Time-dependent CP violation at LHCb

D. Manuzzi on behalf of the LHCb Collaboration

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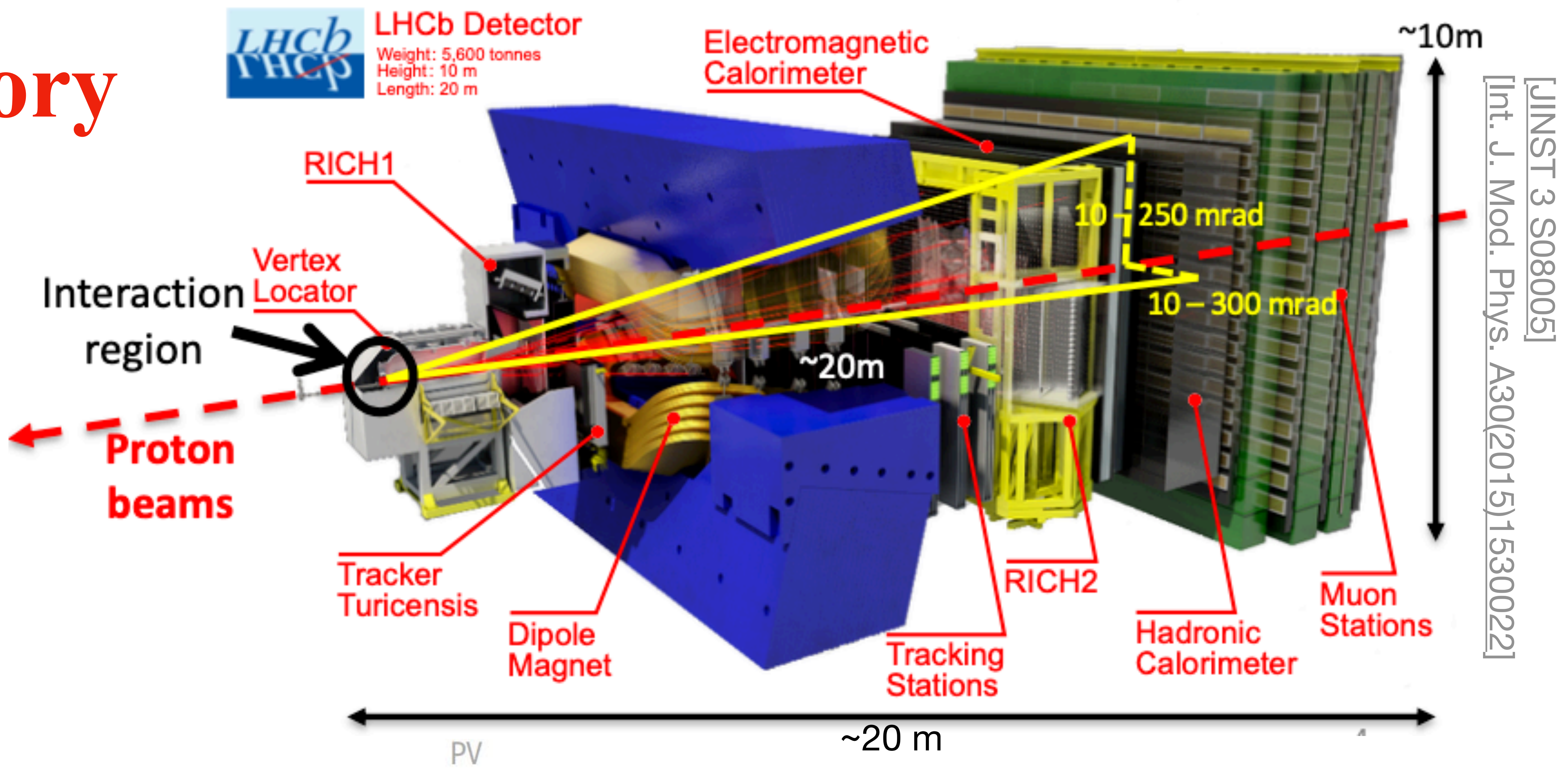
The LHCb experiment @ LHC

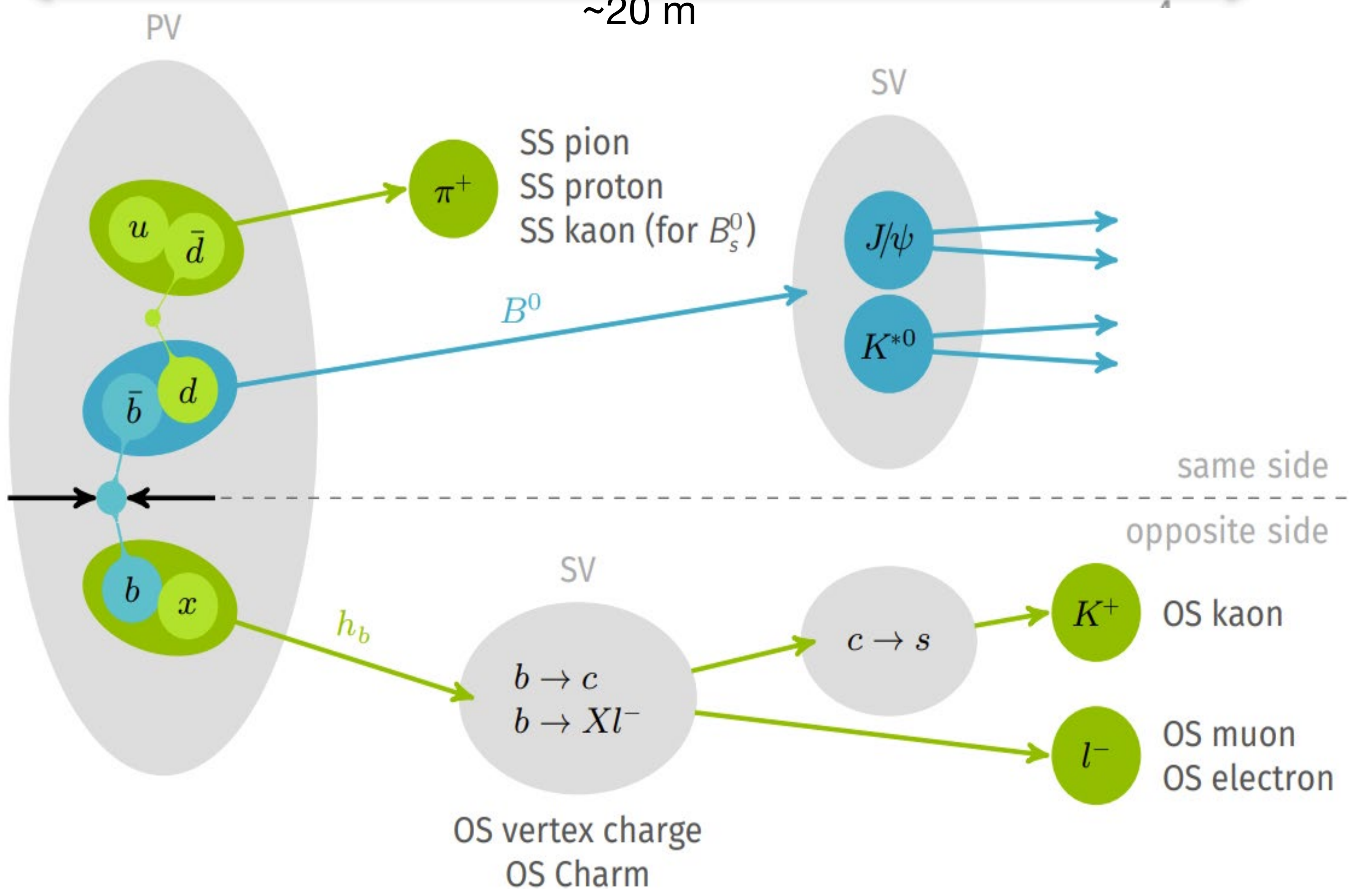
The LHC is a unique heavy-flavour factory

- Large cross-section for production of $b\bar{b}$ and $c\bar{c}$
  - All kinds of beauty hadrons
  - Datasets with millions of charm candidates



LHCb is designed to exploit it

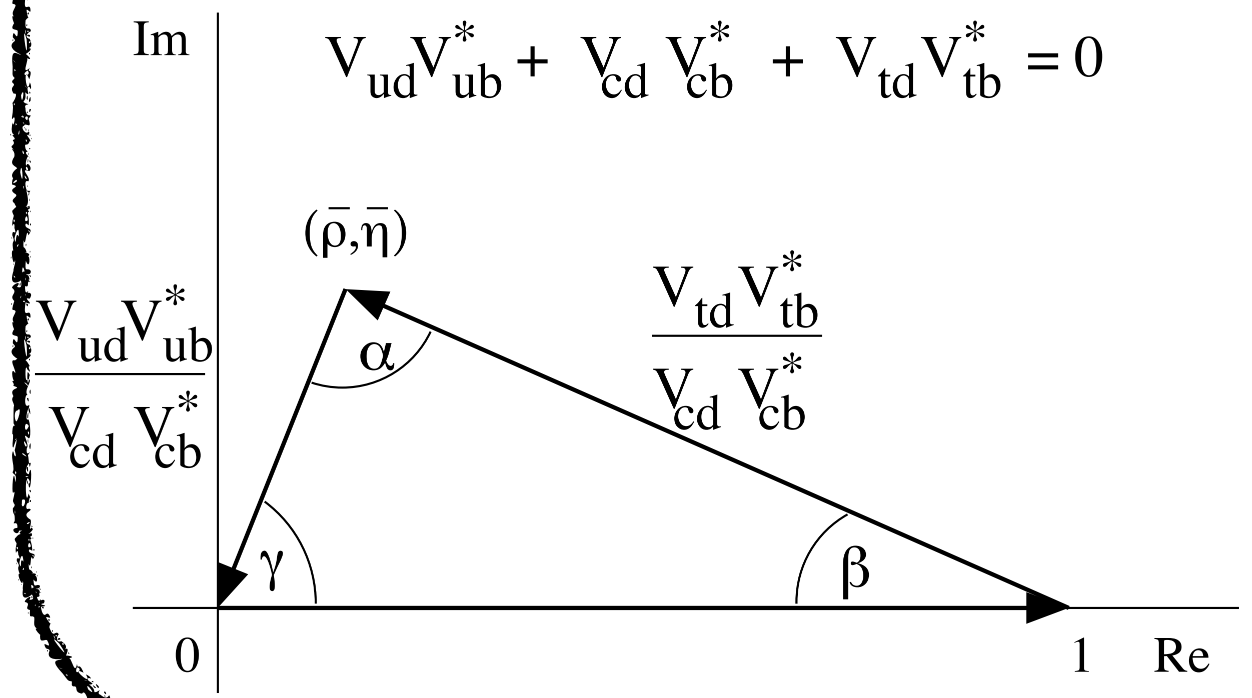
- Low trigger threshold on hadrons, muons and photons
- Excellent **decay-time resolution** ($\sigma_t \sim 45$ fs), momentum resolution ($\sigma_p/p \sim 0.4 - 0.6\,\%$), PID performances ($K$ eff. 95% for 5% $\pi \to K$ misID)
- Challenging environment for **Flavour-Tagging** of $B^0_{(s)}$
  - $\varepsilon_{\text{eff}}^{\text{LHCb}} \equiv \epsilon(1-2\omega)^2 \approx 4 - 8\,\%$, with large samples ($\varepsilon_{\text{eff}}^{\text{BelleII}} \approx 30\,\%$ in cleaner env., but smaller samples)
  - D^0 flavour tagged with the abundant prompt-$D^{*+} \to D^0\pi^+$ decays

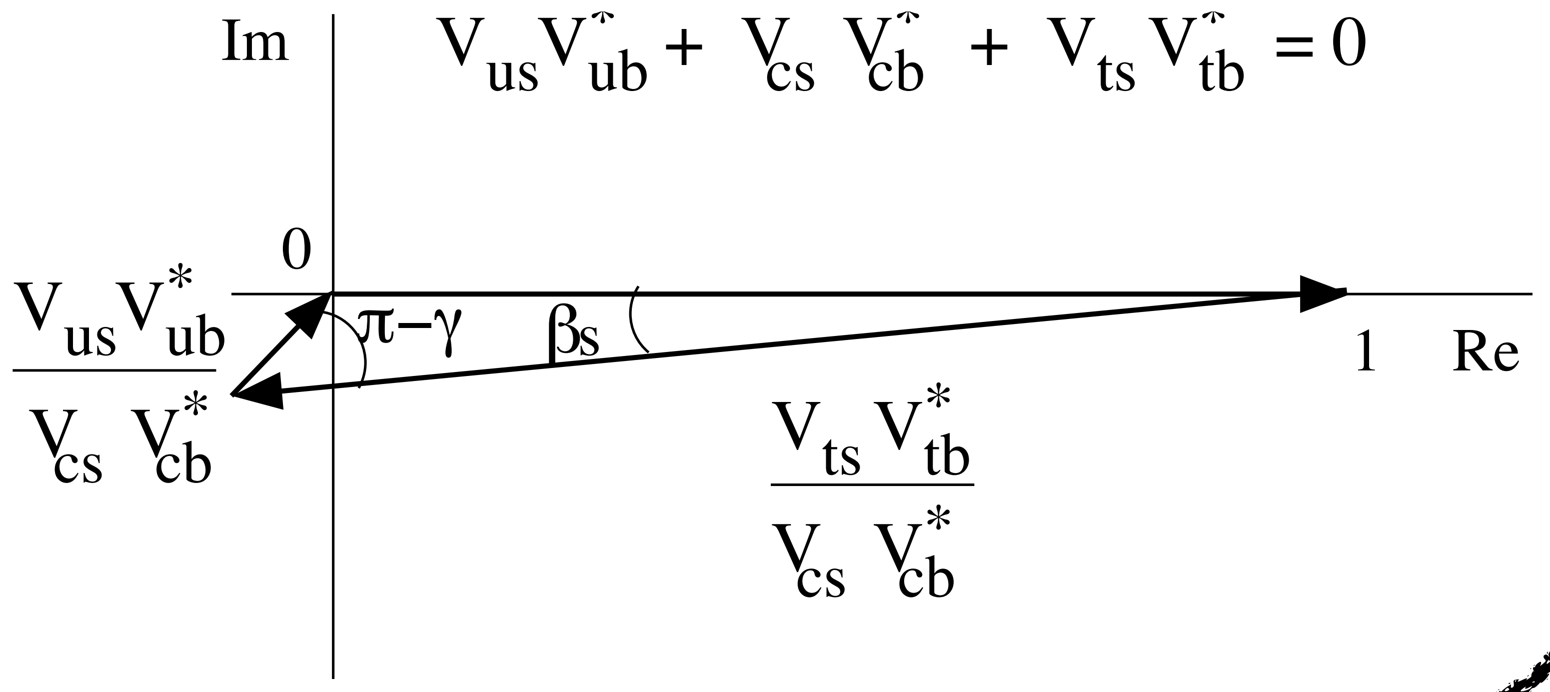


Unitarity triangle and TD-CPV

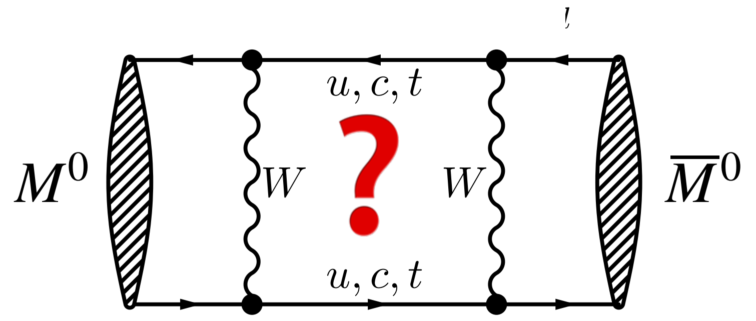
- The CKM matrix:
  - rules all quark-flavour and CPV phenomena in the Standard Model (SM)
  - is unitary
- Experimental checks of Unitarity Triangles are redundant
  - Tree-level dominated processes $\Longrightarrow$ SM benchmarks
  - Sizeable loop-level diagrams $\Longrightarrow$ Eventual New Physics contributions
- **Powerful SM tests**

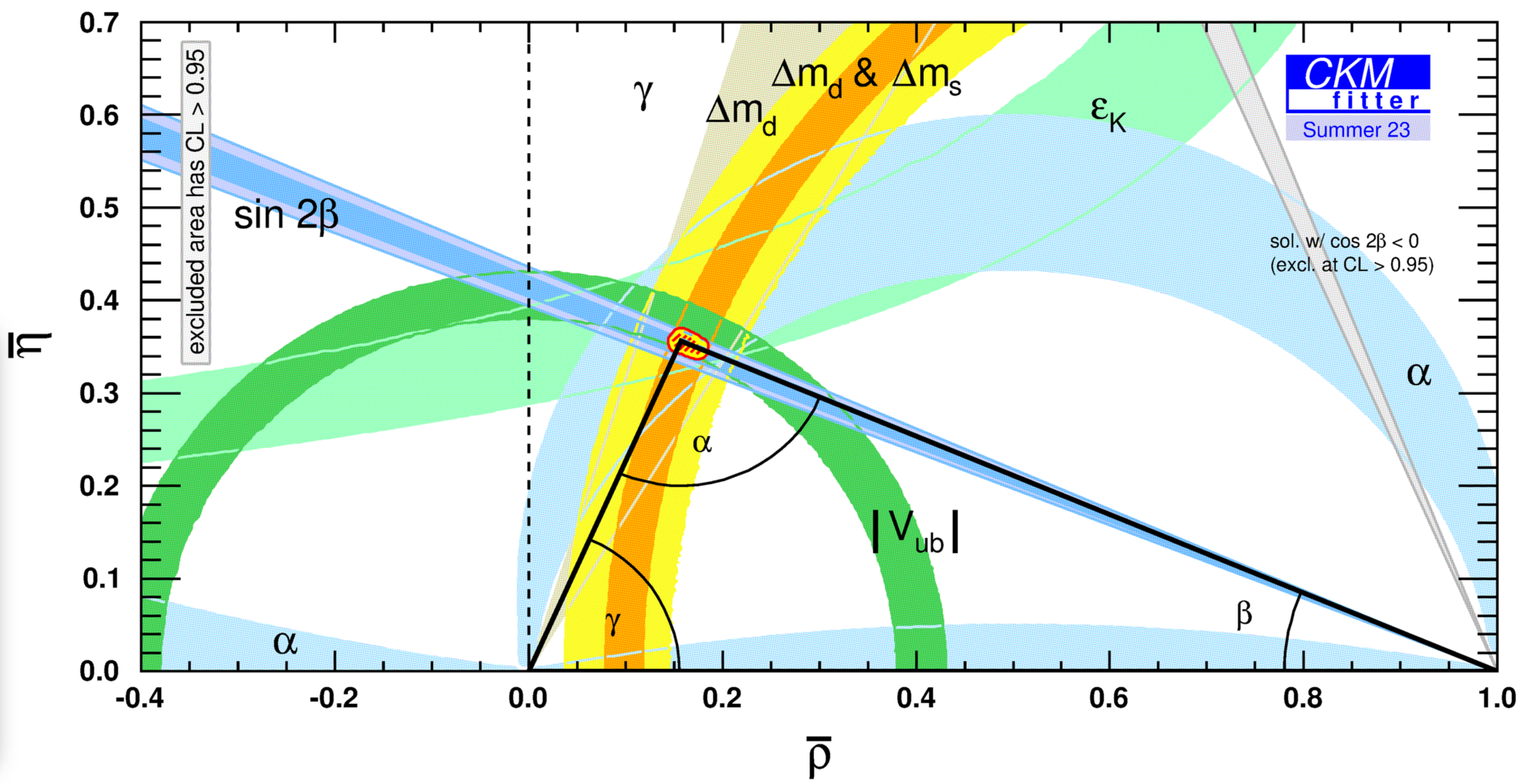
$$V_{CKM,\mathrm{Wolfenstein}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$





TD-CPV case





TODAY
- World-leading TD measurements of β, β_s, and γ
- Improved searches for TD-CPV in $D^0 \to K^+\pi^-$ and $D^0 \to \pi^+\pi^-\pi^0$

Beauty formalism for TD-CP asymmetries

$|B_{L,H}\rangle = |B_q^0\rangle q \pm |\overline{B}_q^0\rangle p$

$A_f = \langle f | H_W | B_{(s)}^0 \rangle$

$\overline{A}_f = \langle f | H_W | \overline{B}_{(s)}^0 \rangle$

$$(q\overline{A}_f)/(pA_f) \equiv \lambda_f = |\lambda_f| e^{i\phi^f_{d(s)}}$$

$$(S_f)^2 + (C_f)^2 + (A_f^{\Delta\Gamma})^2 = 1$$

No CPV in mixing $|q/p| = 1$

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

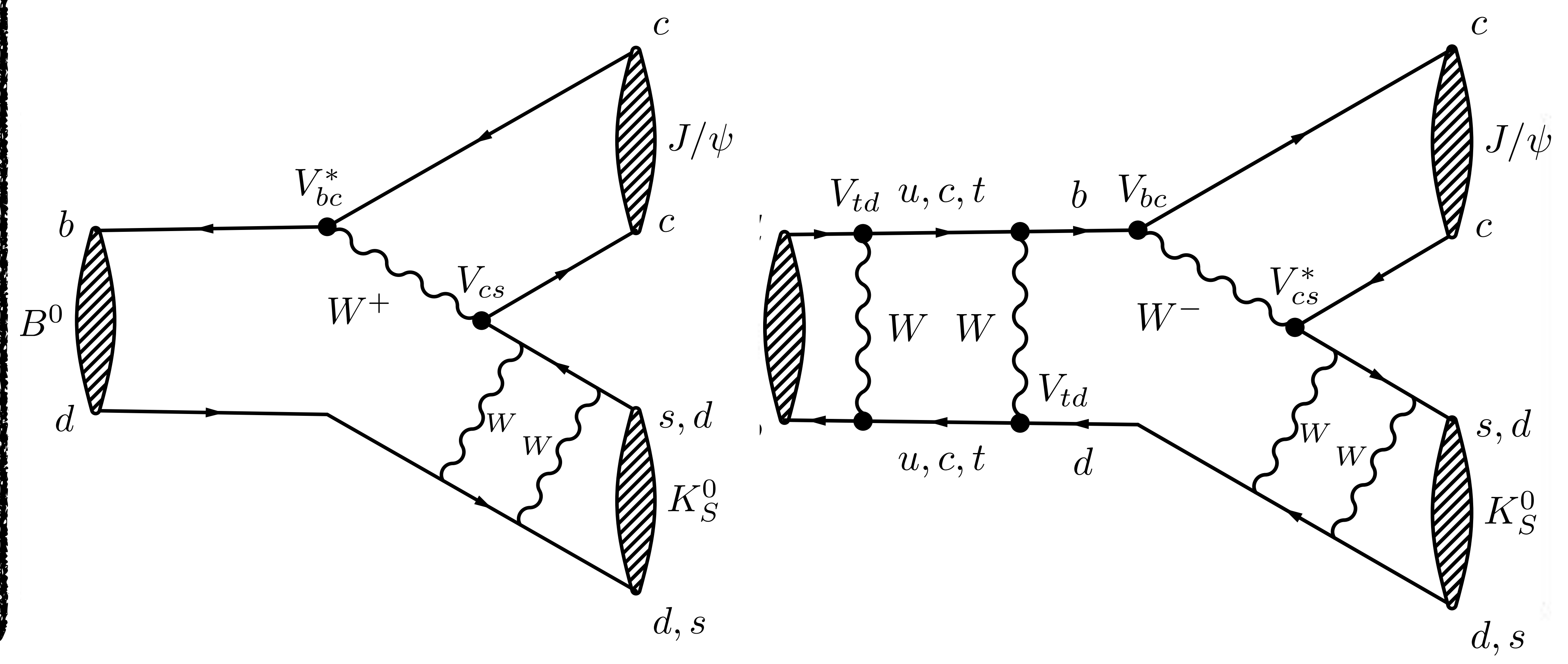
$$C_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} \qquad S_{f_{CP}} = \frac{2\mathrm{Im}[\lambda_{f_{CP}}]}{1 + |\lambda_{f_{CP}}|^2}$$

CPV in the decay

CPV in interference of mixing and decay

- **$B^0 \to J/\psi K_S^0$ and $B_s^0 \to J/\psi\phi$ are golden modes**
  - Ruled by $B^0_{(s)}$ mixing and tree-level $b \to c\bar{c}s$ transitions
    - Penguin contributions are measured to be negligible
  - No CPV in the decay: $C_{f_{CP}} = 0 \iff |\lambda_{f_{CP}}| = 1$
  - $\beta_{(s)}$ accessible due to CPV in interference of decay with and without mixing: $S_{f_{CP}} = \sin(\pm 2\beta_{(s)}) \iff \phi_{d(s)}^{c\bar{c}s} = \pm 2\beta_{(s)}$

