# CP violation at LHCb

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on behalf of the LHCb collaboration
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第十届中国LHC物理会议 (CLHCP2024)

2024.11.15, Qingdao

# Outline

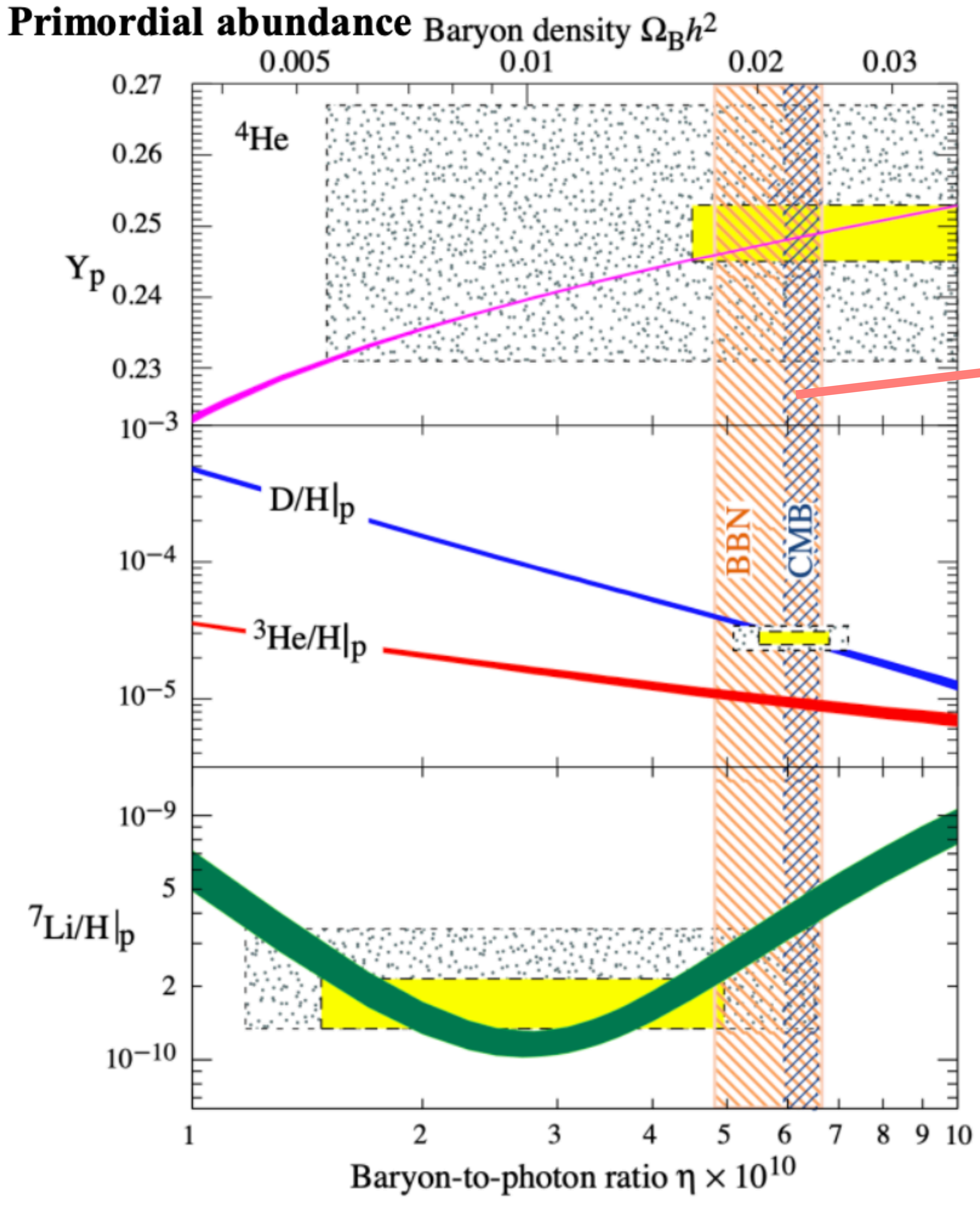
- Introduction
- Recent results for
  - CKM angle $\gamma$ and $\beta_{(s)}$
  - Direct CPV in $B$ meson
  - CPV in Baryons
  - CPV in Charm (back up)
- Summary


*Disclaimer: many new and interesting results, only a few selected*
*More dedicated talks in parallel sessions and public page*

# Matter and anti-matter asymmetry

Rev. Mod. Phys. 88(2016)015004

arXiv: 1801.10059




PLB667 (2008) 1

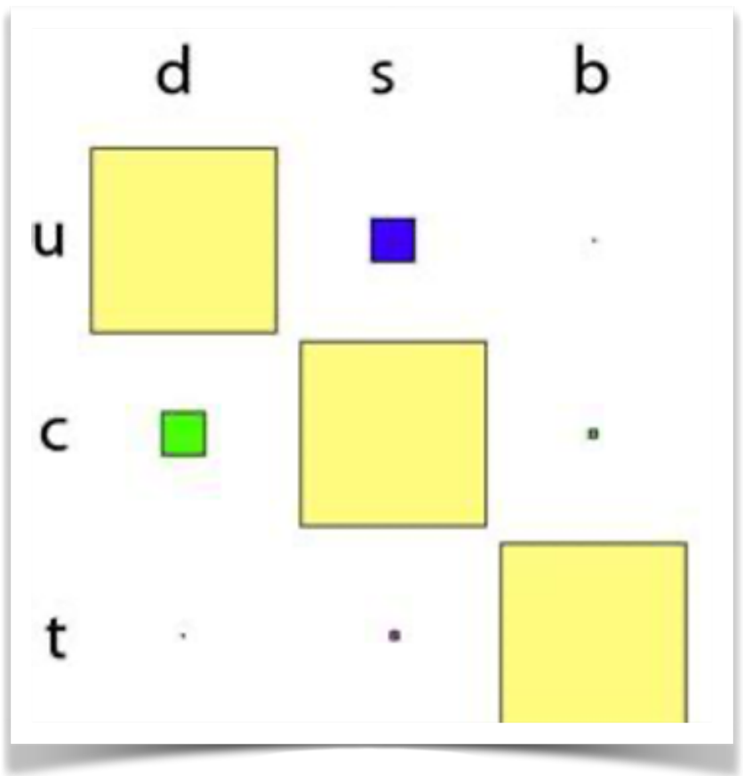
- Large matter-antimatter imbalance in the Universe

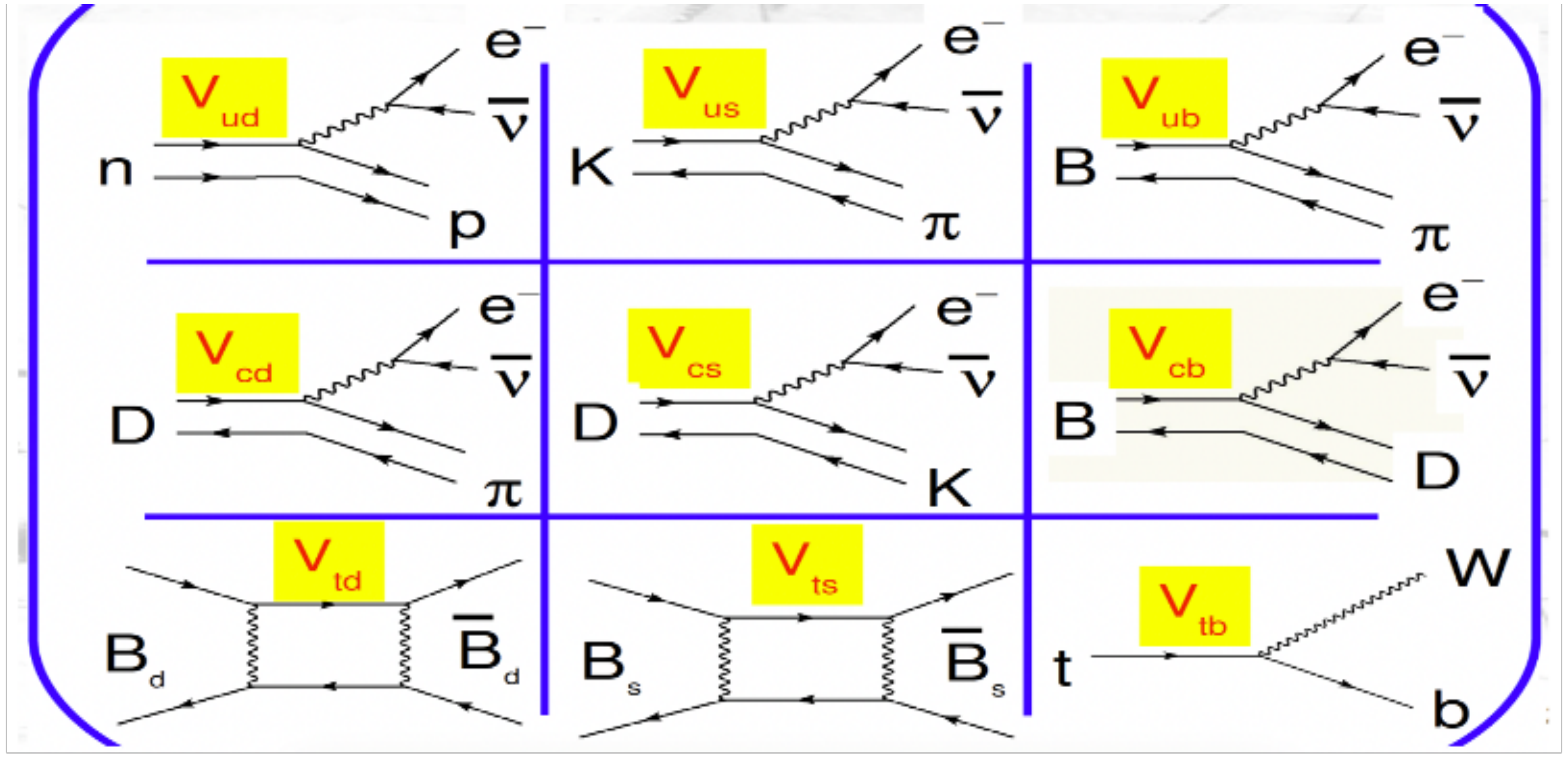
$(n_B - n_{\bar{B}})/n_\gamma$ ~ $6\times10^{-10}$

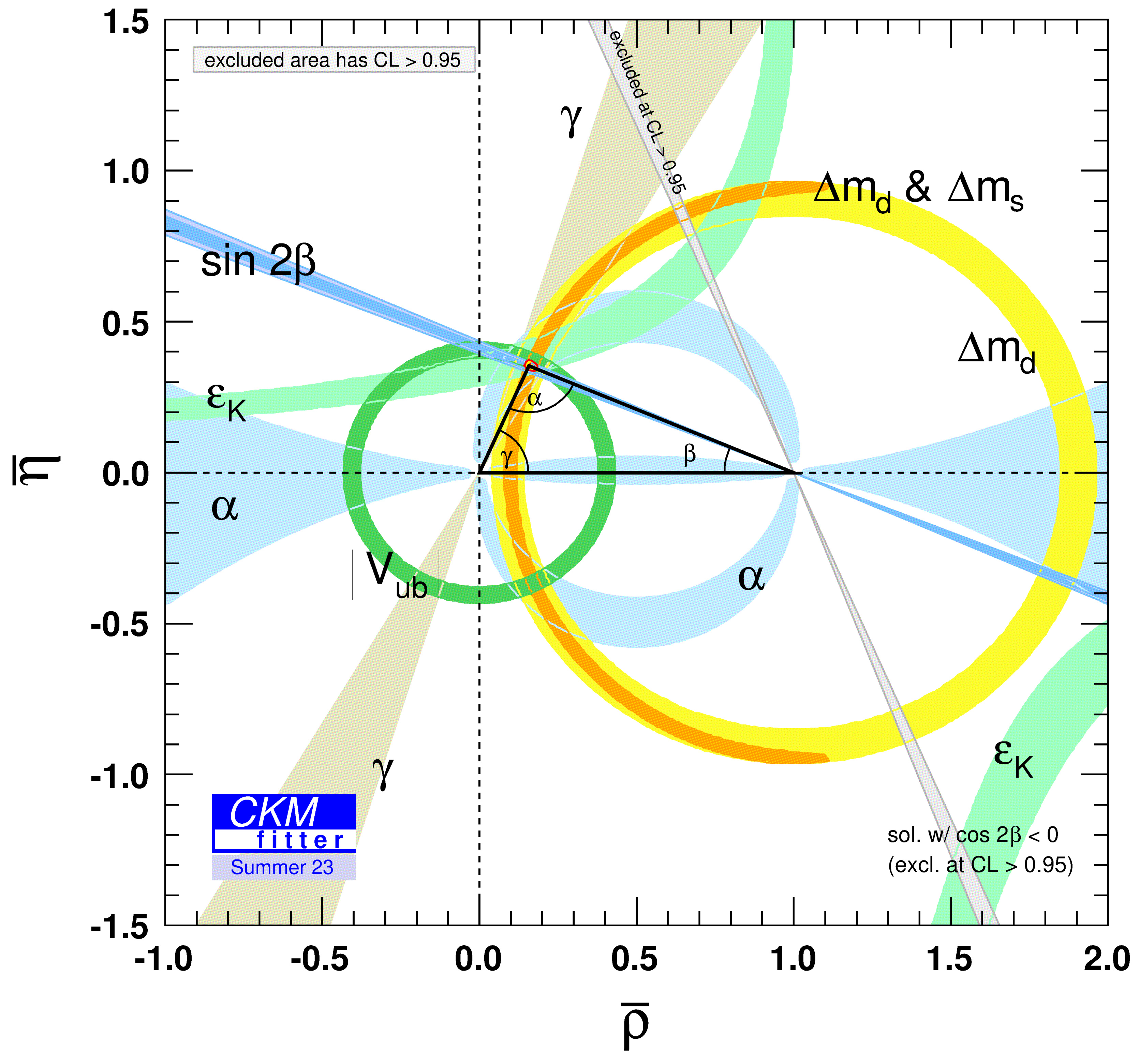
- CP violation in SM ~ $10^{-17}$, not enough!
- Extra sources of CP violation necessitated

# CKM matrix

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




- Key test of the SM: Verify unitarity of CKM matrix
- Only source of CP violation in SM

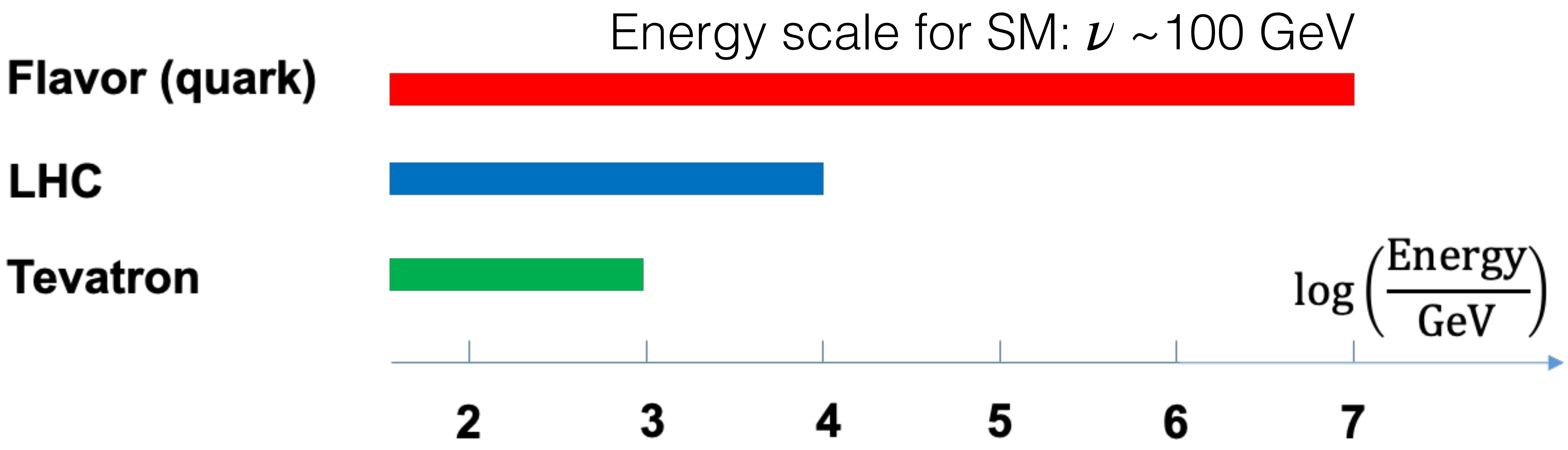
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

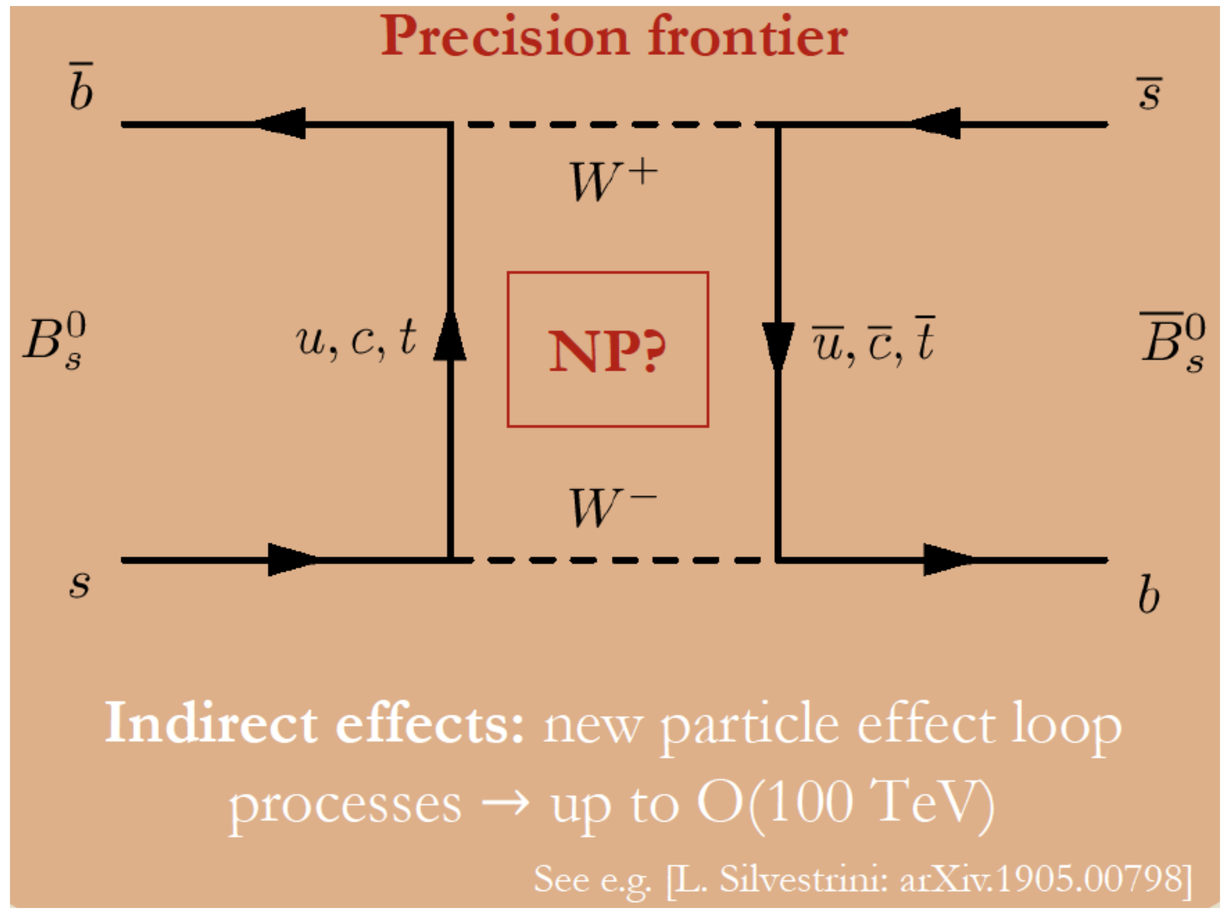
# Indirect search for New Physics

- Sensitivity to New Physics scale much higher than direct search: 1~ $10^4$ GeV

$$\mathcal{A}(\psi_i \to \psi_j + X) = \mathcal{A}_0 \left( \frac{c_{\mathrm{SM}}}{v^2} + \frac{c_{\mathrm{NP}}}{\Lambda^2} \right)$$

NP scale: $\Lambda$

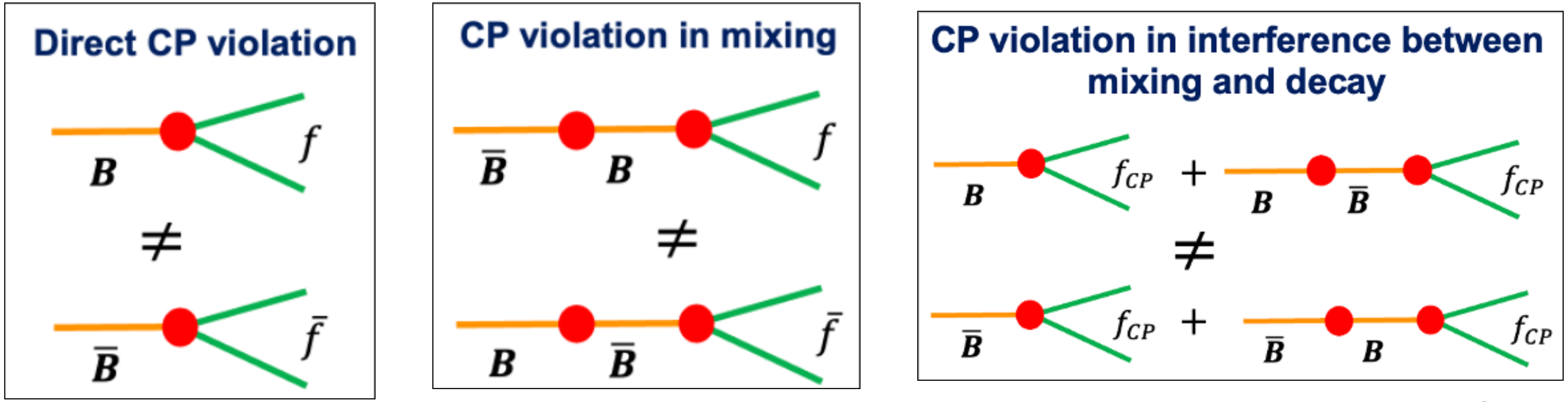



- Statistics or precision essential for flavour physics
  - NP scale, i.e. Dim = 6, proportional to $\sqrt[4]{\text{statisitics}}$
- Would tell not only if there is NP but also which flavour it couples to

# Types of CP Violation

- CP-violating nature of weak interaction has multiple manifestations
- Requires two interfering amplitudes with different strong and weak phases




credit: Wenbin Qian

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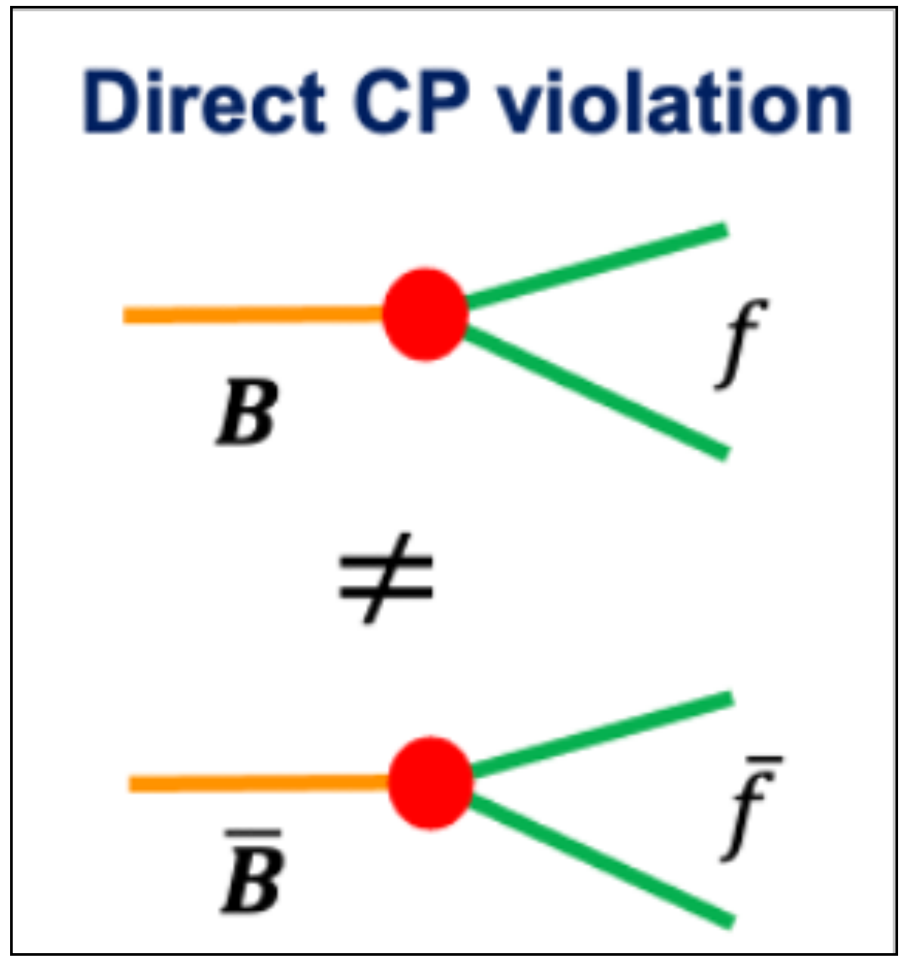
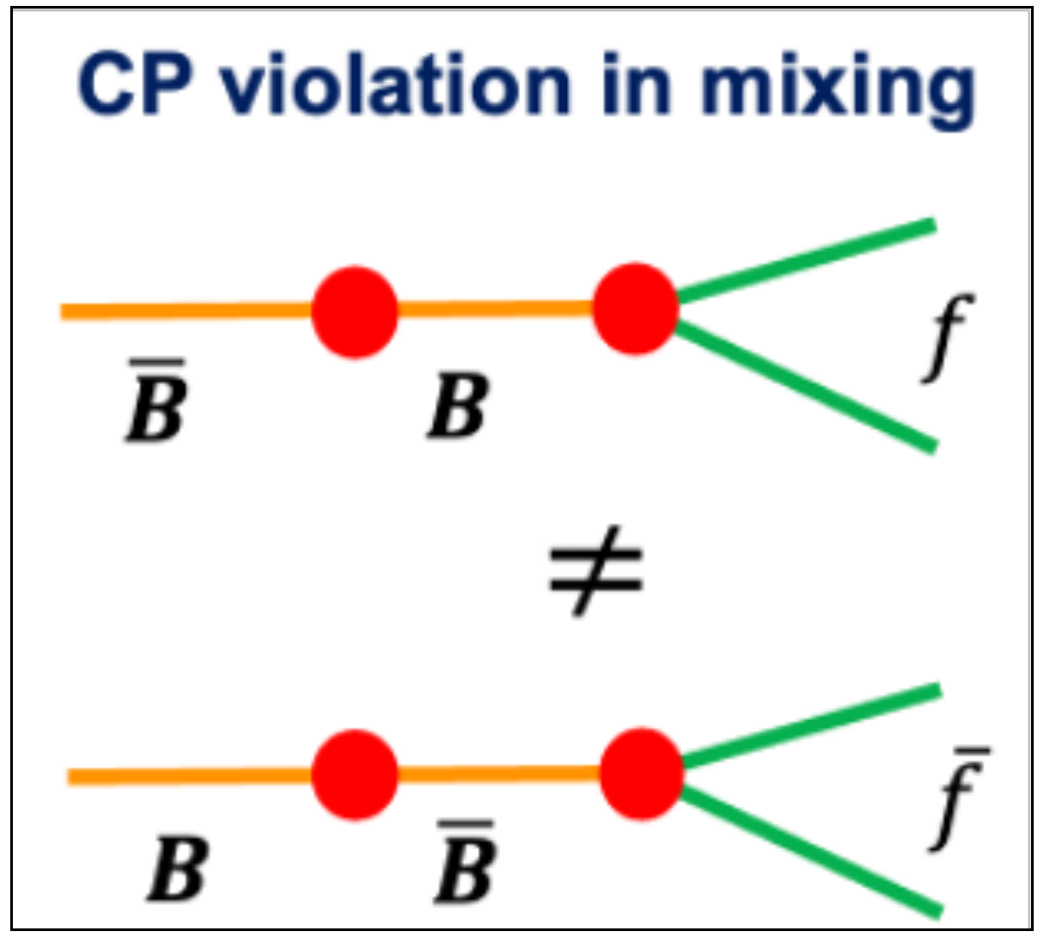
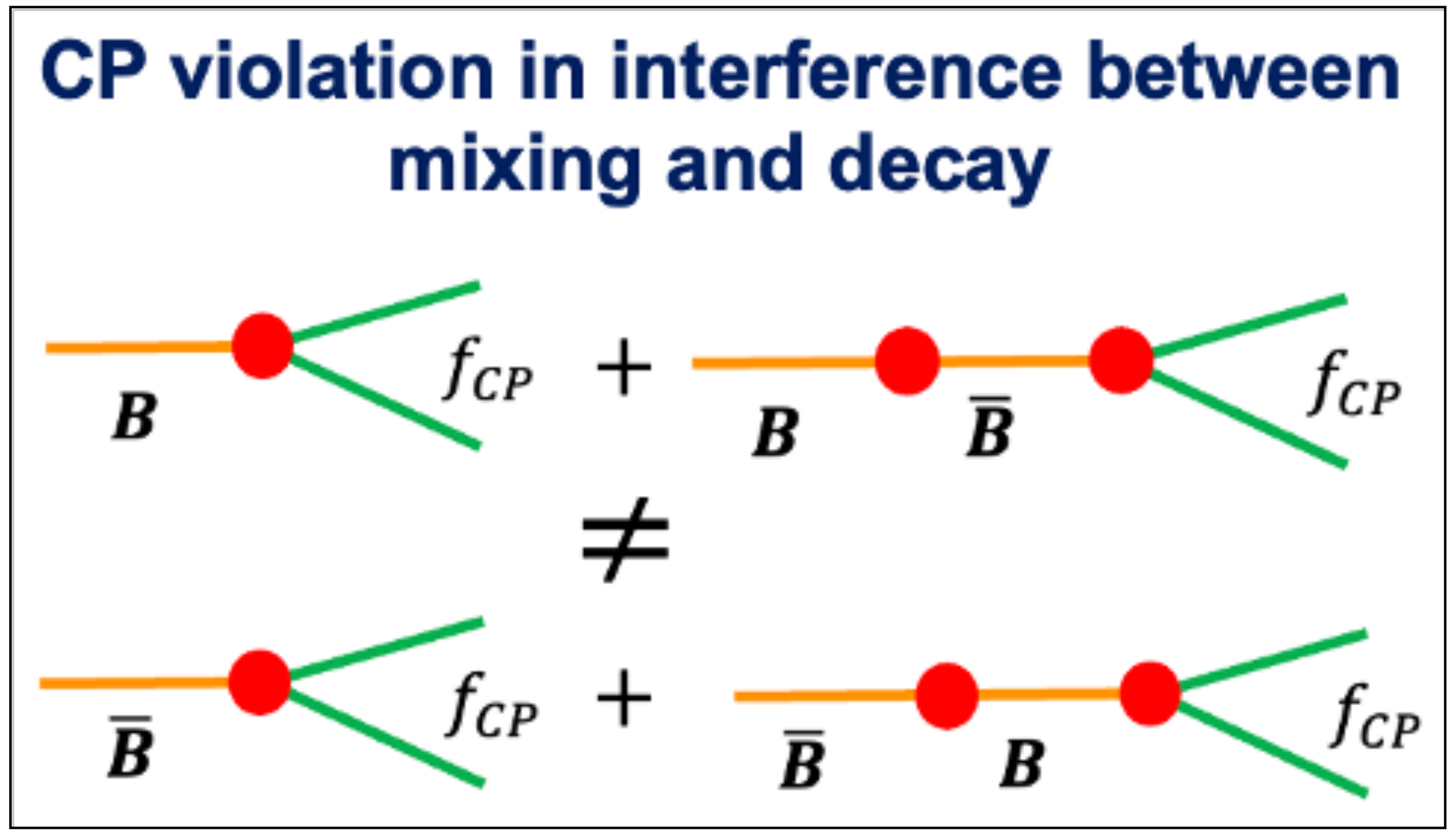
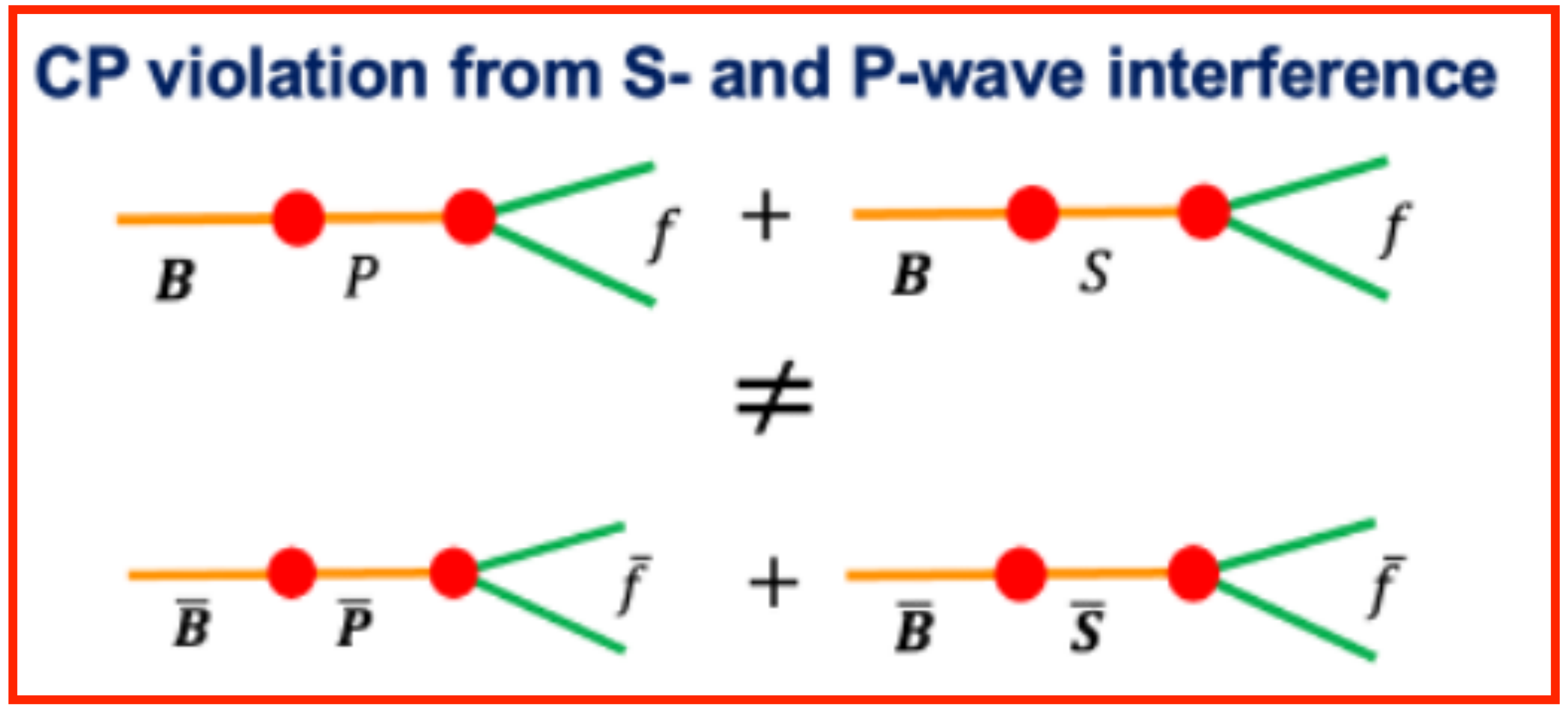



