OZLEM OZCELIK

(ON BEHALF OF LHCB, ATLAS AND CMS COLLABORATIONS)

CKM AND CPV MEASUREMENTS IN THE BEAUTY AND CHARM SECTOR

LHCP BOSTON, 2024

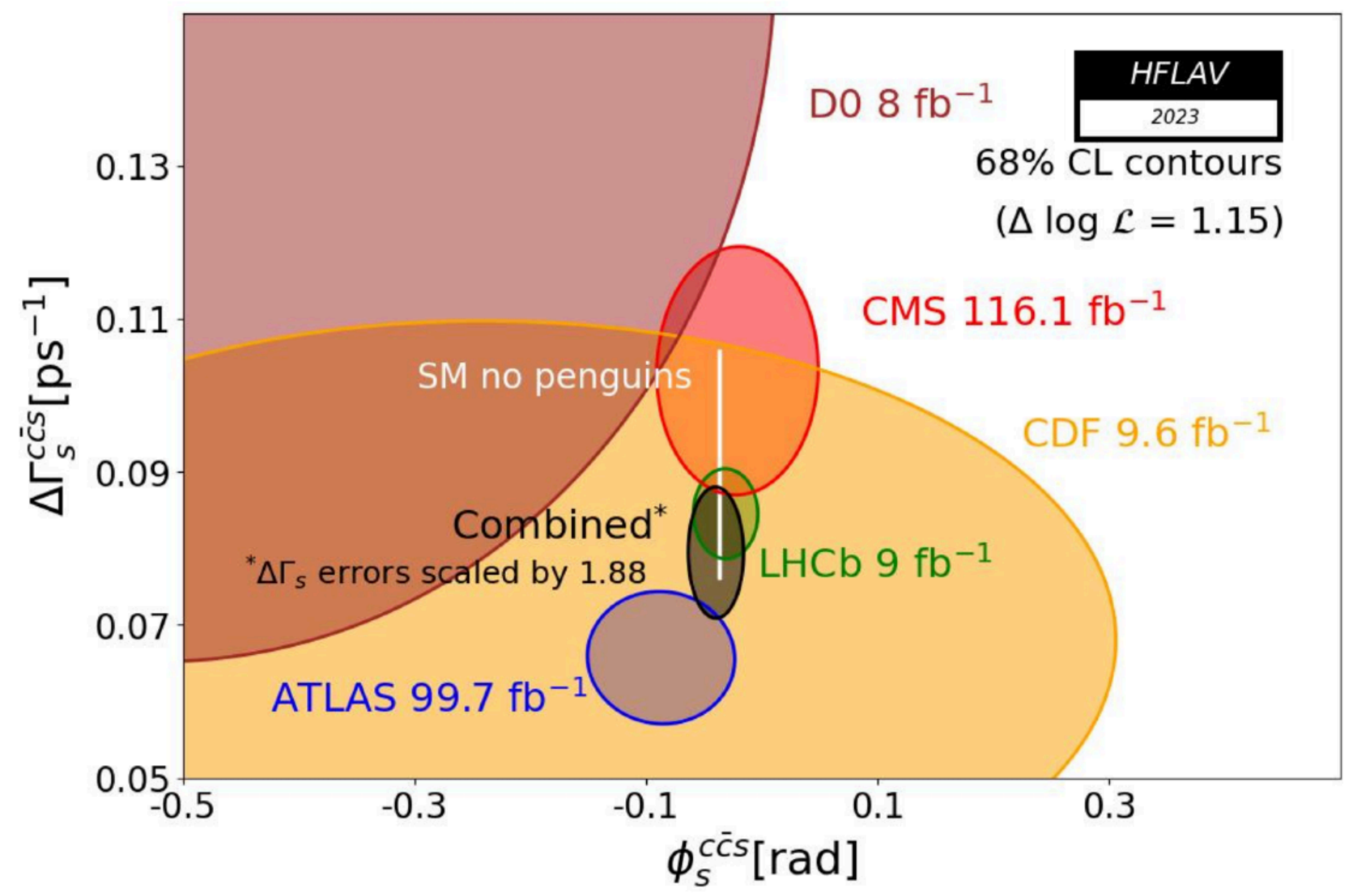
Outline

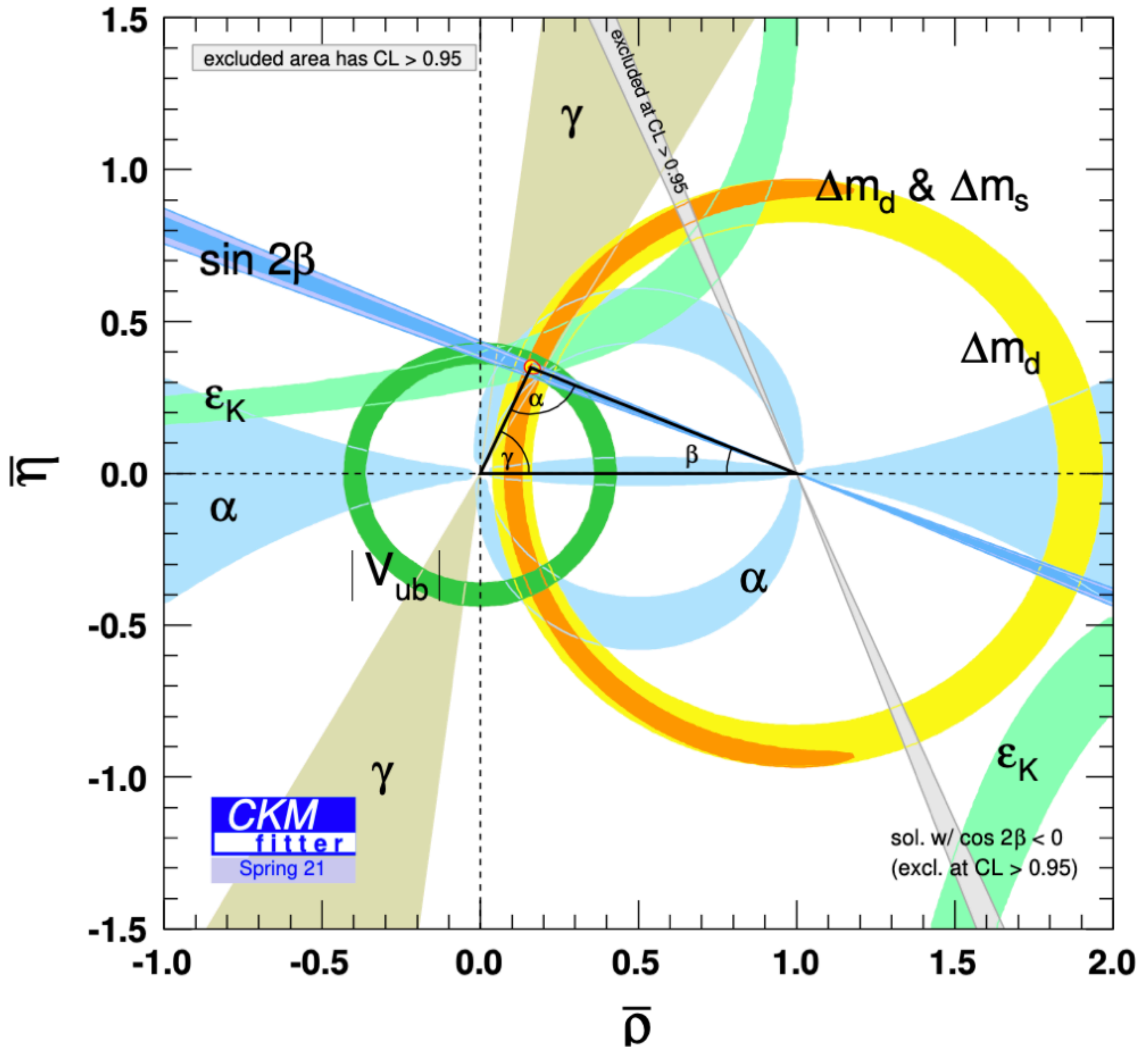
Only Run 1 and Run 2 results today!

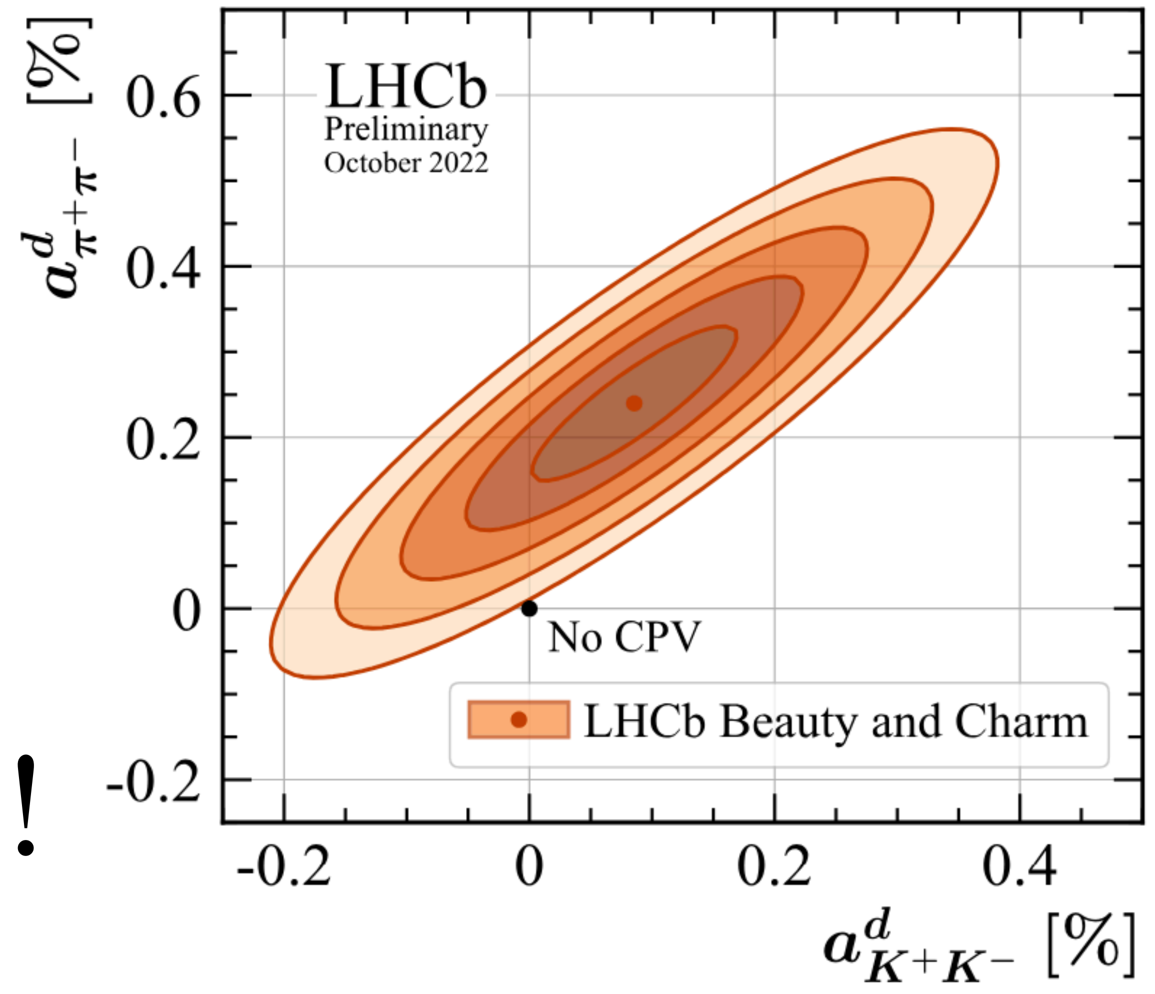
CKM angles of γ and β

Effective lifetimes..

CPV in charm sector
with LHCb and now **CMS**!

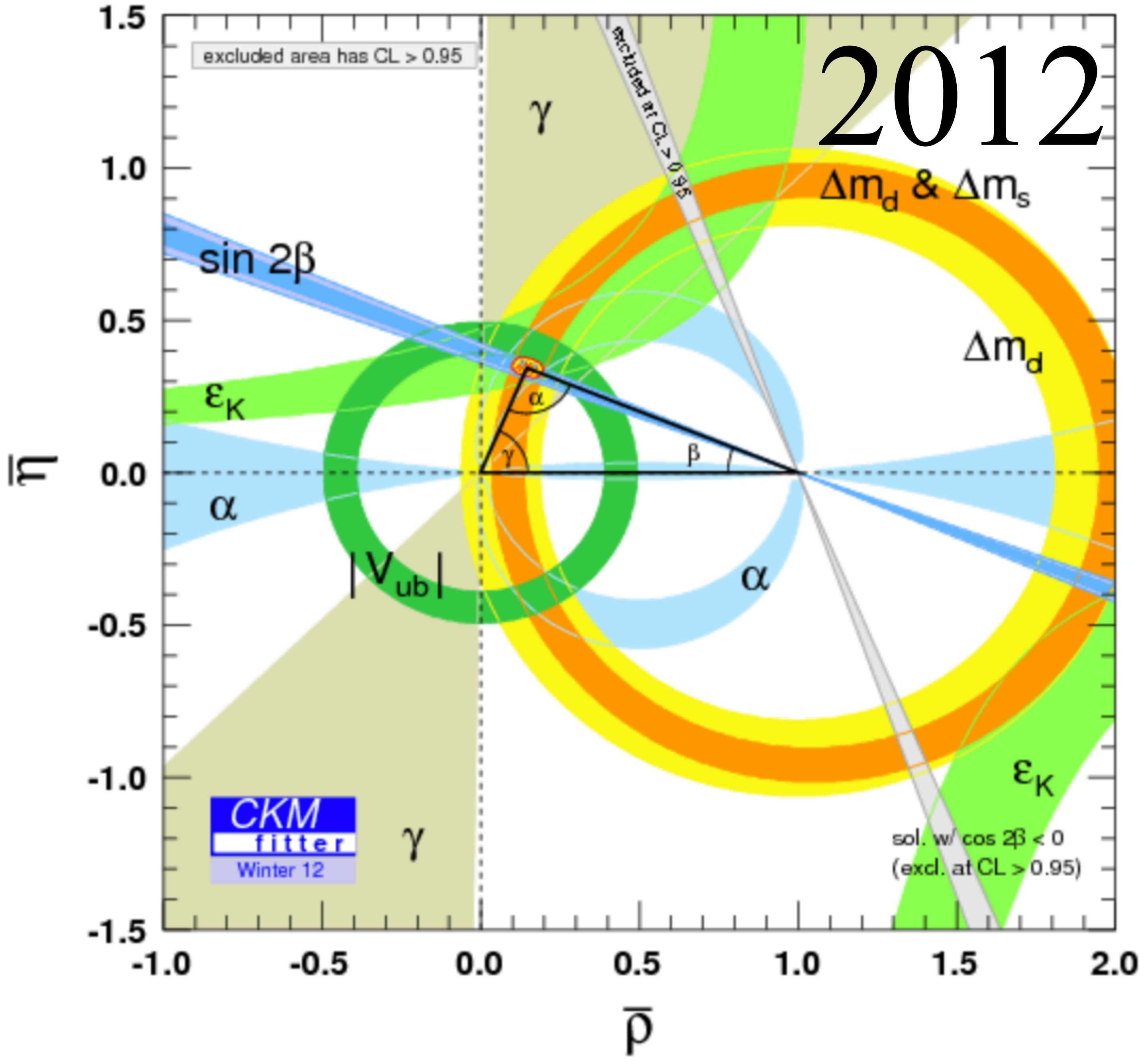




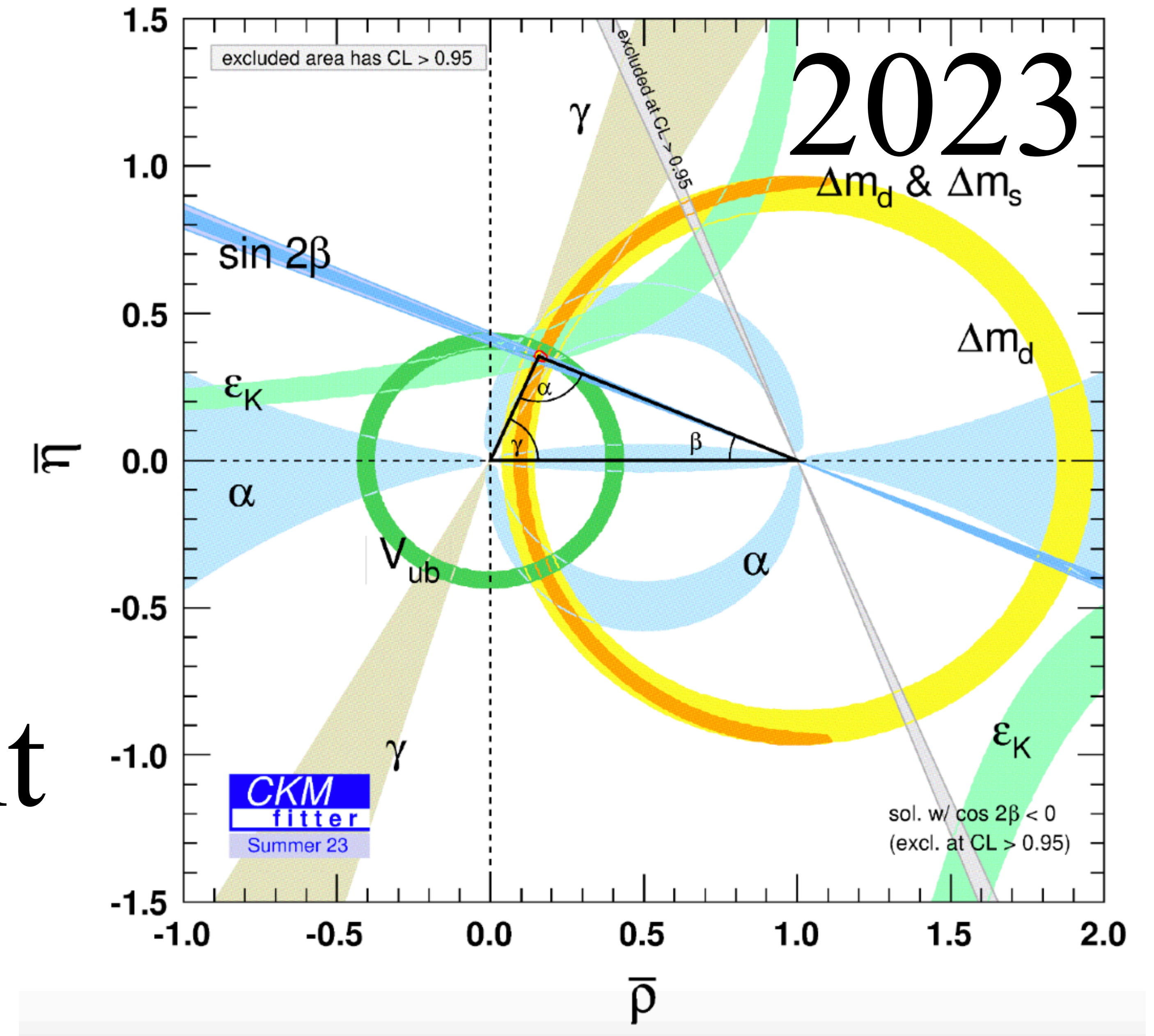


γ measurement !

