Global analysis of D mixing data and determination of the CKM angle γ

Update from the UT*fit* collaboration

42^{nd} International Conference on High Energy Physics (ICHEP), Prague, 20/07/2024

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on behalf of the UT*fit* collaboration

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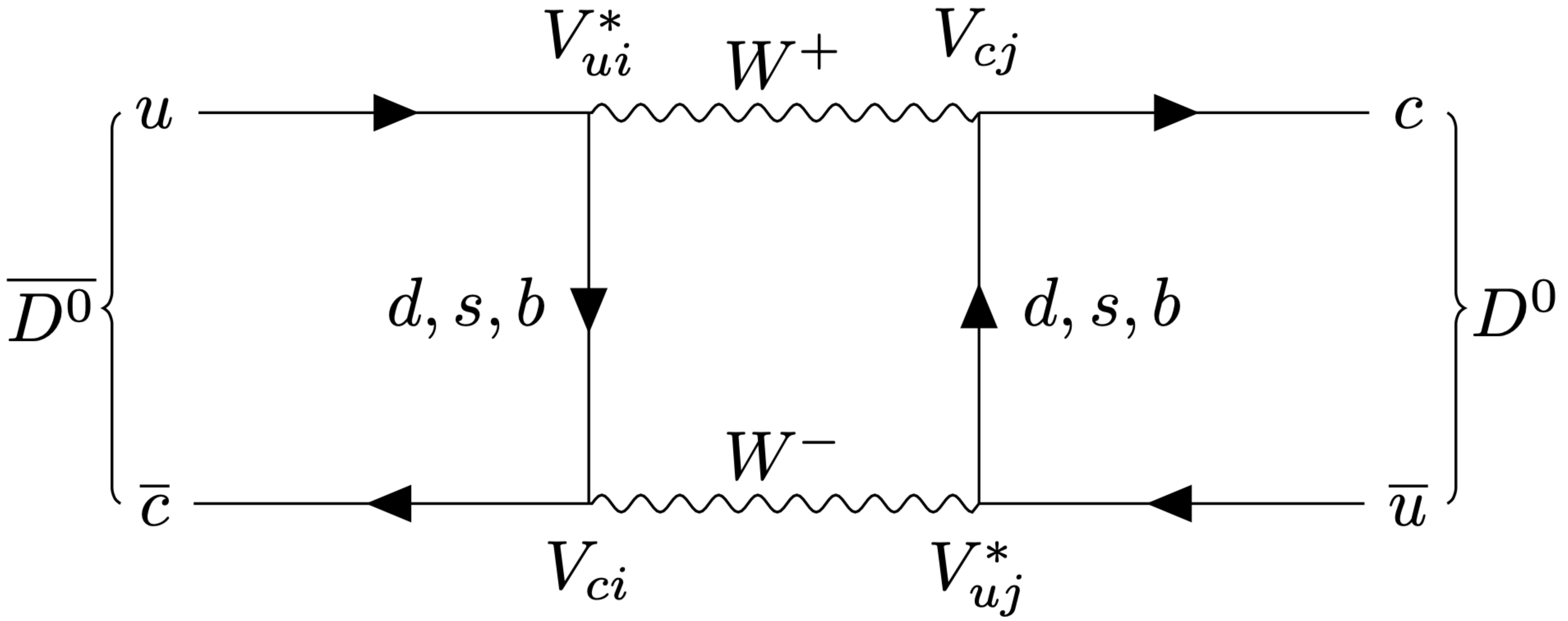
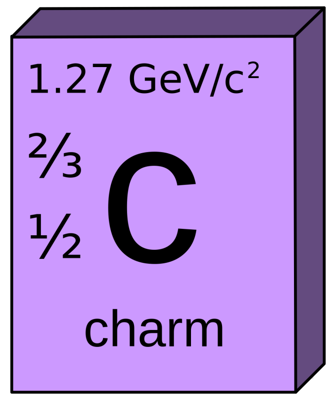
Why charm mixing?

- NO FCNC at the tree-level in the SM



FCNC LEGACY

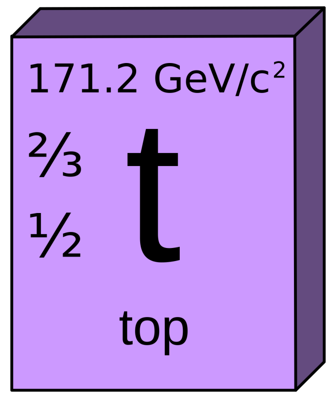


Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

(Received 5 March 1970)



Mass of the top quark and induced decay and mixing of neutral *B* mesons

Bruce A. Campbell and Patrick J. O'Donnell

Department of Physics and Scarborough College, University of Toronto, West Hill, Ontario, Canada M1C 1A4

(Received 22 May 1981)

- GIM-like search for heavy new physics (NP) coupled to up-type quarks

- Increase in the experimental precision

CP-conserving parameters

$$\mathbf{H} = \mathbf{M} - i/2\,\mathbf{\Gamma}$$

- **Dispersive part: $\mathbf{M}$**

$$x_{12} = \frac{2\,|M_{12}|}{\Gamma} \simeq \frac{|m_S - m_L|}{\Gamma}$$

- **Absorptive part: $\mathbf{\Gamma}$**

$$y_{12} = \frac{|\Gamma_{12}|}{\Gamma} \simeq \frac{|\Gamma_S - \Gamma_L|}{2\Gamma}$$

CP-violating parameters

- **CPV in pure mixing** A. Kagan, M. D. Sokoloff Y. Grossman, Y. Nir, G. Perez

$$\overline{D^0} \underset{H_{21}}{\overset{H_{12}}{\rightleftarrows}} D^0 \qquad |H_{12}| \neq |H_{21}| \;\Rightarrow\; \boxed{\phi_{12} = \arg \frac{M_{12}}{\Gamma_{12}} \neq 0}$$

- **CPV in the interference between mixing and decay**

$$\lambda_f^M,\ \lambda_f^\Gamma :\quad \begin{tikzcd} D^0 \arrow[r, "{M_{12},\ \Gamma_{12}}"] \arrow[rr, bend right, "\mathcal{A}_f"'] & \overline{D^0} \arrow[r, "\overline{\mathcal{A}}_f"] & f \end{tikzcd}$$

$$\phi_f^M = \arg \lambda_f^M + \arg \lambda_{\bar{f}}^M \neq 0$$
$$\phi_f^\Gamma = \arg \lambda_f^\Gamma + \arg \lambda_{\bar{f}}^\Gamma \neq 0$$

$$\phi_{12} = \phi_f^M - \phi_f^\Gamma$$

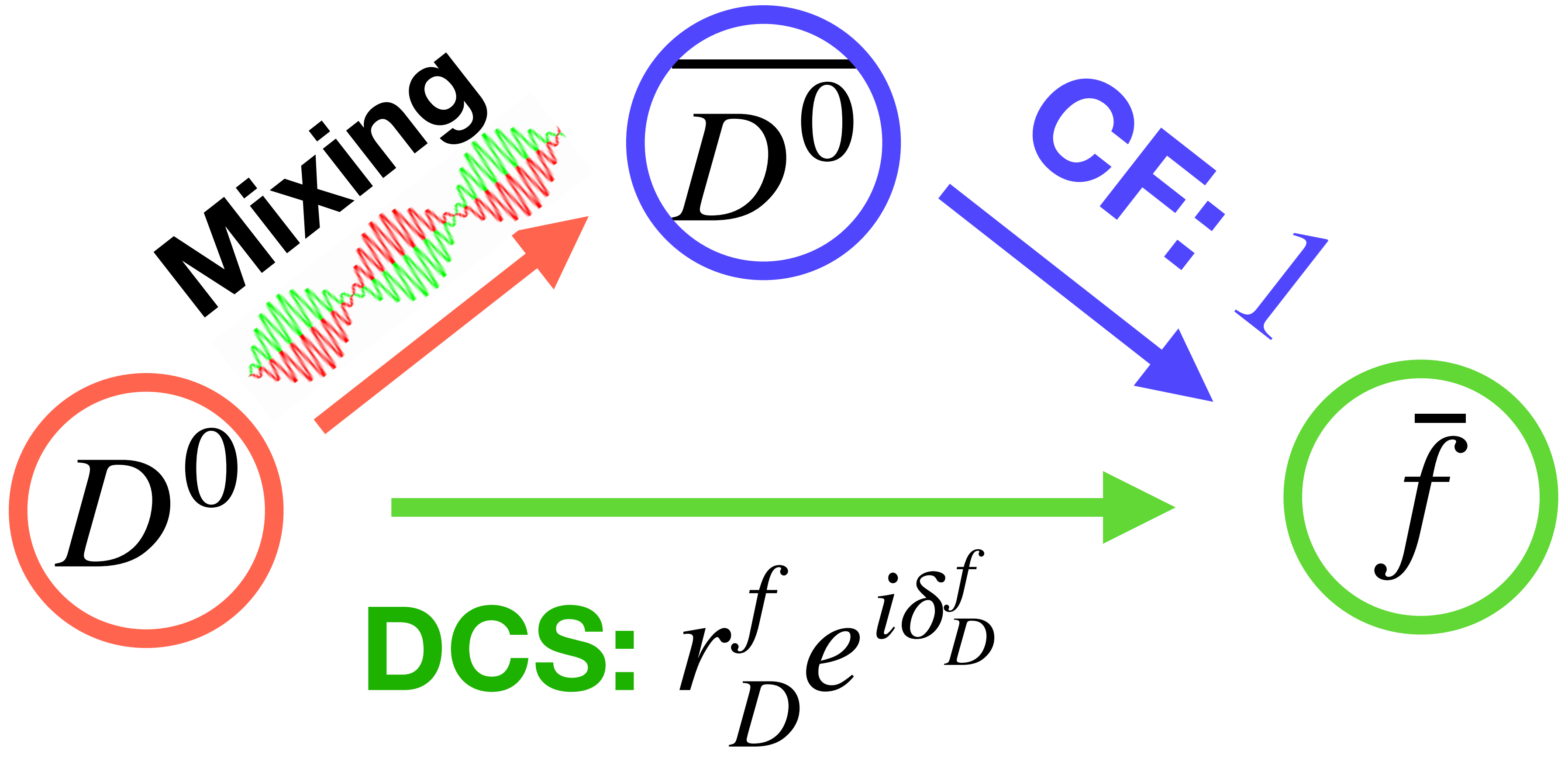
Measuring CPV: WS/RS ratios

- Exploiting CF/DCS decays of the D mesons (e.g. $f = K^-\pi^+$)

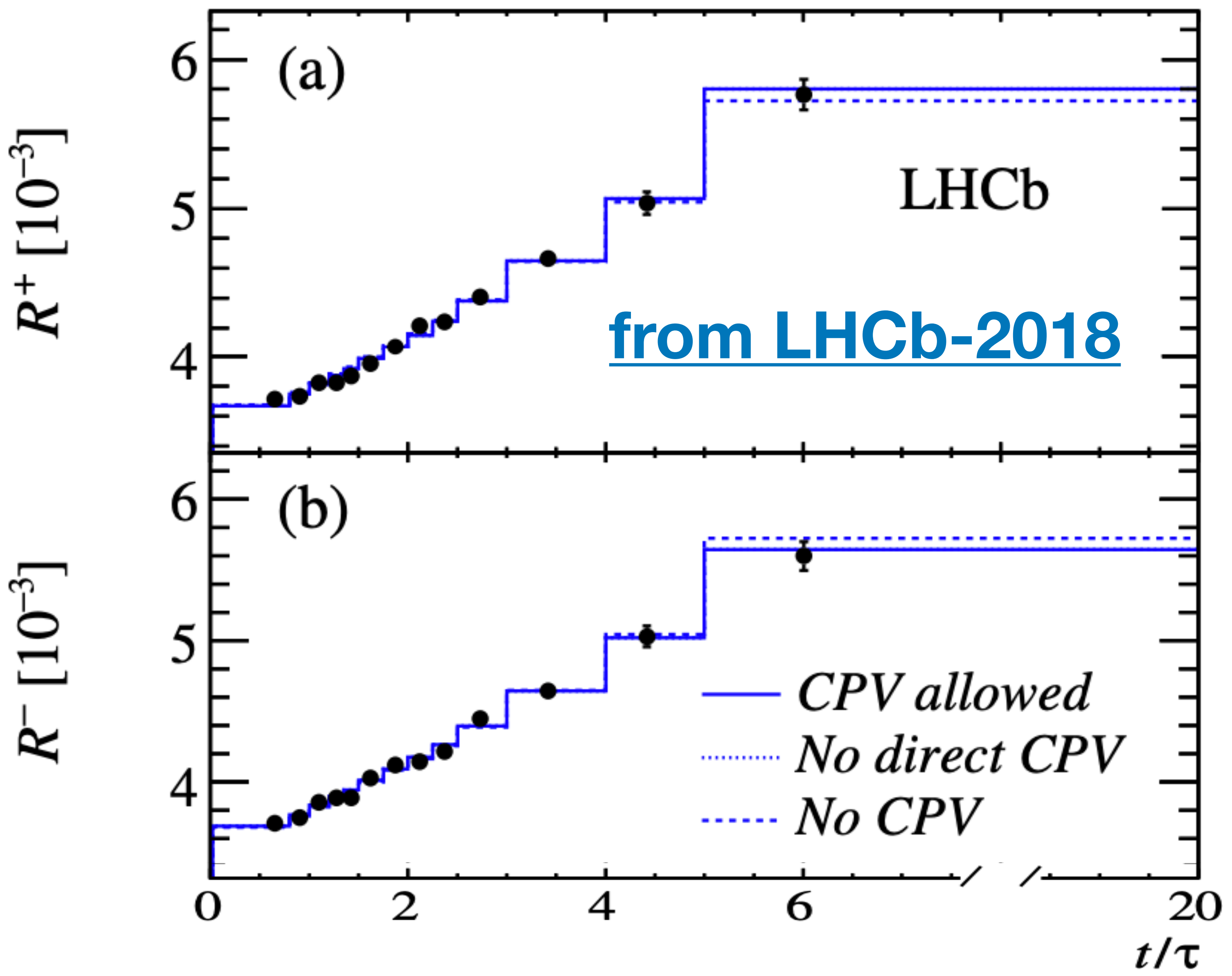
RS

$$D^0 \xrightarrow{\text{CF: } 1} f$$

WS



- Fitting the time-dependent WS/RS ratios



$$WS/RS = (r_D^f)^2 + r_D^f L^{\pm} t/\tau + Q_f^{\pm}(t/\tau)^2$$

UNTIL NOW

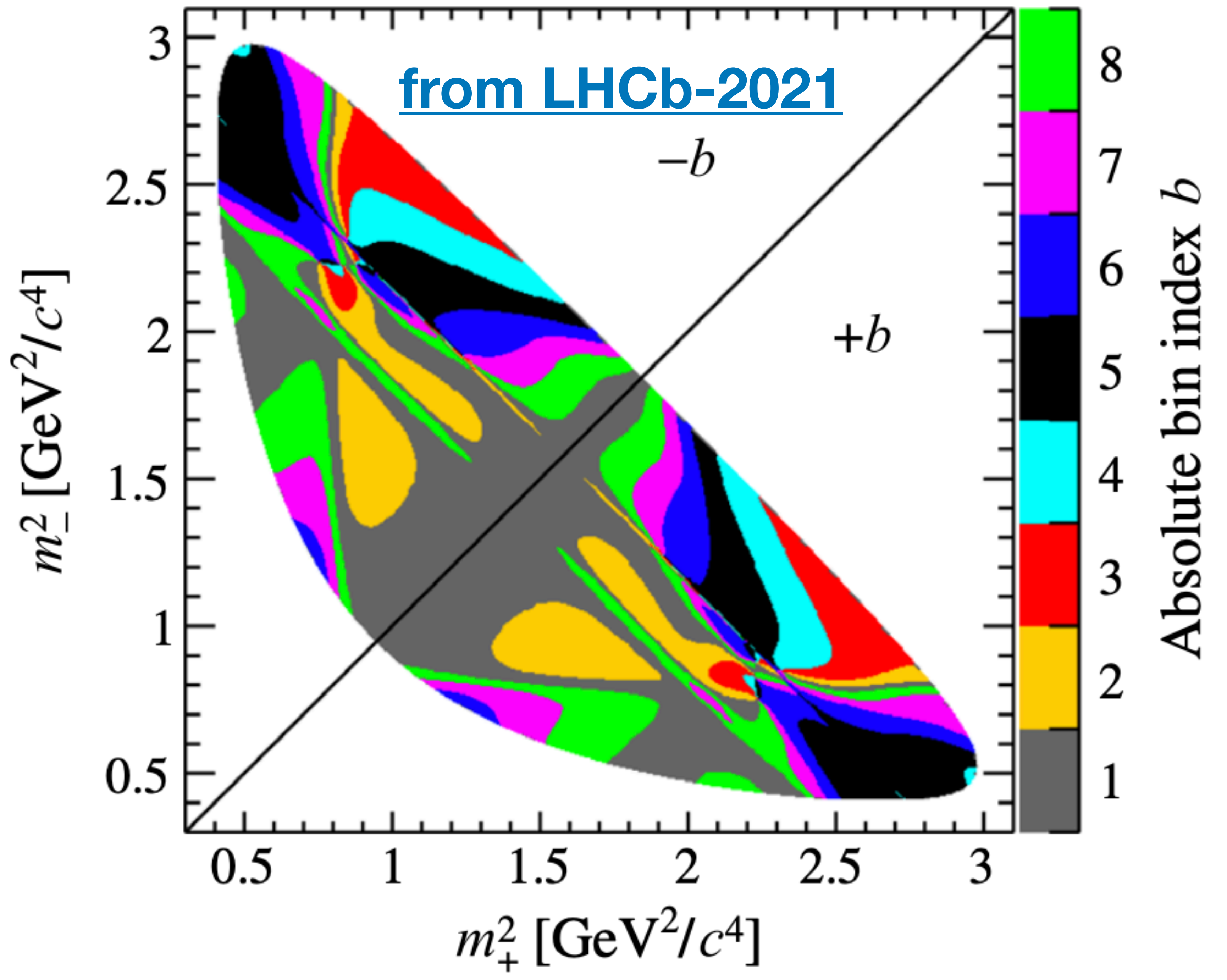
$$L^{\pm}(x_{12}, y_{12}, \phi_f^{M,\Gamma})$$
$$Q^{\pm}(x_{12}, y_{12}, \phi_f^{M,\Gamma})$$