credit: Wenbin Qian




We continue to discover new types of CP violation

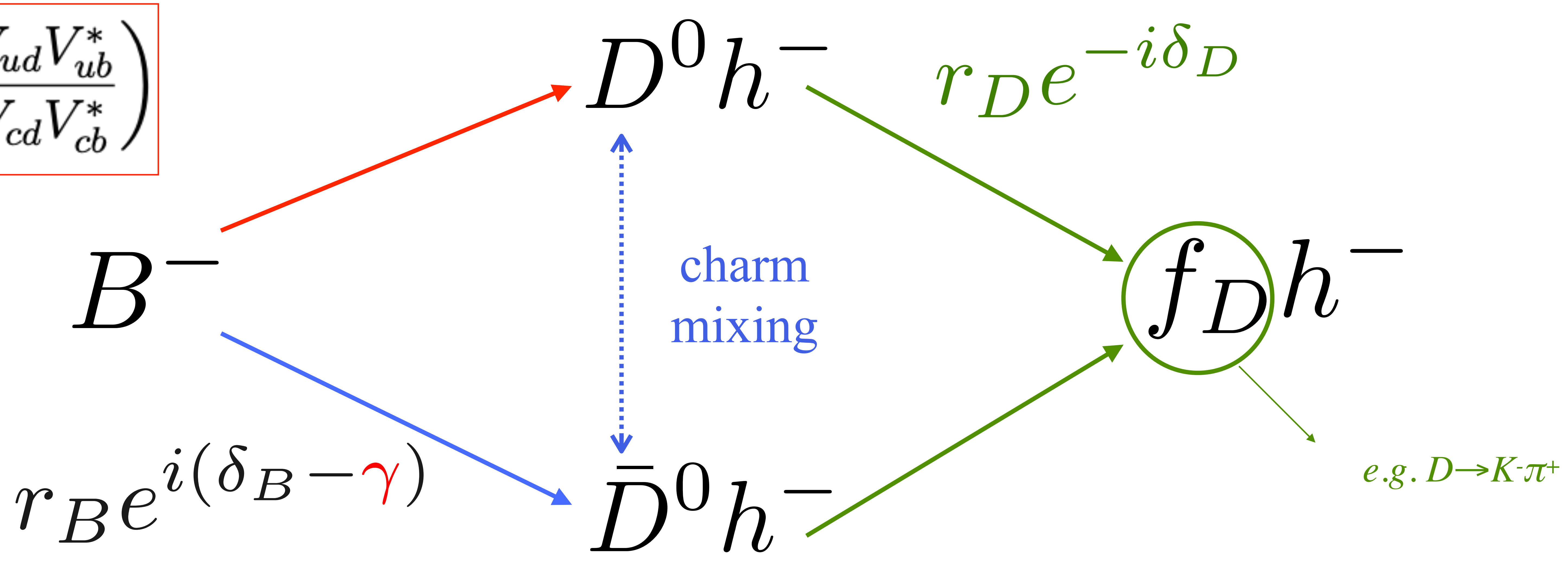
PRL124 (2020) 031801

PRD101 (2020) 012006

# CKM angel $\gamma$

- Relative weak phase $\gamma$ in interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transition
- Measured with tree-level decays, theoretically clean observable ($\delta\gamma/\gamma \sim 10^{-7}$)

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



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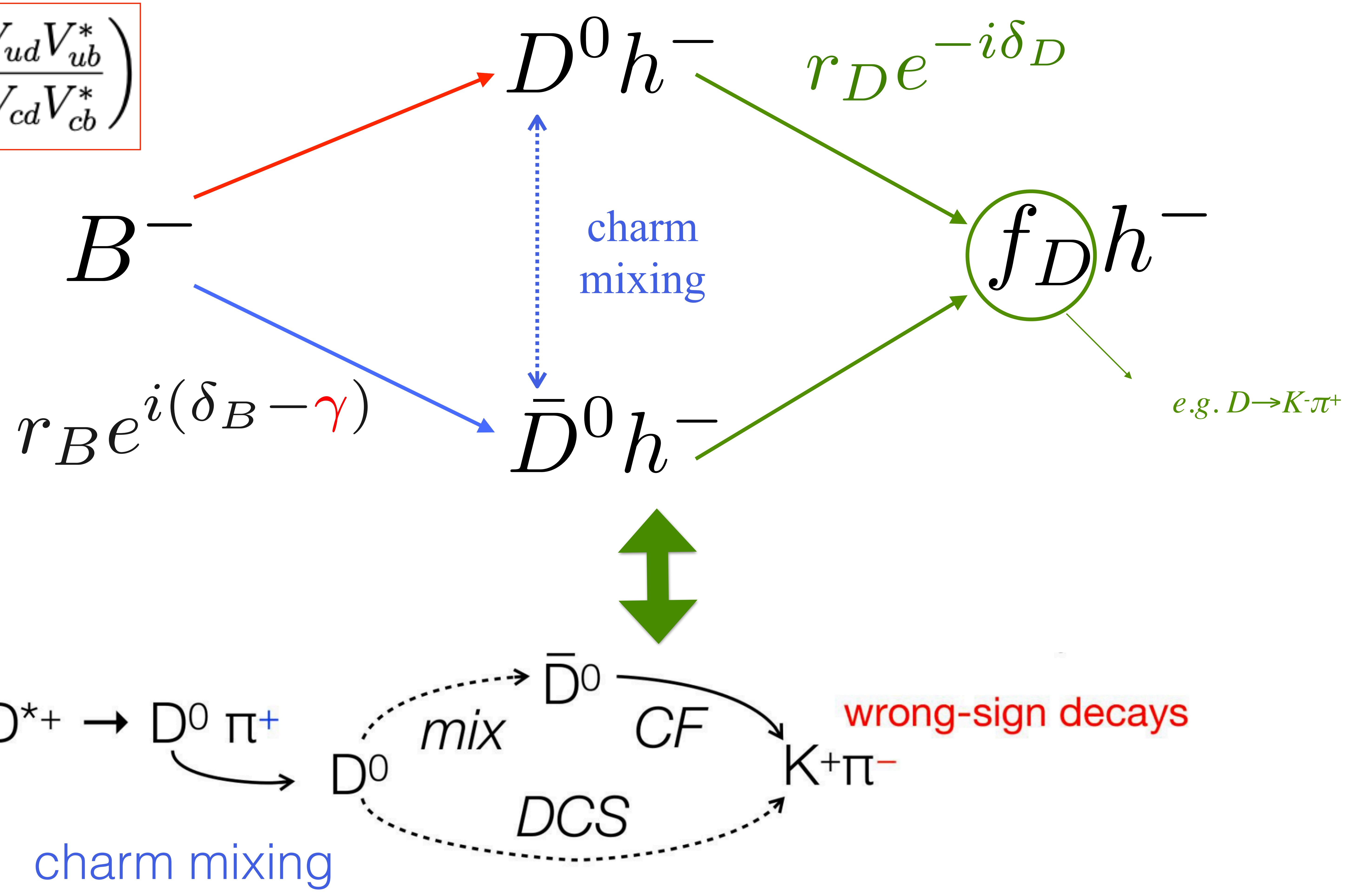

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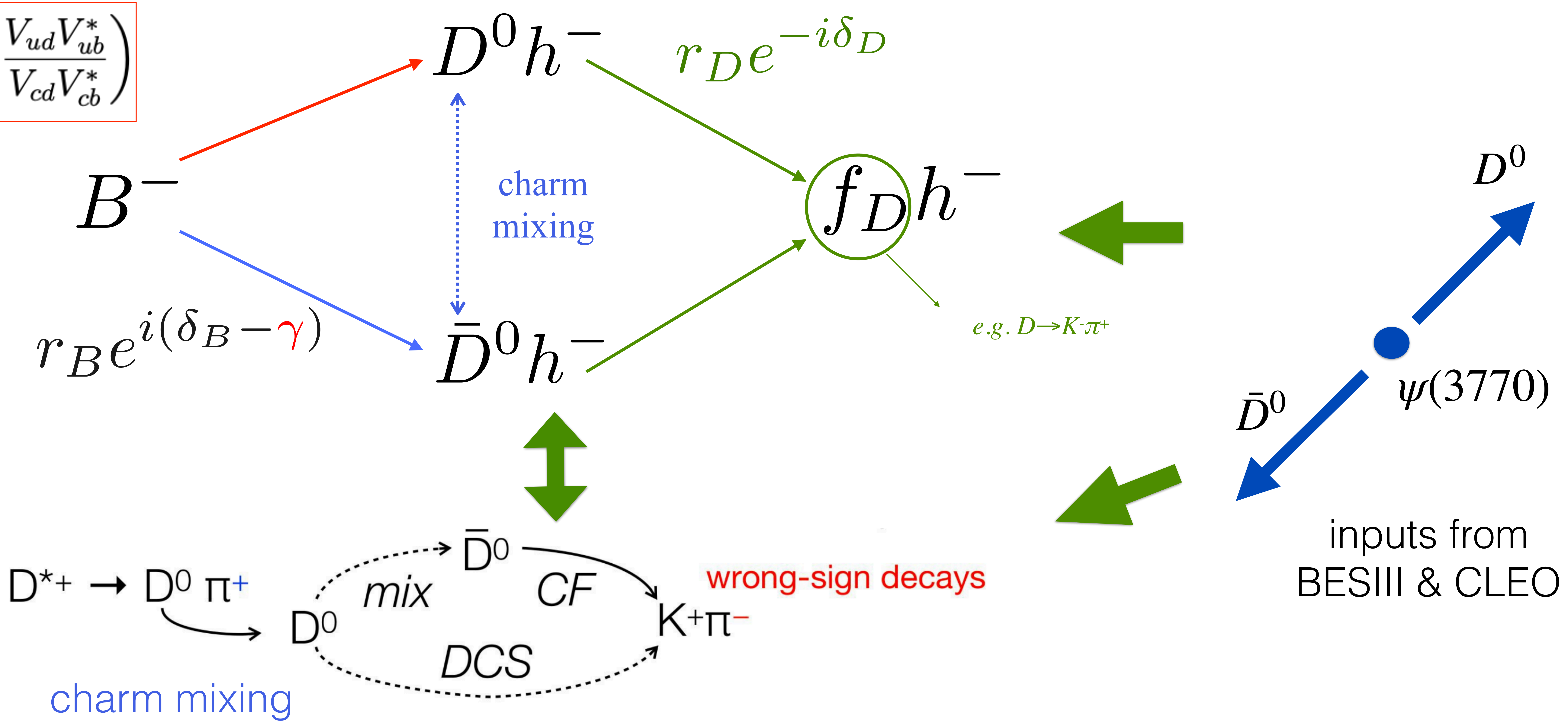
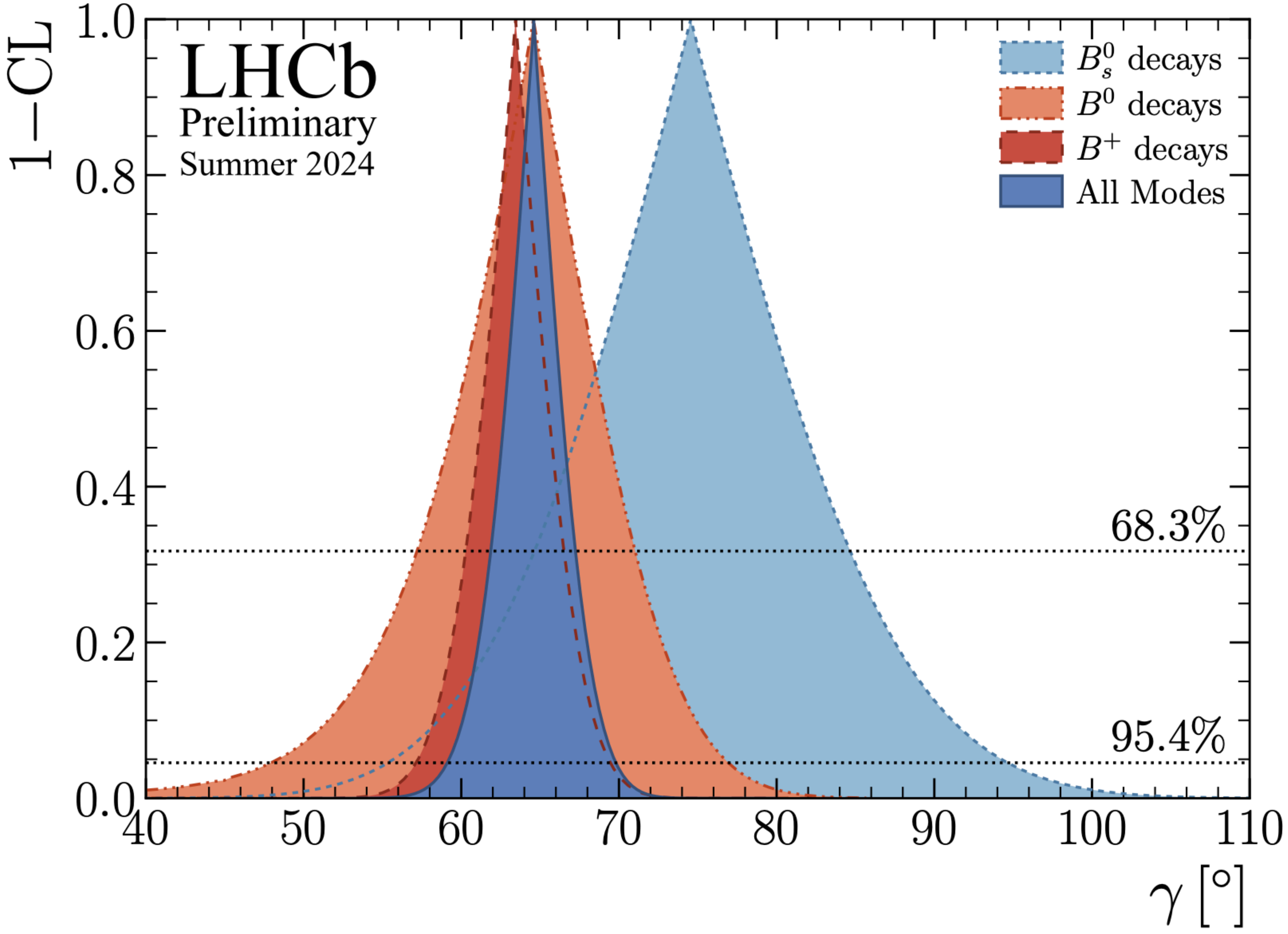


# Latest $\gamma$ combination

LHCb-CONF-2024-004

- **19** LHCb $B$ decay measurements + **11** $D$ decay measurements + 27 external inputs
- **29** physics parameters of interest + additional nuisance parameters




$$\gamma = (64.6 \pm 2.8)^{\circ}$$

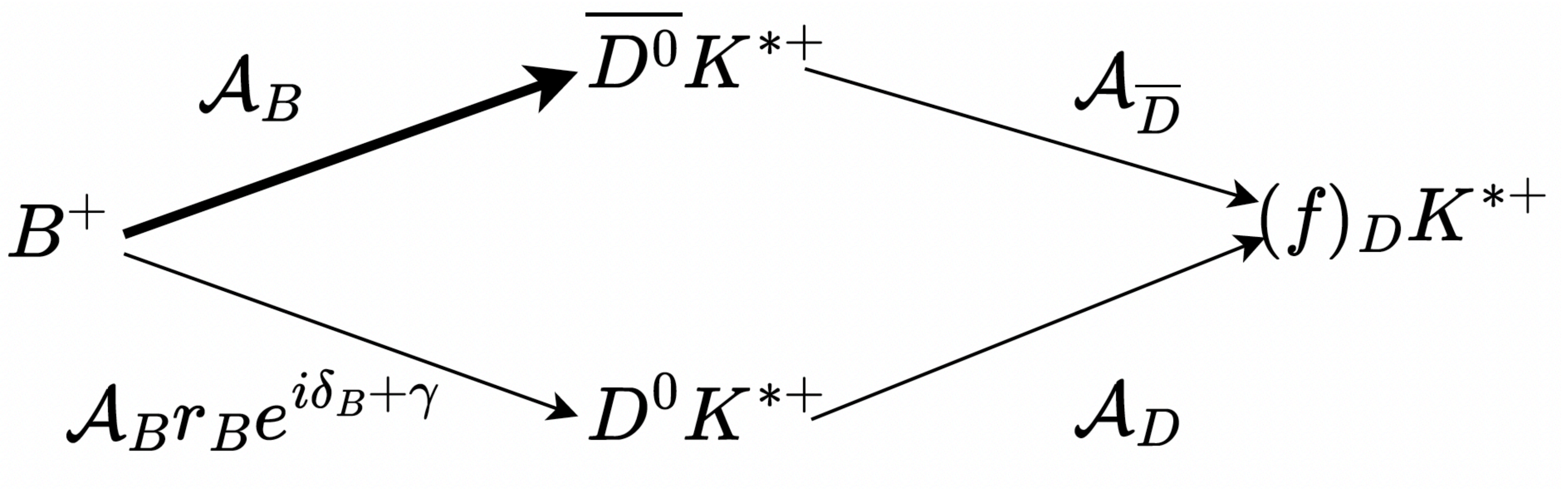
- Surpass LHCb design: 4°
- Consistent with SM predictions $(65.5^{+0.09}_{-2.65})^{\circ}$

# $\gamma$ measurement in $B^+ \to DK^{*+}(\to K_S^0\pi^+)$

LHCb-PAPER-2024-023
arXiv: 2410.21115

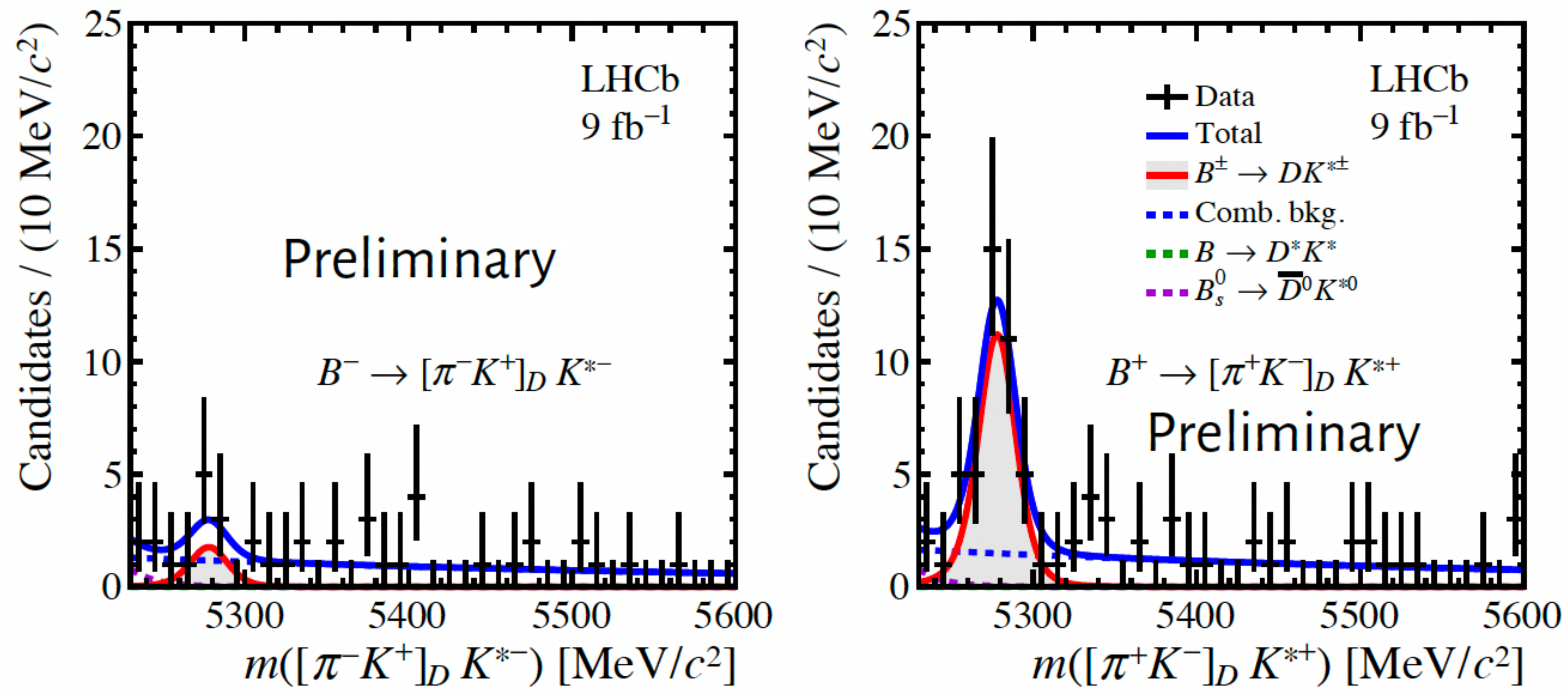
- CP eigenstates $D^0 \to hh, \pi\pi\pi\pi$
- Suppressed decays $D^0 \to K\pi, K\pi\pi\pi$
- Self-conjugated multi-body decays $D^0 \to K_S^0 hh$
- Inputs for $D^0 \to K_S^0 hh, \pi\pi\pi\pi$ from BESIII

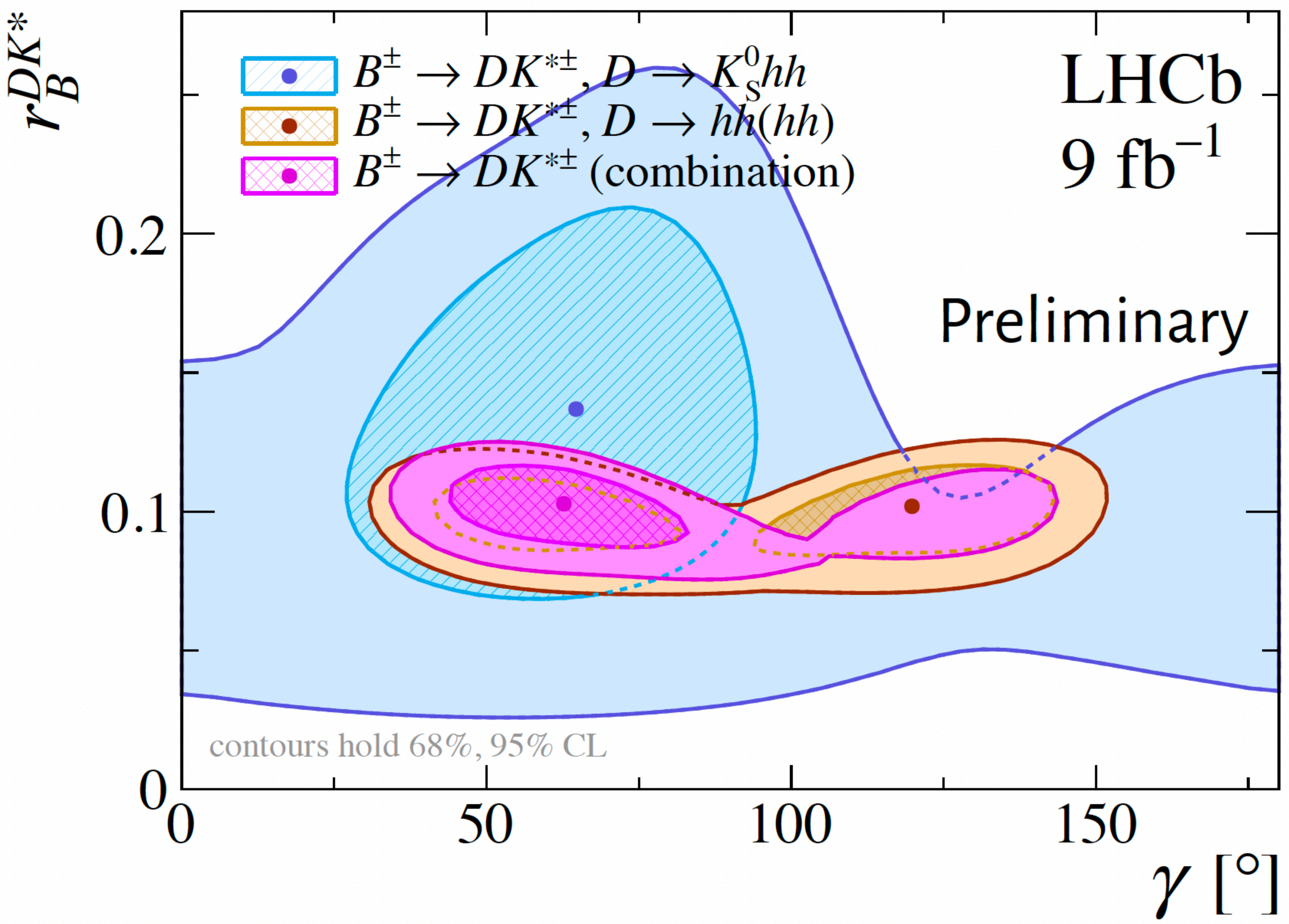
[PRD106.092004, PRD82(2010)112006, PRD102(2020)]