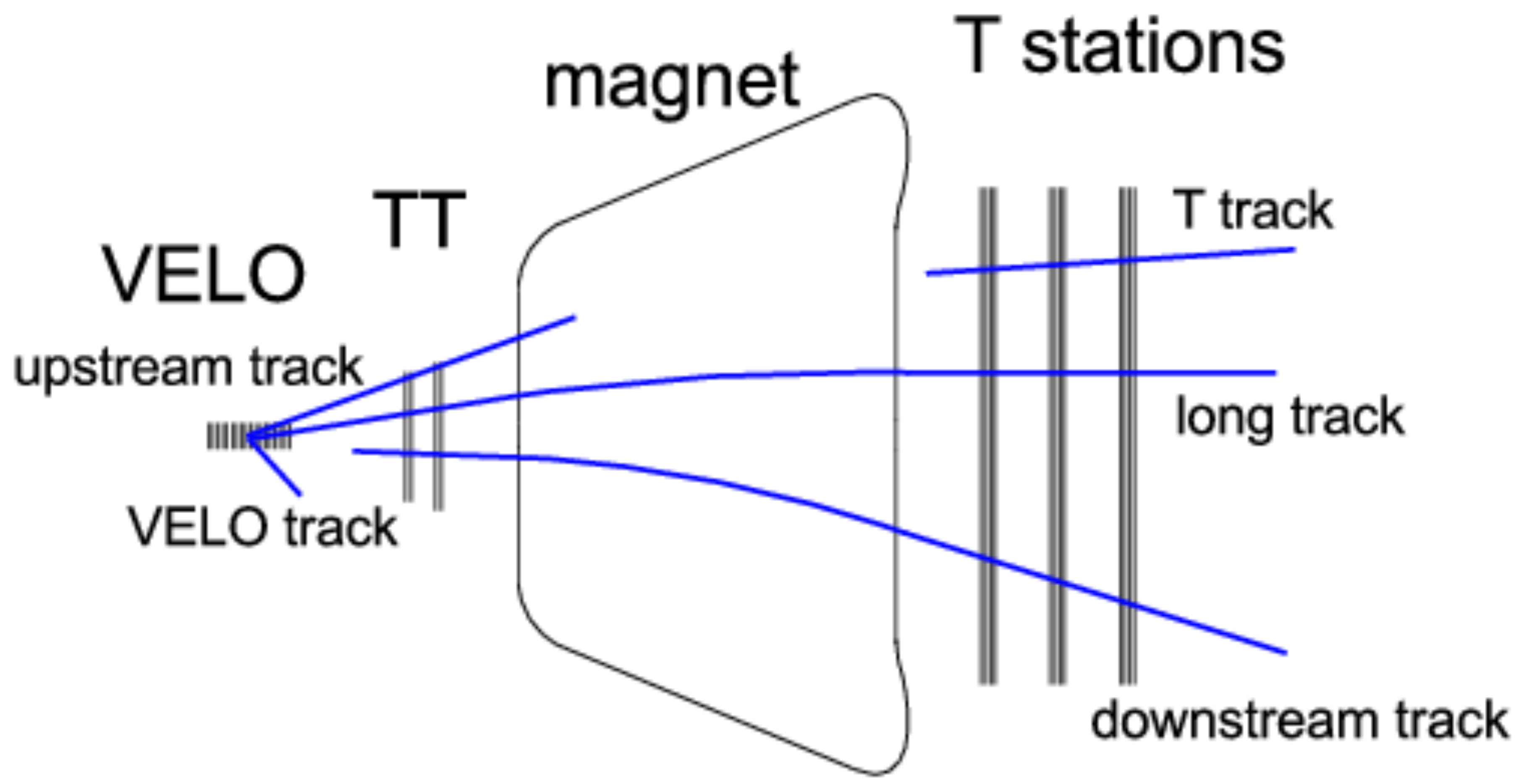
SM



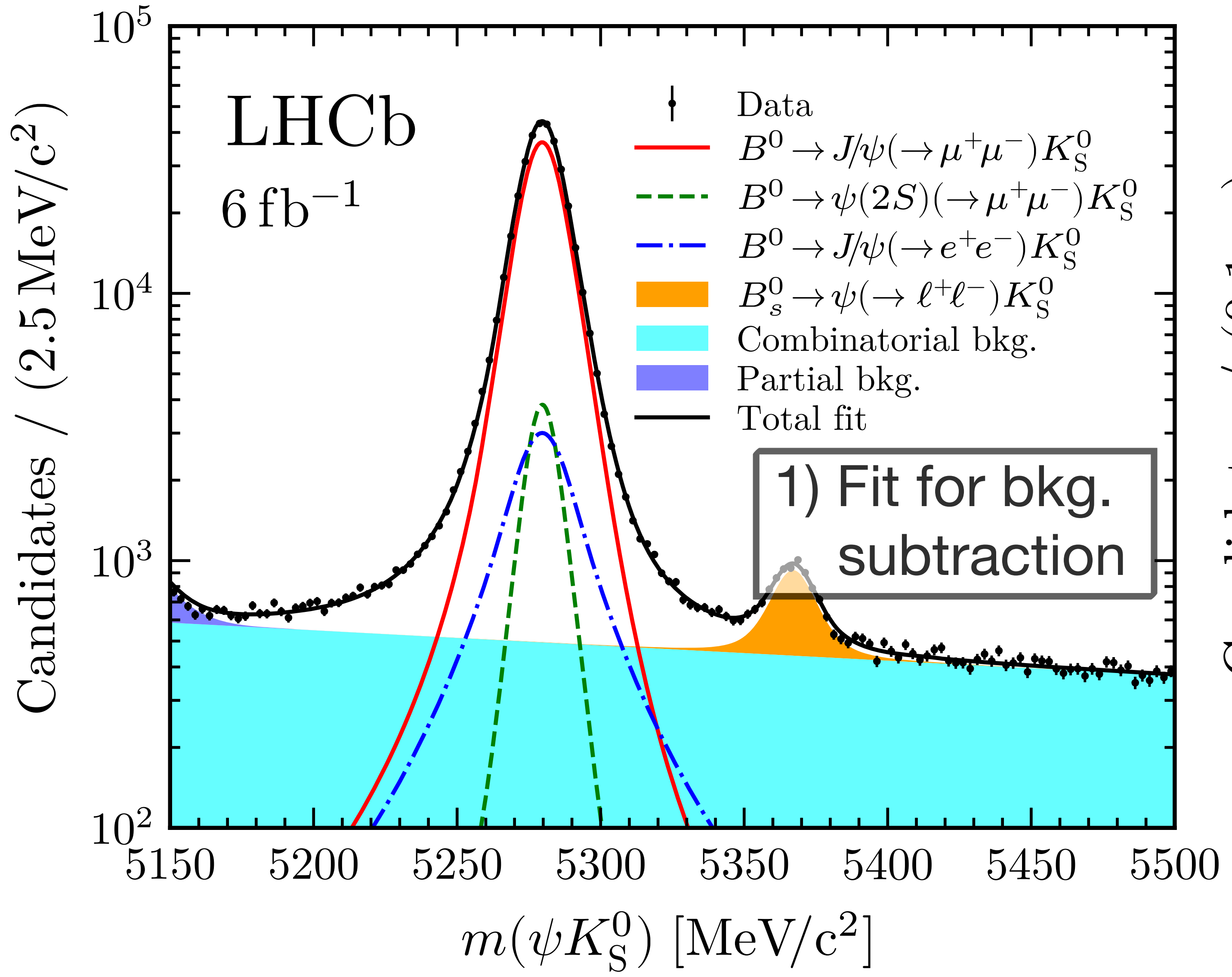
Measurement of $\sin 2\beta$ with $B^0 \to \psi K^0_S$ decays [PRL132(2024)021801]

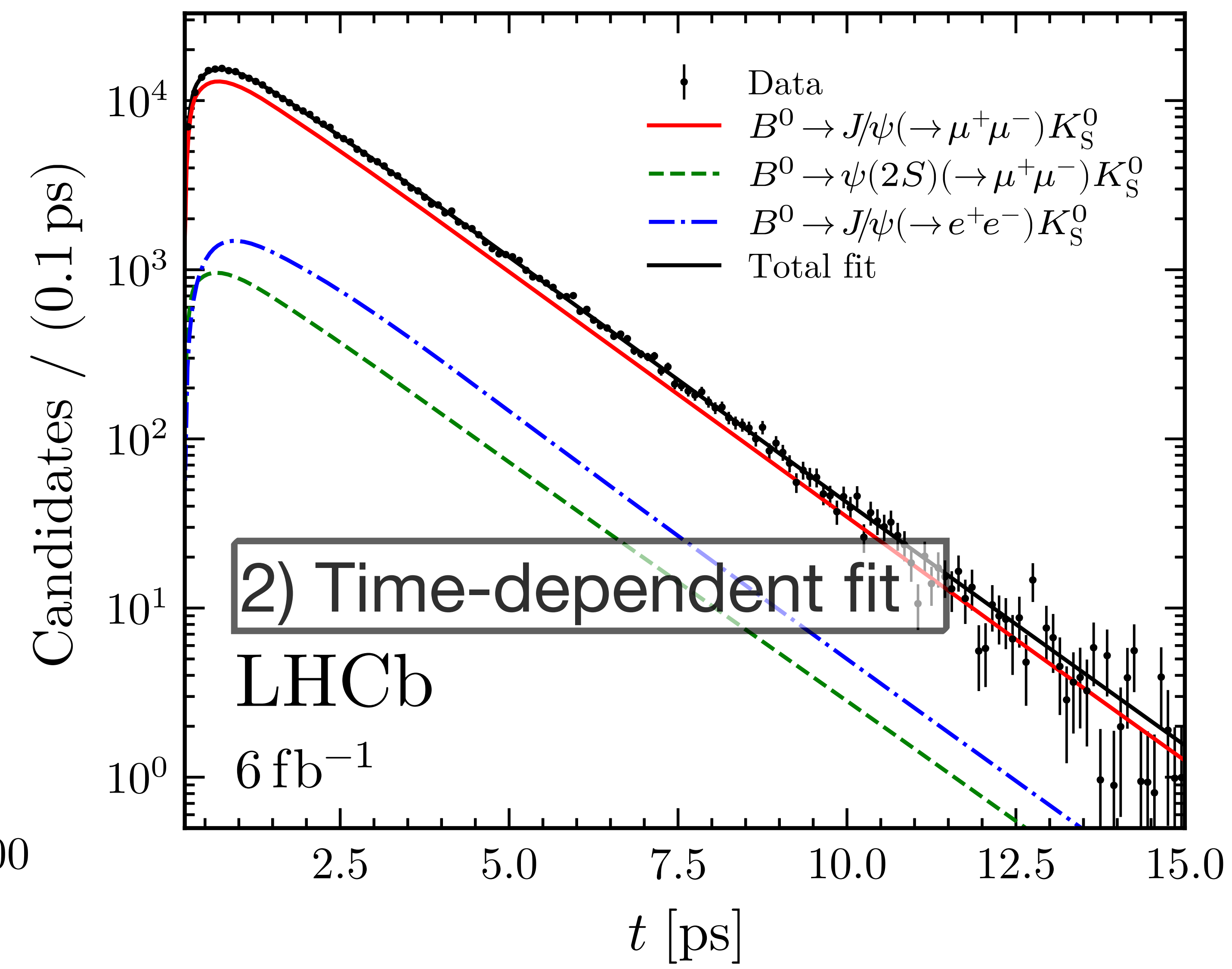
- Run2 analysis then combined with Run1 result
  - 6+3 fb^{-1}
- Four $K^0_s \to \pi^+\pi^-$ reconstructions categories
  - LL, DD, LD,UL

used for the first time in TD measurements (~13% of signal yields)



- Three ψ modes considered
  - $B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S \sim 306\text{k}, \varepsilon_{\text{eff}} = 4\,\%$
  - $B^0 \to J/\psi(\to e^+e^-)K^0_S \sim 24\text{k}, \varepsilon_{\text{eff}} = 6\,\%$
  - $B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_S \sim 43\text{k}, \varepsilon_{\text{eff}} = 4\,\%$
- Flavour Tagging calibrated with $B^+ \to \psi K^+$ and $B^0 \to \psi K^{*0}$





Measurement of $\sin 2\beta$ with $B^0 \rightarrow \psi K^0_S$ decays [PRL132(2024)021801]

Syst. 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

Run 2 result:

$$\boxed{\begin{aligned} S_{\psi K^0_S} &= 0.717 \pm 0.013(\text{stat}) \pm 0.008(\text{syst}) \\ C_{\psi K^0_S} &= 0.008 \pm 0.012(\text{stat}) \pm 0.003(\text{syst}) \end{aligned}}$$

Results from all ψ modes are consistent

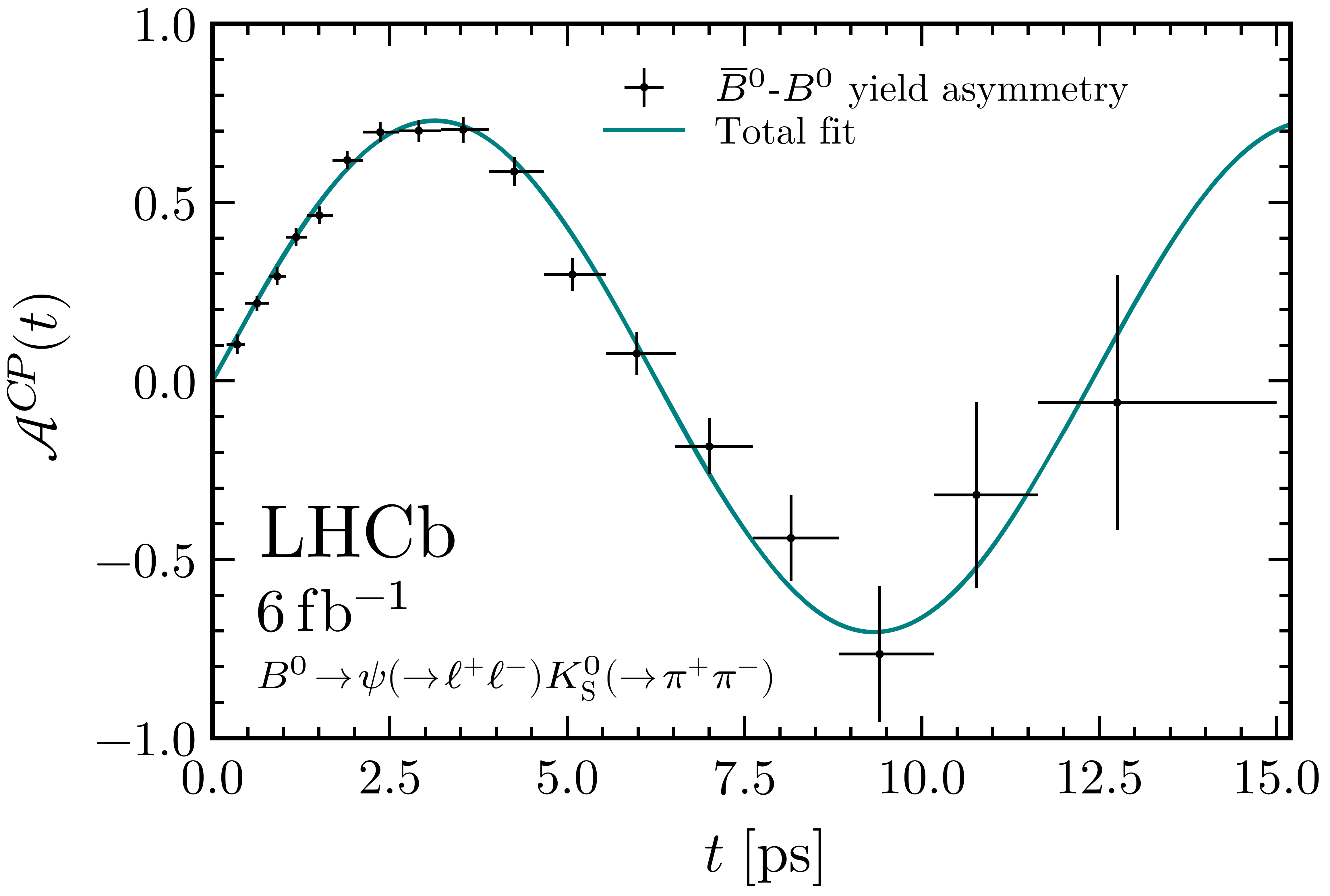
BETTER PRECISION THAN THE PREVIOUS WORLD AVERAGE ($\sin(2\beta) = 0.699 \pm 0.17$) [PRD107. 052008(2023)]

Final result:

$$S^{\text{Run 1\&2}}_{\psi K^0_S} = 0.724 \pm 0.014(\text{stat} + \text{syst})$$ ~ sin2ß

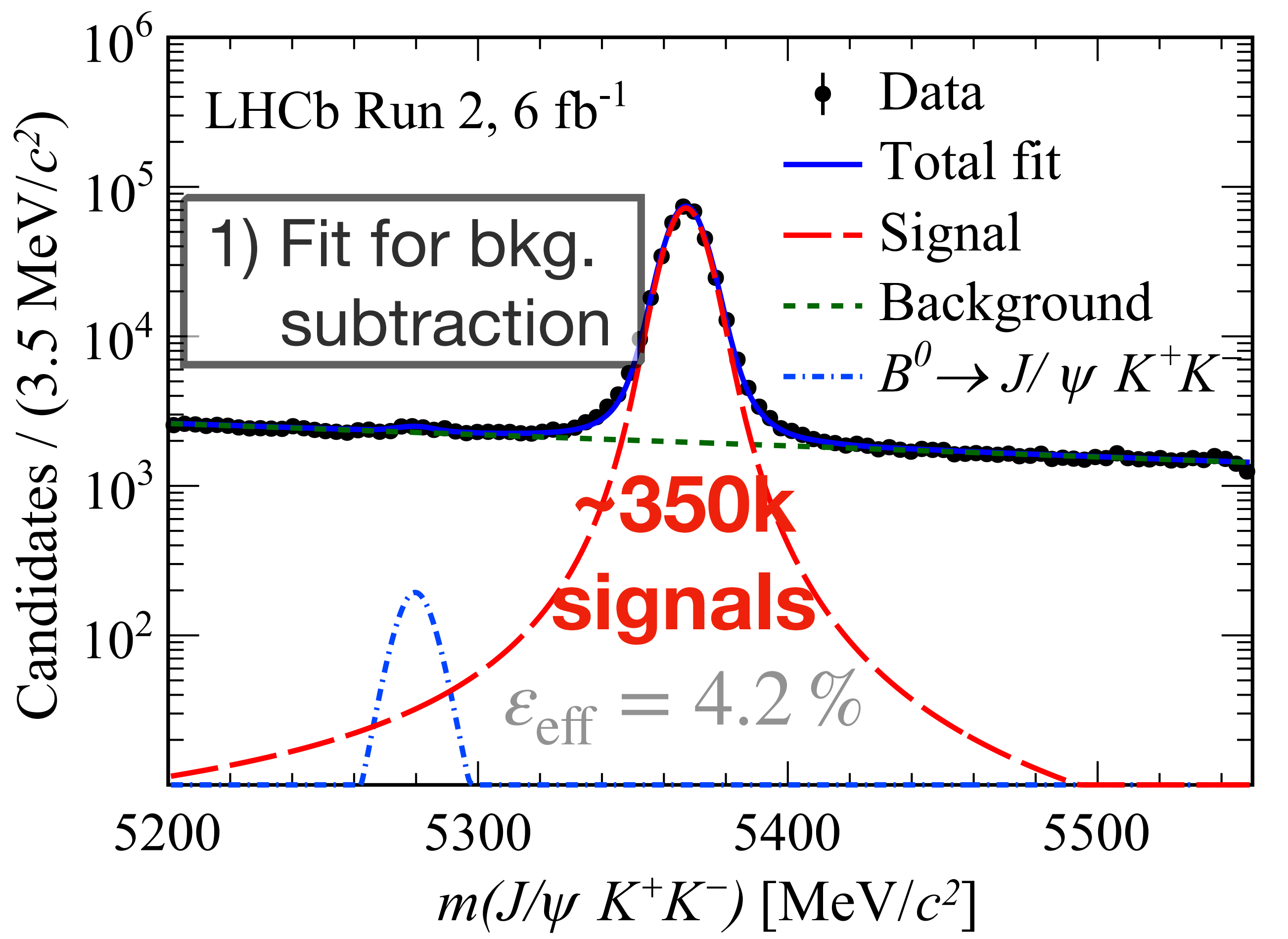
$$C^{\text{Run 1\&2}}_{\psi K^0_S} = 0.004 \pm 0.012(\text{stat} + \text{syst})$$ ~ 0

In agreement with predictions by CKMfitter and UTfit groups [PRD91.073007(2015)] [JHEP10(2006)081]



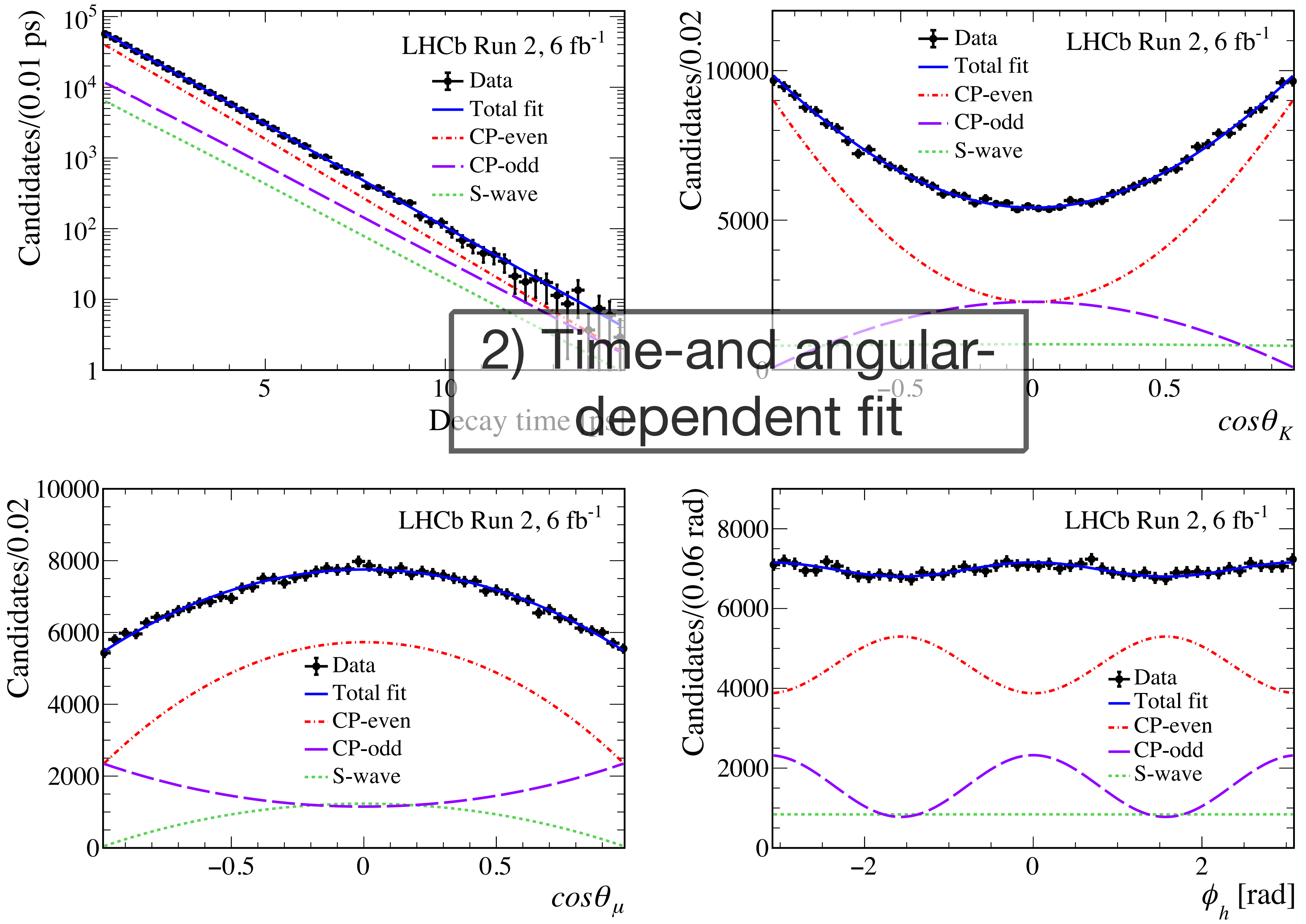
Measurement of ϕ_s with $B_s^0 \to J/\psi K^+K^-$ decays [PRL 132 (2024) 051802]

- The SM predicts a precise and small value of ϕ_s → **Highly sensitive to NP contributions in mixing** [RevModPhys.88.045002]
  - $\phi_s = -0.0368^{+0.0006}_{-0.0009}$ (CKMFitter), $\phi_s = -0.0368 \pm 0.010$ (UTFit)



- K^+K^-pair selected in the vicinity of the $\phi(1020)$ resonance
  - Run2 analysis, then combined with Run1 result

- An angular analysis is needed to disentangle CP-even and CP-odd contributions



- Flavour tagging calibrated with $B^+ \to J/\psi K^+$ and $B_s^0 \to D_s^- \pi^+$ decays
  - $\varepsilon^{\rm eff} = 4\,\%$

- Decay-time resolution calibrated with prompt fake signals ($\sigma_t \approx 42$ fs)

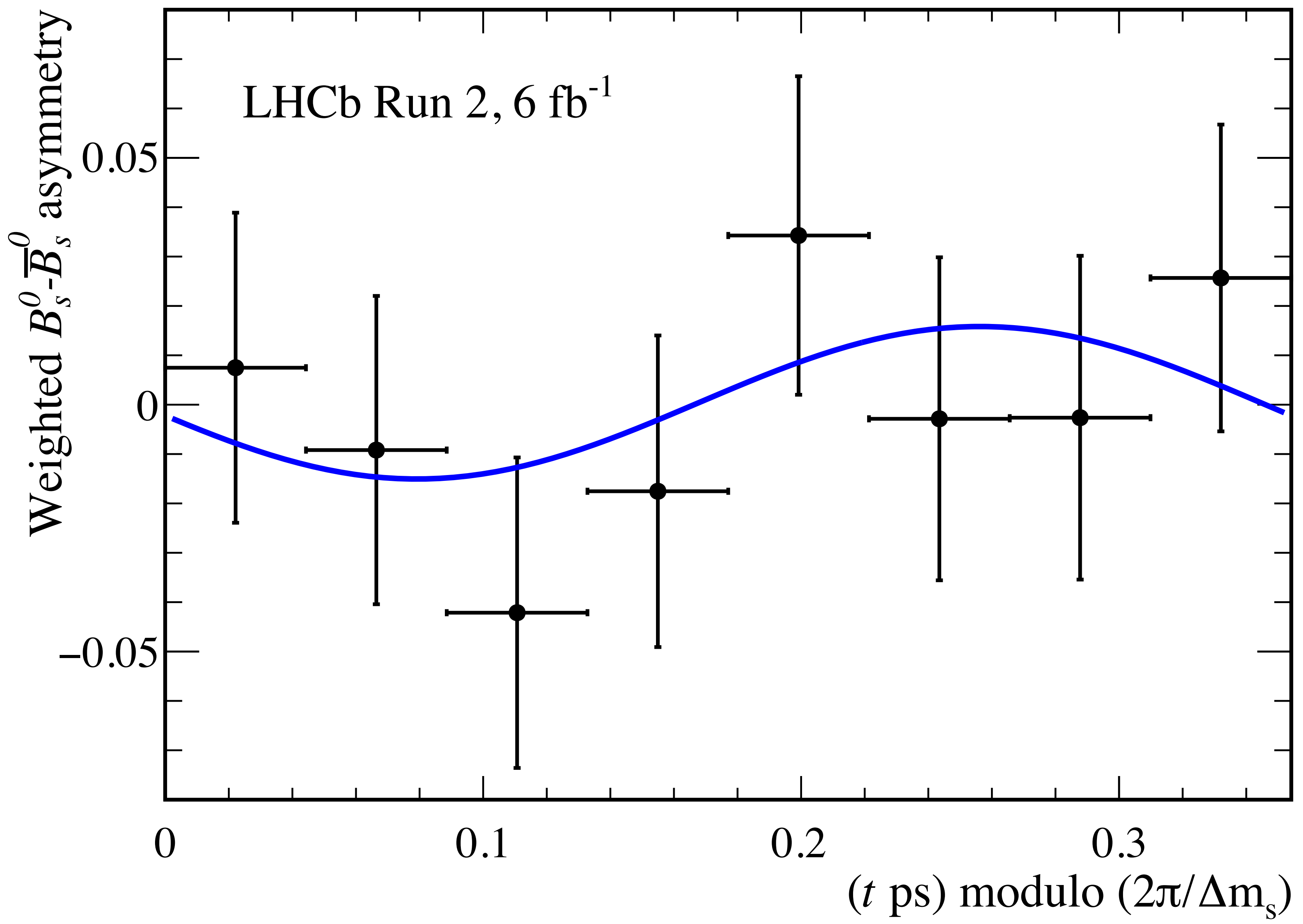
Measurement of ϕ_s with $B_s^0 \to J/\psi K^+K^-$ decays [PRL 132 (2024) 051802]