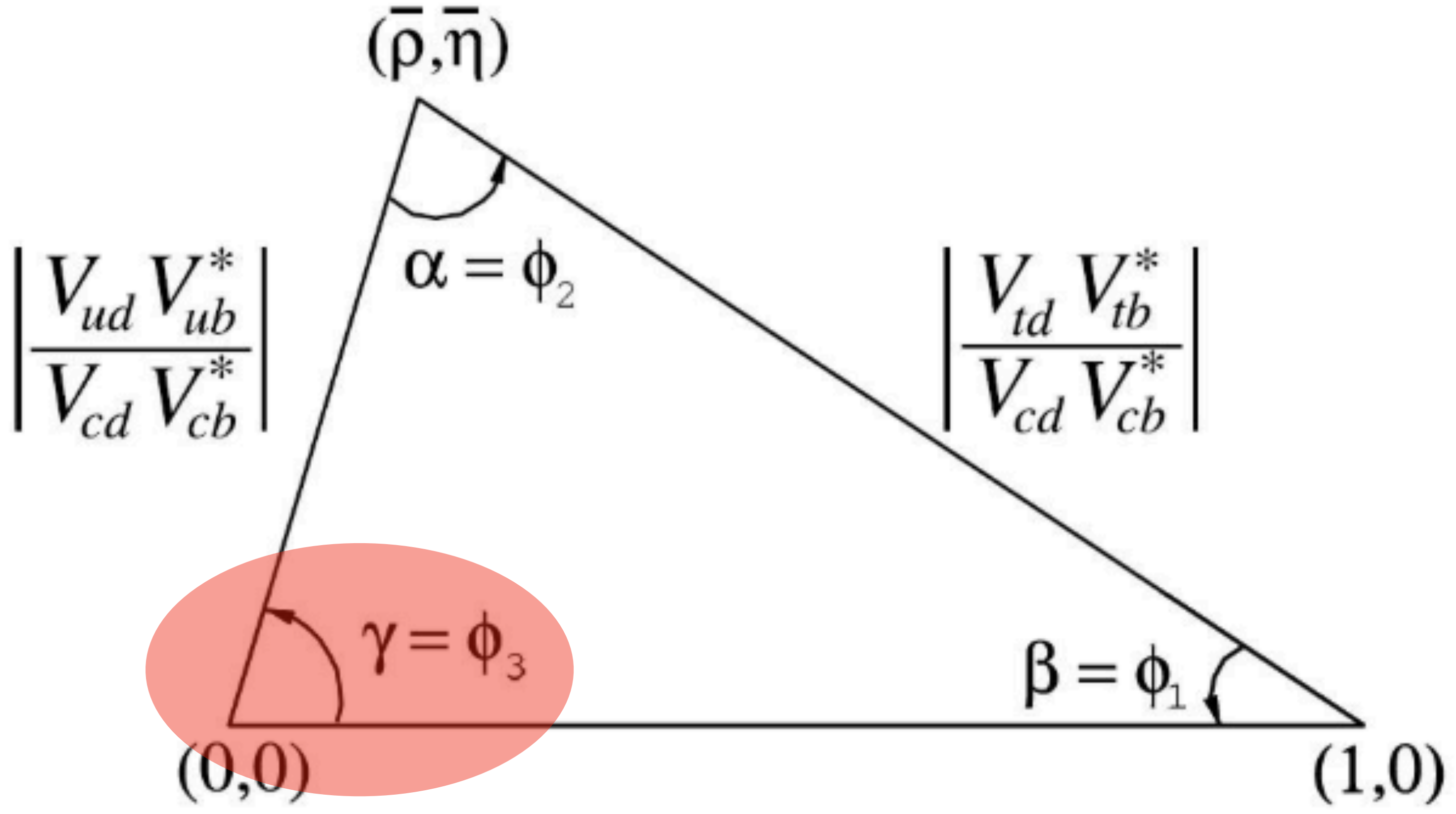
http://ckmfitter.in2p3.fr



a decade of CKM
massive improvement



through the tree level decays ..

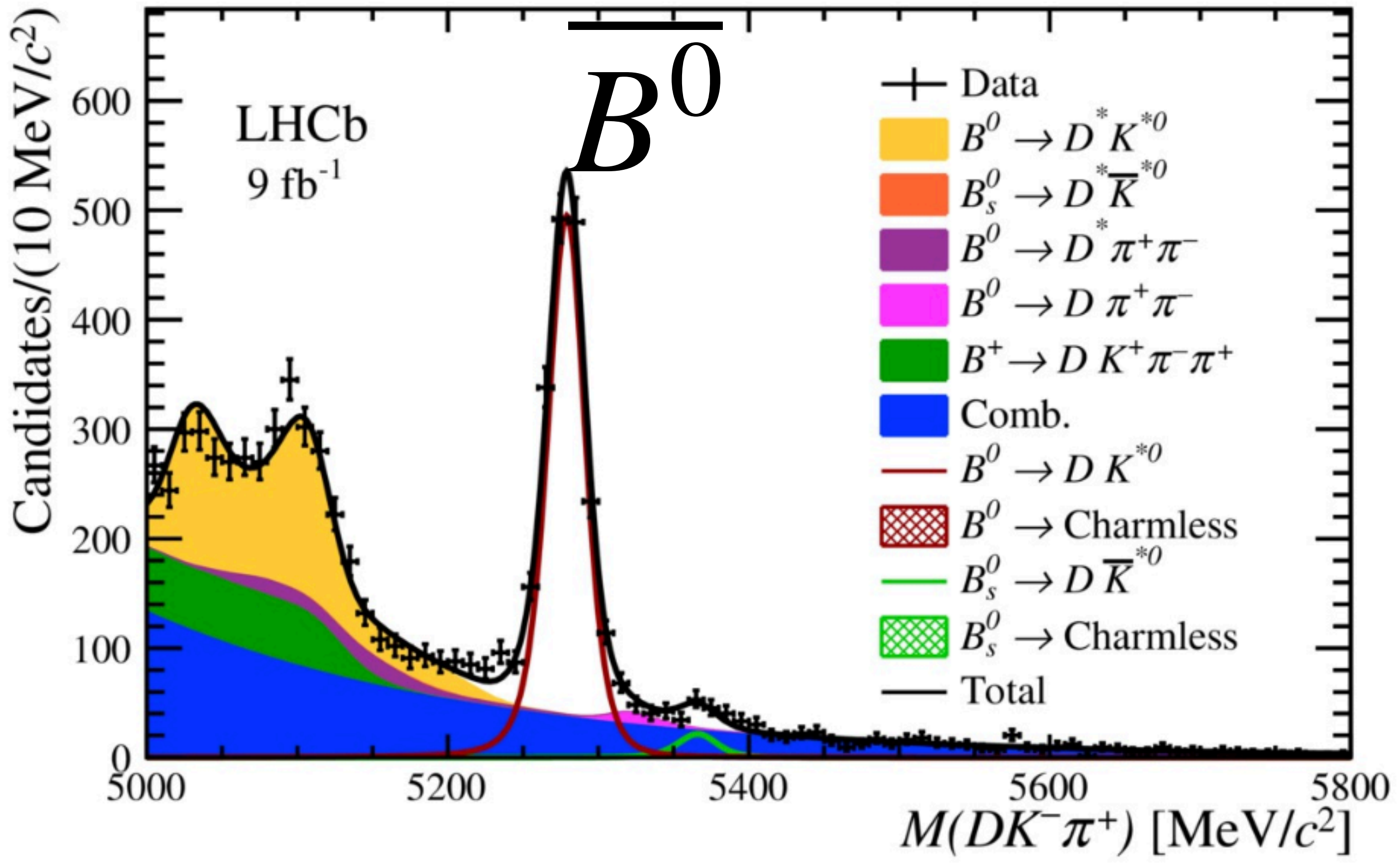


CPV in $B^0 \to DK^*(892)^0$

JHEP 05(2024)025

$D^0/\overline{D^0}$ meson is reconstructed through various hadronic states ($\pi^+\pi^-$, K^+K^-, $4\pi^\pm$) and ($K^\mp\pi^\pm$, $K^\pm\pi^\mp\pi^+\pi^-$)

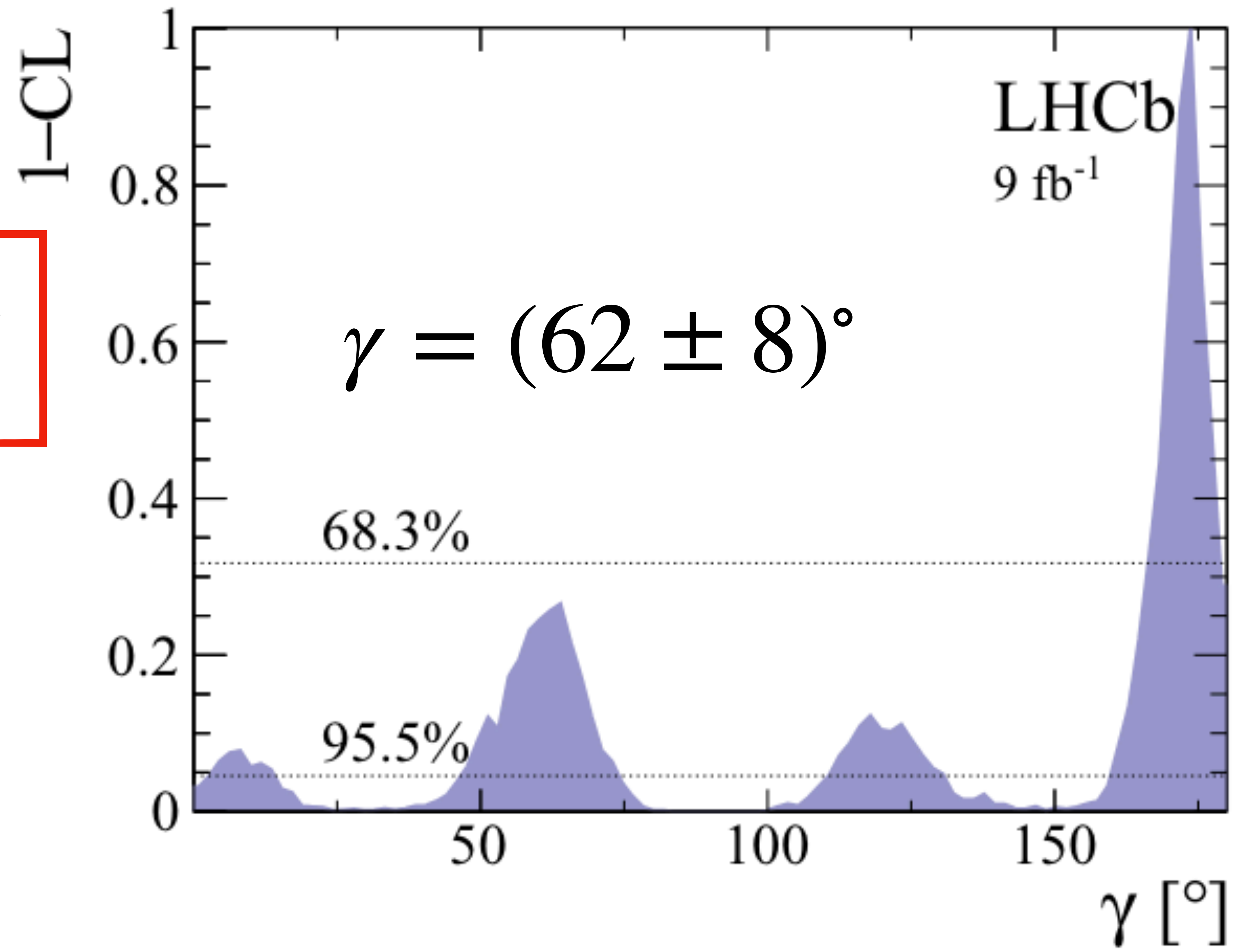
Simultaneous fit to D final states in $B^0/\overline{B^0}$ invariant mass to extract CPV observables.



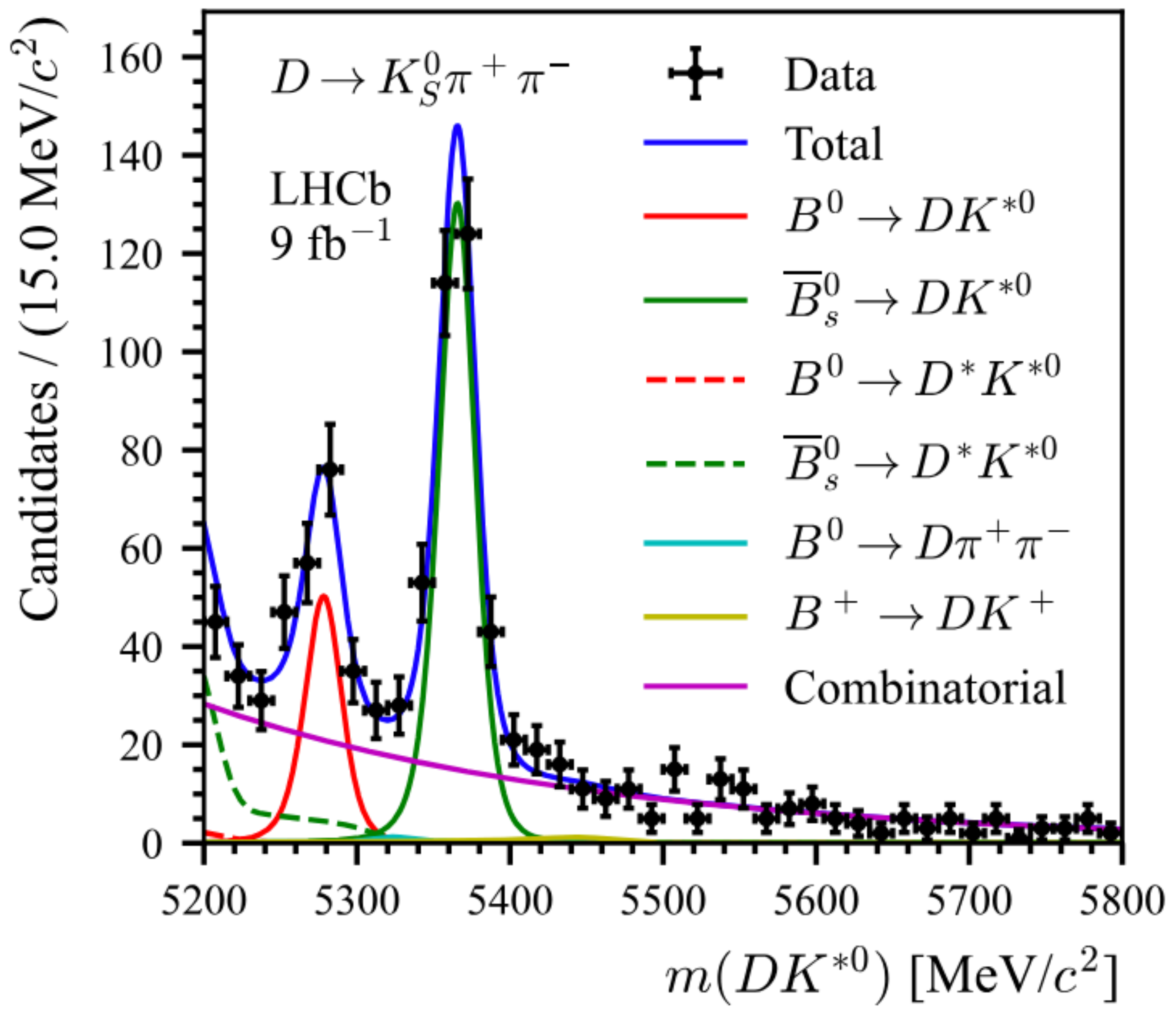
$\overline{B^0} \to D^0(\to K3\pi)\overline{K}^*$

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

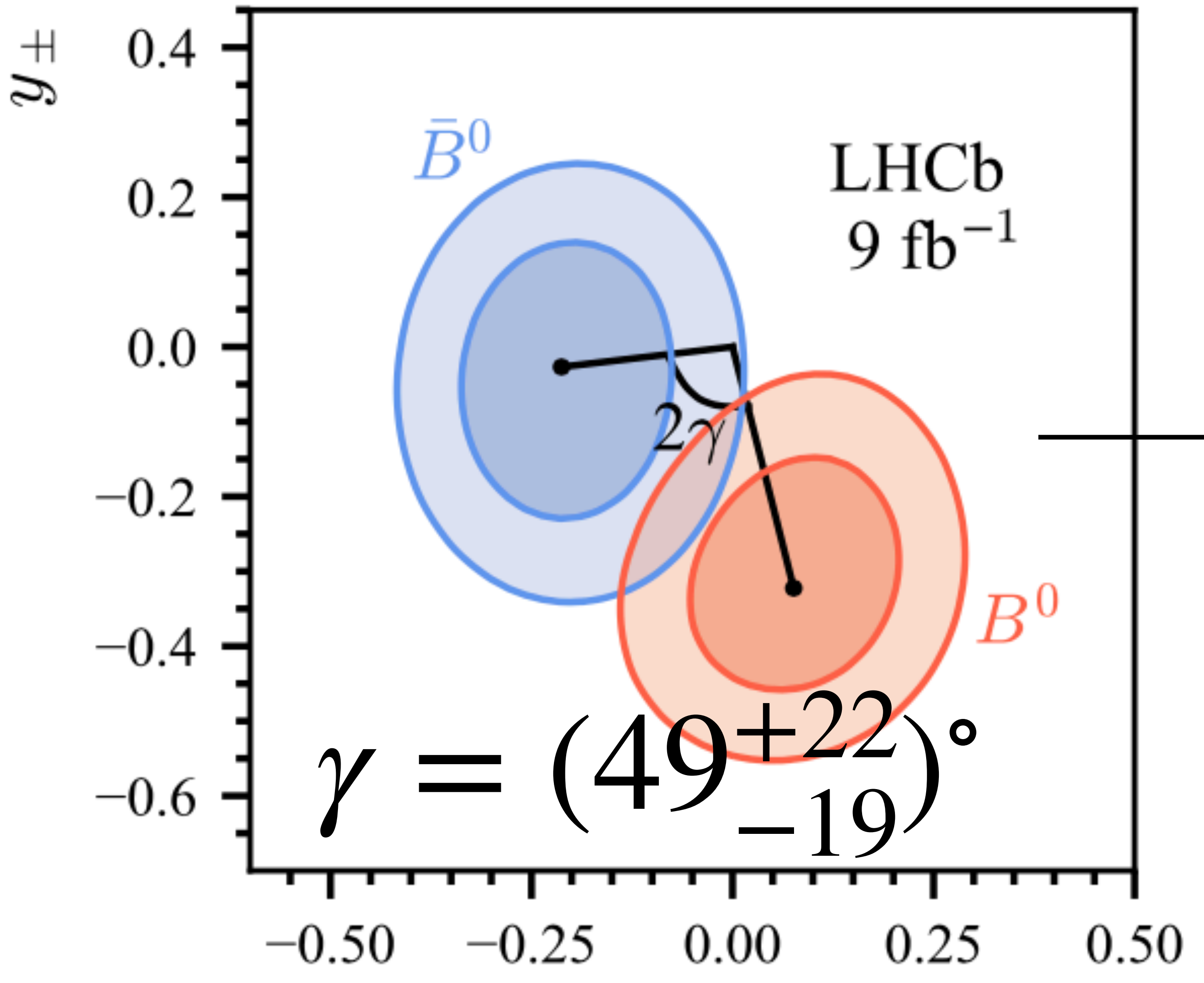
60% improvement compared to the previous best