NEW LHCb MEASUREMENT

$$L^{\pm}(x_{12}, y_{12}, \phi_f^{M,\Gamma}) = c_f^{\pm} \pm \Delta c_f^{\pm}$$
$$Q^{\pm}(x_{12}, y_{12}, \phi_f^{M,\Gamma}) = c_f'^{\pm} \pm \Delta c_f'^{\pm}$$

Measuring CPV: three-body decays

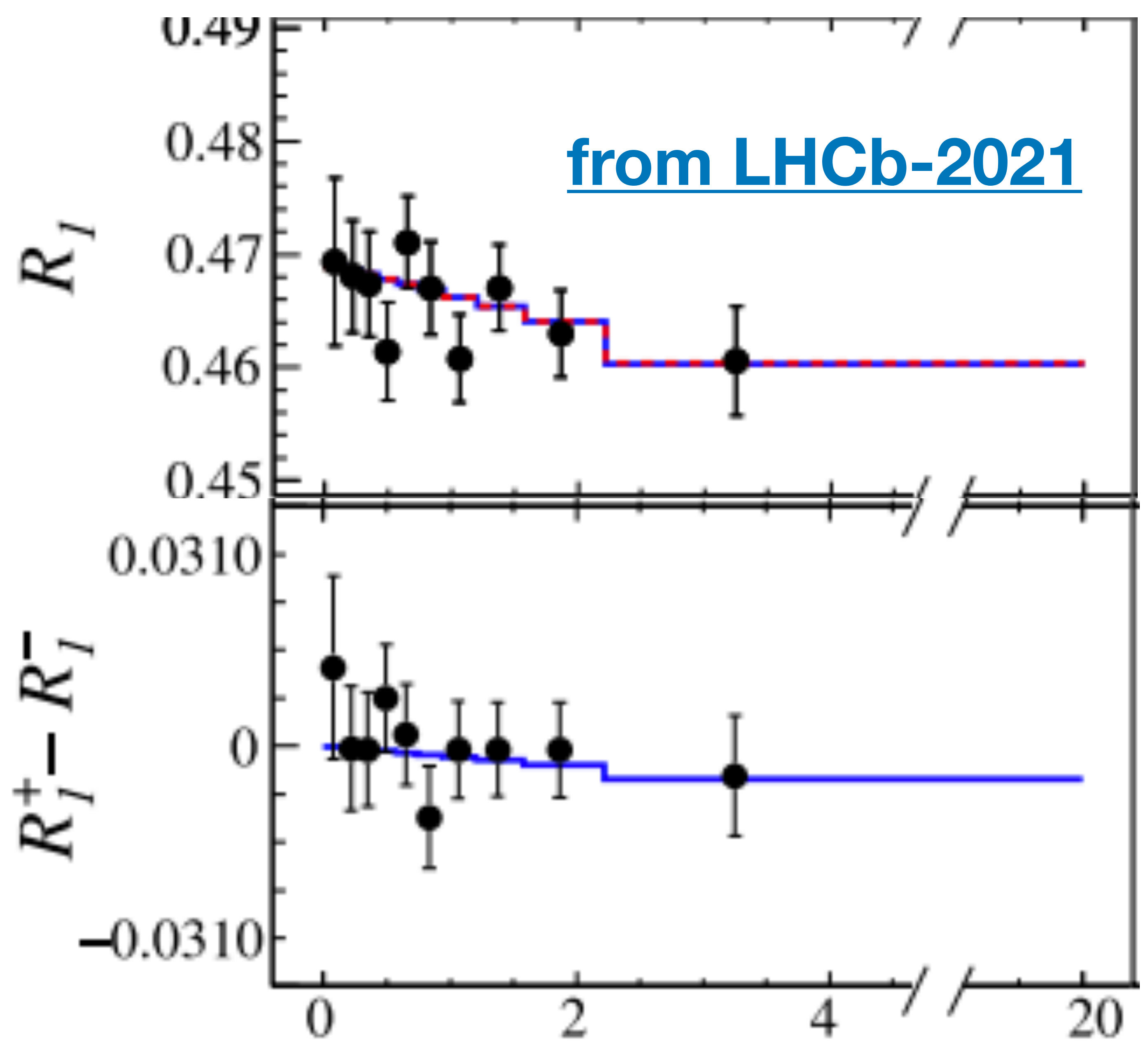
- Model-independent analysis of the 2D phase space of $D \to K_S^0\pi^+\pi^-$



Measuring CPV: three-body decays

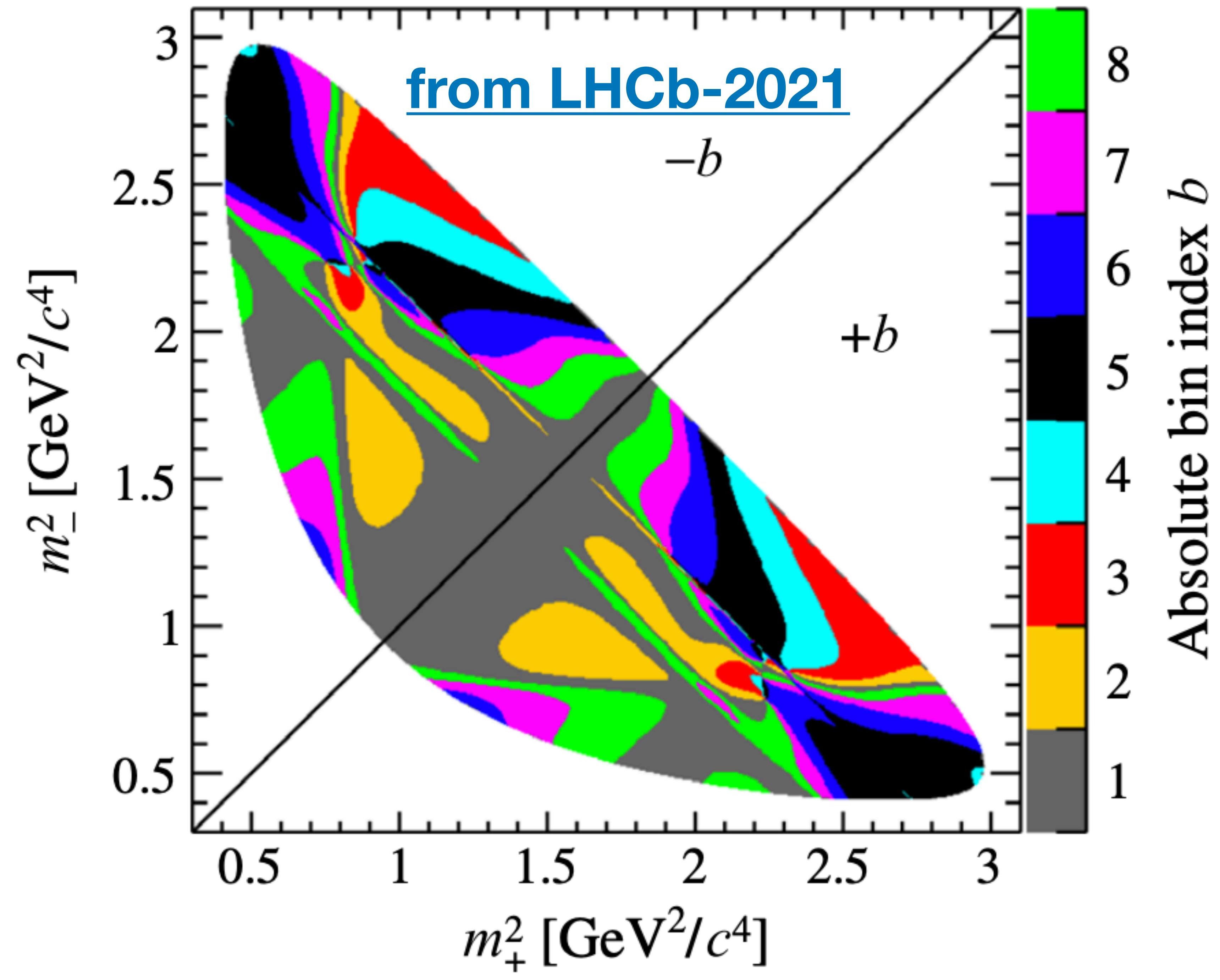
- Model-independent analysis of the 2D phase space of $D \to K^0_S \pi^+ \pi^-$

- WS/RS-like analysis $$R^{\pm}_{ij} = \frac{d\Gamma_{\mp ij}\left(\overset{(-)}{D^0} \to f\right)}{d\Gamma_{\pm ij}\left(\overset{(-)}{D^0} \to f\right)}$$



CP-conserving observables!!

$$x^f_{CP} = x_{12}\cos(\phi^M_f)$$
$$y^f_{CP} = y_{12}\cos(\phi^\Gamma_f)$$



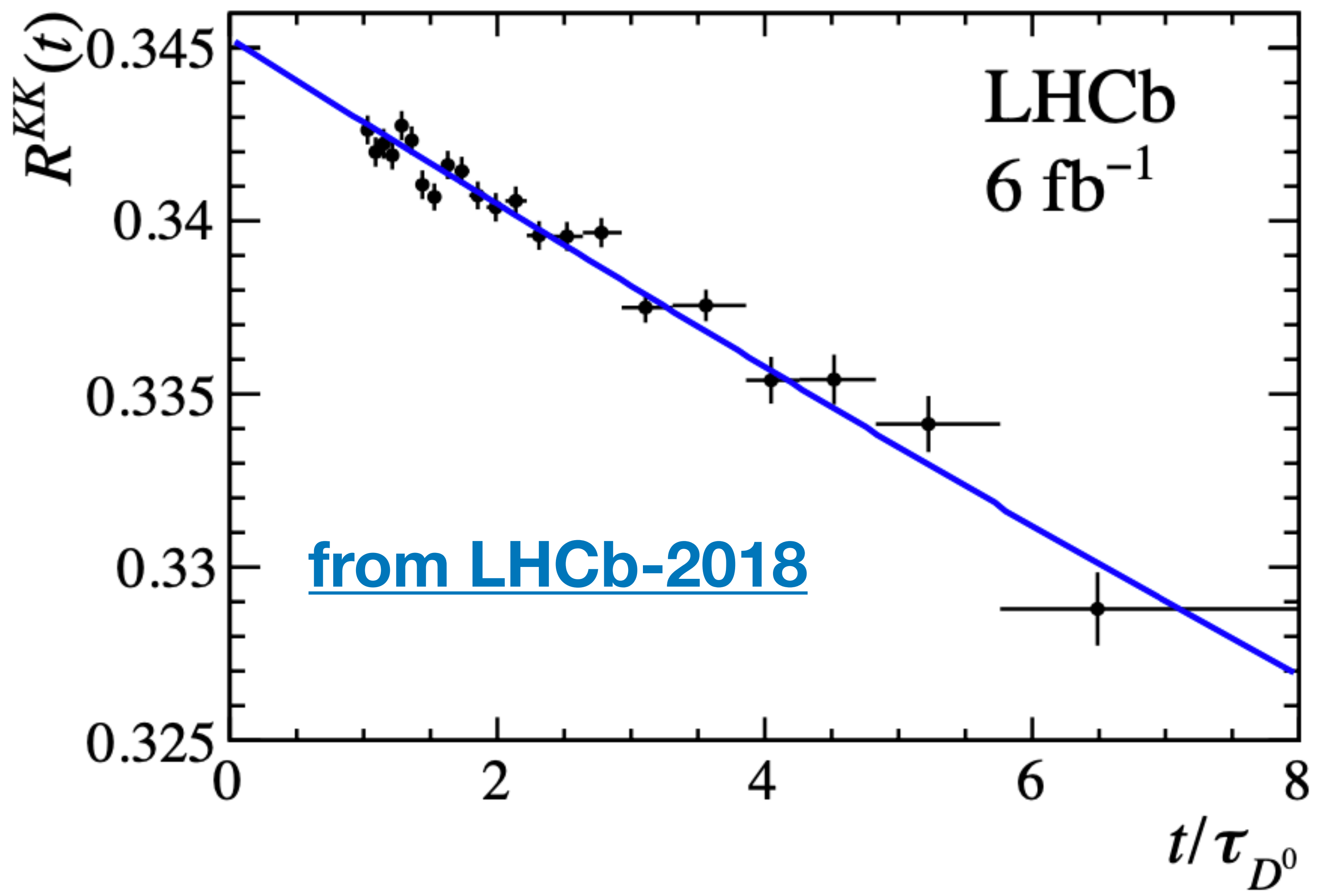
CPV observables!!

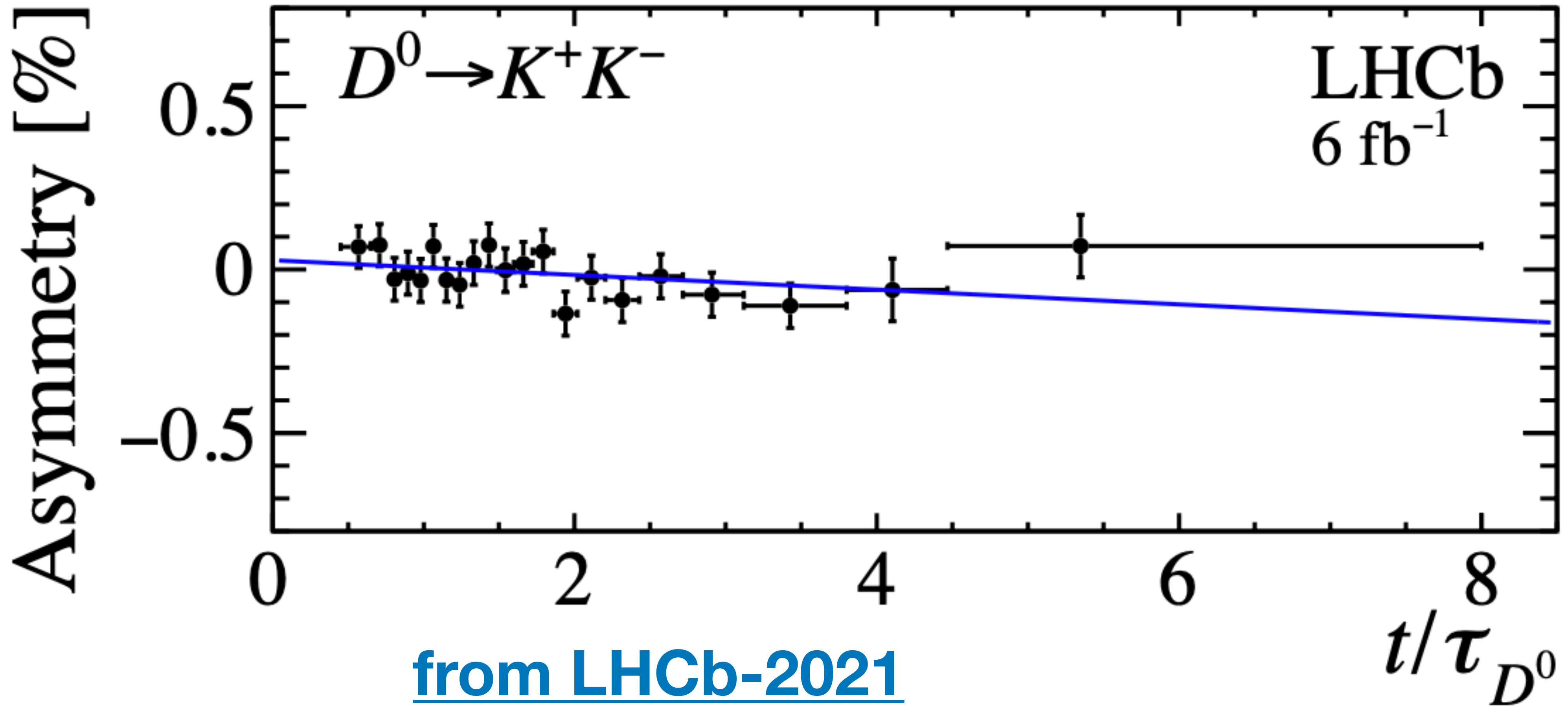
$$\Delta x^f = -y_{12}\sin(\phi^\Gamma_f)$$
$$\Delta y^f = x_{12}\sin(\phi^M_f)$$

