

$$F_i \equiv \frac{\int_i \mathrm{d}m_-^2\,\mathrm{d}m_+^2\,|A_D(m_-^2, m_+^2)|^2\eta(m_-^2, m_+^2)}{\sum_j \int_j \mathrm{d}m_-^2\,\mathrm{d}m_+^2\,|A_D(m_-^2, m_+^2)|^2\eta(m_-^2, m_+^2)}$$

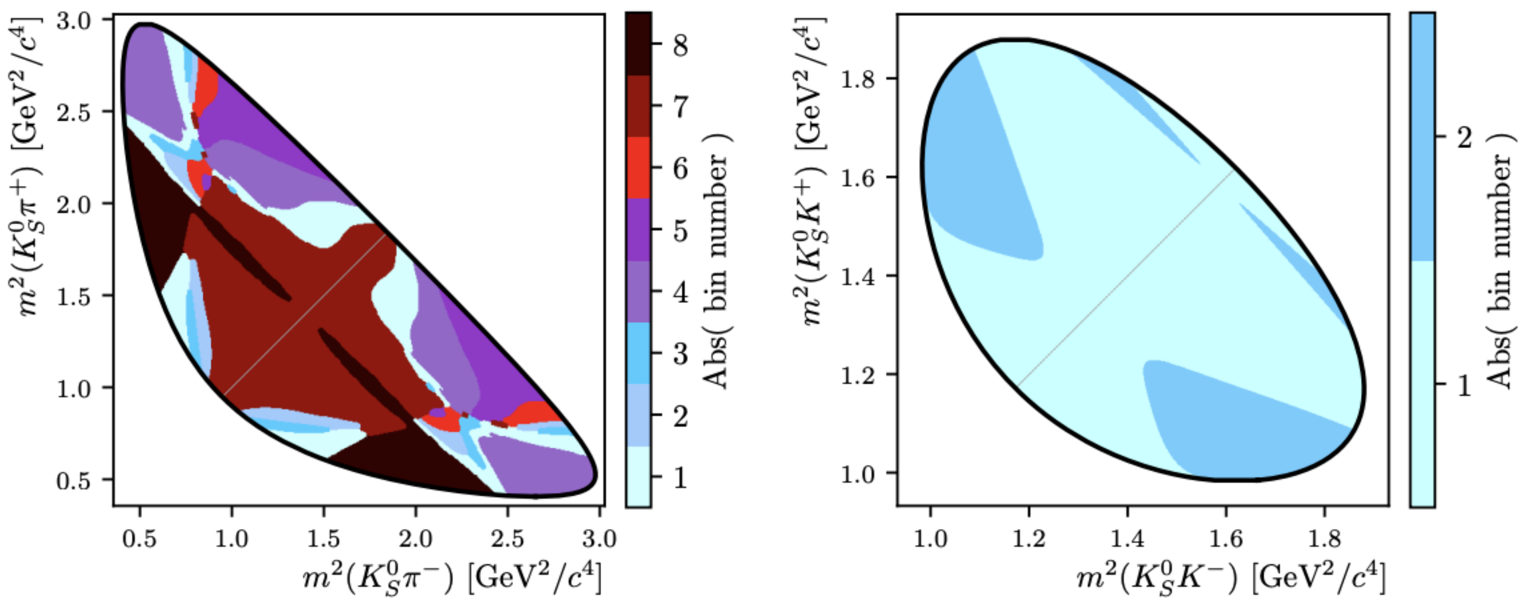
Efficiency

Integrated yields

$$K_i = \int_i \mathrm{d}m_-^2\,\mathrm{d}m_+^2\,|A_D(m_-^2, m_+^2)|^2,$$
$$c_i = \frac{1}{\sqrt{K_iK_{-i}}}\int_i \mathrm{d}m_-^2\,\mathrm{d}m_+^2\,|A_D(m_-^2, m_+^2)||A_{\bar{D}}(m_-^2, m_+^2)|\cos\delta_D(m_-^2, m_+^2),$$
$$s_i = \frac{1}{\sqrt{K_iK_{-i}}}\int_i \mathrm{d}m_-^2\,\mathrm{d}m_+^2\,|A_D(m_-^2, m_+^2)||A_{\bar{D}}(m_-^2, m_+^2)|\sin\delta_D(m_-^2, m_+^2).$$

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

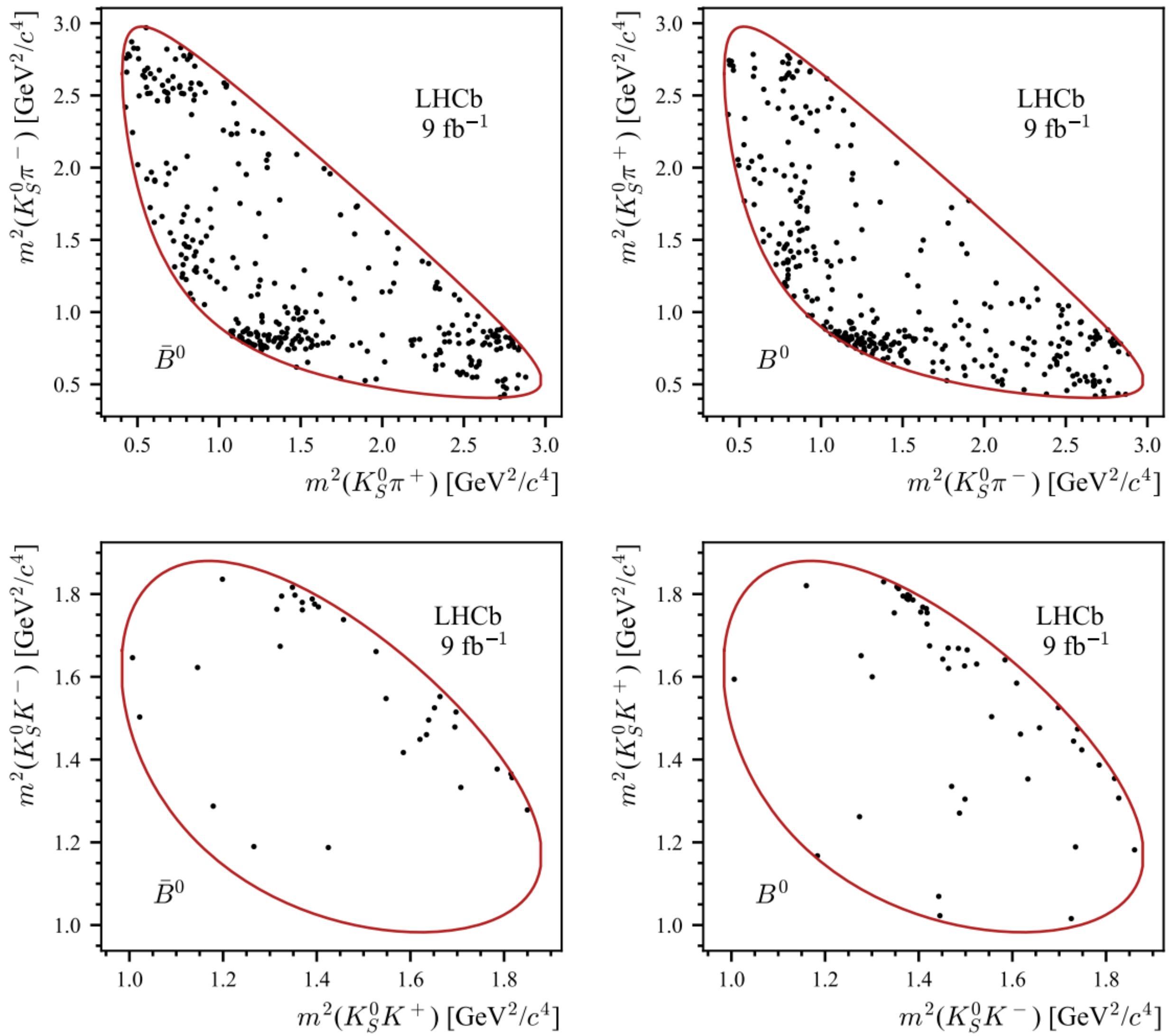
[Eur.Phys.J.C 84 (2024) 2, 206 (arXiv:2309.05514)]



Model-independent approach: strong phases take from binned measurements by BESIII and CLEO

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

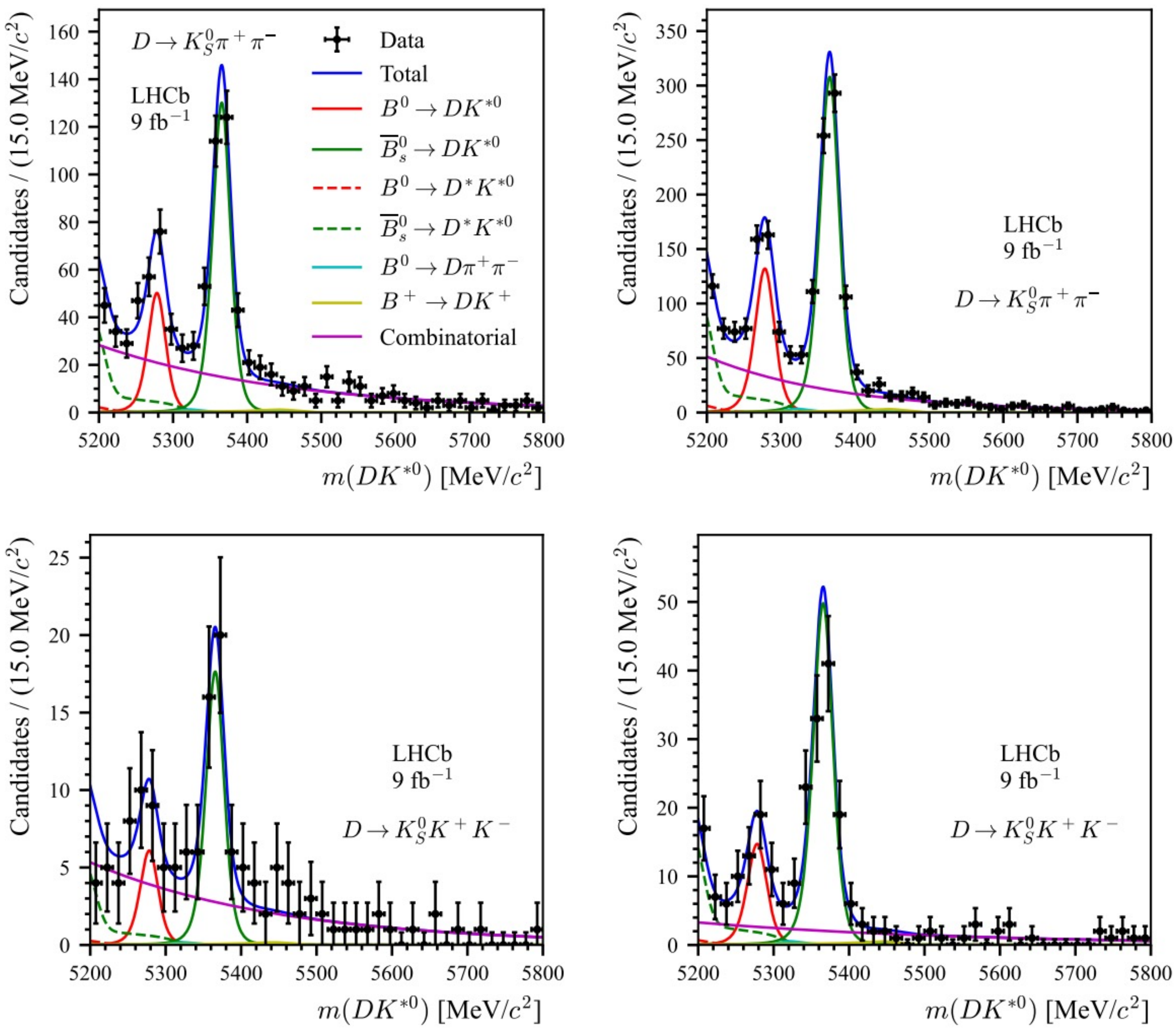
Eur.Phys.J.C 84 (2024) 2, 206 (arXiv:2309.05514)



Dalitz plots for selected events

Left: $\bar{B}^0$
Right: B^0

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays



[Eur.Phys.J.C 84 (2024) 2, 206 (arXiv:2309.05514)]

Fits used to obtain yields (global fits)

Left: *long* K_S^0
Right: *downstream* K_S^0

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

[Eur.Phys.J.C 84 (2024) 2, 206 (arXiv:2309.05514)]

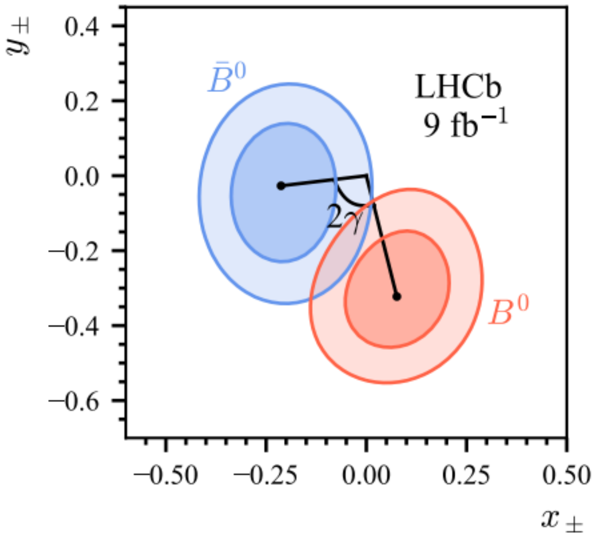
Yields for signal and non-negligible backgrounds:

Component	$D \to K^0_S\pi^+\pi^-$ *long*	$D \to K^0_S\pi^+\pi^-$ *downstream*	$D \to K^0_S K^+K^-$ *long*	$D \to K^0_S K^+K^-$ *downstream*
$B^0 \to DK^{*0}$	102 ± 17	288 ± 25	12 ± 6	32 ± 8
$\overline{B}{}^0_s \to D^0K^{*0}$	2.4 ± 0.4	7.1 ± 0.6	0.32 ± 0.08	1.2 ± 0.2
Combinatorial	84 ± 8	133 ± 11	16 ± 3	11 ± 4
$\overline{B}{}^0_s \to D^{*0}K^{*0}$	17.1 ± 1.4	44 ± 2	2.3 ± 0.5	7.1 ± 0.8
$B^0 \to D^*K^{*0}$	≤ 1	≤ 1	≤ 1	≤ 1
$B^0 \to D\pi^+\pi^-$	≤ 1	1.8 ± 0.5	≤ 1	≤ 1
$B^\pm \to DK^\pm$	≤ 1	2.0 ± 0.4	≤ 1	≤ 1

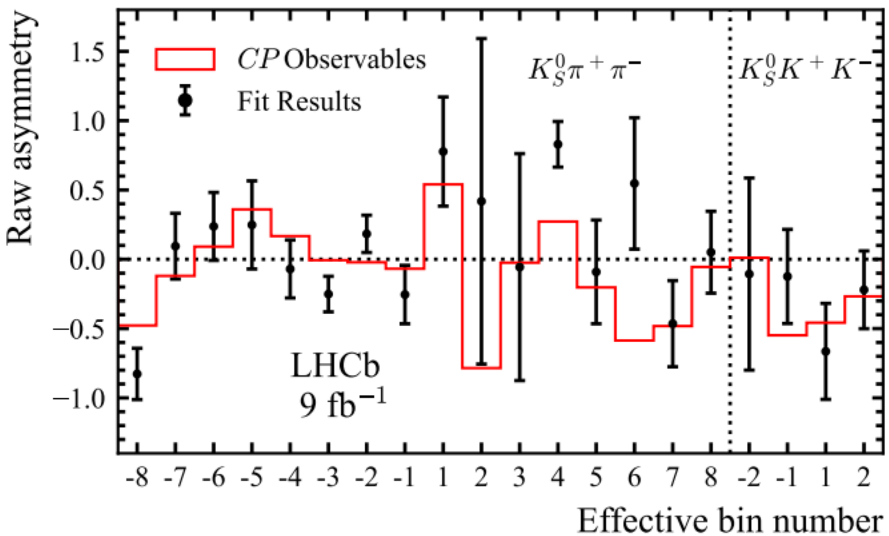
Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

Eur.Phys.J.C 84 (2024) 2, 206
(arXiv:2309.05514)

2D confidence regions for CP asymmetry measurement



Raw asymmetry per Dalitz bin pair



$$
\begin{aligned}
x_+ &= 0.074 \pm 0.086 \pm 0.005 \pm 0.011 \\
x_- &= -0.215 \pm 0.086 \pm 0.004 \pm 0.013 \\
y_+ &= -0.336 \pm 0.105 \pm 0.017 \pm 0.009 \\
y_- &= -0.012 \pm 0.128 \pm 0.024 \pm 0.011
\end{aligned}
\quad \Rightarrow \quad
\begin{aligned}
\gamma &= (49^{+22}_{-19})^\circ \\
r_{B^0} &= 0.271^{+0.065}_{-0.066} \\
\delta_{B^0} &= (236^{+19}_{-21})^\circ
\end{aligned}
$$

Extra: CPV in $B^0 \to \overset{(-)}{D}{}^0 K^*(892)^0$ decays

Eur.Phys.J.C 84 (2024) 2, 206
(arXiv:2309.05514)

Systematic uncertainties. Statistical precision dominates.

Source	$\sigma(x_+)$	$\sigma(x_-)$	$\sigma(y_+)$	$\sigma(y_-)$
Efficiency correction of (c_i, s_i)	0.001	0.001	0.002	0.001
F_i inputs	0.006	0.007	0.001	0.000
Mass Fit	0.002	0.006	0.005	0.004
$B^0 \to D^* K^{*0}$ CP violation	0.001	0.001	0.001	0.001
Value of κ	0.000	0.001	0.003	0.002
Charmless background	0.009	0.008	0.000	0.005
Bin migration	0.001	0.001	0.000	0.002
Fitter bias	0.003	0.003	0.006	0.004
Total of above systematics	0.011	0.013	0.009	0.011
Strong-phase measurements	0.005	0.004	0.017	0.024
Statistical uncertainty	0.086	0.086	0.105	0.128

Extra: $B^{\pm} \to D^{*} h^{\pm}$, $D \to K^0_S h^+ h^-$

Decay amplitude:

$$A(B^- \to D^* h^-) \propto A_D(s_-, s_+) + f_{D^*} A_{\bar{D}}(s_-, s_+) r_B^{D^*h} e^{i(\delta_B^{D^*h} - \gamma)}$$

CF decay

CS decay

Strong and weak phase differences

Ratio of magnitudes

$D^0\pi^0$: +1
$D^0\gamma$: −1

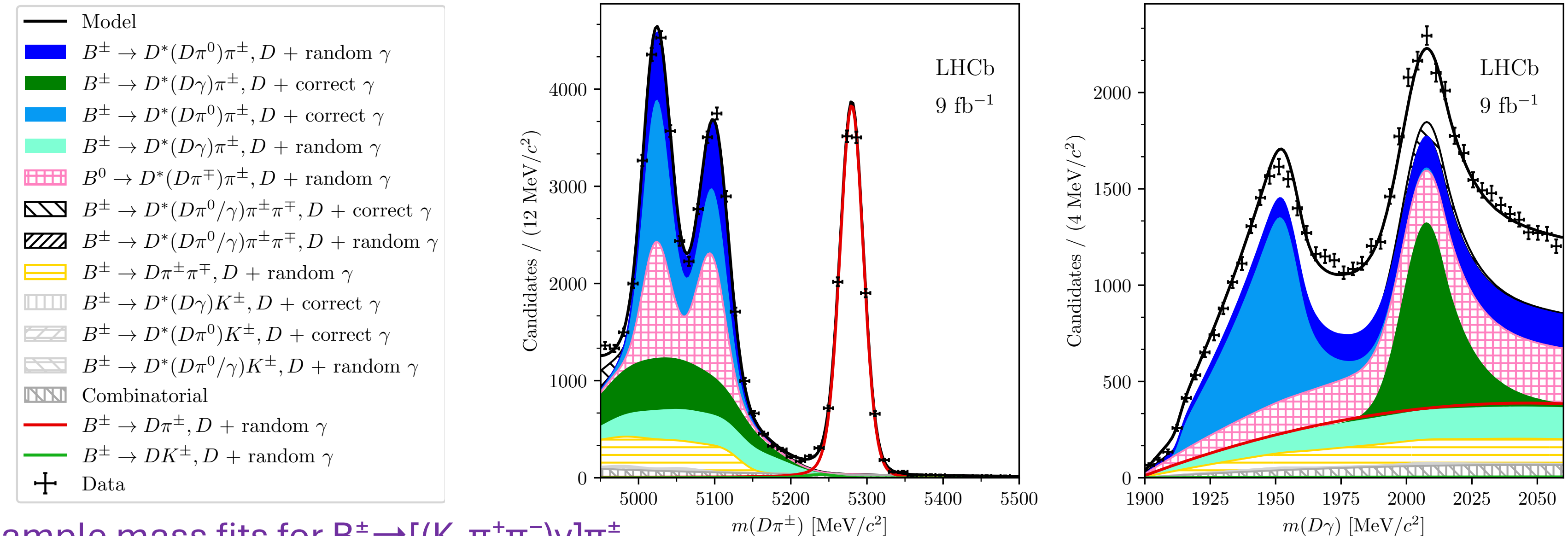
With D^0 decay amplitude:

Strong-phase depends on Dalitz coordinates

$$A_D(s_-, s_+) \equiv A(D^0 \to K^0_S h^+ h^-) = |A_D(s_-, s_+)| e^{i\delta_D(s_-, s_+)}$$

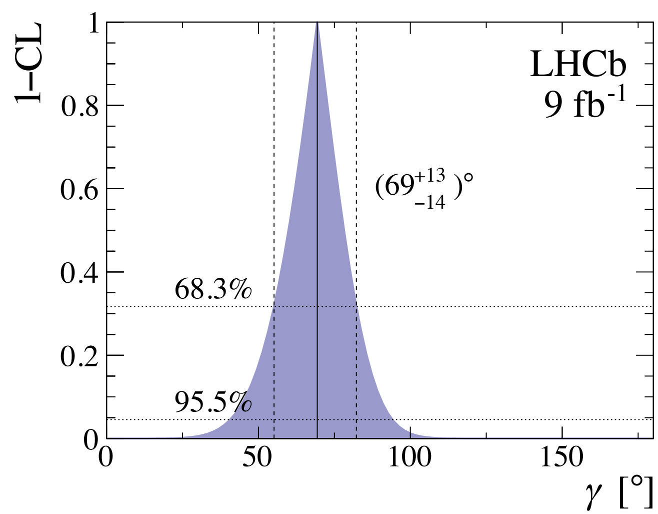
Extra: $B^{\pm} \rightarrow D^{*} h^{\pm}$, $D \rightarrow K^0_S h^+ h^-$ (full reco)

arXiv:2310.04277
(JHEP 12 (2023) 013)



Example mass fits for $B^{\pm} \rightarrow [(K_S\pi^+\pi^-)\gamma]\pi^{\pm}$

- Single clear maximum
- Statistically limited
- Main systematics from backgrounds, DP migration, external CP asymmetries



$$\gamma = (69^{+13}_{-14})^\circ,$$
$$r_B^{D^*K} = 0.15 \pm 0.03,$$
$$r_B^{D^*\pi} = 0.01 \pm 0.01,$$
$$\delta_B^{D^*K} = (311 \pm 14)^\circ,$$
$$\delta_B^{D^*\pi} = (37 \pm 37)^\circ.$$

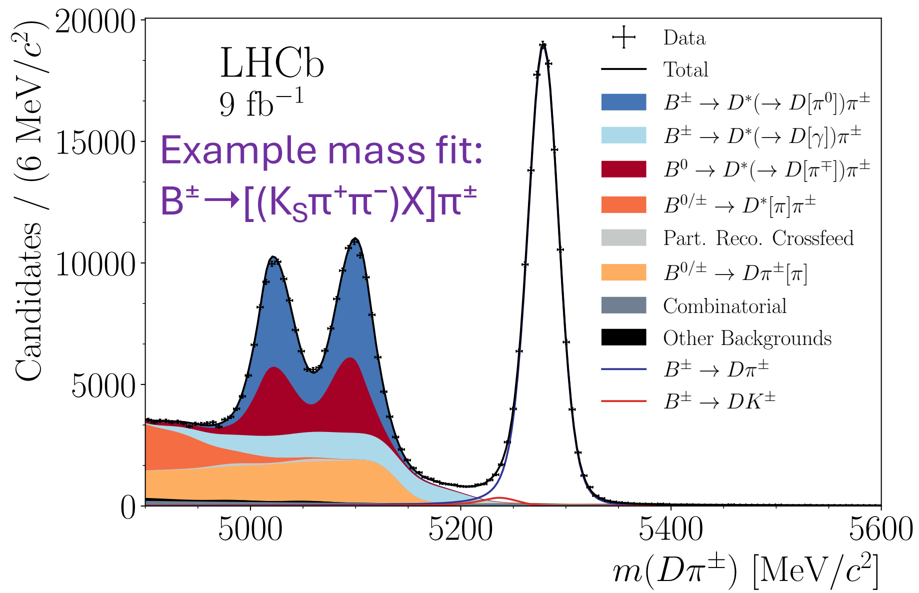
Extra: $B^\pm \to D^* h^\pm$, $D \to K^0_S h^+ h^-$ (part reco)

arXiv:2311.10434
(JHEP 02 (2024) 118)

$D^* \to D\gamma$ / $D\pi^0$ separated via $m(Dh^\pm)$ exploiting spin-parity structure.