$\gamma = (63 \pm 13)^\circ$

First observation of $B^+ \to [D^0]_{\pi K,\pi K\pi\pi} K^{*+}$

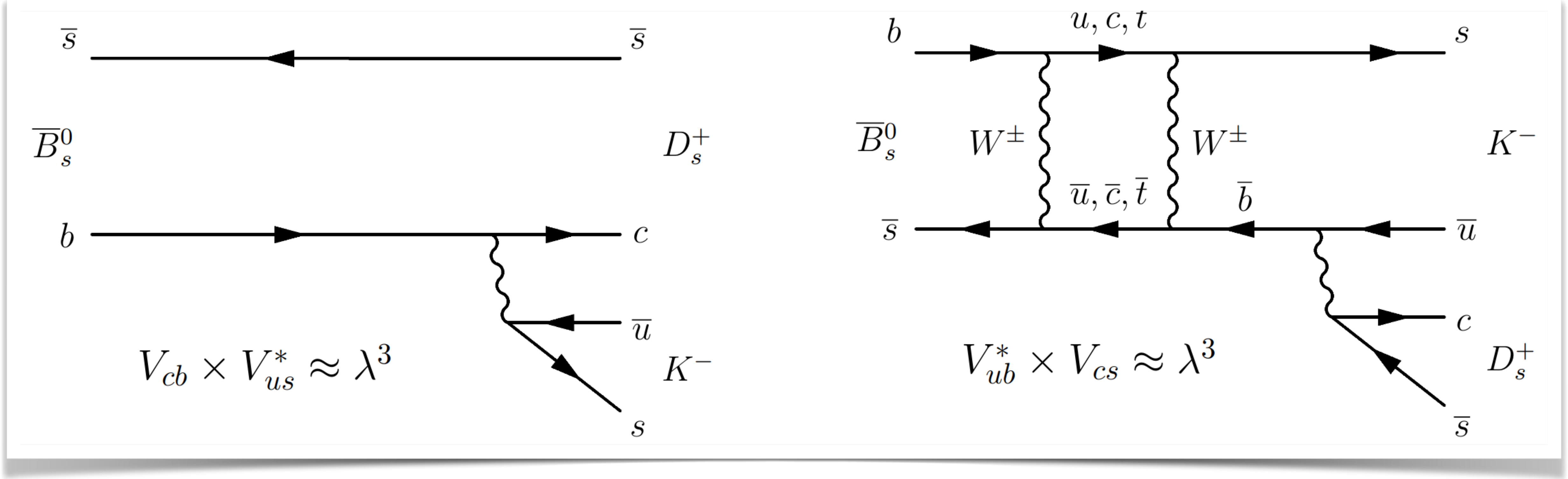


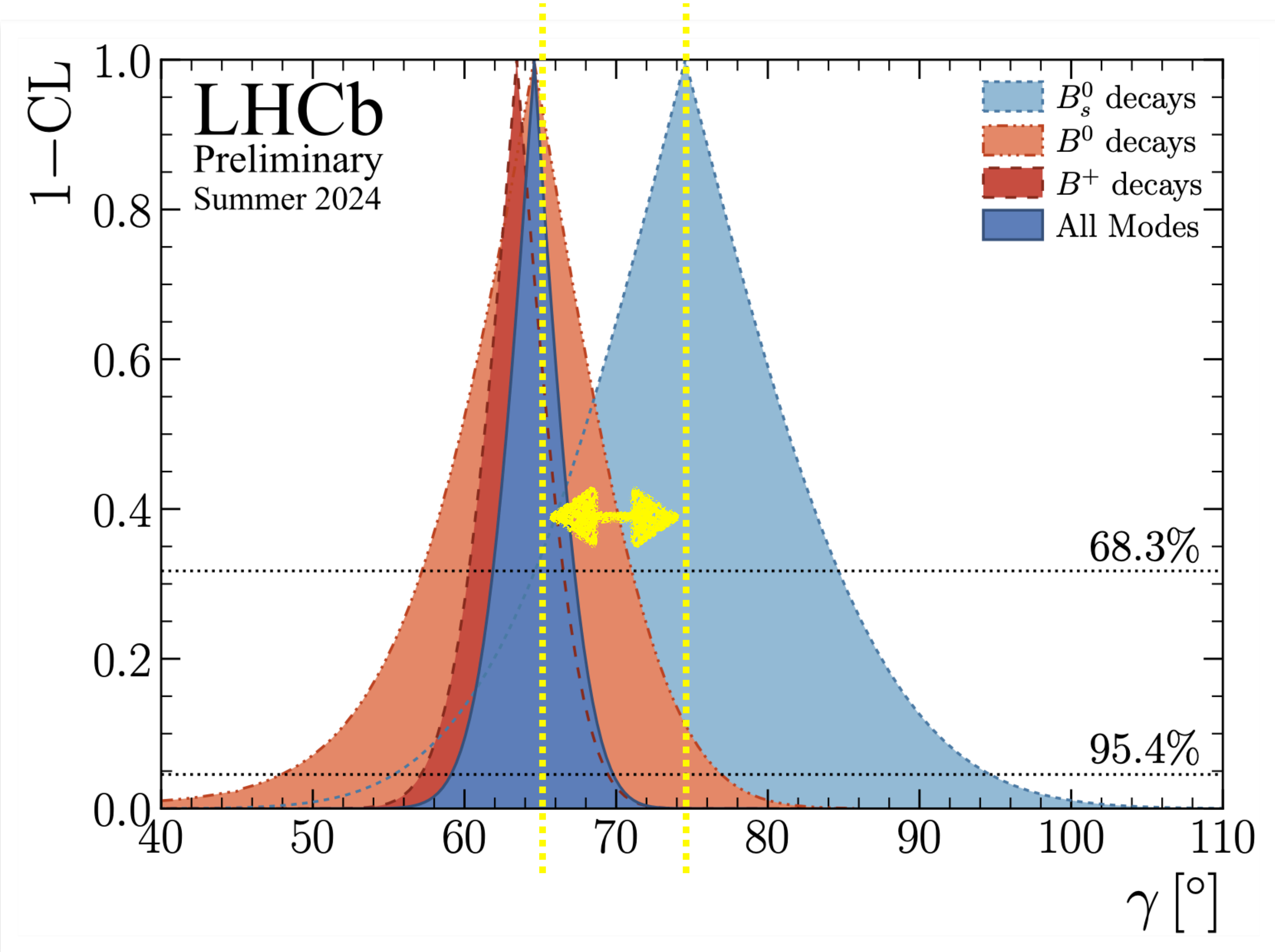



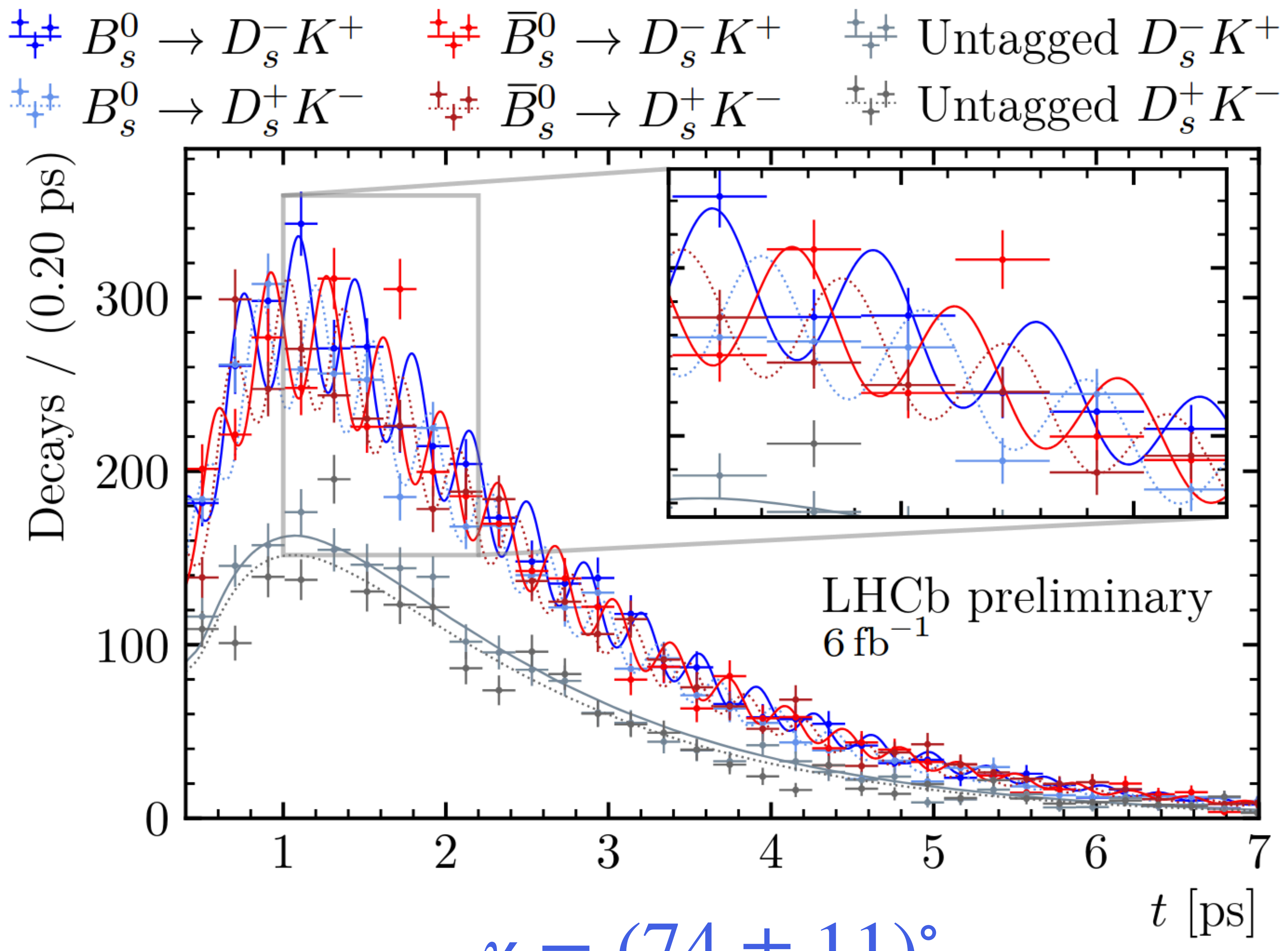
# $\gamma$ measurement in $B_s^0 \to D_s^{\mp} K^{\pm}$

LHCb-PAPER-2024-020
in preparation

- Time-dependent CP violation measurement
- Interference between mixing and decay $\to$ relative phase difference of $\gamma - 2\beta_s$




$\gamma = (74 \pm 11)^\circ$

# CKM angles $\beta_{(s)}$

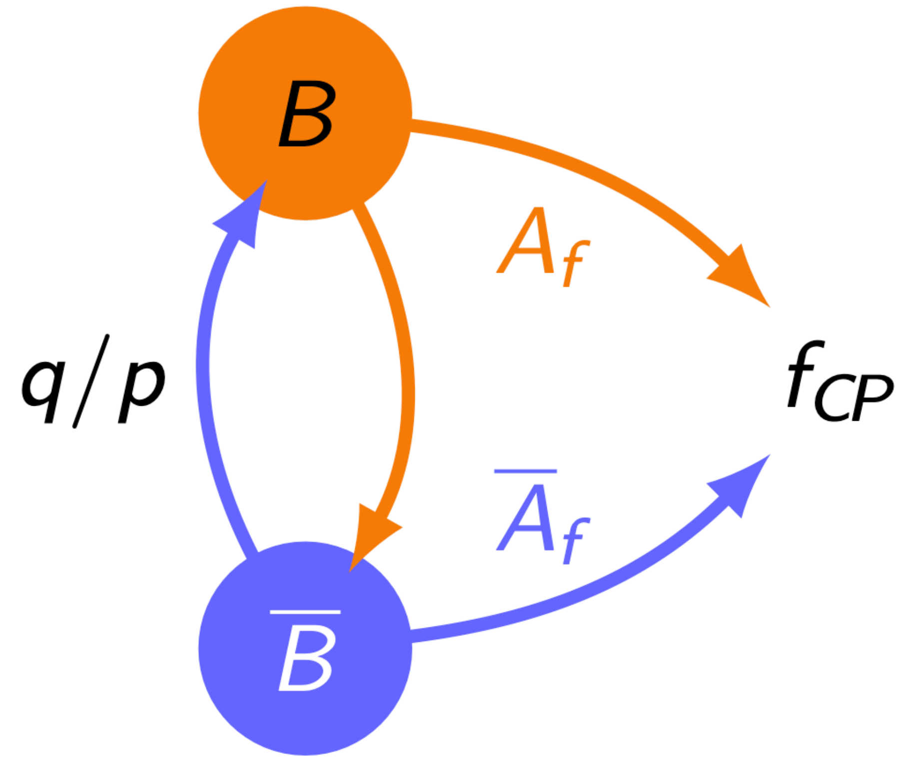
Phys. Rev. Lett. 132 (2024) 021801

Phys. Rev. Lett. 132 (2024) 051802

- Tree dominated $b \to c\bar{c}s$ transition offers access to the CKM angle $\beta_{(s)}$
- CP violation in the interference between mixing and decays

$$\beta_{(s)} = arg\left(-\frac{V_{cq}V_{cb}^*}{V_{tq}V_{tb}^*}\right)$$

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} \quad \propto -D_{\rm tag} \cdot D_t \cdot \eta_f \cdot \sin 2\beta_{(s)} \cdot \sin(\Delta m_{(s)} t)$$



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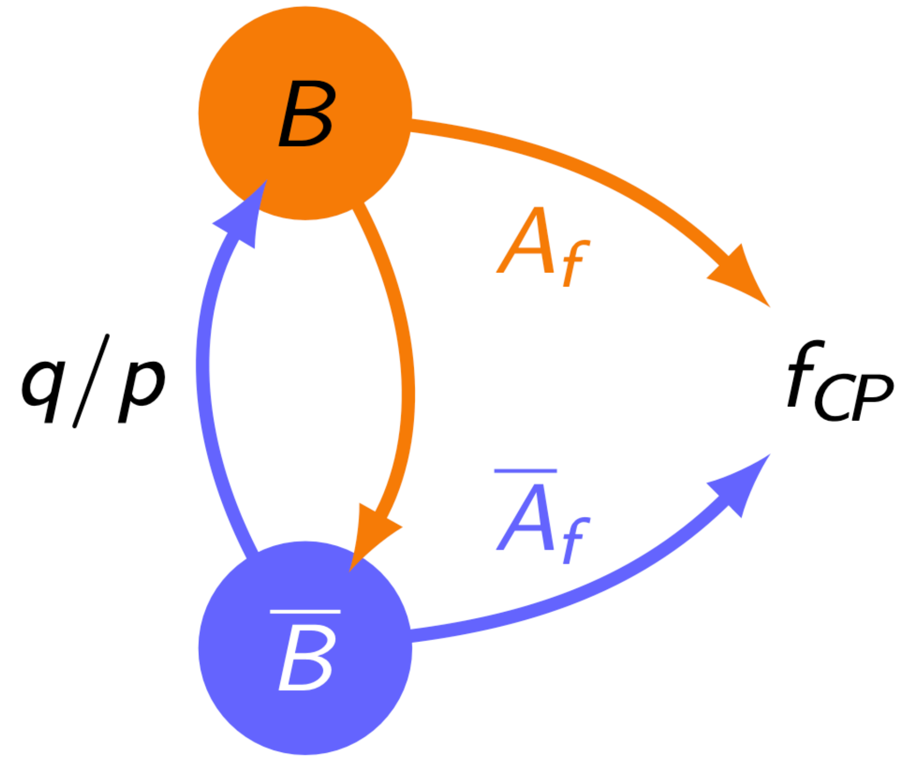
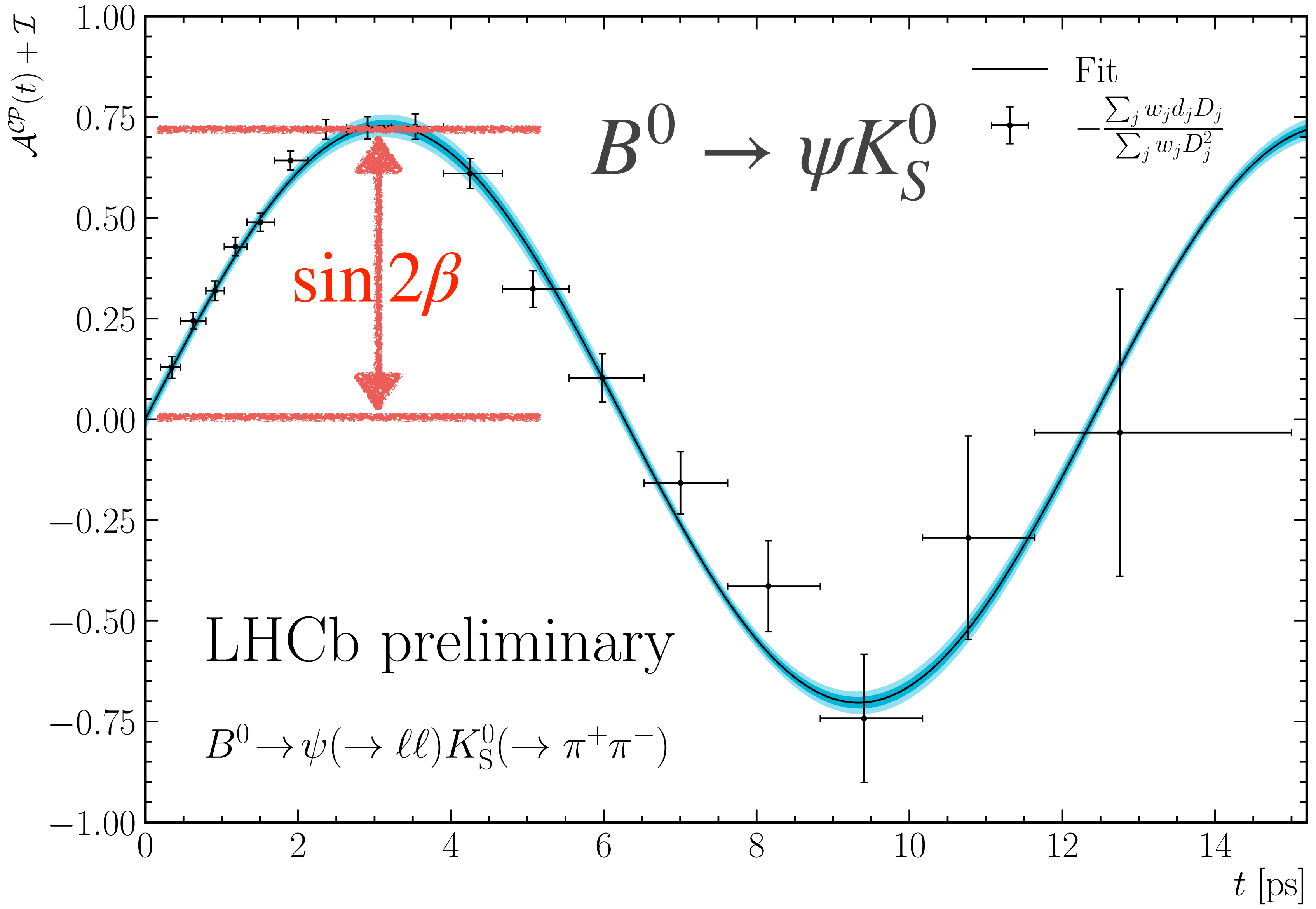
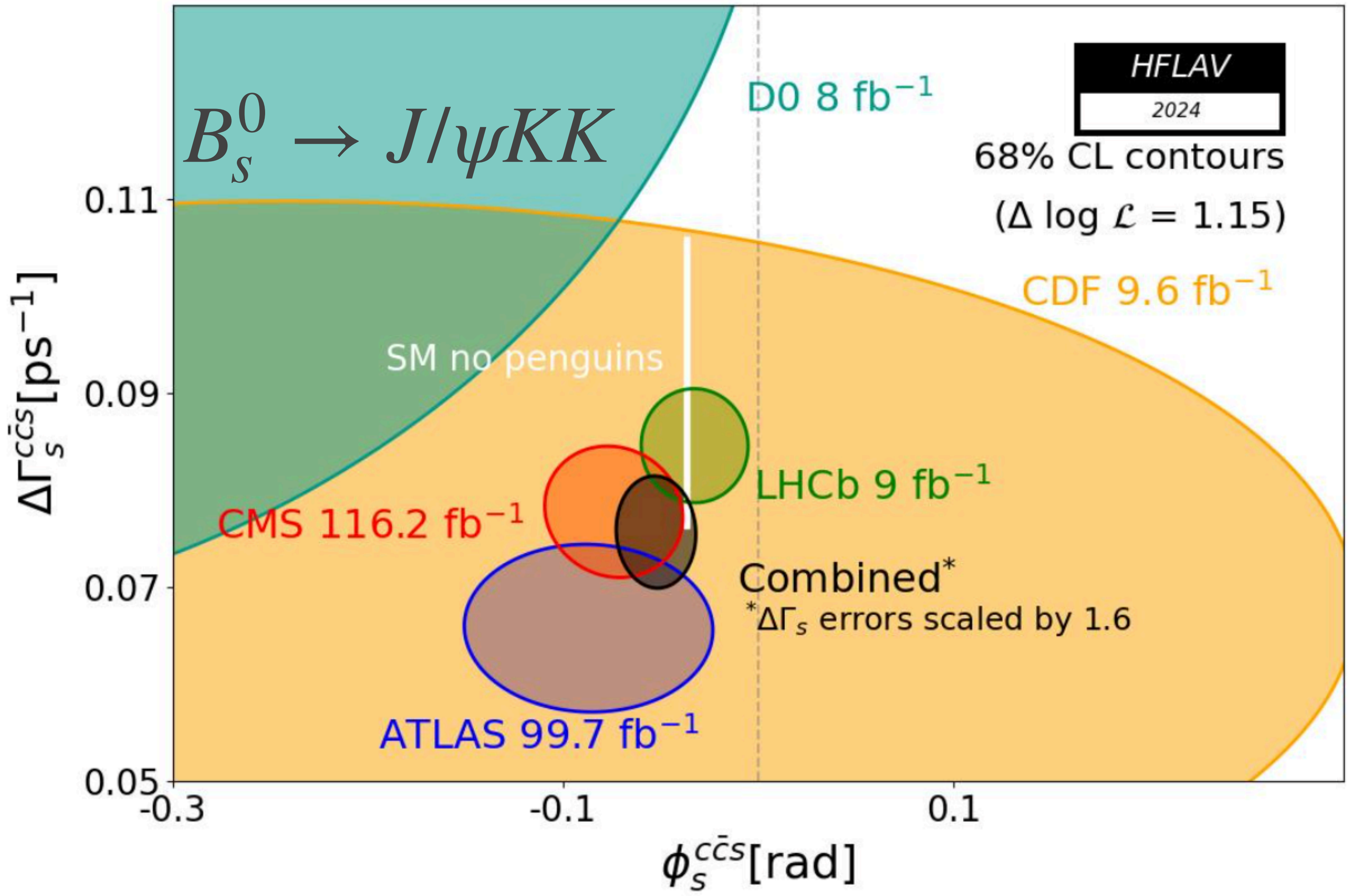



World best measurements!

$$S^{\text{Run 2}}_{\psi K^0_S} = 0.716 \pm 0.013 \pm 0.008$$

$$\phi_s^{c\bar{c}s} = -0.031 \pm 0.018 \text{ rad}$$




$$\phi_s^{CKMFitter} \approx -2\beta_s$$
$$= (-0.0368^{+0.0006}_{-0.0009}) \text{ rad}$$

# Direct CPV in $B^+ \to J/\psi\pi^+$

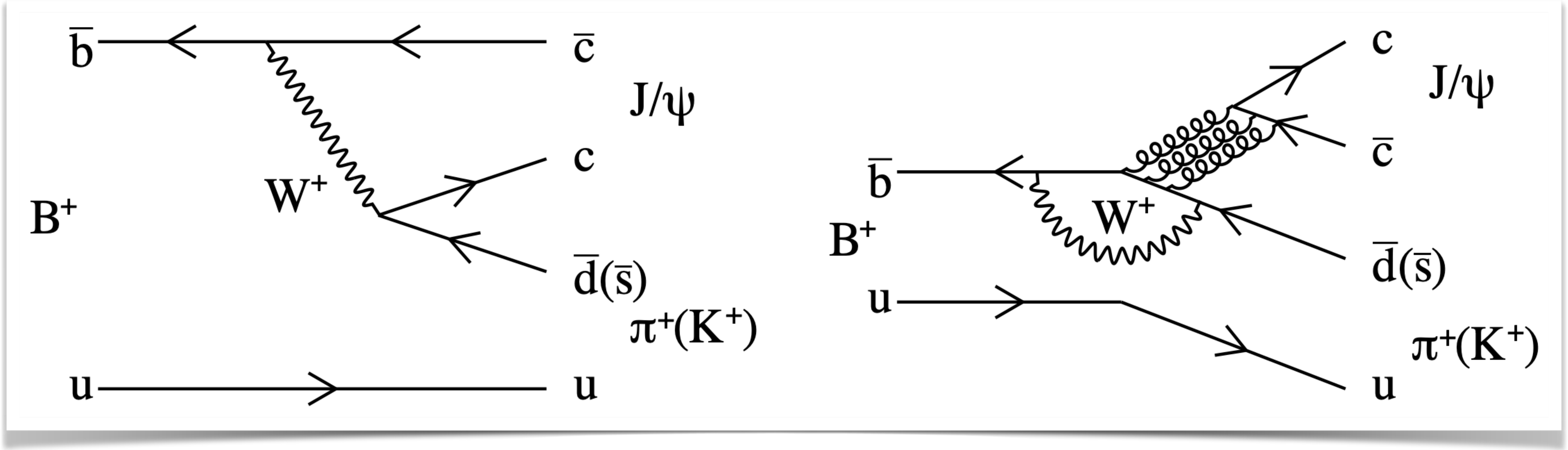
**New**

LHCb-PAPER-2024-31
in preparation

- O(1%) direct CP violation expected in $B^+ \to J/\psi\pi^+$ [PRD 49 (1994) 5904, PRD 52 (1995) 242]
- Important control channel to understand penguin effects in $\sin 2\beta$ measurement in $B^0 \to J/\psi K^0$

[PRD 79 (2009) 014030, JHEP 03 (2015) 145]

$A_T \propto \lambda^3$ $A_P \propto \lambda^3$



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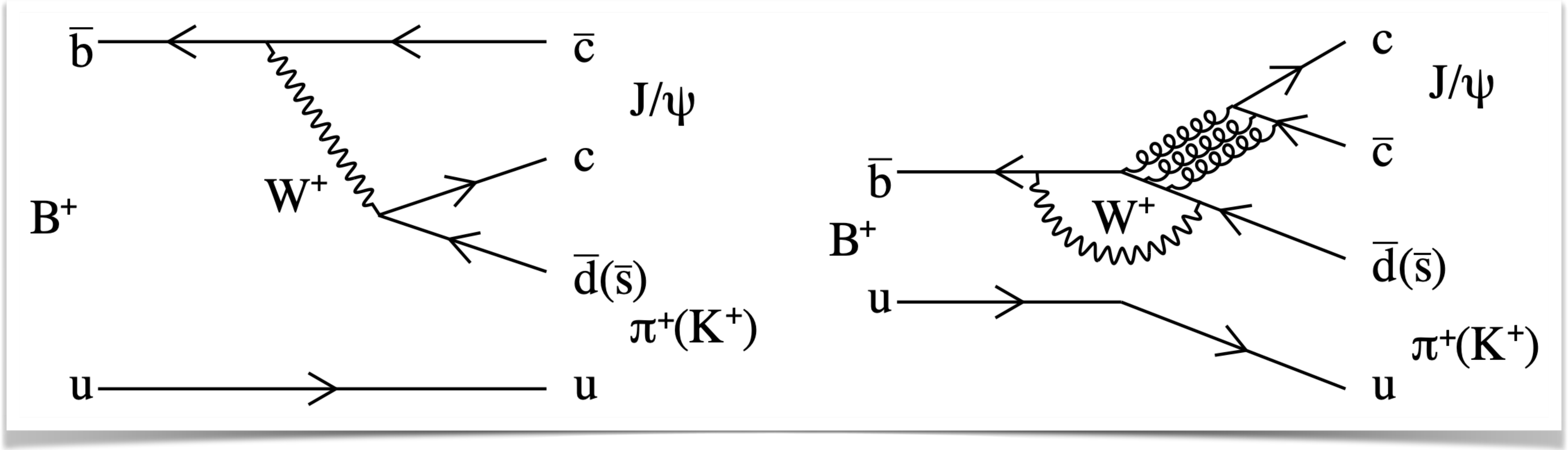
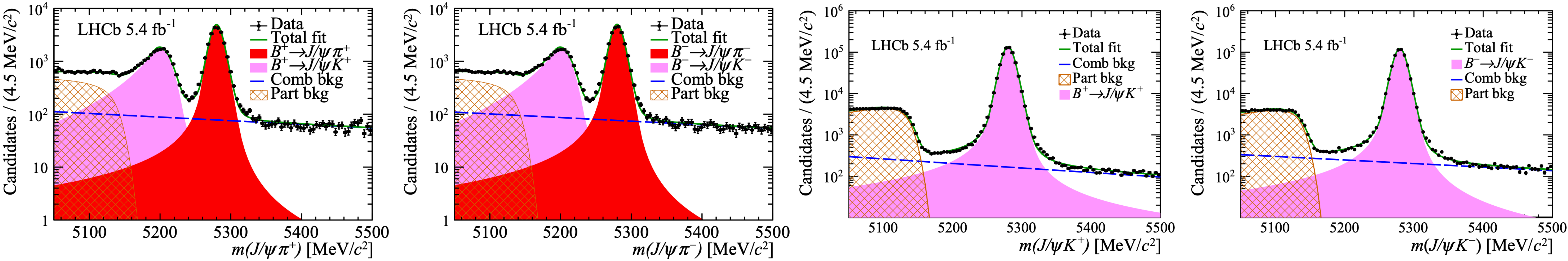


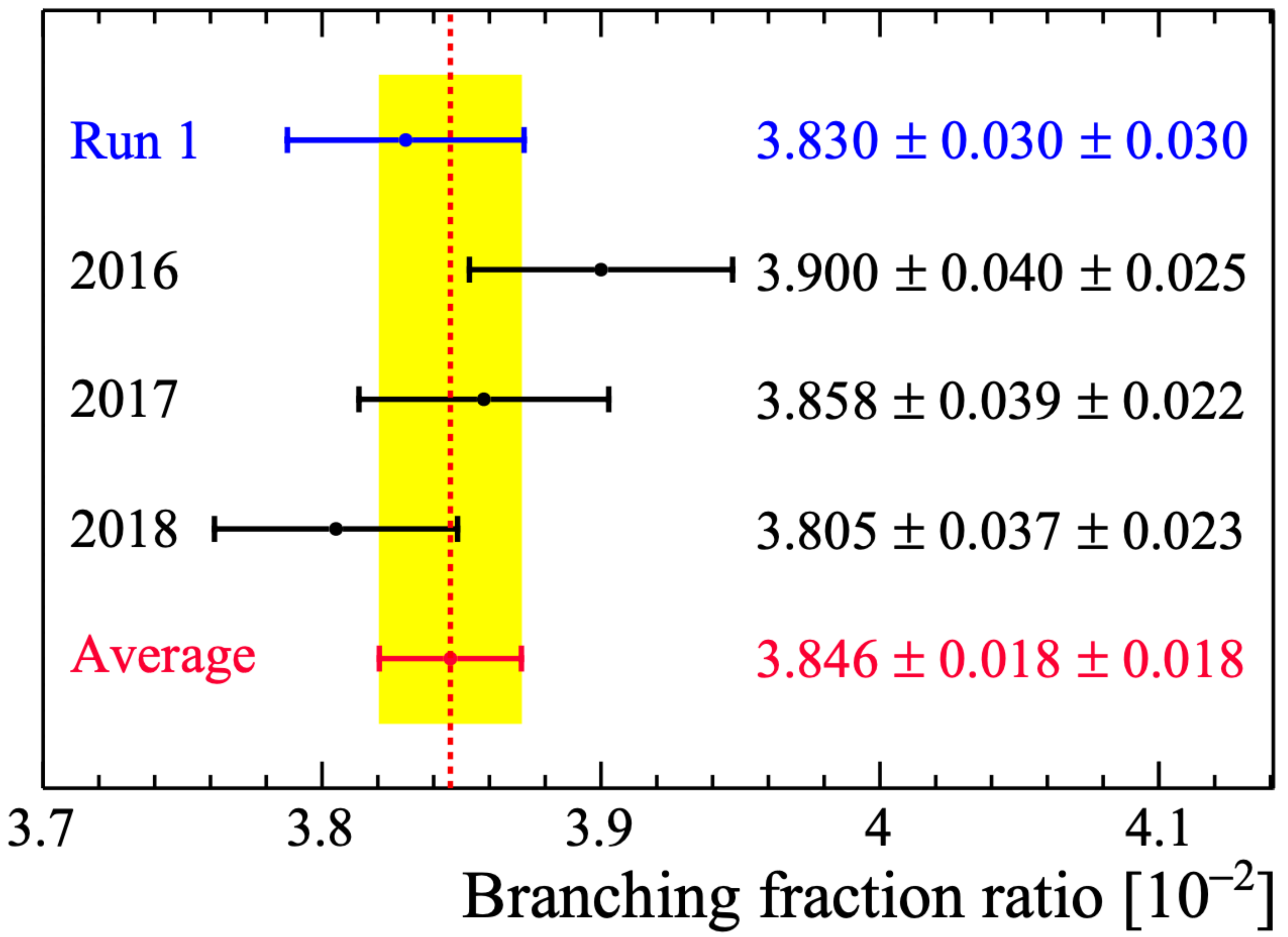

$$\mathcal{R}_{\pi/K} \equiv \frac{B(B^+ \to J/\psi\pi^+)}{B(B^+ \to J/\psi K^+)} = \frac{N_\pi}{N_K} \times \frac{\epsilon_K}{\epsilon_\pi}$$



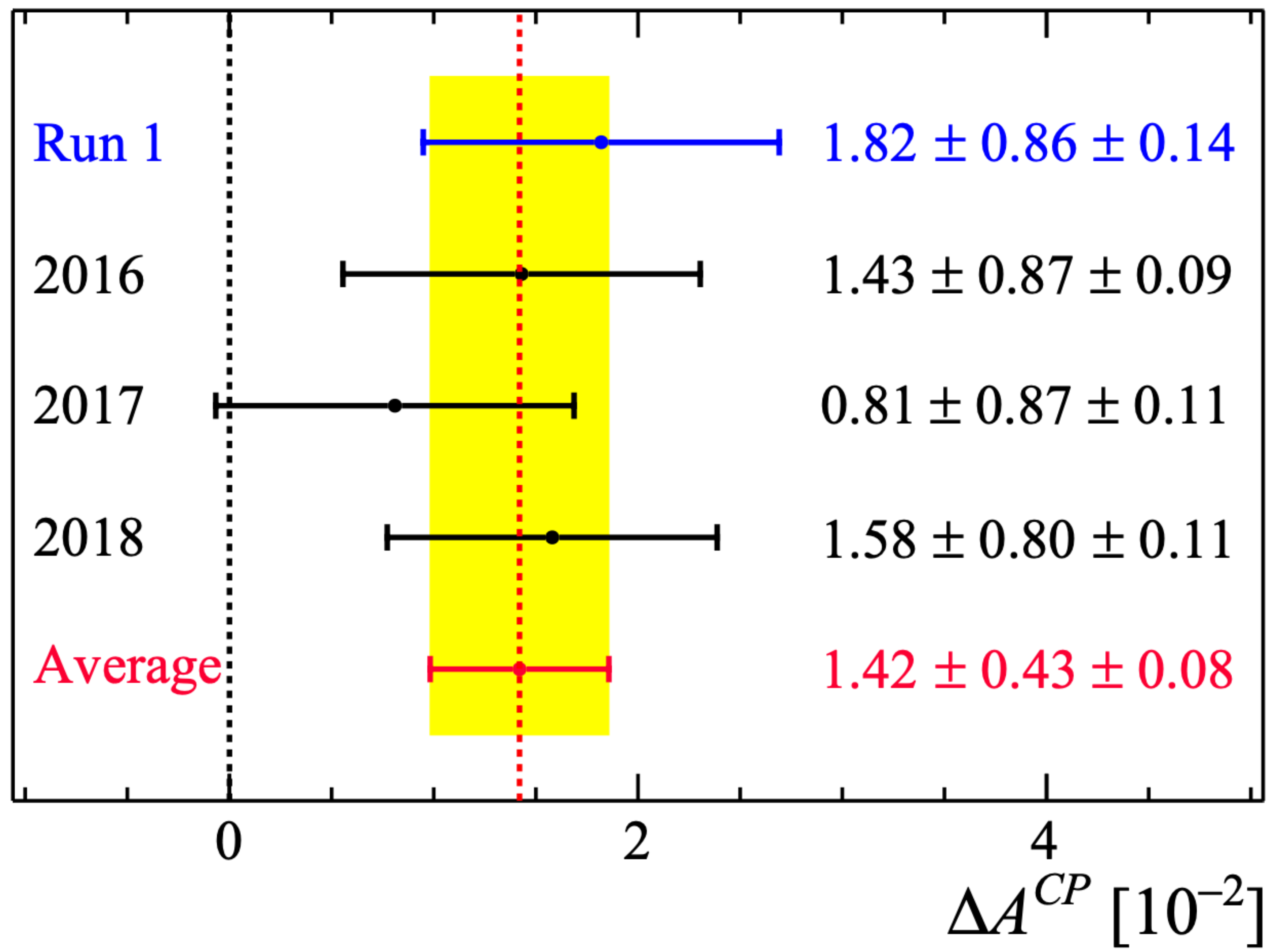
# Direct CPV in $B^+ \to J/\psi\pi^+$

**New** LHCb-PAPER-2024-31
in preparation

First evidence for direct CP violation in beauty decays to charmonium final states (3.2 $\sigma$)