POLARISATION-INDEPENDENT RESULTS

Parameter	Result	Stat.	Syst.
ϕ_s [rad]	-0.039	±0.022	±0.006
$\lvert\lambda\rvert$	1.001	±0.011	±0.005
$\Gamma_s - \Gamma_d [\mathrm{ps}^{-1}]$	-0.0056	$^{+0.0013}_{-0.0015}$	±0.0014
$\Delta\Gamma_s [\mathrm{ps}^{-1}]$	0.0845	±0.0044	±0.0024
$\Delta m_s [\mathrm{ps}^{-1}]$	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

STAT. LIMITED

POLARISATION-DEPENDENT RESULTS ARE CONSISTENT WITH EACH OTHER



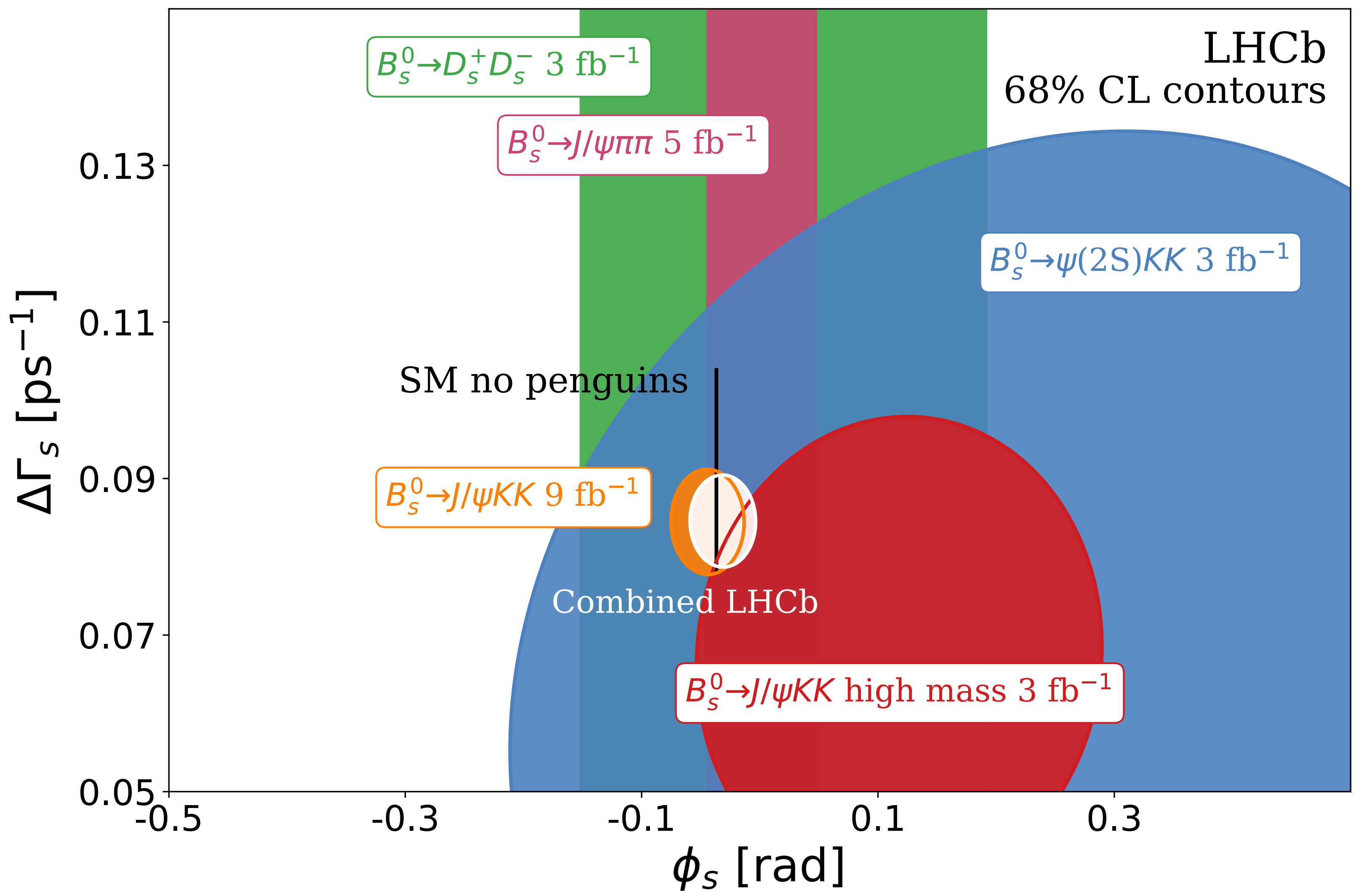
Run1+Run2

$$\boxed{\begin{aligned}\phi_s &= -0.044 \pm 0.020 \text{ rad}\\ |\lambda| &= 0.990 \pm 0.010\end{aligned}}$$

MOST PRECISE DETERMINATION

CONSISTENT WITH SM PREDICTIONS

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



Measurement of ϕ_s with $B_s^0 \to J/\psi K^+K^-$ decays [PRL 132 (2024) 051802]

POLARISATION-INDEPENDENT RESULTS

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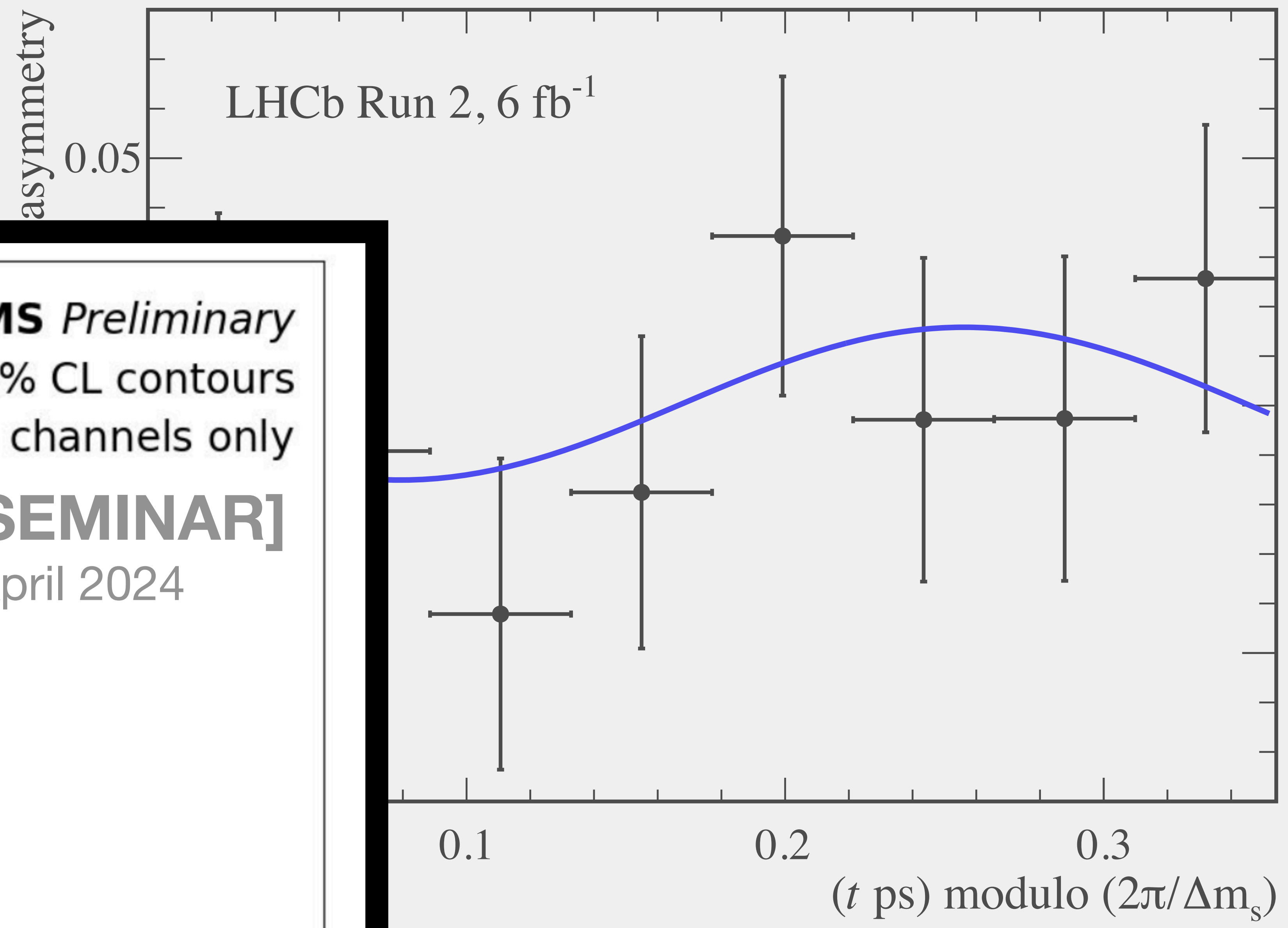
$\lvert\lambda\rvert$	1.001	± 0.011
$\Gamma_s - \Gamma_d [\mathrm{ps}^{-1}]$	-0.0056	$^{+0.0013}_{-0.0015}$
$\Delta\Gamma_s [\mathrm{ps}^{-1}]$	0.0845	± 0.004
$\Delta m_s [\mathrm{ps}^{-1}]$	17.743	± 0.033
$\lvert A_\perp\rvert^2$	0.2463	± 0.002
$\lvert A_0\rvert^2$	0.5179	± 0.001
$\delta_\perp - \delta_0$ [rad]	2.903	$^{+0.075}_{-0.074}$
$\delta_\parallel - \delta_0$ [rad]	3.146	± 0.061

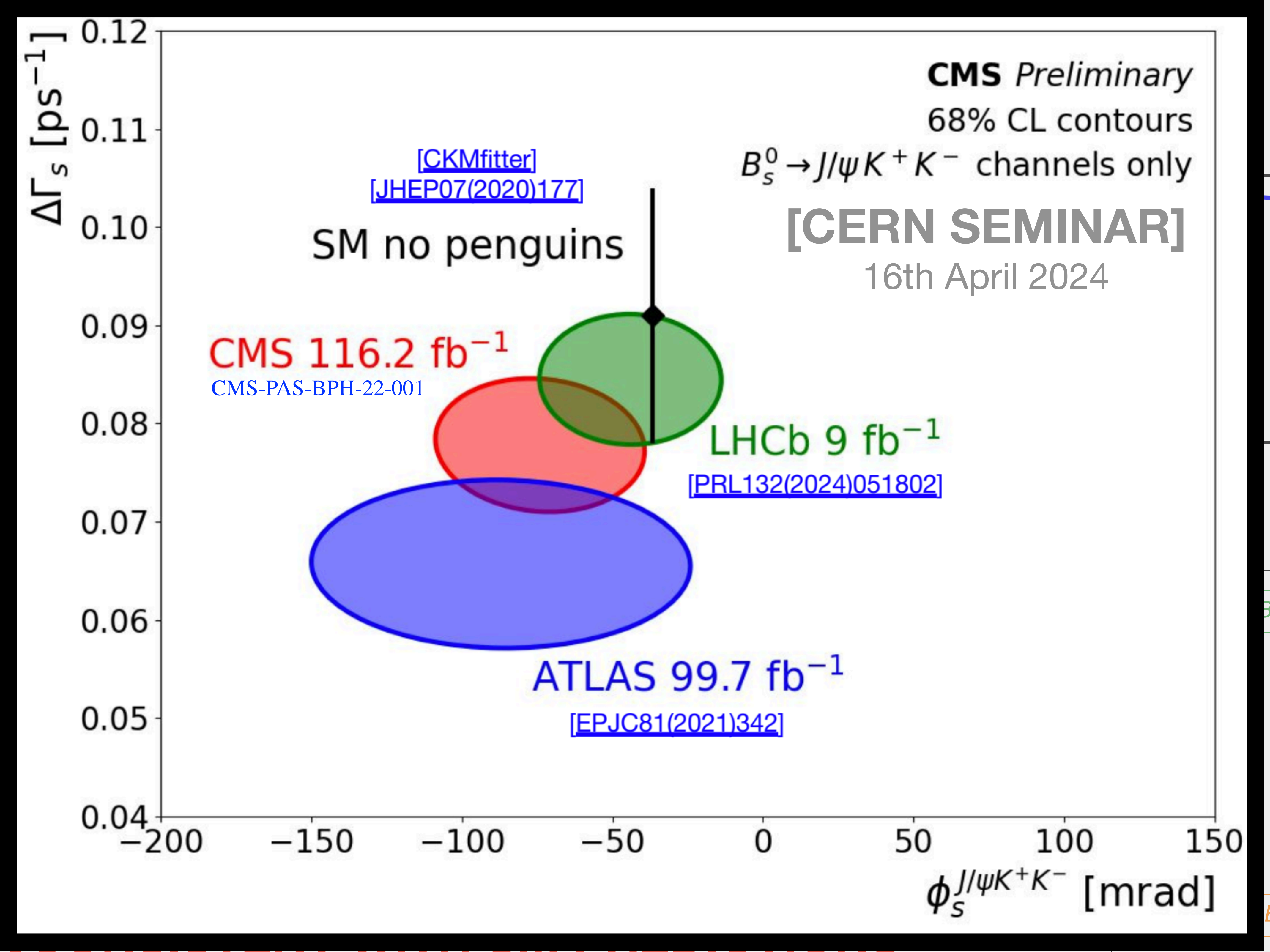
Run1+Run2

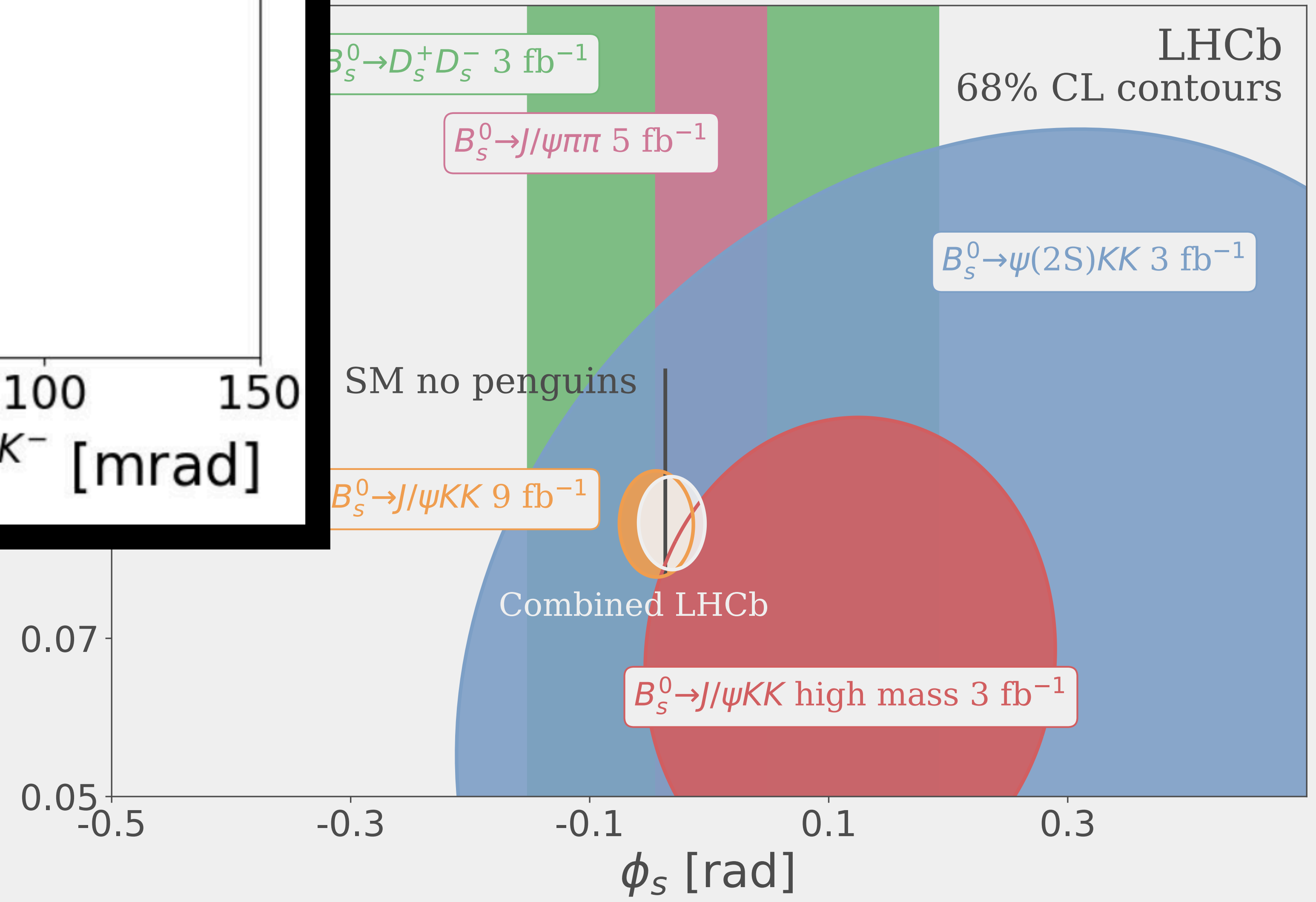
$$\phi_s = -0.044 \pm 0.020 \text{ rad}$$

$$|\lambda| = 0.990 \pm 0.010$$

LHCb COMBINATION: $\phi_s = 0.031 \pm 0.018$ rad







A measurement of $\Delta\Gamma_s$

- Not perfect agreement of $(\Gamma_s, \Delta\Gamma_s)$ measurements in $J/\psi K^+K^-$ channel
  $\Longrightarrow$ need of independent checks
- $B_s^0 \to J/\psi[\pi^+\pi^-]_{f_0(980)}$ (CP-odd)
  $\Longrightarrow$ measure τ_H
- $B_s^0 \to J/\psi(\eta' \to \rho^0\gamma)$ (CP-even)
  $\Longrightarrow$ measure τ_L

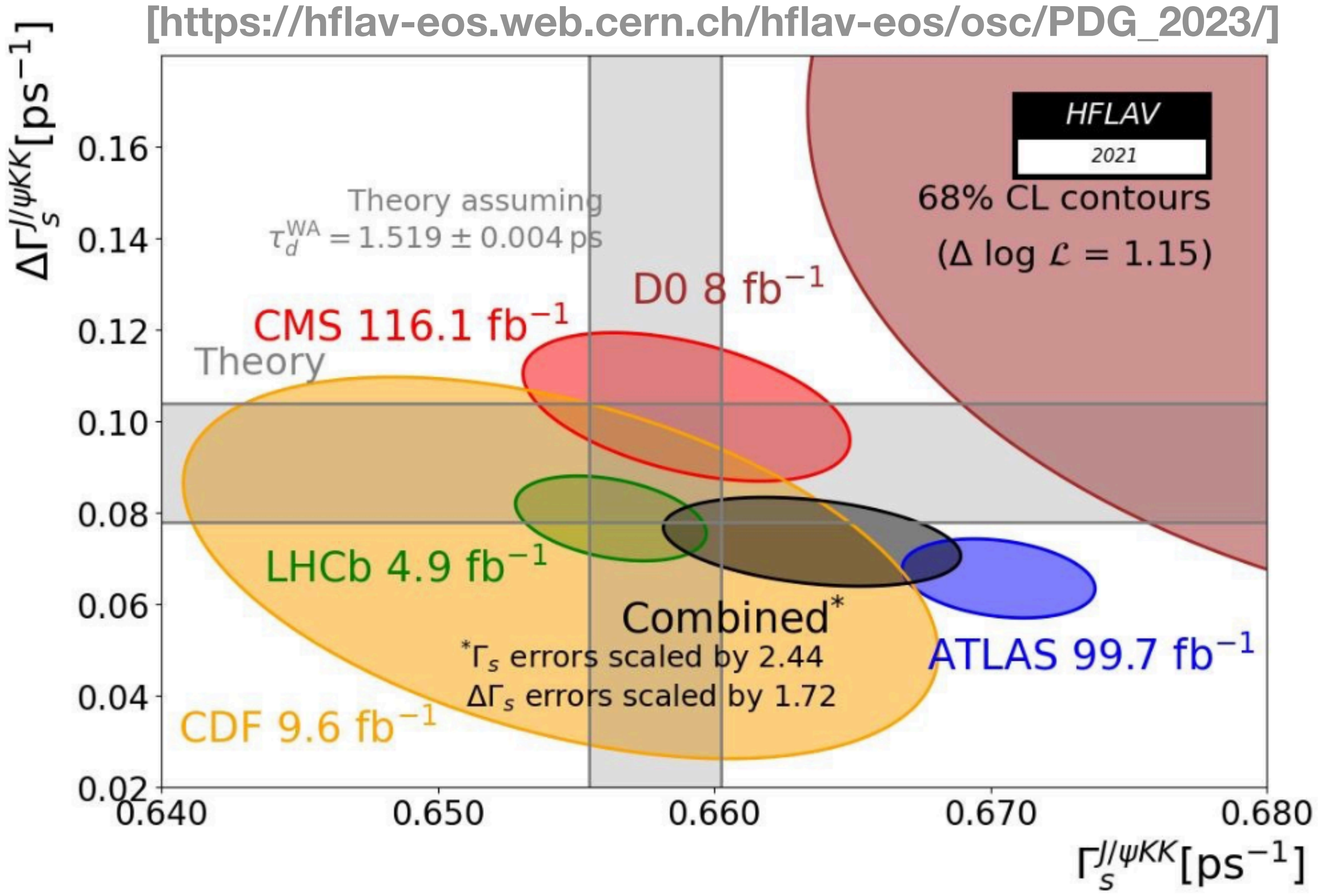
Run1+Run2

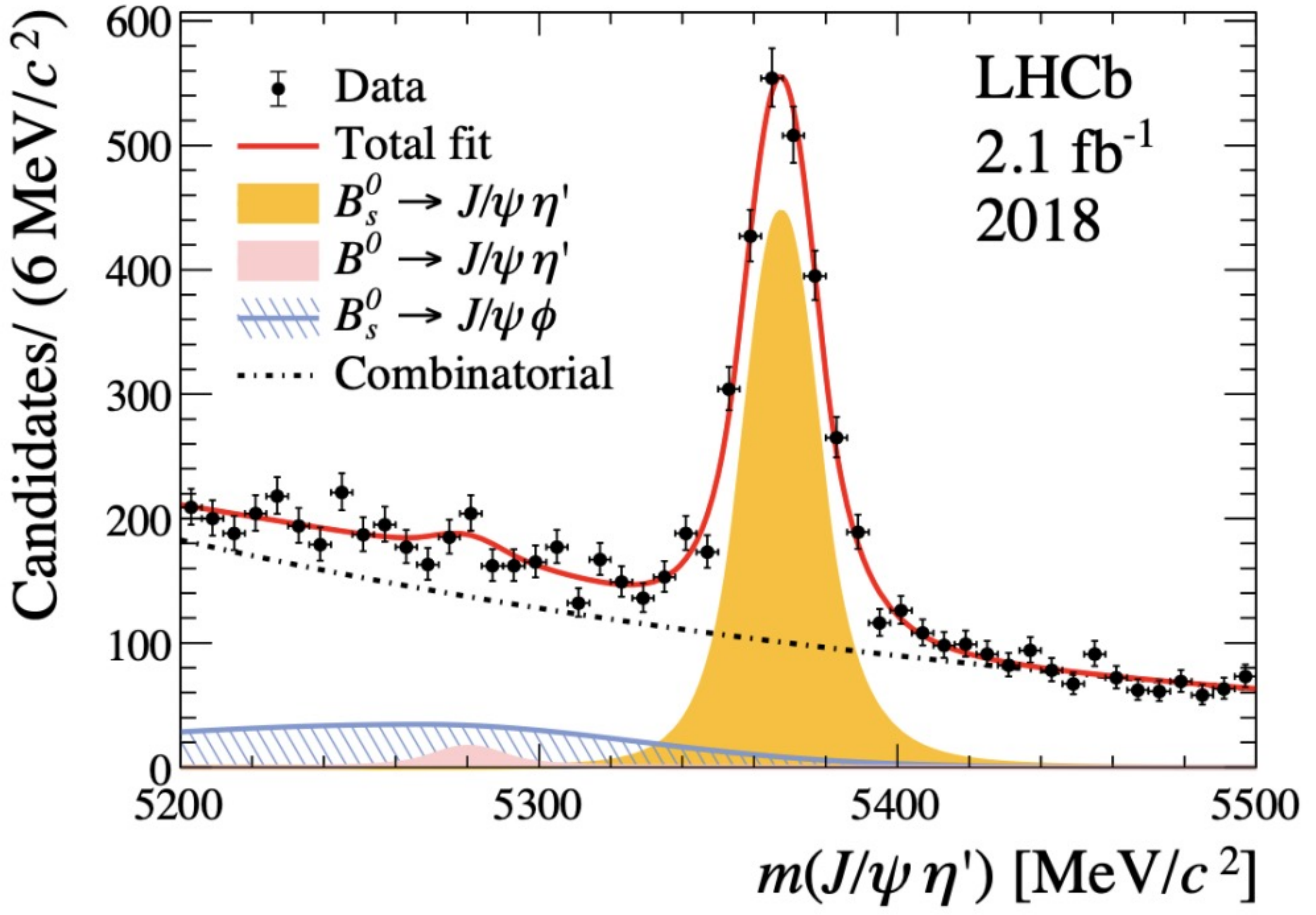
$$\boxed{\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009\ \text{ps}^{-1}}$$