Measuring CPV: SCS decays to CP eigenstates

- Time-dependent **CP-conserving** ratio

$$R^f(t) = \frac{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to K^-\pi^+) + \Gamma(\overline{D^0} \to K^+\pi^-)} \propto 1 - \tilde{y}^f_{CP} t/\tau$$





- Time-dependent **CP-violating** ratio

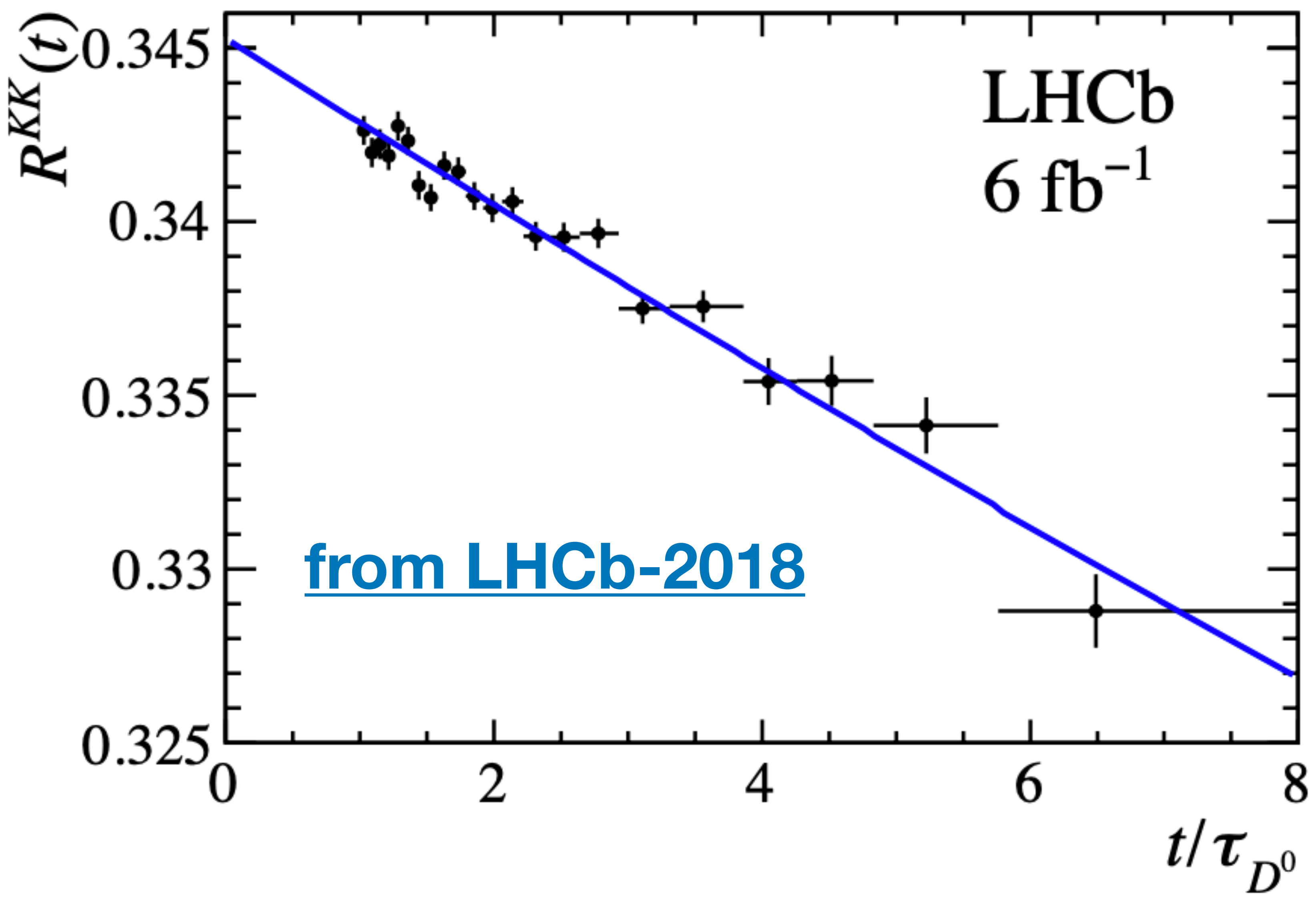
$$A_f(t) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)} = a_f + \Delta Y_f t/\tau$$

Measuring CPV: SCS decays to CP eigenstates

- Time-dependent **CP-conserving** ratio

$$R^f(t) = \frac{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to K^-\pi^+) + \Gamma(\overline{D^0} \to K^+\pi^-)} \propto 1 - \tilde{y}^f_{CP} t/\tau$$

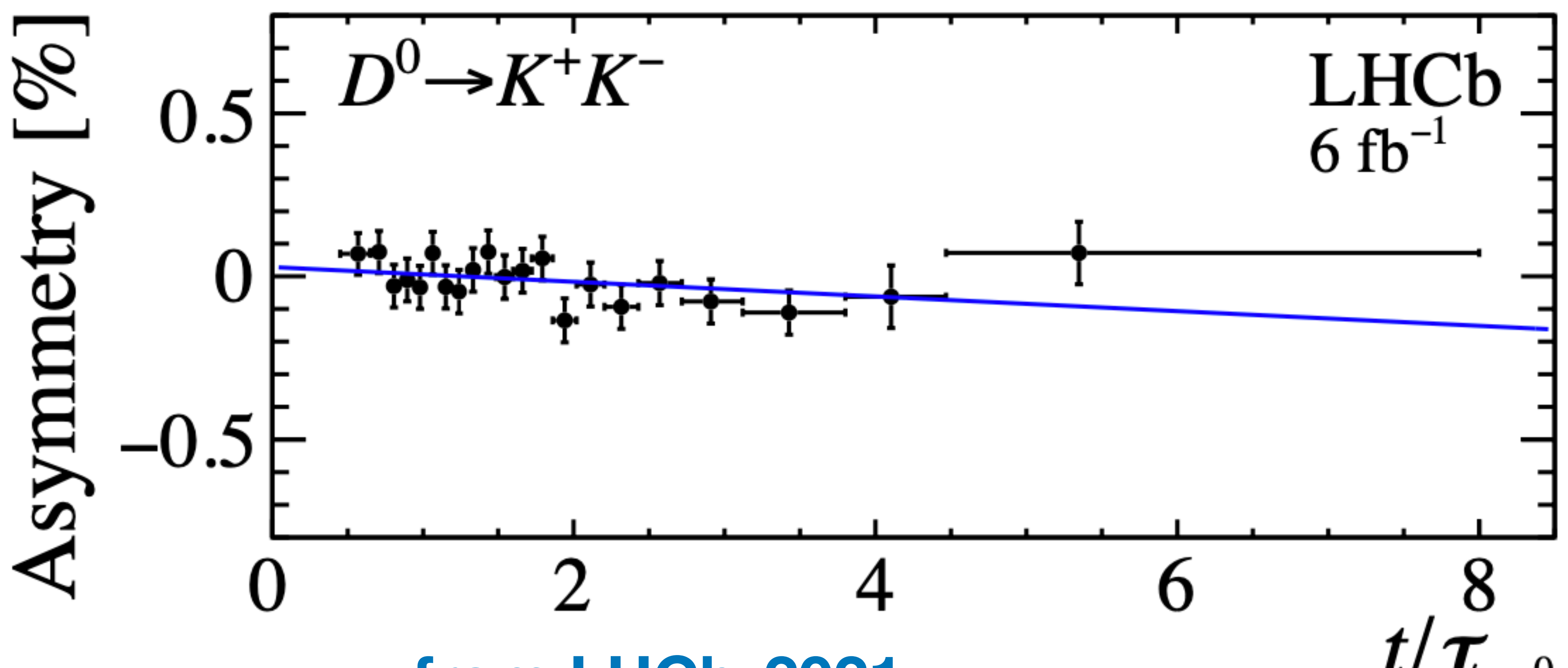
$\tilde{y}^f_{CP}(x_{12}, y_{12}, \phi_f^{M,\Gamma})$ NO CPV: $\tilde{y}^f_{CP} \approx y_{12}$



- Time-dependent **CP-violating** ratio

$$A_f(t) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to f)} = a_f + \Delta Y_f t/\tau$$

$$\Delta Y_f = \eta_f(-x_{12}\sin(\phi_f^M) + a_f y_{12})$$



Charm parameters

Beauty observables
More information about decay and mixing parameters

- Decay amplitudes $r_D^f \quad \delta_D^f$

Introduced by LHCb-2021

- Mixing parameters $x_{12} \quad y_{12}$

Approximate Universality
Dropping the final-state dependent parts of ϕ_f^M and ϕ_f^Γ

$$\phi_f^M, \phi_f^\Gamma \rightarrow \phi_{\cancel{f}}^M, \phi_{\cancel{f}}^\Gamma$$

UNIVERSAL

A. Kagan, L. Silvestrini

Approximate Universality

- Flavour structures of $\mathbf{M}$ and $\mathbf{\Gamma}$ in the SM

$$\Gamma_{12}^{SM} = \sum_{i,j=d,s} \lambda_{uc}^{i}\lambda_{uc}^{j}\Gamma_{ij} \qquad M_{12}^{SM} = \sum_{i,j=d,s,b} \lambda_{uc}^{i}\lambda_{uc}^{j}M_{ij}$$

On-shell states **Off-shell states**

- Employing the Unitarity of the CKM

Dominant

$$\Gamma_{12}^{SM} = \boxed{\frac{(\lambda_{uc}^{s} - \lambda_{uc}^{d})^2}{4}\Gamma_2} + \frac{(\lambda_{uc}^{s} - \lambda_{uc}^{d})\lambda_{uc}^{b}}{2}\Gamma_1 + \frac{(\lambda_{uc}^{b})^2}{4}\Gamma_0$$

U-spin amplitudes
$\Gamma_n \approx \mathcal{O}(\epsilon^n)$

Approximate Universality

- **CPV phases** w.r.t. the dominant contribution in the SM

$$\phi_2^\xi = \arg\left[\frac{\xi_{12}}{\xi_2(\lambda_{uc}^s - \lambda_{uc}^d)^2/4}\right], \ \xi = M, \Gamma$$

SM +
Possible **NP**

- **Approximate universality** $\phi_2^{M,\Gamma} \approx \phi_f^{M,\Gamma} \quad \forall f$

- U-spin estimate

$$(\phi_2^{M,\Gamma})^{U-spin} \approx 0.13°$$

Short-distance NP signal

$$\phi_2^M > \phi_2^\Gamma \simeq (\phi_2^\Gamma)^{U-spin}$$

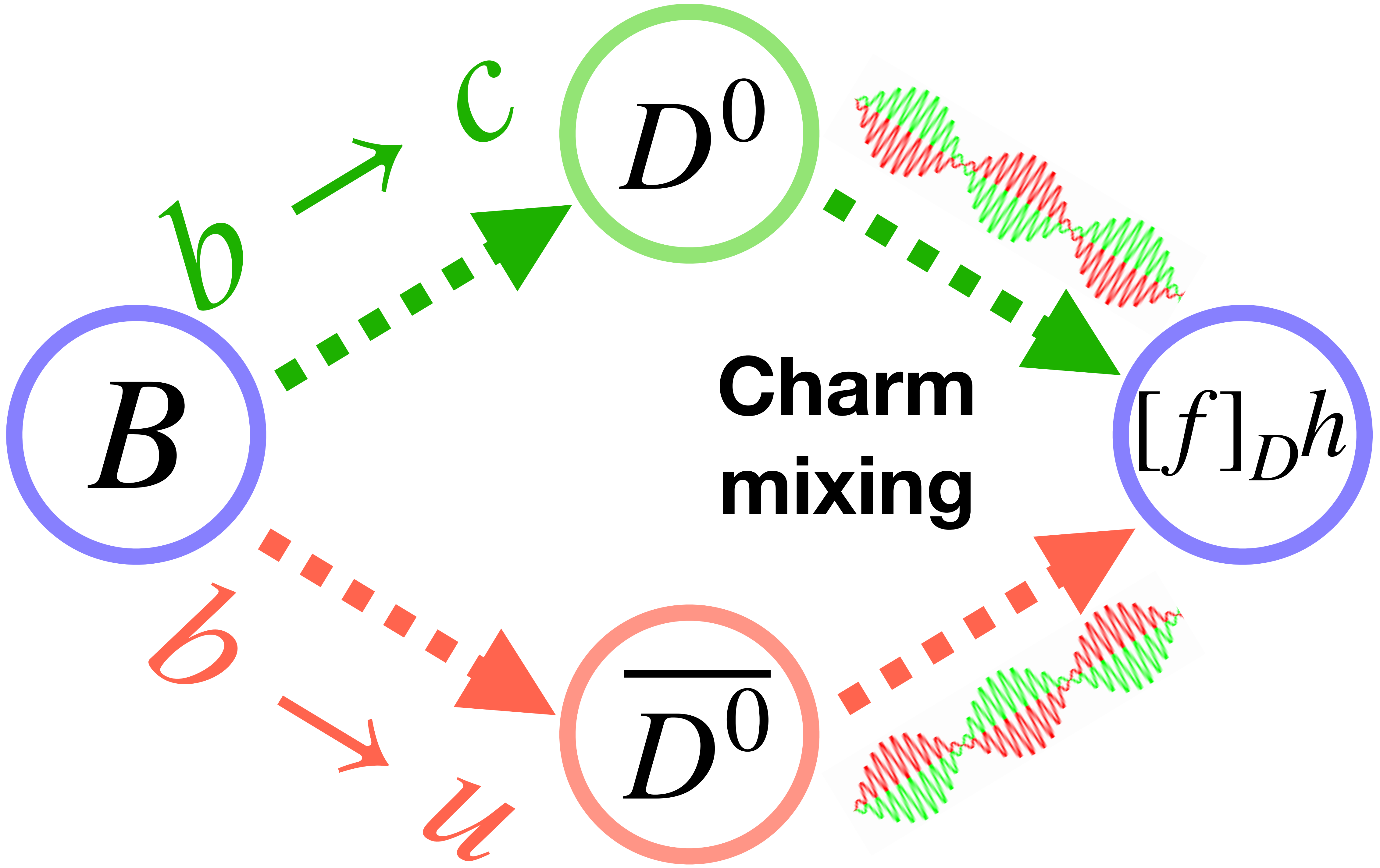
B Cascade decays

- $B \to D$ decays:

CKM ANGLE

$$\gamma = \arg - \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- D mixing + $D \to f$ decays: $r_D^f e^{-i\delta_D^f}$



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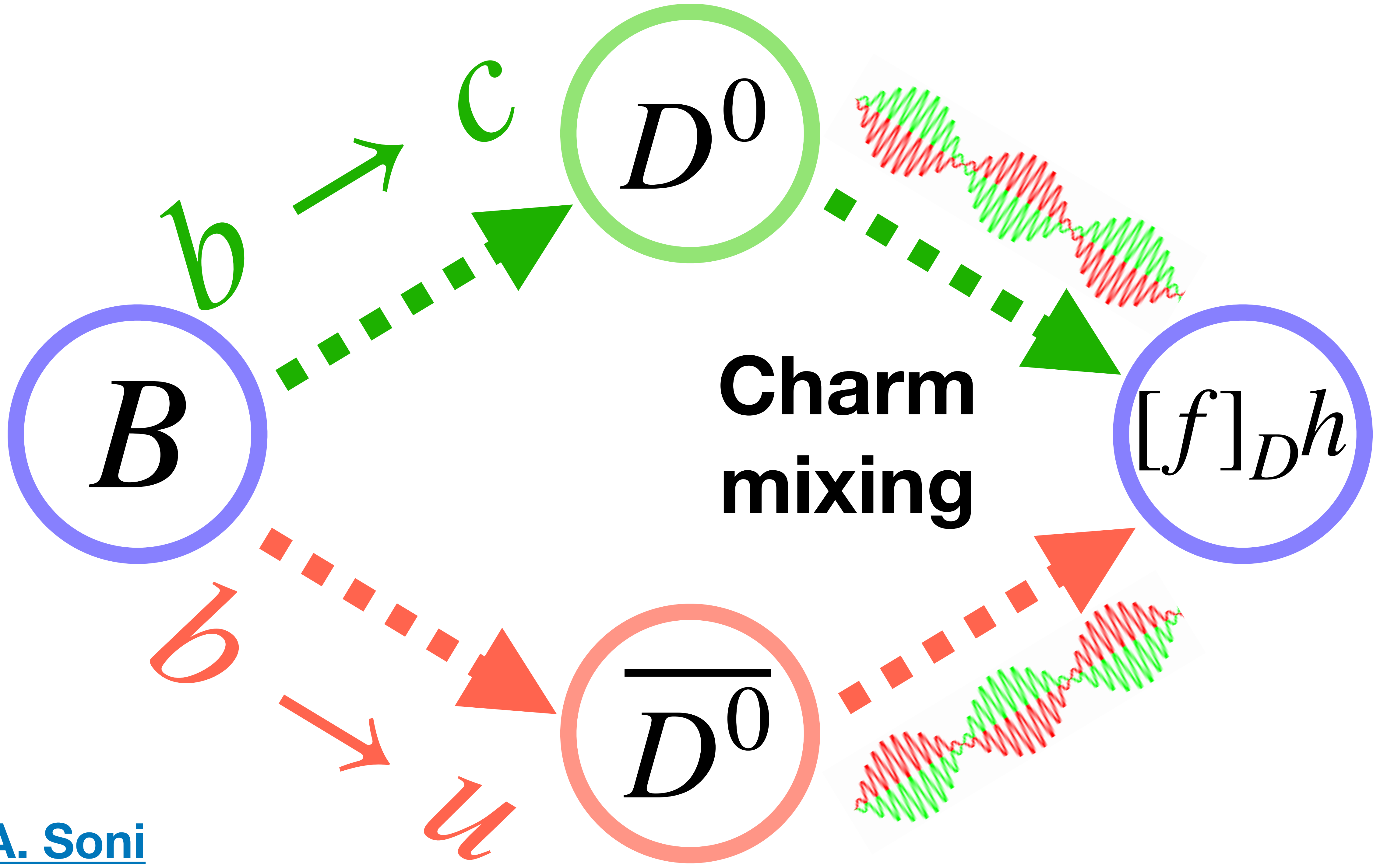