CPV in $B^0 \to DK^*(892)^0$

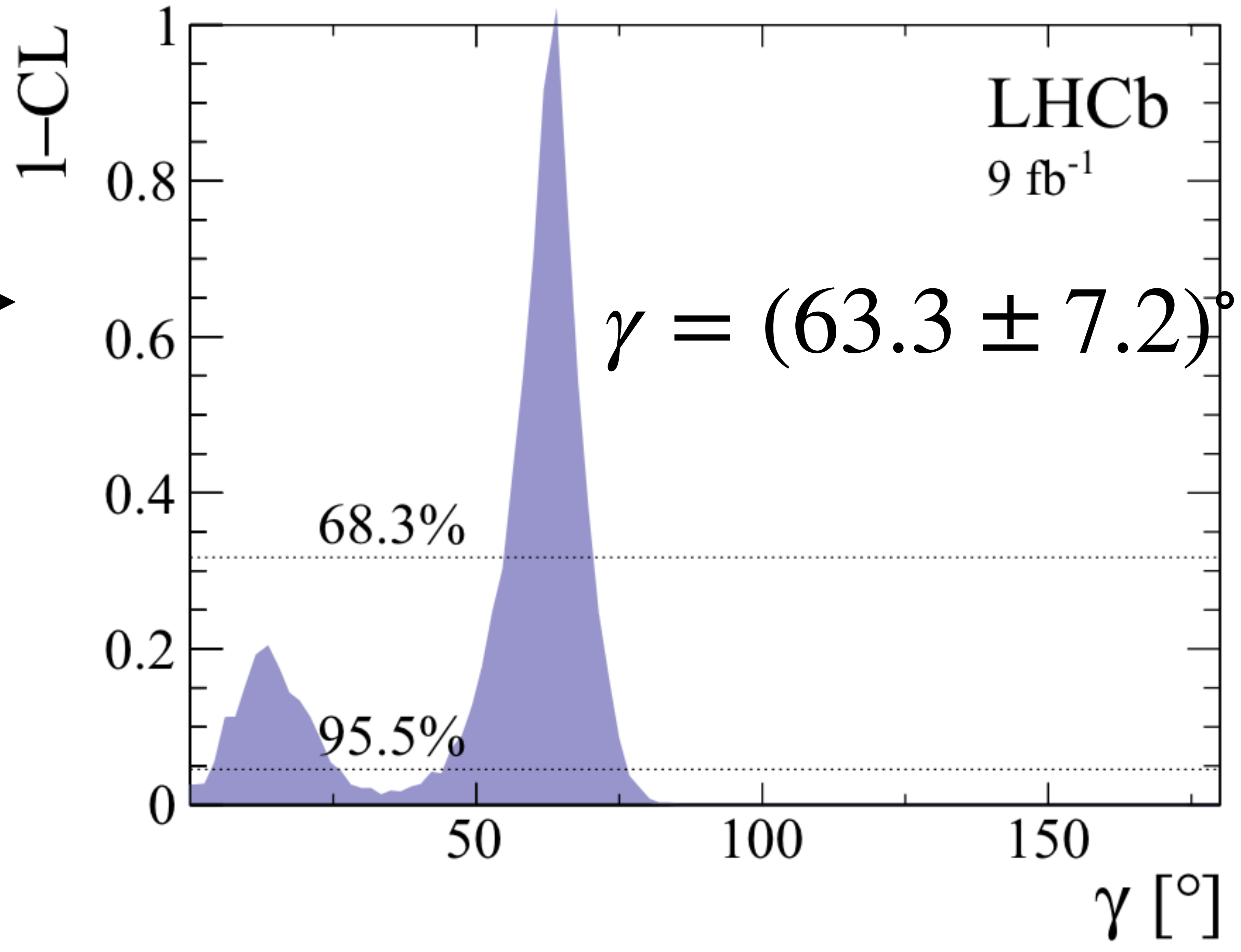


Combined with recent LHCb measurement of $B^0 \to D^0K^*$ with $D^0 \to K_s^0h^+h^-$ $[h = K, \pi]$



$\gamma = (49^{+22}_{-19})^\circ$

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



$\gamma = (63.3 \pm 7.2)^\circ$

JHEP 05(2024)025

γ in $B^{\pm} \to D^{*}h^{\pm}$

JHEP12(2023)013

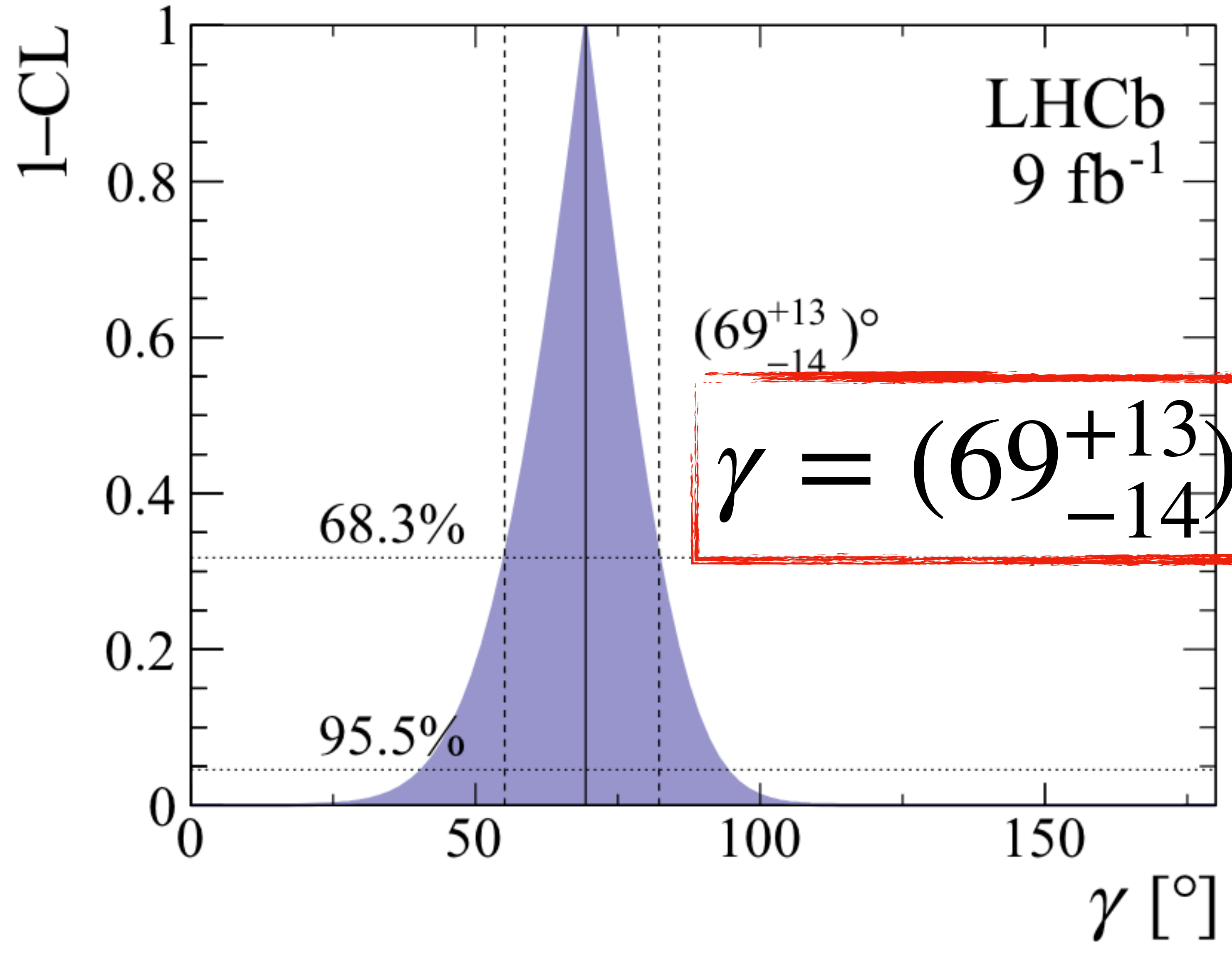
$D^{*} \to D\pi^{0}/\gamma$ as $D \to K_s^0\pi^+\pi^-/K_s^0K^+K^-$

strong phase inputs from BESIII and CLEO

Approach 1 : fully reconstructed final states

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

Most precise measurement in these modes!



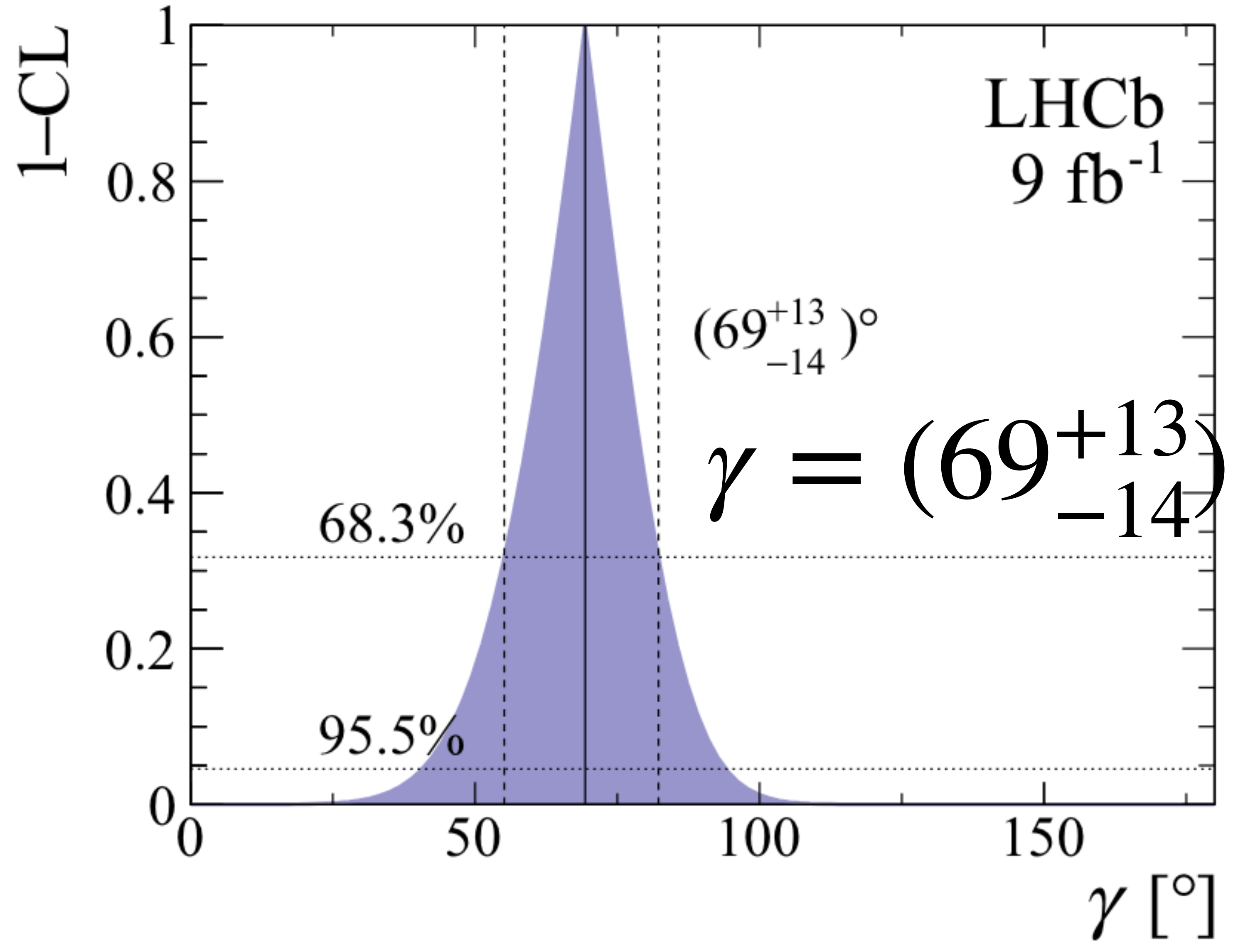
$\gamma = (69^{+13}_{-14})^{\circ}$

γ in $B^{\pm} \to D^{*}h^{\pm}$

JHEP12(2023)013

$D^{*} \to D\pi^{0}/\gamma$ as $D \to K_{s}^{0}\pi^{+}\pi^{-}/K_{s}^{0}K^{+}K^{-}$

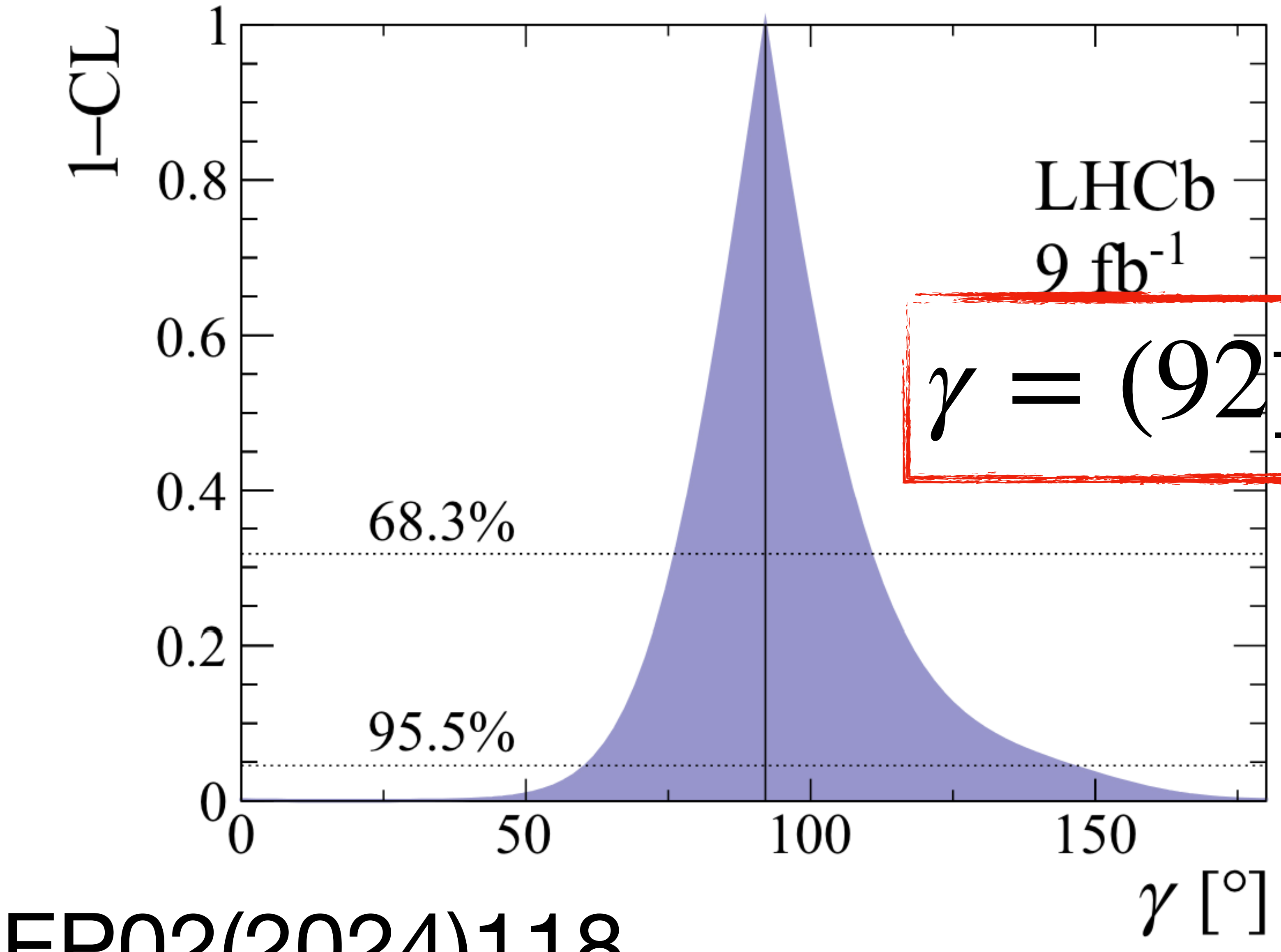
strong phase inputs from BESIII and CLEO