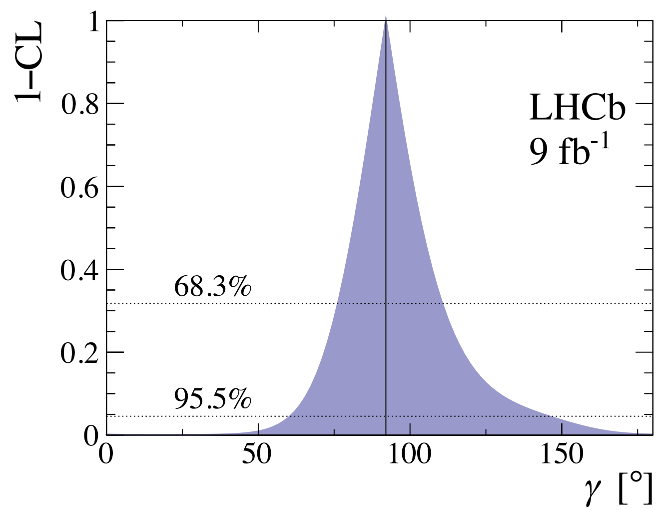
Much larger yields than fully-reco mode: ~113k $B^\pm \to [(K_S\pi^+\pi^-)X]\pi^\pm$

Precision suppressed by larger backgrounds and more complicated fit



Outlook for γ

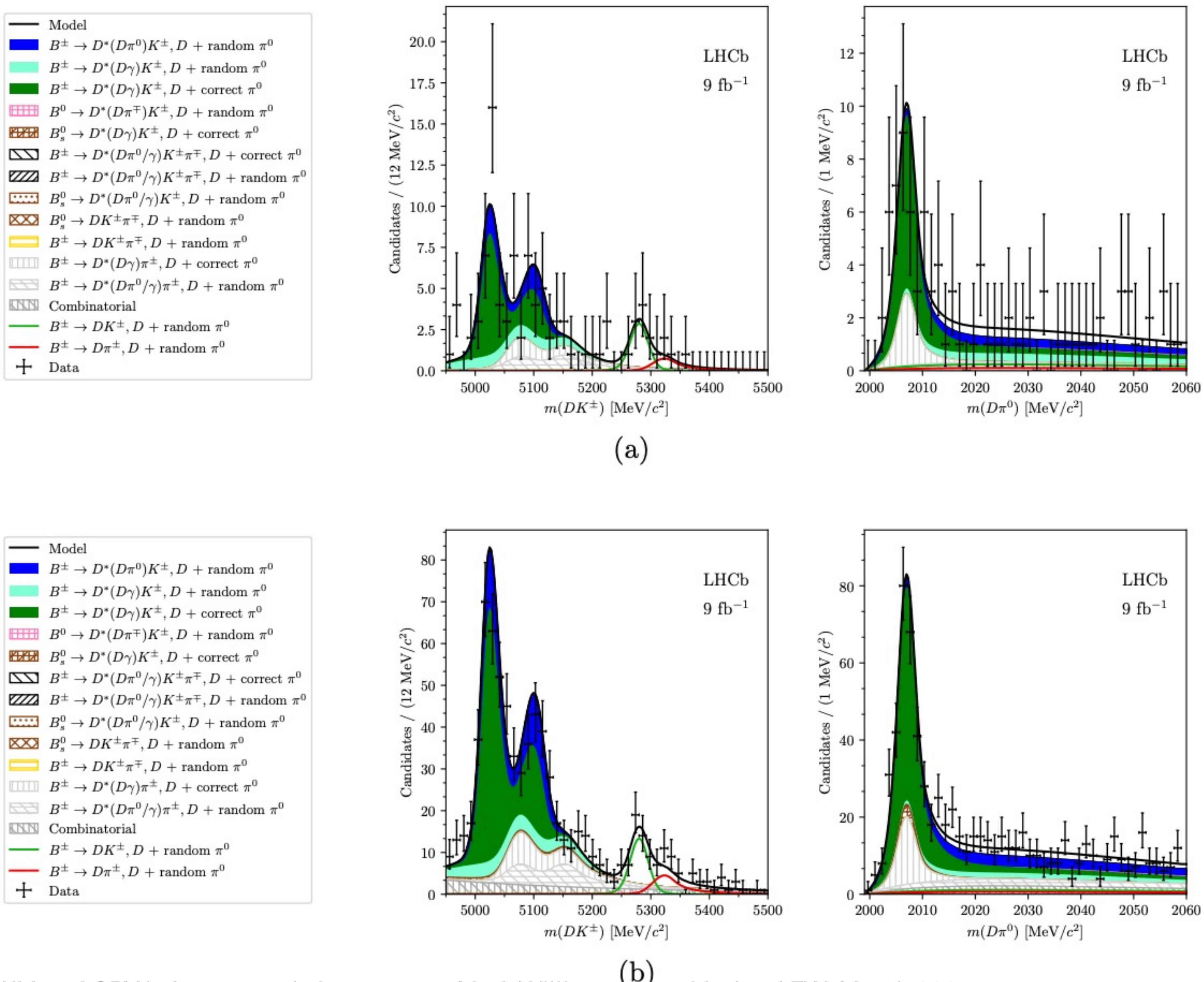
- Most benchmark channels completed with Run 1+2
- A few remain (e.g. $B_s \to D_s K$)
- Statistically limited
- Investigating new channels for full exploitation in Run 3
- Adding + Improving triggers



$$\gamma = (92^{+21}_{-17})^\circ,$$
$$r_B^{D^*K} = 0.080^{+0.022}_{-0.023},$$
$$\delta_B^{D^*K} = (310^{+15}_{-20})^\circ,$$
$$r_B^{D^*\pi} = 0.009^{+0.005}_{-0.007},$$
$$\delta_B^{D^*\pi} = (304^{+37}_{-38})^\circ.$$

Extra: $B^\pm \to D^* h^\pm$, $D \to K^0_S h^+ h^-$ (full reco)

arXiv:2310.04277
(JHEP 12 (2023) 013)



m(Dh$^\pm$) (left)
m(Dπ^0) (right)

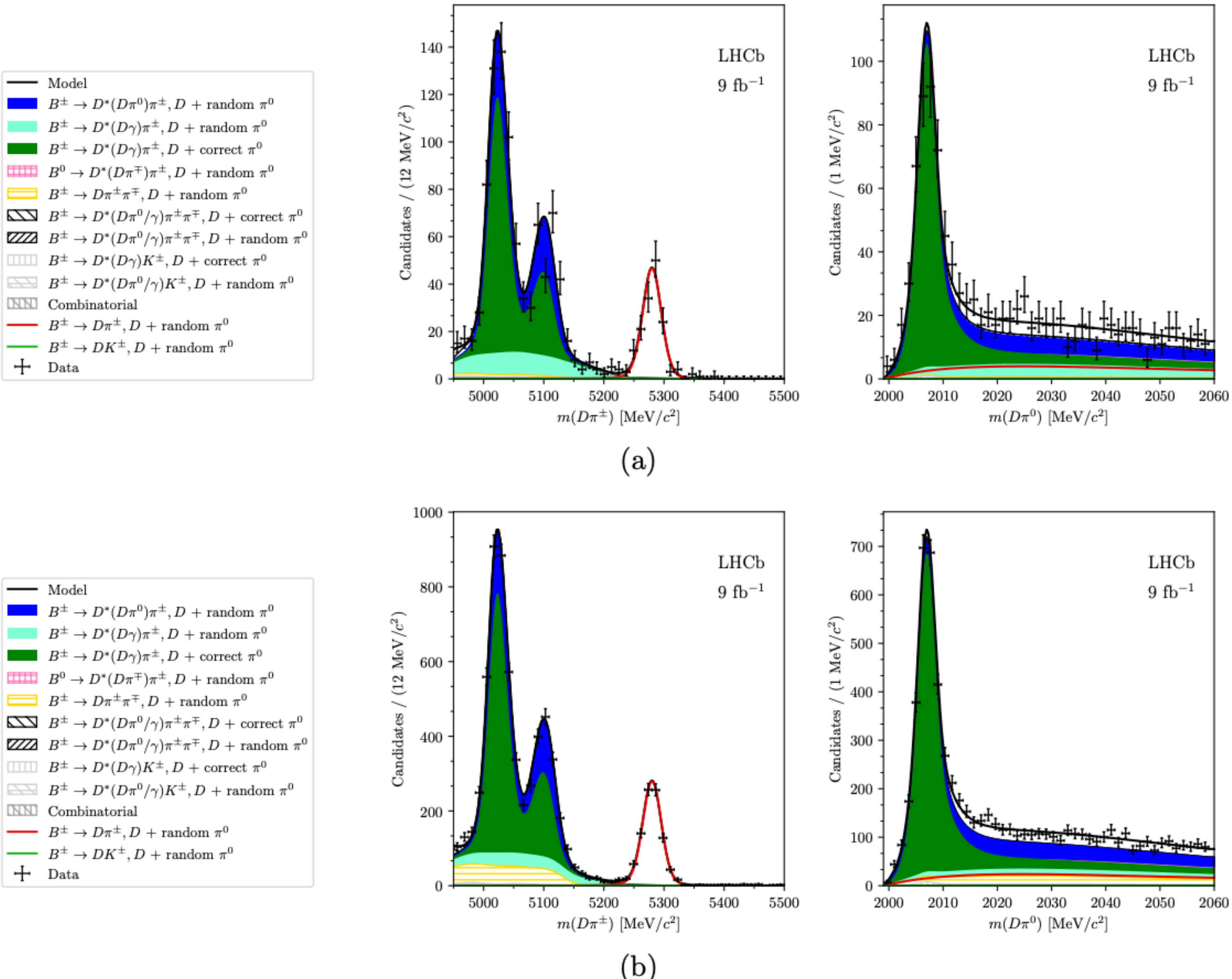
$D^0 \to K_S K^+ K^-$ (top)
$D^0 \to K_S \pi^+ \pi^-$ (bottom)

$B^\pm \to D^* K^\pm$ channels

$D^* \to D\pi^0$ mode

Extra: $B^{\pm} \to D^{*} h^{\pm}$, $D \to K^0_S h^+ h^-$ (full reco)

arXiv:2310.04277
[(JHEP 12 (2023) 013)](JHEP 12 (2023) 013)



m(Dh±) (left)
m(Dπ0) (right)

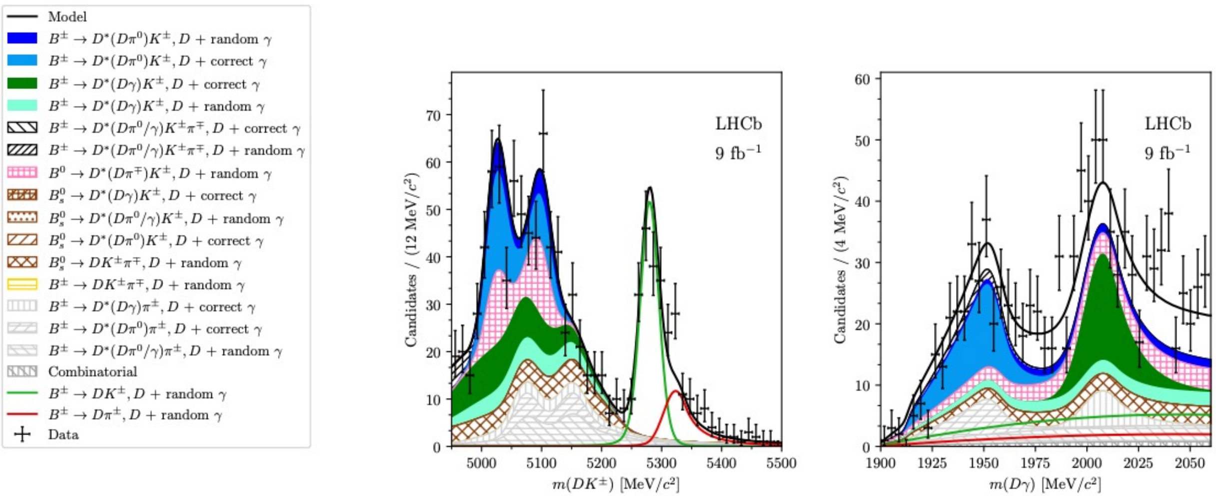
$D^0 \to K_S K^+ K^-$ (top)
$D^0 \to K_S \pi^+ \pi^-$ (bottom)

$B^{\pm} \to D^{*}\pi^{\pm}$ channels

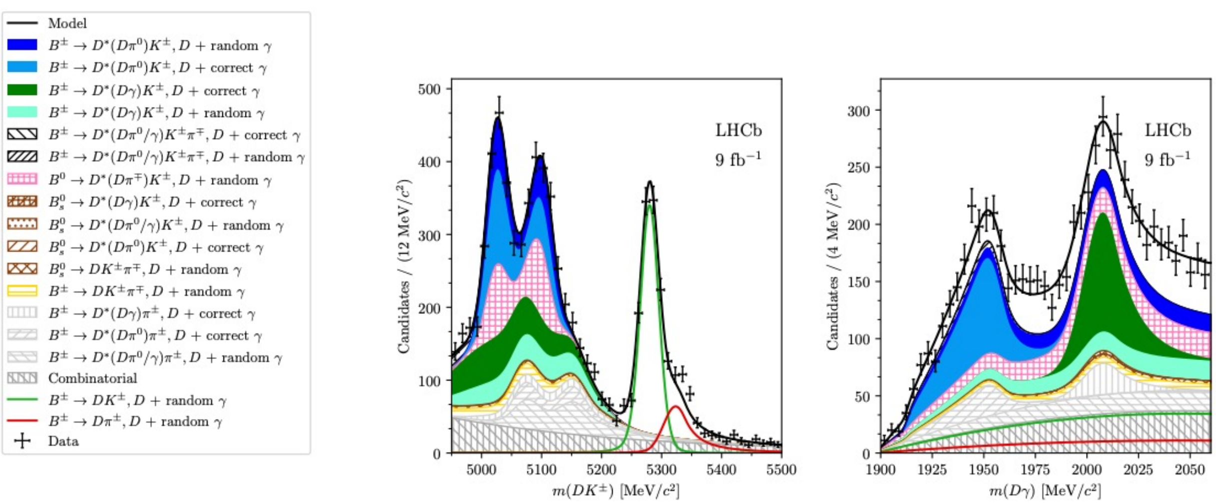
$D^{*} \to D\pi^0$ mode

Extra: $B^\pm \rightarrow D^* h^\pm$, $D \rightarrow K^0_S h^+ h^-$ (full reco)

arXiv:2310.04277
(JHEP 12 (2023) 013)