- **GLW/ADS Observables**

M. Gronau, D. Wyler, M. Gronau, D. London, D. Atwood, I. Dunietz, A. Soni

$$\Gamma(B \to [f]_D h) - \Gamma(\overline{B} \to [\bar{f}]_D \bar{h}) \propto \sin\gamma$$

- **GGSZ Observables** Study of the phase-space dependent decay rates for $f = K_S^0 K^+ K^-$, $K_S^0 \pi^+ \pi^-$, $K^+ K^- \pi^+ \pi^-$

A. Giri, Y. Grossman, A. Soffer, J. Zupan

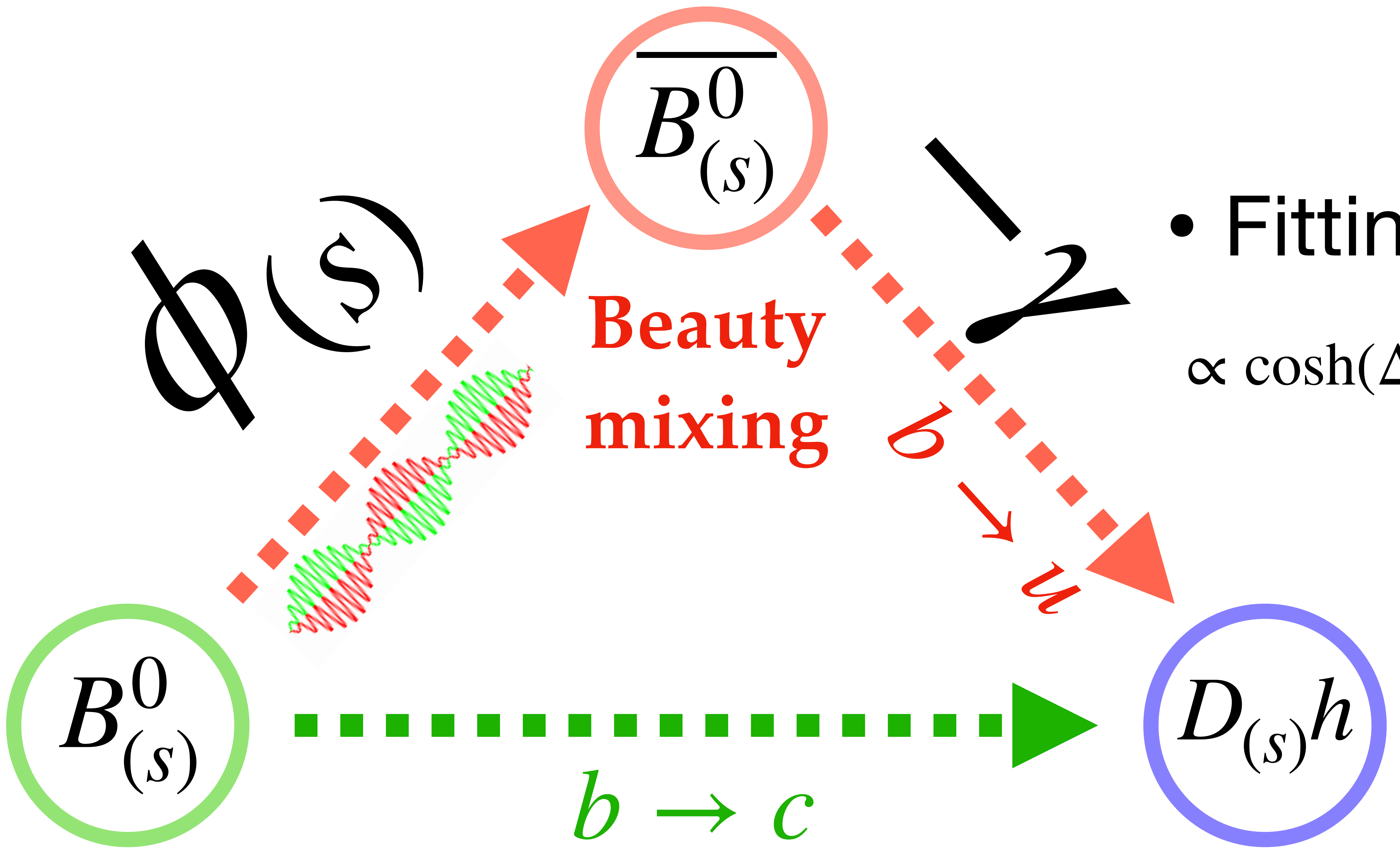
Polar Observables

$$x_\pm^{Dh} = r_B^{Dh} \cos(\delta_B^{Dh} \pm \gamma)$$
$$y_\pm^{Dh} = r_B^{Dh} \sin(\delta_B^{Dh} \pm \gamma)$$

Neutral B meson observables

- Exploiting the **CPV phase of the interference** between $B^0_{(s)}$ mixing and decay to charmed mesons $D^{\mp}_{(s)}h^{\pm}$

Mixing phases $\phi = -2\beta$ $\phi_s = 2\beta_s$



- Fitting the time-dependent decay rates

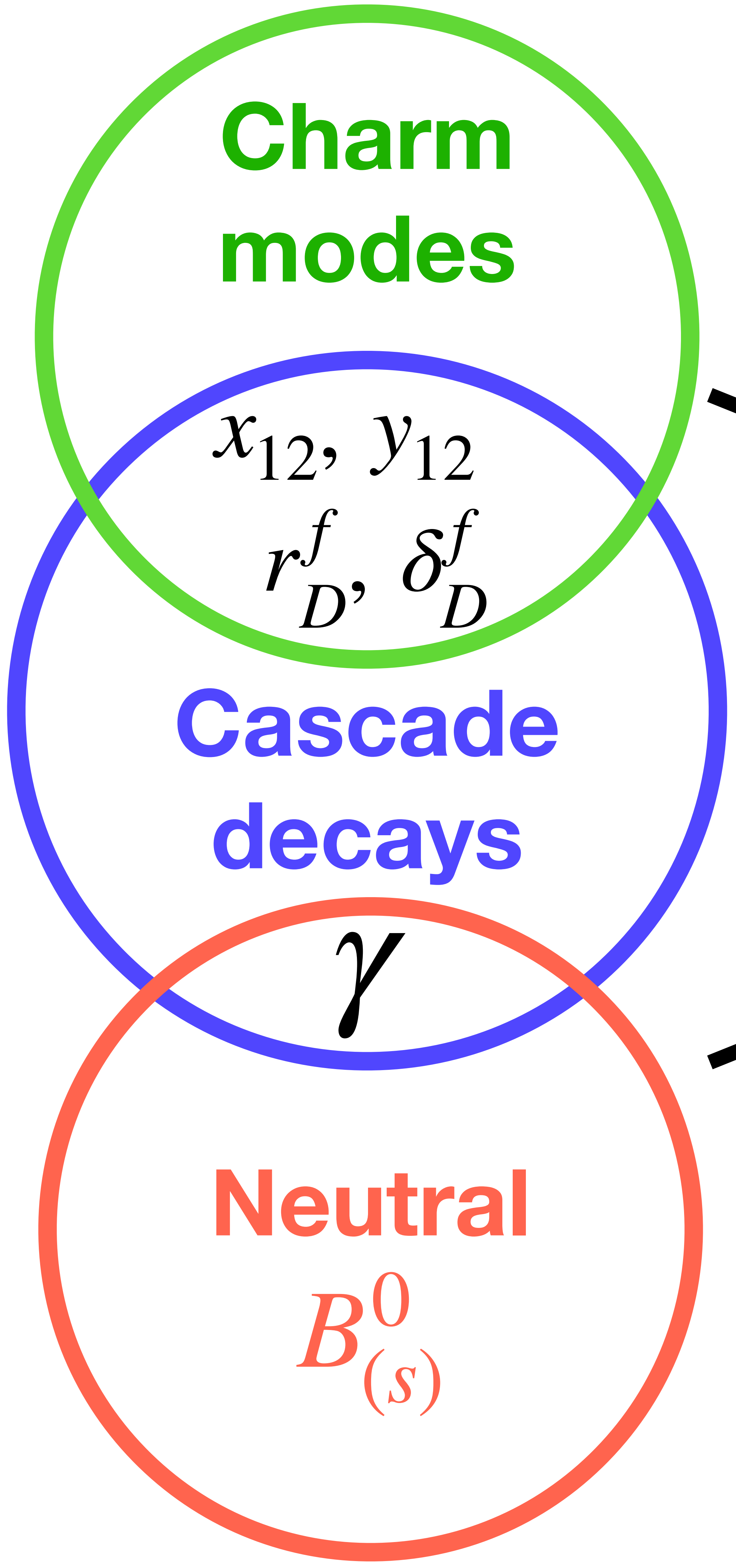
$$\propto \cosh(\Delta\Gamma_{(s)}t/2) - G_f \sinh(\Delta\Gamma_{(s)}t/2) + C_f \cos(\Delta m_{(s)}t) - S_f \sin(\Delta m_{(s)}t)$$

Observables!!

C_f $\quad G_f \propto \cos(\delta^f_{B^0_{(s)}} + (\phi_{(s)} - \gamma))$

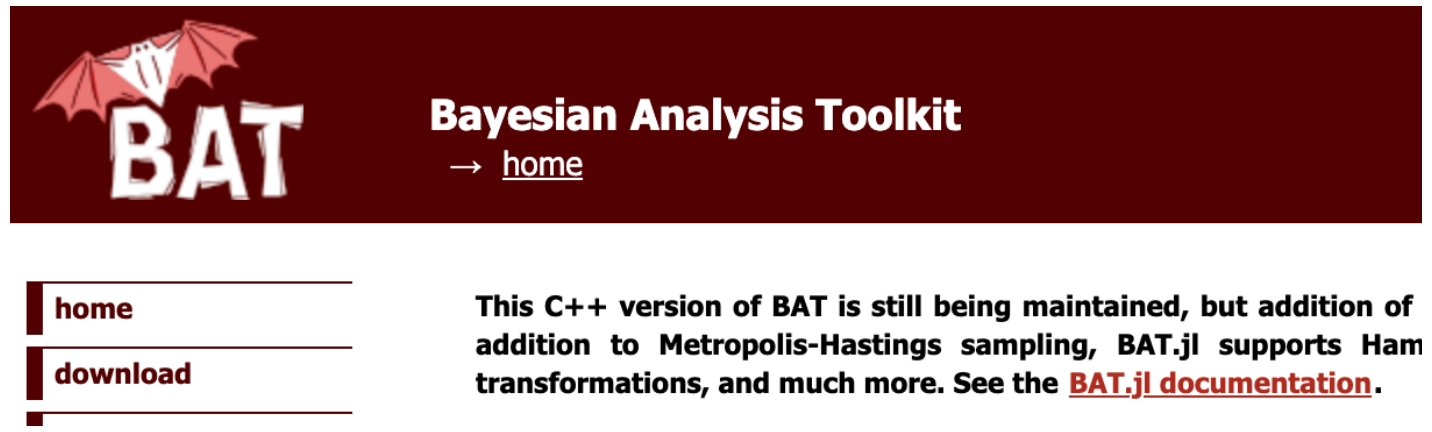
$S_f \propto \sin(\delta^f_{B^0_{(s)}} + (\phi_{(s)} - \gamma))$