$\gamma = (69^{+13}_{-14})°$

Approach 2 : partially reconstructed final states

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



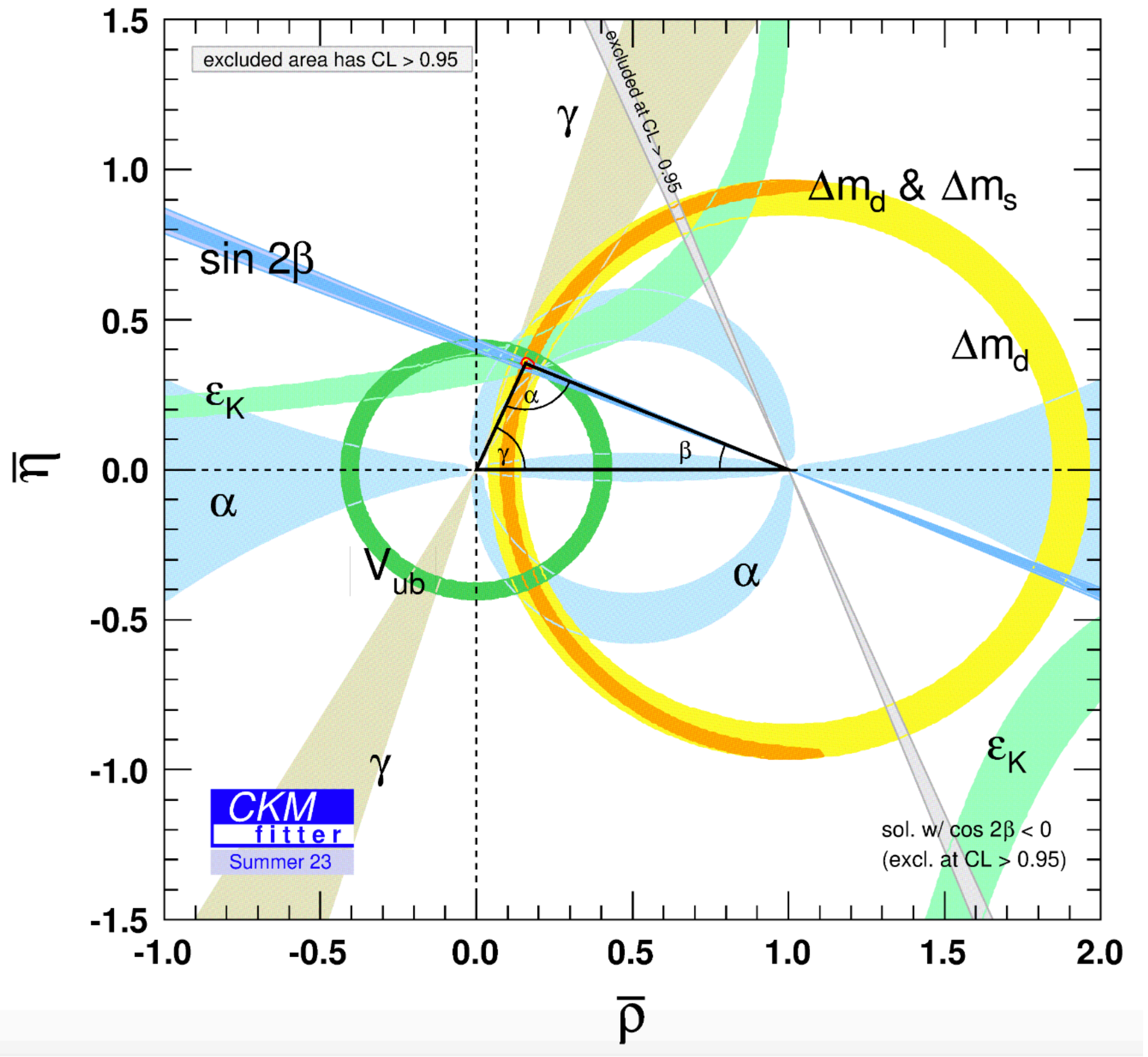
$\gamma = (92^{+21}_{-17})°$

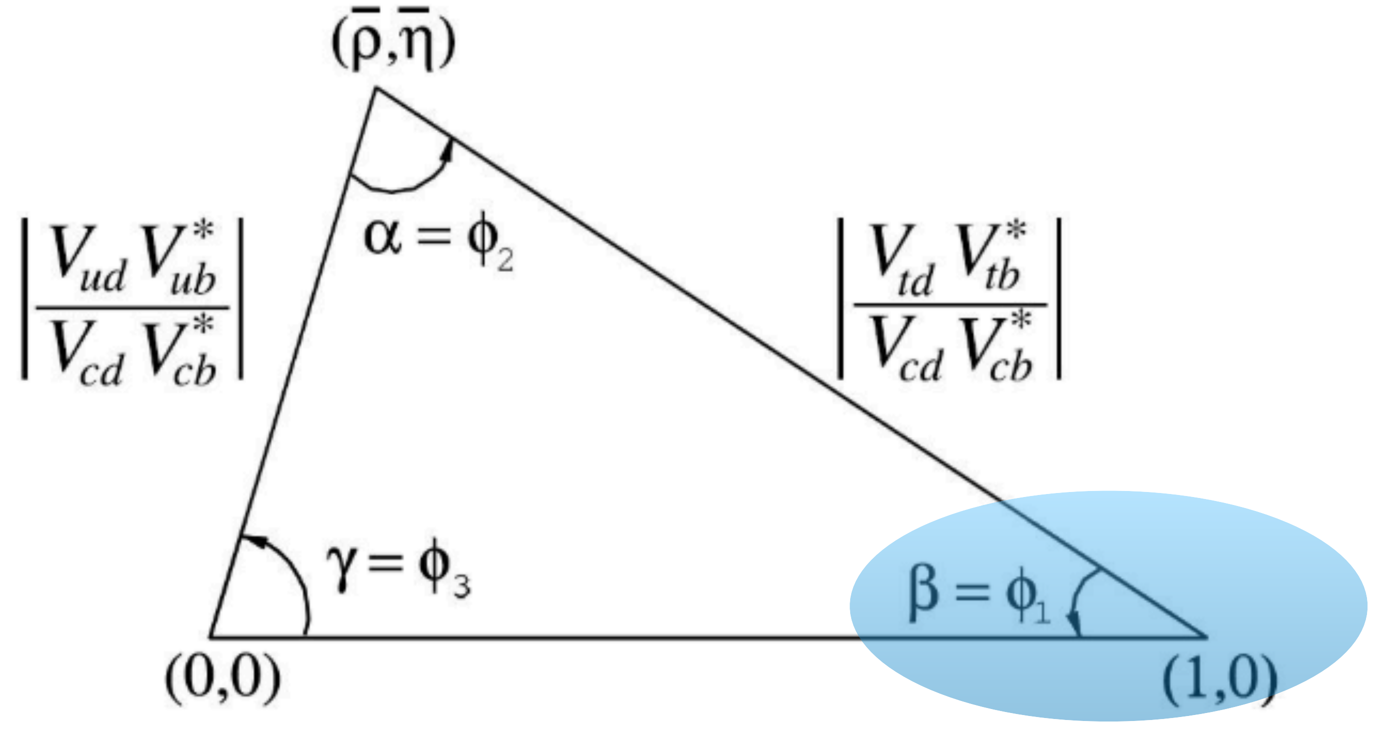
r_B parameters propagates the difference in γ precision.

Negligible correlation within two approaches.

JHEP02(2024)118

$\beta_{(s)}$ angle through the $b \to c\bar{c}s$ decays





β angle with $B^0 \to \psi(\to ll)K_s$

[Phys. Rev. Lett. 132 (2024) 021801]

$B^0 \to J/\psi(\to \mu^+\mu^-)K_s$: ~306K
$B^0 \to \psi(2S)(\to \mu^+\mu^-)K_s$: ~43K
$B^0 \to J/\psi(\to e^+e^-)K_s$: 24K

Pure CP-even mode, no angular analysis needed

$$\mathscr{A}^{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = \frac{S\ \sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh(1/2\Delta\Gamma_d t) + A_{\Delta\Gamma}\sinh(1/2\Delta\Gamma_d t)}$$

CPV parameters:

S= CPV in mixing

C= CPV in direct decays

time-dependent CP asymmetry

$S \approx \sin 2\beta$

β angle with $B^0 \to \psi(\to ll)K_s$

[Phys. Rev. Lett. 132 (2024) 021801]

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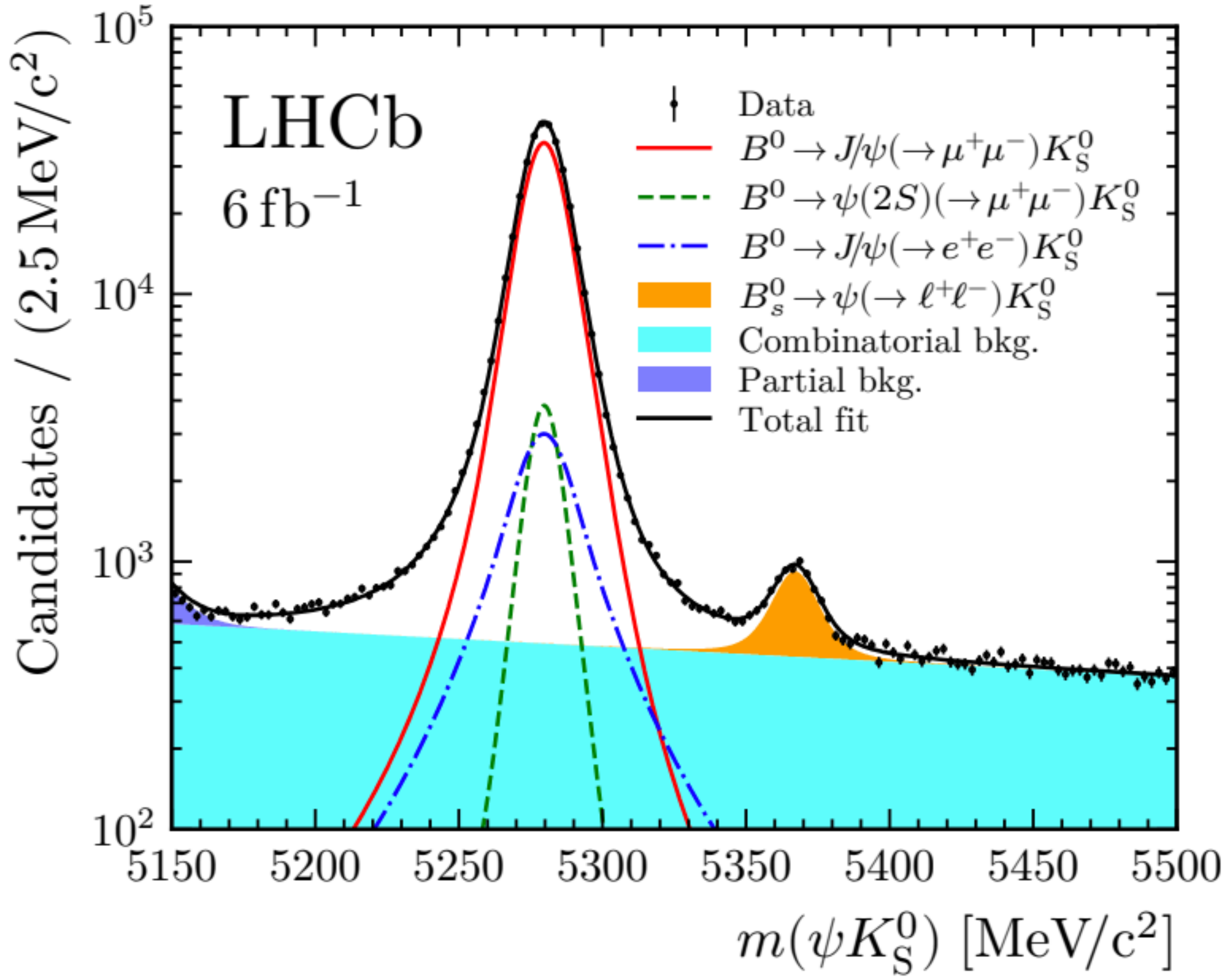
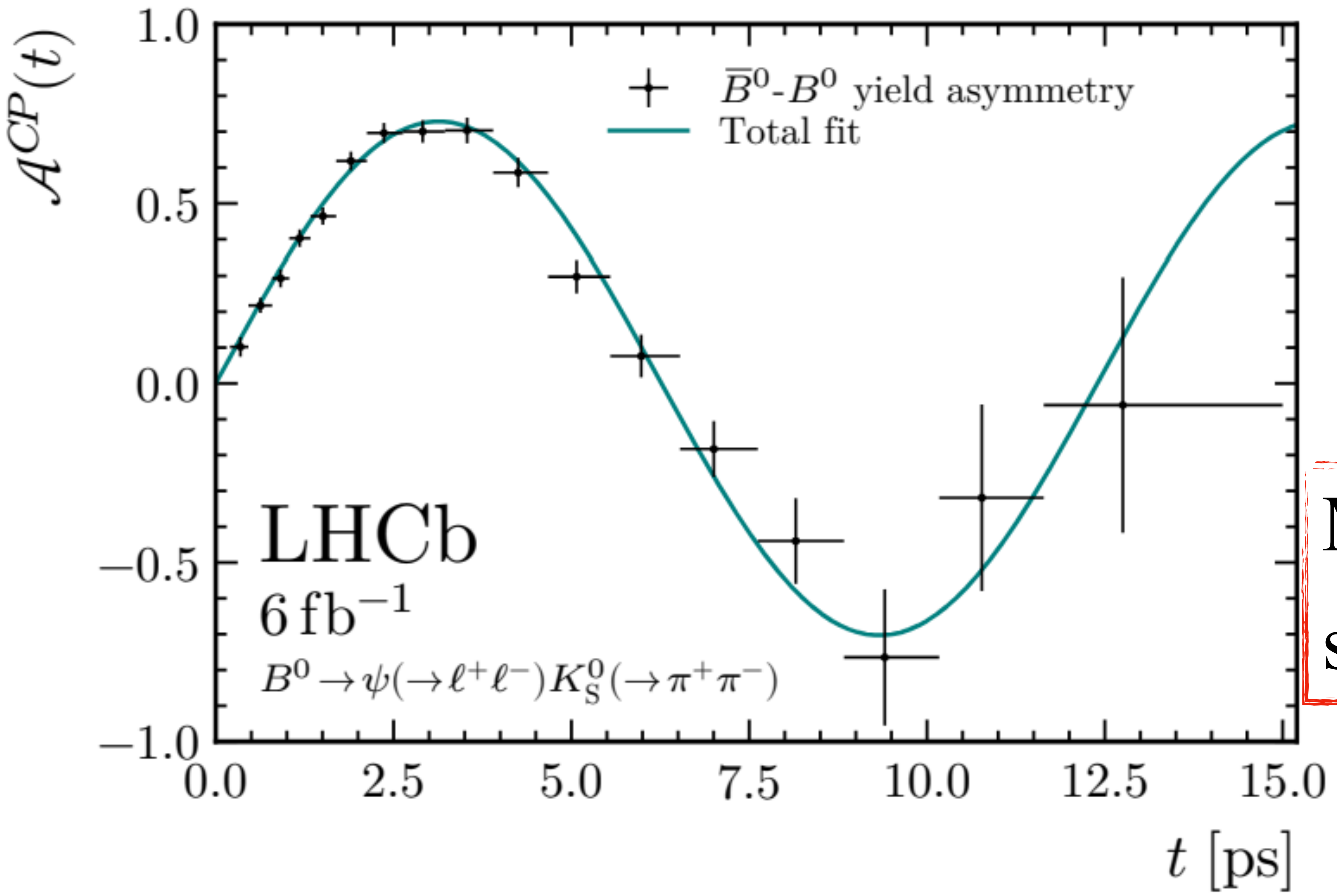
$$S_{\psi K^0_S} = 0.717 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})\,,$$
$$C_{\psi K^0_S} = 0.008 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})\,,$$

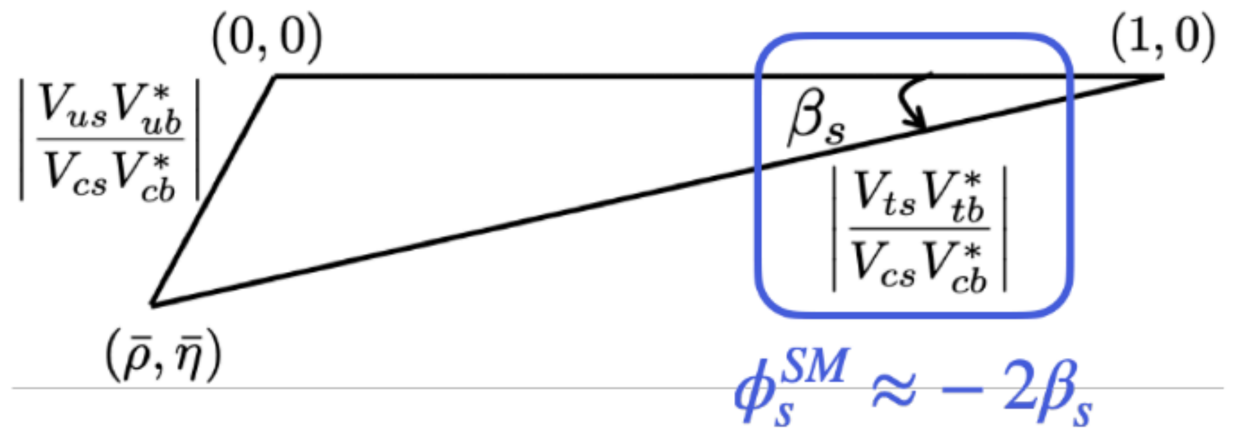




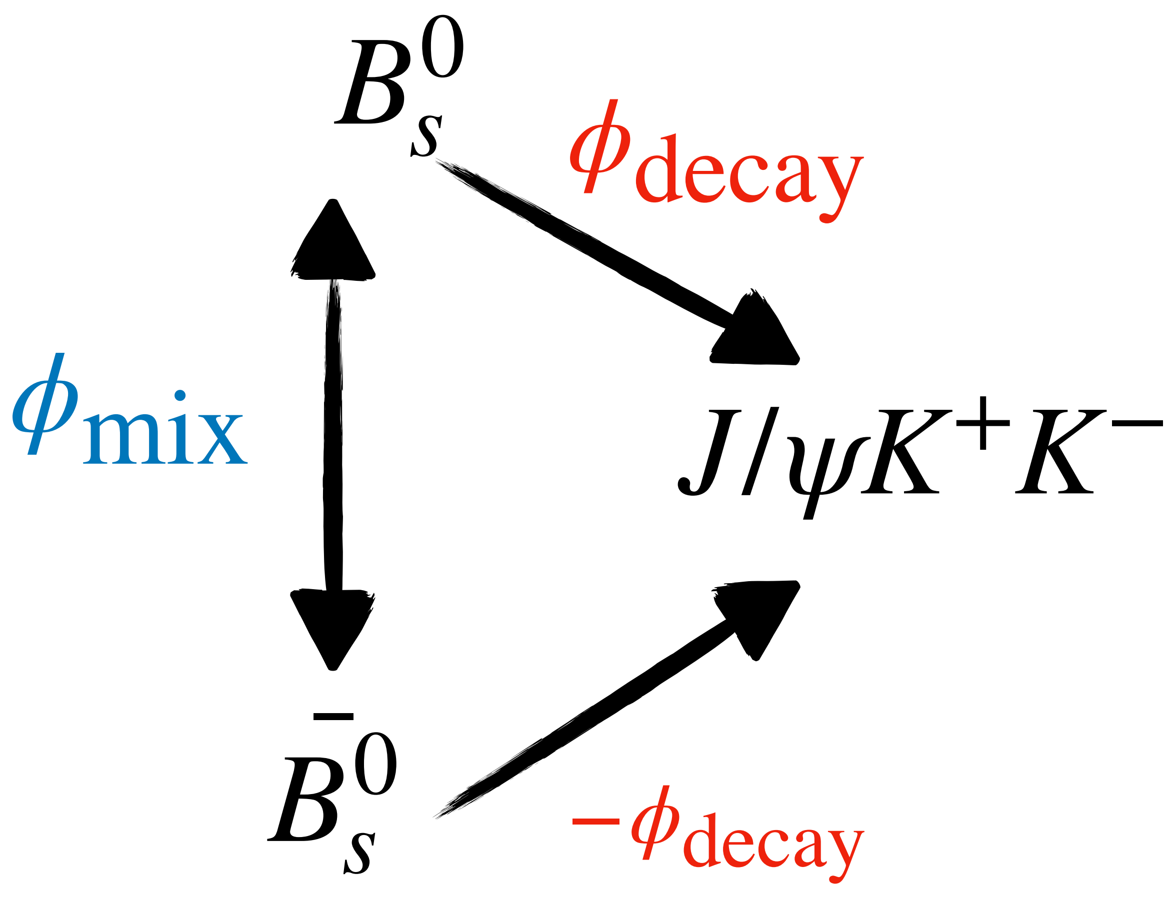
Phys. Rev. D 107, 052008

More precise than WA!
$\sin(2\beta) = 0.699 \pm 0.017$

Time-dependent CPV - ϕ_s



Time-dependent CP violation by the interference between direct decays and B_s^0 mixing