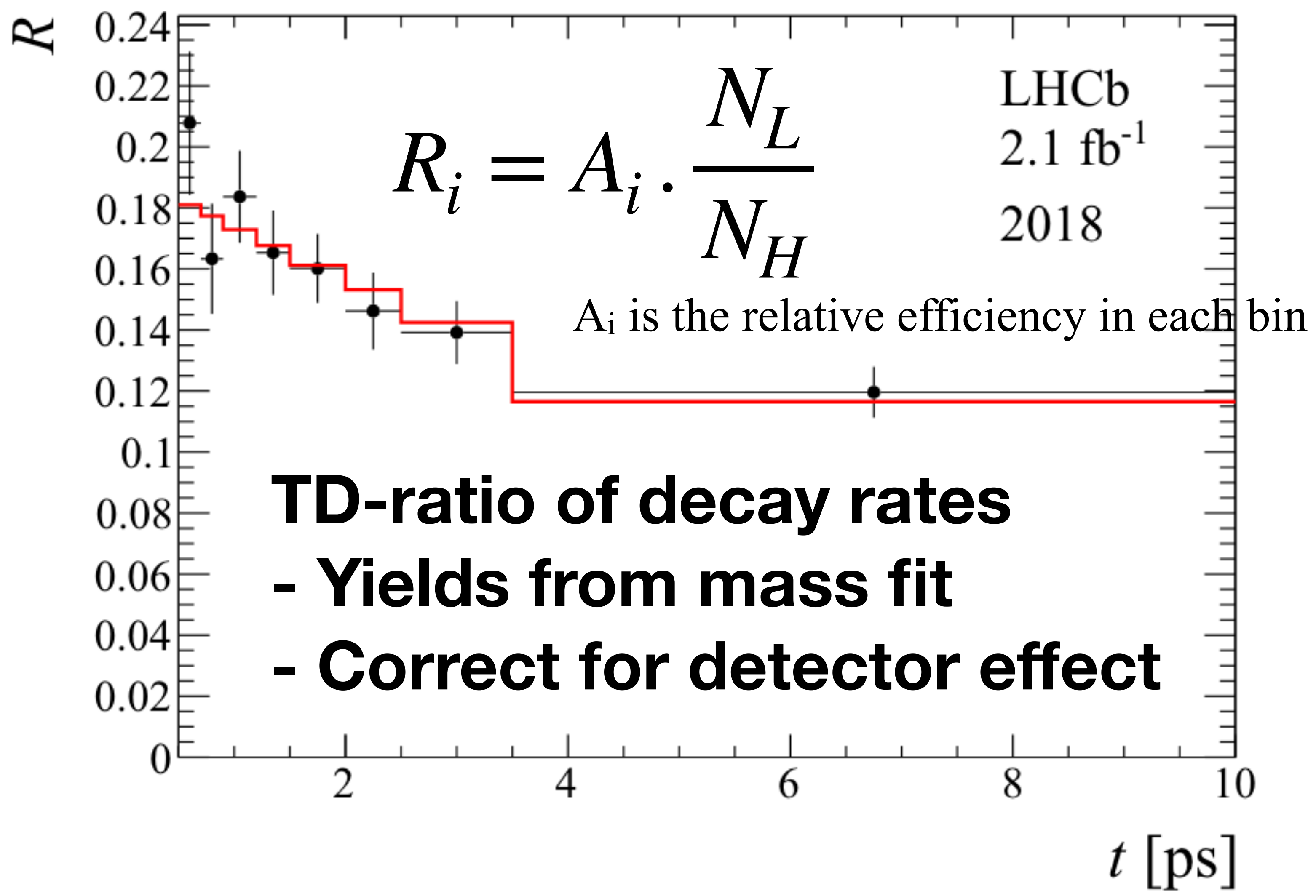
GOOD AGREEMENT WITHIN LHCb

$\Delta\Gamma_s(J/\psi\phi) = 0.0845 \pm 0.0044 \pm 0.0024\ \text{ps}^{-1}$

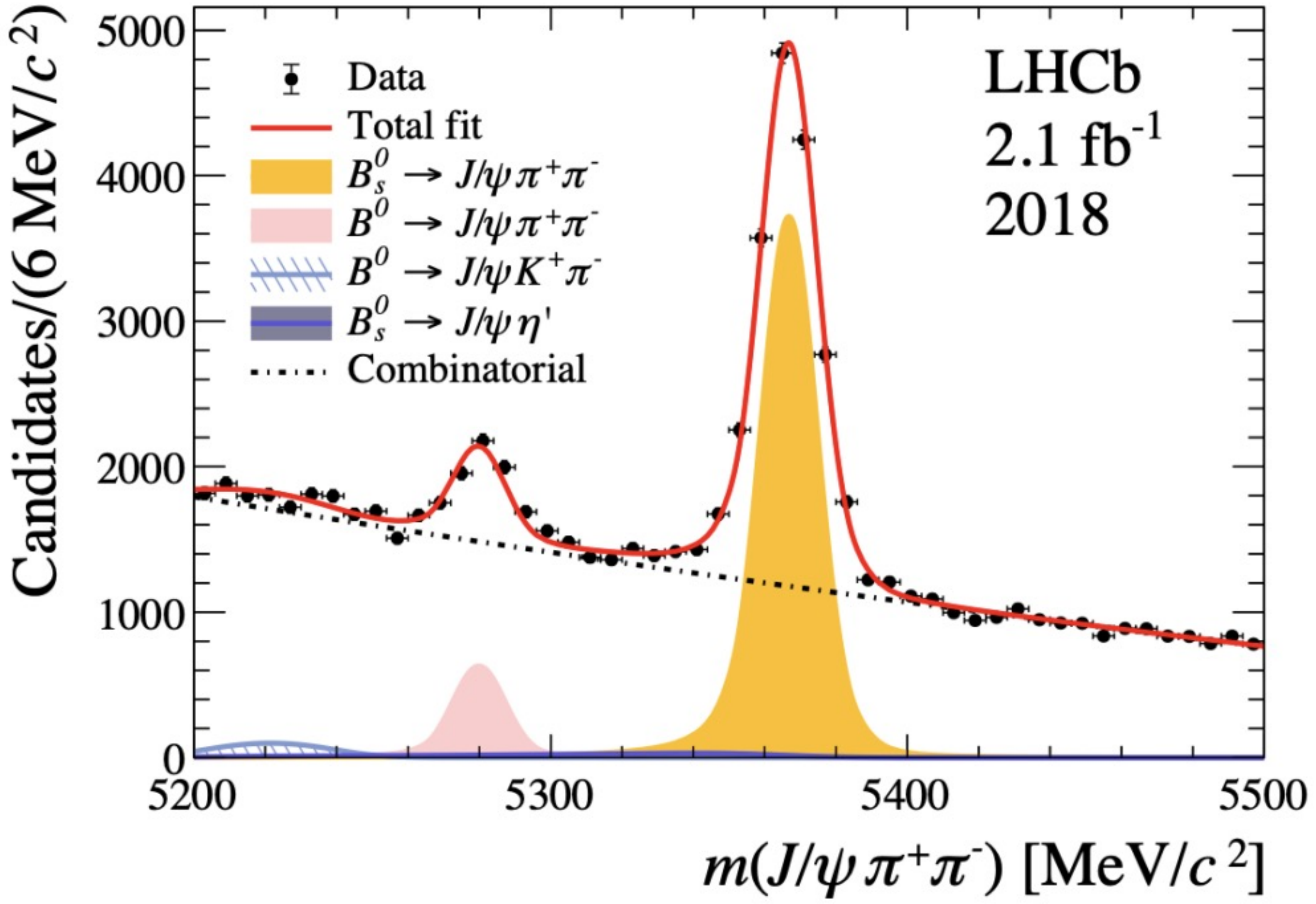
[https://hflav-eos.web.cern.ch/hflav-eos/osc/PDG_2023/]







TD-ratio of decay rates
- Yields from mass fit
- Correct for detector effect



Measurement of γ with $B_s^0 \to D_s^\mp K^\pm$ decays [LHCb-CONF-2023-004]

$$C_f = -C_{\bar f} = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2}$$

magnitude of amplitude ratio

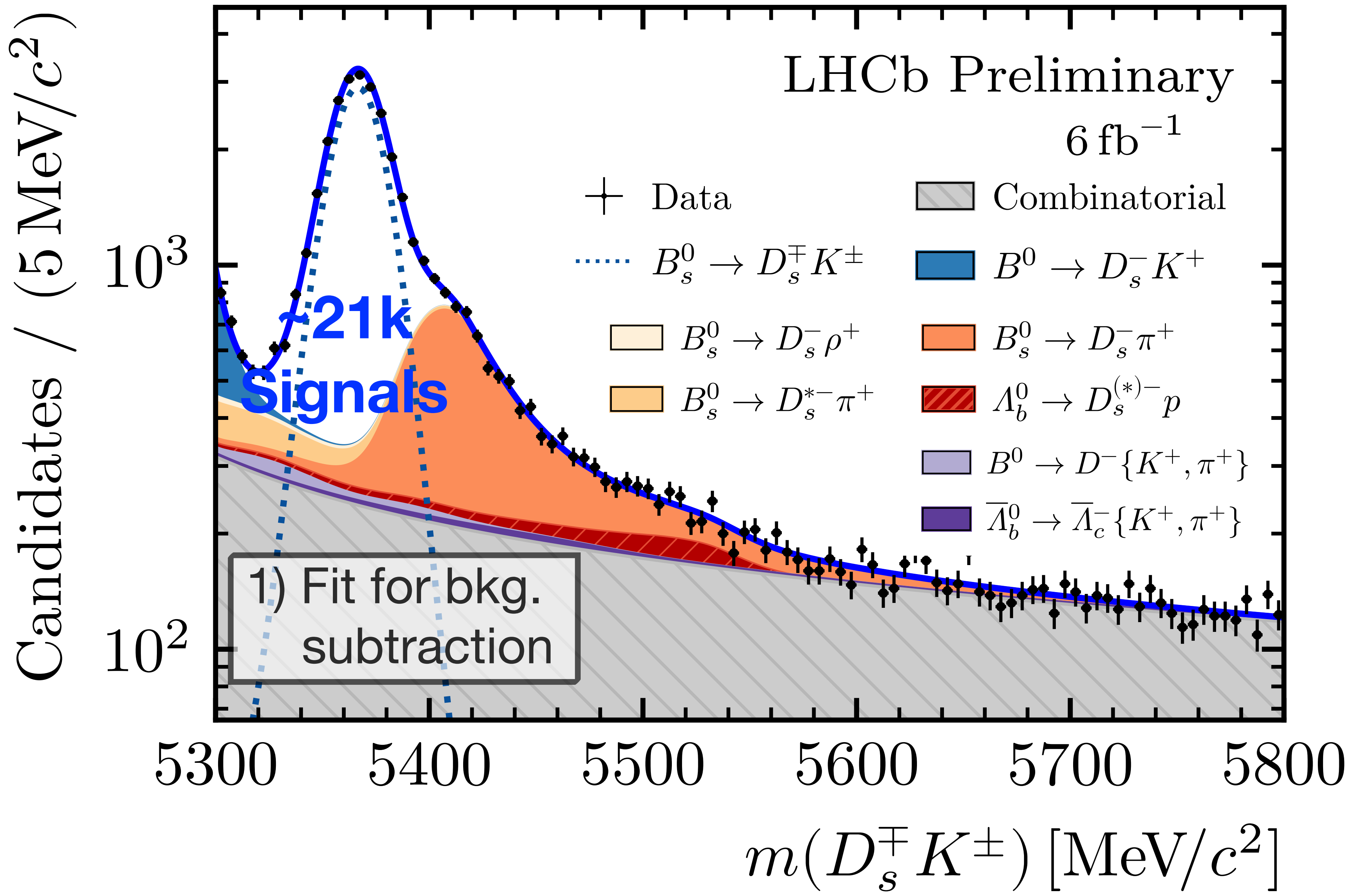
$r_{D_sK} \equiv |\lambda_f| = |A(\overline{B}_s^0 \to D_s^- K^+)/A(B_s^0 \to D_s^- K^+)|$

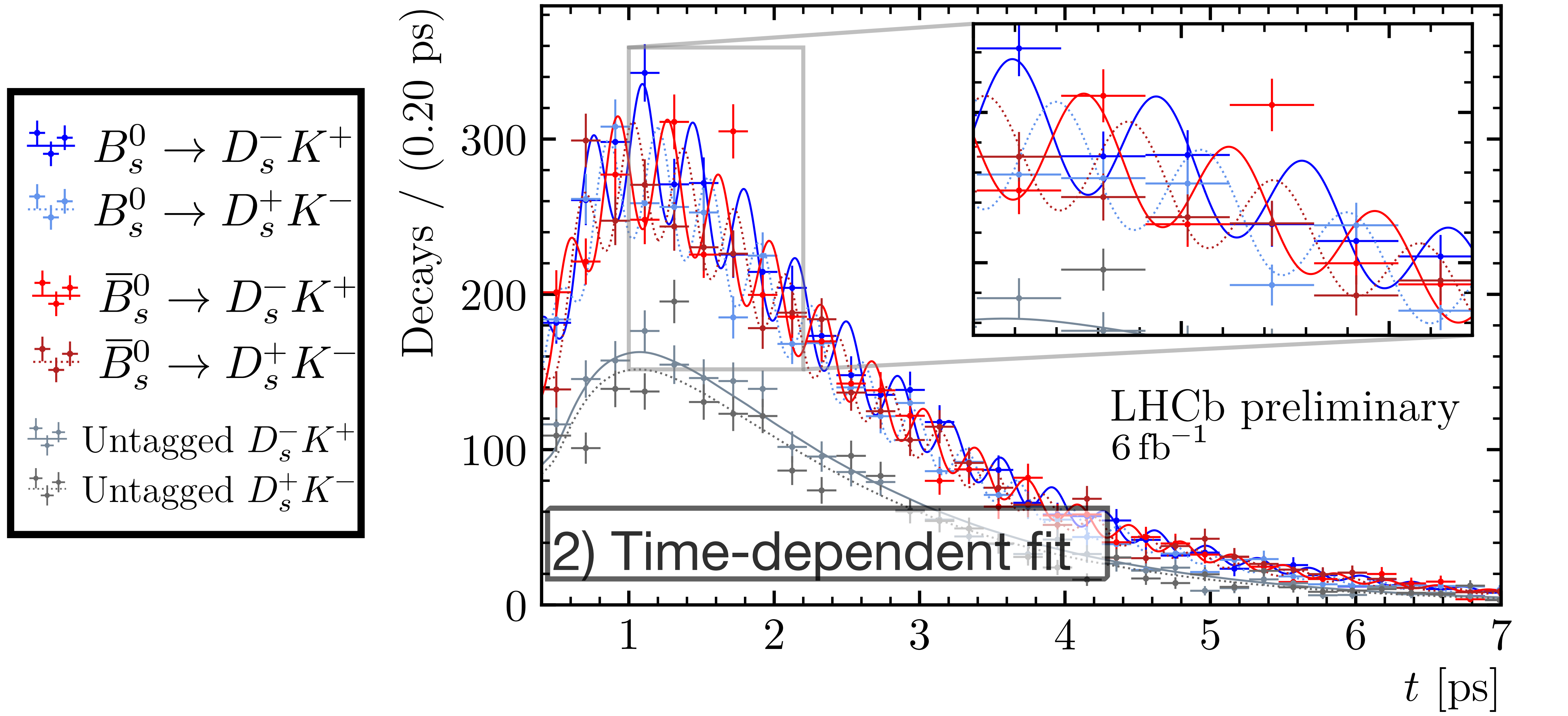
Strong phase difference

$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \quad A_{\bar f}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2},$$

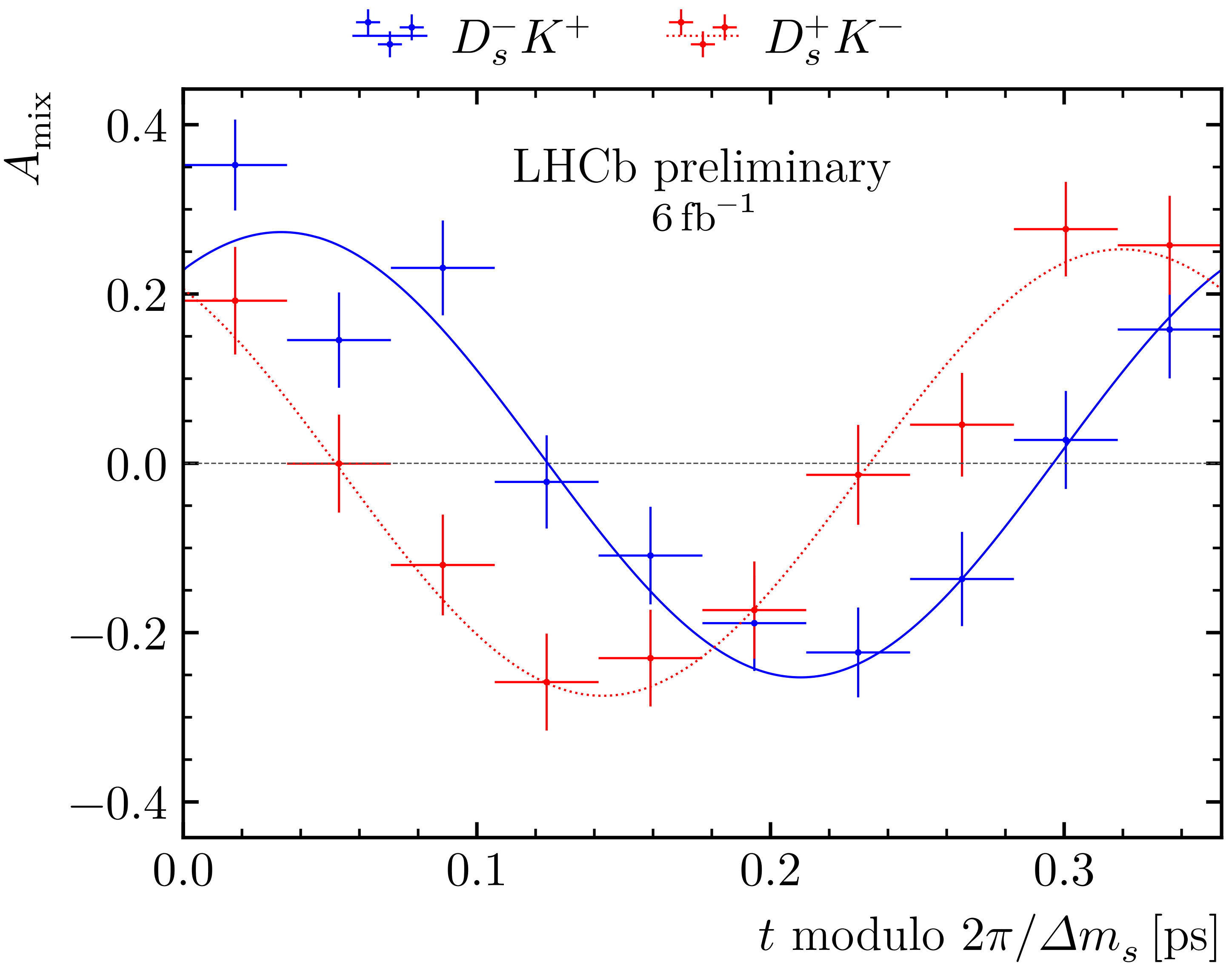
$$S_f = \frac{2r_{D_sK}\sin(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \quad S_{\bar f} = \frac{-2r_{D_sK}\sin(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}.$$

- Common final states for both B_s^0 and $\overline{B}_s^0$
  - 4 decay rates, 5 CP-asymmetry observables
  - γ is determinable including ϕ_s as an external input
- $D_s^\mp$ reconstructed with 5 decay modes
  - $\pi^\mp\pi^+\pi^-$, $K^\mp\pi^+\pi^-$, $\phi\pi^\mp$, $K^{*0}(892)K^\mp$
- $B_s^0 \to D_s^-\pi^+$ used to calibrate the FT ($\varepsilon_{\text{eff}} = 6\,\%$)
  - Also used for Δm_s measurement





CKM-phase γ with $B_s^0 \to D_s^{\mp} K^{\pm}$ decays [LHCb-CONF-2023-004]



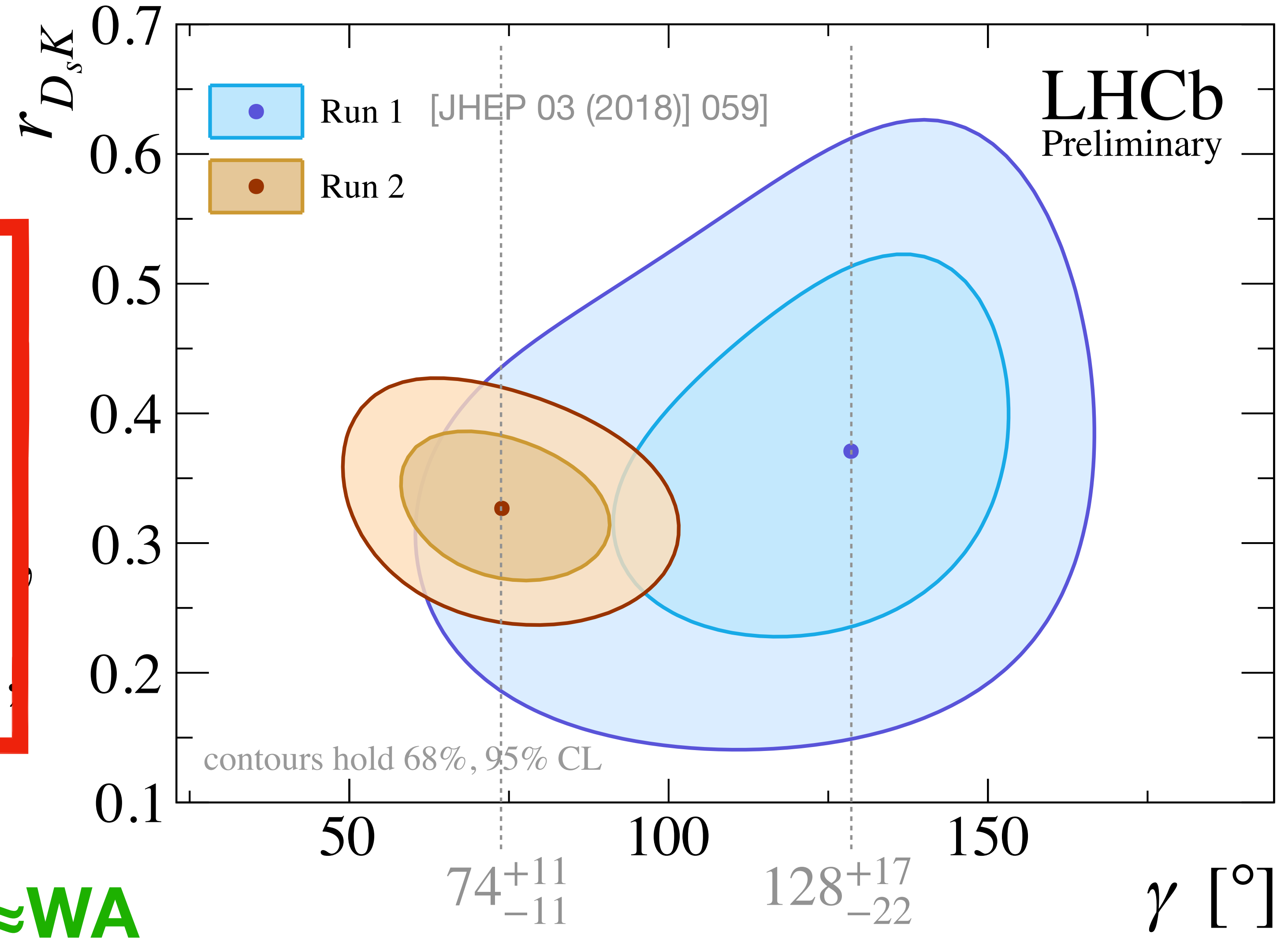
Final results from $B_s^0 \to D_s^{\mp} K^{\pm}$ Run2 (6 fb[-1])

$$C_f = 0.791 \pm 0.061 \pm 0.022$$
$$A_f^{\Delta\Gamma} = -0.051 \pm 0.134 \pm 0.037$$
$$A_{\bar{f}}^{\Delta\Gamma} = -0.303 \pm 0.125 \pm 0.036$$
$$S_f = -0.571 \pm 0.084 \pm 0.023$$
$$S_{\bar{f}} = -0.503 \pm 0.084 \pm 0.025$$

with ϕ_s from latest LHCb combination:

$$\gamma = (74 \pm 11)^\circ\,,$$
$$\delta = (346.9 \pm 6.6)^\circ$$
$$r_{D_sK} = 0.327 \pm 0.038$$