Statistical treatment



Bayesian approach

MCMC Algorithm



https://bat.mpp.mpg.de/

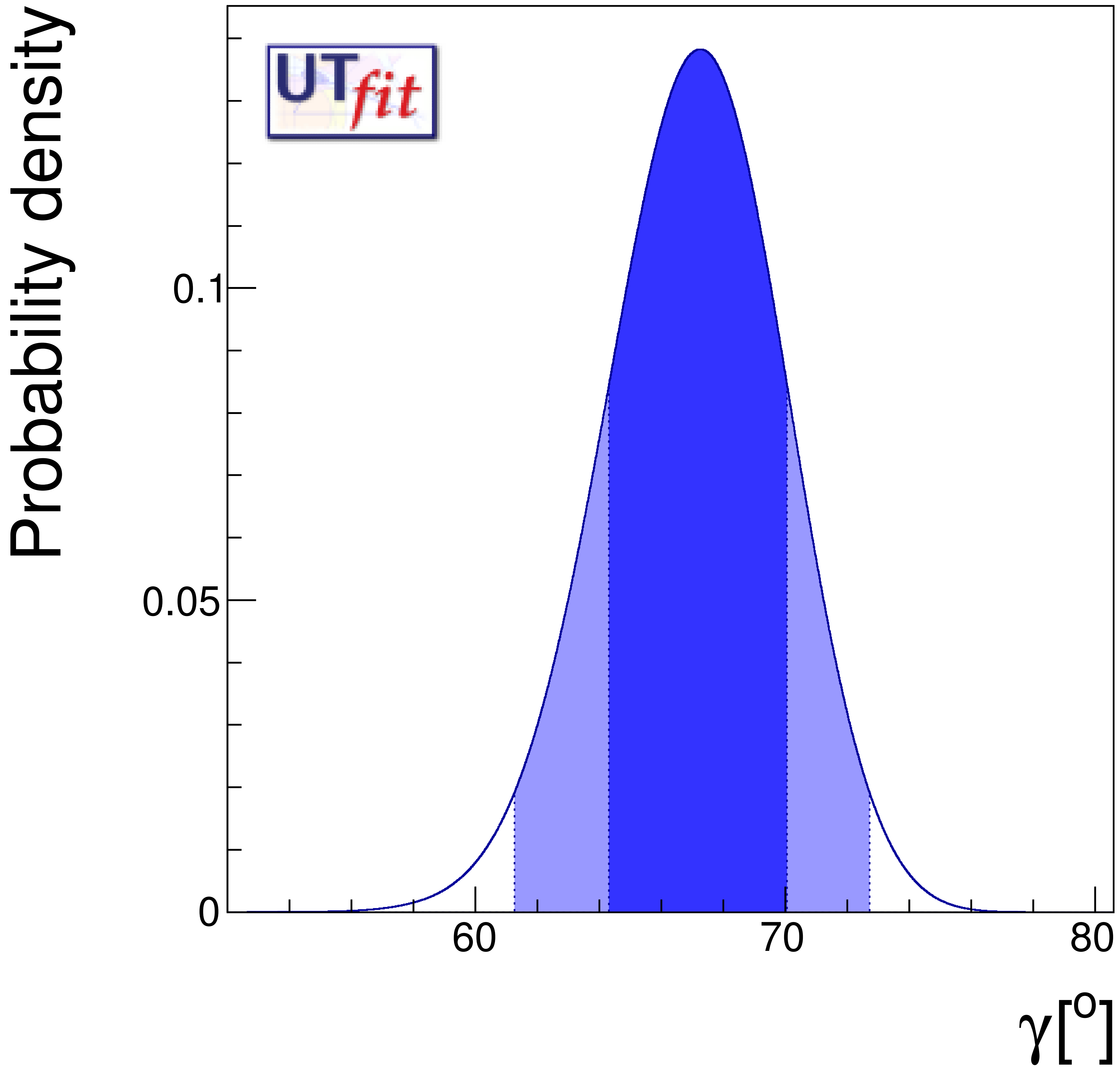
Posterior p.d.f

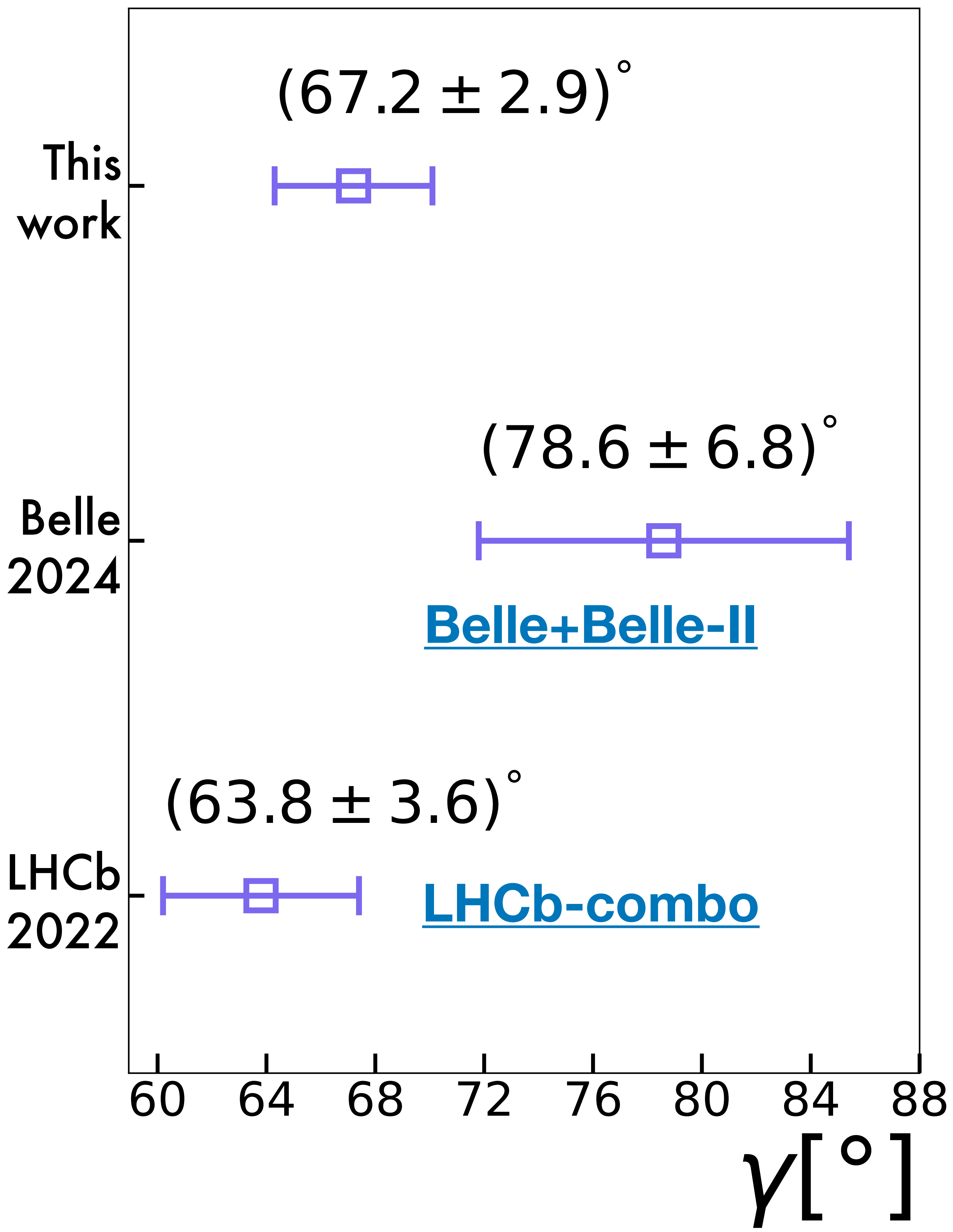
$$P(\vec{\lambda} \,|\, \mathbf{O}) \propto P(\mathbf{O} \,|\, \vec{\lambda})\, P_0(\vec{\lambda})$$

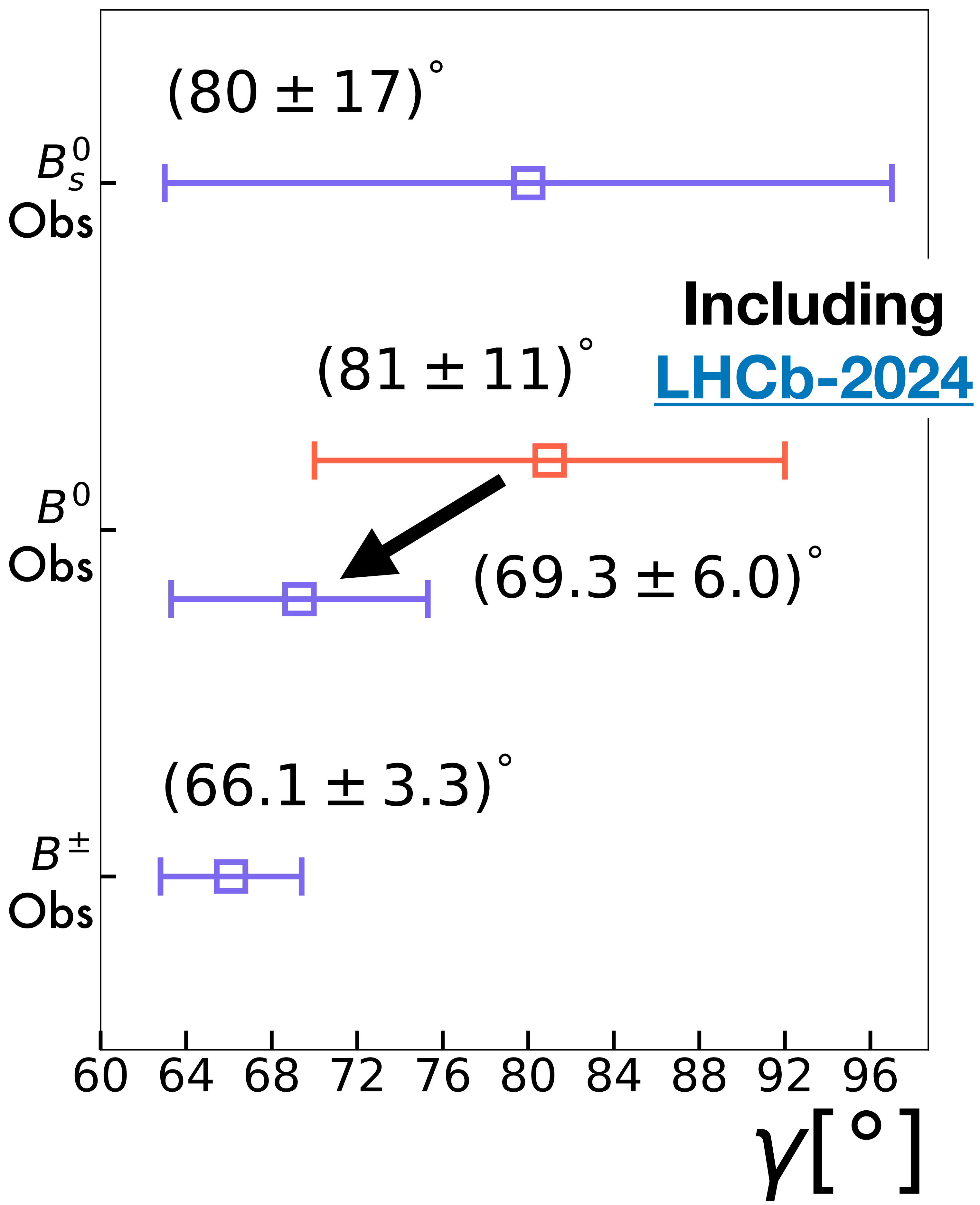
- **Gaussian likelihood:** $P(\mathbf{O} \,|\, \vec{\lambda})$
- **Flat priors:** $P_0(\vec{\lambda}) \propto \text{const}$

Results: CKM angle γ

Consistency check

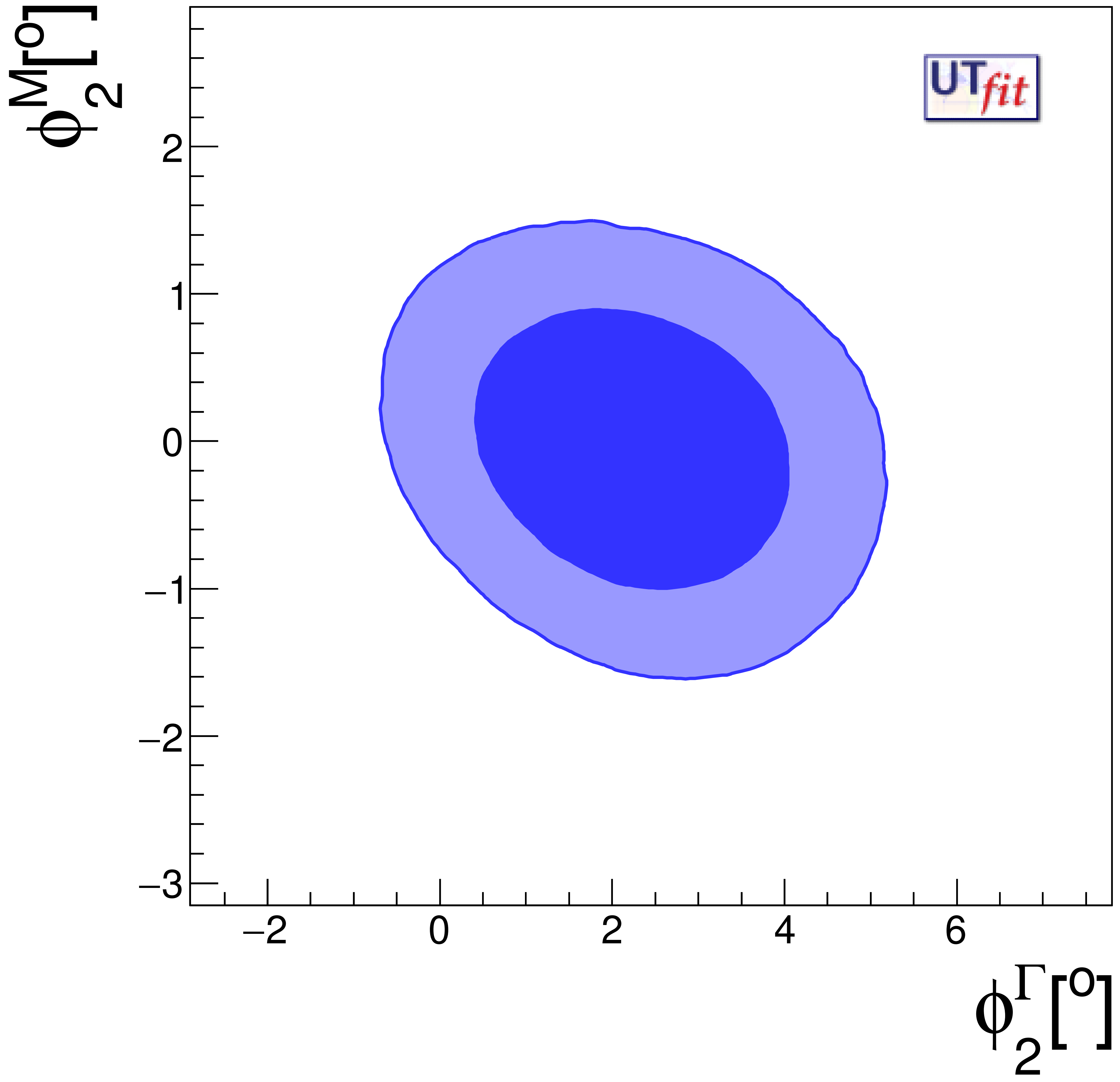


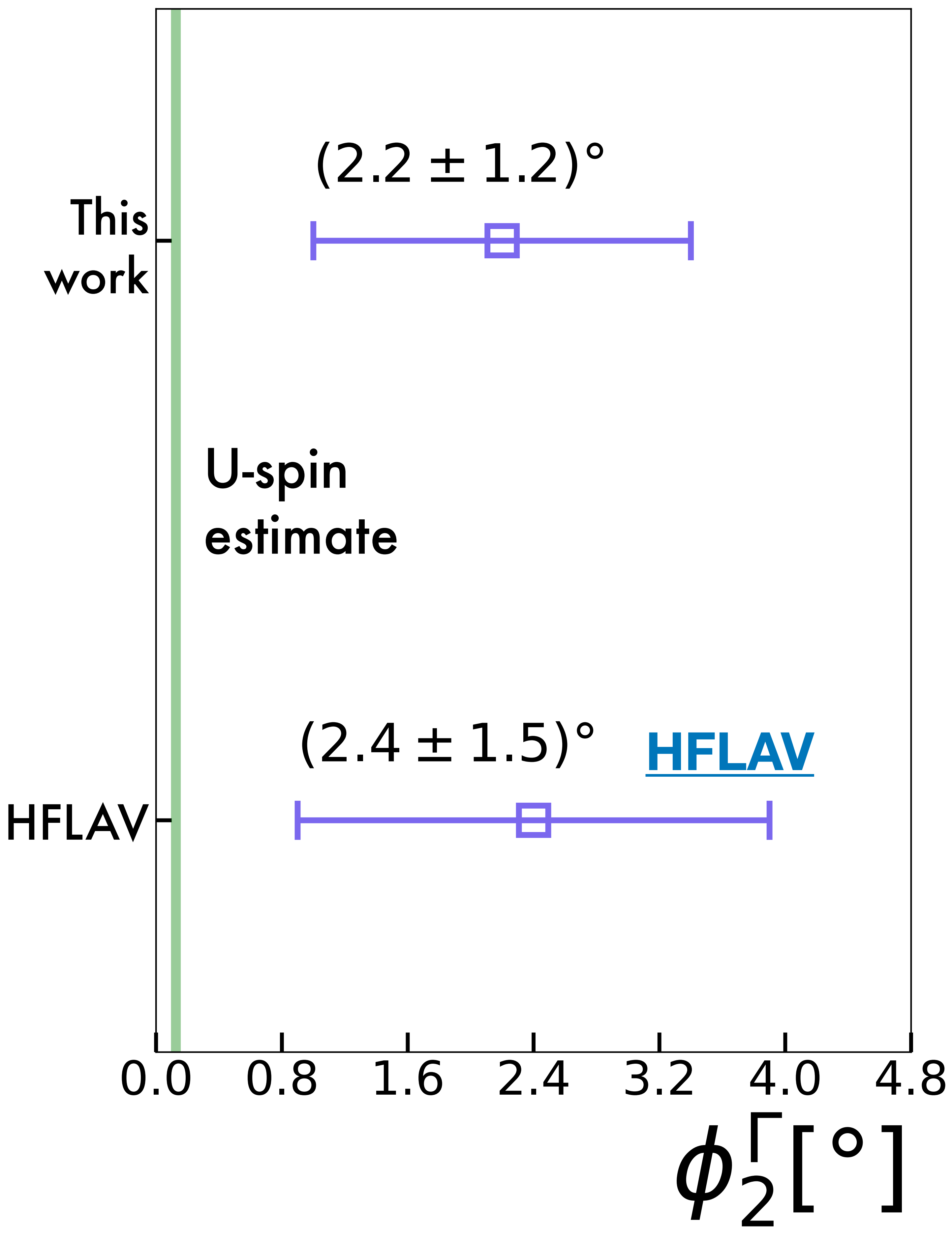


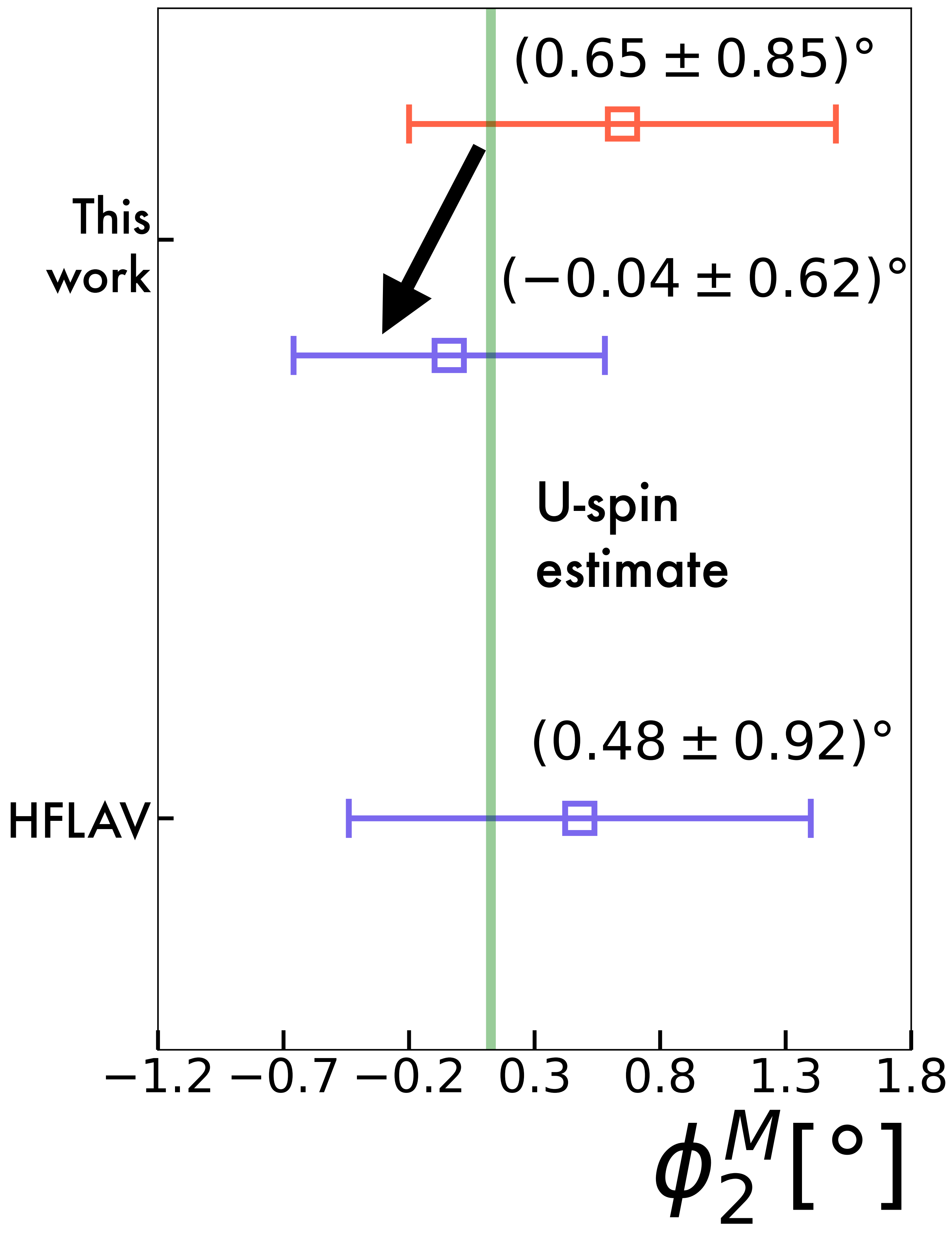


Results: CPV parameters

Including New LHCb most precise measurement of $D \to K\pi$







Summary

- CPV in charm mixing can be used as a powerful probe for **heavy NP**. In the *Approximate universality* framework

$$\phi_2^M > \phi_2^\Gamma \simeq (\phi_2^{M,\Gamma})^{U-spin} \approx 0.13^\circ$$