(a)



(b)

$m(Dh^\pm)$ (left)
$m(D\pi^0)$ (right)

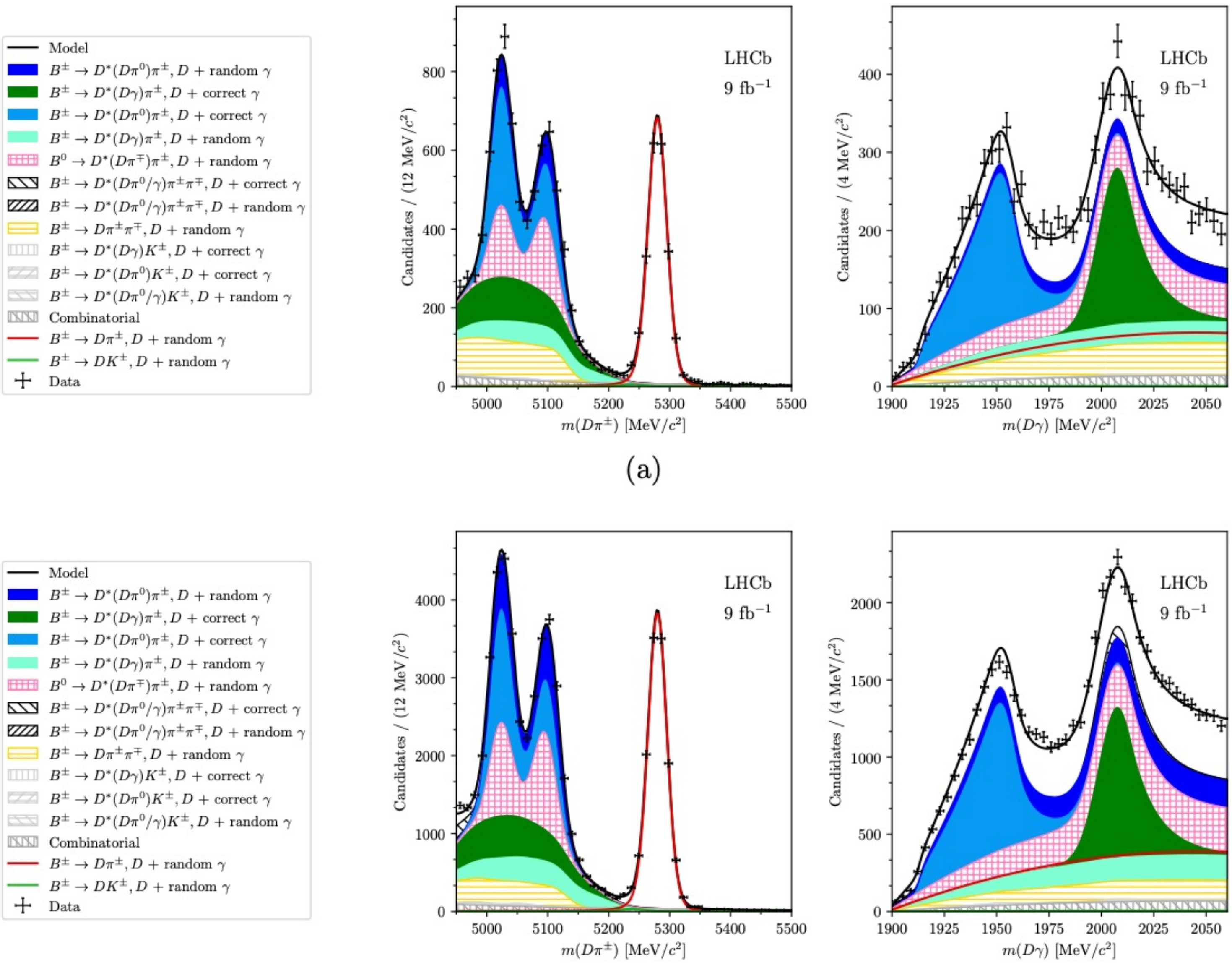
$D^0 \rightarrow K_S K^+ K^-$ (top)
$D^0 \rightarrow K_S \pi^+ \pi^-$ (bottom)

$B^\pm \rightarrow D^* K^\pm$ channels

$D^* \rightarrow D\gamma$ mode

Extra: $B^{\pm} \rightarrow D^{*} h^{\pm}$, $D \rightarrow K^0_S h^+ h^-$ (full reco)

arXiv:2310.04277
(JHEP 12 (2023) 013)



m(Dh±) (left)
m(Dπ0) (right)

$D^0 \rightarrow K_S K^+ K^-$ (top)
$D^0 \rightarrow K_S \pi^+ \pi^-$ (bottom)

$B^{\pm} \rightarrow D^{*}\pi^{\pm}$ channels

$D^{*} \rightarrow D\gamma$ mode

Extra: $B^{\pm} \rightarrow D^{*} h^{\pm}$, $D \rightarrow K^0_S h^+ h^-$ (full reco)

arXiv:2310.04277
(JHEP 12 (2023) 013)

Yields for datasets with $D^0 \rightarrow K_S \pi^+ \pi^-$:

Component	Yield
$B^+ \to D^*\pi^+, D^* \to D\pi^0$	1273 ± 32
$B^+ \to D^*\pi^+, D^* \to D\gamma$	3692 ± 158
$B^- \to D^*\pi^-, D^* \to D\pi^0$	1290 ± 33
$B^- \to D^*\pi^-, D^* \to D\gamma$	3683 ± 160
$B^+ \to D^*K^+, D^* \to D\pi^0$	112 ± 7
$B^+ \to D^*K^+, D^* \to D\gamma$	358 ± 33
$B^- \to D^*K^-, D^* \to D\pi^0$	109 ± 6
$B^- \to D^*K^-, D^* \to D\gamma$	419 ± 35

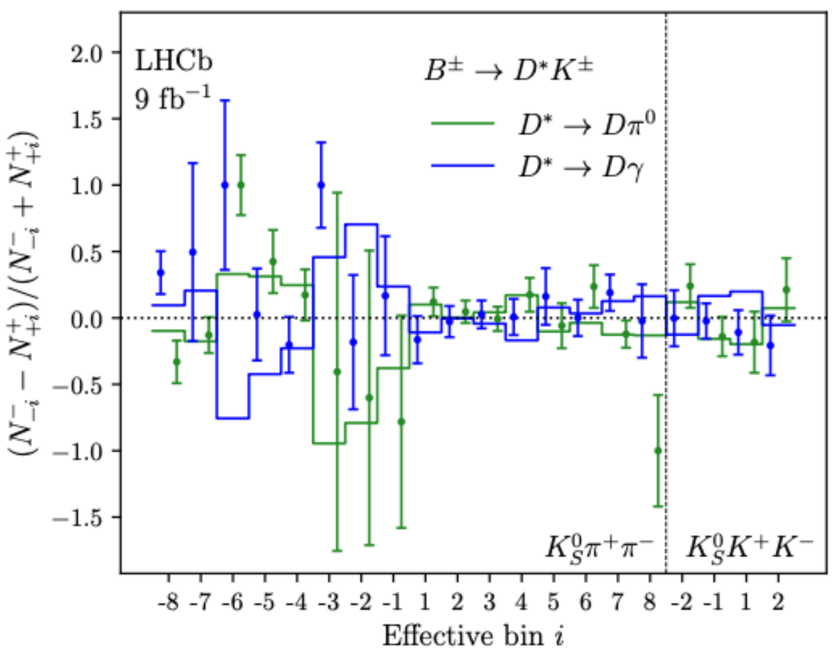
Yields for datasets with $D^0 \rightarrow K_S K^+ K^-$:

Component	Yield
$B^+ \to D^*\pi^+, D^* \to D\pi^0$	199 ± 13
$B^+ \to D^*\pi^+, D^* \to D\gamma$	782 ± 49
$B^- \to D^*\pi^-, D^* \to D\pi^0$	197 ± 13
$B^- \to D^*\pi^-, D^* \to D\gamma$	740 ± 48
$B^+ \to D^*K^+, D^* \to D\pi^0$	13 ± 2
$B^+ \to D^*K^+, D^* \to D\gamma$	69 ± 11
$B^- \to D^*K^-, D^* \to D\pi^0$	13 ± 2
$B^- \to D^*K^-, D^* \to D\gamma$	57 ± 11

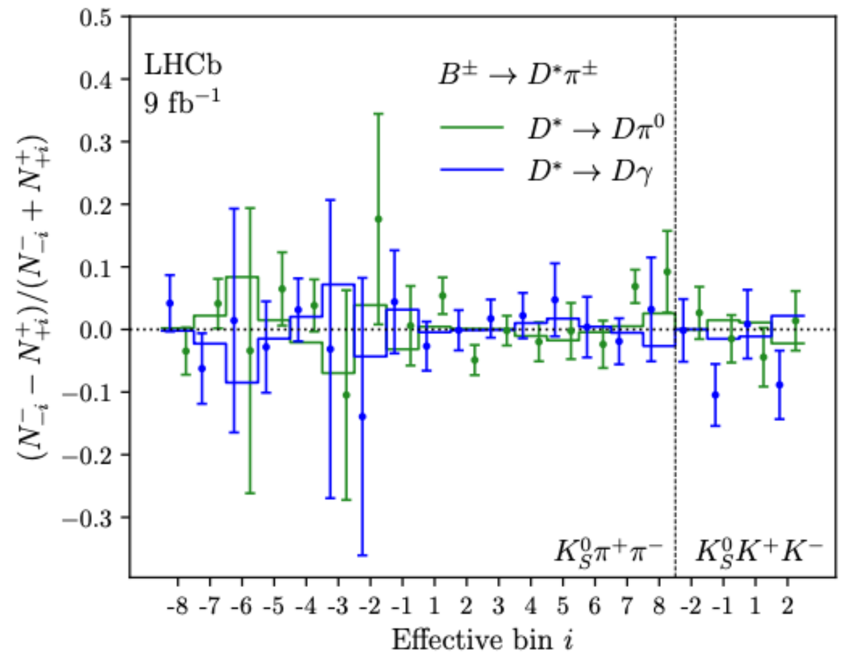
Extra: $B^{\pm} \rightarrow D^{*} h^{\pm}$, $D \rightarrow K^0_S h^+ h^-$ (full reco)

arXiv:2310.04277
(JHEP 12 (2023) 013)

CP asymmetries per bin for $B^{\pm} \rightarrow D^{*} K^{\pm}$



CP asymmetries per bin for $B^{\pm} \rightarrow D^{*} \pi^{\pm}$



Extra: $B^{\pm} \to D^* h^{\pm}$, $D \to K^0_S h^+ h^-$ (full reco)

arXiv:2310.04277 (JHEP 12 (2023) 013)

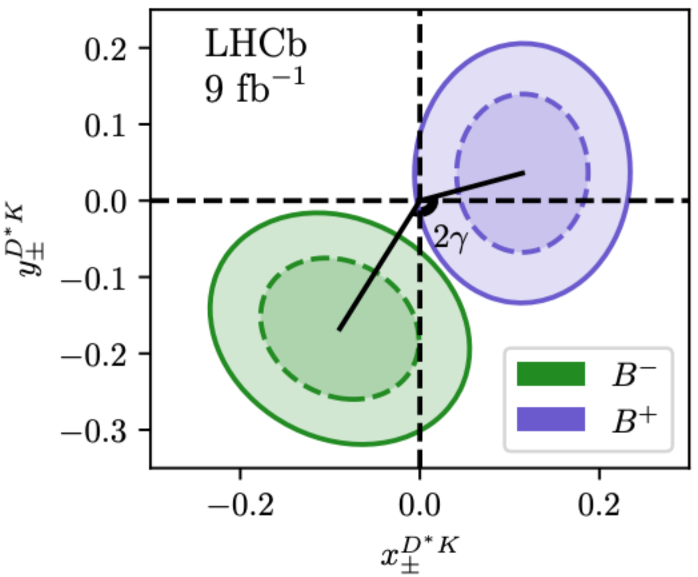
$$
\begin{aligned}
x_+^{D^*K} &= (\ \ 11.42 \pm 3.16 \pm 1.26 \pm 0.41) \times 10^{-2}, \\
x_-^{D^*K} &= (-8.91 \pm 3.55 \pm 2.04 \pm 0.23) \times 10^{-2}, \\
y_+^{D^*K} &= (\ \ 3.60 \pm 4.41 \pm 2.12 \pm 0.30) \times 10^{-2}, \\
y_-^{D^*K} &= (-16.75 \pm 3.98 \pm 1.48 \pm 0.64) \times 10^{-2}, \\
x_\xi^{D^*\pi} &= (\ \ 0.51 \pm 5.00 \pm 2.66 \pm 0.93) \times 10^{-2}, \\
y_\xi^{D^*\pi} &= (\ \ 7.92 \pm 5.04 \pm 3.78 \pm 0.83) \times 10^{-2},
\end{aligned}
$$