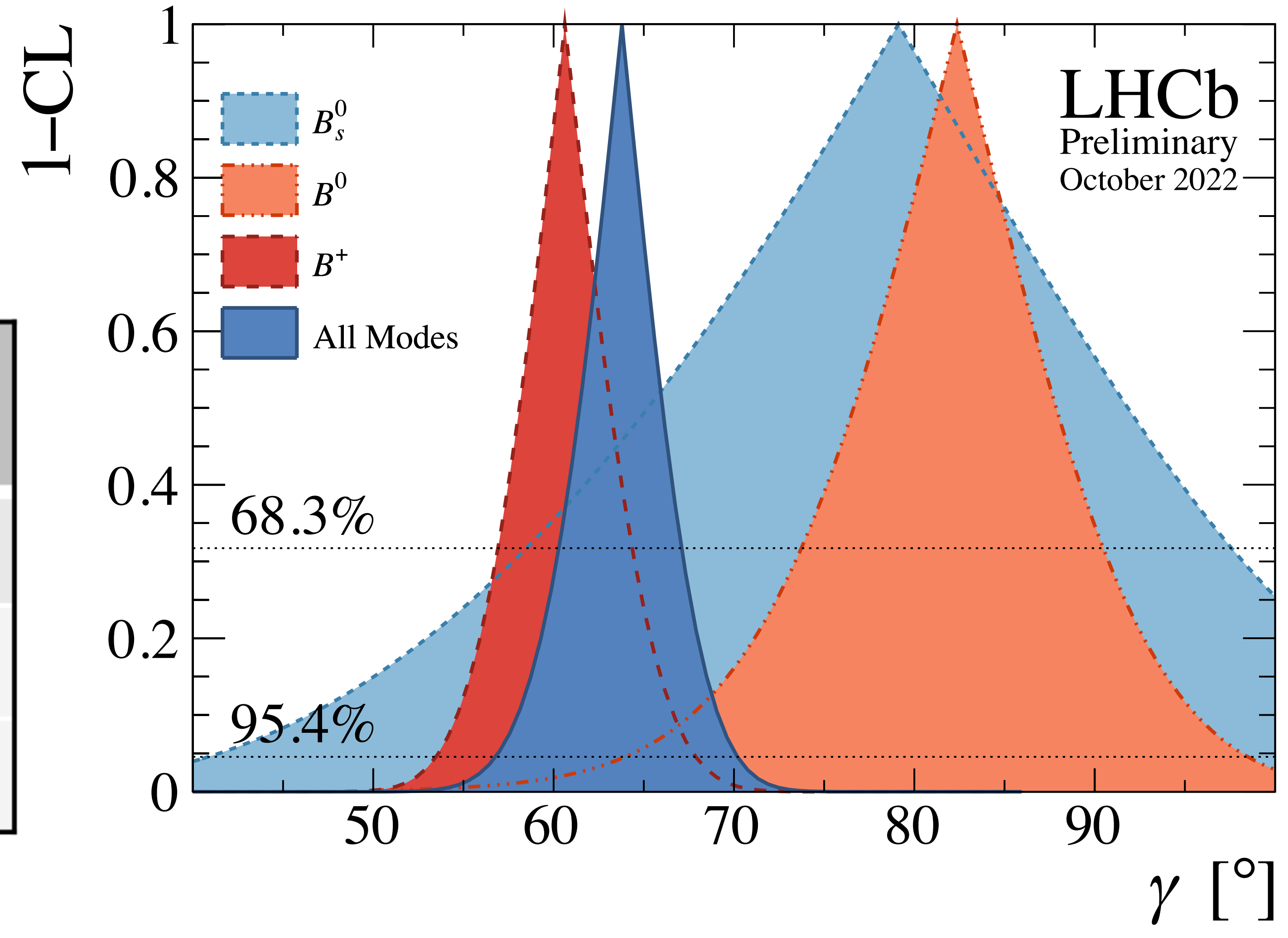
GOOD AGREEMENT WITH LHCb's AVERAGE ≈WA



- The latest γ combination by LHCb was released in October 2022
  - Frequentist approach
  - **Inputs from beauty and charm sectors**
    - 173 observables and 52 parameters
  - The inclusion of the results released since then solves the previous tension between B^+ and B^0
    - **A new combination is on the way**

[LHCb-CONF-2022-003]

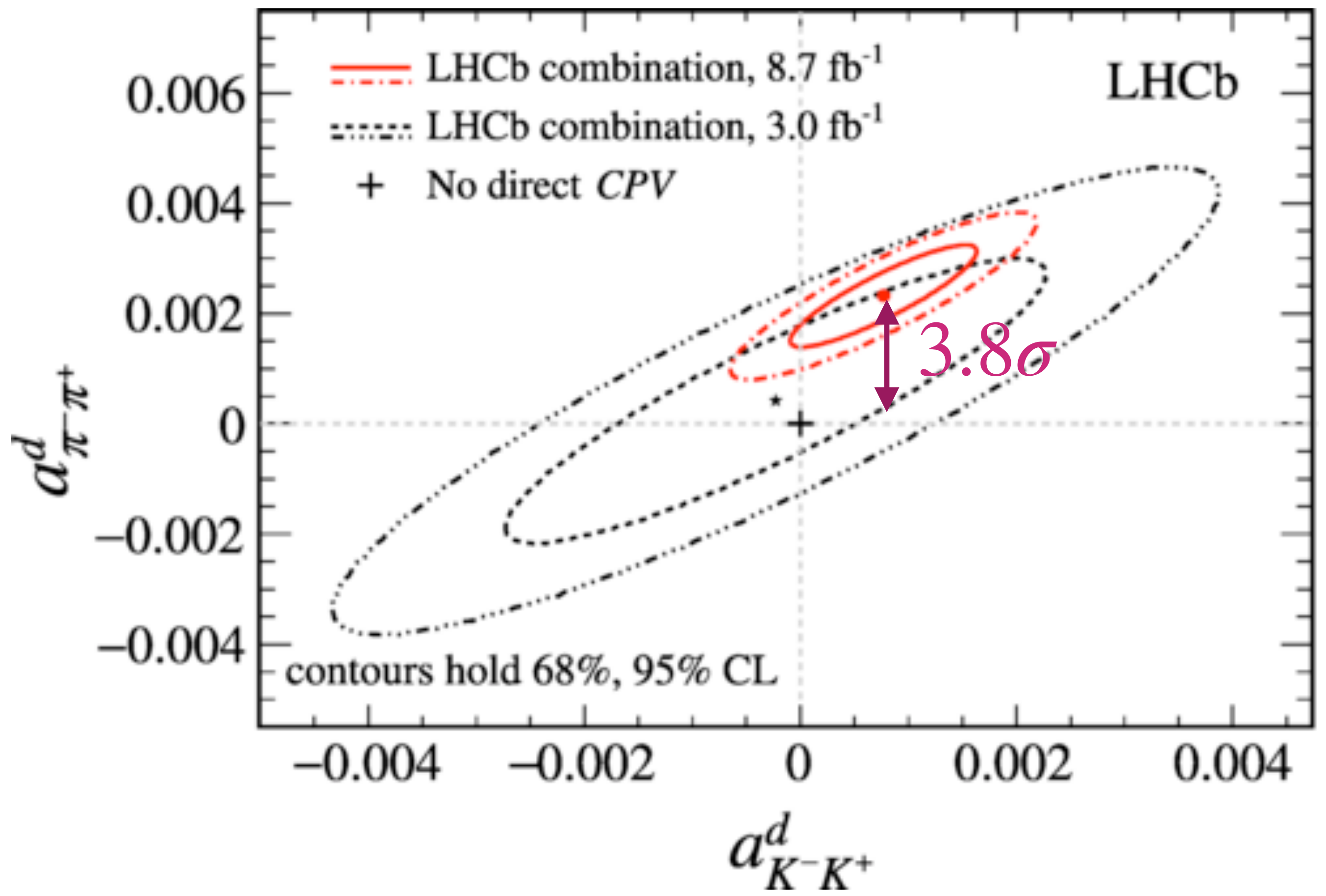
	γ (°)
LHCb	$\mathbf{63.8^{+3.5}_{-3.7}}$ °
CKMfitter	$65.6^{+1.1}_{-2.7}$ °
UTFit	$65.8^{+2.2}_{-2.2}$ °



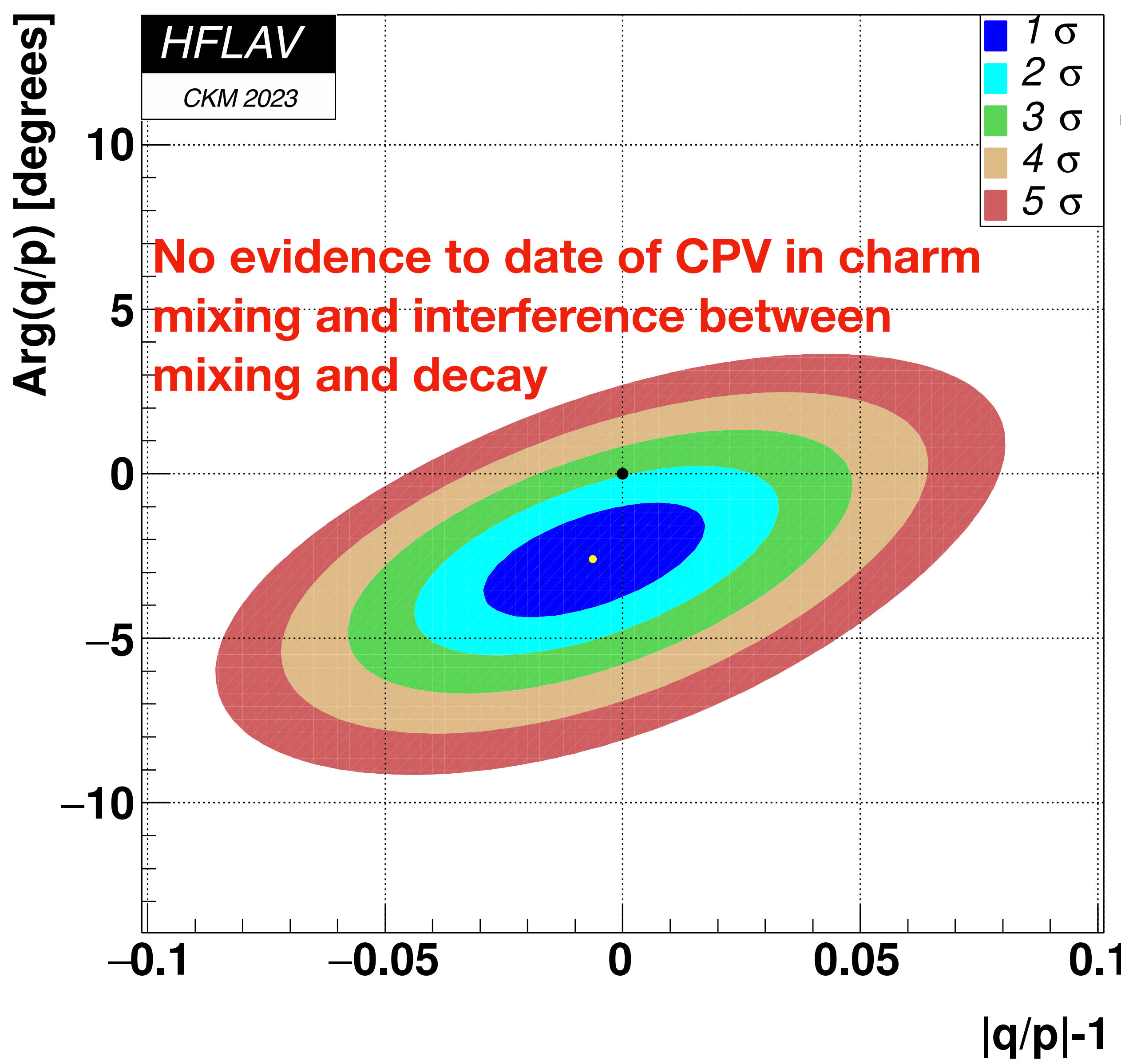
Seeking charm CPV

- **Unique laboratory to study CPV in the up-type quarks**
- Theory predictions complicated by QCD effects that are difficult to compute
- CPV in charm is **highly suppressed in the SM**
  - Beauty loop suppressed by the smallness of the CKM elements
  - Strange-down loops suppressed by GIM mechanism
- **An eventual observation of CPV enhancement would be a signature of New Physics**
  - For a review see arXiv:2208.05769v2 and references therein
- Huge charm data sample from LHCb led to the **unique observation** of CPV in D^0 decays in 2019
  $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$ (5.3σ)
  [PRL122.211803]
- **New measurements in more channels are needed**

Unique evidence of CPV in single decay ($D^0 \to \pi^+\pi^-$)



[PRL131.091802]



https://hflav.web.cern.ch/

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

NEW!

[LHCb-PAPER-2024-008]

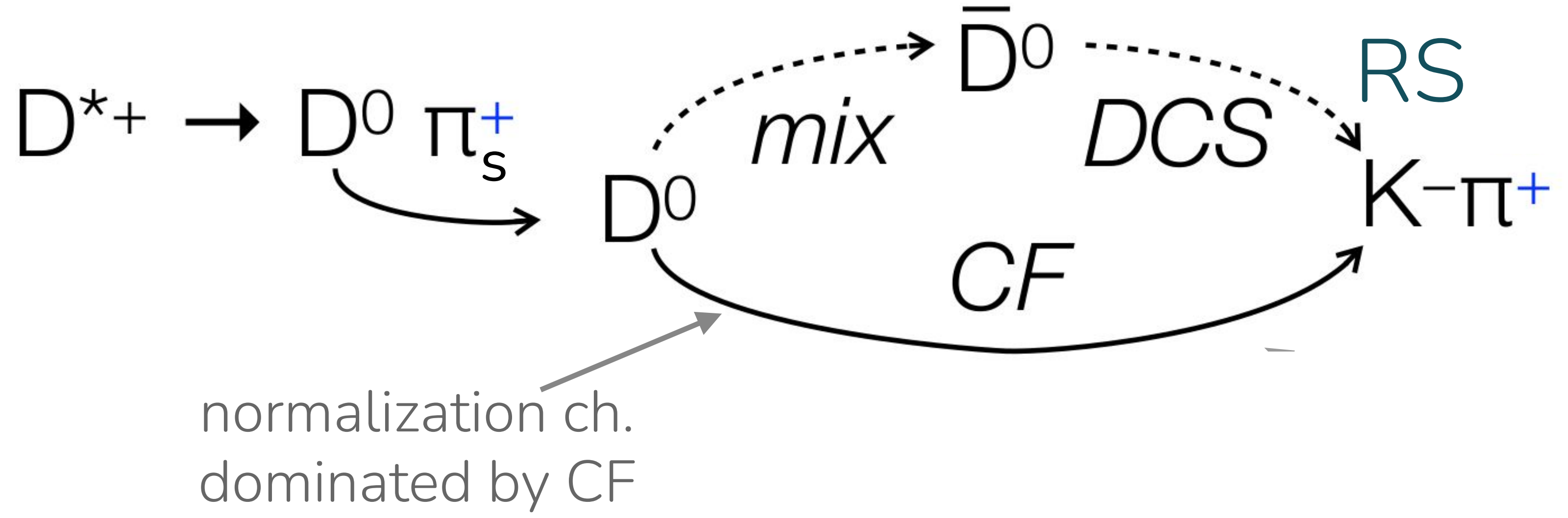
[CERN Seminar 26-MAR-2024]

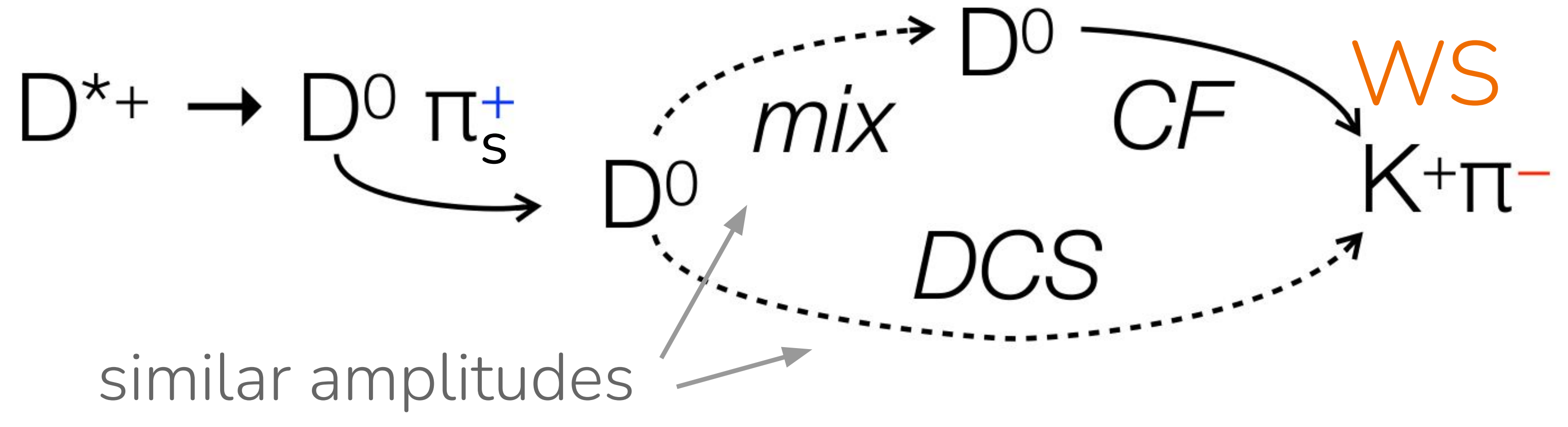
- **$D^0 \to K^\mp\pi^\pm$ decays allow the simultaneous measurement of mixing and all types of CPV**
  - Common final states for both D^0 and $\overline{D}^0$
  - One mode is favoured (RS), while the other is suppressed (WS)
  - Two time-dependent WS/RS ratios

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

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

[JHEP2022.1]





$$R^\pm_{K\pi}(t) = R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}\,(c_{K\pi} \pm \Delta c_{K\pi})\, t/\tau_{D^0} + (c'_{K\pi} \pm \Delta c'_{K\pi})\,(t/\tau_{D^0})^2$$

magnitude amplitude ratio

$$\frac{|A(D^0 \to K^+\pi^-)|^2}{|A(D^0 \to K^-\pi^+)|^2}$$

CPV in DSC decays

$A_{K\pi} = 0$ expected in the SM

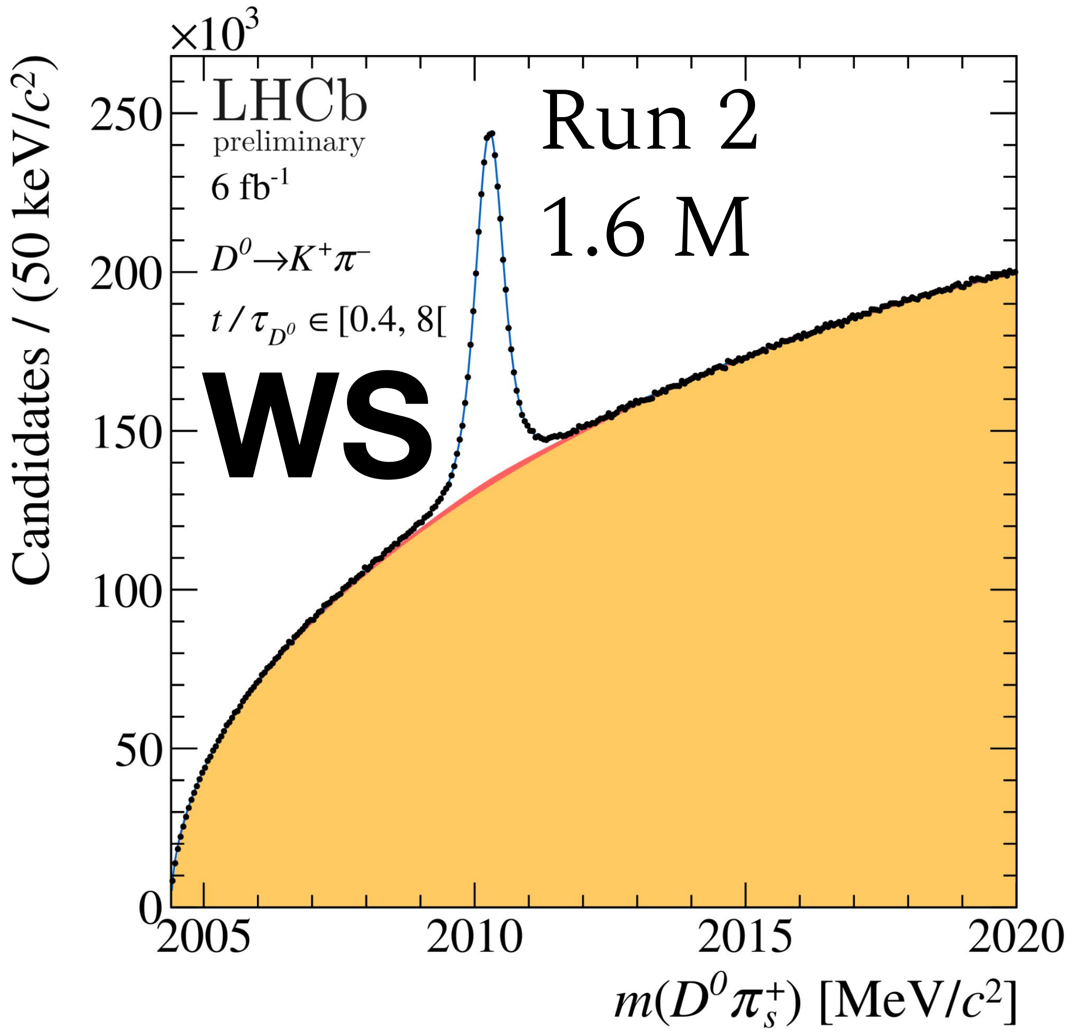
D^0 mixing

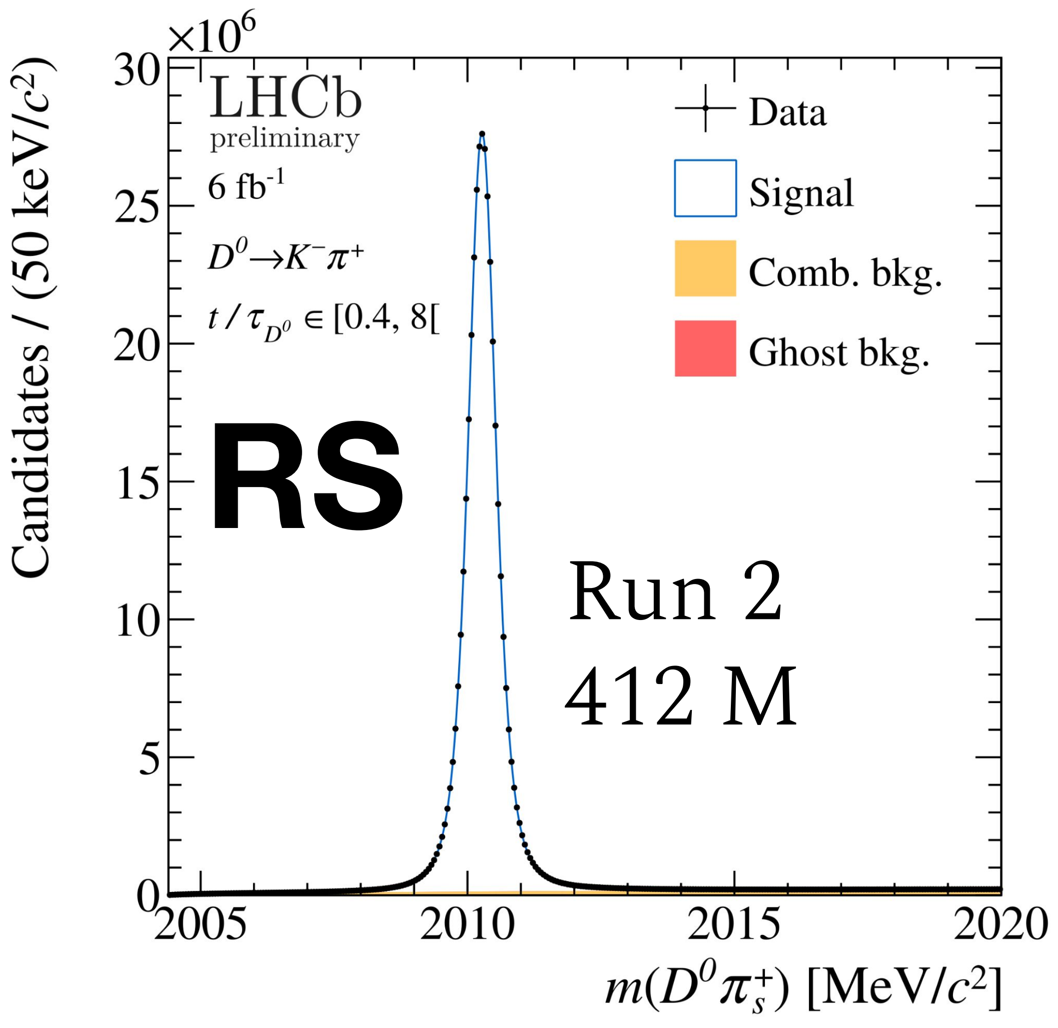
CPV in *interference*

CPV in mixing

Detailed formalism in the backup

$c_{K\pi}$ and $\Delta c_{K\pi}$ include strong phase difference of DCS/CF ($\Delta_{K\pi}$)



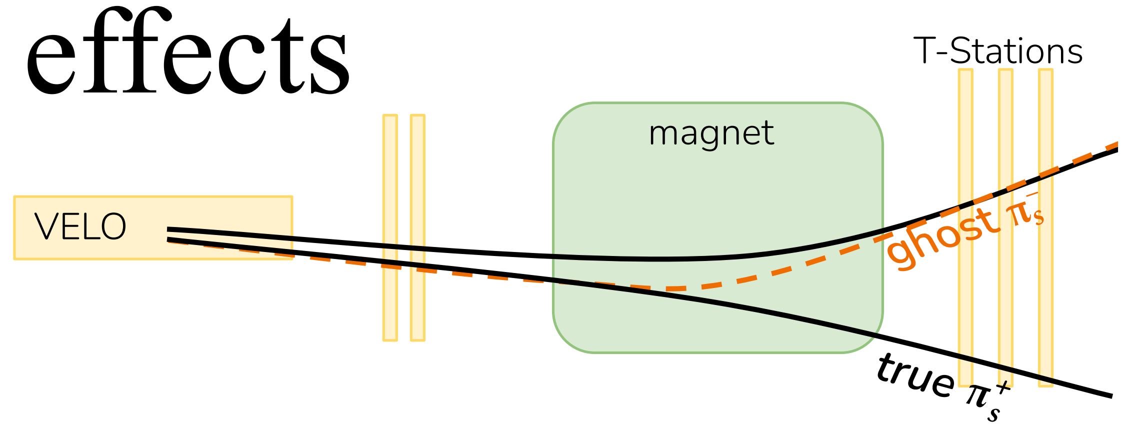


- Run2 analysis, then combined with Run1 result
- D flavour tagged with prompt-$D^{*+} \to D^0\pi^+$ decays