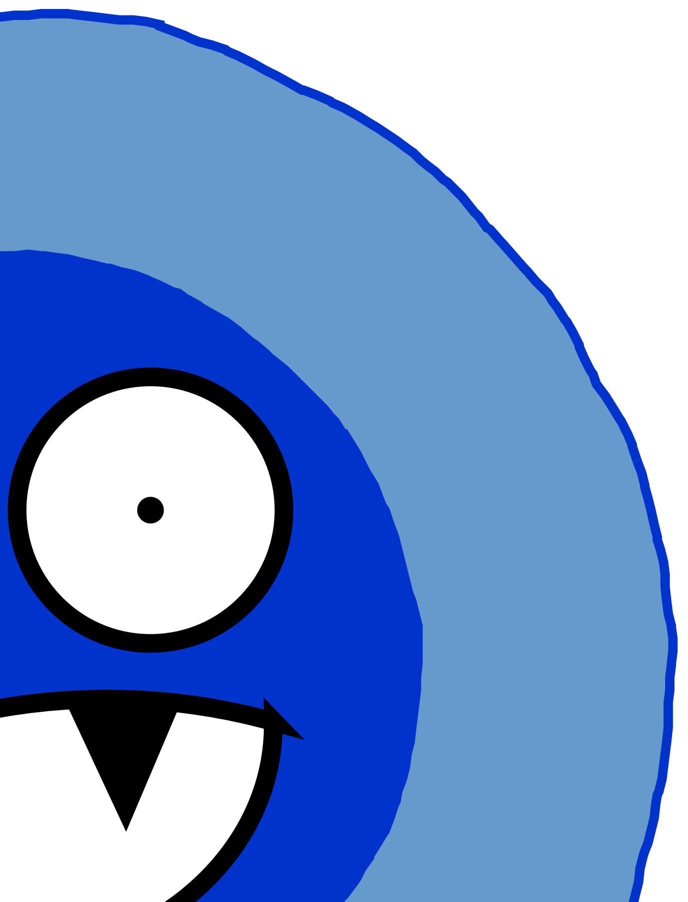
- **One order of magnitude** away from testing the SM

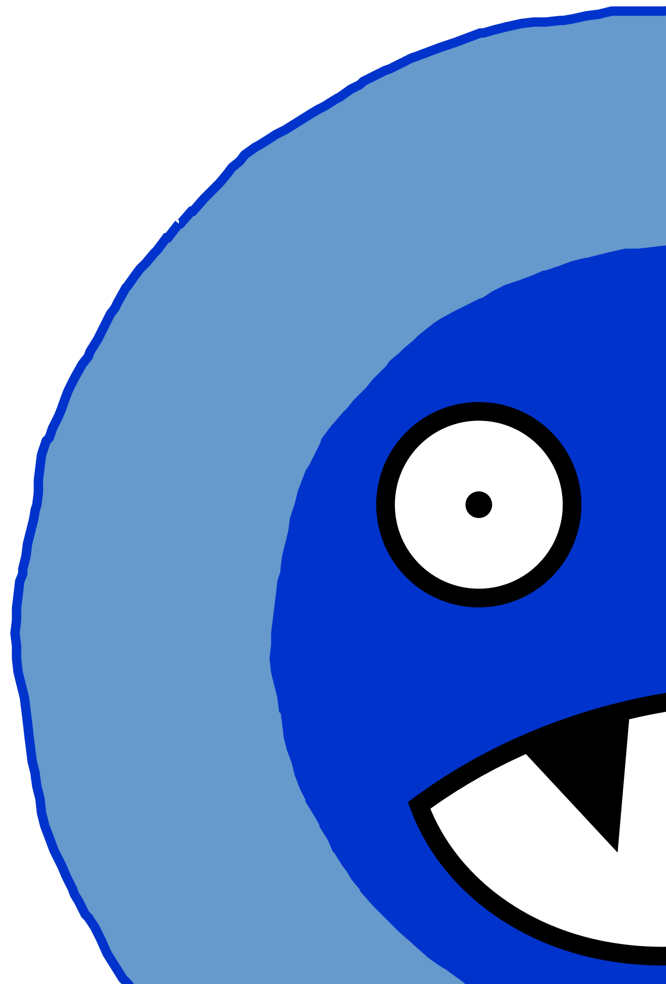
- Consistency between γ estimates and error at the level of $5\,\%$

Used as input for the new UT analysis by UT*fit*

See the [Talk by M. Bona](#)

Thank you!





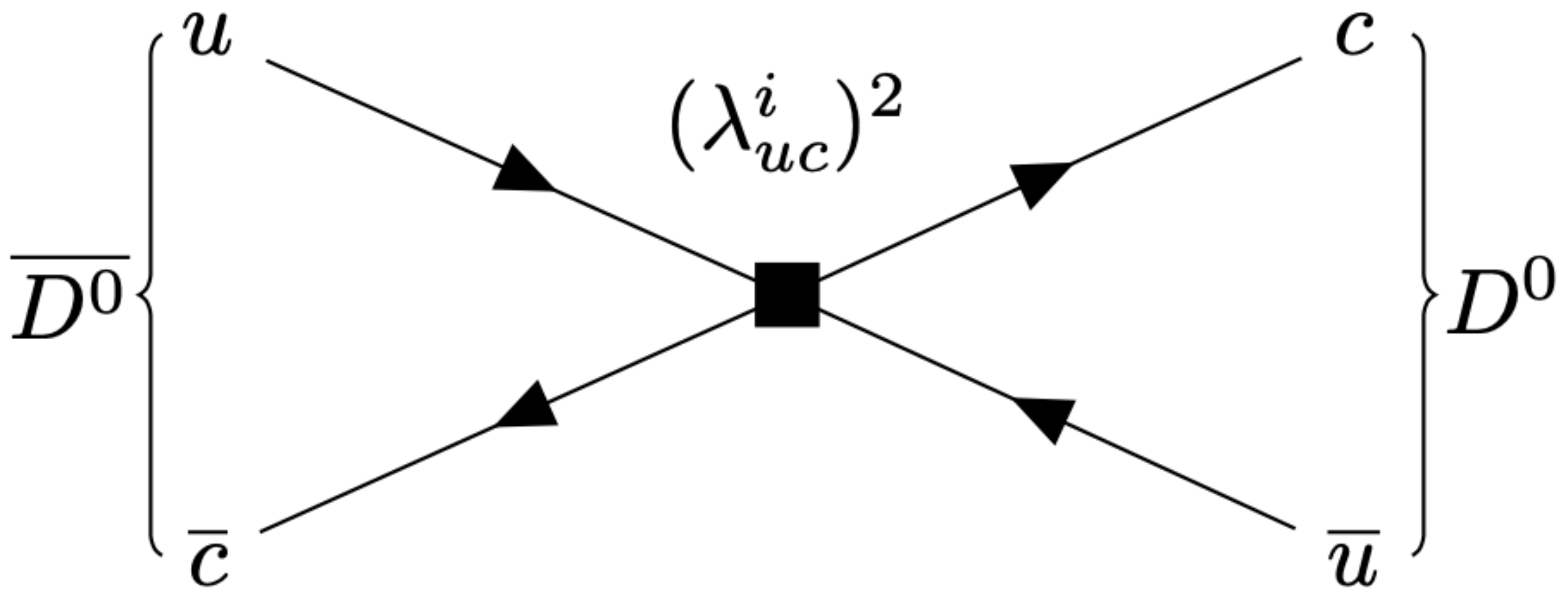
Backup slides

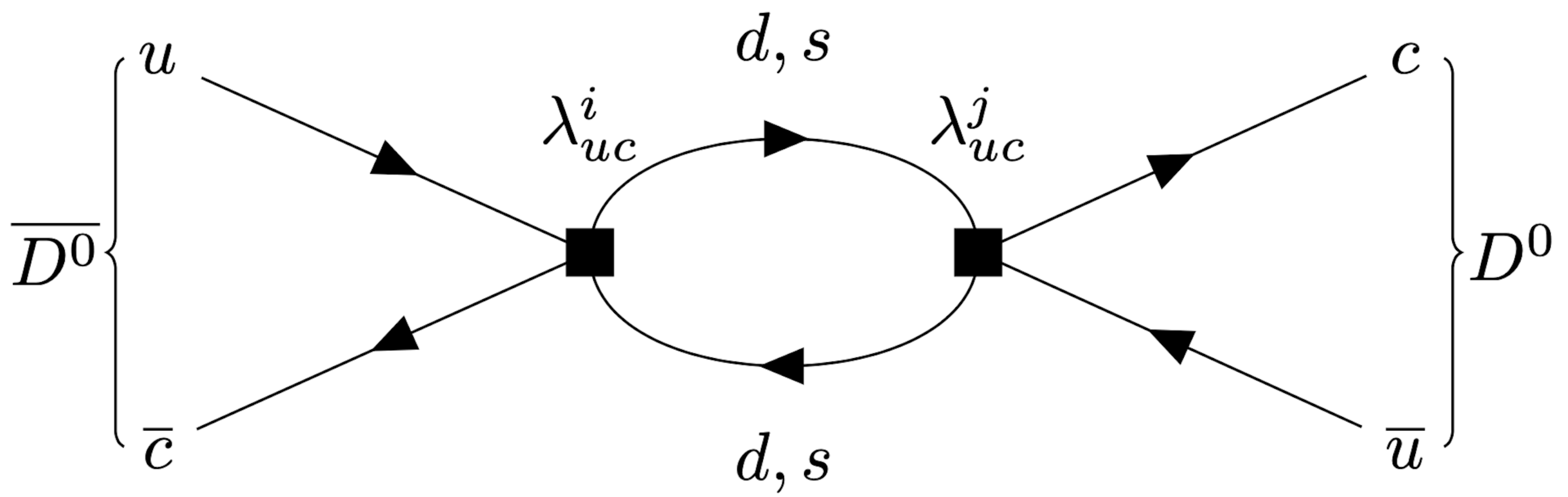
Charm mixing contributions

CKM + GIM: order of magnitude estimate

- **Short distance:** $m_i^2 > m_c^2$ sensitive to heavy NP

SM: $\propto (\lambda^b_{uc} m_b)^2 \approx (\theta_C^5 m_b)^2$





- **Long distance:** $m_i^2 < m_c^2$ inherently non-perturbative, leading contribution in the SM

SM: $\propto (\lambda^s_{uc} m_s)^2 \approx (\theta_c m_s)^2 \approx 10^2 \times$ **SD**

U-spin decomposition

$$\Gamma_2 = (\bar{s}s - \bar{d}d)^2 = \mathcal{O}(\epsilon^2)$$

$$\Gamma_1 = (\bar{s}s - \bar{d}d)(\bar{s}s + \bar{d}d) = \mathcal{O}(\epsilon)$$

$$\Gamma_0 = (\bar{s}s + \bar{d}d)^2 = \mathcal{O}(1)$$

$$\lambda_{uc}^s - \lambda_{uc}^d \approx 0.44 - i1.2 \times 10^{-4}$$

$$\lambda_{uc}^b \approx (5.7 + i12) \times 10^{-5}$$

$$\Gamma_{12}^{SM} = \boxed{\frac{(\lambda_{uc}^s - \lambda_{uc}^d)^2}{4}\Gamma_2 \times} \Rightarrow$$

Dominant contribution

$$\left[1 + (0.86 + i1.8) \times 10^{-3}\left(\frac{0.3}{\epsilon}\right) + (-6.4 + i7.8) \times 10^{-7}\left(\frac{0.3}{\epsilon}\right)^2\right]$$

CPV phases in the SM

$$\phi_f^{M,\Gamma} = \phi_2^{M,\Gamma}(1 + \mathcal{O}(\epsilon))$$

CF/DCS $\phi_f^{M,\Gamma} = \phi_2^{M,\Gamma} + \mathcal{O}(\theta_C^6)$ **SCS** $(\phi_{KK}^{M,\Gamma} + \phi_{\pi\pi}^{M,\Gamma})/2 = \phi_2^{M,\Gamma}(1 + \mathcal{O}(\epsilon^2))$

$$\phi_2^\Gamma \Big|_{SM} = \arg\left[1 + \frac{2\lambda_{uc}^b}{\lambda_{uc}^s - \lambda_{uc}^d}\frac{\Gamma_1}{\Gamma_2}\right] = \arg\left[1 - \frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} \times \left(\frac{2}{1 - \frac{V_{us}^* V_{cs}}{V_{ud}^* V_{cd}}}\right)\epsilon^{-1}\right]$$

$$\simeq \left|\frac{\lambda_{uc}^b}{\lambda_{uc}^d}\right| \sin(\gamma)\epsilon^{-1} \approx (2.2 \times 10^{-3}) \times \left[\frac{0.3}{\epsilon}\right]$$

Equivalent formalisms

F A M I L I A R

- **CP-conserving**

$$|x| = 1/\sqrt{2}\left[x_{12}^2 - y_{12}^2 + \sqrt{(x_{12}^2+y_{12}^2)^2 - 4x_{12}^2 y_{12}^2 \sin^2\phi_{12}}\right]^{1/2} = x_{12} + \mathcal{O}(\phi_{12}^2)$$

$$y = 1/\sqrt{2}\left[y_{12}^2 - x_{12}^2 + \sqrt{(x_{12}^2+y_{12}^2)^2 - 4x_{12}^2 y_{12}^2 \sin^2\phi_{12}}\right]^{1/2} = y_{12} + \mathcal{O}(\phi_{12}^2)$$

- **CP-violating**

$$\left|\frac{q}{p}\right| = \left[\frac{x_{12}^2 + y_{12}^2 + 2x_{12}y_{12}\sin\phi_{12}}{x_{12}^2 + y_{12}^2 - 2x_{12}y_{12}\sin\phi_{12}}\right]^{1/4} = 1 + \frac{x_{12}y_{12}}{x_{12}^2+y_{12}^2}\sin\phi_{12} + \mathcal{O}(\phi_{12}^2)$$

$$\tan(2\phi_{\lambda_f}) = -\frac{x_{12}^2\sin 2\phi_f^M + y_{12}^2\sin 2\phi_f^\Gamma}{x_{12}^2\cos 2\phi_f^M + y_{12}^2\cos 2\phi_f^\Gamma} \approx -\frac{x_{12}^2}{x_{12}^2+y_{12}^2}\phi_f^M - \frac{y_{12}^2}{x_{12}^2+y_{12}^2}\phi_f^\Gamma + \mathcal{O}(\phi_{12}^2)$$