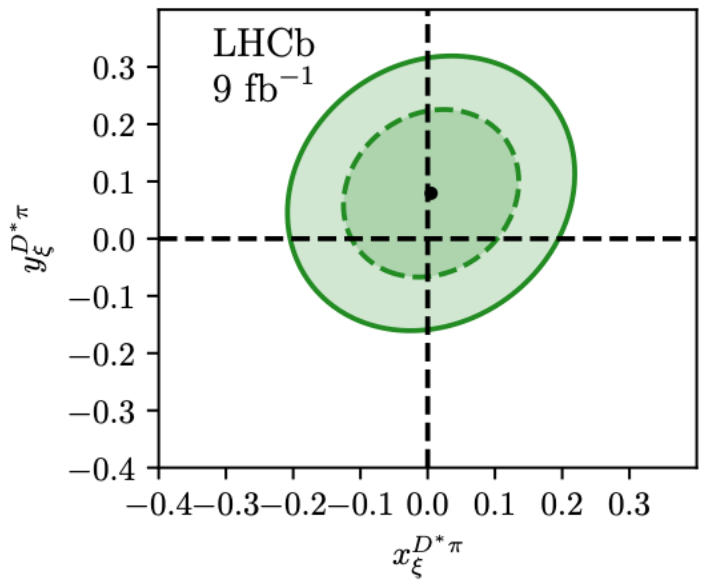
$$
\begin{aligned}
\gamma &= (69^{+13}_{-14})^\circ, \\
r_B^{D^*K} &= 0.15 \pm 0.03, \\
r_B^{D^*\pi} &= 0.01 \pm 0.01, \\
\delta_B^{D^*K} &= (311 \pm 14)^\circ, \\
\delta_B^{D^*\pi} &= (37 \pm 37)^\circ.
\end{aligned}
$$

Source	$\sigma(x_+^{D^*K})$	$\sigma(x_-^{D^*K})$	$\sigma(y_+^{D^*K})$	$\sigma(y_-^{D^*K})$	$\sigma(x_\xi^{D^*\pi})$	$\sigma(y_\xi^{D^*\pi})$
Neglecting correlations	0.05	0.03	0.19	0.04	0.70	1.48
Efficiency correction of (c_i, s_i)	0.53	0.18	0.18	0.20	0.64	1.73
Invariant mass shape parameter	0.09	0.16	0.20	0.05	0.39	0.06
Fixed yield ratios	0.09	0.03	0.03	0.01	0.33	0.15
Bin dependence of the invariant-mass shape	0.40	0.38	0.41	0.33	1.78	1.57
DP bin migration	0.32	0.70	0.03	0.17	1.2	2.0
Λ_b^0 background	0.97	1.34	0.55	0.77	1.13	1.43
Semileptonic B backgrounds	0.27	1.29	0.02	0.67	0.03	0.04
Merging data subsamples	0.06	0.02	0.12	0.03	0.06	0.34
CP-violation in $B^{\pm,0} \to DK^{\pm}\pi^{0,\mp}$	0.03	0.13	1.97	0.99	0.13	0.68
Total systematic	1.26	2.04	2.12	1.48	2.66	3.78
Strong-phase inputs (external)	0.41	0.23	0.30	0.64	0.93	0.83
Statistical	3.16	3.55	4.41	3.98	5.00	5.04

Extra: $B^\pm \to D^* h^\pm$, $D \to K^0_S h^+ h^-$ (full reco)

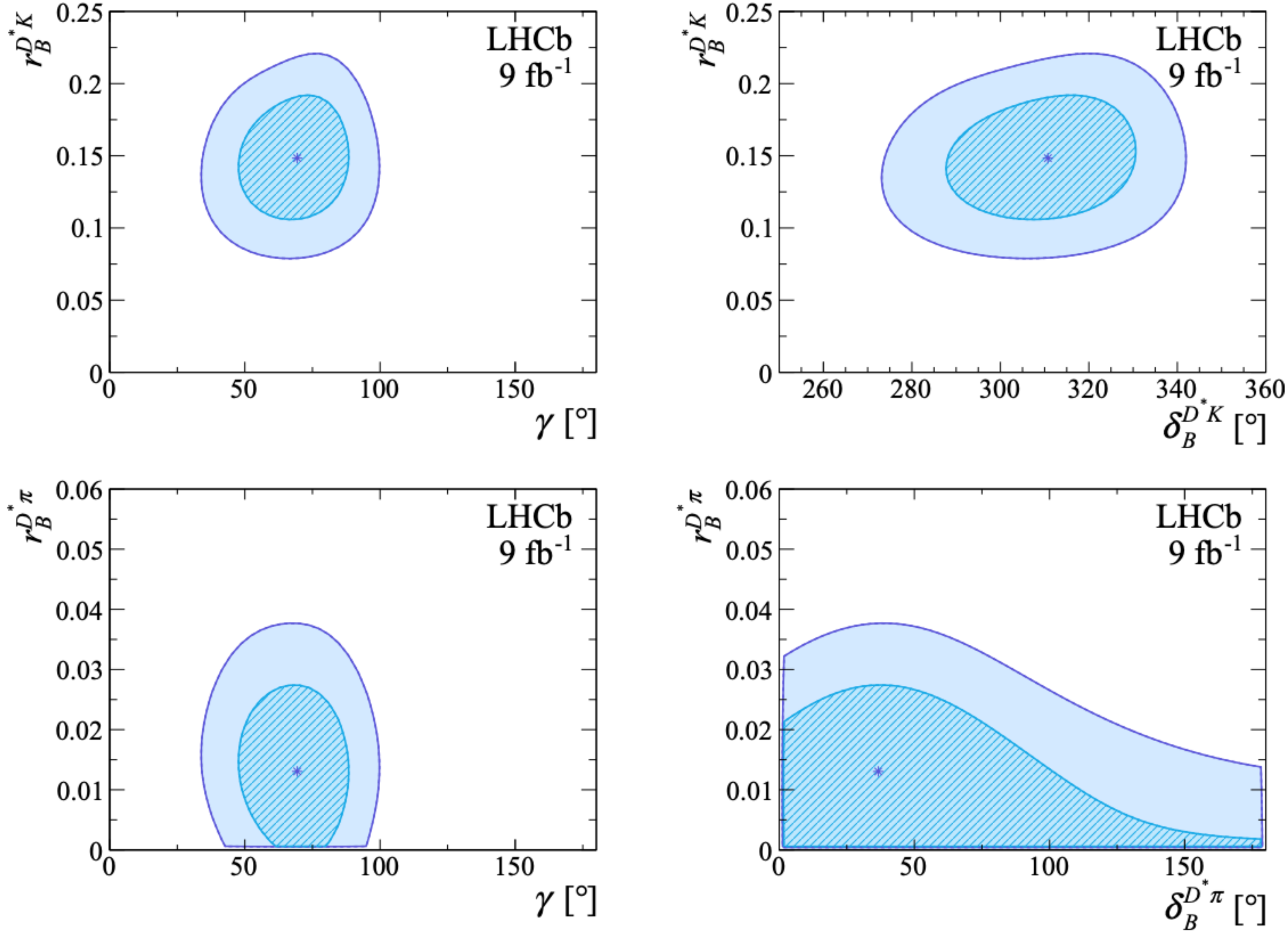
arXiv:2310.04277
(JHEP 12 (2023) 013)





Extra: $B^\pm \to D^* h^\pm$, $D \to K^0_S h^+ h^-$ (full reco)

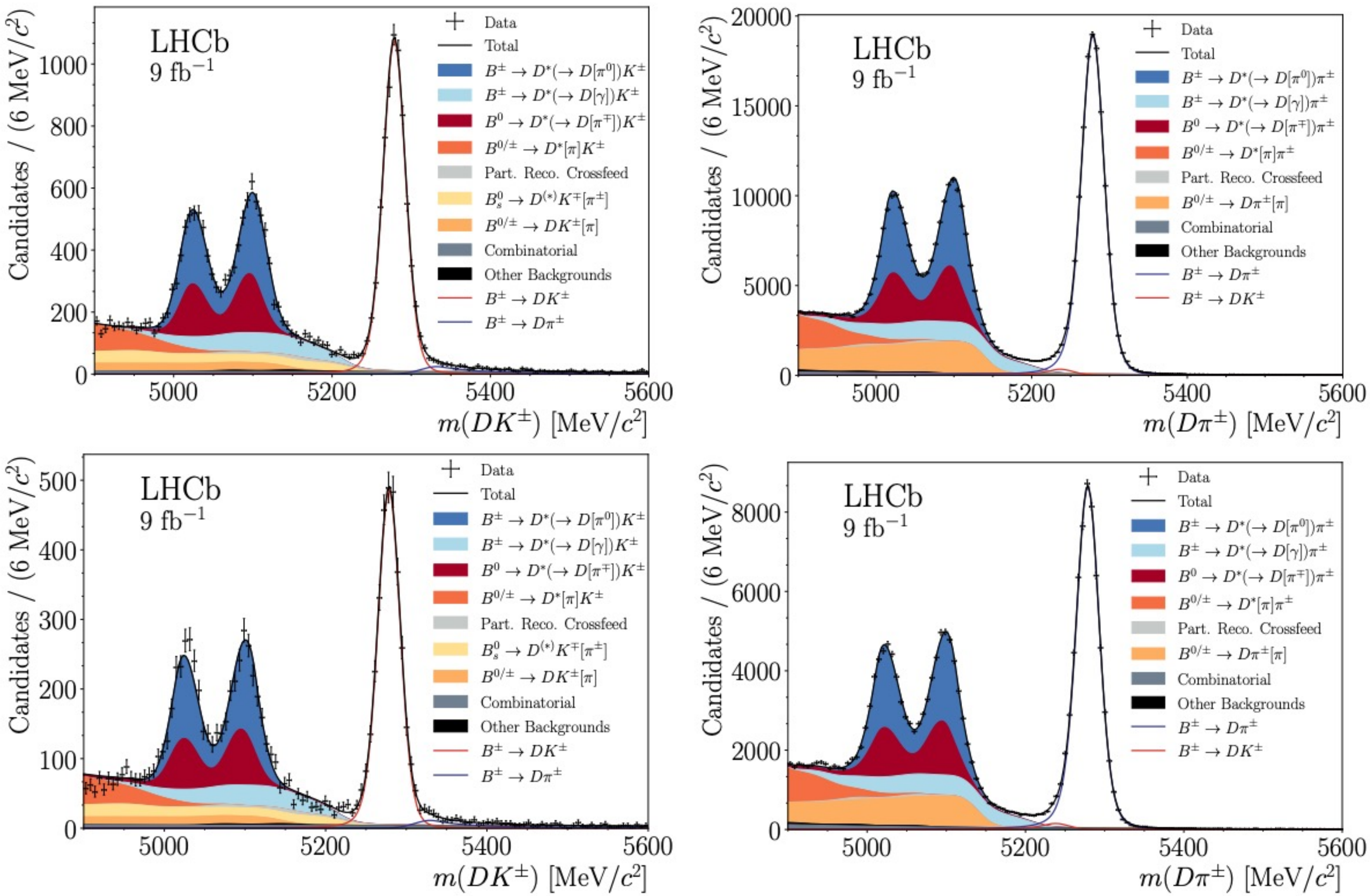
arXiv:2310.04277
(JHEP 12 (2023) 013)



Extra: $B^{\pm} \to D^{*} h^{\pm}$, $D \to K^0_S h^+ h^-$ (part reco)

arXiv:2311.10434
(JHEP 02 (2024) 118)