SM prediction of ϕ_s is highly suppressed compared to B^0 system

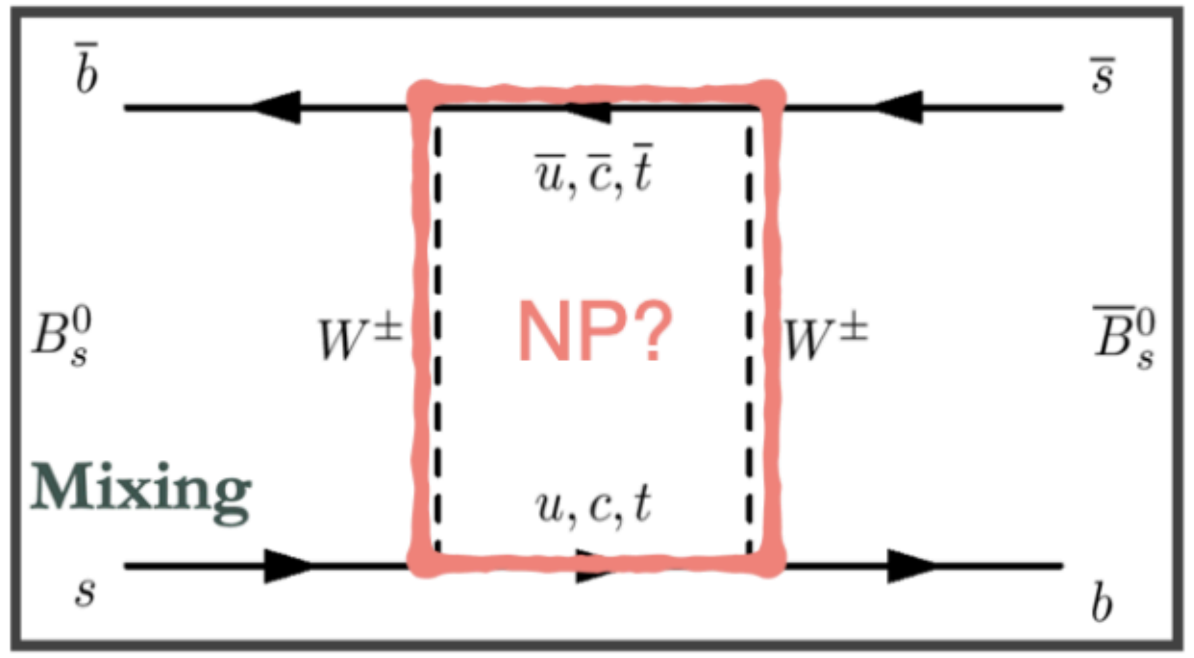
$\phi_s \approx -2\beta_s = -0.037 \pm 0.001$ rad.

$$\phi_s = \phi_{mix} - 2\phi_{decay}$$

It is highly sensitive to New Physics contributions in mixing up to $\mathcal{O}(100\%)$

[RevModPhys.88.045002]

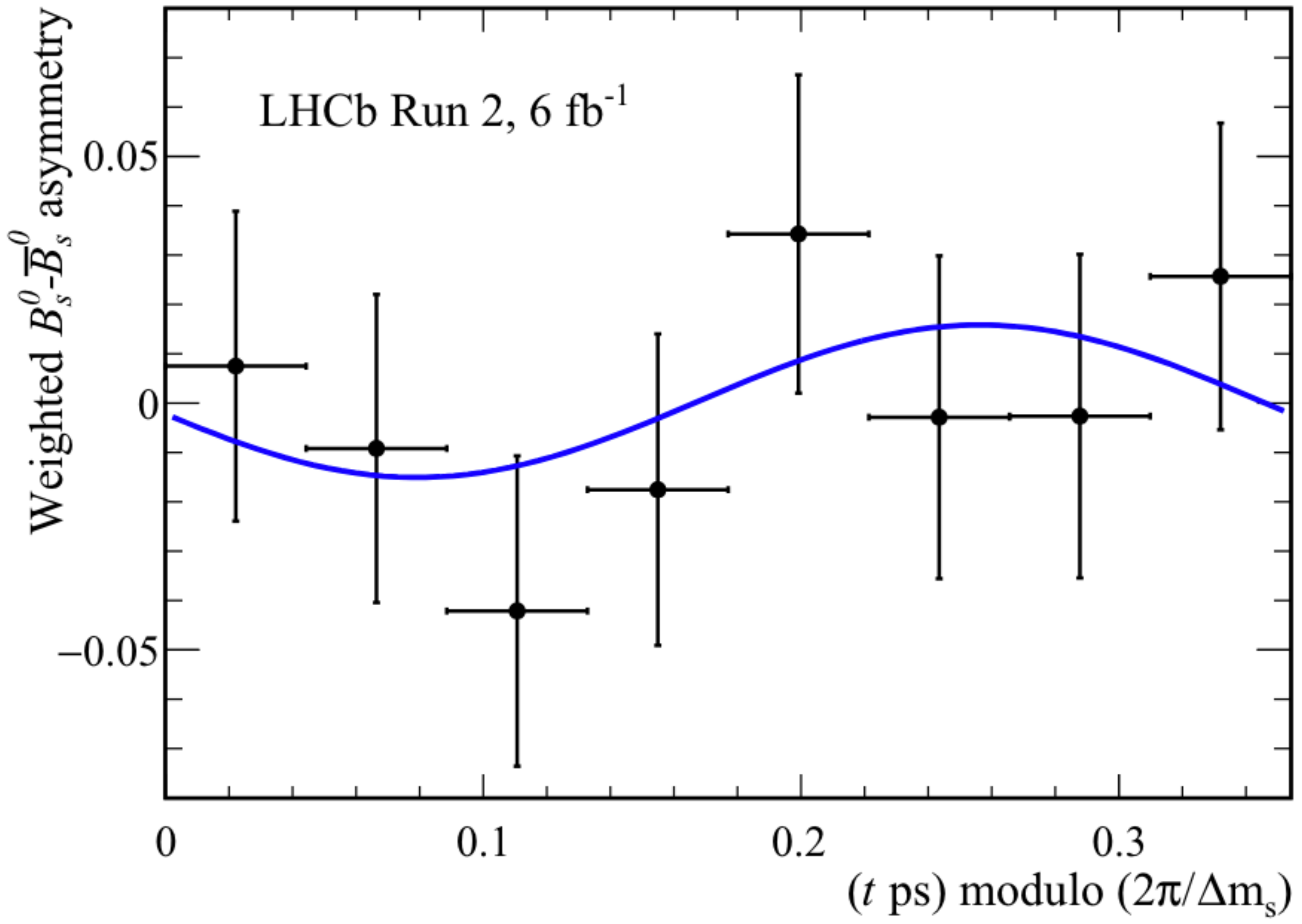
$$\phi_s^{SM} = -2\beta_s = arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$$



ϕ_s in LHCb

[Phys. Rev. Lett. 132 (2024) 051802]

Parameter	Values		
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

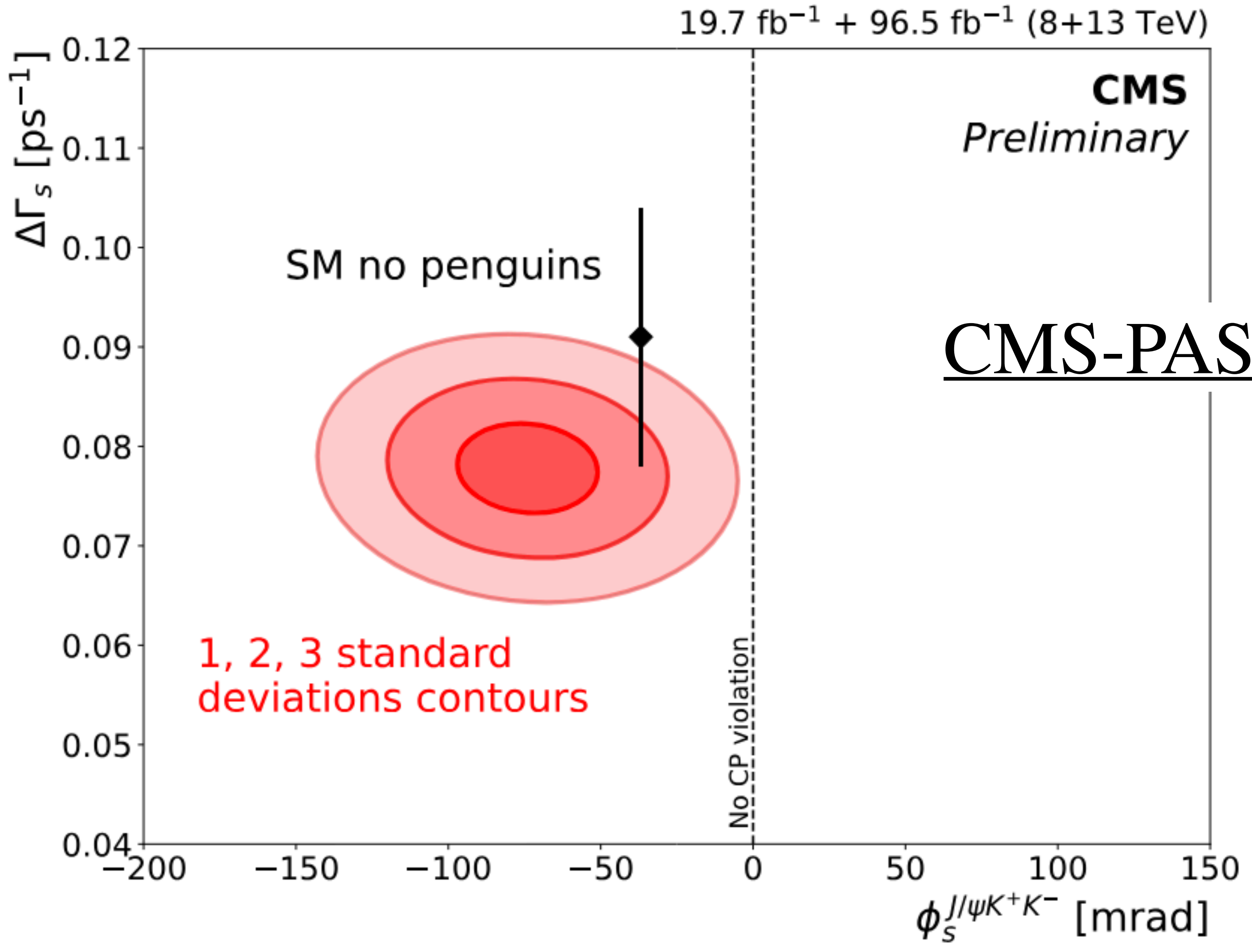


- Full Run 2 dataset used in the analysis

  $\phi_s^{J/\psi KK} = -0.039 \pm 0.022 \pm 0.006$ rad
- No evidence for CP asymmetry observed.
- Most precise measurement but still statistically limited.

ϕ_s in CMS

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-73	$\pm$ 23	$\pm$ 7
$\Delta\Gamma_s$ [ps^{-1}]	0.0761	$\pm$ 0.0043	$\pm$ 0.0019
Γ_s [ps^{-1}]	0.6613	$\pm$ 0.0015	$\pm$ 0.0028
Δm_s [$\hbar$ps^{-1}]	17.757	$\pm$ 0.035	$\pm$ 0.017
$\lvert\lambda\rvert$	1.011	$\pm$ 0.014	$\pm$ 0.012
$\lvert A_0\rvert^2$	0.5300	$\pm$ 0.0016	$\pm$ 0.0044
$\lvert A_\perp\rvert^2$	0.2409	$\pm$ 0.0021	$\pm$ 0.0030
$\lvert A_S\rvert^2$	0.0067	$\pm$ 0.0033	$\pm$ 0.0009
$\delta_\parallel$	3.145	$\pm$ 0.074	$\pm$ 0.025
$\delta_\perp$	2.931	$\pm$ 0.089	$\pm$ 0.050
$\delta_{S\perp}$	0.48	$\pm$ 0.15	$\pm$ 0.05



CMS-PAS-BPH-23-004

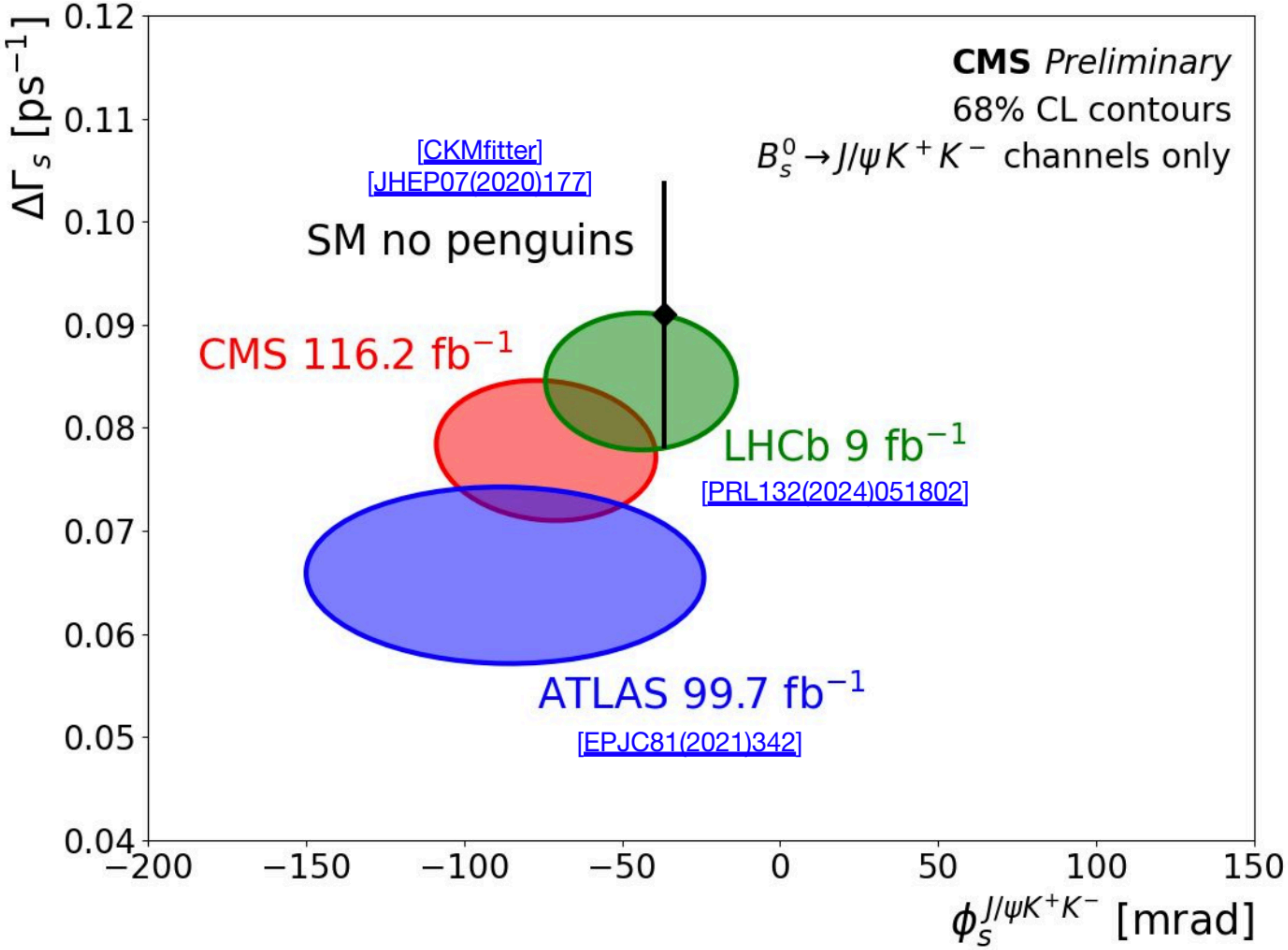
* Major improvement on the flavour tagging algorithm and the trigger strategies.

Combination with results at 8 TeV [PLB757(2016)97]

$$\phi_s = -0.074 \pm 0.023 \text{ [rad]}$$
$$\Delta\Gamma = 0.0780 \pm 0.0045 \text{ ps}^{-1}$$

The first evidence of CPV found in $B_s^0 \to J/\psi K^+K^-$ mode with 3.2σ
The most precise measurement of $\Delta\Gamma_s$ in single measurement.