D I S P - A B S

Charm parameters

Final-state dependent

- Decay amplitudes

r_D^f δ_D^f

CPV phases

ϕ_f^M, ϕ_f^Γ

Final-state independent

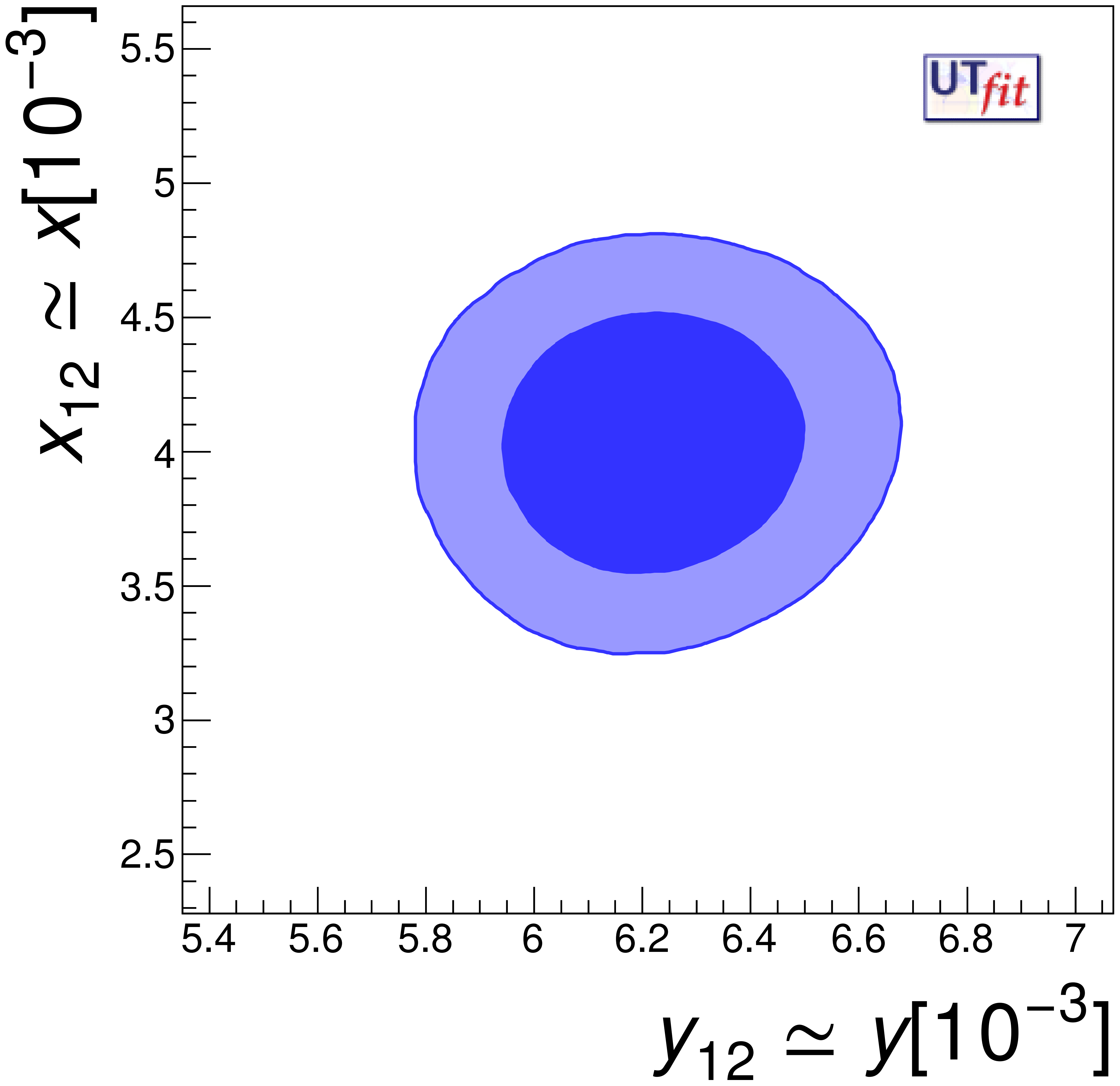
- Mixing parameters

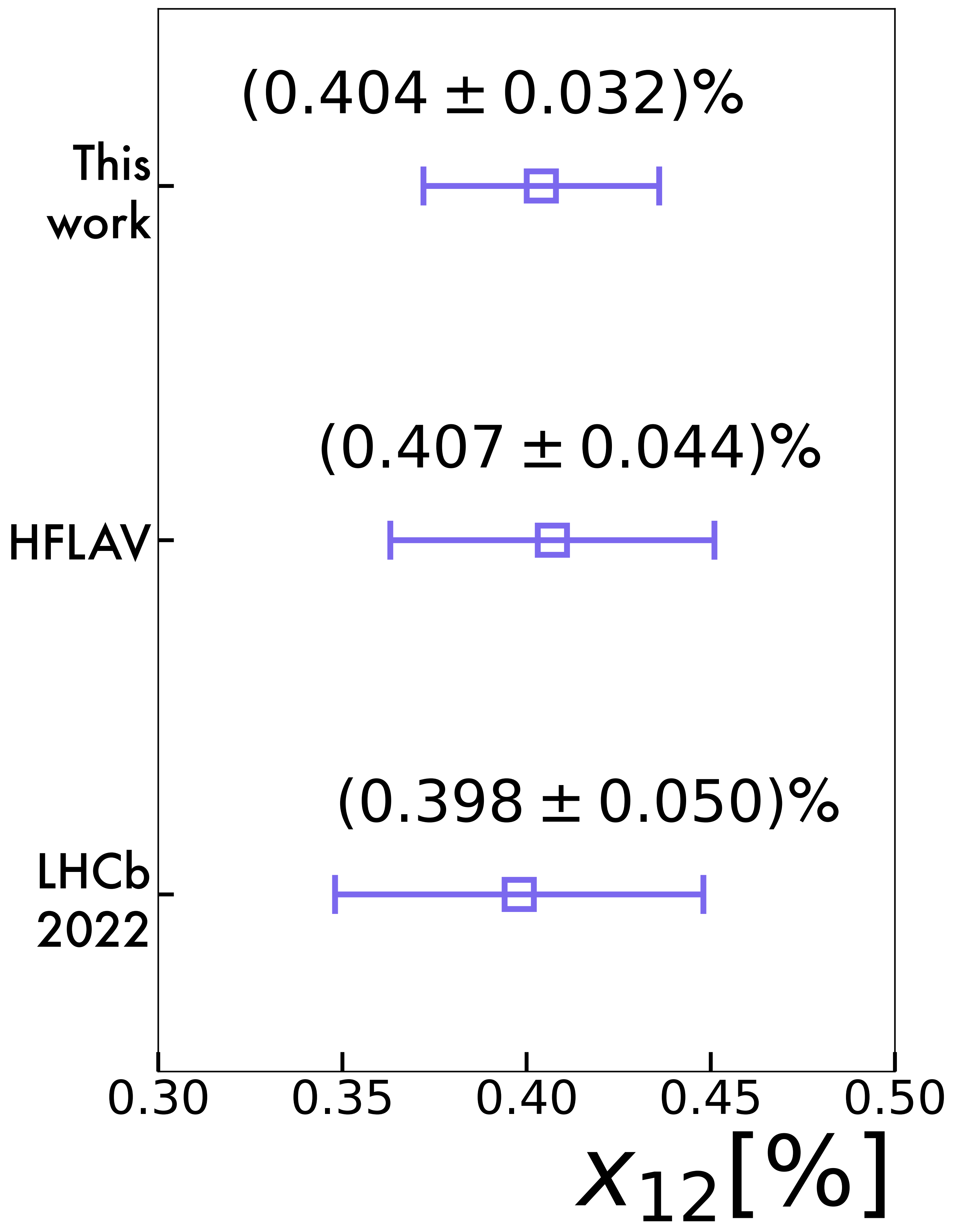
x_{12} y_{12}

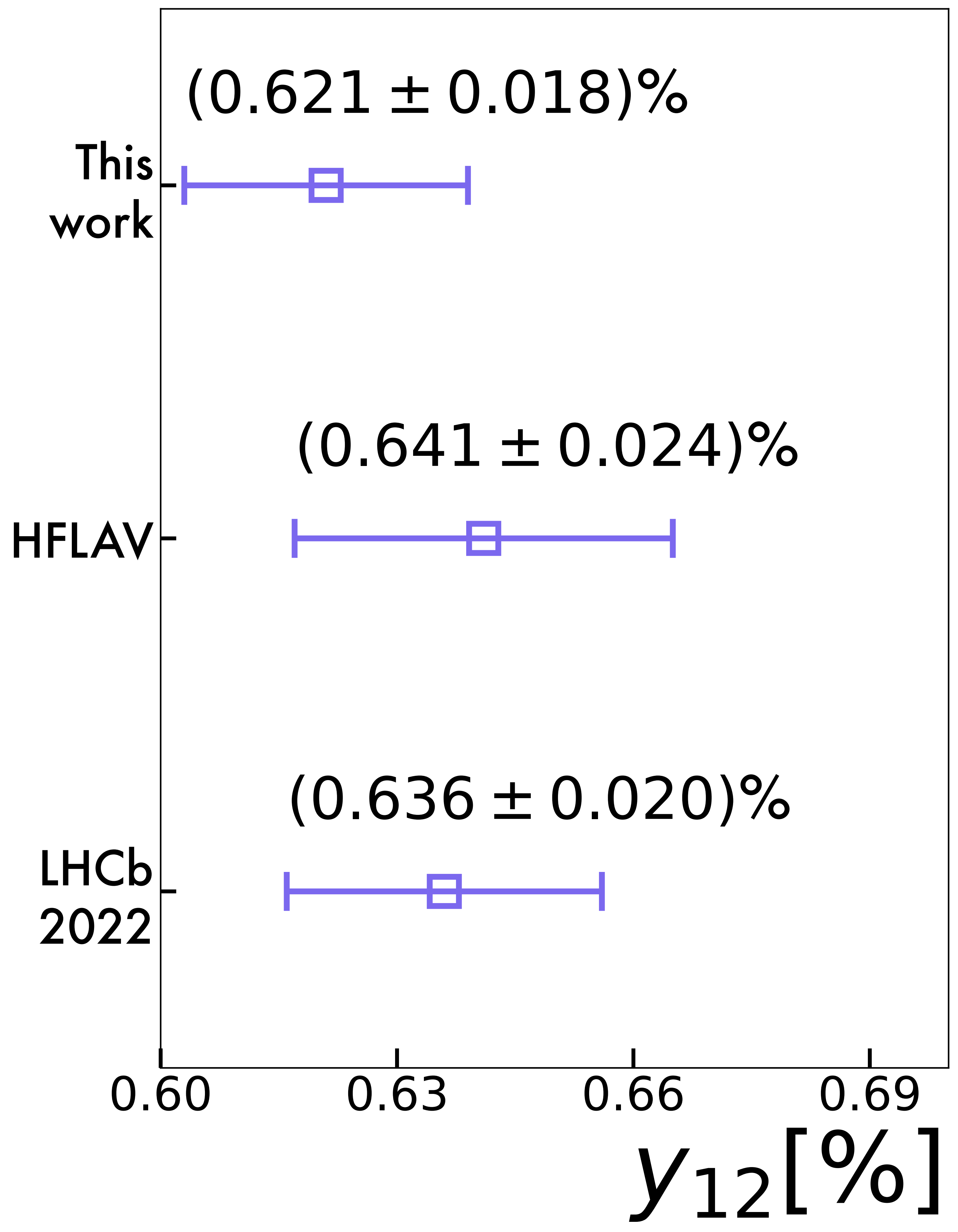
Beauty observables
More information about decay and mixing parameters

Approximate Universality
Dropping the final-state dependent parts of ϕ_f^M and ϕ_f^Γ