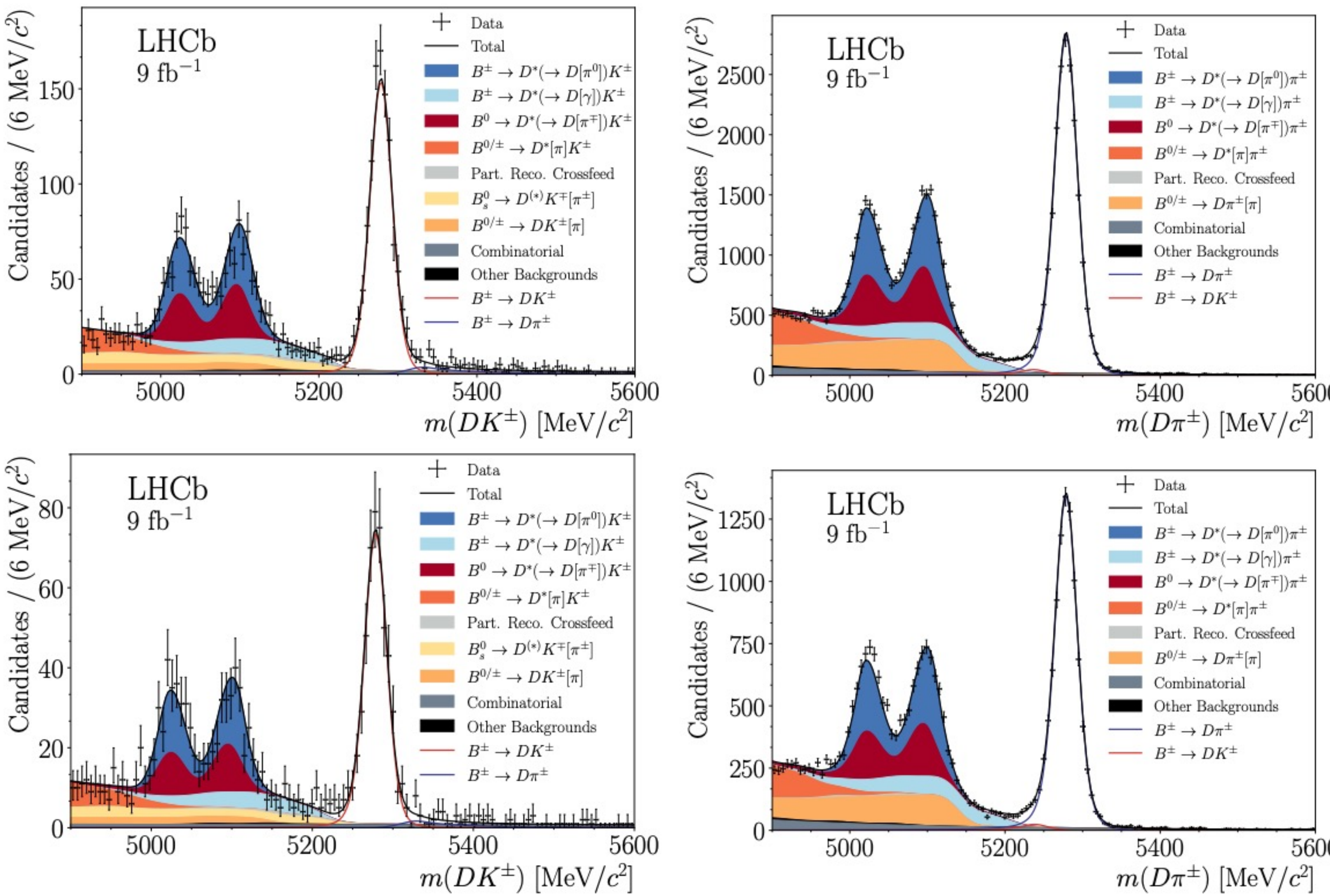
$K_S\pi\pi$ channels. DK (left); Dπ (right). top/bottom are different KS categories



Extra: $B^{\pm} \to D^{*} h^{\pm}$, $D \to K^0_S h^+ h^-$ (part reco)

arXiv:2311.10434
(JHEP 02 (2024) 118)

$K_S KK$ channels. DK (left); Dπ (right). top/bottom are different KS categories



Extra: $B^\pm \to D^* h^\pm$, $D \to K^0_S h^+ h^-$ (part reco)

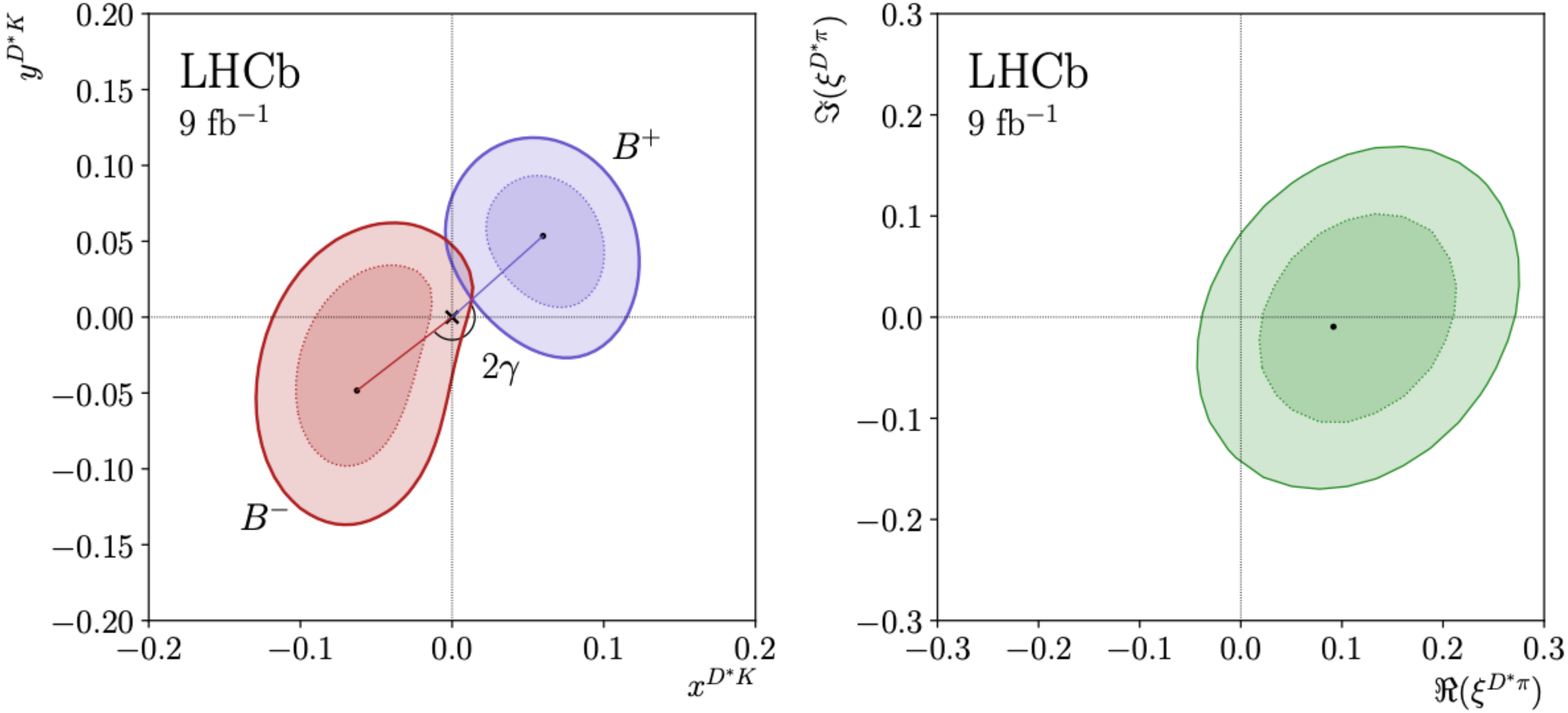
arXiv:2311.10434
(JHEP 02 (2024) 118)

Signal and BG yields:

D decay	Component	Reconstructed as: $B^\pm \to DK^\pm$	$B^\pm \to D\pi^\pm$
$D \to K^0_S \pi^+\pi^-$	$B^\pm \to D^*[D\pi^0]K^\pm$	6244 ± 12	2716 ± 5
	$B^\pm \to D^*[D\pi^0]\pi^\pm$	340 ± 1	$113\,170 \pm 229$
	$B^\pm \to D^*[D\gamma]K^\pm$	3144 ± 6	1247 ± 2
	$B^\pm \to D^*[D\gamma]\pi^\pm$	166 ± 1	$60\,285 \pm 121$
	$B^\pm \to DK^\pm$	$10\,398 \pm 21$	4726 ± 9
	$B^\pm \to D\pi^\pm$	590 ± 1	$196\,804 \pm 398$
	Other backgrounds	$10\,402 \pm 105$	$206\,664 \pm 592$
	Combinatorial background	1343 ± 147	$15\,177 \pm 706$
$D \to K^0_S K^+K^-$	$B^\pm \to D^*[D\pi^0]K^\pm$	790 ± 3	344 ± 1
	$B^\pm \to D^*[D\pi^0]\pi^\pm$	43 ± 1	$14\,327 \pm 65$
	$B^\pm \to D^*[D\gamma]K^\pm$	397 ± 1	157 ± 1
	$B^\pm \to D^*[D\gamma]\pi^\pm$	21 ± 1	7636 ± 34
	$B^\pm \to DK^\pm$	1527 ± 6	694 ± 2
	$B^\pm \to D\pi^\pm$	88 ± 1	$29\,786 \pm 135$
	Other backgrounds	1573 ± 15	$31\,278 \pm 115$
	Combinatorial background	263 ± 46	4413 ± 261

Extra: $B^{\pm} \to D^{*} h^{\pm}$, $D \to K^0_S h^+ h^-$ (part reco)

arXiv:2311.10434
(JHEP 02 (2024) 118)



Extra: $B^{\pm} \to D^* h^{\pm}$, $D \to K^0_S h^+ h^-$ (part reco)

arXiv:2311.10434
(JHEP 02 (2024) 118)

Results:

$$
\begin{aligned}
x_-^{D^*K} &= (-6.3 \pm 2.9 \pm 1.1 \pm 0.6) \times 10^{-2}, \\
y_-^{D^*K} &= (-4.8 \pm 5.7 \pm 1.4 \pm 1.5) \times 10^{-2}, \\
x_+^{D^*K} &= (\ \ 6.0 \pm 2.6 \pm 0.9 \pm 0.2) \times 10^{-2}, \\
y_+^{D^*K} &= (\ \ 5.4 \pm 2.9 \pm 0.9 \pm 0.4) \times 10^{-2}, \\
\Re(\xi^{D^*\pi}) &= (\ 11.5 \pm 9.4 \pm 3.3 \pm 2.3) \times 10^{-2}, \\
\Im(\xi^{D^*\pi}) &= (-0.9 \pm 9.7 \pm 2.5 \pm 2.1) \times 10^{-2},
\end{aligned}
$$

$$
\begin{aligned}
\gamma &= (92^{+21}_{-17})^\circ, \\
r_B^{D^*K} &= 0.080^{+0.022}_{-0.023}, \\
\delta_B^{D^*K} &= (310^{+15}_{-20})^\circ, \\
r_B^{D^*\pi} &= 0.009^{+0.005}_{-0.007}, \\
\delta_B^{D^*\pi} &= (304^{+37}_{-38})^\circ.
\end{aligned}
$$

Extra: $B^\pm \to D^* h^\pm$, $D \to K^0_S h^+ h^-$ (part reco)

arXiv:2311.10434
(JHEP 02 (2024) 118)

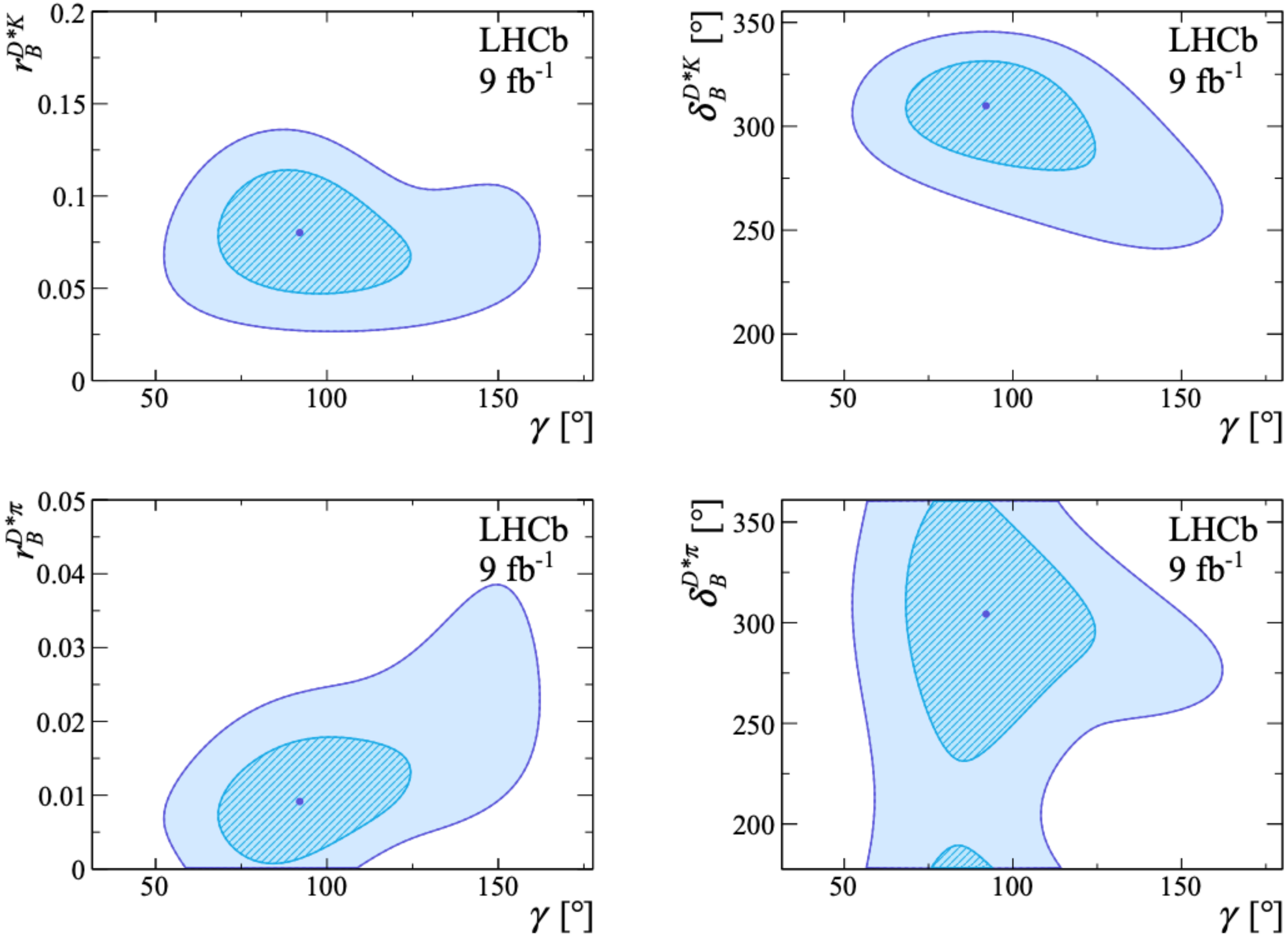
Systematic uncertainties:

Source	$x_-^{D^*K}$	$y_-^{D^*K}$	$x_+^{D^*K}$	$y_+^{D^*K}$	$\Re(\xi^{D^*\pi})$	$\Im(\xi^{D^*\pi})$
Efficiency correction of (c_i, s_i)	0.23	0.29	0.21	0.20	0.47	0.31
Mass shape parameterisation	0.35	0.58	0.38	0.33	1.17	0.90
Fixed $\xi_{D\gamma}$ parameter	0.14	0.19	0.15	0.08	0.22	0.32
Fixed branching ratios	0.58	0.44	0.33	0.50	1.09	0.54
Fixed efficiencies	0.23	0.48	0.18	0.27	0.70	0.38
Fixed yield ratios	0.66	0.85	0.46	0.43	1.45	0.77
Bias Correction	0.29	0.35	0.12	0.16	0.62	0.51
Dalitz-bin migration	0.00	0.02	0.04	0.10	0.03	0.11
Inputs for CPV backgrounds	0.35	0.33	0.38	0.21	2.22	1.93
Total of above uncertainties	1.11	1.36	0.85	0.87	3.28	2.46
Strong-phase inputs	0.57	1.54	0.18	0.41	2.33	2.13
Total systematic uncertainty	1.25	2.05	0.87	0.95	4.02	3.26
Statistical uncertainty	2.93	5.69	2.58	2.87	9.37	9.67

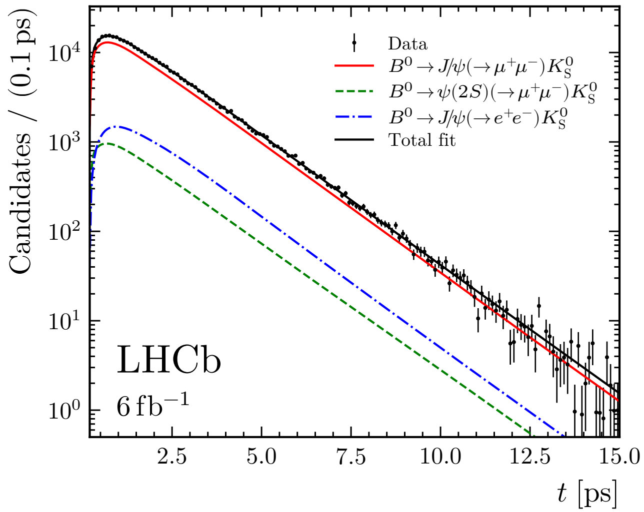
Extra: $B^\pm \to D^* h^\pm$, $D \to K^0_S h^+ h^-$ (part reco)

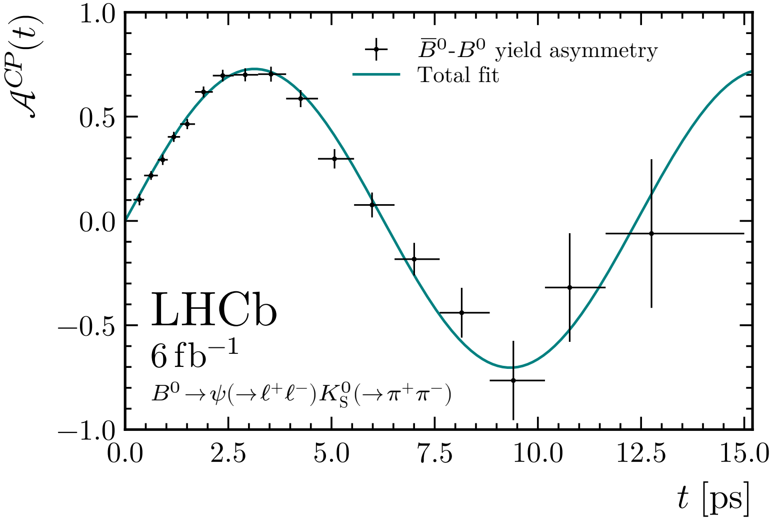
arXiv:2311.10434
(JHEP 02 (2024) 118)

Systematic uncertainties:



Extra: Time-dependent CPV in B_s^0 decays: β





[PRL 132 (2024) 021801 (arXiv:2309.09278)]

Flavour tagging efficiency and dilution

Channel	ϵ_{tag} [%]	$\mathcal{D}^2$ [%]
$B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S$	85.34 ± 0.05	4.661 ± 0.013
$B^0 \to J/\psi(\to e^+e^-)K^0_S$	92.20 ± 0.08	6.462 ± 0.032
$B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_S$	84.81 ± 0.15	4.59 ± 0.04

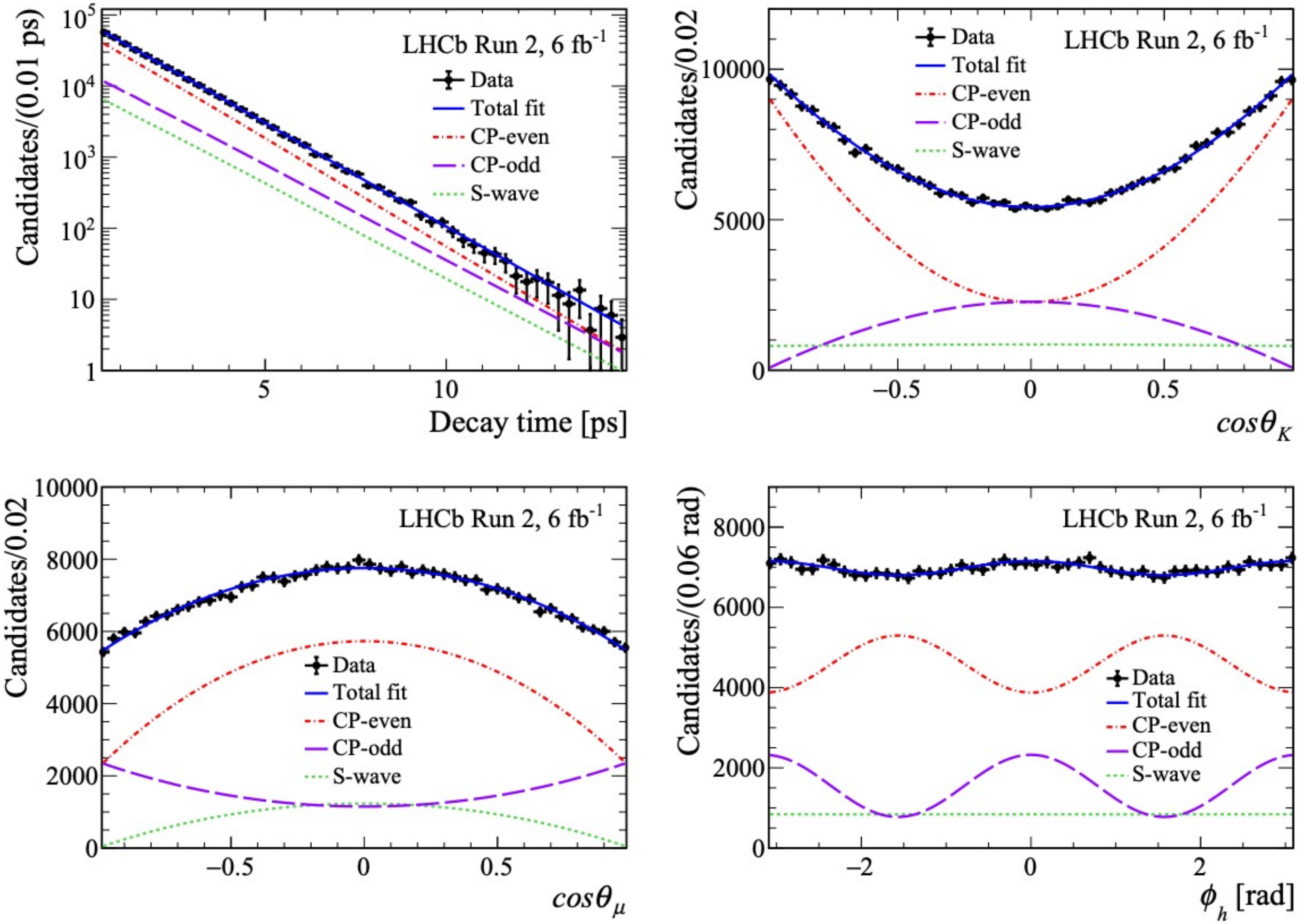
Systematic uncertainties:

Source	$\sigma(S)$	$\sigma(C)$
Fitter validation	0.0004	0.0006
Decay-time bias model	0.0007	0.0013
FT $\Delta\epsilon_{\text{tag}}$ portability	0.0014	0.0017
FT calibration portability	0.0053	0.0001
$\Delta\Gamma_d$ uncertainty	0.0055	0.0017

Extra: Time-dep. CPV in B_s^0 decays: ϕ_s

PRL 132 (2024) 051802 (arXiv:2308.01468)

Projections of background-subtracted signal distributions on four fit variables



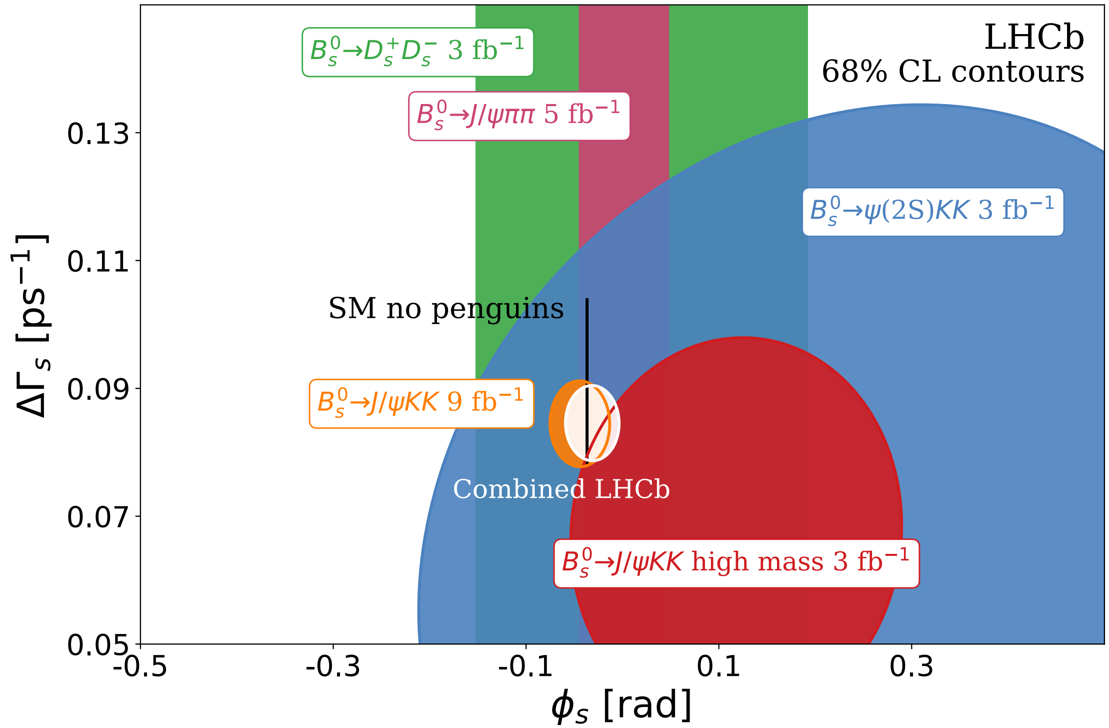
Extra: Time-dep. CPV in B_s^0 decays: ϕ_s

PRL 132 (2024) 051802 (arXiv:2308.01468)

Fit results with CPV parameters floating separately for each polarization mode:

Parameters	Values
ϕ_s^0 [rad]	-0.034 ± 0.023
$\phi_s^{\parallel} - \phi_s^0$ [rad]	-0.002 ± 0.021
$\phi_s^{\perp} - \phi_s^0$ [rad]	$-0.001\,^{+0.020}_{-0.021}$
$\phi_s^{S} - \phi_s^0$ [rad]	$0.022\,^{+0.027}_{-0.026}$
$\lvert\lambda^0\rvert$	$0.969\,^{+0.025}_{-0.024}$
$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$0.982\,^{+0.055}_{-0.052}$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$1.107\,^{+0.082}_{-0.076}$
$\lvert\lambda^{S}/\lambda^0\rvert$	$1.121\,^{+0.084}_{-0.078}$