$\Delta A^{CP} = A^{CP}(B^+ \to J/\psi\pi^+) - A^{CP}(B^+ \to J/\psi K^+)$



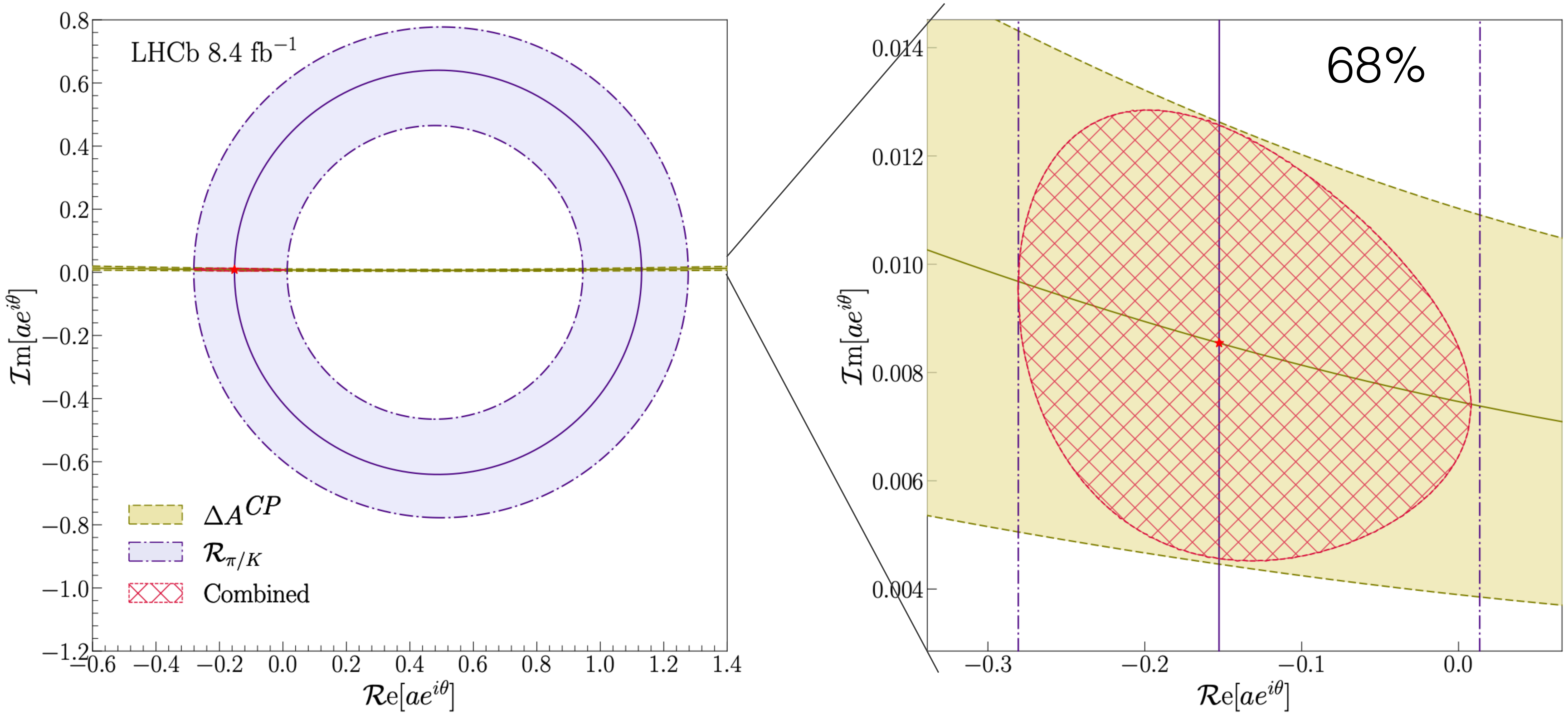

- Taking previous LHCb result of $A^{CP}(B^+ \to J/\psi K^+)$ to extract: [Phys. Rev. D 95, 052005 (2017)]

$$A^{CP}(B^+ \to J/\psi\pi^+) = (1.51 \pm 0.50 \pm 0.11)\times 10^{-2}$$

# Penguin constraint

***New*** LHCb-PAPER-2024-31 in preparation

$$A(B^+ \to J/\psi\pi^+) = -\lambda\mathcal{A}(1 + ae^{i\theta}e^{i\gamma}) \quad A(B^+ \to J/\psi K^+) = (1 - \lambda^2/2)\mathcal{A}'(1 + \epsilon a'e^{i\theta'}e^{i\gamma})$$



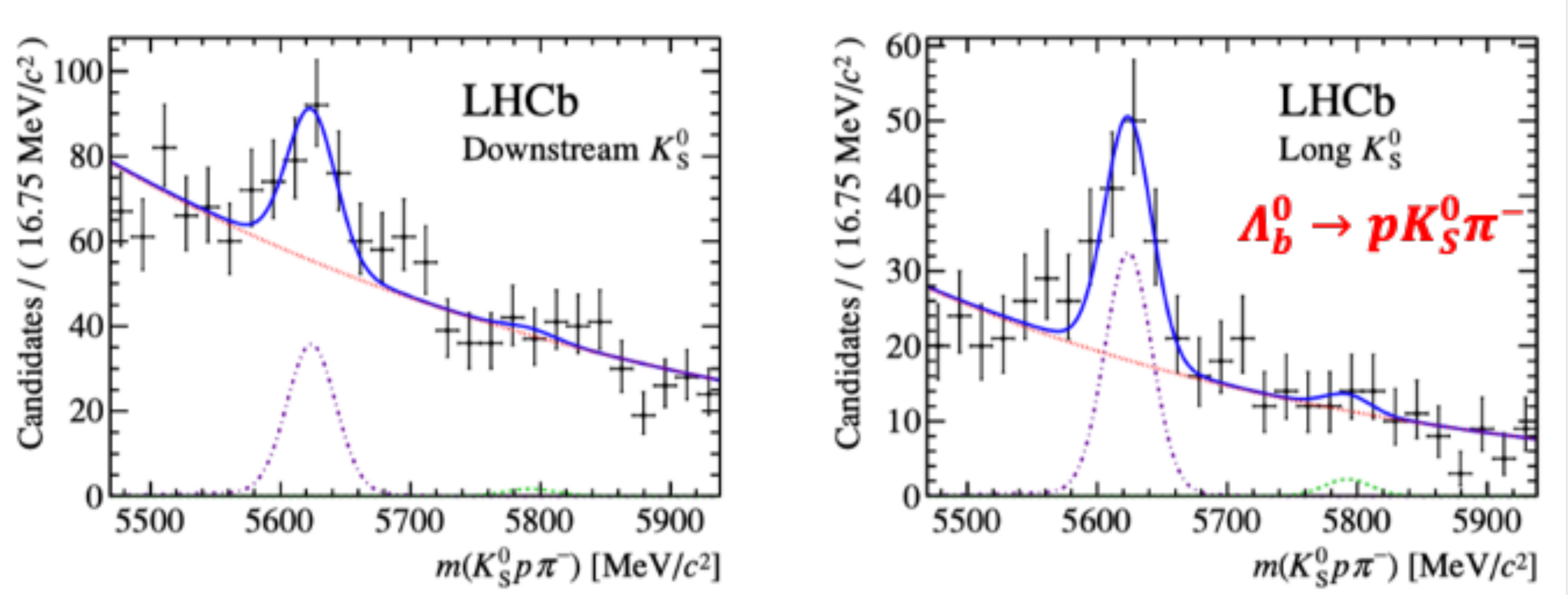

- SU(3) flavour symmetry: $a = a', \theta = \theta'$
- Constraints on the relative size (a) and strong phase difference ($\theta$) between penguin and tree contributions

See more details in Manshu Li's talk (Thursday afternoon)

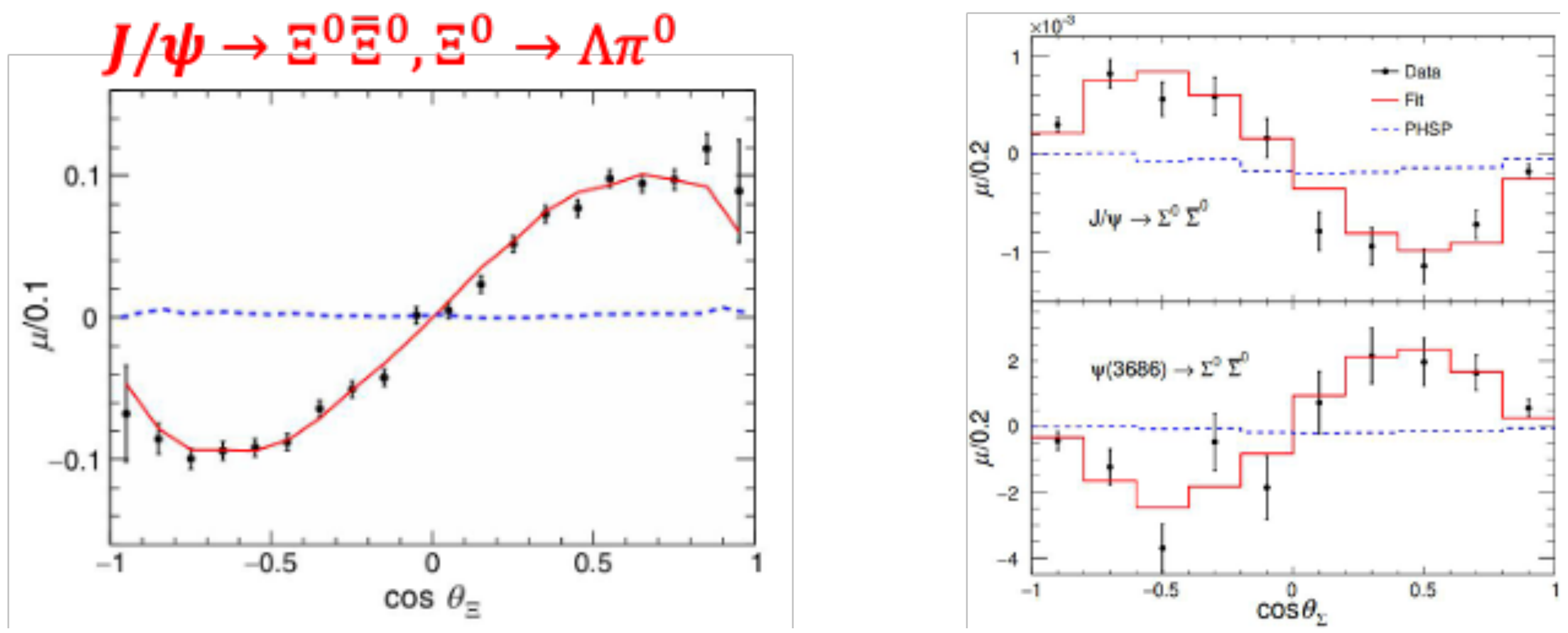
# CP violation in baryonic decays?

- Baryons crucial for asymmetries in Universe, no CP violation in baryons observed yet
- CPV: $b$ baryons $\mathcal{O}(1-10\%)$, $c$ baryons $\mathcal{O}(0.1\%)$, hyperon $\mathcal{O}(0.001-0.01\%)$

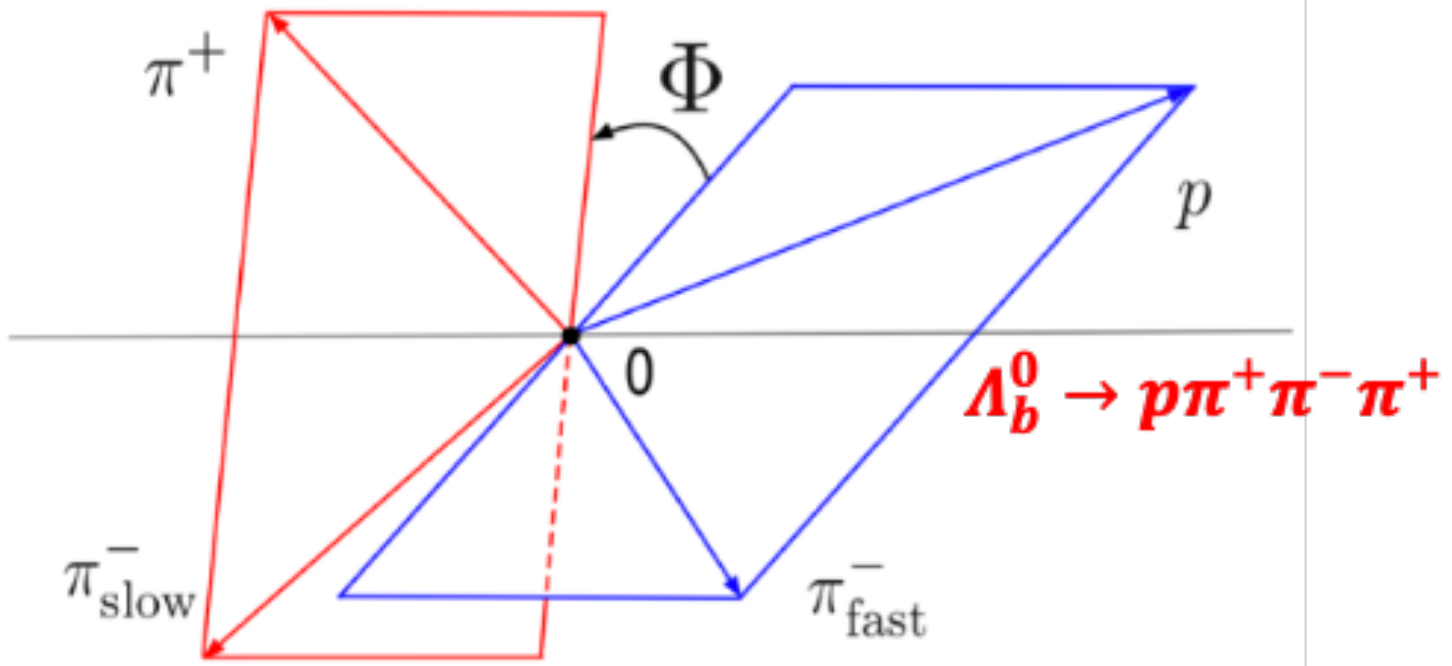
**Direct CP violation ($\propto \sin(\Delta\delta_{ST})\sin(\Delta\phi_{EW})$)**




**Decay parameters asymmetry**

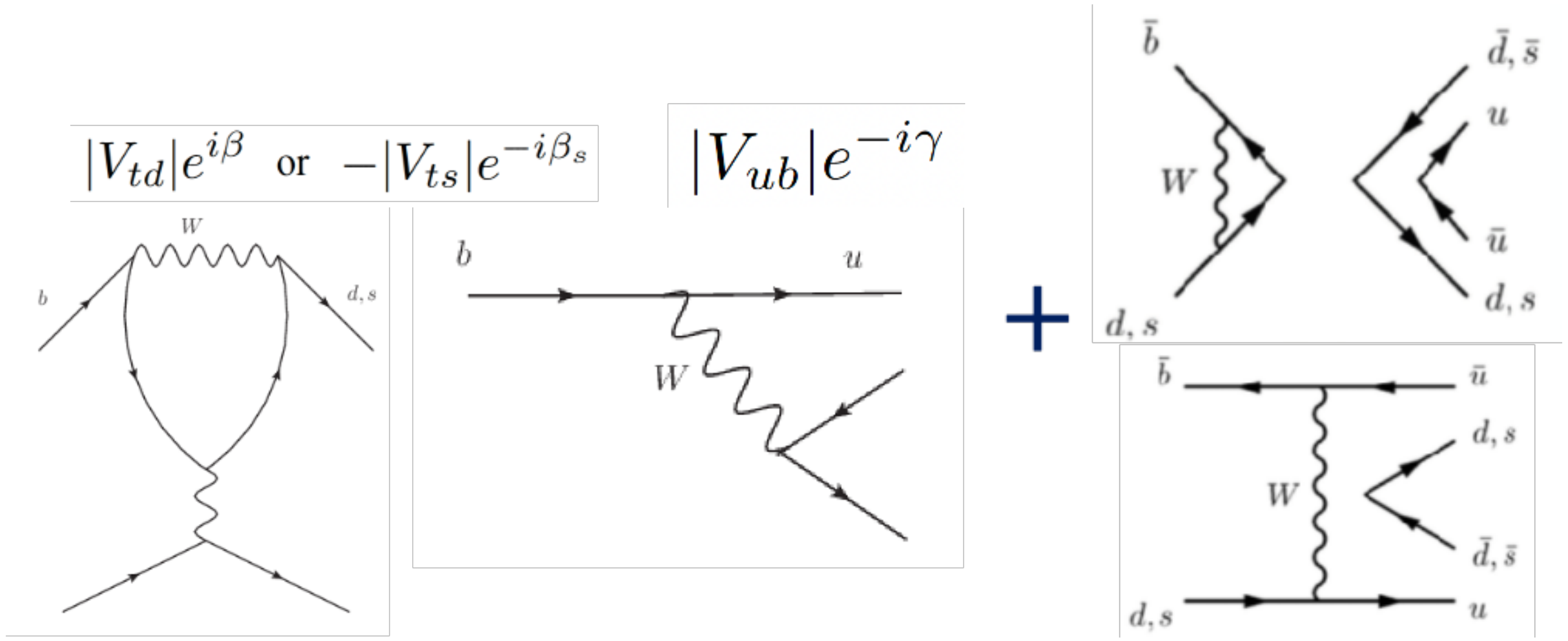


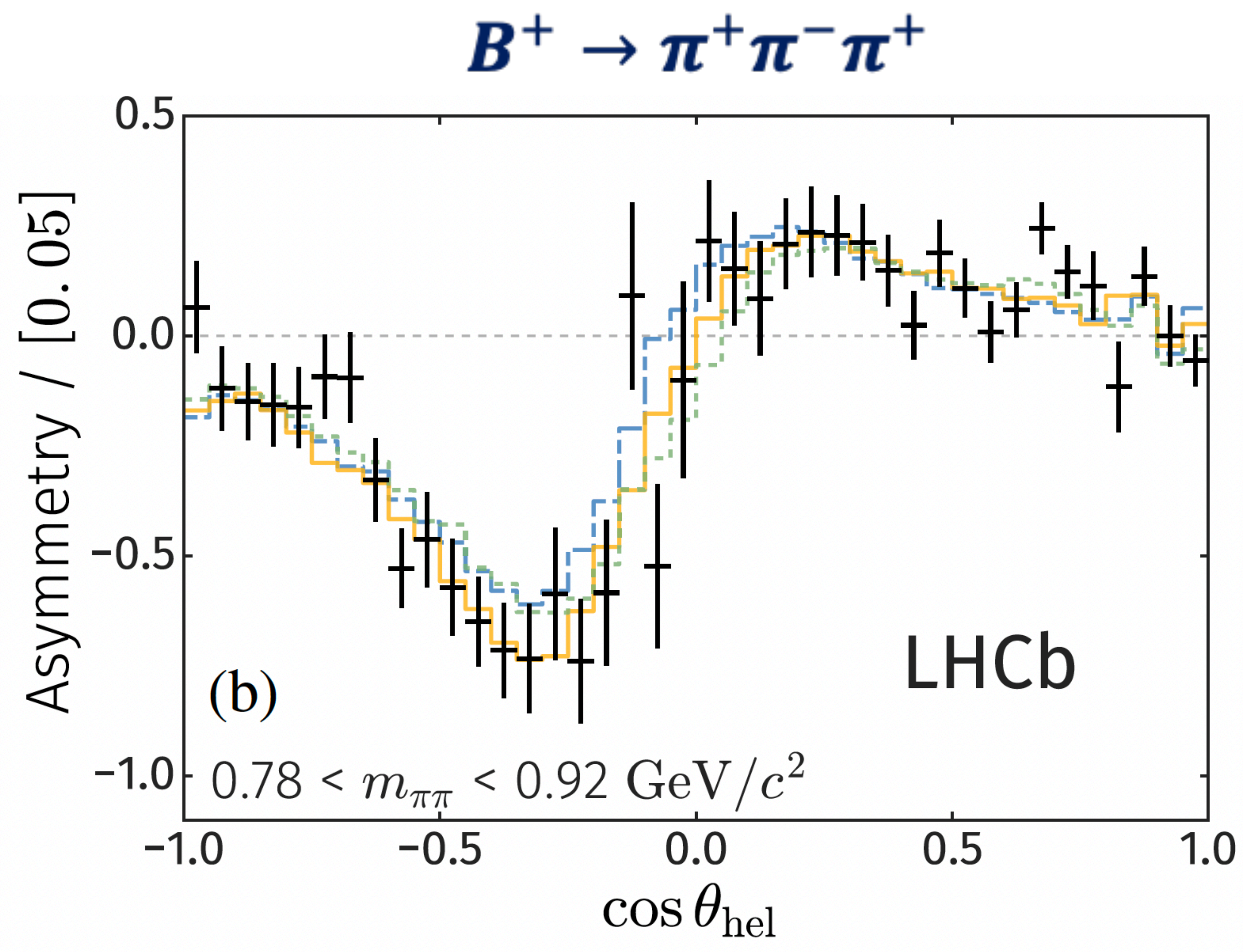

**Triple-product asymmetry ($\propto \cos(\Delta\delta_{ST})\sin(\Delta\phi_{EW})$)**

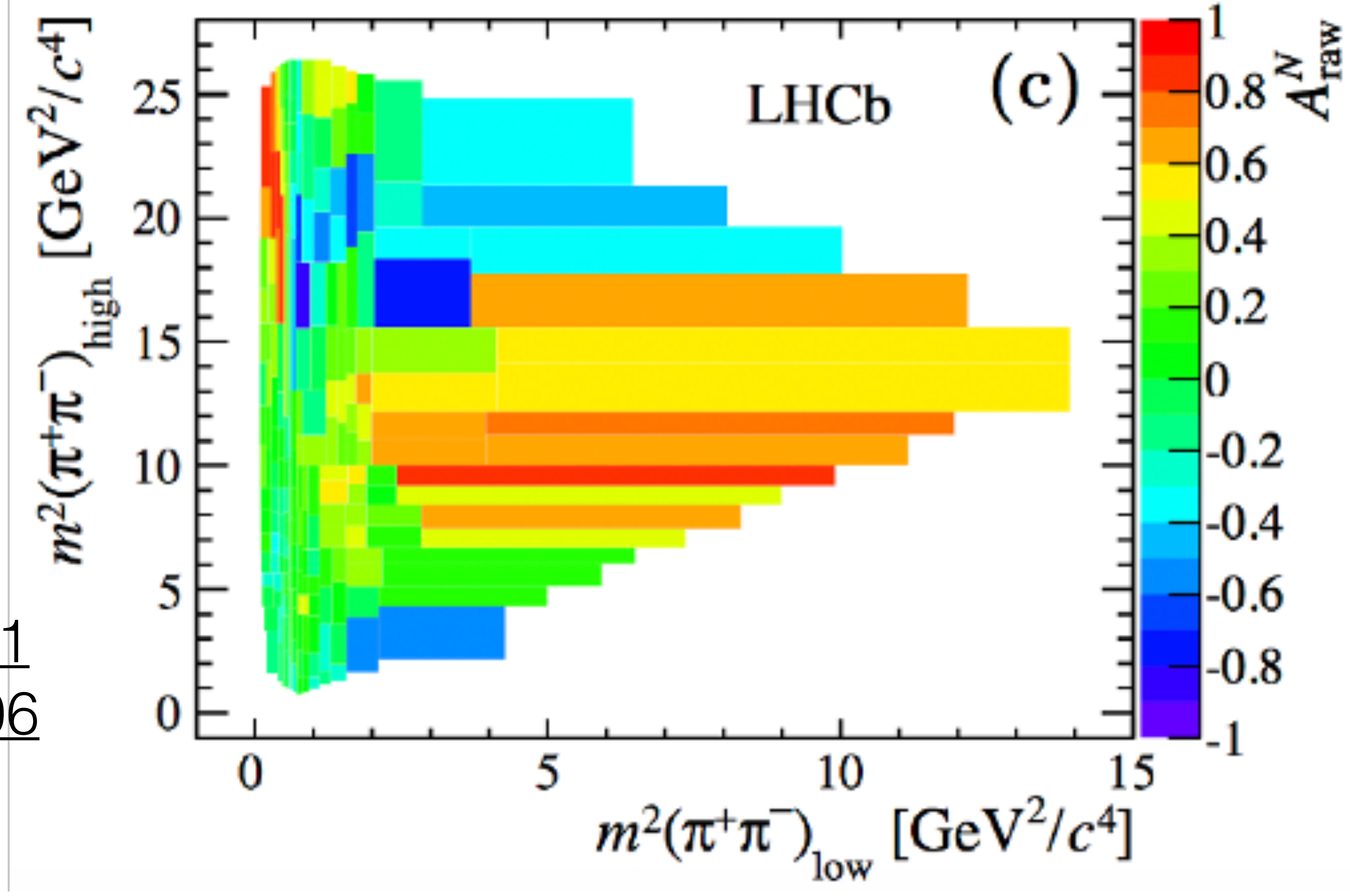



- Puzzling situation: similar $\Lambda^0_b$ production as $B^+$, huge significance of CPV in $B^+$, none in $\Lambda^0_b$?

# Charmless three-body $b$ decays




- Complex CP violation pattern in multi-body $B$ decays, as large as 80%
- Interesting to search for CP violation in $\Lambda_b^0 \to \Lambda h^+ h^{\prime -}$

PRL124 (2020) 031801
PRD101 (2020) 012006

# First observation of $\Lambda_b^0(\Xi_b^0) \to \Lambda\pi^+\pi^-(K^-)$

***New***

CERN Seminar by W. Qian

LHCb-PAPER-2024-043
in preparation

- Systematic study of $\Lambda_b^0/\Xi_b^0 \to \Lambda h^+ h^{'-}$ with control mode to reduce systematic uncertainty

$$\frac{\mathcal{B}\left(\Lambda_b^0\left(\Xi_b^0\right) \to \Lambda h^+ h'^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+\left(\to \Lambda\pi^+\right)\pi^-\right)} = \frac{N_{\Lambda_b^0\left(\Xi_b^0\right) \to \Lambda h^+ h'^-}}{N_{\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-}} \times \frac{\epsilon_{\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-}}{\epsilon_{\Lambda_b^0\left(\Xi_b^0\right) \to \Lambda h^+ h'^-}} \times \frac{f_{\Lambda_b^0}}{f_{\Lambda_b^0(\Xi_b^0)}}$$

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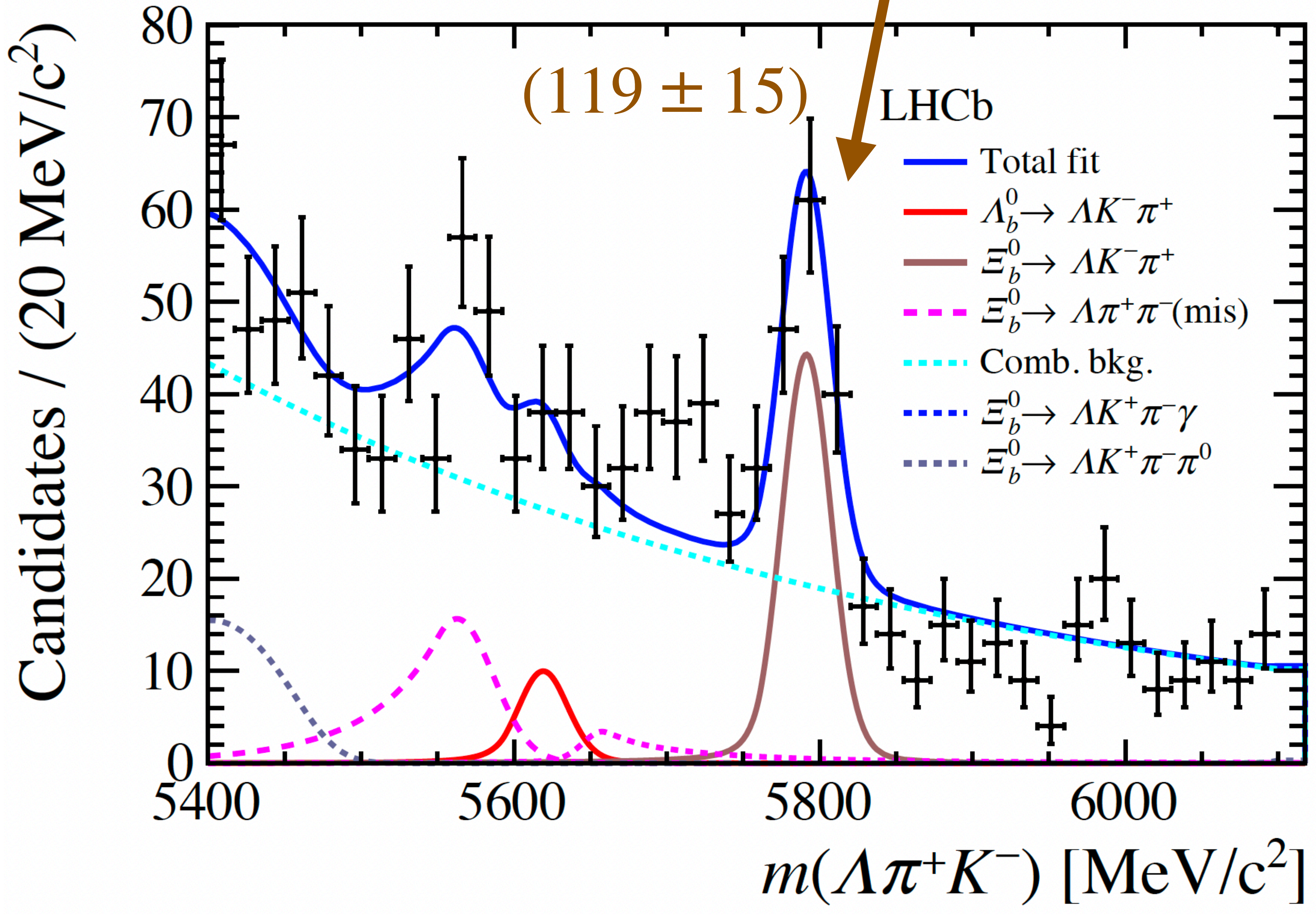
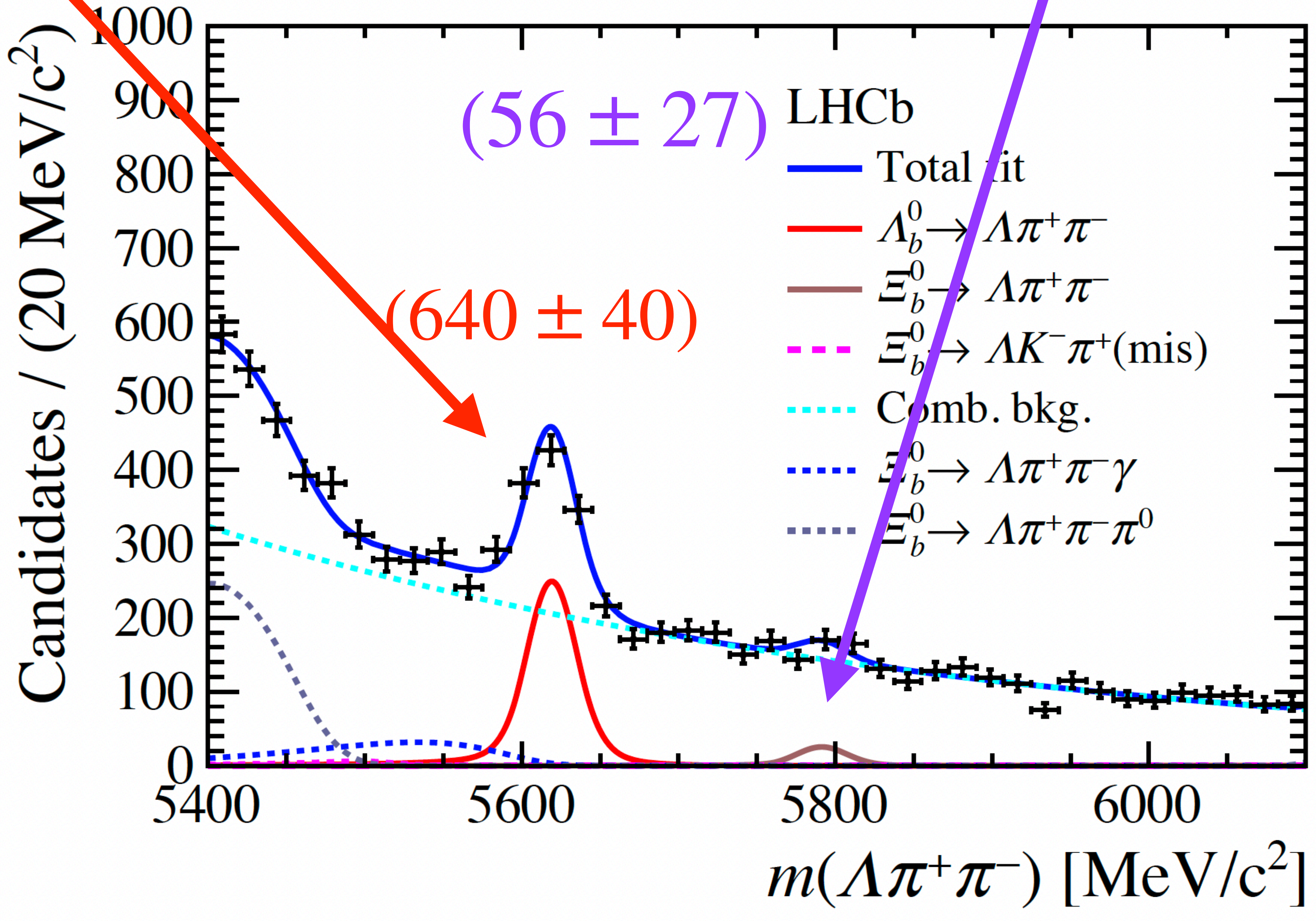
First observations of $\Xi_b^0 \to \Lambda K^-\pi^+$ & $\Lambda_b^0 \to \Lambda\pi^+\pi^-$ and evidence for $\Xi_b^0 \to \Lambda\pi^+\pi^-$ ($4\sigma$)