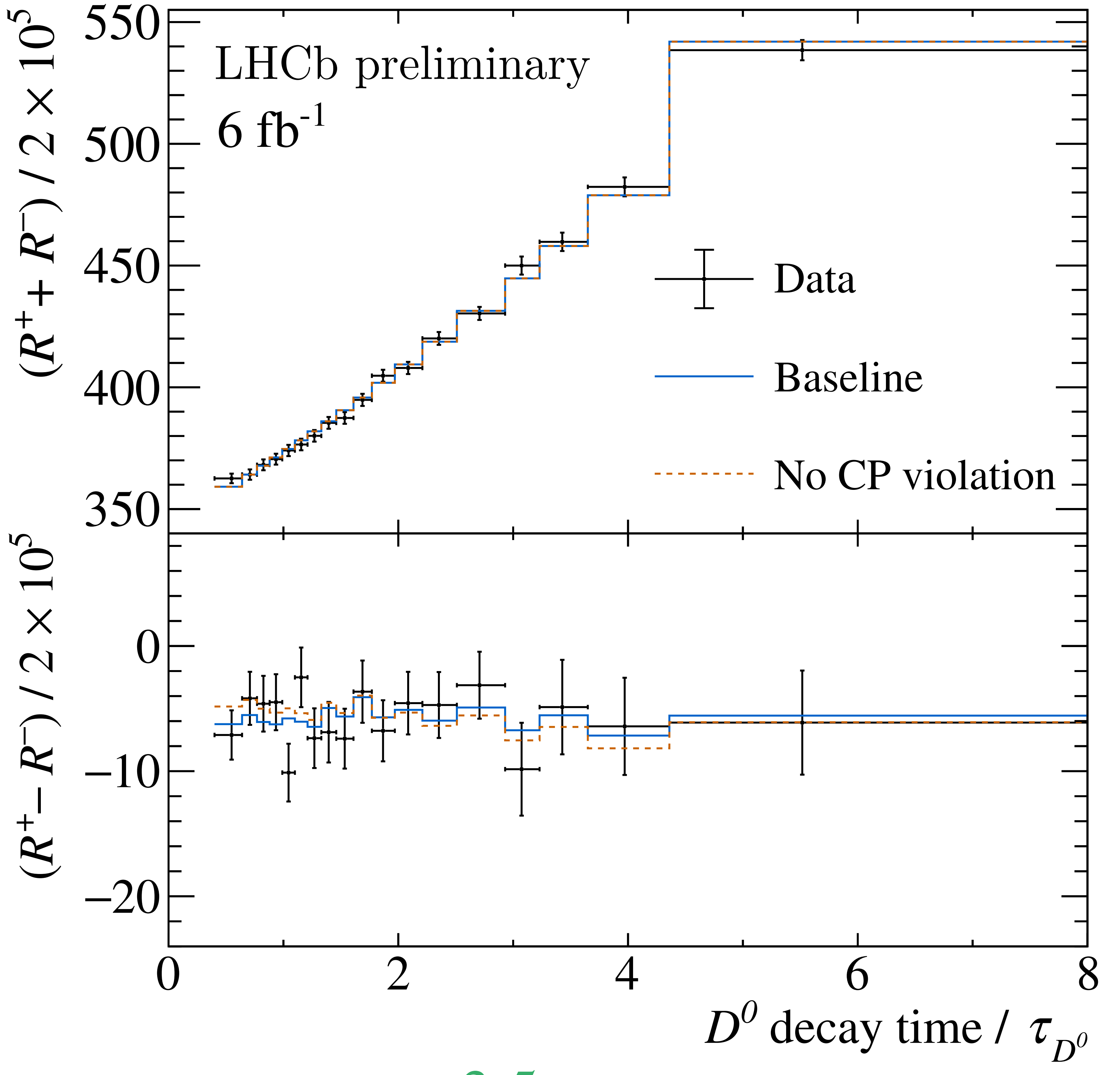
Mixing and CPV in $D^0 \to K^+\pi^-$ decays

NEW!
[LHCb-PAPER-2024-008]
[CERN Seminar 26-MAR-2024]

- Yields of WS and RS measured in 18 bins of decay time
- Challenge: precise correction of syst. effects
  - Ghosts soft pions
  - Detection asymmetries
    - Determined from $D^0 \to K^+K^-$ control mode
  - Decay-time bias (D^* from B decays)
    - Novel method improved syst. uncertainty by one order of magnitude compared to the previous analysis



- Final time-dependent χ^2 fit for the 6 target observables



Main syst. uncertainties (Preliminary)

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 modeling	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
Total syst. 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

STILL STATISTICALLY DOMINATED
(Total syst. improved by factor 2, compared to previous analysis)

LHCb Preliminary (Run1+Run2)

$R_{K\pi}$	$(342.7 \pm 1.9)\times10^{-5}$
$c_{K\pi}$	$(52.8 \pm 3.3)\times10^{-4}$
$c'_{K\pi}$	$(12.0 \pm 3.5)\times10^{-6}$
$A_{K\pi}$	$(-6.6 \pm 5.7)\times10^{-3}$
$\Delta c_{K\pi}$	$(2.0 \pm 3.4)\times10^{-4}$
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6)\times10^{-6}$

FIRST EVIDENCE (3.5σ) OF QUADRATIC TERM

NO EVIDENCE OF CPV

40% improvement in total uncertainties compared to the previous best [PRD97.031101(2018)]

Search for TD-CPV in $D^0 \to \pi^+\pi^-\pi^0$ decays

NEW!
[ArXiv:2405.06556]

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

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

Related to mixing and indirect CPV

Universal

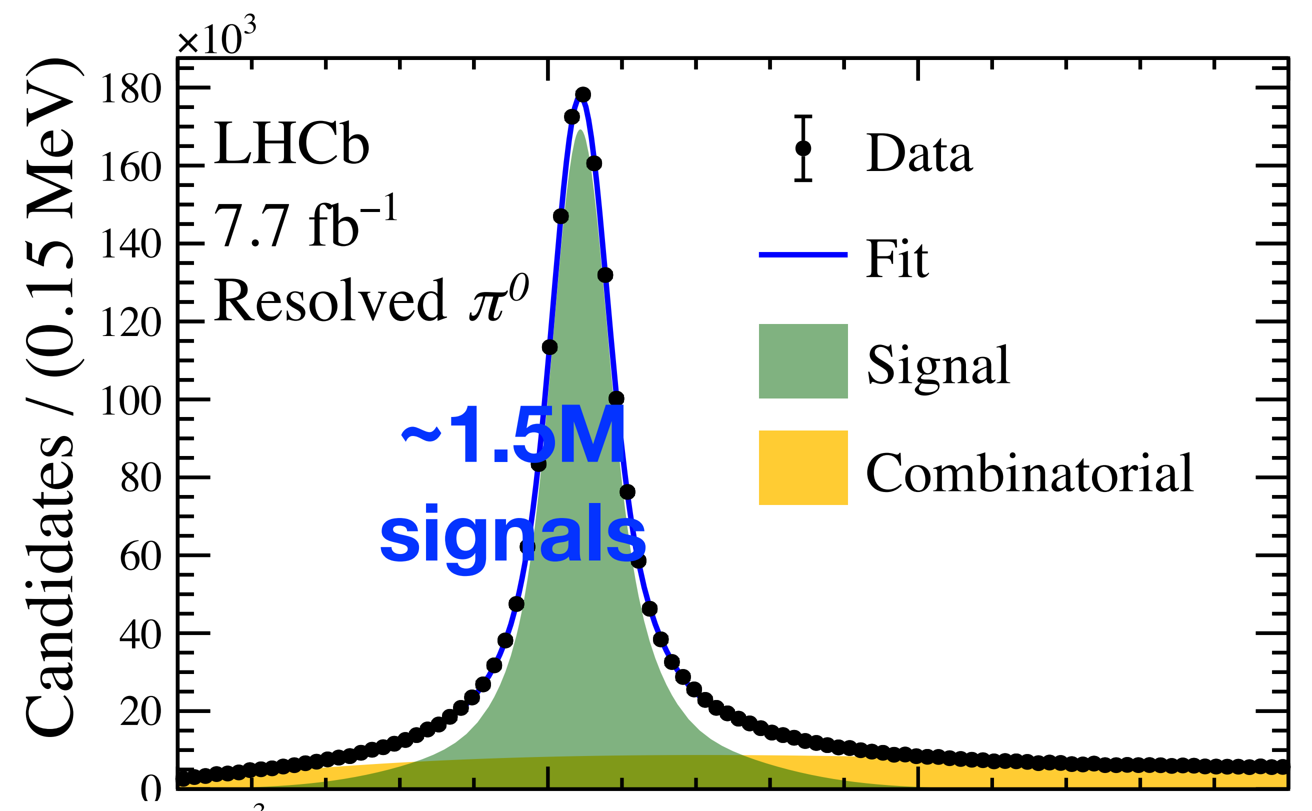
- $D^0 \to \pi^+\pi^-\pi^0$ has almost entirely CP-even final state
  - $\Delta Y^{\mathrm{eff}}_f = (2F^f_+ - 1)\Delta Y$, in this case: $F^{\pi\pi\pi}_+ = 0.973 \pm 0.017$ [PLB747(2015)9]
  - **Optimal sensitivity for PHSP-integrated measurement**
- Run1+Run2 datasets
- Fit to $\Delta m \equiv m(D^{*+}) - m(D^0)$ in bins of t/τ_{D^0} to extract $A_{CP}(t)$
  - D flavour from $D^{*+} \to D^0\pi^+$ decays
  - Merged and resolved $\pi^0 \to \gamma\gamma$ cases
  - Correct for nuisance asymmetries
- Linear fit to $A_{CP}(t)$ to extract ΔY
  - Validation with $D^0 \to K^+\pi^-\pi^0$
    - CF $\Rightarrow |\Delta Y_{K\pi\pi} < 2.5 \times 10^{-5}|$@90 CL

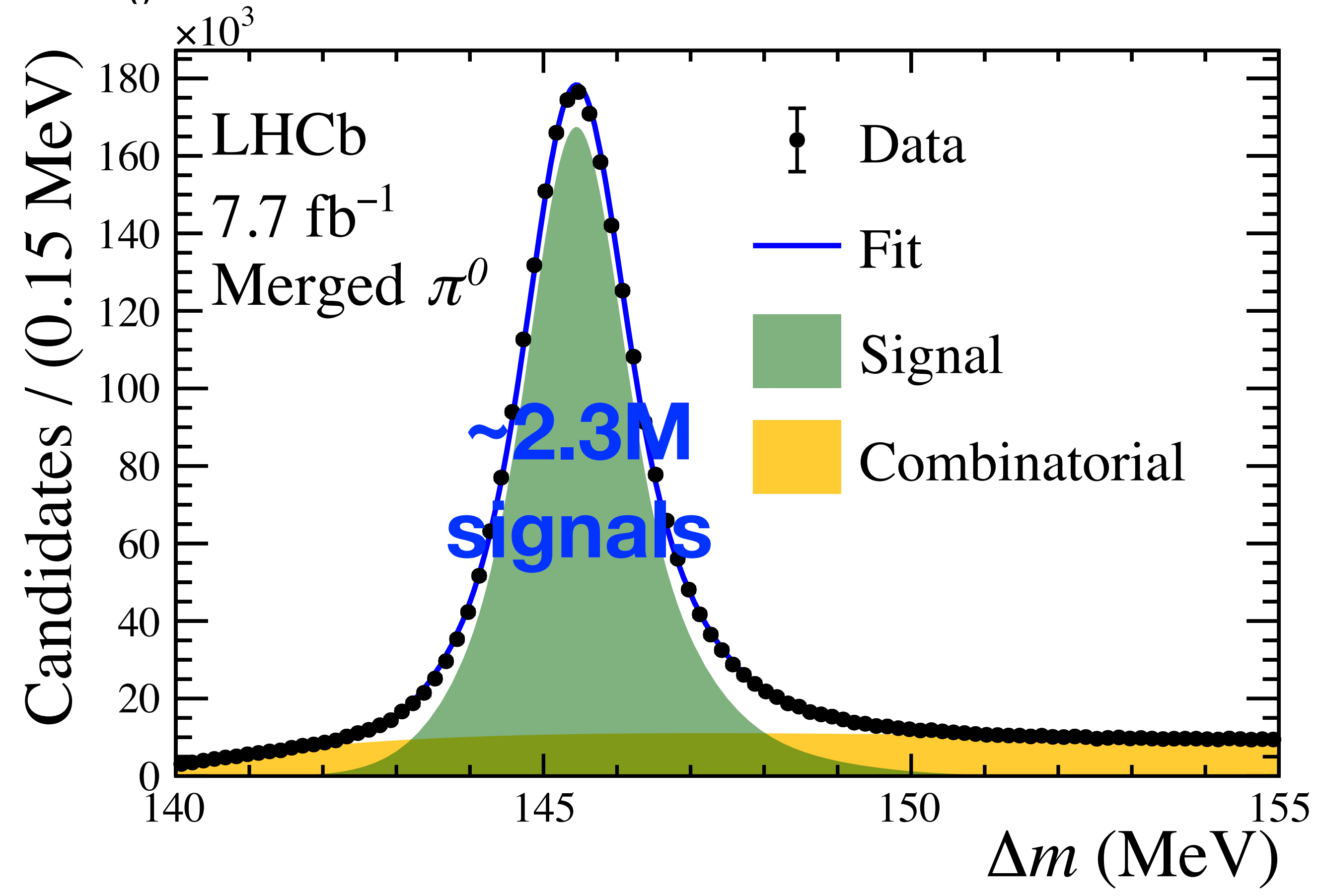
No evidence for CPV

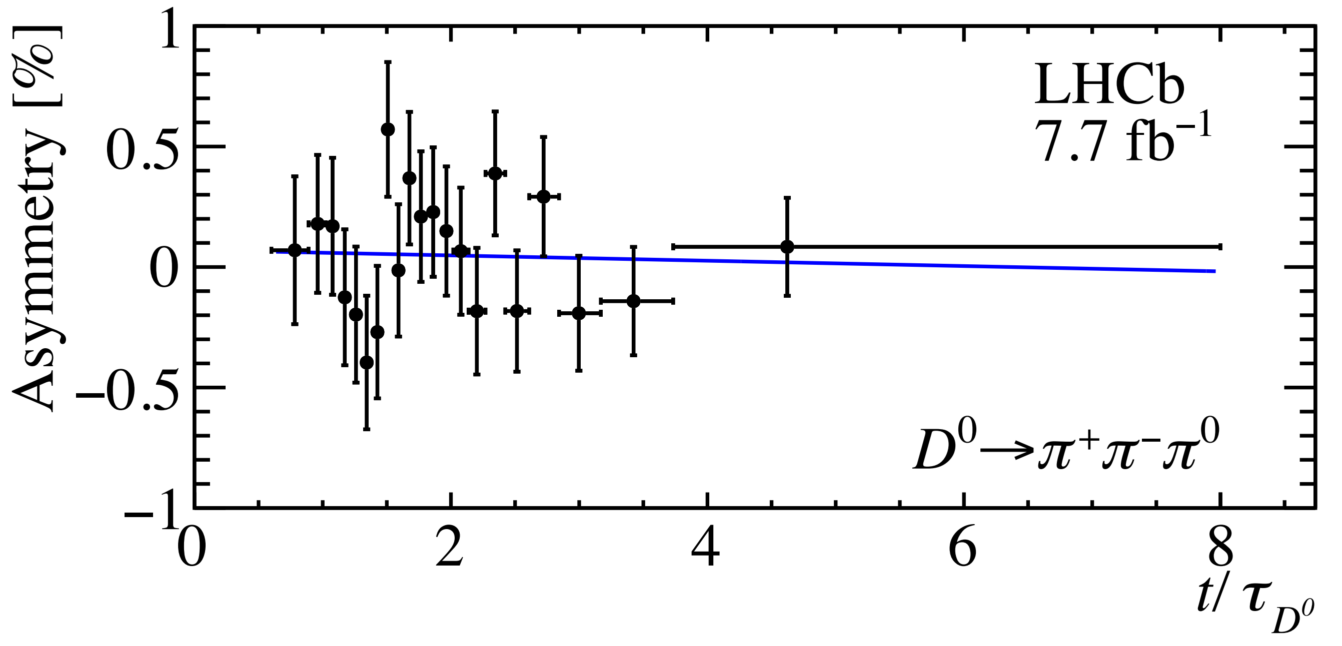
$$\Delta Y = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$$

- First measurement of TD-CPV in D^0 decays with neutral pion at hadron collider
- Compatible, but not yet competitive with WA

($-\Delta Y \approx A_\Gamma = (0.9 \pm 1.1) \times 10^{-4}$ [Phys. Rev. D107, 052008])







Conclusions and outlook

- **A lot of results are still being produced with LHCb Run1+Run2**
  - World-leading measurements of $\sin(2\beta)$ and ϕ_s
  - New measurements of $B \to Dh$ decays continuously improving the constraints on the γ angle
  - LHCb is still exploiting its enormous charm data sample to chase new evidence of CPV

- **No evidence of discrepancies from SM expectations is observed**
  - Shrinking the precision on many CPV observables will be fundamental to testing the CKM paradigm to its ultimate precision
  - LHCb Upgrade I is going to start to collect data with the potential to more than double its sample in the next two years

Backup slides

ϕ_s with $B_s^0 \to J/\psi K^+K^-$ decays

[PRL 132 (2024) 051802]

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]	$0.022\,^{+0.027}_{-0.026}$
$\lvert\lambda^0\rvert$	$0.969\,^{+0.025}_{-0.024}$
$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$0.982\,^{+0.055}_{-0.052}$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$1.107\,^{+0.082}_{-0.076}$
$\lvert\lambda^S/\lambda^0\rvert$	$1.121\,^{+0.084}_{-0.078}$

A measurement of $\Delta\Gamma_s$

[JHEP 05(2024)253]

Systematic uncertainties:

Source	Value $[\mathrm{ns}^{-1}]$
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

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

[LHCb-PAPER-2024-008]

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

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

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

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

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

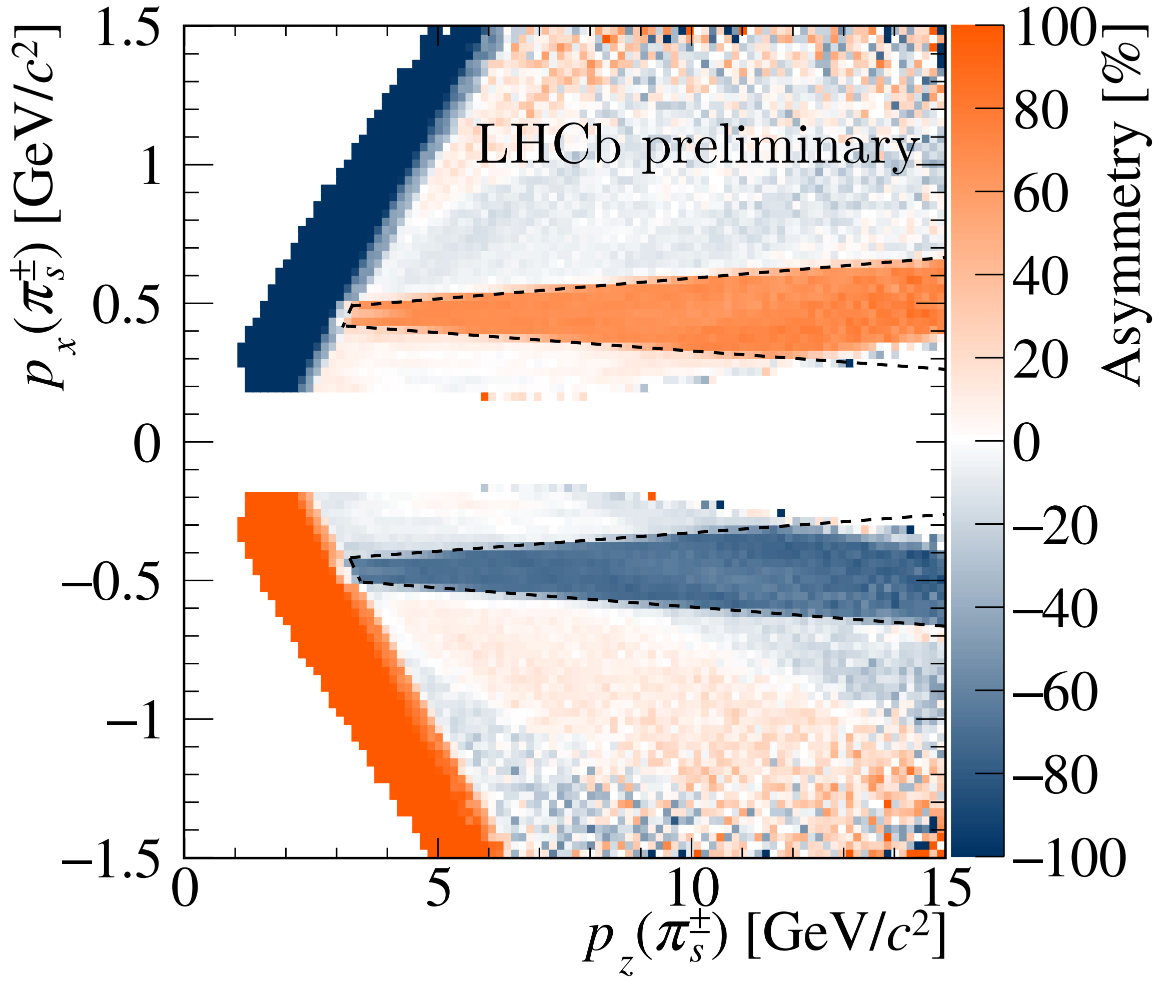
$$c'_{K\pi} \approx \frac{1}{4}(x^2_{12} + y^2_{12}),$$

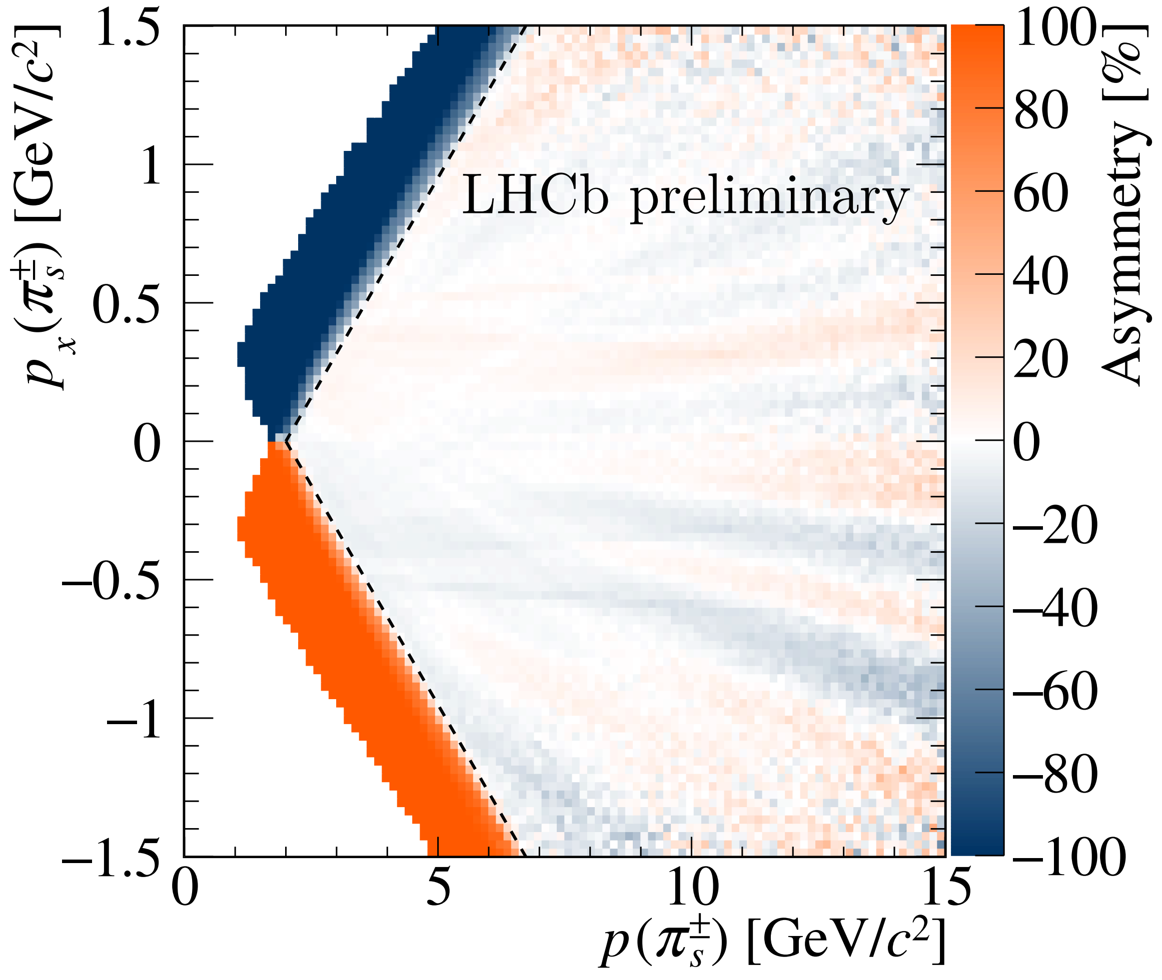
$$\Delta c'_{K\pi} \approx \frac{1}{2}x_{12}y_{12}\sin(\phi^M_f - \phi^\Gamma_f).$$

Probe mixing-induced CPV

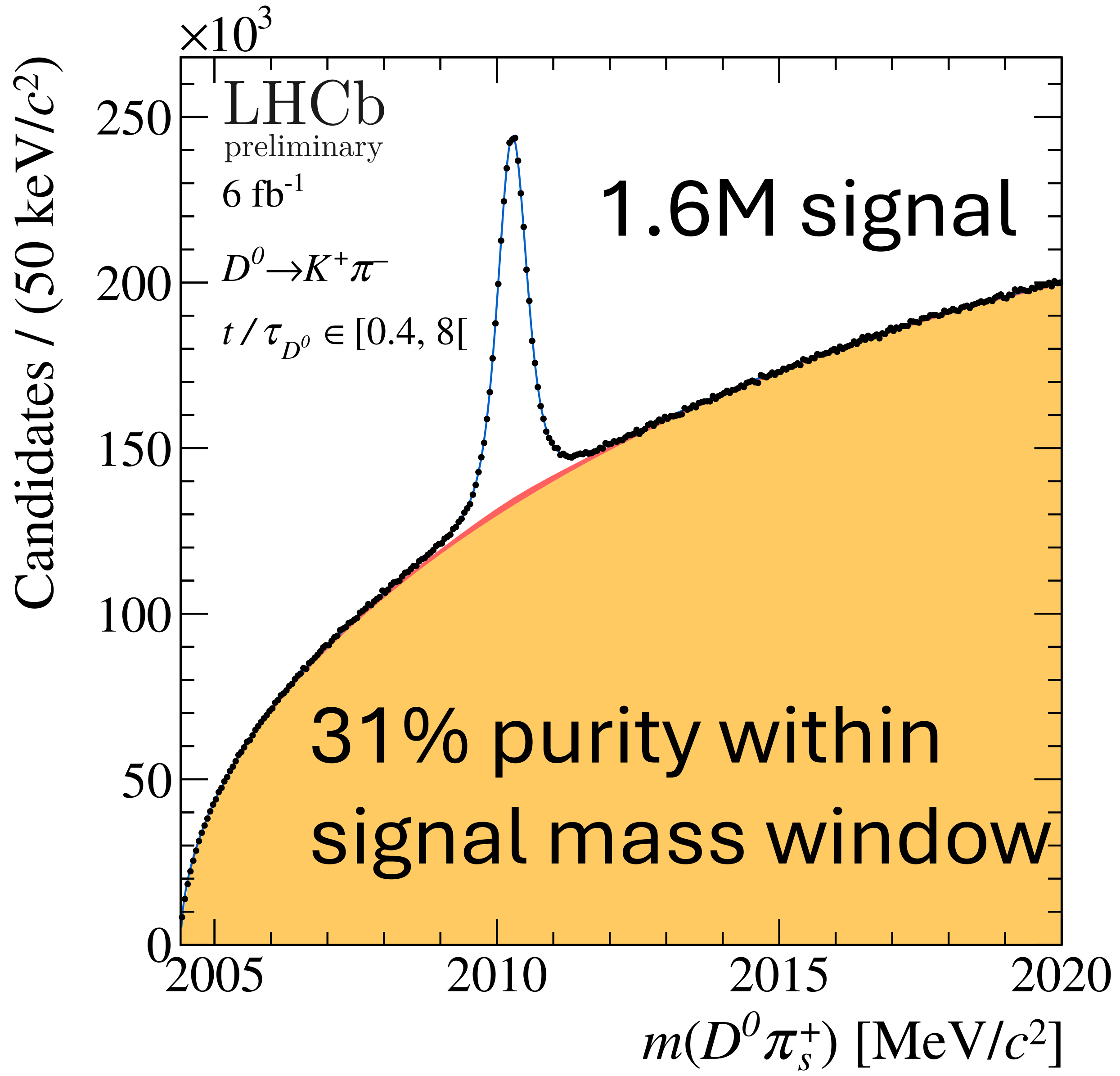
$$\phi^M_f - \Delta_f \equiv \arg(-M_{12}\,A_f/\bar{A}_f), \qquad \phi^M_f + \Delta_f \equiv \arg(-M_{12}\,A_{\bar{f}}/\bar{A}_{\bar{f}}),$$
$$\phi^\Gamma_f - \Delta_f \equiv \arg(-\Gamma_{12}\,A_f/\bar{A}_f), \qquad \phi^\Gamma_f + \Delta_f \equiv \arg(-\Gamma_{12}\,A_{\bar{f}}/\bar{A}_{\bar{f}}).$$