Comparison within LHC



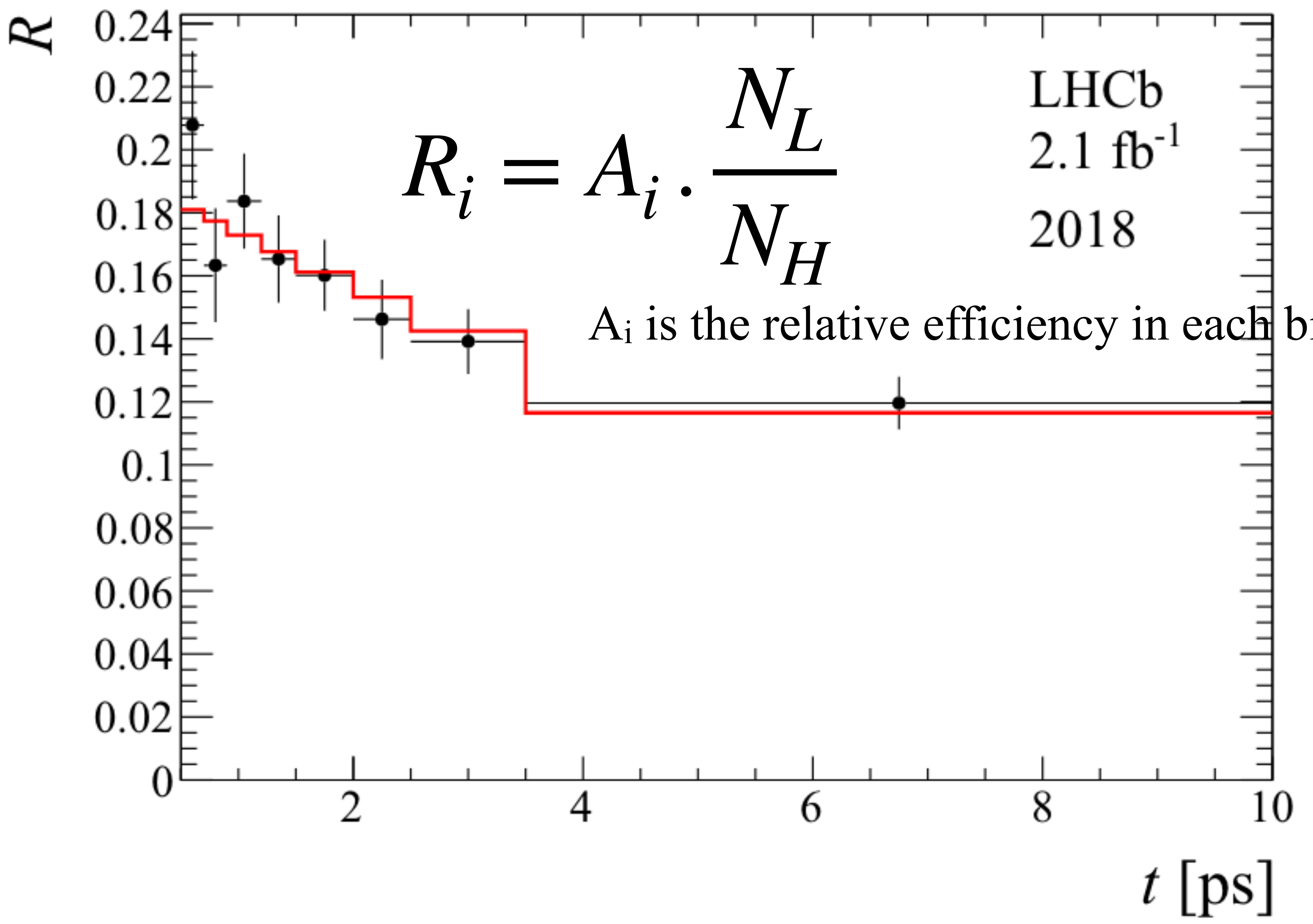
cern seminar

$\Delta\Gamma_s$ measurement

JHEP 05(2024)253

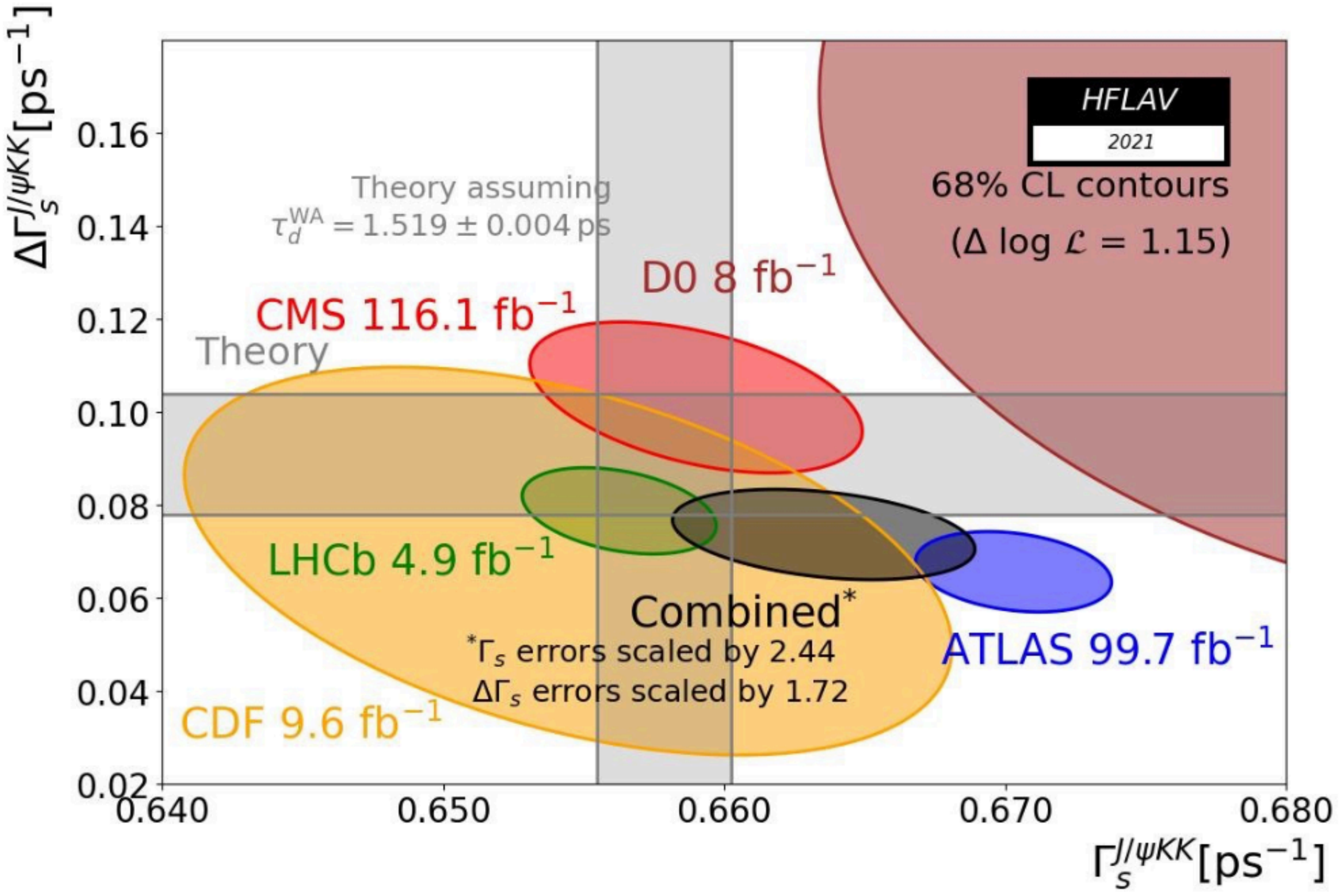
CP-even $B_s \to J/\psi\eta'$ to measure $\tau_L = 1/\Gamma_L$
CP-odd $B_s \to J/\psi\pi^+\pi^-$ to measure $\tau_H = 1/\Gamma_H$

Important to measure in single measurements to resolve the tension within LHC.



$$R_i = A_i \cdot \frac{N_L}{N_H}$$

A_i is the relative efficiency in each bin



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

Excellent agreement with LHCb [Phys. Rev. Lett. 132 (2024) 051802]

$\Delta\Gamma_s(J/\psi\phi) = 0.0845 \pm 0.0044 \pm 0.0024$ ps−1

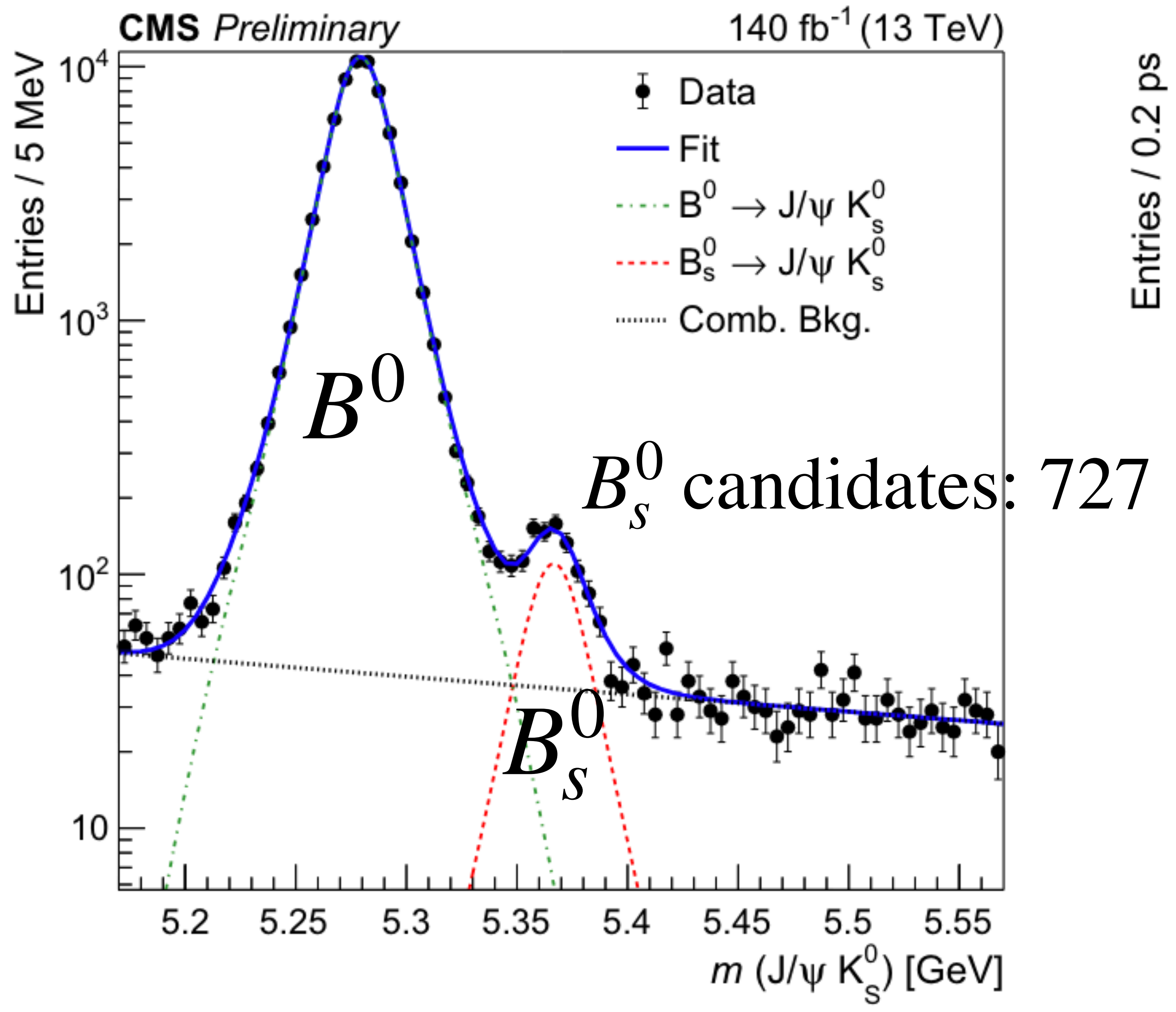
τ_H with $B_s^0 \to J/\psi K_s^0$ decays

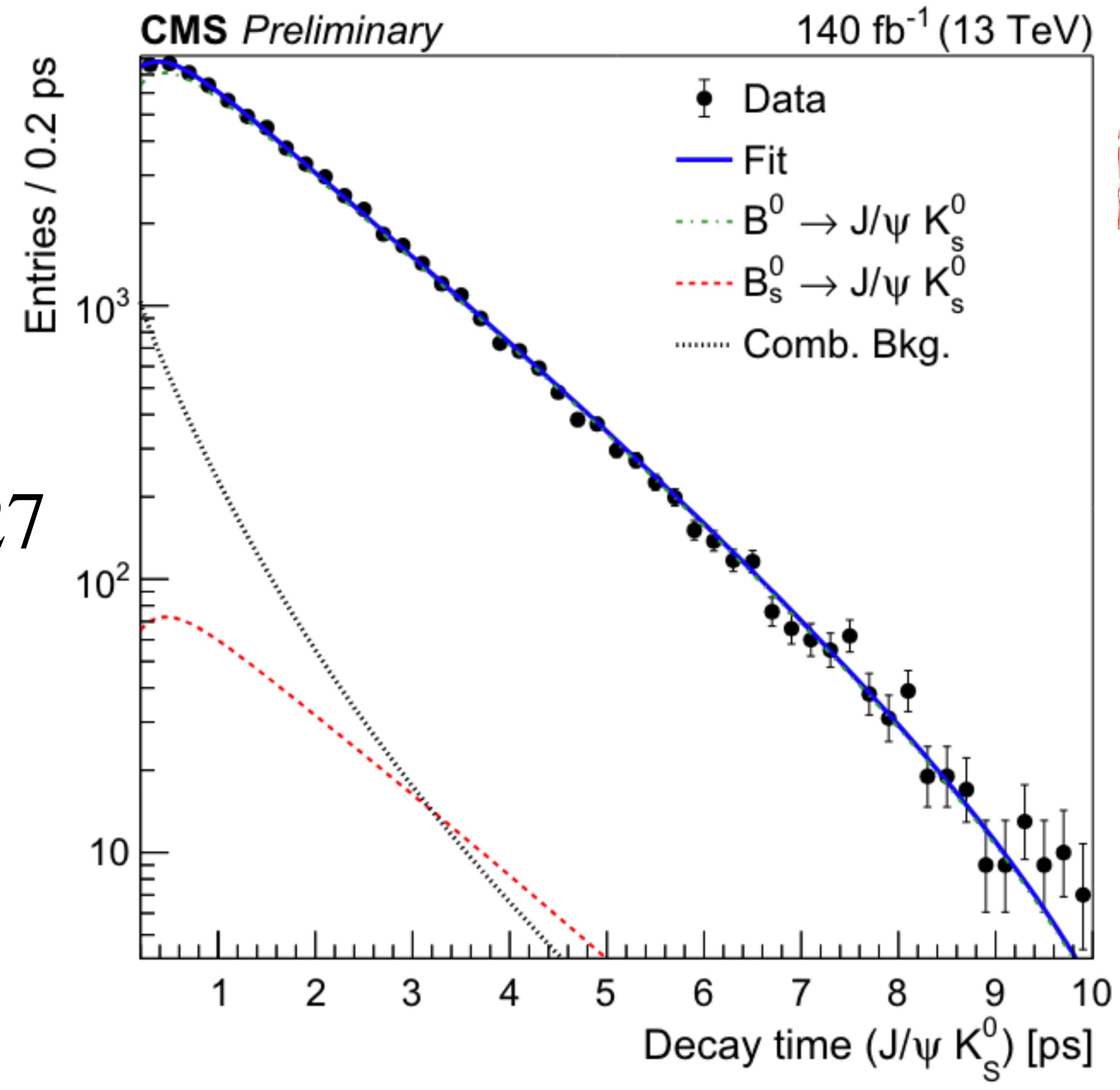
CMS-PAS-BPH-22-001

CPV conserved: CP-odd (CP-even) mode to measure τ_H (τ_L)

Complementary channel of $B^0 \to J/\psi K_s^0$ as related through U-spin symmetry ($\sin(2\beta + \Delta\phi_d)$)

2D maximum likelihood fit to decay time and invariant mass to extract the τ_H from $B_s^0 \to J/\psi K_s^0$ decays.





$\tau(J/\psi K_s^0)^{eff} = 1.59 \pm 0.07$ (stat) ± 0.03 (syst) ps

Good agreement with the SM prediction of 1.62 ± 0.02 ps.

Compatible within 2.1σ with LHCb measurement $\tau(J/\psi K_s^0)^{eff} = 1.75(0.12)$ ps.

Charm decays

Direct CPV in $D^0 \to K_s K_s$

arXiv:2405.11606 submitted to Eur. Phys. J. C

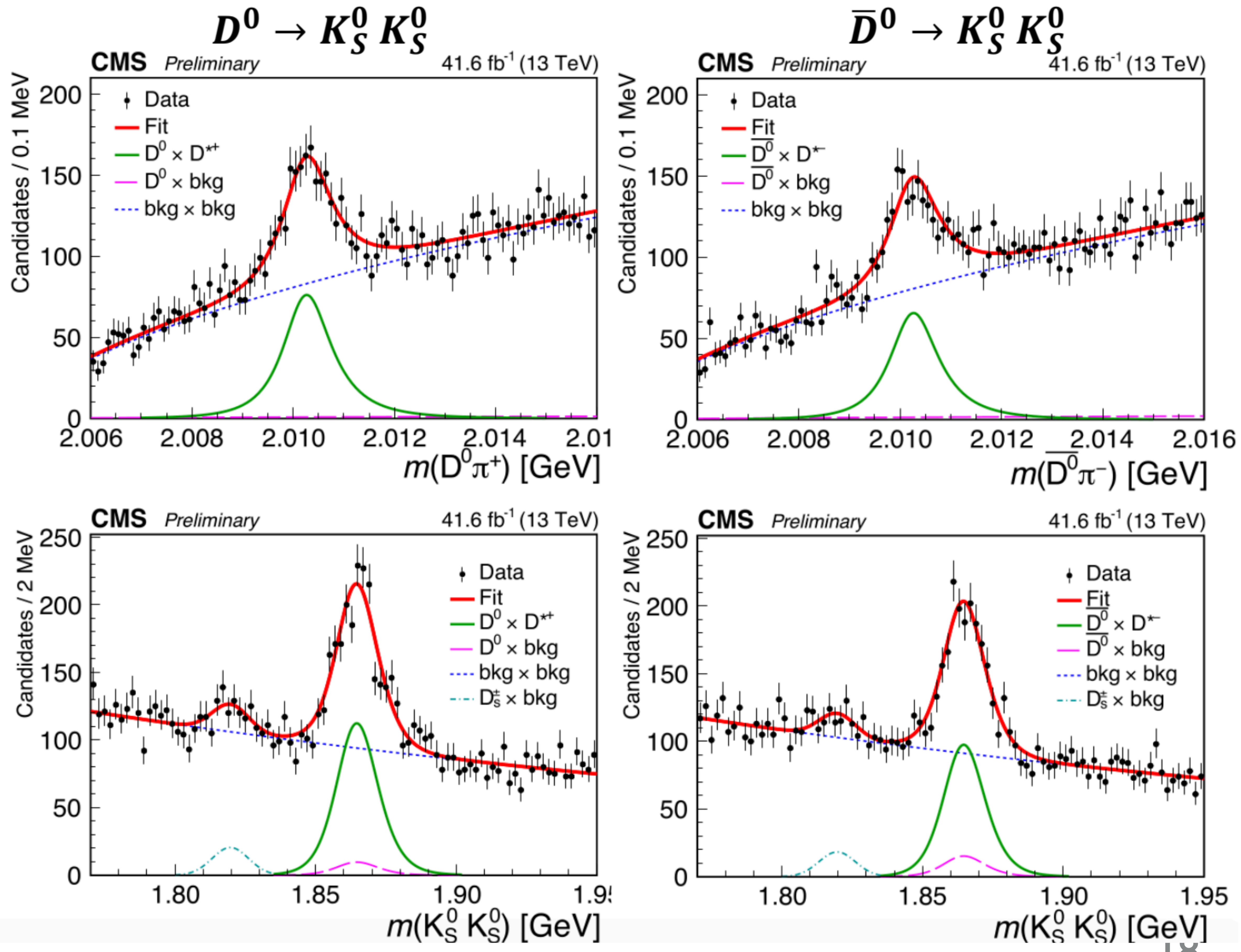
- First! CMS CP measurement in charm sector
  - Uses D^0 from the $D^{*\pm} \to D^0\pi^{\pm}$ decays to tag D^0s from π charge.