$\mathcal{B} = (10.4 \pm 1.4 \pm 1.2 \pm 3.5) \times 10^{-6}$ $\mathcal{B} = (5.3 \pm 0.4 \pm 0.5 \pm 0.5) \times 10^{-6}$ $\mathcal{B} = (11.0 \pm 2.6 \pm 1.4 \pm 3.8) \times 10^{-6}$



# Evidence of CP violation in baryonic decays

CERN Seminar by W. Qian

**New** LHCb-PAPER-2024-043
in preparation

**Signal channel**

$$A_{CP}^{S} = A_{\mathrm{Raw}}^{S} - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^{S}$$

**Control channel**

$$A_{CP}^{C} = A_{\mathrm{Raw}}^{C} - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^{C}$$

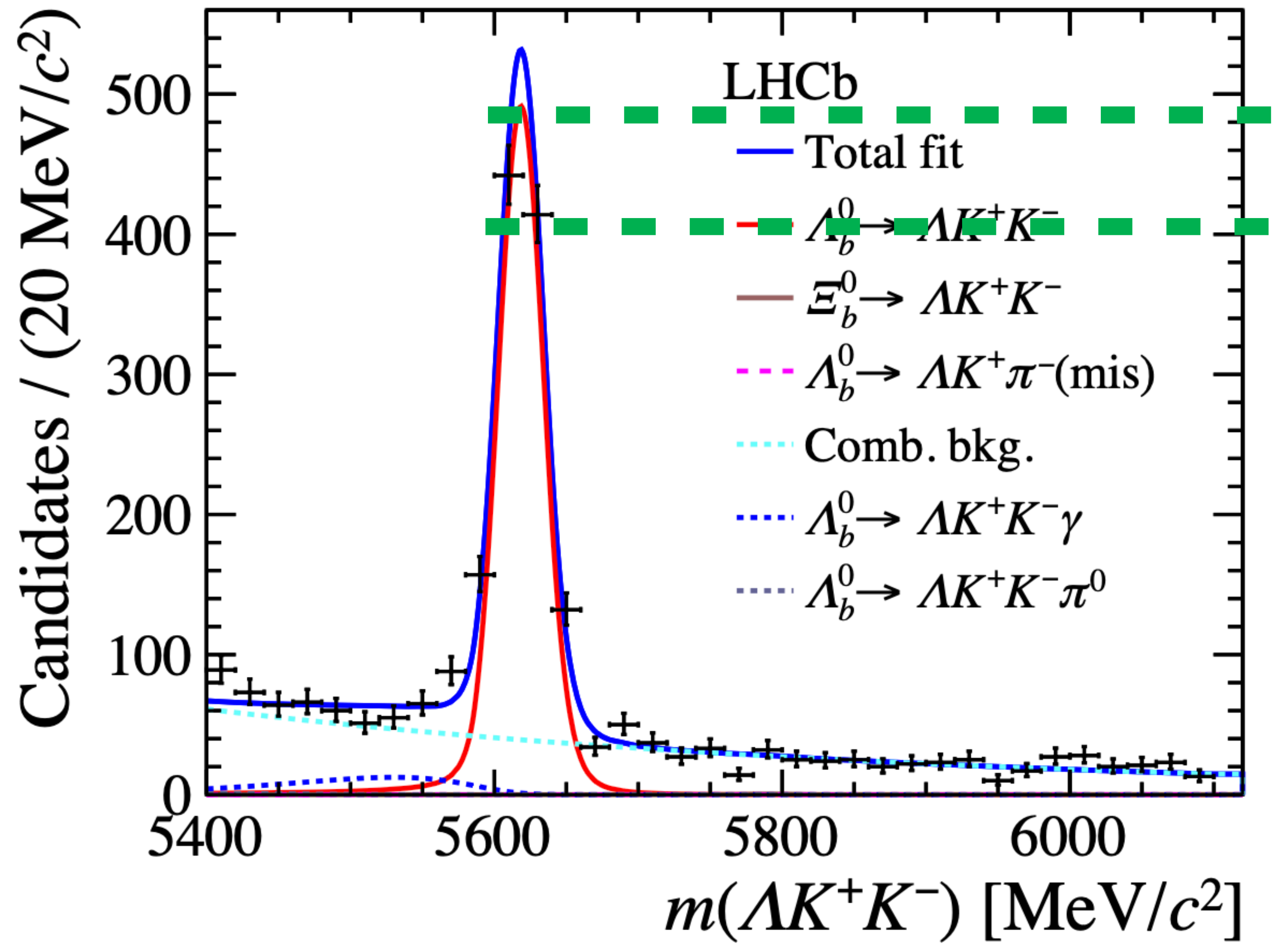
$$\Delta A_{CP} = \Delta A_{\mathrm{Raw}} - \Delta A_{\mathrm{P}}^{\Lambda_b^0} - \Delta A_{\mathrm{D}}$$

$\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-$

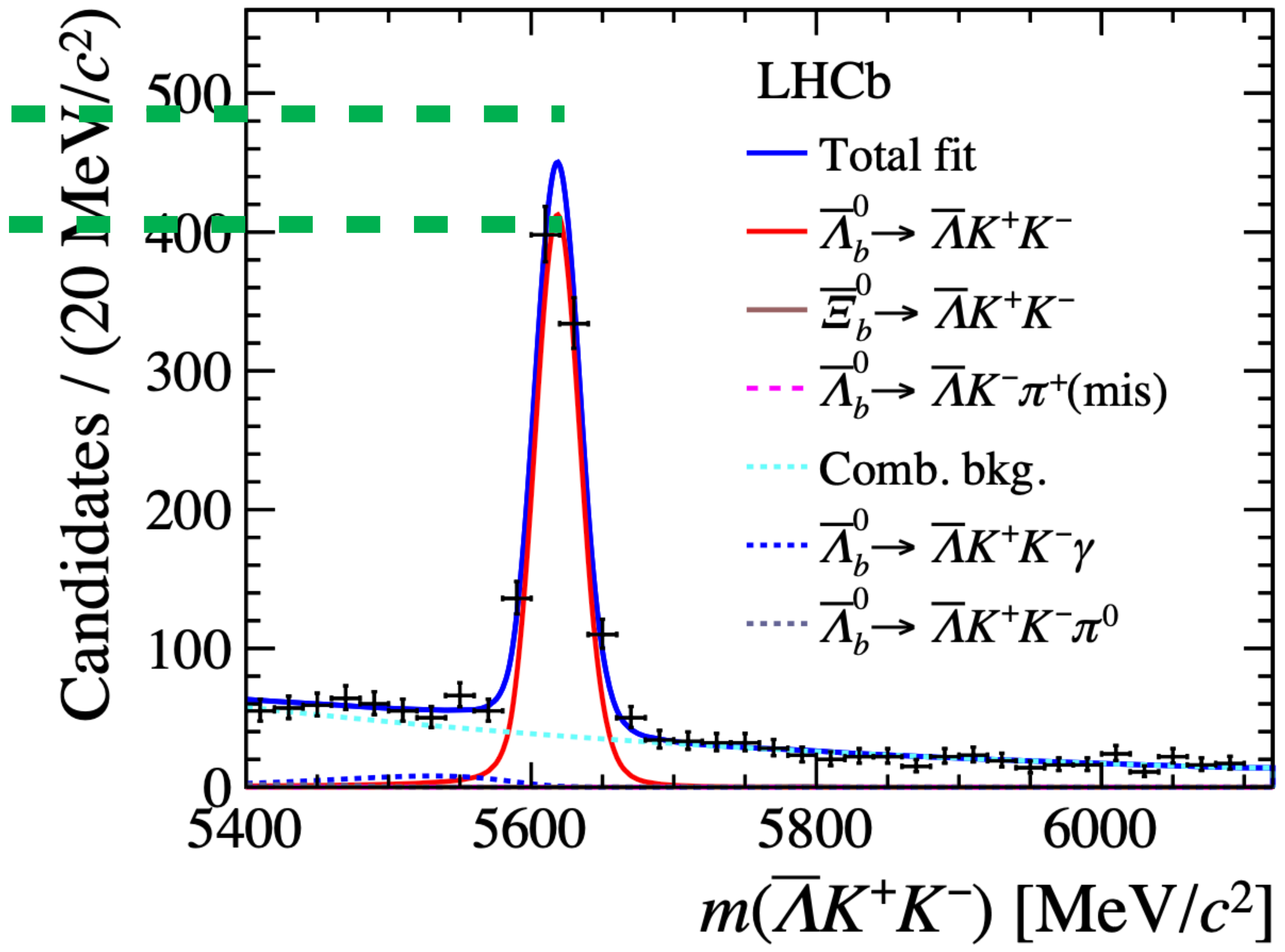
$A_{CP} \sim 0$

$$\mathcal{A}^{CP}(\Lambda_b^0/\Xi_b^0 \to f) \equiv \frac{\Gamma(\Lambda_b^0/\Xi_b^0 \to f) - \Gamma(\overline{\Lambda}_b^0/\overline{\Xi}_b^0 \to \overline{f})}{\Gamma(\Lambda_b^0/\Xi_b^0 \to f) + \Gamma(\overline{\Lambda}_b^0/\overline{\Xi}_b^0 \to \overline{f})}$$

Preliminary




$\Lambda_b^0 \to \Lambda K^+K^-$




$\bar{\Lambda}_b^0 \to \bar{\Lambda} K^+K^-$

$$\Delta A_{CP} = 0.083 \pm 0.023 \pm 0.016$$

First evidence for CP violation, $3.1\sigma$

# Evidence of CP violation in baryonic decays

CERN Seminar by W. Qian

***New*** LHCb-PAPER-2024-043
in preparation

**Signal channel**

$$\boldsymbol{A_{CP}^{S} = A_{\mathrm{Raw}}^{S} - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^{S}}$$

**Control channel**

$$\boldsymbol{A_{CP}^{C} = A_{\mathrm{Raw}}^{C} - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^{C}}$$

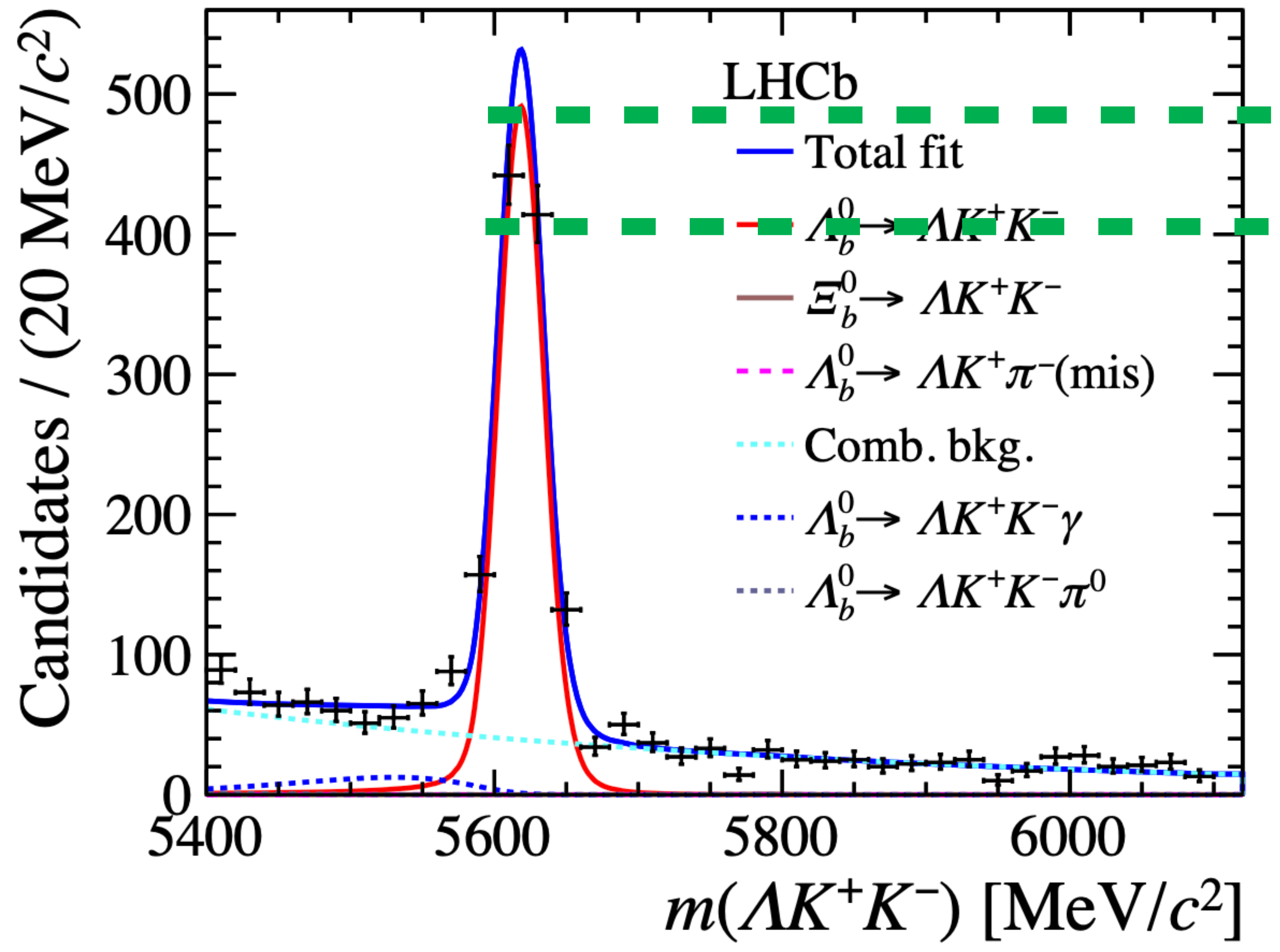
$$\boldsymbol{\Delta A_{CP} = \Delta A_{\mathrm{Raw}} - \Delta A_{\mathrm{P}}^{\Lambda_b^0} - \Delta A_{\mathrm{D}}}$$

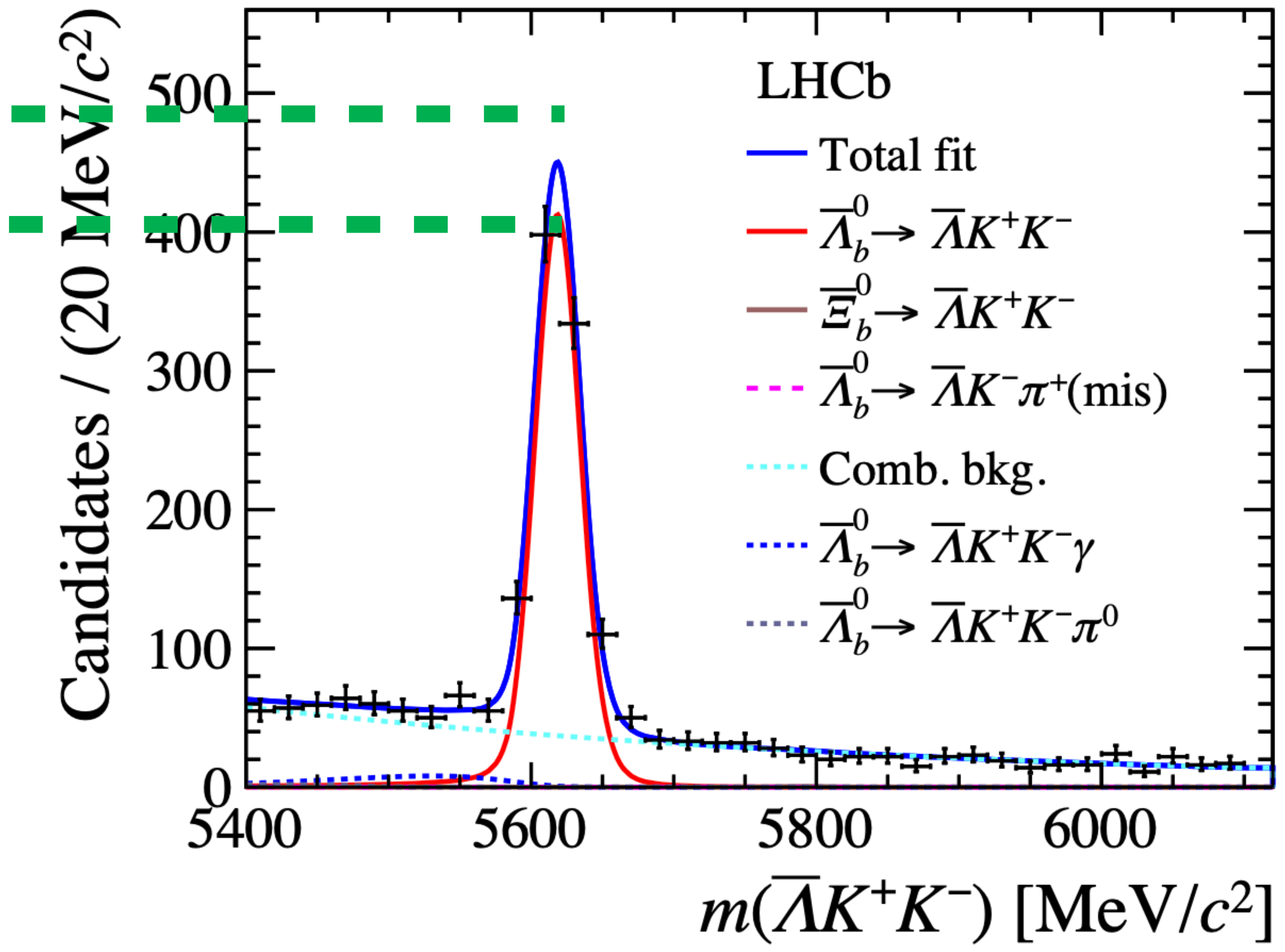
$\boldsymbol{\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-}$

$\boldsymbol{A_{CP} \sim 0}$

$$\mathcal{A}^{CP}(\Lambda_b^0/\Xi_b^0 \to f) \equiv \frac{\Gamma(\Lambda_b^0/\Xi_b^0 \to f) - \Gamma(\overline{\Lambda}_b^0/\overline{\Xi}_b^0 \to \overline{f})}{\Gamma(\Lambda_b^0/\Xi_b^0 \to f) + \Gamma(\overline{\Lambda}_b^0/\overline{\Xi}_b^0 \to \overline{f})}$$

Preliminary



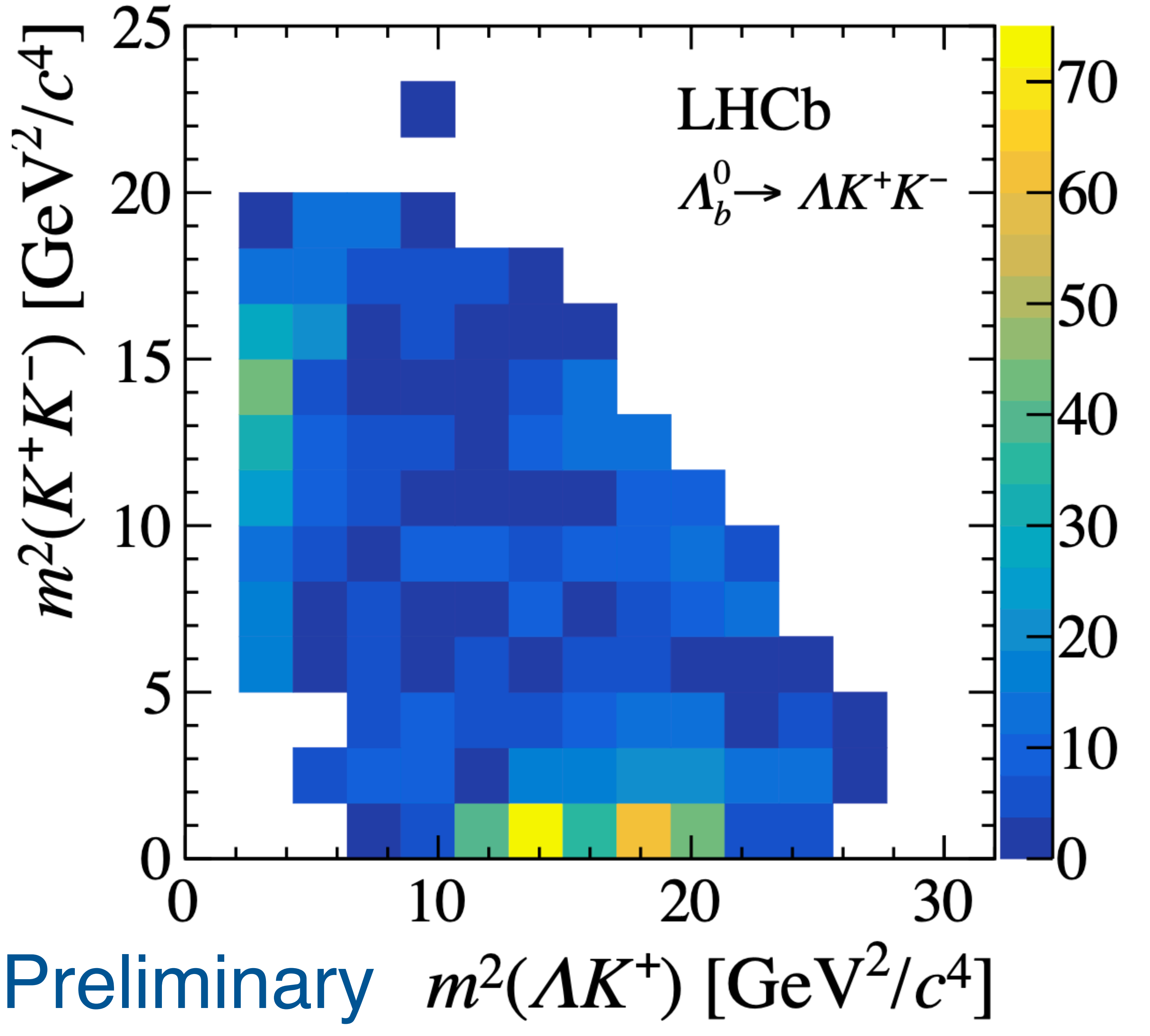




$\Lambda_b^0 \to \Lambda K^+K^-$ $\quad$ $\bar{\Lambda}_b^0 \to \bar{\Lambda} K^+K^-$

$$\Delta A_{CP} = 0.083 \pm 0.023 \pm 0.016$$

First evidence for CP violation, $3.1\sigma$

$\Lambda_b^0 \to \Lambda K^+K^-$ yields




Preliminary

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**New** LHCb-PAPER-2024-043
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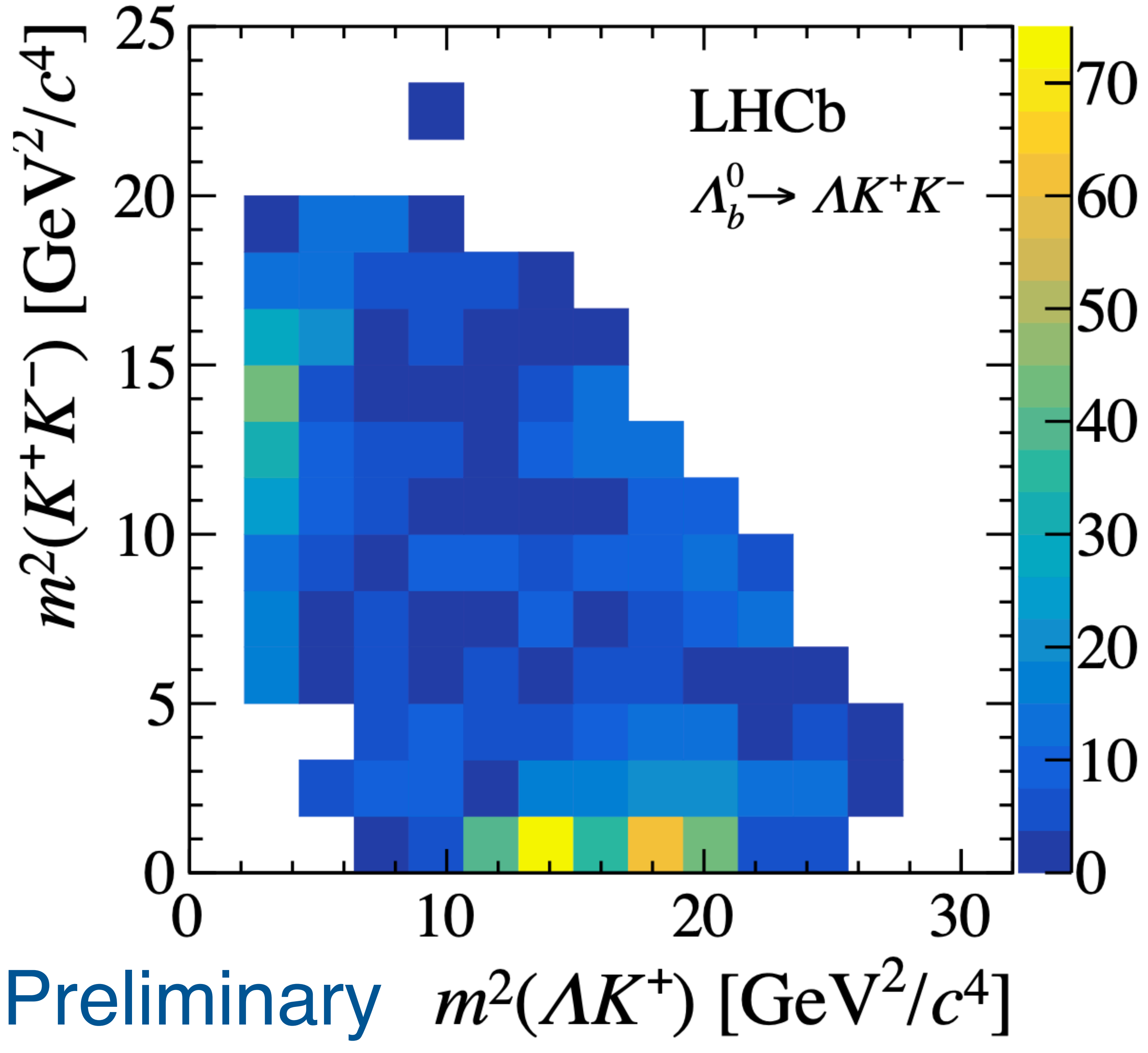
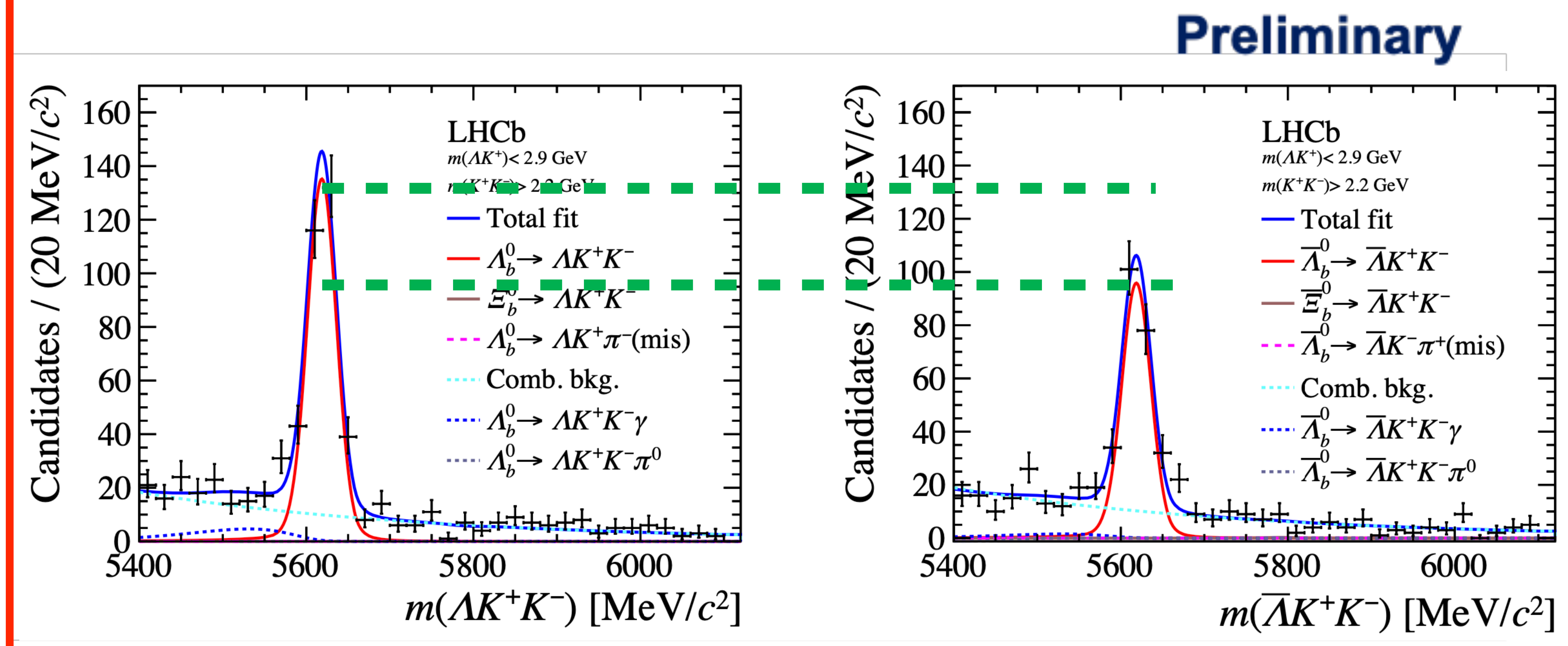