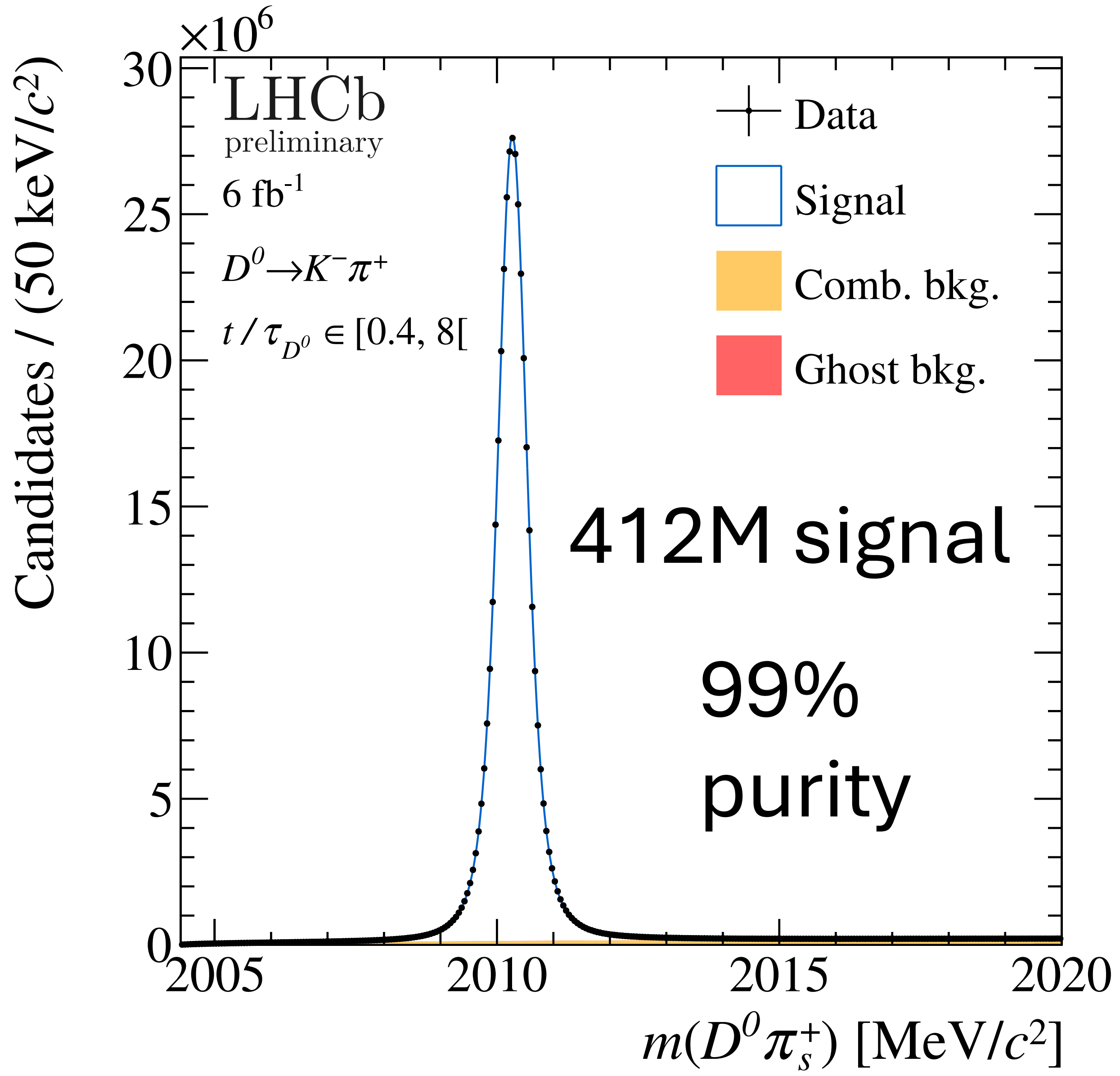
Mixing and CPV in $D^0 \to K^+\pi^-$ decays [LHCb-PAPER-2024-008]





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

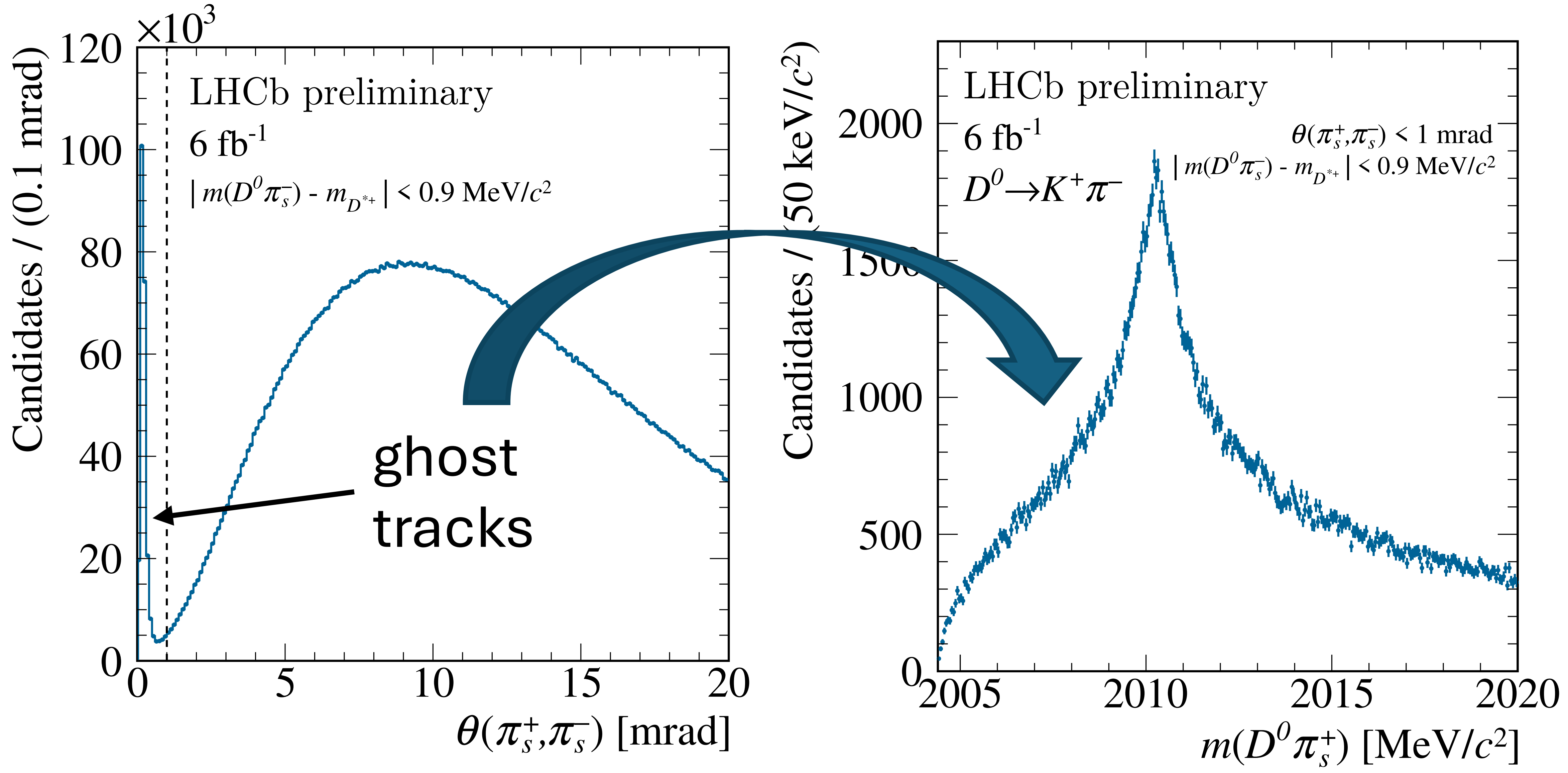




$m(D^0\pi)$ distribution for WS and RS samples after all selections.

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

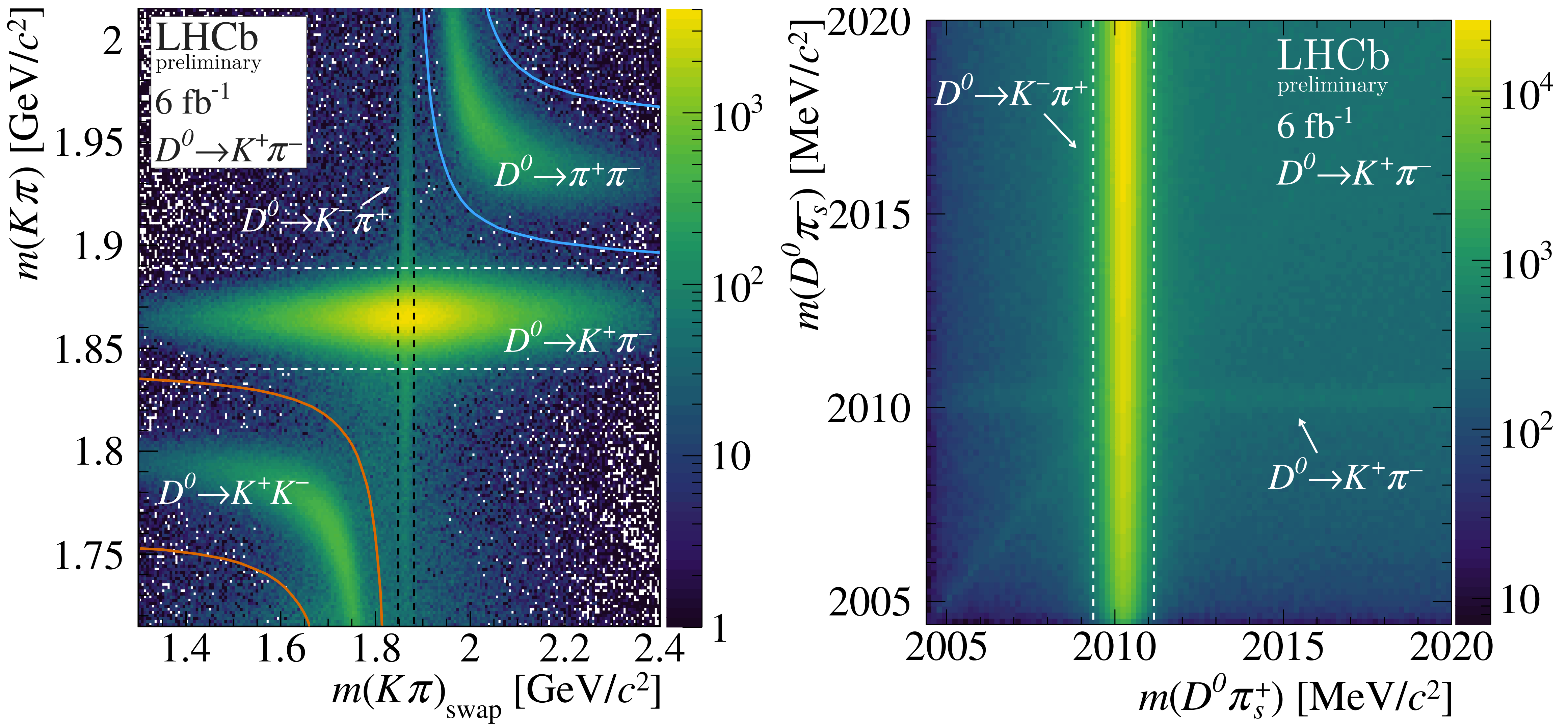
Mixing and CPV in $D^0 \to K^+\pi^-$ decays [LHCb-PAPER-2024-008]



'Ghost' tracks from random hits give problematic BG.

Suppressed with fiducial and track-quality cuts.

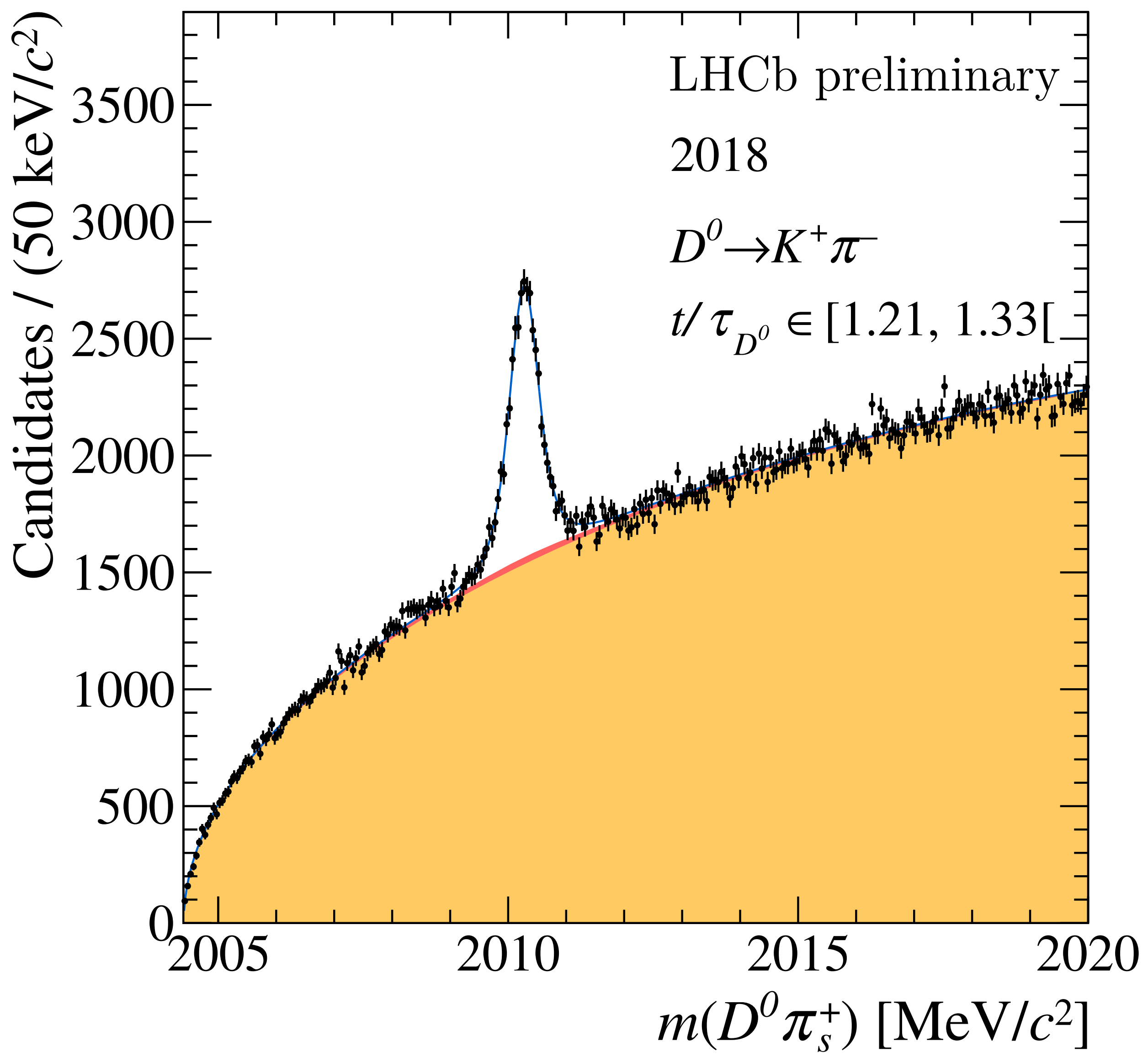
Modelled with data-driven approach.