$$A_{CP} = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}$$

- A_{CP} is measured relative to $D^0 \to K_s\pi^+\pi^-$ reference channel to cancel the production and detection asymmetries,
  $\Delta A_{CP} = A_{CP}^S - A_{CP}^R$

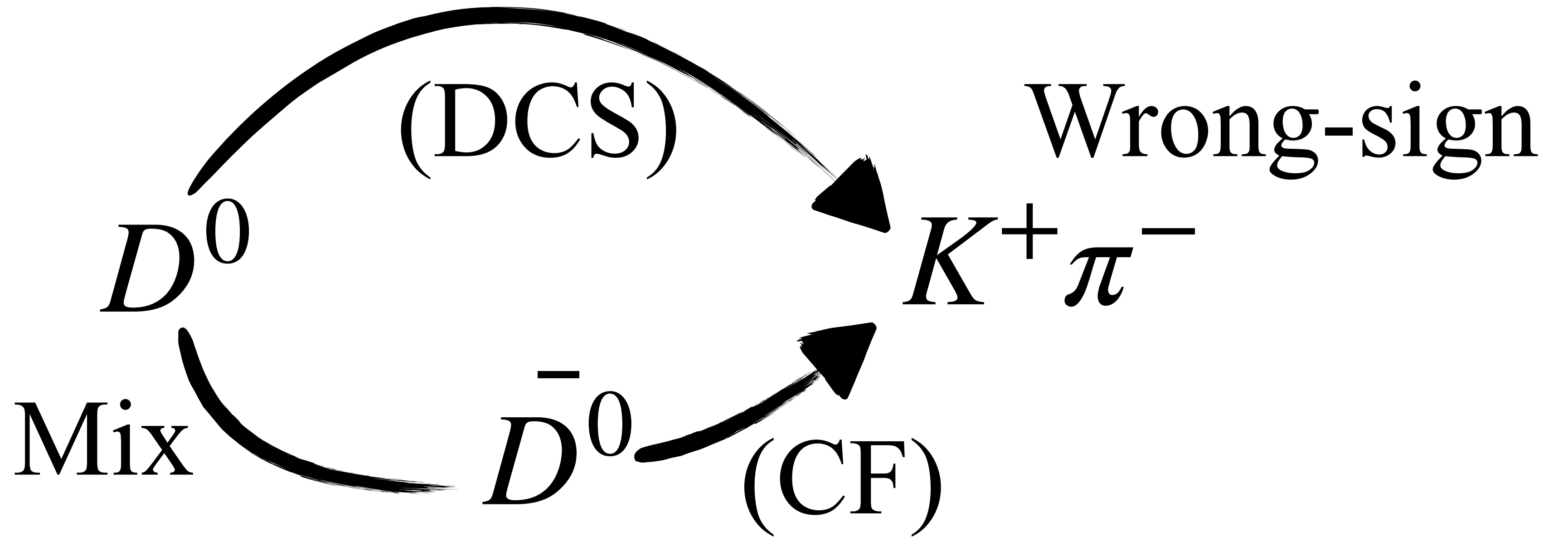
  - 2D ML fit is to the D^{*+} and D^0 invariant mass to extract the yields.

- $A_{CP}(K_sK_s) = [6.3 \pm 3.0 \pm 0.2 \pm 0.8\ (A_{CP}(K_s\pi^+\pi^-)]\ \%$
  - Consistent with no CP violation
  - Consistent with LHCb $(3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$ and Belle $(0.02 \pm 1.53 \pm 0.02 \pm 0.17)\%$

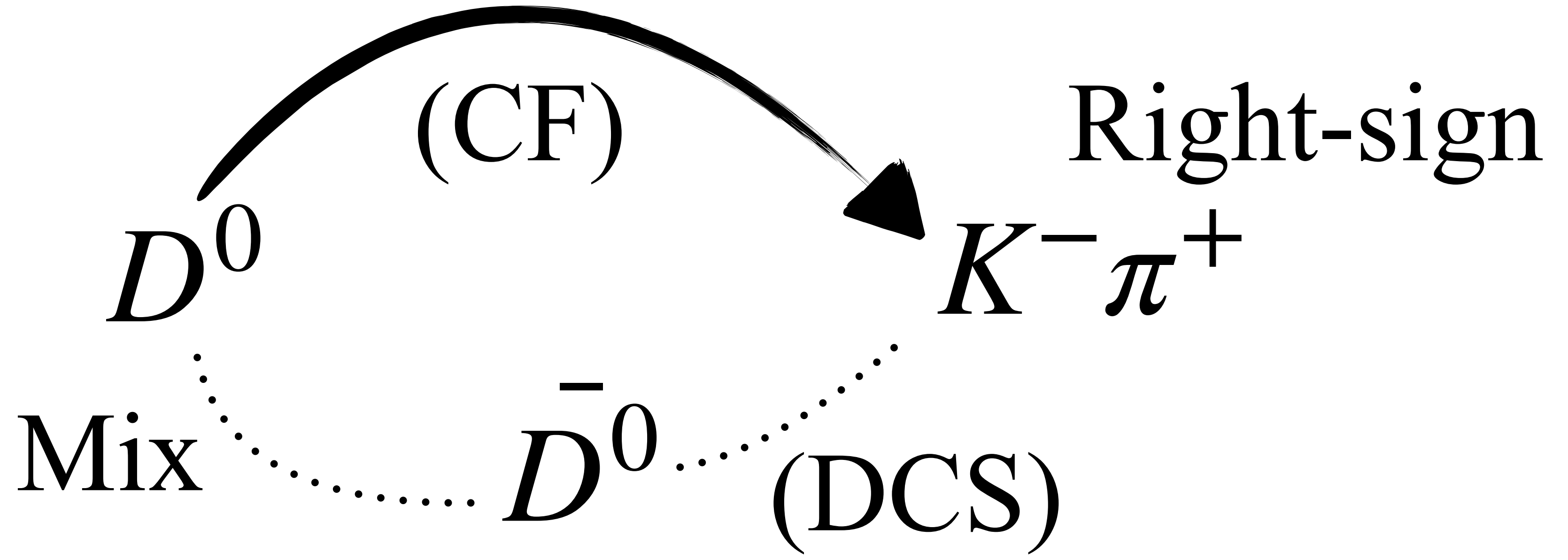


Mixing and CPV in $D^0 \to K^+\pi^-$

LHCb-PAPER-2024-008



Tagging D^0s from $D^{*\pm} \to D^0\pi^\pm$ decays via π charge



To measure the CPV fit time-dependent WS/RS ratios

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

since oscillating parameters of $x, y \ll 1$

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

CP-violating parameters

mixing parameters

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

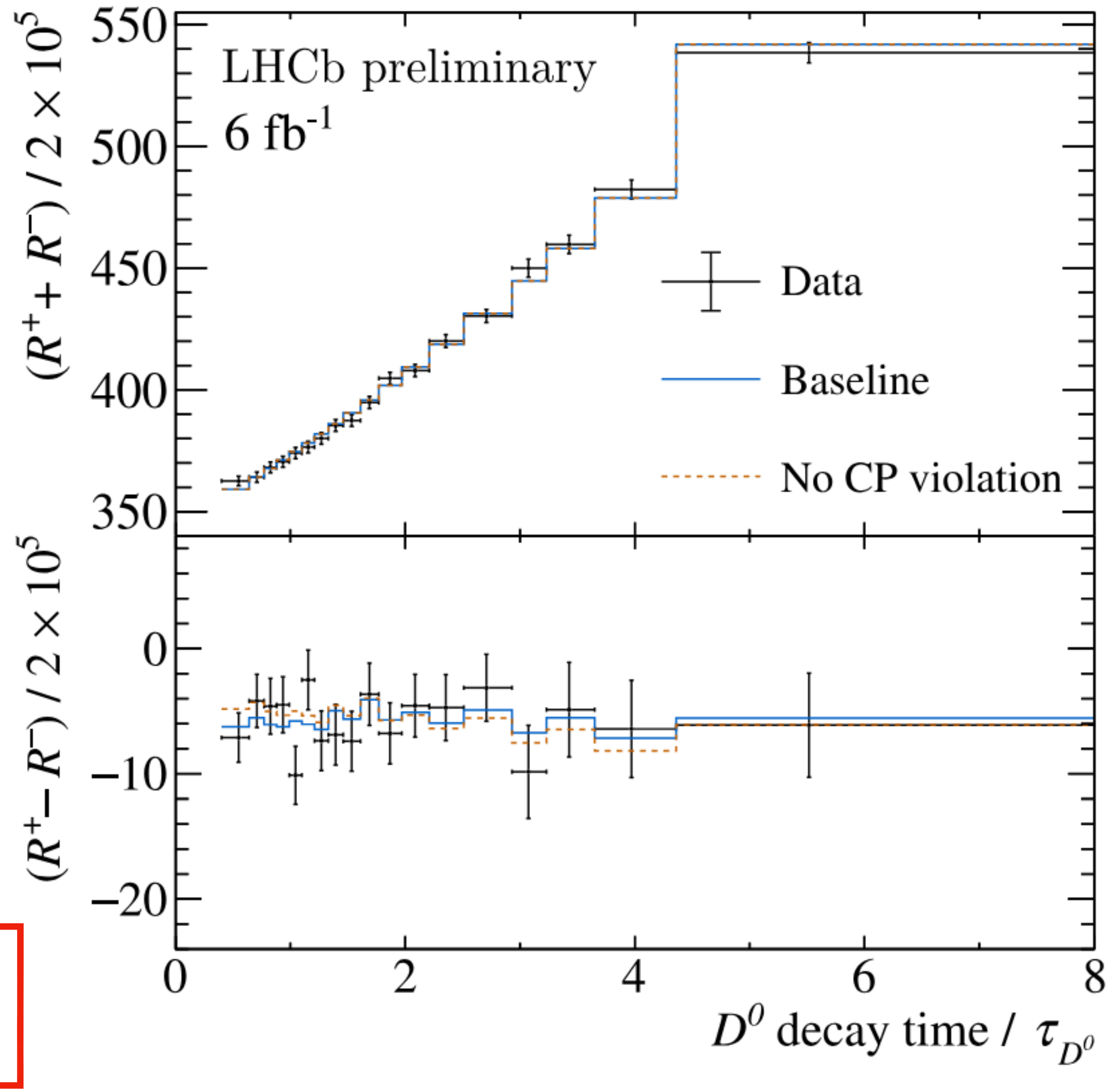
LHCb-PAPER-2024-008

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

40% improvement in precision wrt the previous best Phys. Rev. D 97, 031101 (2018)



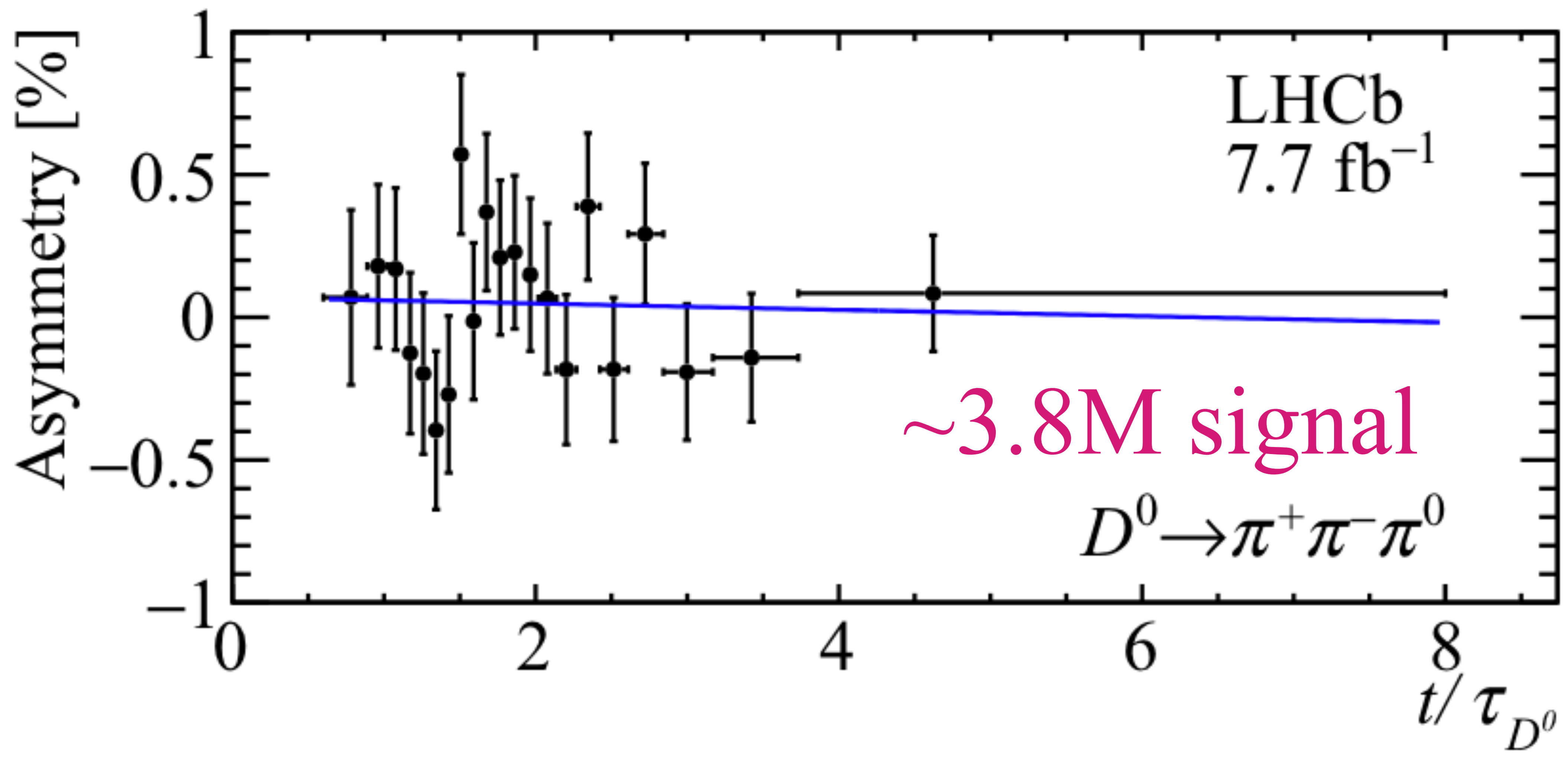
Time dependent CPV in $D^0 \rightarrow \pi^+\pi^-\pi^0$

arXiv:2405.06556

Time dependent asymmetry

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

direct CPV mixing CPV



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

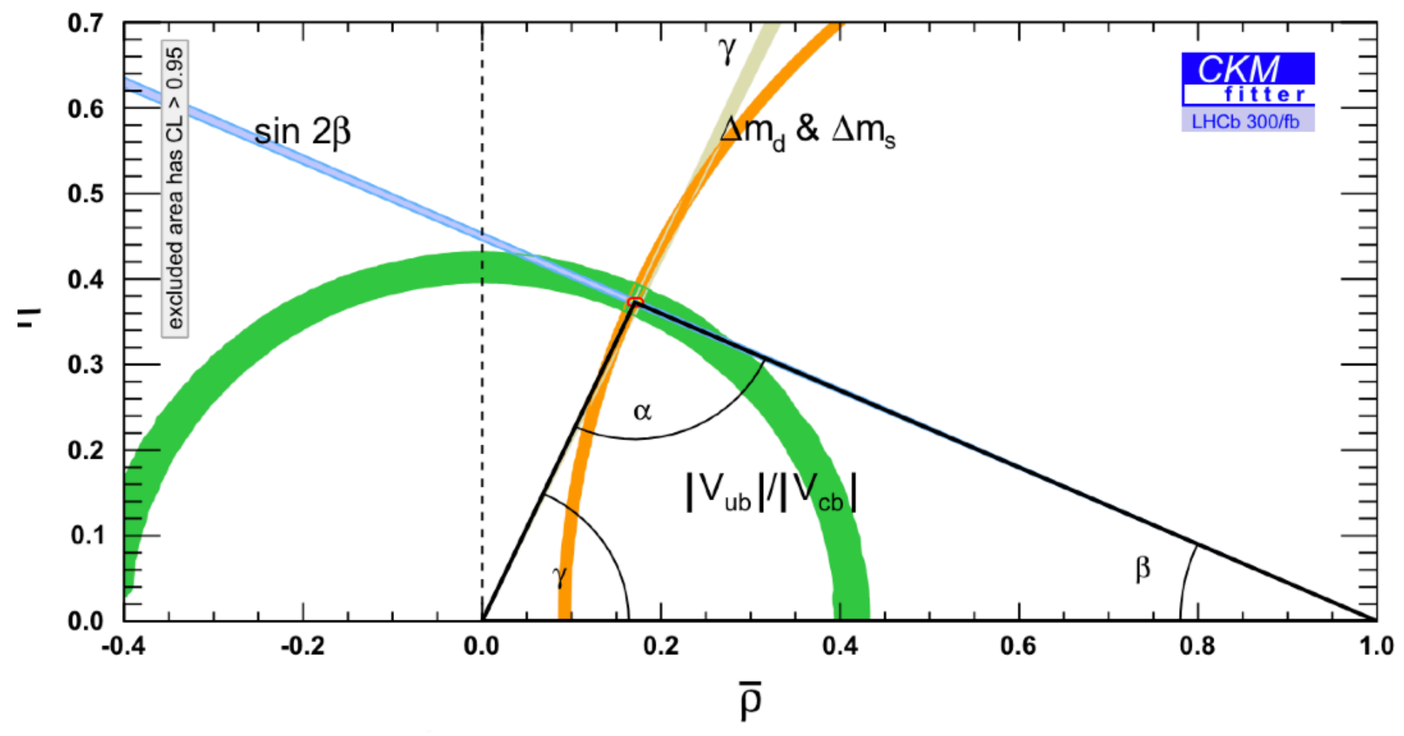
No CPV is observed.