PRD107 (2023) 053009

# Evidence of CP violation in baryonic decays

CERN Seminar by W. Qian

**New** LHCb-PAPER-2024-043 in preparation

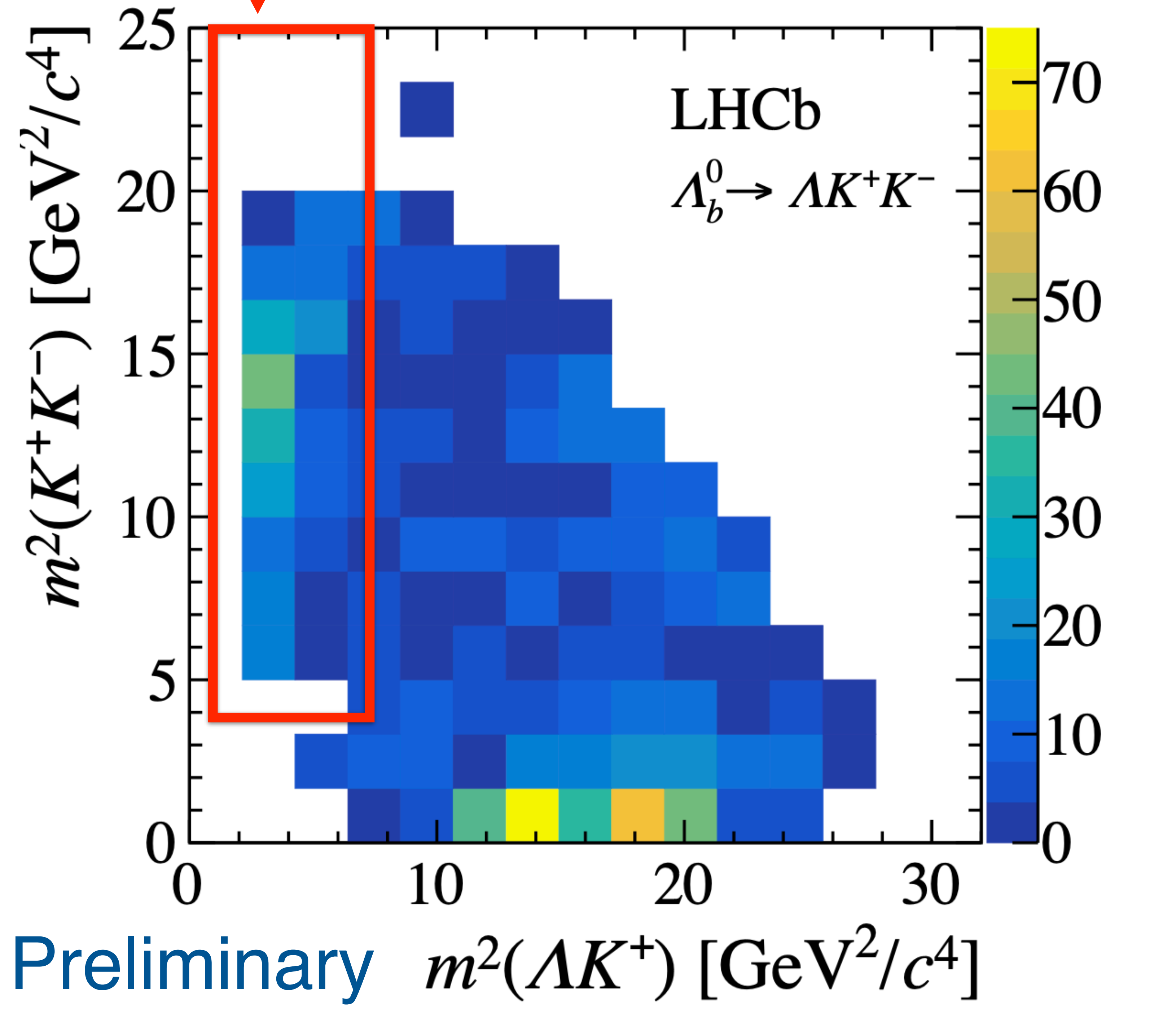



$$\Delta A_{CP}(N^{*+}K^-) = 0.165 \pm 0.048 \pm 0.017$$

**First evidence of CP violation in local resonant region, 3.2$\sigma$**

$\Lambda_b^0 \to N^{*+}K^-$

$\Lambda_b^0 \to \Lambda K^+K^-$ yields



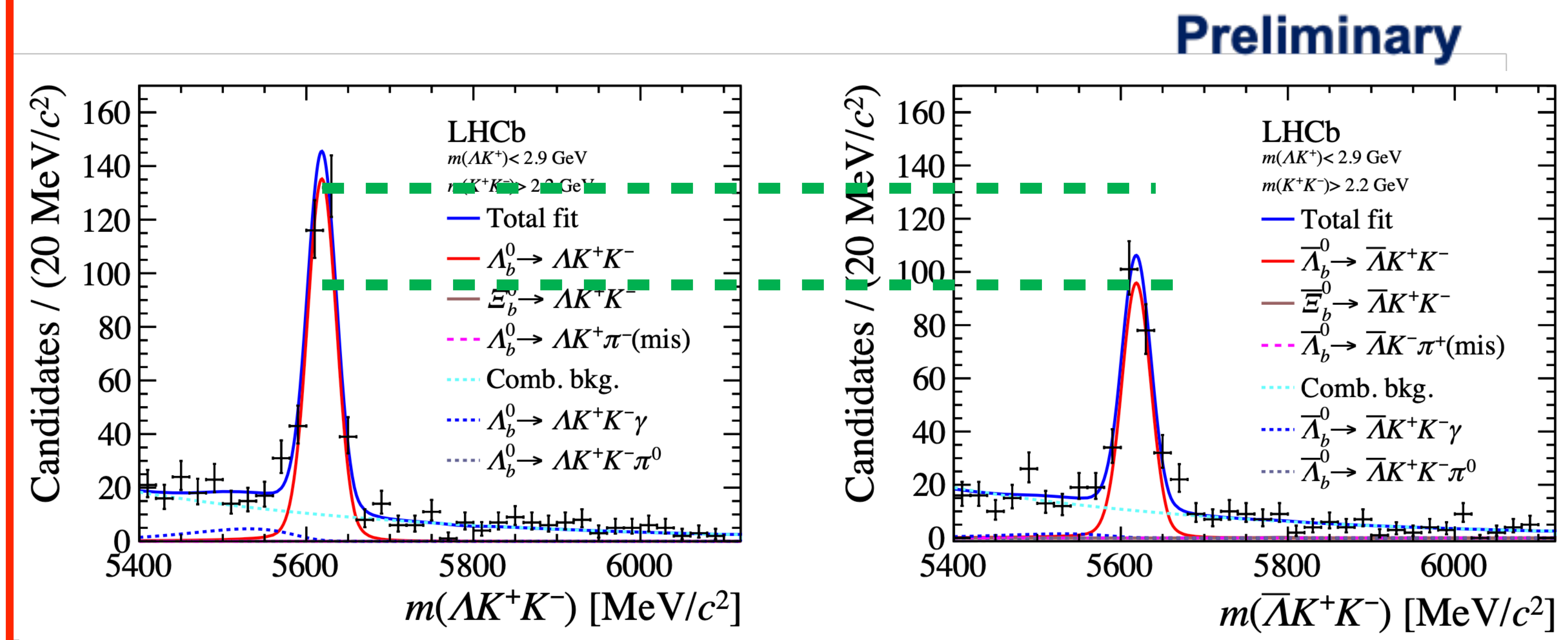

Preliminary

PRD107 (2023) 053009

# Evidence of CP violation in baryonic decays

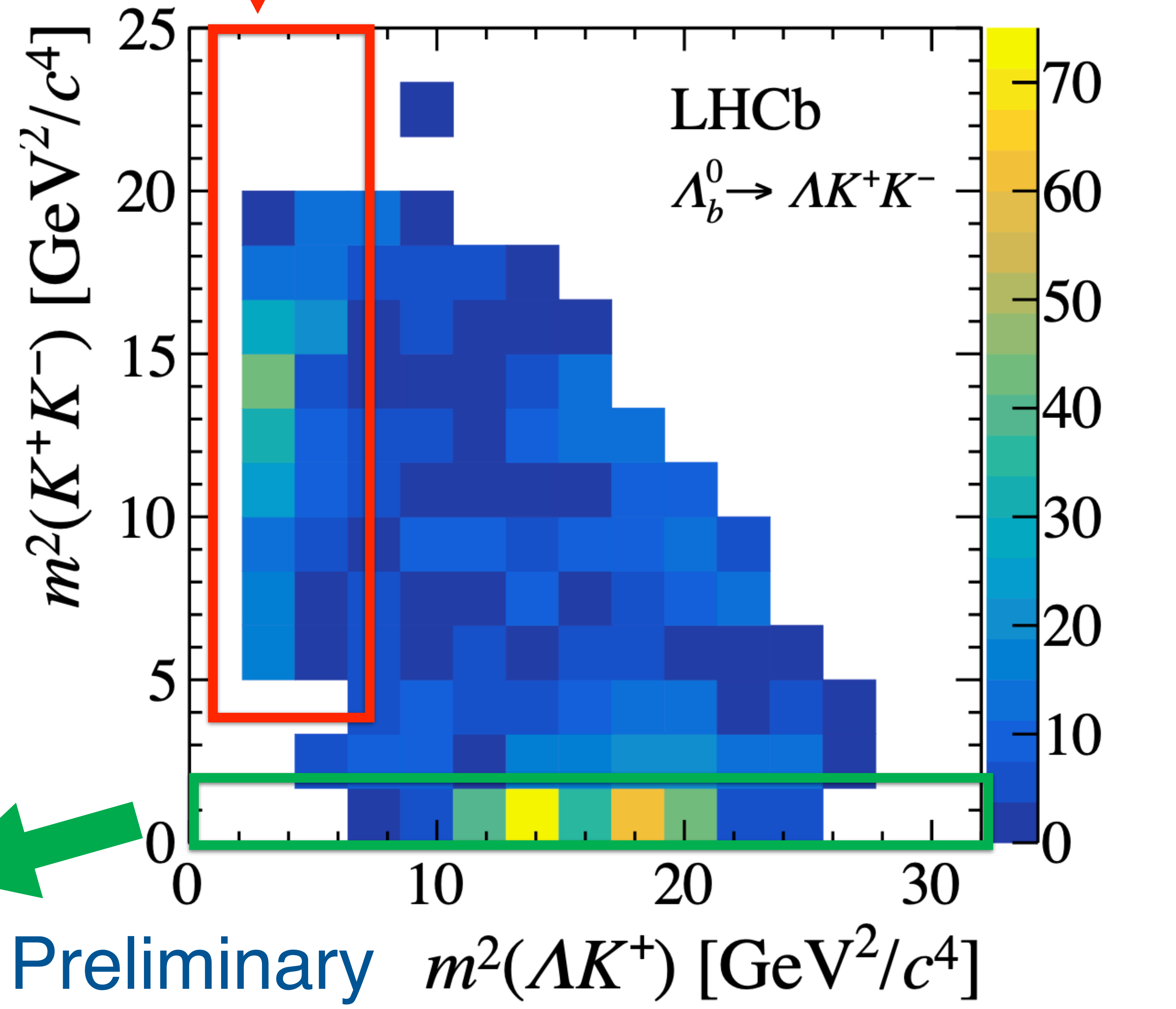
CERN Seminar by W. Qian

**New** LHCb-PAPER-2024-043 in preparation




$\Lambda_b^0 \to N^{*+}K^-$

$\Lambda_b^0 \to \Lambda K^+K^-$ yields




Preliminary

$$\Delta A_{CP}(N^{*+}K^-) = 0.165 \pm 0.048 \pm 0.017$$

**First evidence of CP violation in local resonant region, 3.2$\sigma$**

$\Lambda_b^0 \to \Lambda\phi, \Lambda f(1500)$ region

$$\Delta A_{CP}(\Lambda\phi) = 0.150 \pm 0.055 \pm 0.021$$

**Consistent with 0 within 2.5$\sigma$**

**Predicted CPV (resonant), ~1.5%**

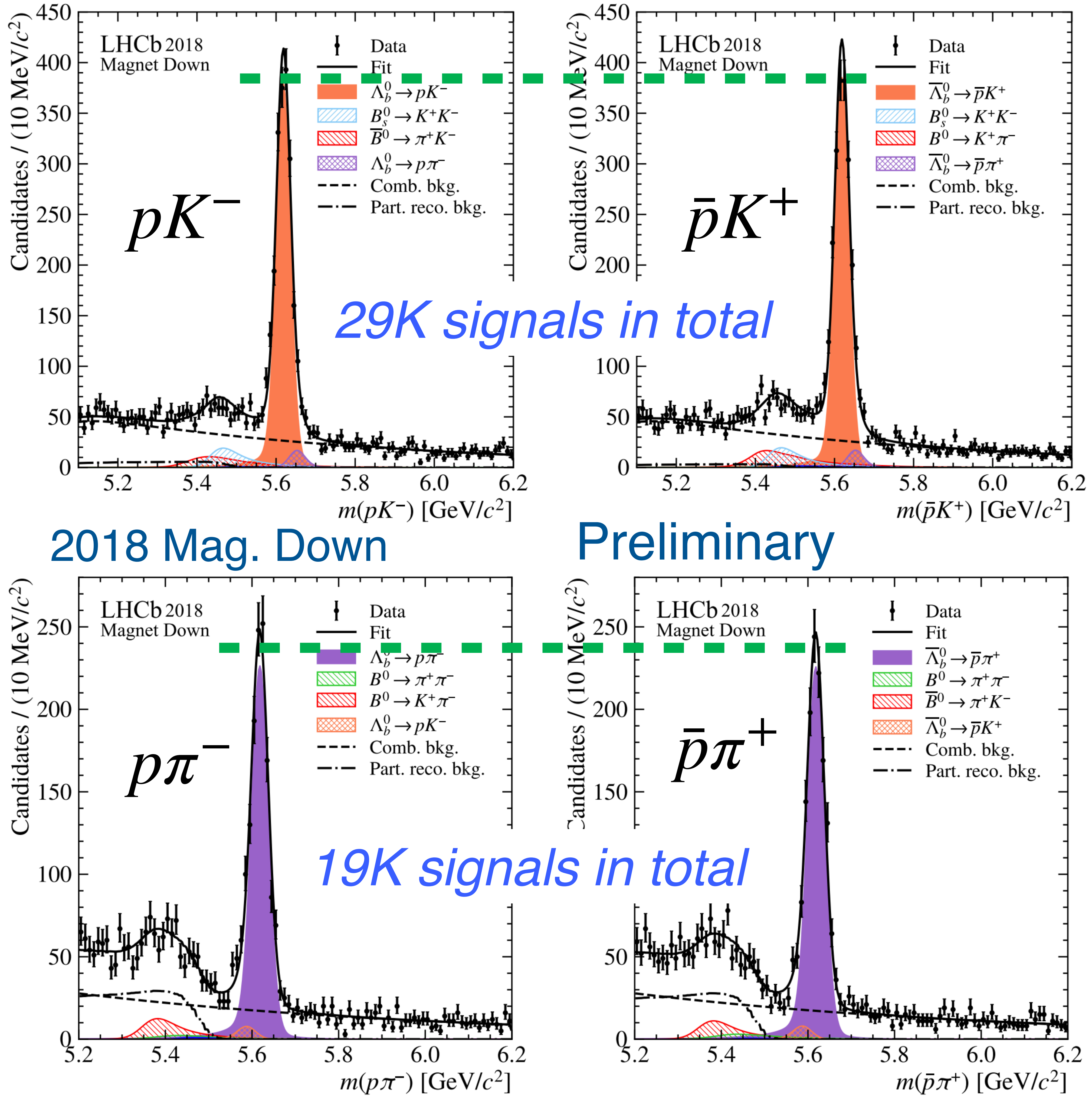
PRD107 (2023) 053009

*See more details in Chenxu Yu's talk (Friday afternoon)*

# CP violation in $\Lambda_b^0 \to ph$

***New*** LHCb-PAPER-2024-048
in preparation

- Sizeable CP violation found in $B^0_{(s)} \to h^+h'^-$
- Golden channel in baryon decays, with predictions of CPV ranges from few percent to 30%




- No clear asymmetry observed directly

$$A_{CP}^{pK^-} = (-1.14 \pm 0.67 \pm 0.36)\,\%$$

$$A_{CP}^{p\pi^-} = (-0.20 \pm 0.83 \pm 0.37)\,\%$$

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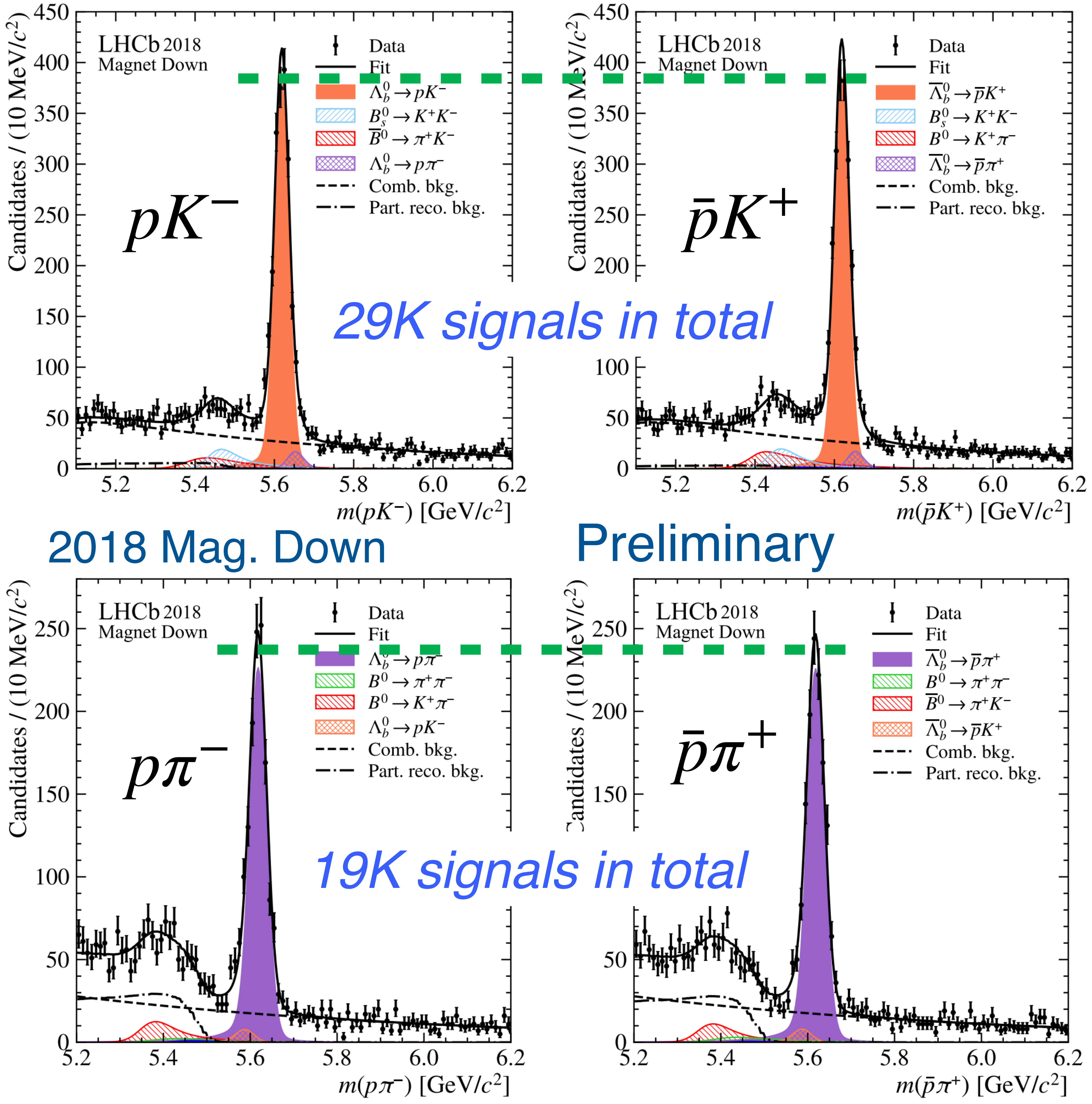


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$$A_{CP}^{pK^-} = (-1.14 \pm 0.67 \pm 0.36)\,\%$$

$$A_{CP}^{p\pi^-} = (-0.20 \pm 0.83 \pm 0.37)\,\%$$

*Why CP violation so small?*

$$A = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)} \qquad \bar{A} = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2) \qquad \delta_1 - \delta_2 \sim 0?$$

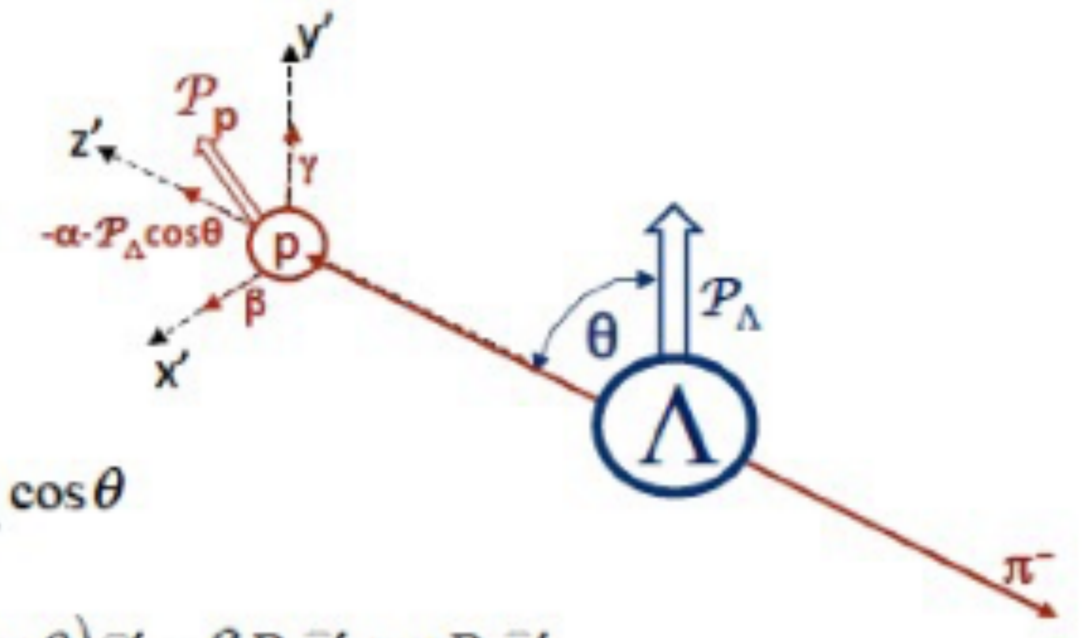
- Small strong phase difference?
- Cancellation between S, P waves? arXiv:2409.02821

*See more details in Xinchen Dai's talk (Thursday afternoon)*

# What’s more?

Phys. Rev. 108 (1959) 1645

- Decay parameter, first proposed by Lee and Yang (1959) to study hyperon decays




$$\frac{d\Gamma}{d\cos\theta} \propto 1+\alpha P_\Lambda \cos\theta$$

$$P_p = \frac{(\alpha + P_\Lambda \cos\theta)\bar{z}' + \beta P_\Lambda \bar{x}' + \gamma P_\Lambda \bar{y}'}{1+\alpha P_\Lambda \cos\theta}$$

Chen Ning Yang

Tsung-Dao Lee

$$\alpha_\mp = \pm\frac{2\Re(S^*P)}{|S|^2+|P|^2} = \pm\frac{2|S||P|\cos(\delta\pm\phi)}{|S|^2+|P|^2}$$

$$\beta_\mp = \pm\frac{2\Im(S^*P)}{|S|^2+|P|^2} = \pm\frac{2|S||P|\sin(\delta\pm\phi)}{|S|^2+|P|^2}$$

$$\gamma = \frac{|S|^2-|P|^2}{|S|^2+|P|^2} \qquad \alpha^2+\beta^2+\gamma^2 = 1$$

* $\delta, \phi$: strong and weak phase difference between S and P waves

- New CP observables

$$A_\alpha = \frac{\alpha_+ + \alpha_-}{\alpha_+ - \alpha_-} = -\tan(\delta)\tan(\phi) \qquad R_{\beta_1} = \frac{\beta_+ + \beta_-}{\alpha_+ - \alpha_-} = \tan(\phi) \qquad R_{\beta_2} = \frac{\beta_+ - \beta_-}{\alpha_+ - \alpha_-} = -\tan(\delta)$$

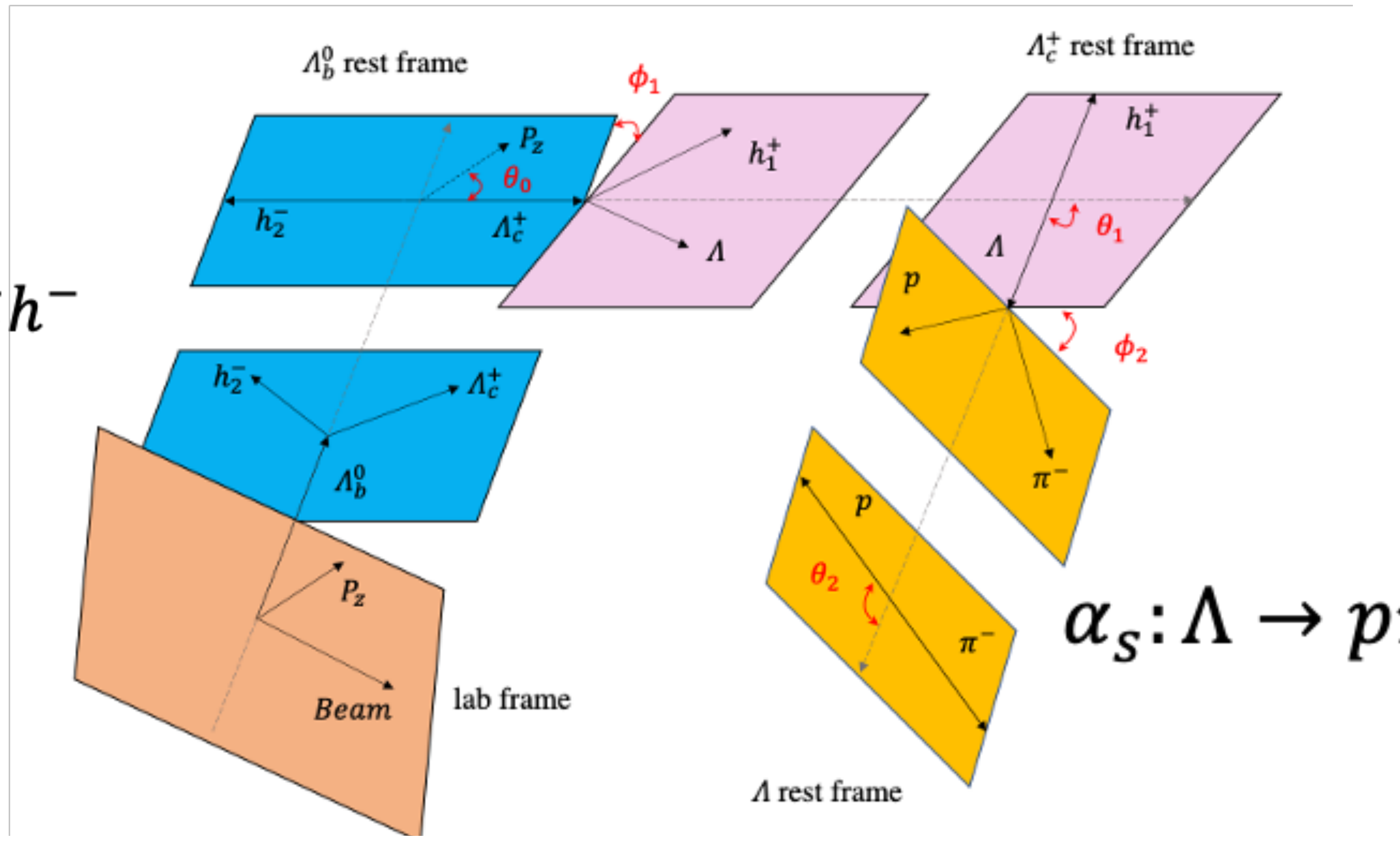
# Decay parameters of $\Lambda_b^0 \to \Lambda_c^+ h^-$

arXiv:2409.02759

$\Lambda_b^0 \to \Lambda_c^+(\to \Lambda h^+)h^-, \Lambda \to p\pi^-$

$\alpha_c, \beta_c, \gamma_c: \Lambda_c^+ \to \Lambda h^+$

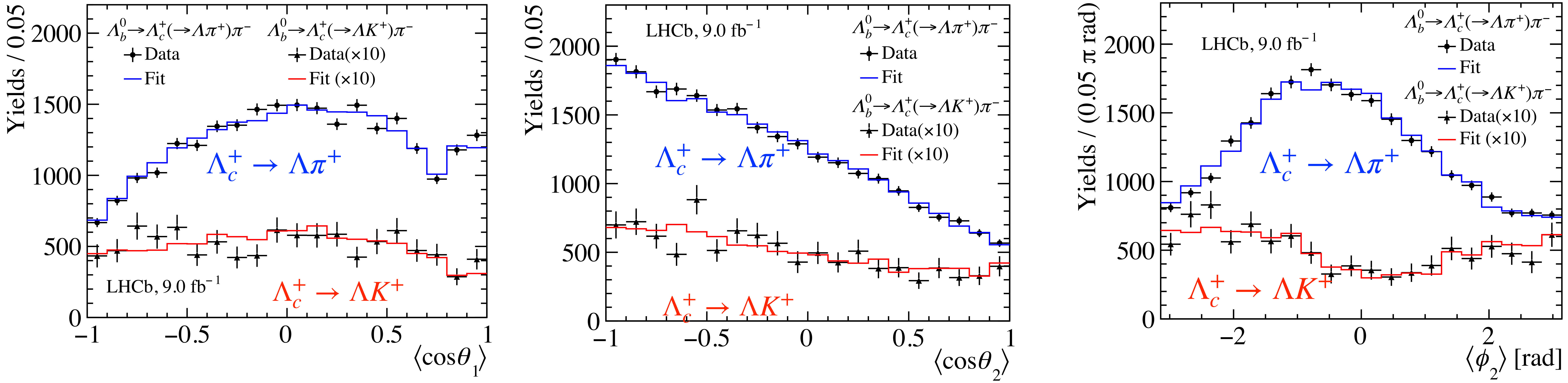
$\alpha_b: \Lambda_b^0 \to \Lambda_c^+ h^-$




$\alpha_s: \Lambda \to p\pi^-$

$$\frac{d\Phi}{d\Omega} \propto \quad (1 + \alpha_b\alpha_c \cos\theta_1 + \alpha_c\alpha_s \cos\theta_2 + \alpha_b\alpha_s \cos\theta_1 \cos\theta_2 - \alpha_b\gamma_c\alpha_s \sin\theta_1 \sin\theta_2 \cos\phi_2 + \alpha_b\beta_c\alpha_s \sin\theta_1 \sin\theta_2 \sin\phi_2)$$

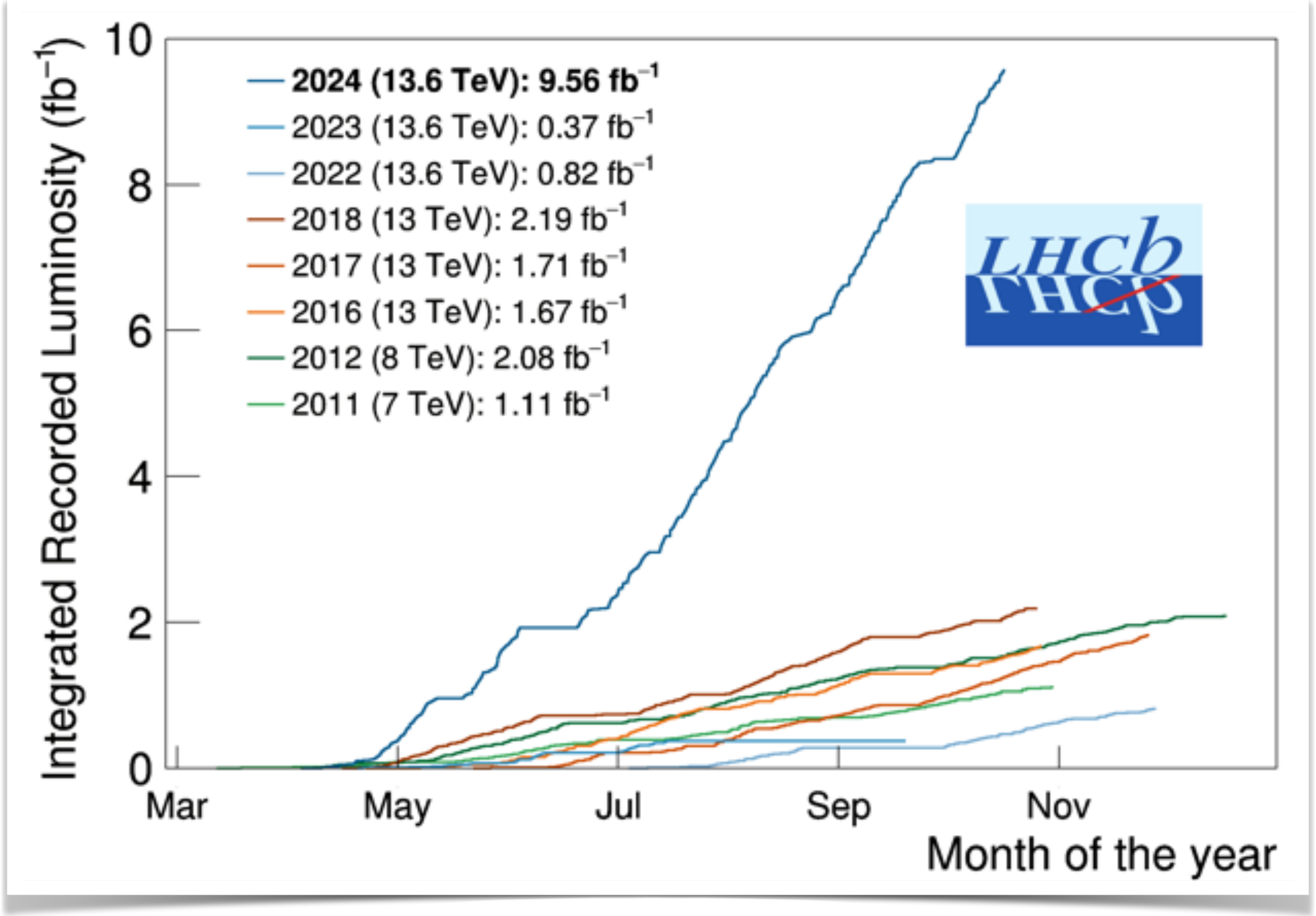
- First determination of $\alpha$ in $\Lambda_b^0 \to \Lambda_c^+ h^-$ decays $\mathcal{O}(0.9\%)$
- Most precise determinations $\alpha$, $(\beta, \gamma)$
- Confirmation of $\alpha(\Lambda \to p\pi^-)$ from BESIII
- Pave the way for other decay parameter measurements