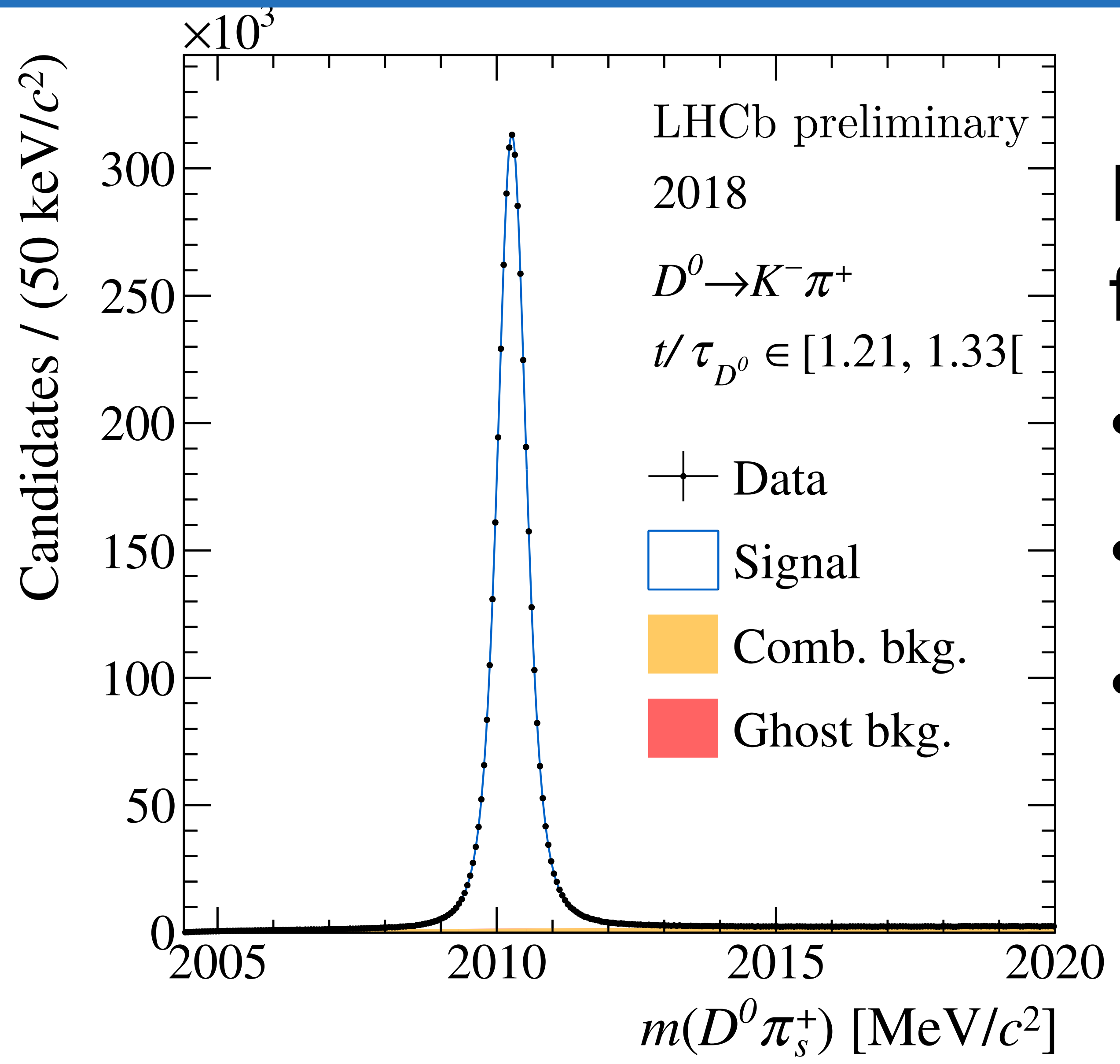


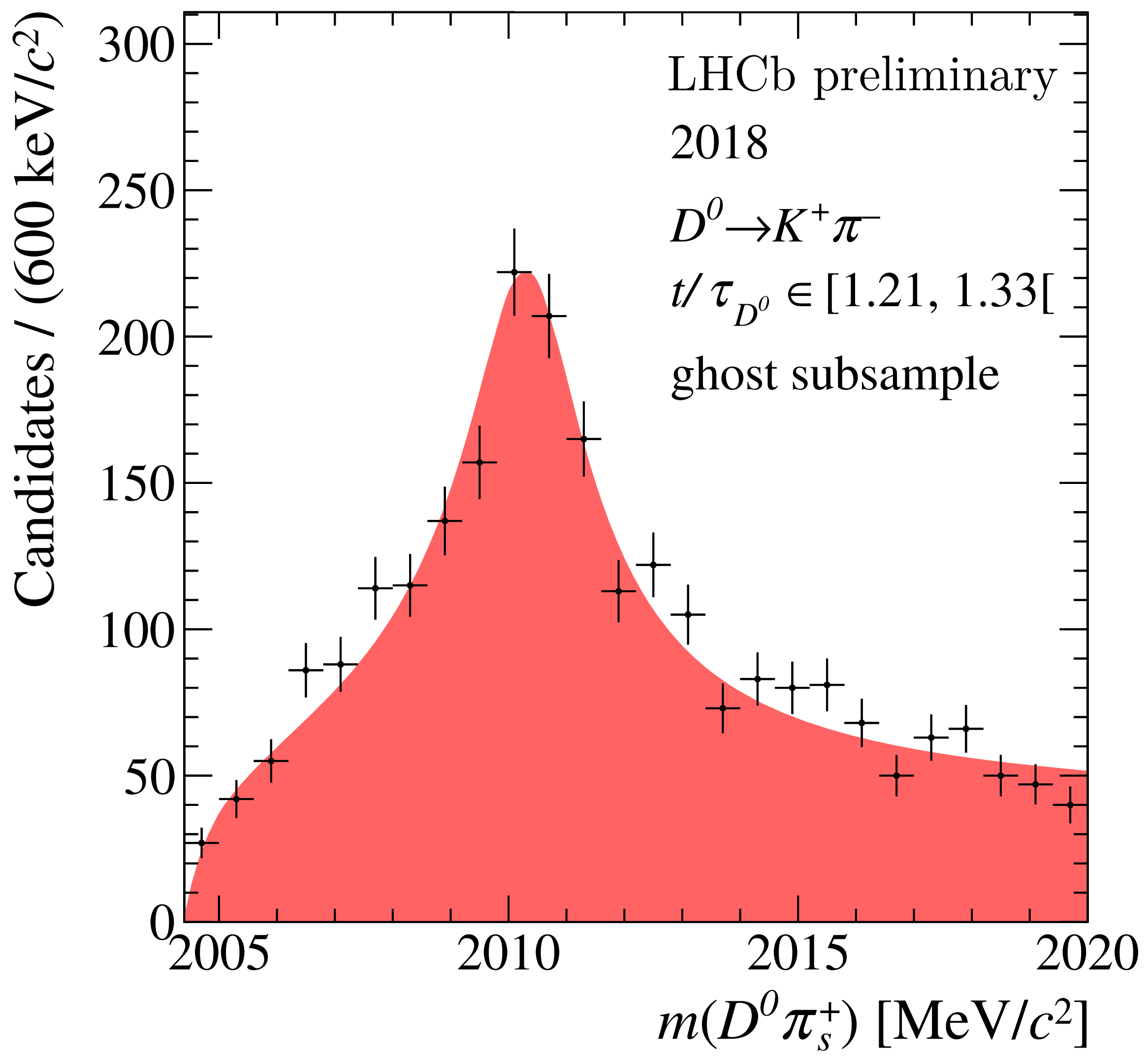
Left: misID backgrounds in WS sample

Right: WS-RS cross-talk

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





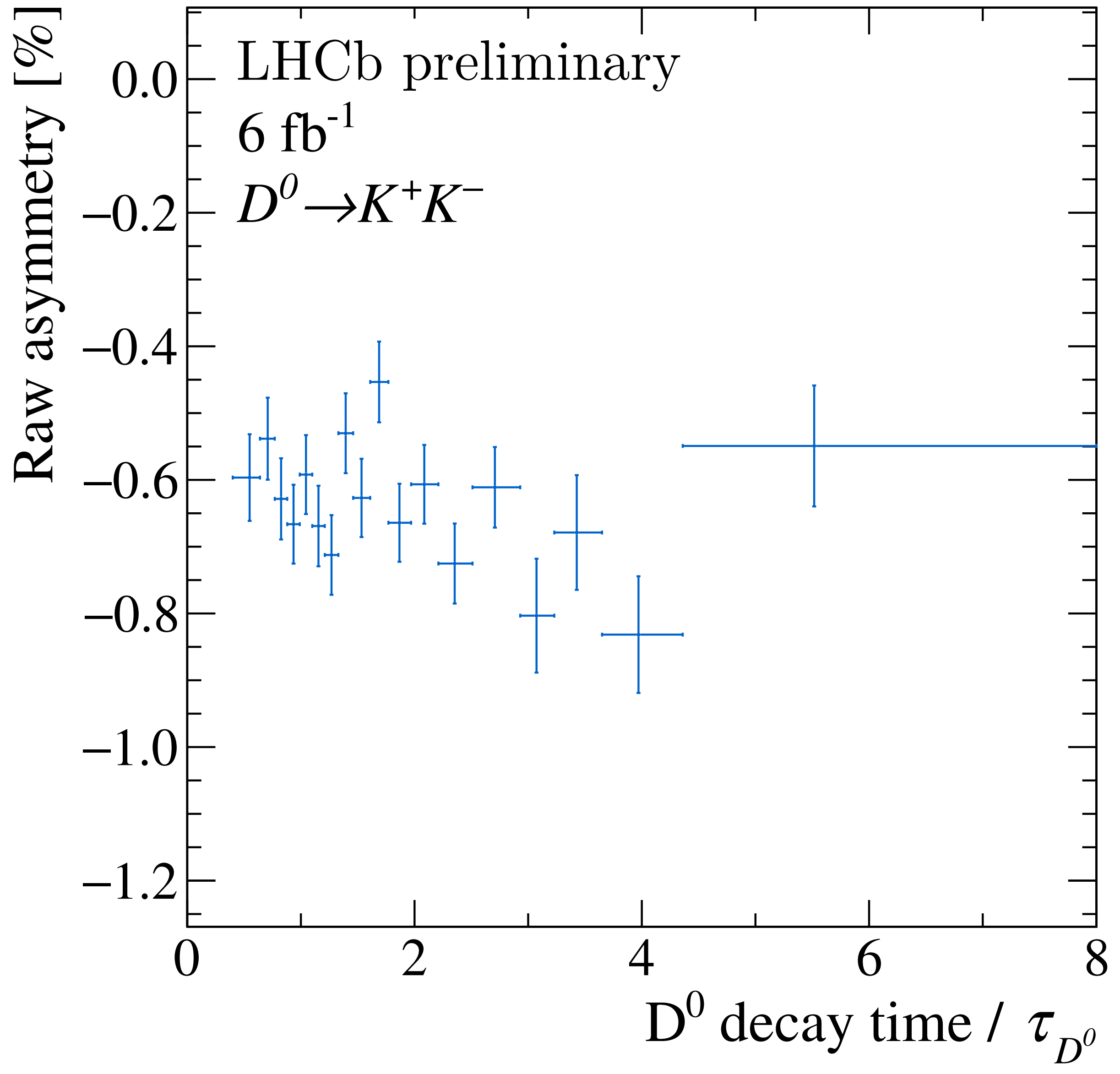


Example set of simultaneous fits in single decay-time bin

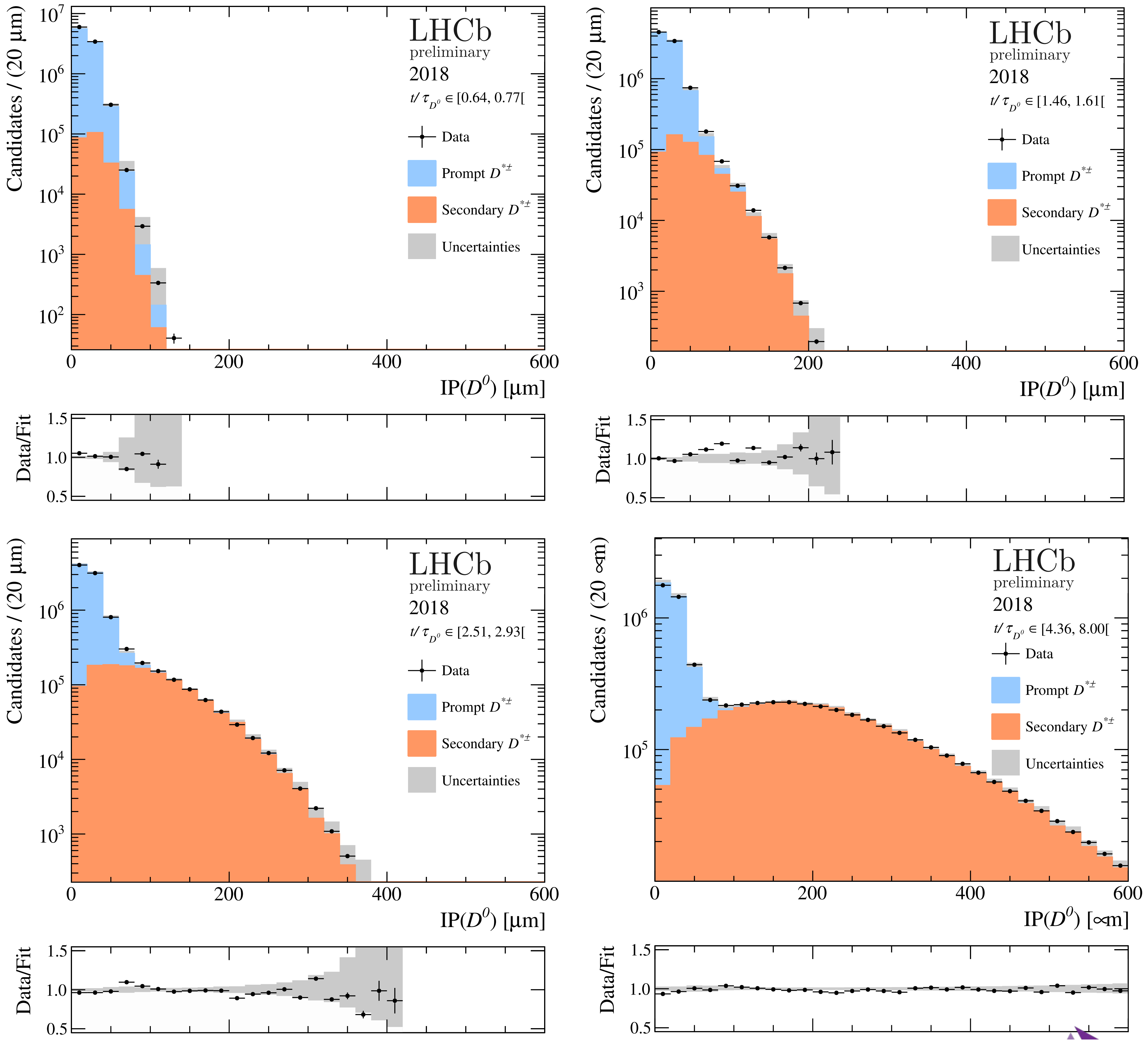
- RS
- WS
- Ghost control-sample

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

[LHCb-PAPER-2024-008]



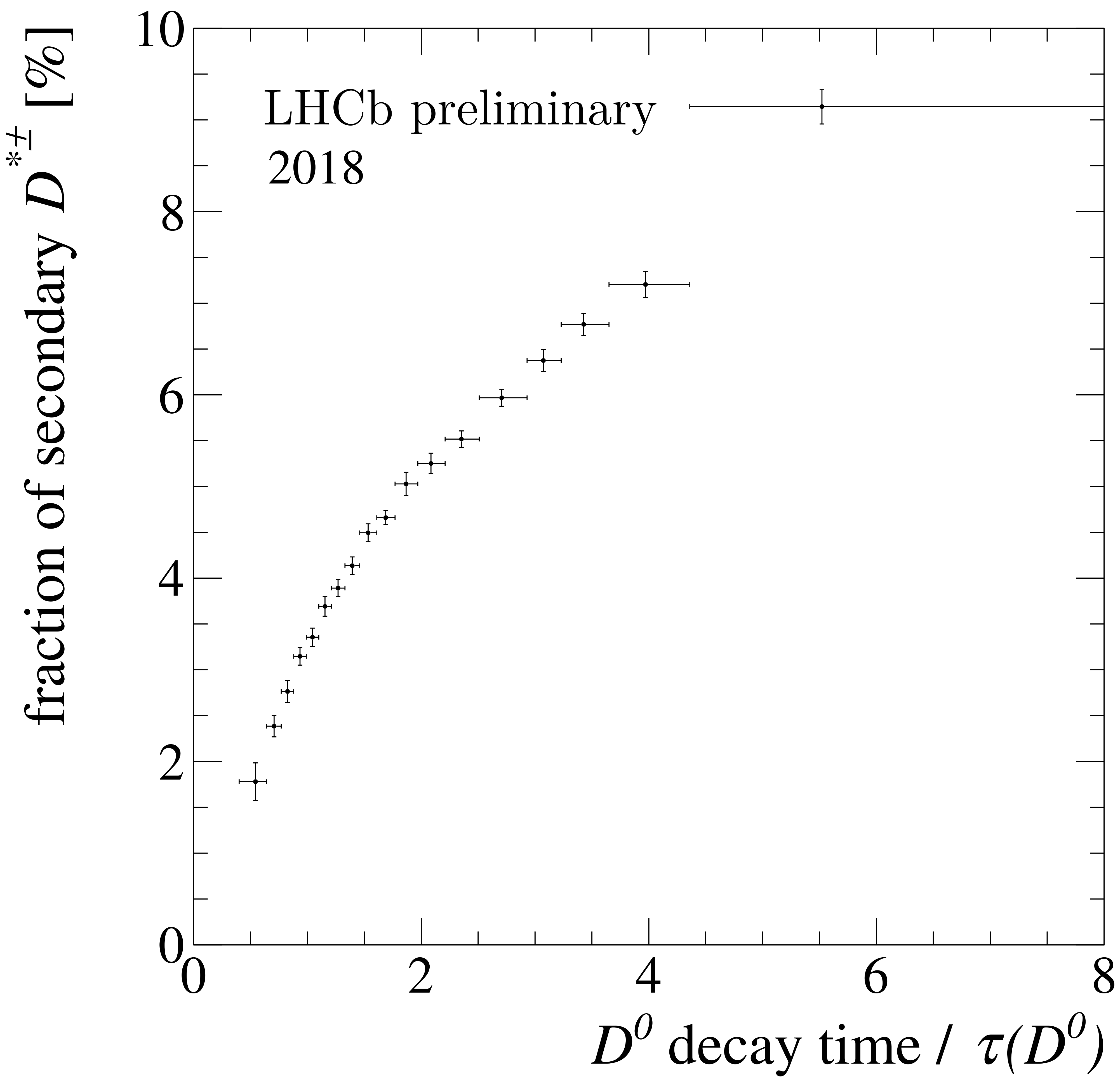
Instrumental asymmetries determined from $D^0 \to K^+K^-$ control mode

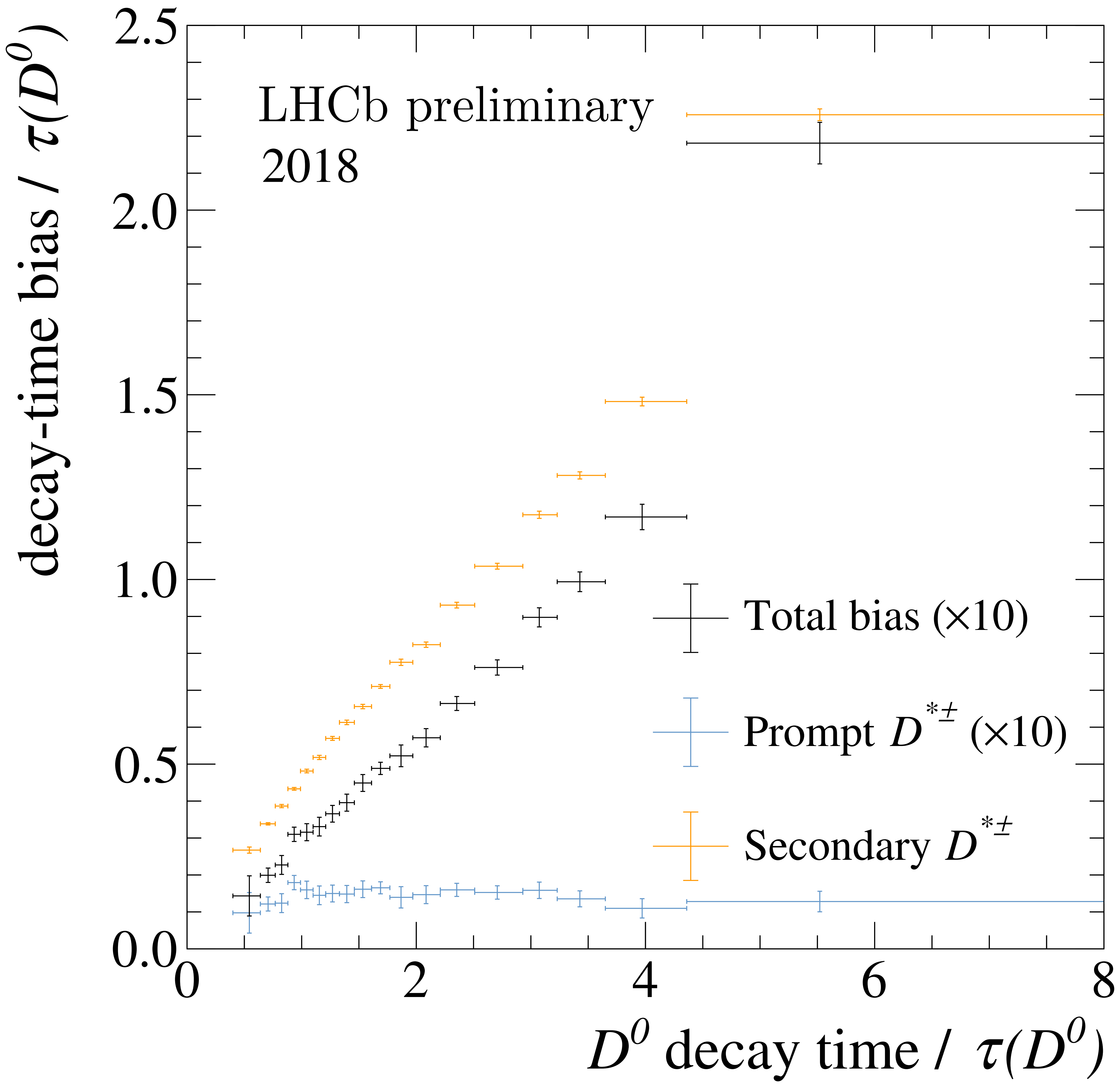


Fits to IP used to statistically disentangle prompt and secondary charm – mitigates and accounts for residual decay time bias.

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

[LHCb-PAPER-2024-008]





Left: Secondary contamination depends on decay time.

Right: Decay time bias from secondary background

Mixing and CPV in $D^0 \to K^+\pi^-$ decays: results [LHCb-PAPER-2024-008]

PRELIMINARY

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

PRELIMINARY

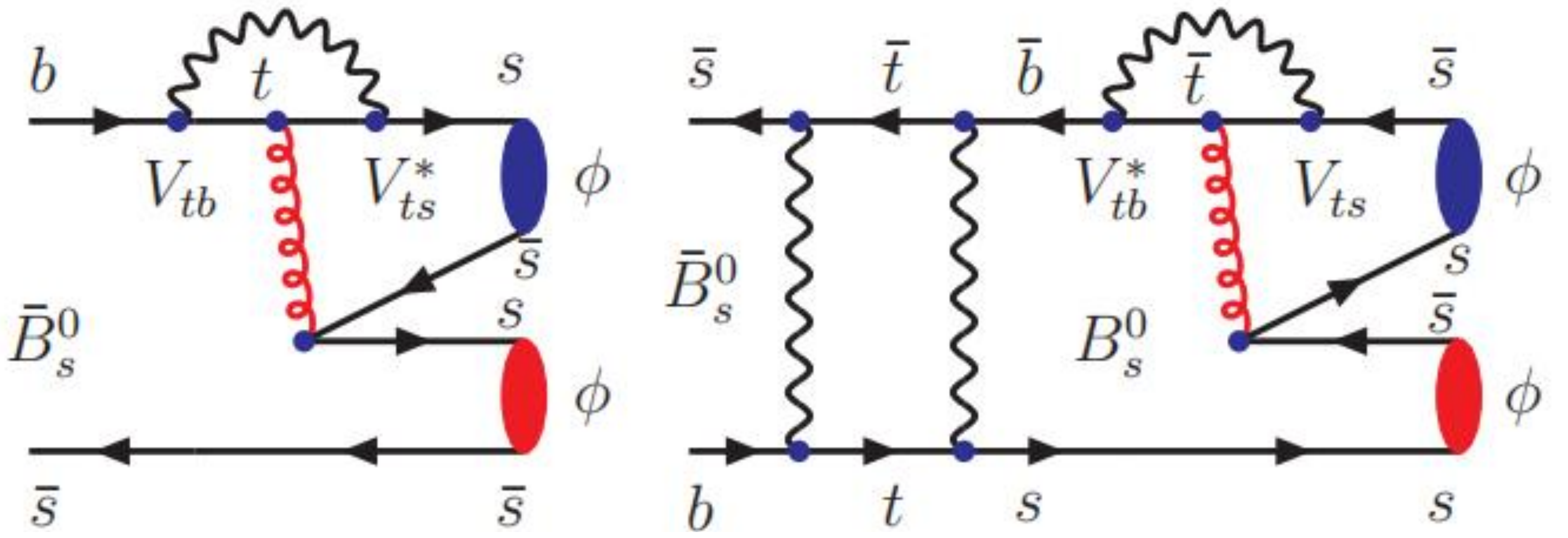
Source	$R_{K\pi}$ $[10^{-5}]$	$c_{K\pi}$ $[10^{-4}]$	$c'_{K\pi}$ $[10^{-6}]$	$A_{K\pi}$ $[10^{-3}]$	$\Delta c_{K\pi}$ $[10^{-4}]$	$\Delta c'_{K\pi}$ $[10^{-6}]$
Mass mismodeling	0.5	0.8	0.9	1.4	0.8	0.8
Ghost soft pions	0.4	0.8	0.8	1.1	0.8	1.1
Instrumental asymmetry	–	–	–	1.2	0.7	0.7
a^d_{KK} external 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

CP violation in $B_s^0 \to \phi\phi$

[PRL 131 (2023) 171802]

- **Motivations:**
  - The SM predicts CPV to be suppressed in this channel
  - Any CPV enhancement would point to new physics in the B_s^0 mixing or in the **penguin-mediated** $b \to s$ decay



- **Caveat:** angular analysis needed to disentangle the three polarisation states of the $B \to VV$ decays
  - (0, CP even), (||, CP even), (⊥, CP odd)

$A_i = \langle f_i | H_W | B_s^0 \rangle$

$\bar{A}_i = \langle f_i | H_W | \bar{B}_s^0 \rangle$

$i \in \{0, \parallel, \perp\}$

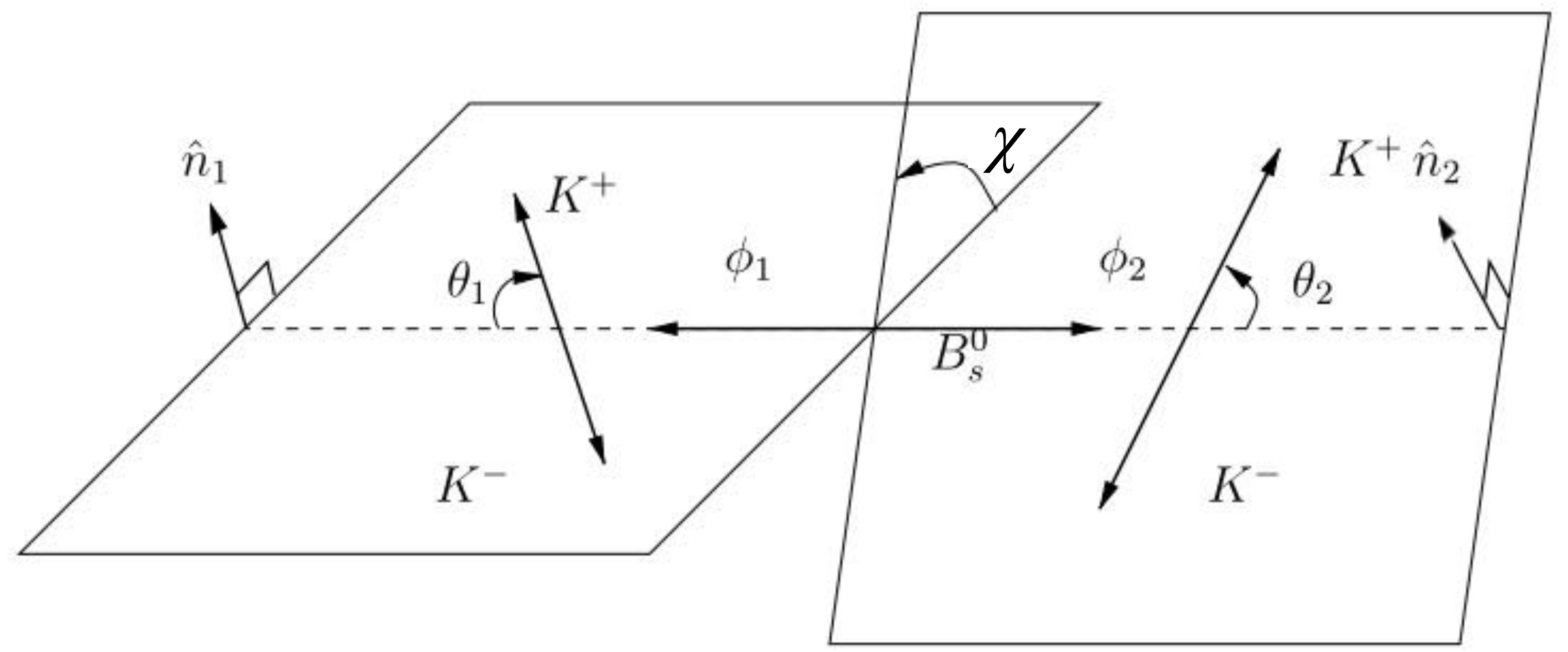
$\eta_{0,\parallel(\perp)} = \pm 1$

$|B^0_{s,H(L)}\rangle = |B_s^0\rangle p \pm |\bar{B}_s^0\rangle q$

$$\boxed{\lambda_i \equiv \eta_i \frac{q}{p}\frac{\bar{A}_i}{A_i} = |\lambda_i| e^{-i\phi_{s,i}}}$$

- **Target CP observables:** $\phi_{s,i}$, $|\lambda_i|$
  - The SM predicts no dependance of the CP observables on the polarisation
    - CP phase: $\phi_i = \phi_s^{s\bar{s}s} \approx 0$
    - Direct CP violation parameter: $|\lambda_i| = |\bar{A}_i/A_i| = |\lambda| \approx 1$

No CPV in mixing



[Nucl. Phys. B 774 (2007) 64] [PRL 89 (2002) 231803][arXiv:0810.0249]
[PRD 80 (2009) 114026] [Nucl. Phys. B 935 (2018) 17][PRD 96 (2017) 073004]

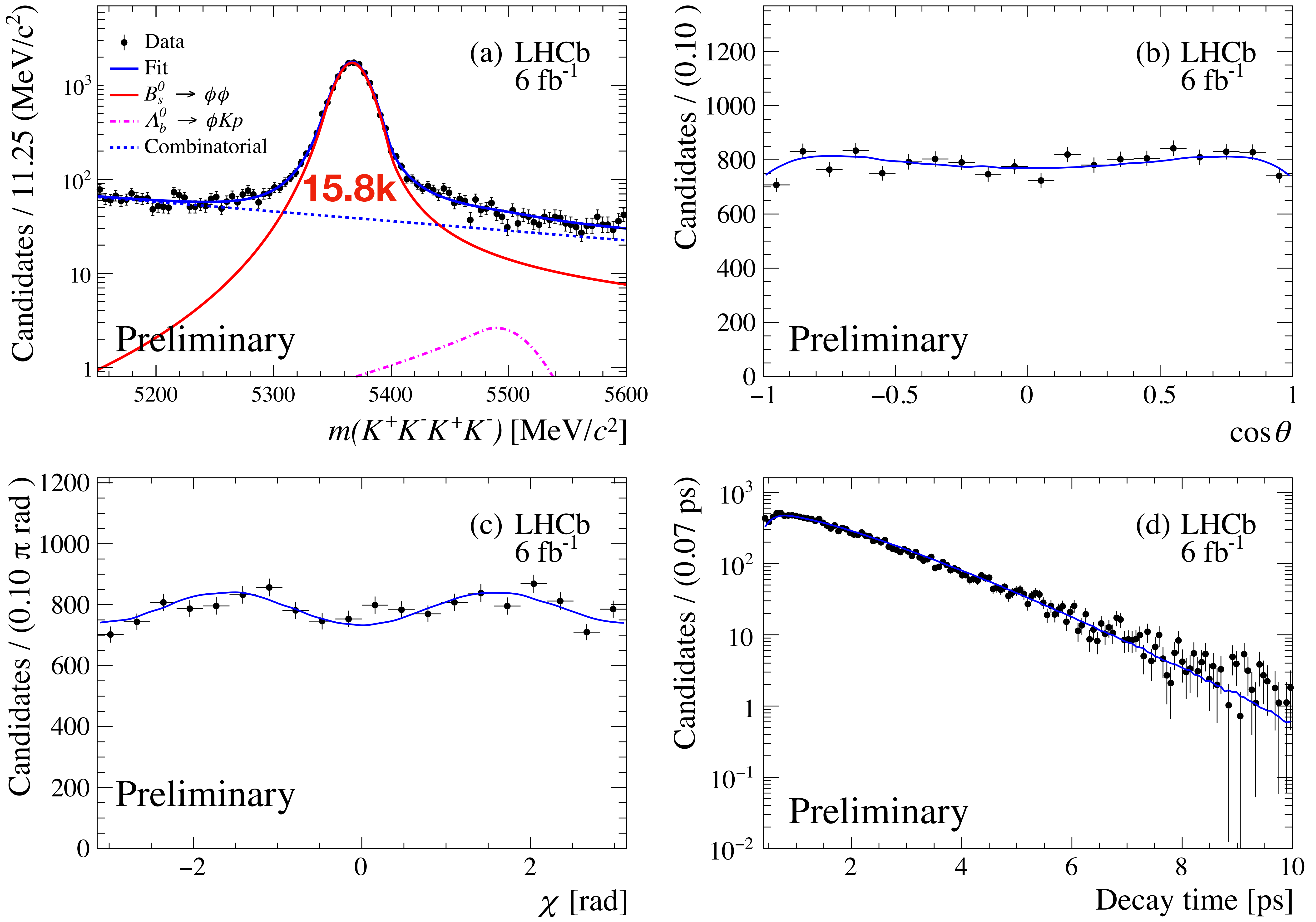
CP violation in $B_s^0 \to \phi\phi$

[PRL 131 (2023) 171802]

- **Data:**
  - **Run2** data ($6\ \mathrm{fb}^{-1}$)
  - Results are then **combined with Run1** measurements (additional $3\ \mathrm{fb}^{-1}$)

- **Strategy:**
  1. Invariant-mass fit to subtract the background
  2. Flavour-tagged fit to decay time and helicity angles to get the CP observables
     [details in the backup]

- **Main experimental challenges:**
  - Decay-time resolution ($\approx 40\ \mathrm{fs}$)
  - Flavour-tagging power ($\approx 6\,\%$)
  - Their calibration



Helicity angles (χ, θ) defined in the previous slide