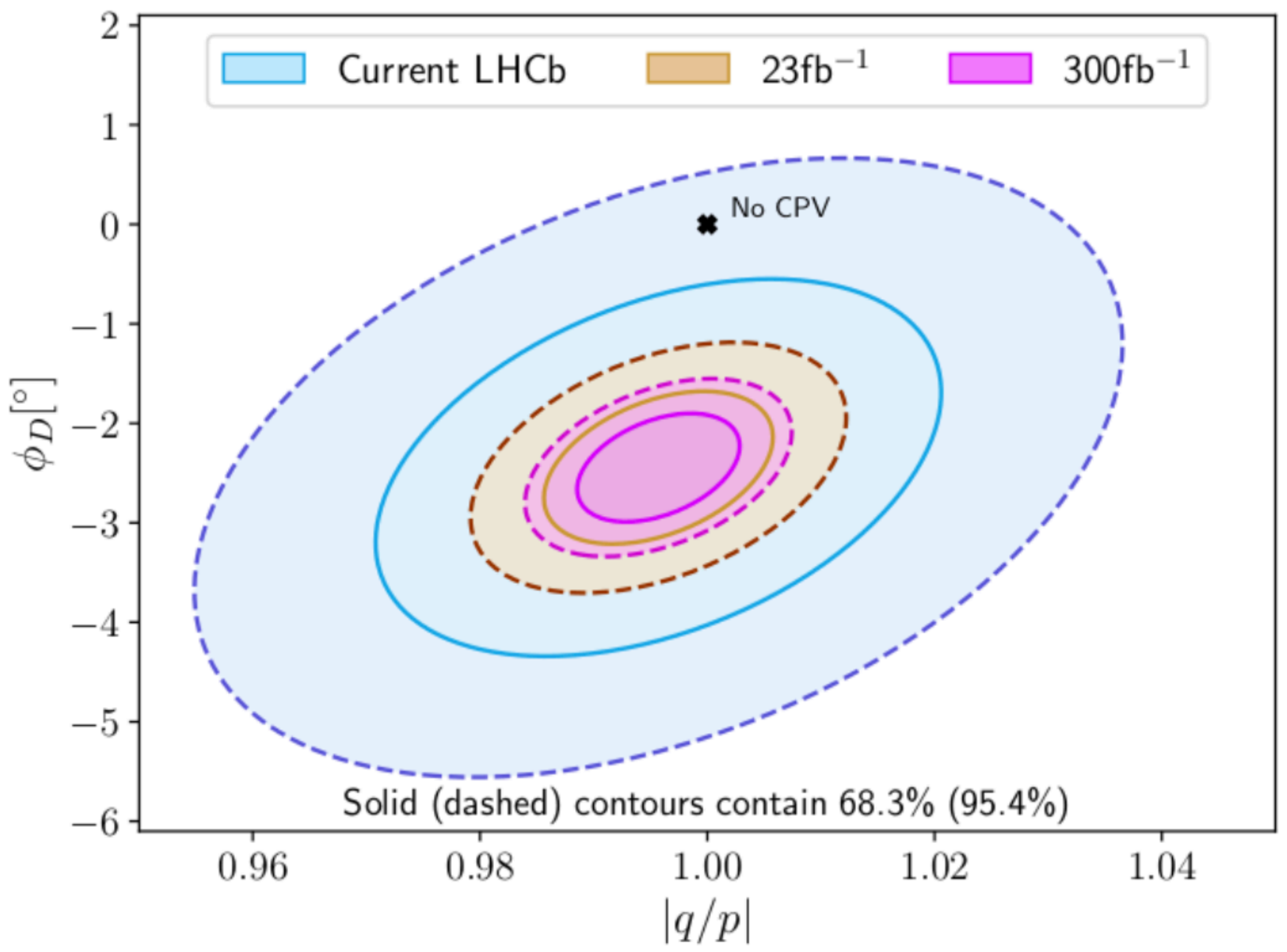
Excellent agreement with WA : Phys. Rev. D 107, 052008

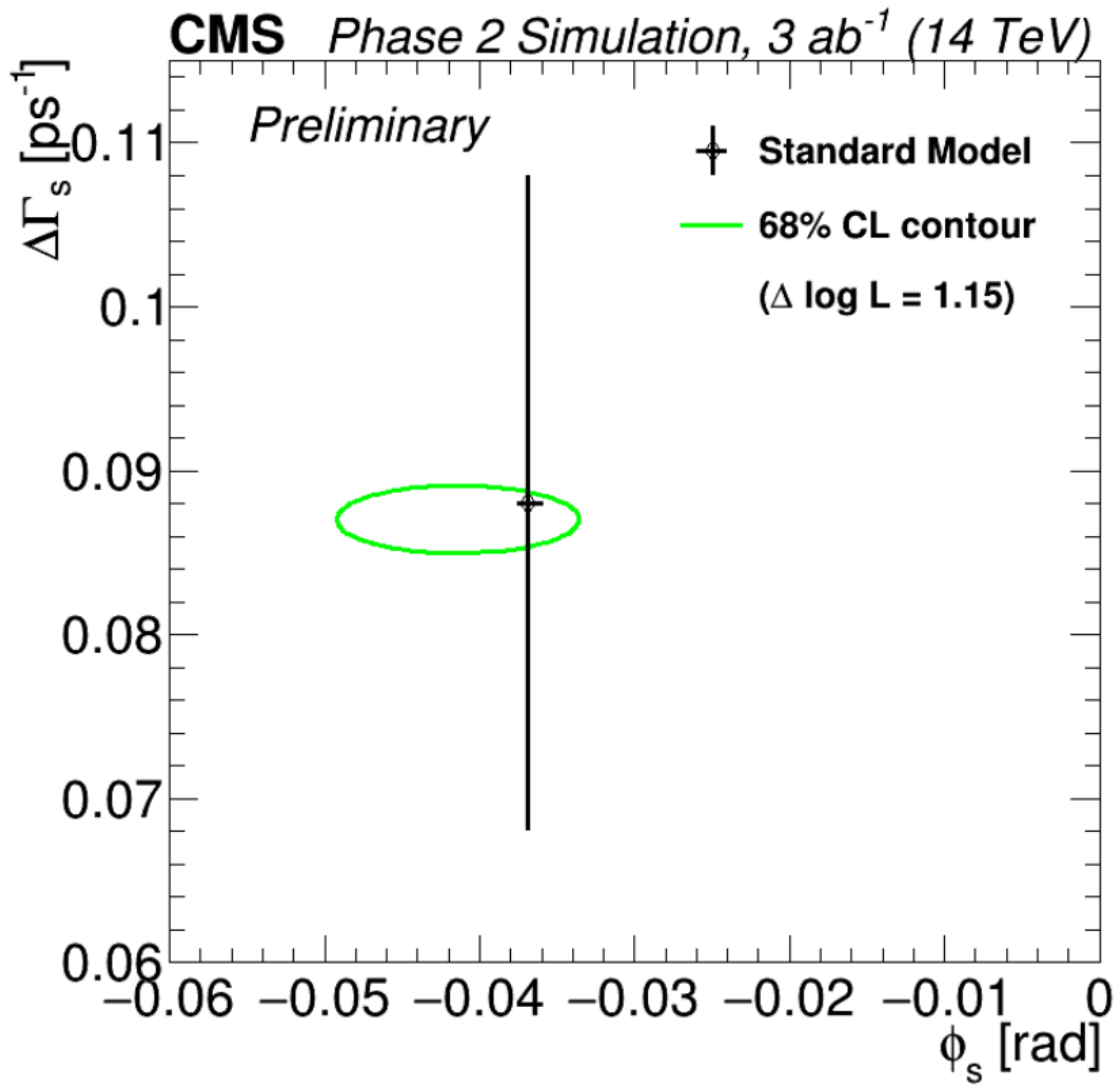
$\Delta Y^{WA} = (0.9 \pm 1.1) \times 10^{-4}$

Summary

- A long journey towards these precise measurements of CPV observables
- Many achievements with the Run 1 + Run 2 data but still statistically limited!
- Upgrade 1 & 2 offers much more in precision.







Extra slides

$B_s^0 \to \mu^+\mu^-$ effective lifetime

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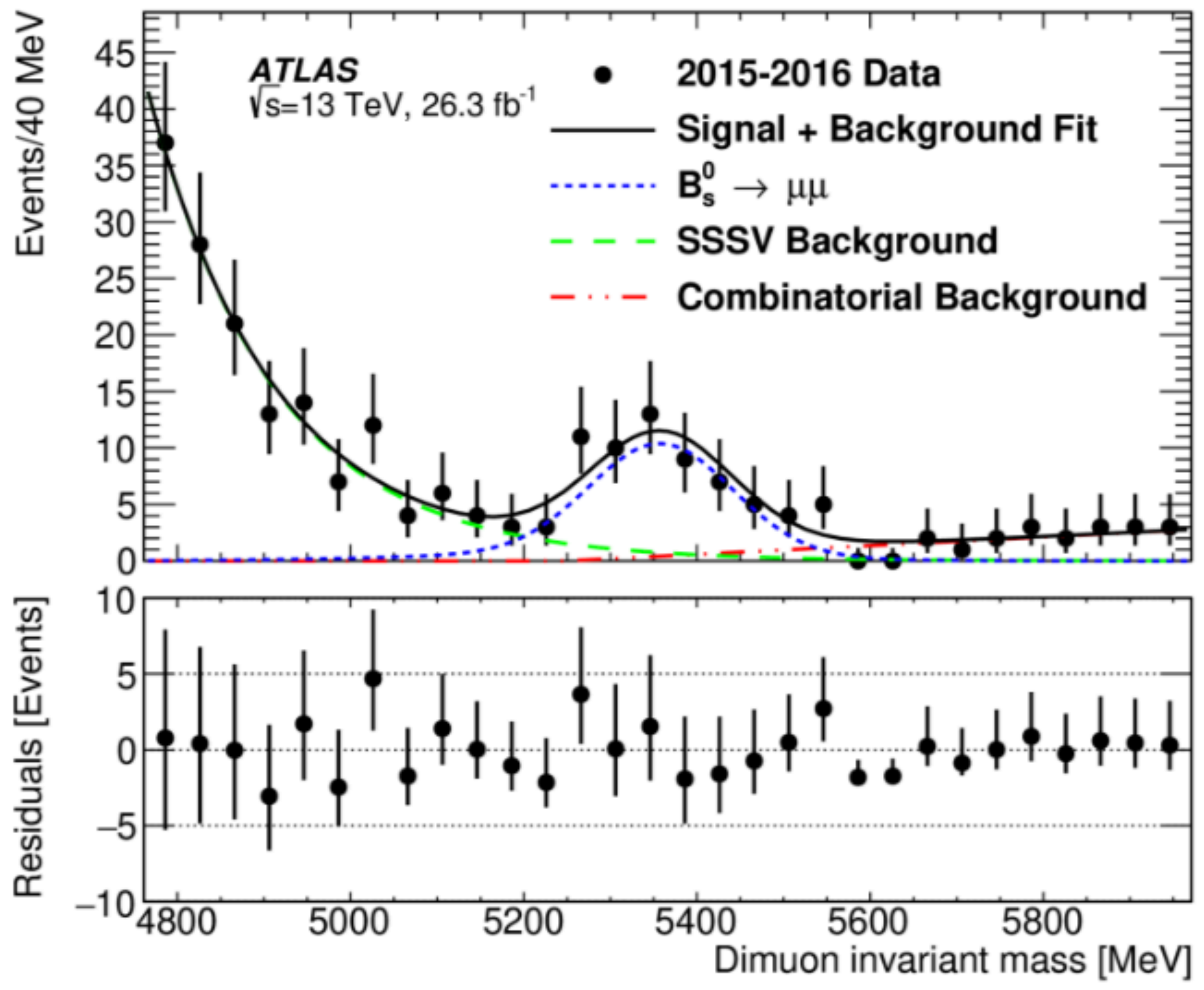
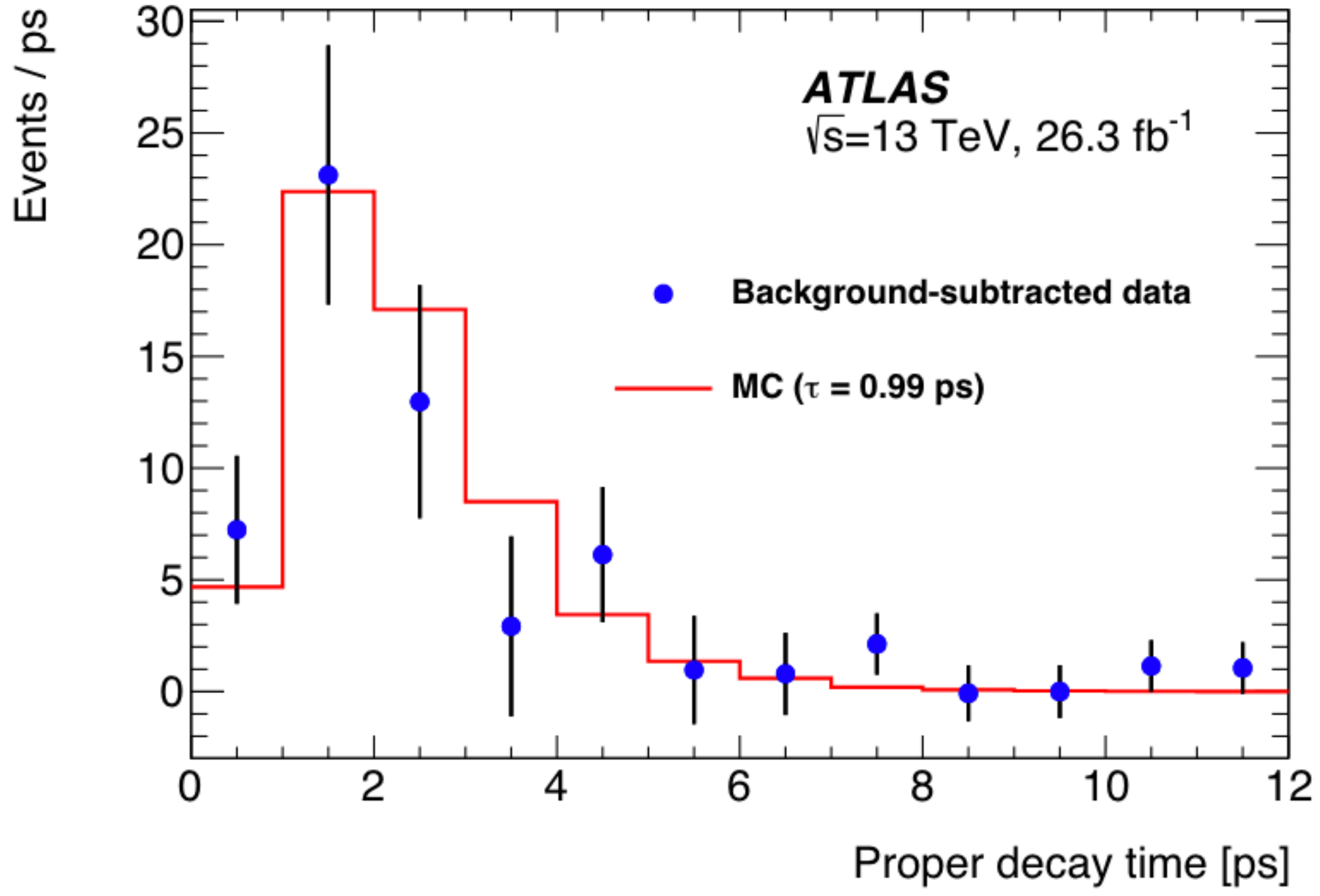
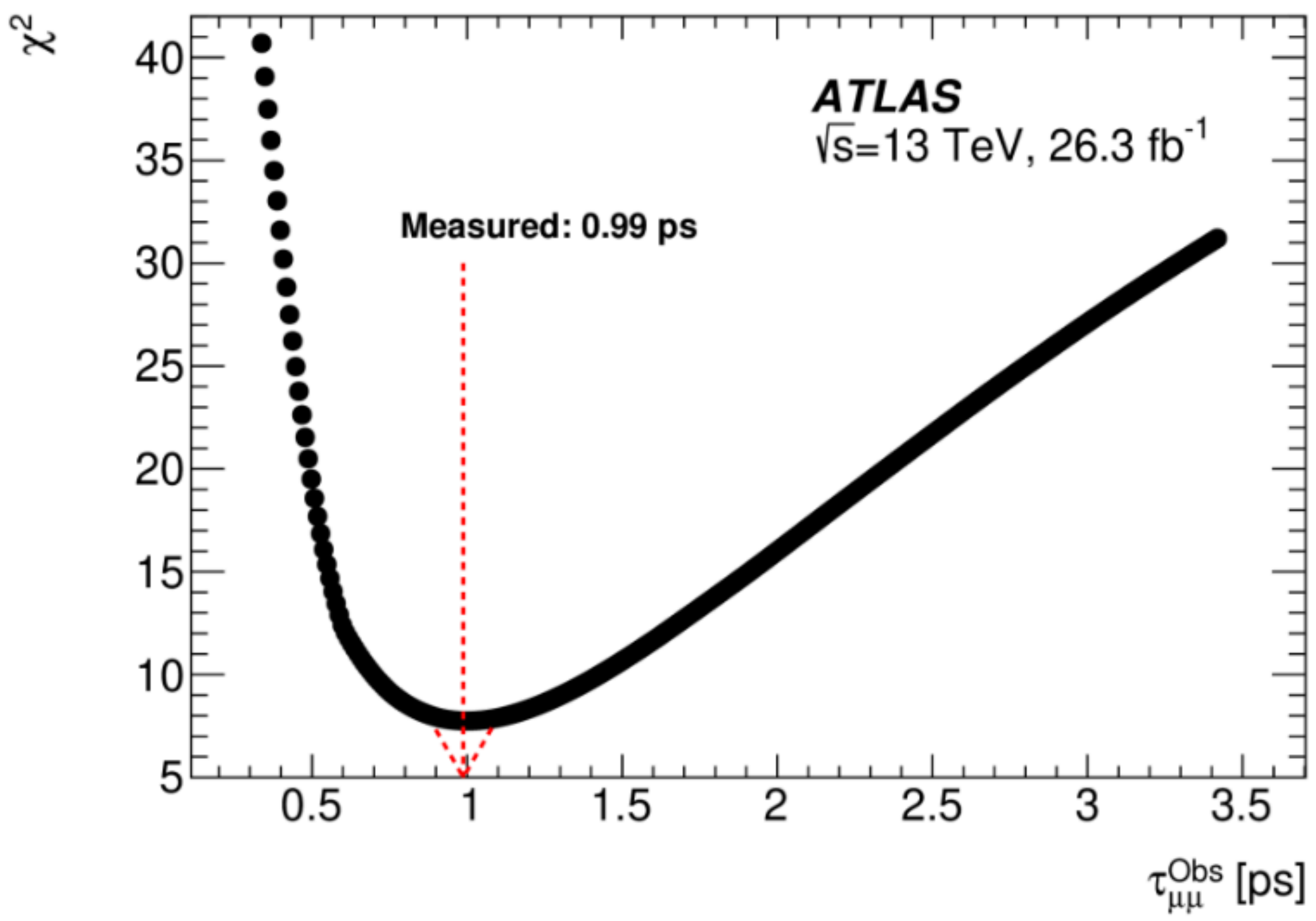
- First! $\tau_{\mu\mu}$ measurement corresponding to 2015 + 2016 pp data (26.3 fb^{-1})
- Background-subtracted decay time is fit with simulated templates
- Data-MC χ^2 scan with several lifetime hypothesis

$$\tau_{\mu\mu} = [0.99^{+0.42}_{-0.07}(\text{stat}) \pm 0.17(\text{syst})]\ \text{ps}$$

consistent with SM prediction of $\tau_{B_s^0,H} = 1.624 \pm 0.009$ ps.







- see talk from Z.Wang