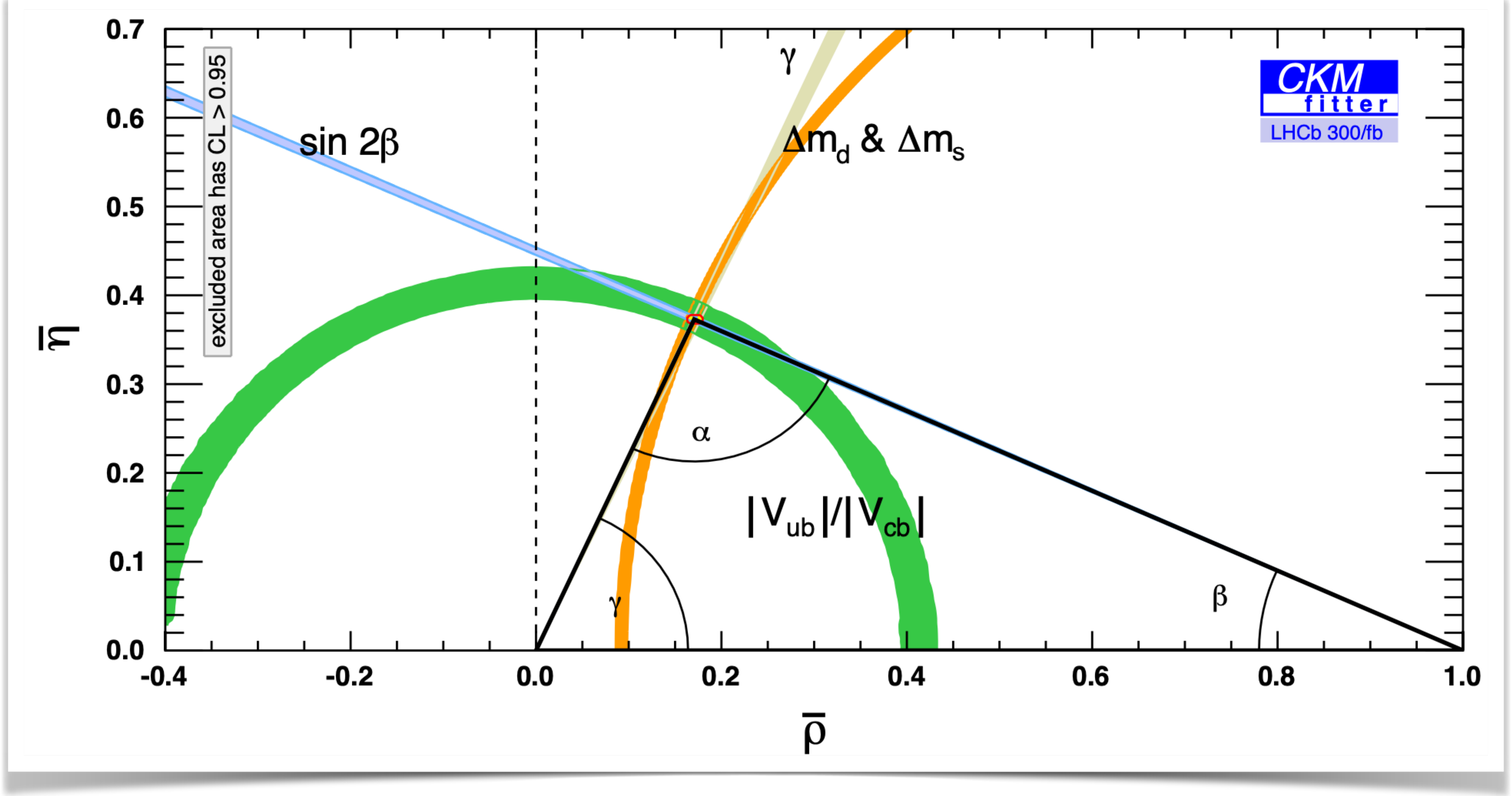

*See more details in Yuhao Wang's talk (Friday afternoon)*

# Summary

- ✓ LHCb dominates the world average of many measurements in CKM and CPV
- ✓ Various precise measurement of CP violation in beauty and charm decays using LHCb Run 1+2 data
- ✓ First evidence of CP violation in $B^+ \to J/\psi\pi^+$ and $\Lambda_b^0 \to \Lambda K^+ K^-$
- ✓ Run 3 provides great opportunities for further test of the SM and search for new physics



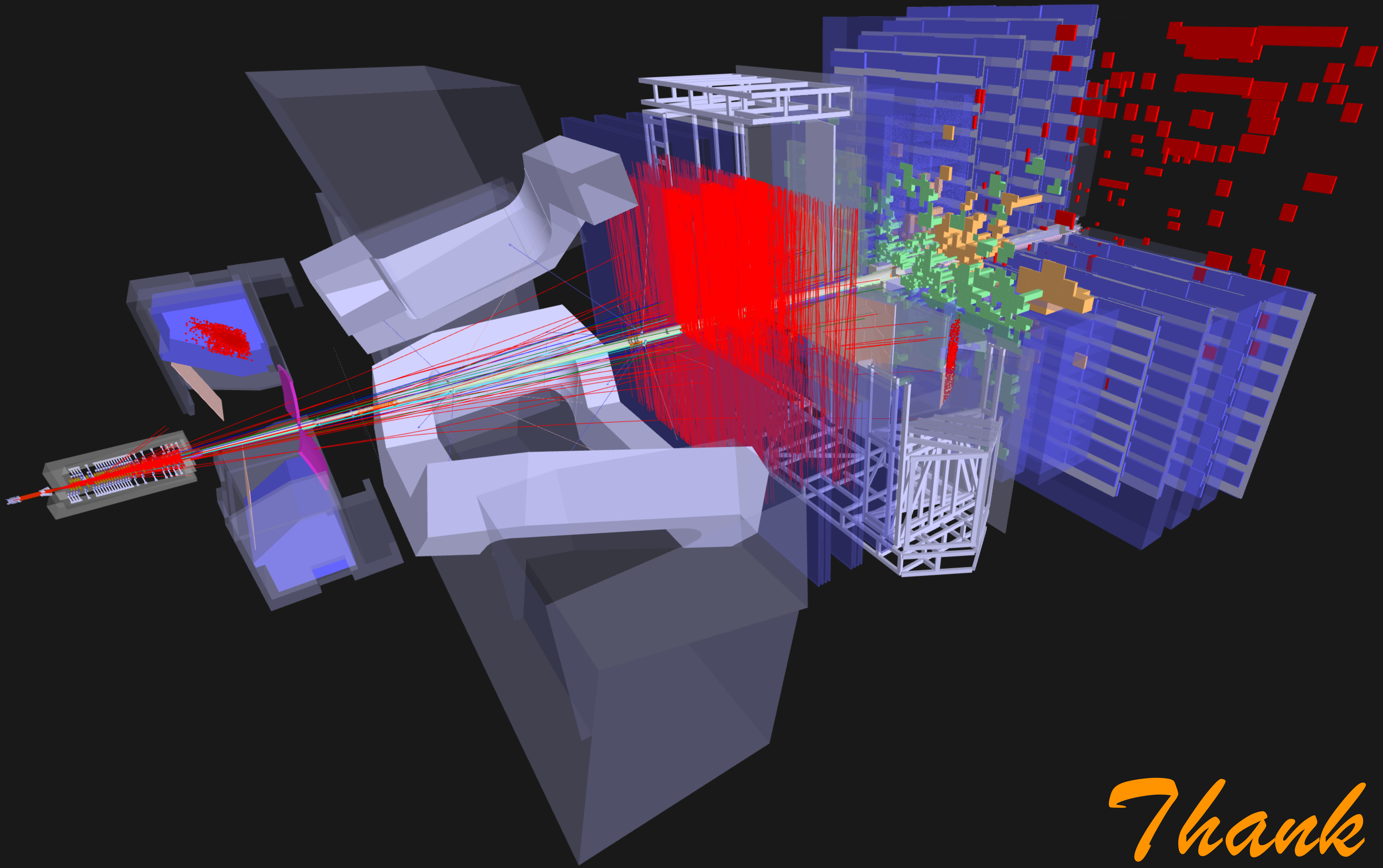

*Run 3 has collected more data than Run 1+2, a lot more new results to come!*



**LHCb Experiment at CERN**

**Run / Event:** 255623 / 300064

**Data recorded:** 2022-11-25 09:40:16 GMT



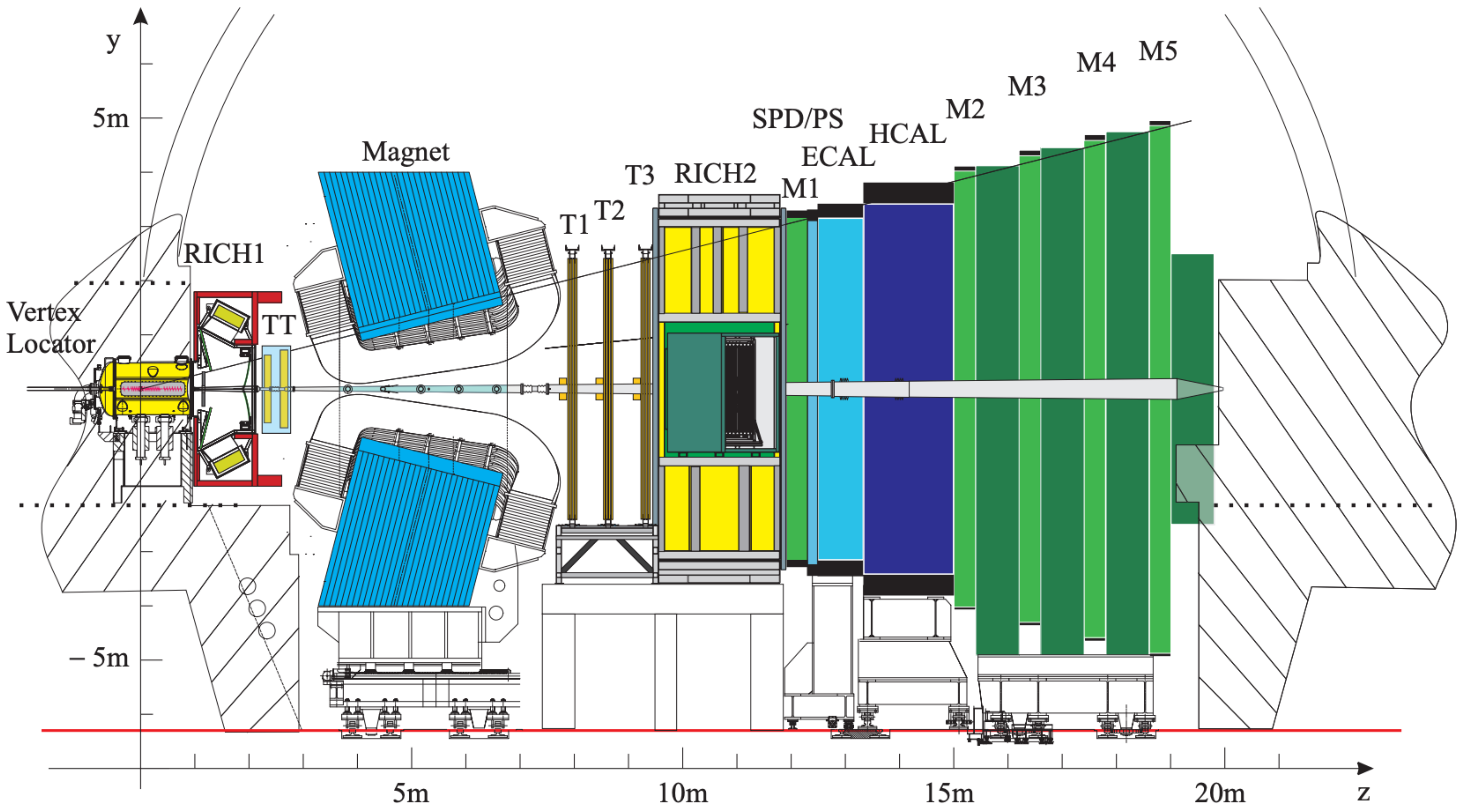
*Thank you*

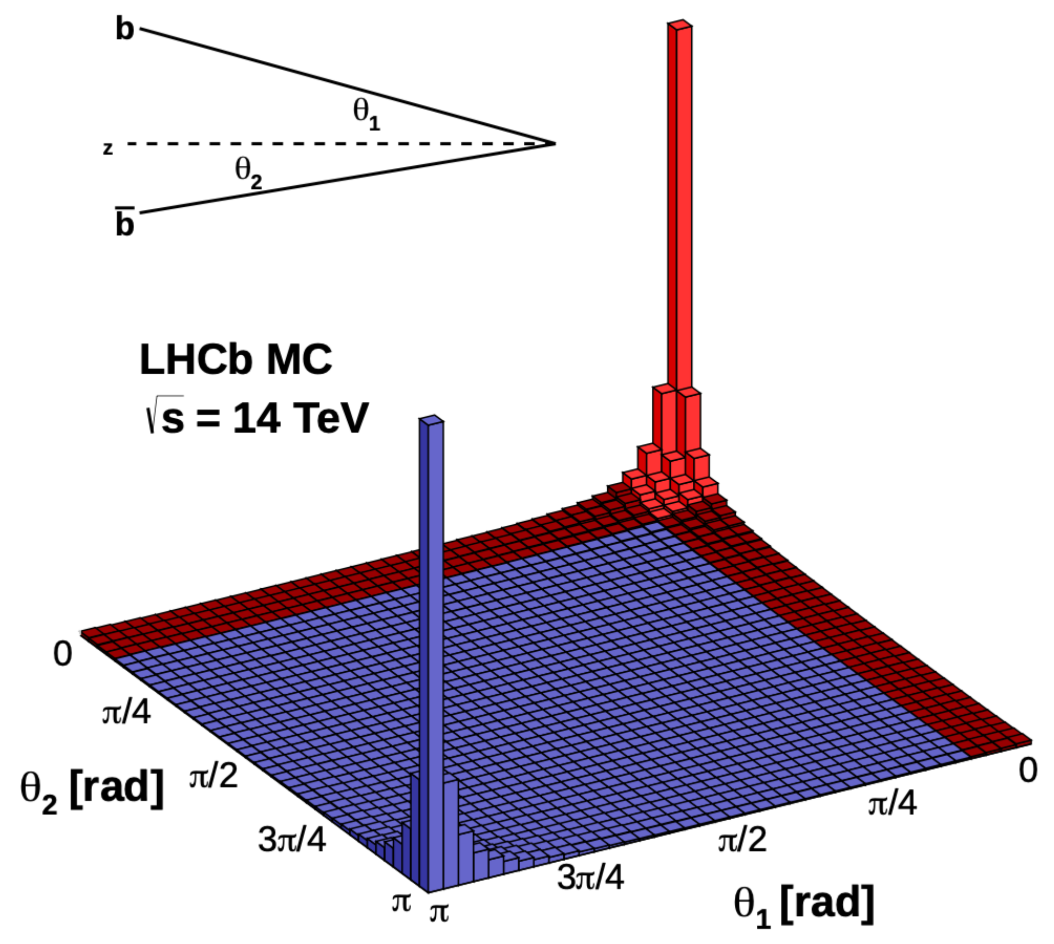
# Back up slides

# LHCb detector

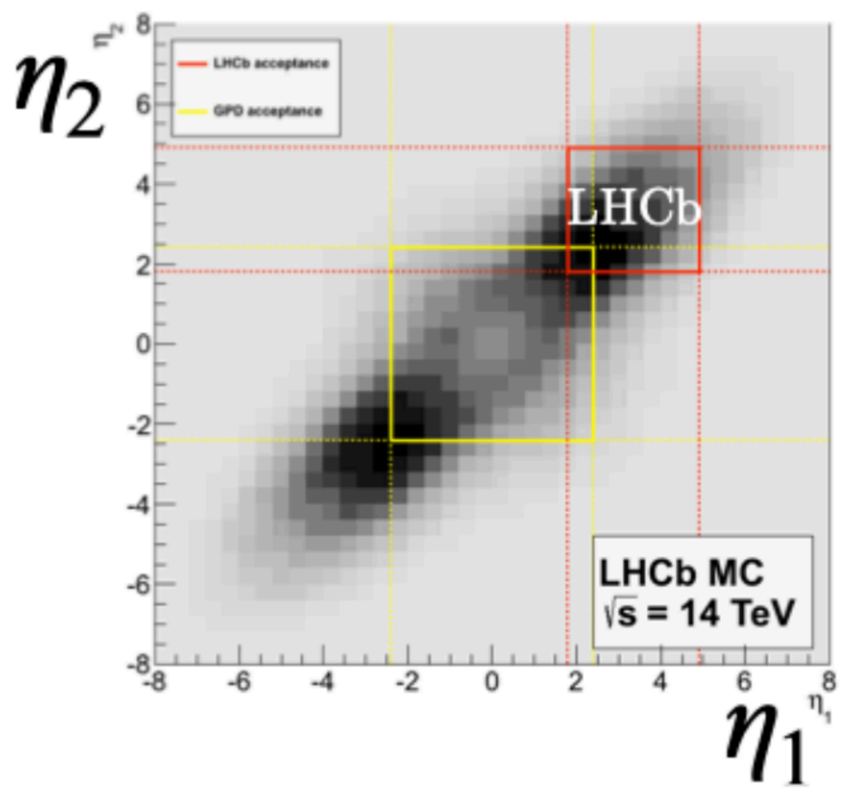
General purpose detector specialised in beauty and charm hadrons

proton beam




$2 < \eta < 5$

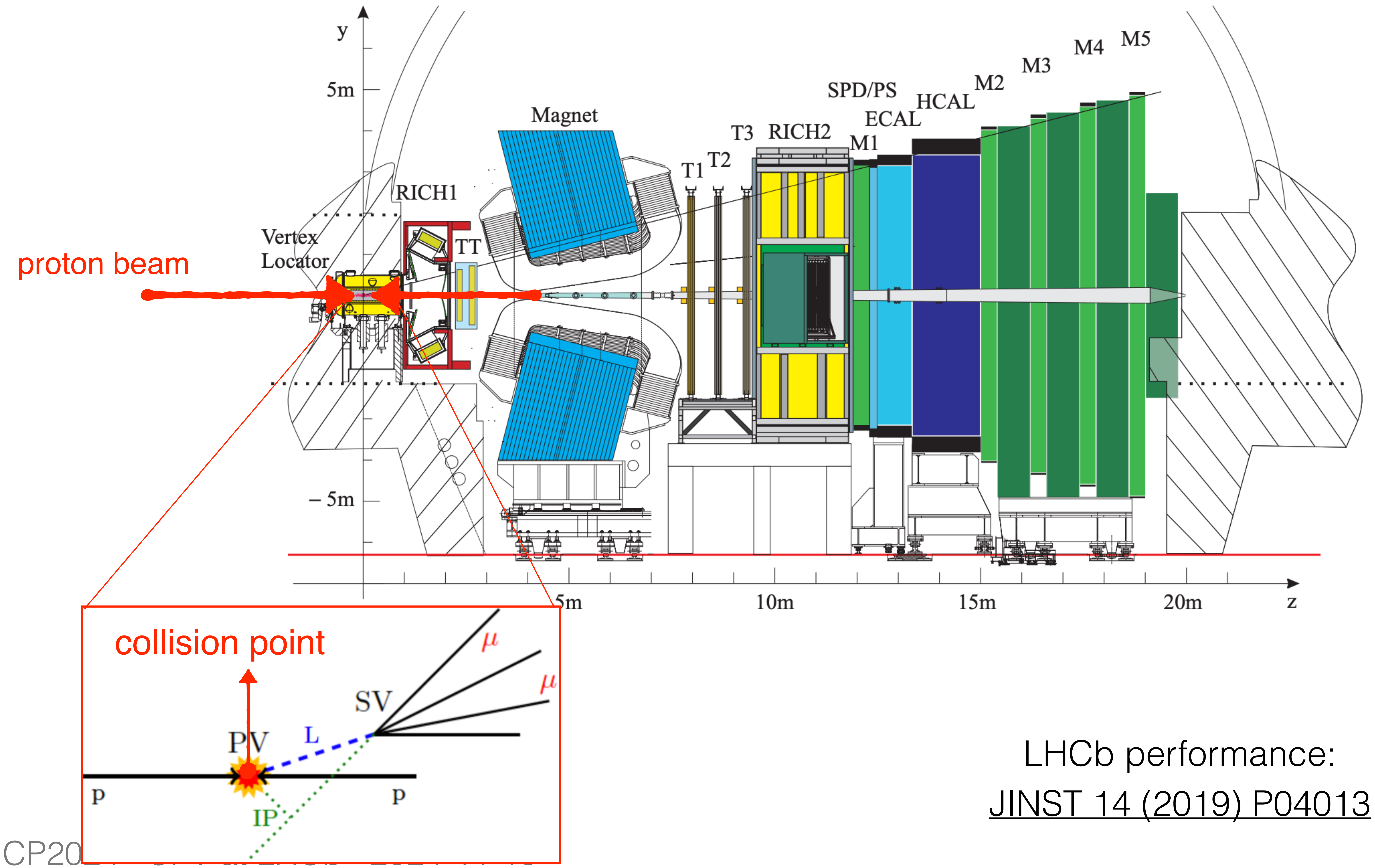


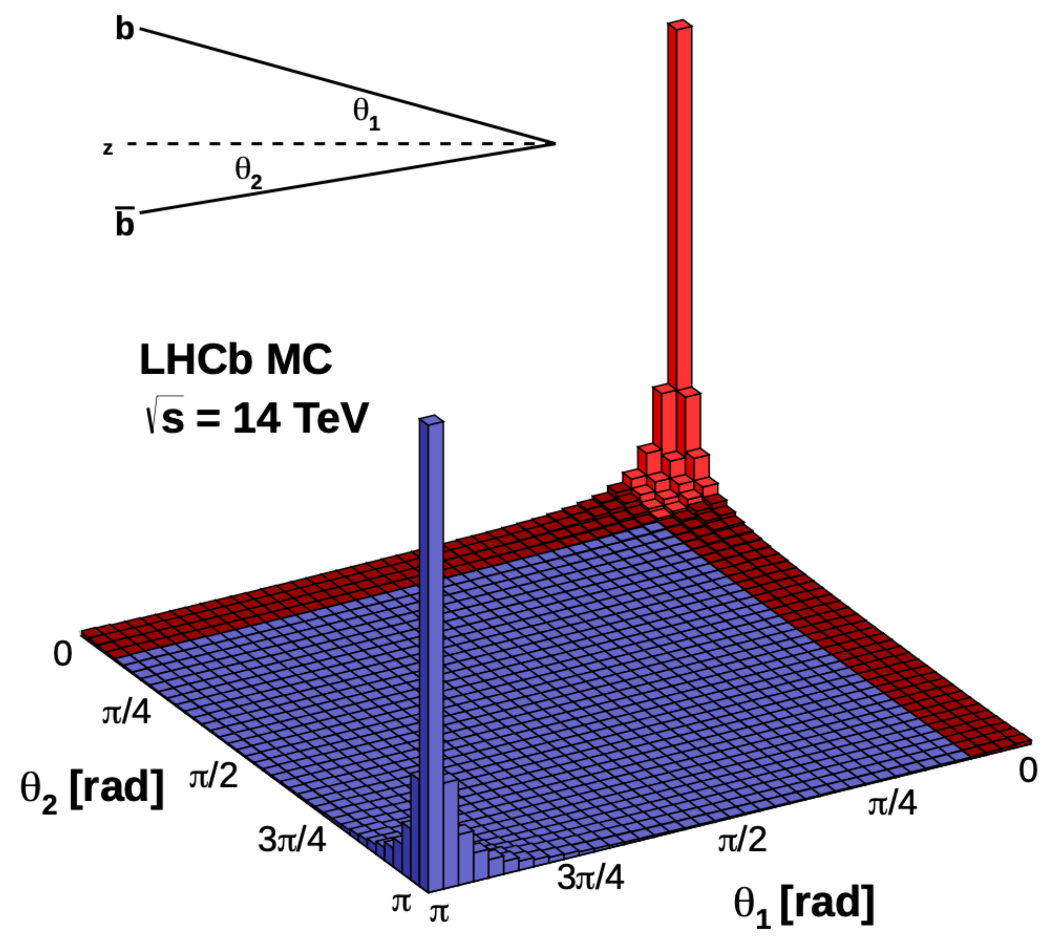

LHCb performance:
JINST 14 (2019) P04013

# LHCb detector

General purpose detector specialised in beauty and charm hadrons

- Daughters of b & c hadron decays: $p_T \sim \mathcal{O}(1\ \mathrm{GeV}/c)$, flight distance L~1mm

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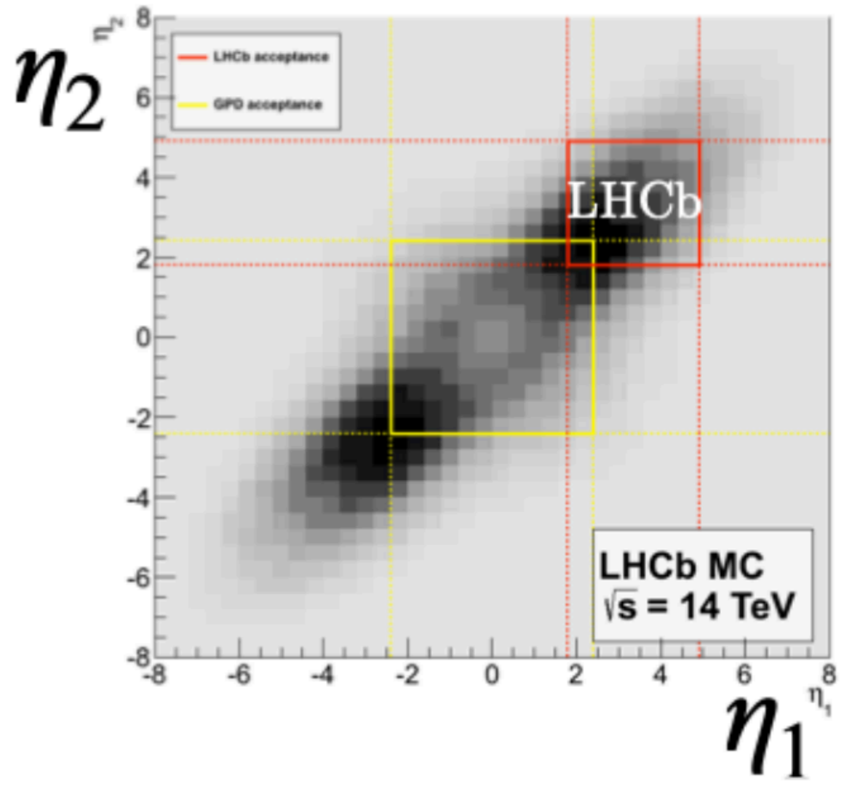


LHCb performance:
JINST 14 (2019) P04013

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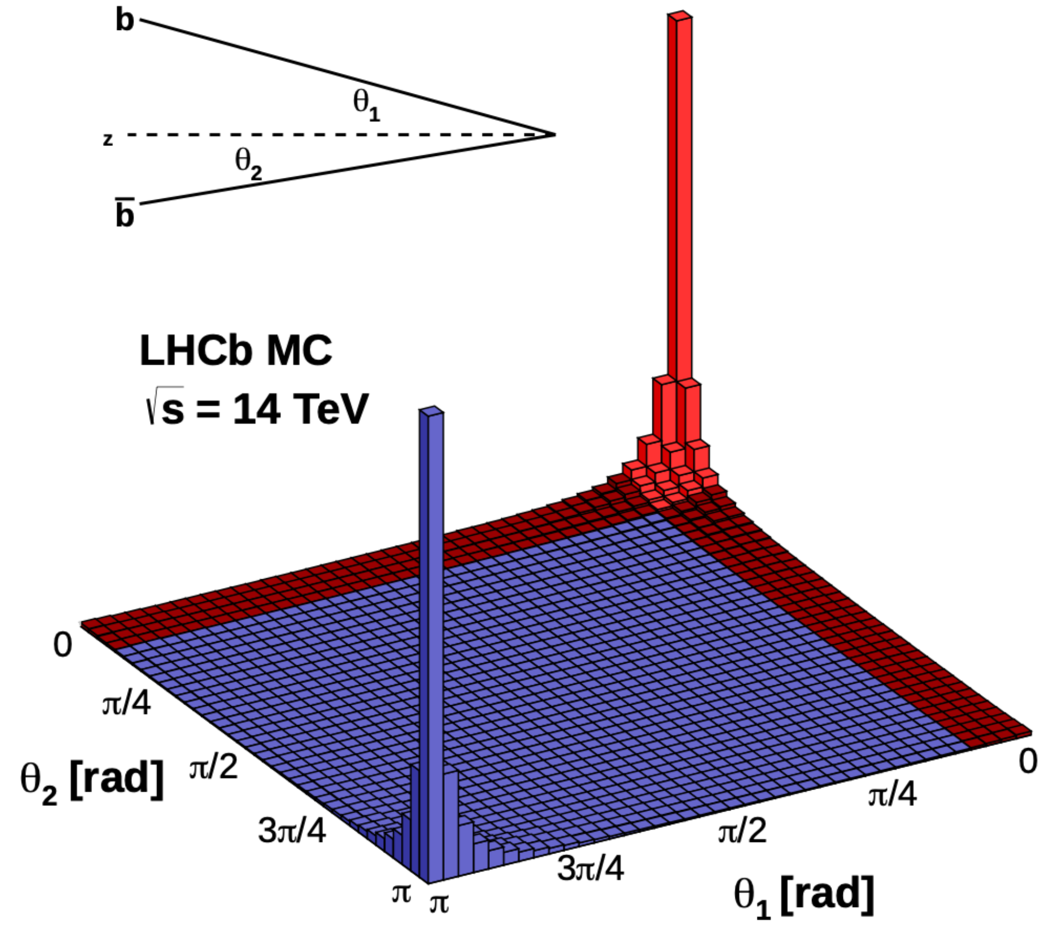
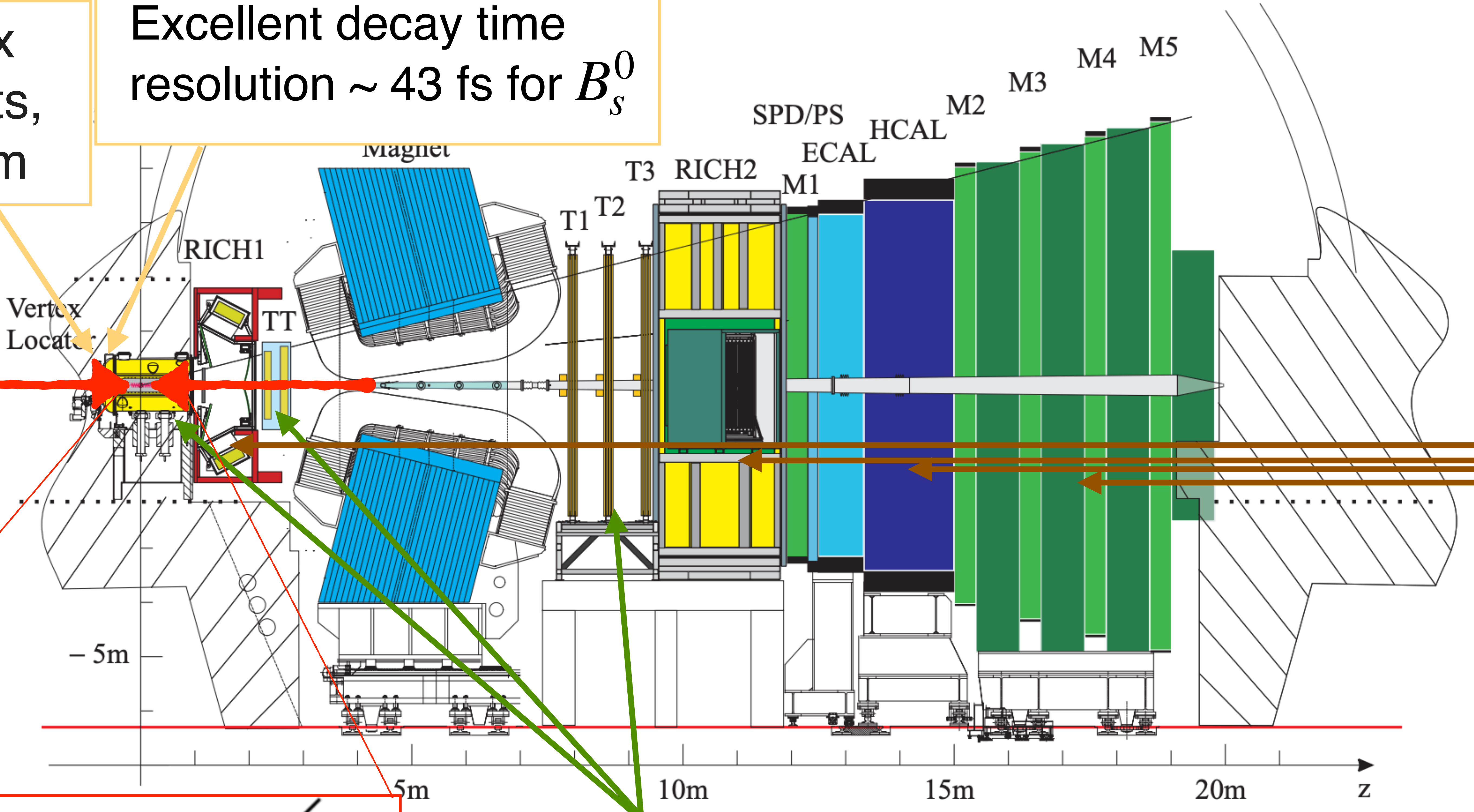