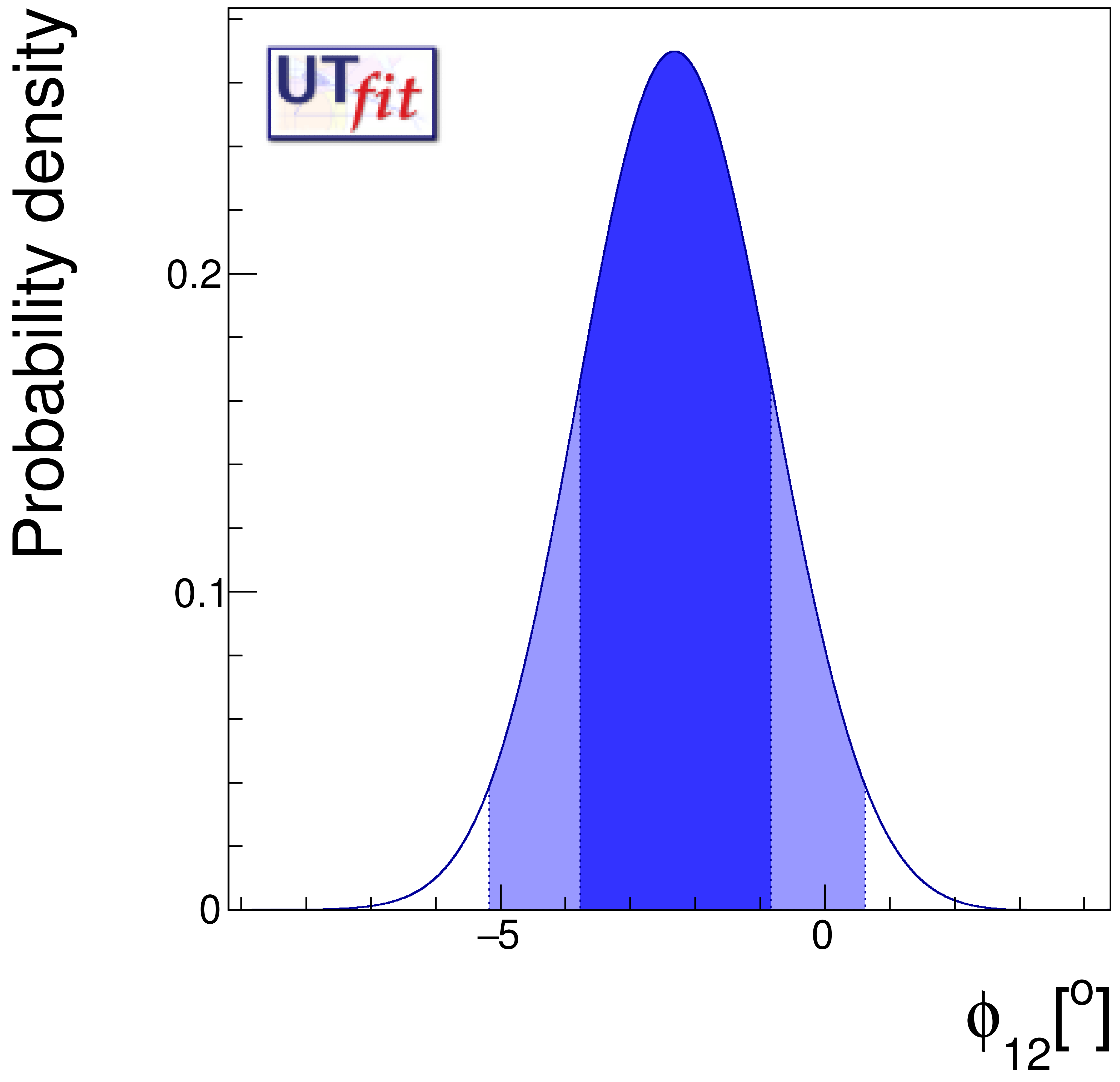
Results: CP-conserving parameters





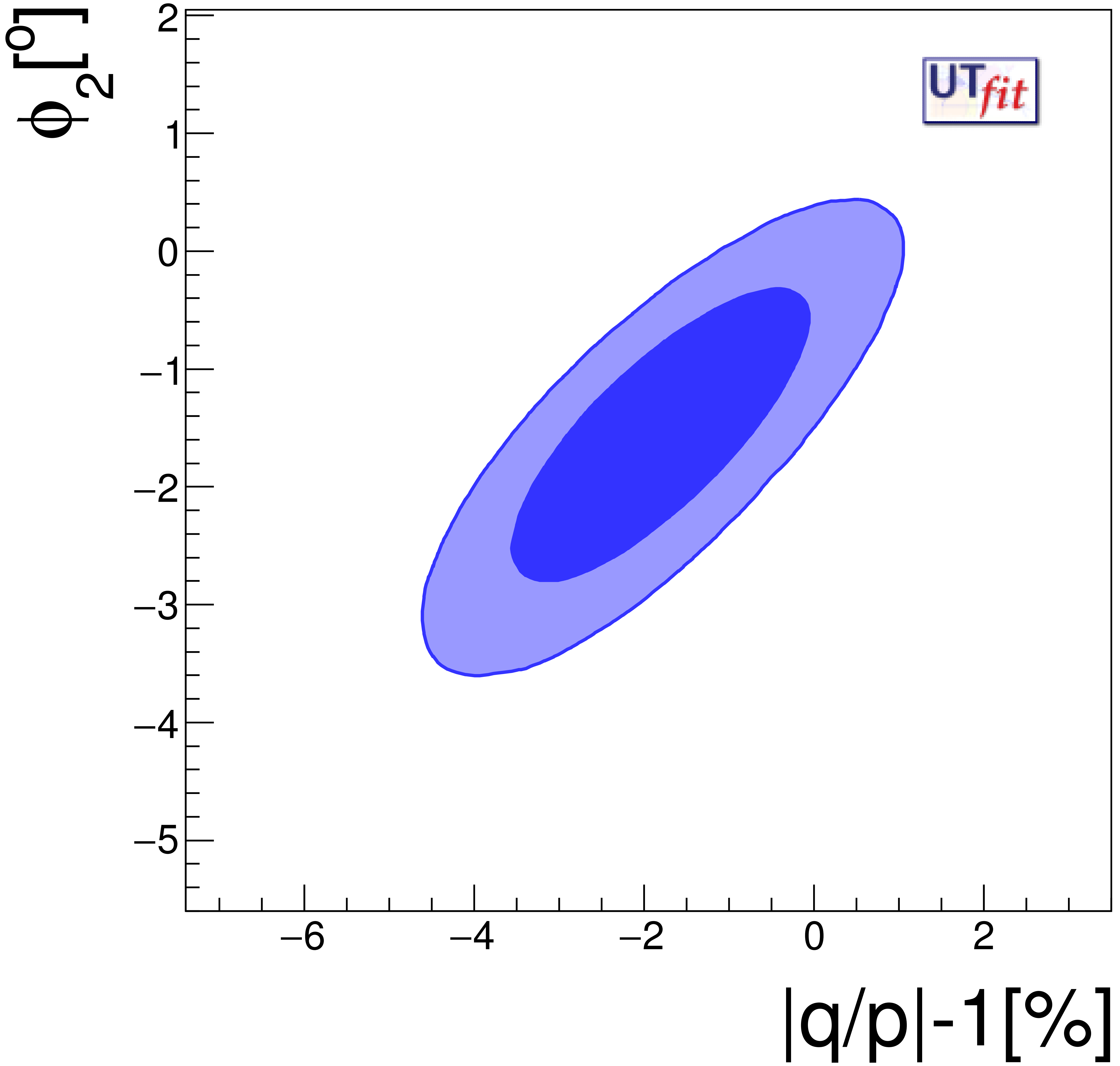


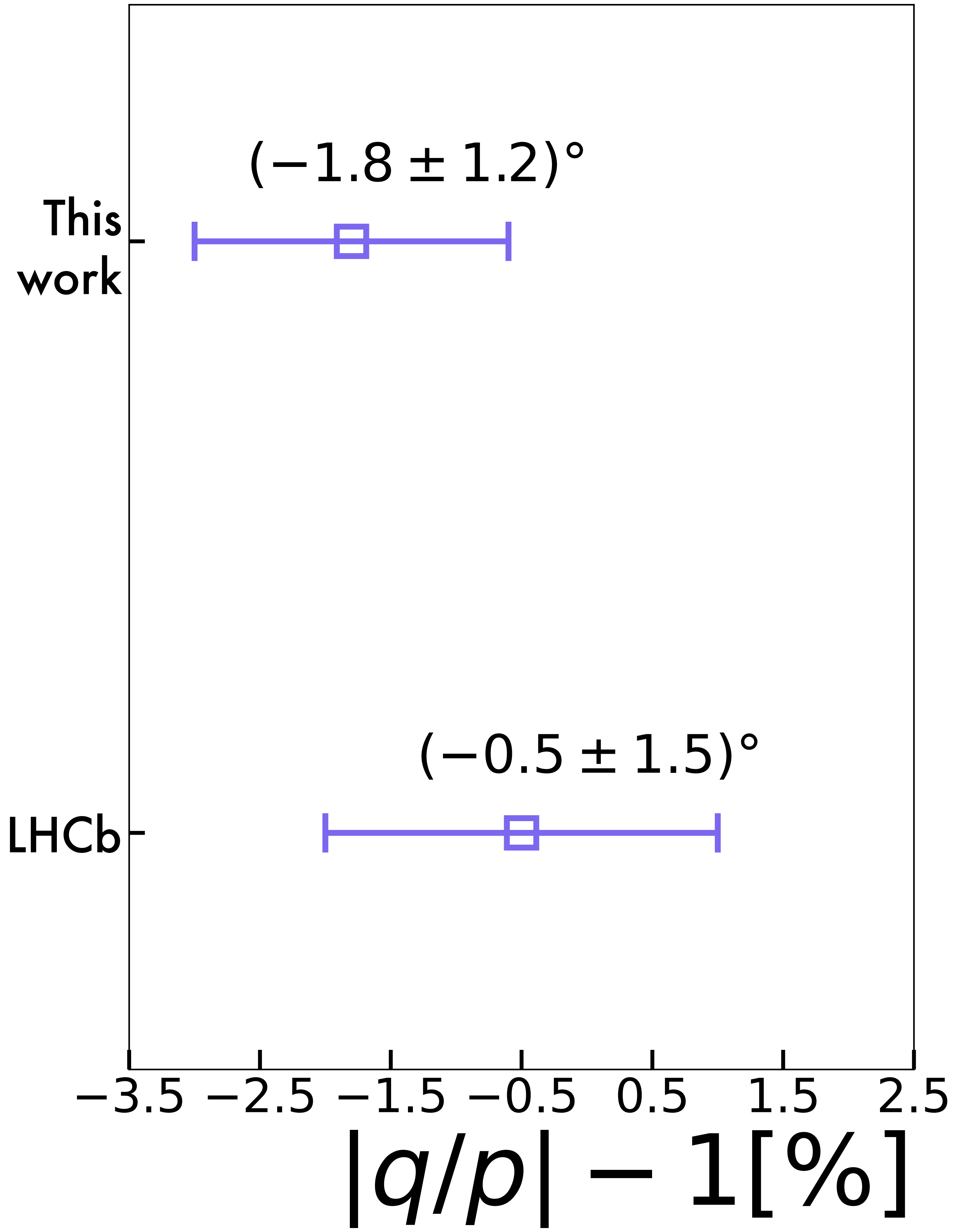
Results: ϕ_{12}

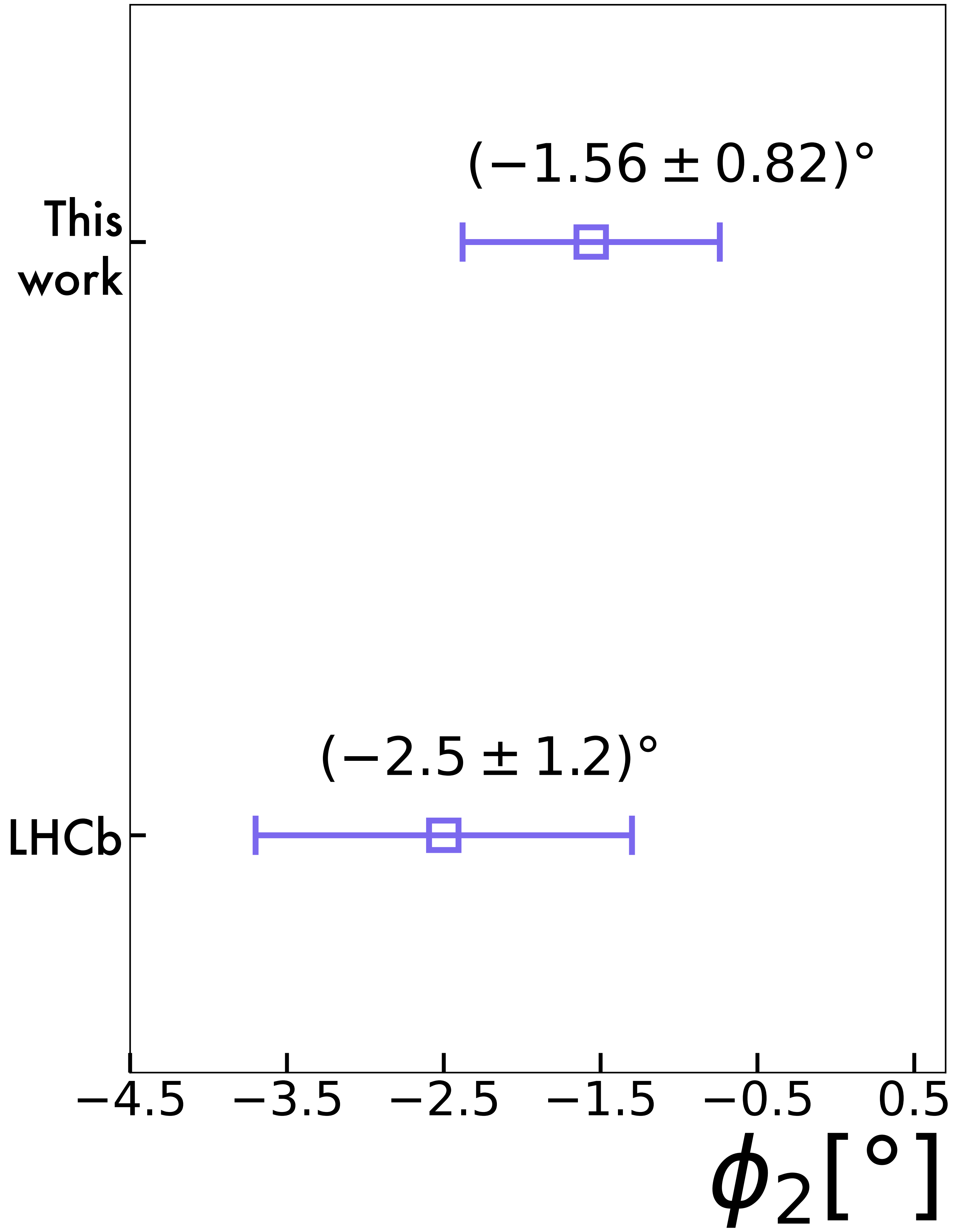


$$\phi_{12} = (-2.3 \pm 1.5)^\circ$$

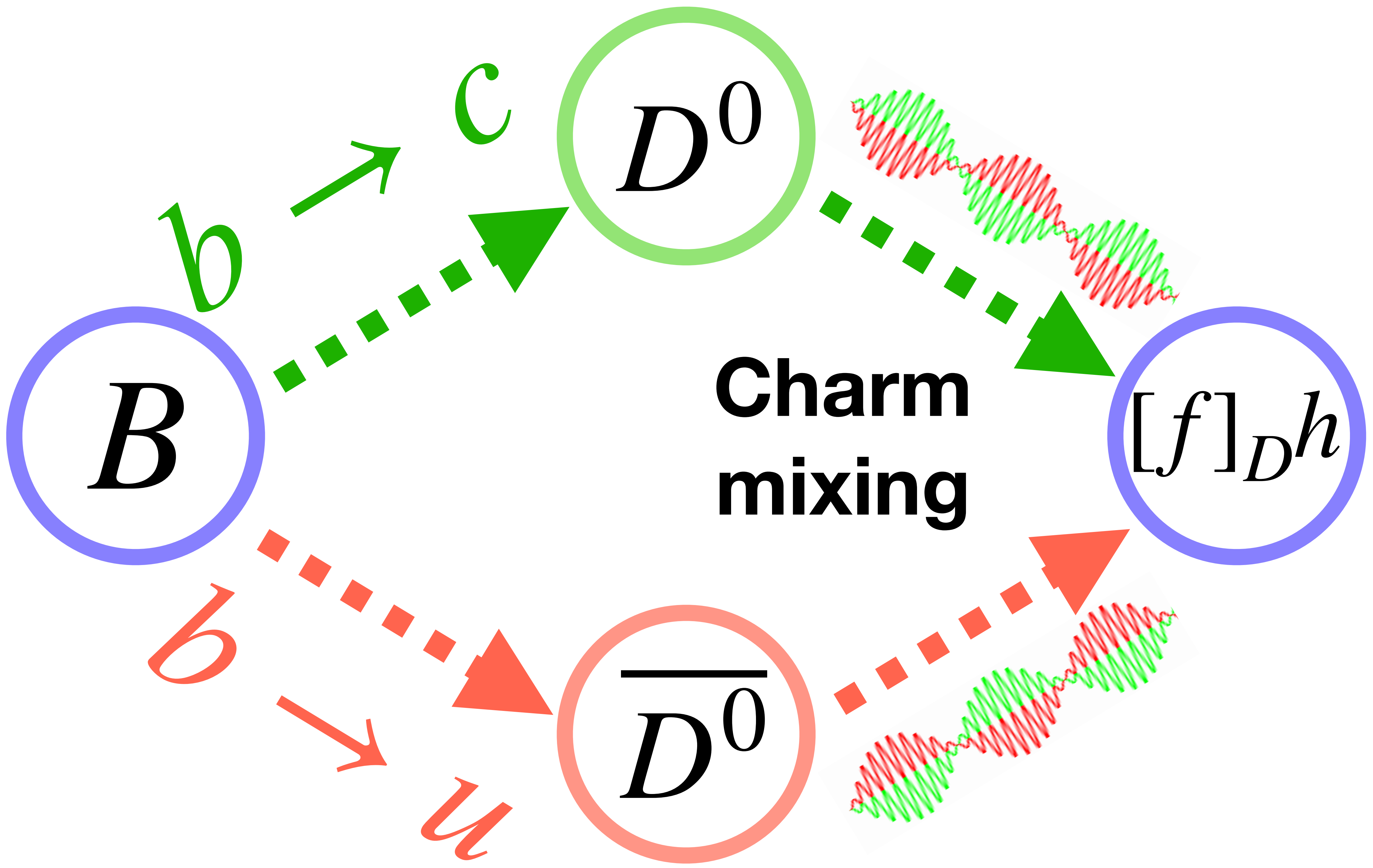
Results: CPV using the familiar formalism







B Cascade decays: GLW/ADS



M. Gronau, D. Wyler

M. Gronau, D. London

- $B \to D$ decays

$$\frac{\mathcal{A}(b \to u)}{\mathcal{A}(b \to c)} = r_B^{Dh} e^{i(\delta_B^{Dh} - \gamma)}$$

CKM ANGLE

$$\gamma = \arg - \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}$$

- D mixing + $D \to f$ decays

$$r_D^f e^{-i\delta_D^f}$$

- Cascade decay rate

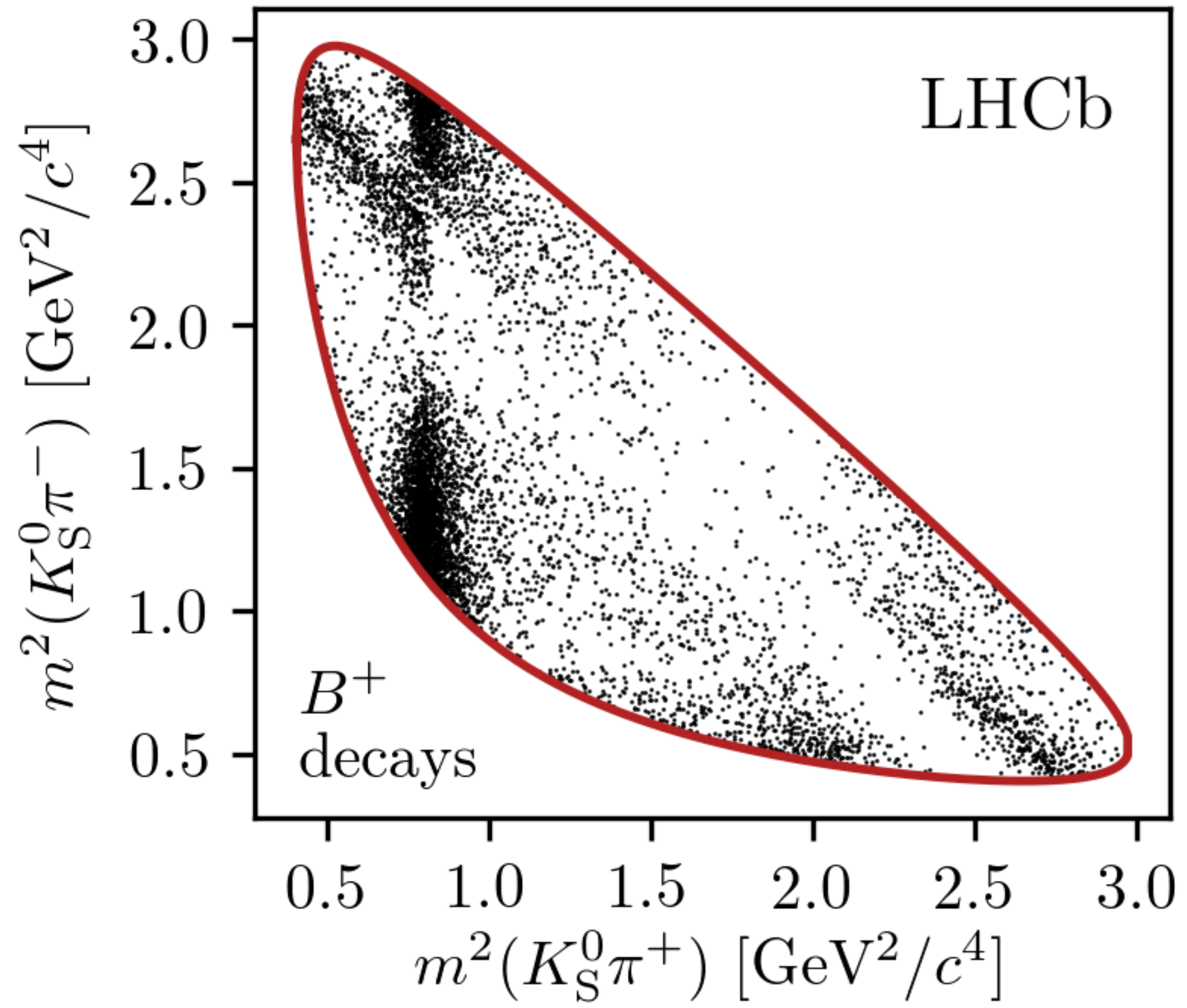
$$\Gamma(B \to [f]_D h) \propto 1 + (r_D^f r_B^{Dh})^2 + 2 r_B^{Dh} r_D^f \cos(\delta_B^{Dh} - \delta_D^f - \gamma) + \Gamma_{mix}$$

- **GLW/ADS Observables**

$$\Gamma(B \to [f]_D h) - \Gamma(\bar{B} \to [\bar{f}]_D \bar{h}) \propto \sin \gamma$$

GGSZ Observables

from LHCb-2021



- Study of the phase-space dependent decay rates for $f = K^0_S K^+ K^-$, $K^0_S \pi^+ \pi^-$, $K^+ K^- \pi^+ \pi^-$

A. Giri, Y. Grossman, A. Soffer, J. Zupan

$$d\Gamma\left(\overset{(-)}{B} \to [f]_D \overset{(-)}{h} \right)/dp$$

- **Model-dependent** approach

- **Model-independent :** Integrating over $2k$ bins and solving a system of $4k$ equations $\Gamma_{\pm i}(\overset{(-)}{B} \to [f]_D \overset{(-)}{h})$ for $2k + 4$ unknowns.

Polar Observables

$$x_{\pm}^{Dh} = r_B^{Dh} \cos(\delta_B^{Dh} \pm \gamma)$$

$$y_{\pm}^{Dh} = r_B^{Dh} \sin(\delta_B^{Dh} \pm \gamma)$$