LHCb constraints and combination from different channels and data samples:

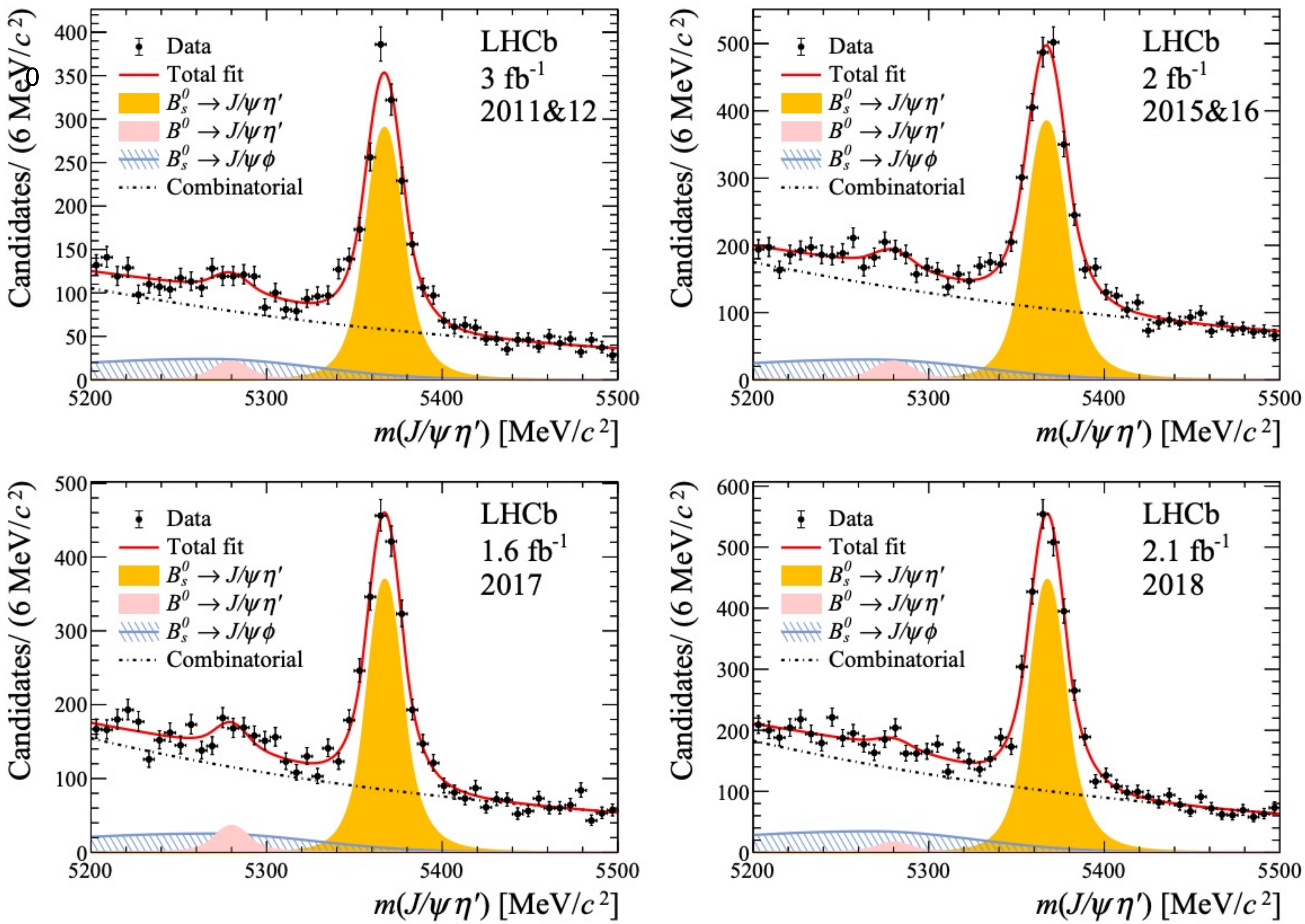


LHCb combination: $$\phi_s = -0.031 \pm 0.018 \text{ rad}$$

Extra: $\Delta\Gamma_s$ measurement

arXiv:2310.12649
(submitted to JHEP)

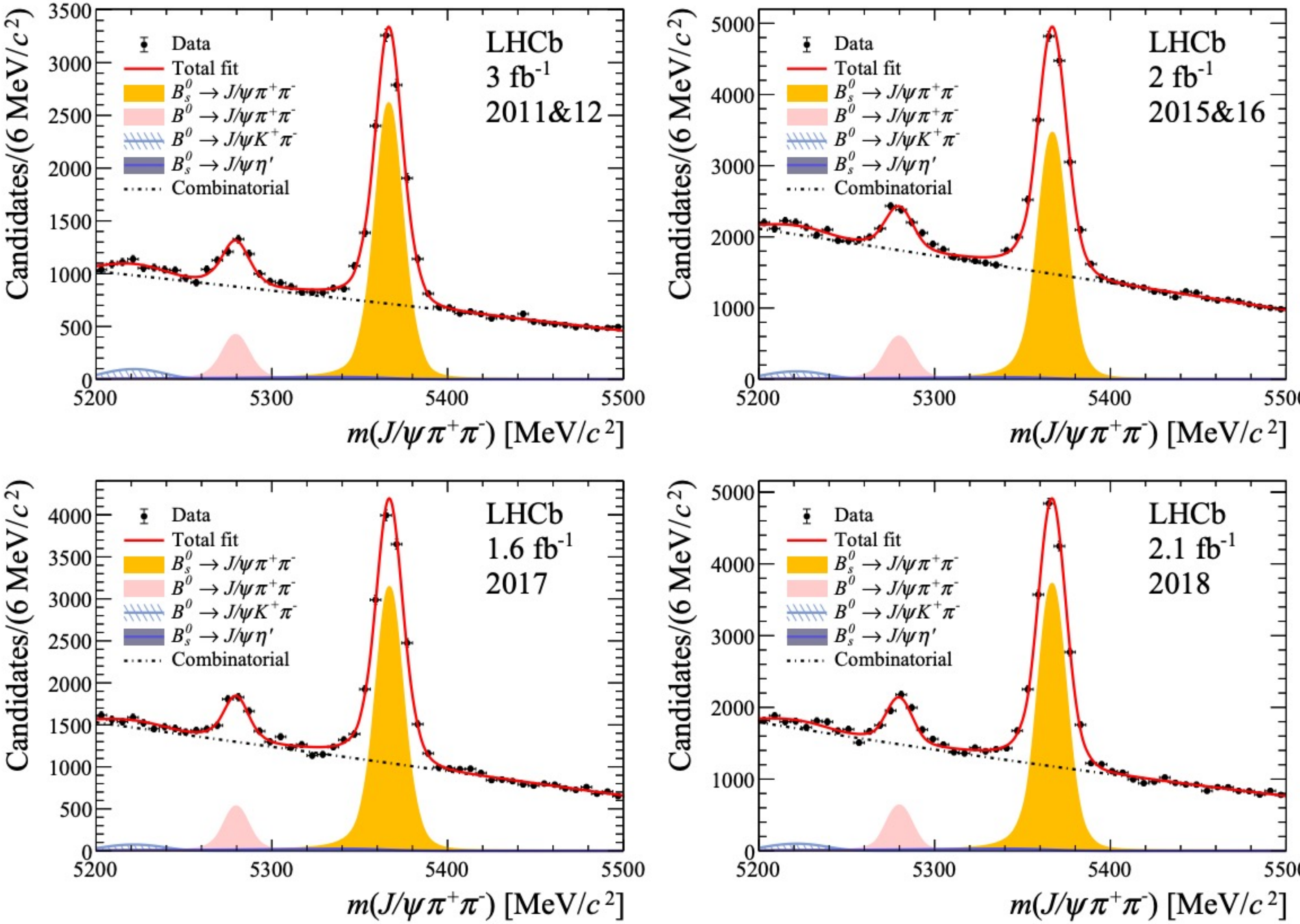
Mass fits: $B_s^0 \to J/\psi\eta'$ ($\eta' \to \rho^0\gamma$) CP-even $\Rightarrow$ measure τ_L



Extra: $\Delta\Gamma_s$ measurement

arXiv:2310.12649
(submitted to JHEP)

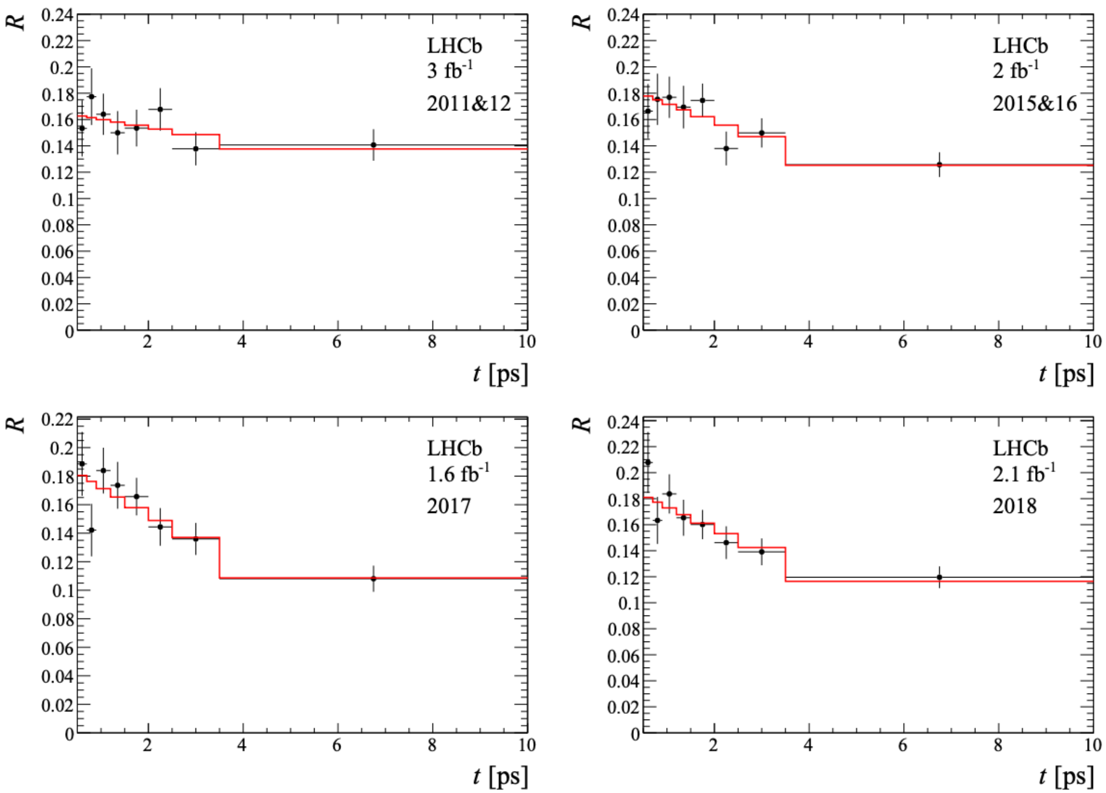
Mass fits: $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ (f_0(980) region) CP-odd $\Rightarrow$ measure τ_H

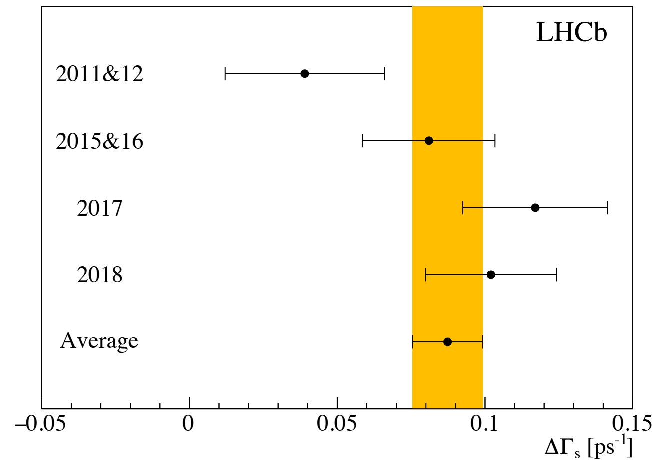


Extra: $\Delta\Gamma_s$ measurement

arXiv:2310.12649
(submitted to JHEP)

Time-dependent ratios of yields:





Results:

Dataset	$\Delta\Gamma_s$ [ps^{-1}]	P(χ^2)
2011&12	0.039 ± 0.026	0.83
2015&16	0.081 ± 0.022	0.77
2017	0.117 ± 0.024	0.57
2018	0.102 ± 0.021	0.78

Systematic uncertainties:

Source	Value [ns^{-1}]
Simulation sample size	4.6
Acceptance model	3.0
Bin centre method	0.3
CP violation	0.1
Γ_s	0.1
$J/\psi\eta'$ background model	6.9
$J/\psi\pi^+\pi^-$ background model	0.8
Total	8.9