$2 < \eta < 5$

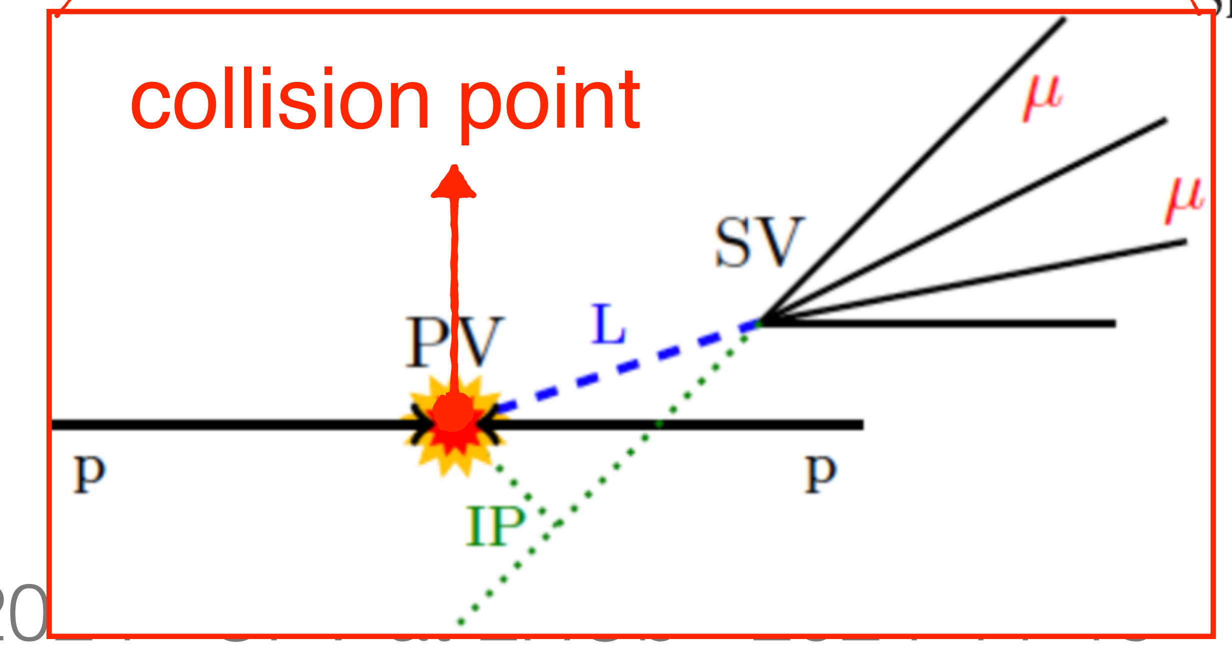
Precise vertex measurements, $\sigma(IP_x)$~ 35 μm

Excellent decay time resolution ~ 43 fs for $B_s^0$

proton beam

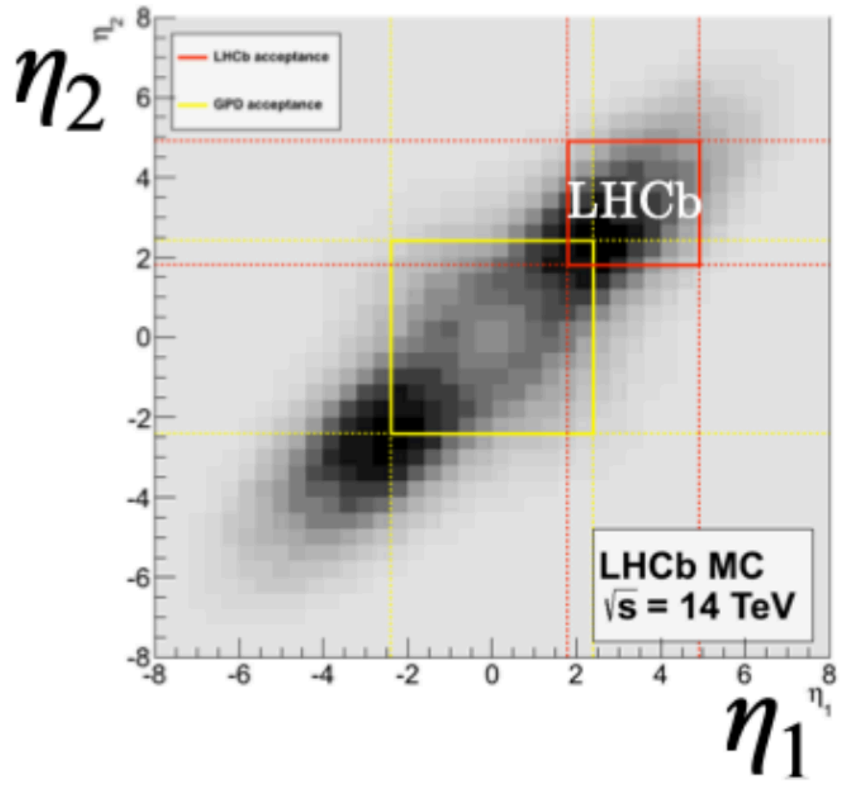



Excellent particle identification
$\epsilon(K) \approx 95\,\%$
misID $p(\pi \to K) \approx 5\,\%$
$\epsilon(\mu) \approx 97\,\%$




Excellent momentum resolution ~ 0.5%

LHCb performance:
JINST 14 (2019) P04013

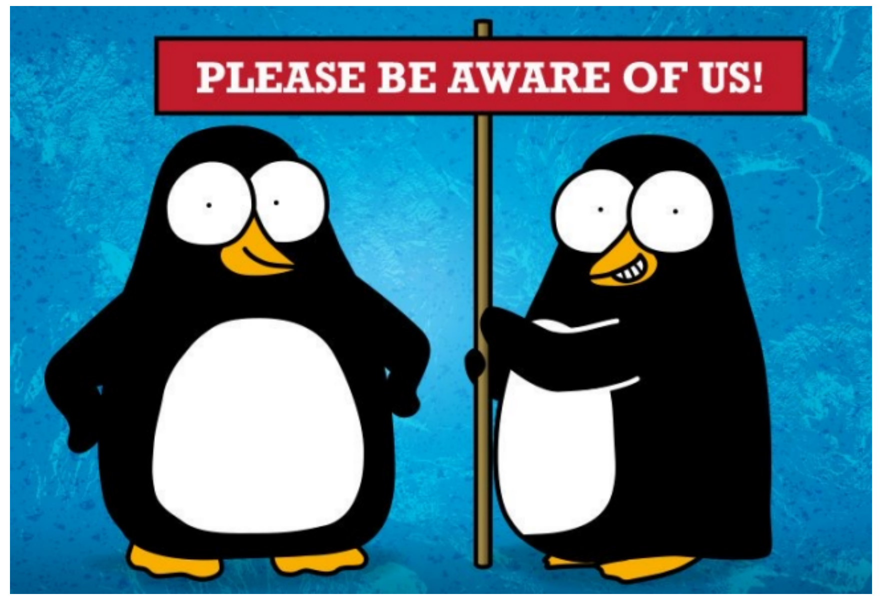


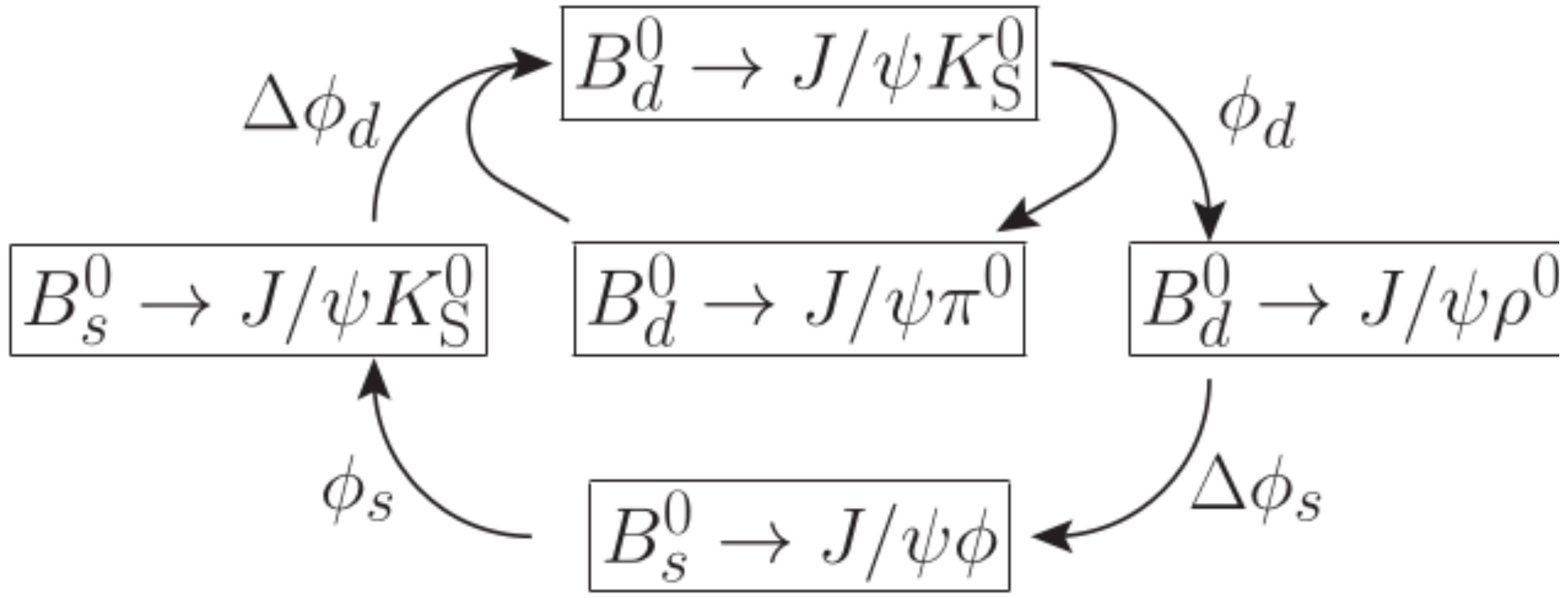
# Control of penguin contribution

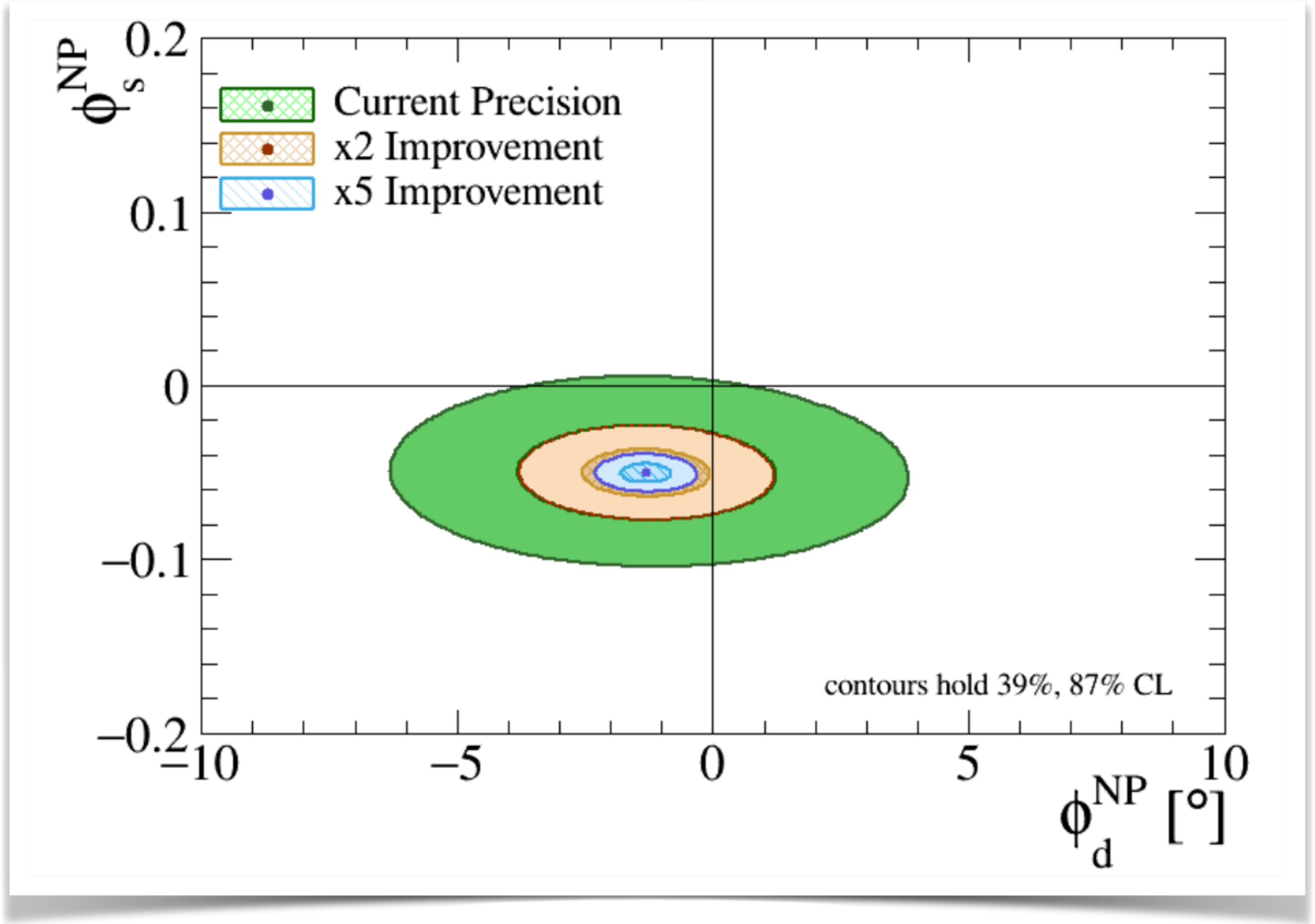
- $\sigma(\phi_s) \sim 0.016$ comparable with the theoretical estimation of $\Delta\phi_s^{penguin} \sim 1^\circ \approx 0.017$, better control of penguin effect necessary
- Combined analysis of penguin contributions in $\phi_s$ and $\phi_d$ $(\sin 2\beta)$, using SU(3) flavour symmetry

$$\phi_d = \sin(2\beta^{\rm tree}) + \Delta\phi_d{}^{\rm penguin} + \phi_d{}^{\rm NP}$$

$$\phi_s = \phi_s^{\rm tree} + \Delta\phi_s^{\rm penguin} + \phi_s^{NP}$$




J.Phys.G 48 (2021) 6, 065002

# Method to measure $\Delta A^{CP}$

- CP asymmetries

$$A^{CP}(B^{\mp} \longrightarrow J/\psi\pi^{\mp}) = \boxed{a^{\mathrm{raw}}(B^{\mp} \longrightarrow J/\psi\pi^{\mp})} - \boxed{a^{\mathrm{prod}}(B^{\mp})} - \boxed{a^{\mathrm{det}}(\pi^{\mp})} - \boxed{a^{\mathrm{PID}}(\pi^{\mp})}$$

$$A^{CP}(B^{\mp} \longrightarrow J/\psi K^{\mp}) = \boxed{a^{\mathrm{raw}}(B^{\mp} \longrightarrow J/\psi K^{\mp})} - \boxed{a^{\mathrm{prod}}(B^{\mp})} - \boxed{a^{Det}(K^{\mp})} - \boxed{a^{\mathrm{PID}}(K^{\mp})}$$

Raw asymmetries from mass fit

Production asymmetries largely cancelled

Detection asymmetries from $D^+$ control data

PID asymmetries from PIDCorr

- CP asymmetry difference

$$\Delta A^{CP} \equiv A^{CP}(B^{\mp} \longrightarrow J/\psi\pi^{\mp}) - A^{CP}(B^{\mp} \longrightarrow J/\psi K^{\mp})$$

$$= \Delta a^{\mathrm{raw}} - \cancel{\Delta a^{\mathrm{prod}}} - \Delta a^{\mathrm{det}} - \Delta a^{\mathrm{PID}}$$

credit: Manshu Li

# $\gamma$ measurements

| $B$ decay | $D$ decay | Ref. | Dataset | Status since Ref. [14] |
|---|---|---|---|---|
| $B^\pm \to Dh^\pm$ | $D \to h^\pm h'^\mp$ | [35] | Run 1&2 | *As before* |
| $B^\pm \to Dh^\pm$ | $D \to h^+h^-\pi^+\pi^-$ | [19] | Run 1&2 | **New** |
| $B^\pm \to Dh^\pm$ | $D \to K^\pm\pi^\mp\pi^+\pi^-$ | [36] | Run 1&2 | *As before* |
| $B^\pm \to Dh^\pm$ | $D \to h^\pm h'^\mp\pi^0$ | [37] | Run 1&2 | *As before* |
| $B^\pm \to Dh^\pm$ | $D \to K^0_S h^+h^-$ | [38] | Run 1&2 | *As before* |
| $B^\pm \to Dh^\pm$ | $D \to K^0_S K^\pm\pi^\mp$ | [39] | Run 1&2 | *As before* |
| $B^\pm \to D^*h^\pm$ | $D \to h^\pm h'^\mp$ (PR) | [35] | Run 1&2 | *As before* |
| $B^\pm \to D^*h^\pm$ | $D \to K^0_S h^+h^-$ (PR) | [20] | Run 1&2 | **New** |
| $B^\pm \to D^*h^\pm$ | $D \to K^0_S h^+h^-$ (FR) | [21] | Run 1&2 | **New** |
| $B^\pm \to DK^{*\pm}$ | $D \to h^\pm h'^\mp$ | [22]$^\dagger$ | Run 1&2 | **Updated** |
| $B^\pm \to DK^{*\pm}$ | $D \to h^\pm\pi^\mp\pi^+\pi^-$ | [22]$^\dagger$ | Run 1&2 | **Updated** |
| $B^\pm \to DK^{*\pm}$ | $D \to K^0_S h^+h^-$ | [22]$^\dagger$ | Run 1&2 | **New** |
| $B^\pm \to Dh^\pm\pi^+\pi^-$ | $D \to h^\pm h'^\mp$ | [40] | Run 1 | *As before* |
| $B^0 \to DK^{*0}$ | $D \to h^\pm h'^\mp$ | [23] | Run 1&2 | **Updated** |
| $B^0 \to DK^{*0}$ | $D \to h^\pm\pi^\mp\pi^+\pi^-$ | [23] | Run 1&2 | **Updated** |
| $B^0 \to DK^{*0}$ | $D \to K^0_S h^+h^-$ | [24] | Run 1&2 | **Updated** |
| $B^0 \to D^\mp\pi^\pm$ | $D^+ \to K^-\pi^+\pi^+$ | [41] | Run 1 | *As before* |
| $B^0_s \to D^\mp_s K^\pm$ | $D^+_s \to h^+h^-\pi^+$ | [25, 42]$^\dagger$ | Run 1&2 | **Updated** |
| $B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$ | $D^+_s \to h^+h^-\pi^+$ | [43] | Run 1&2 | *As before* |

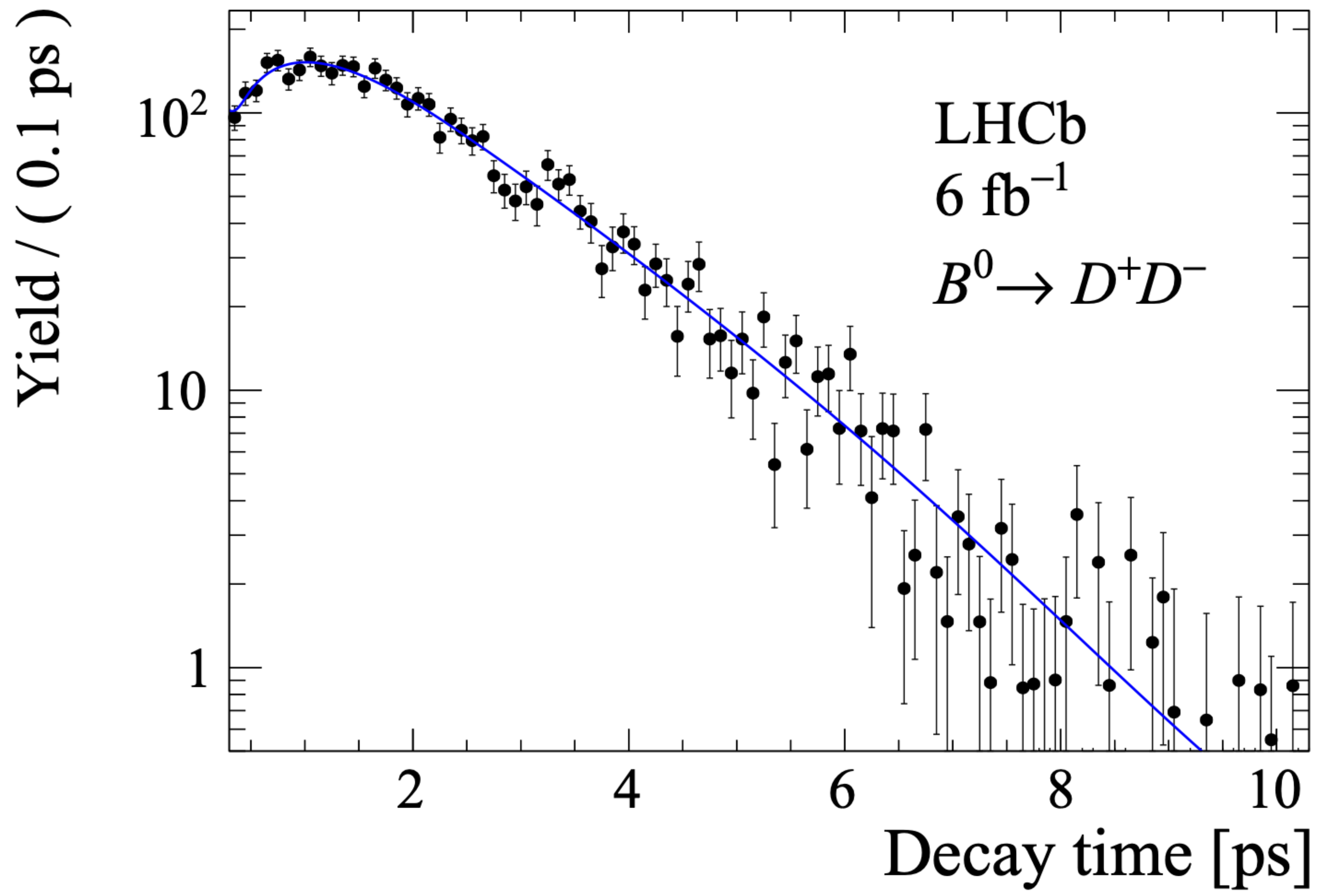
| $D$ decay | Observable(s) | Ref. | Dataset | Status since Ref. [14] |
|---|---|---|---|---|
| $D^0 \to h^+h^-$ | $\Delta A_{CP}$ | [44–46] | Run 1&2 | *As before* |
| $D^0 \to K^+K^-$ | $A_{CP}(K^+K^-)$ | [46–48] | Run 2 | *As before* |
| $D^0 \to h^+h^-$ | $y_{CP} - y_{CP}^{K^-\pi^+}$ | [49, 50] | Run 1&2 | *As before* |
| $D^0 \to h^+h^-$ | $\Delta Y$ | [51–54] | Run 1&2 | *As before* |
| $D^0 \to K^+\pi^-$ (double tag) | $R^\pm$, $(x'^\pm)^2$, $y'^\pm$ | [55] | Run 1 | *As before* |
| $D^0 \to K^+\pi^-$ (single tag) | $R_{K\pi}$, $A_{K\pi}$, $c^{(\prime)}_{K\pi}$, $\Delta c^{(\prime)}_{K\pi}$ | [27, 56] | Run 1&2 | **Updated** |
| $D^0 \to K^\pm\pi^\mp\pi^+\pi^-$ | $(x^2+y^2)/4$ | [57] | Run 1 | *As before* |
| $D^0 \to K^0_S\pi^+\pi^-$ | $x$, $y$ | [58] | Run 1 | *As before* |
| $D^0 \to K^0_S\pi^+\pi^-$ | $x_{CP}$, $y_{CP}$, $\Delta x$, $\Delta y$ | [59] | Run 1 | *As before* |
| $D^0 \to K^0_S\pi^+\pi^-$ | $x_{CP}$, $y_{CP}$, $\Delta x$, $\Delta y$ | [60, 61] | Run 2 | *As before* |
| $D^0 \to \pi^+\pi^-\pi^0$ | $\Delta Y^{\rm eff}$ | [26] | Run 2 | **New** |

# Time-dependent CPV in $B^0 \to D^+D^-$

**New**

arXiv: 2409.03009

$$\frac{\mathrm{d}\Gamma(t,d)}{\mathrm{d}t} \propto e^{-t/\tau_{B^0}}\left(1 + d\,C_{D^+D^-}\cos\Delta m_d t - d\,S_{D^+D^-}\sin\Delta m_d t\right)$$



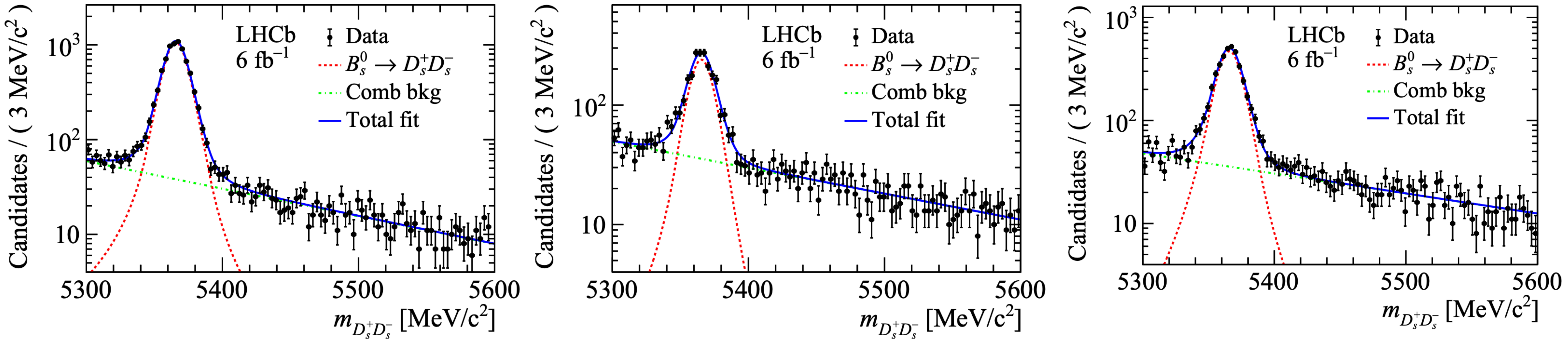

- CP asymmetry observed in $B^0 \to D^+D^-$ for the first time with a significance exceeding $6\sigma$

$$\boxed{\begin{aligned} S_{D^+D^-} &= -0.552 \pm 0.100\,(\text{stat}) \pm 0.010\,(\text{syst}) \\ C_{D^+D^-} &= \quad 0.128 \pm 0.103\,(\text{stat}) \pm 0.010\,(\text{syst}) \end{aligned}}$$

[PRL117 (2016) 261801, BaBar PRD79 (2009) 032002] [Belle PRD85 (2012) 091106]

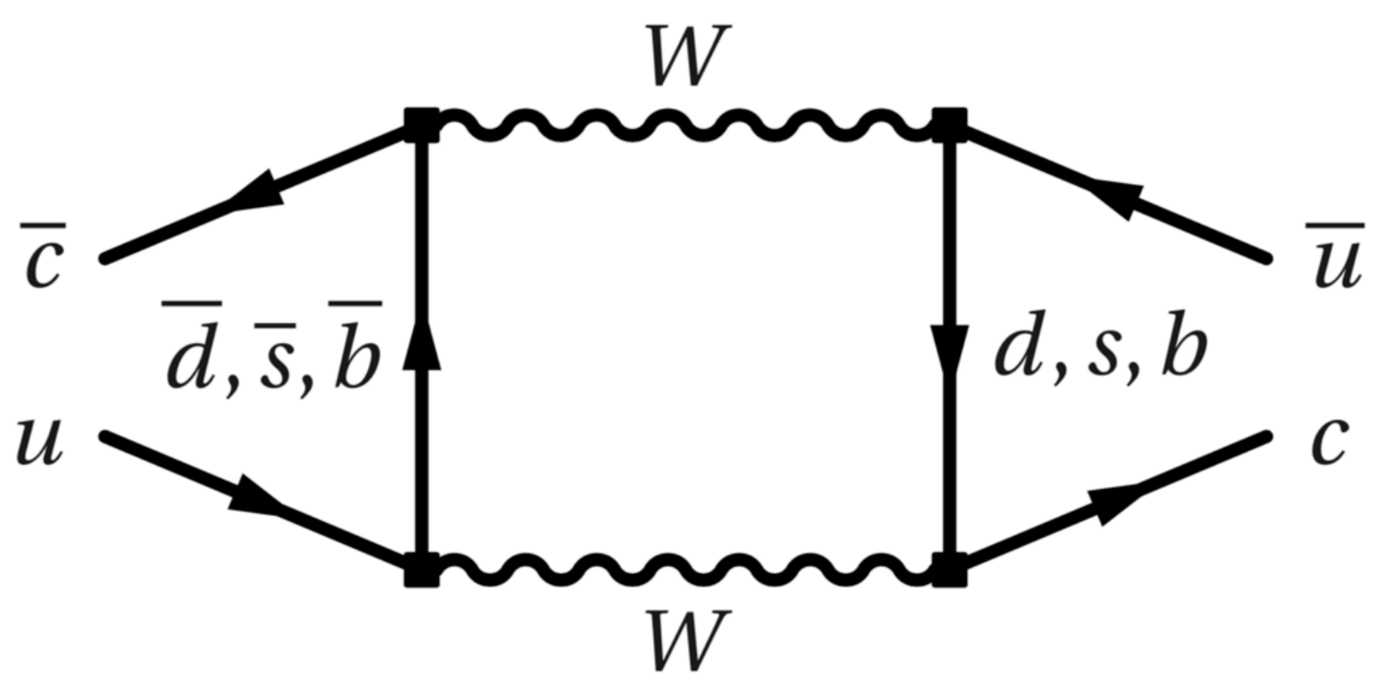
- LHCb combination:

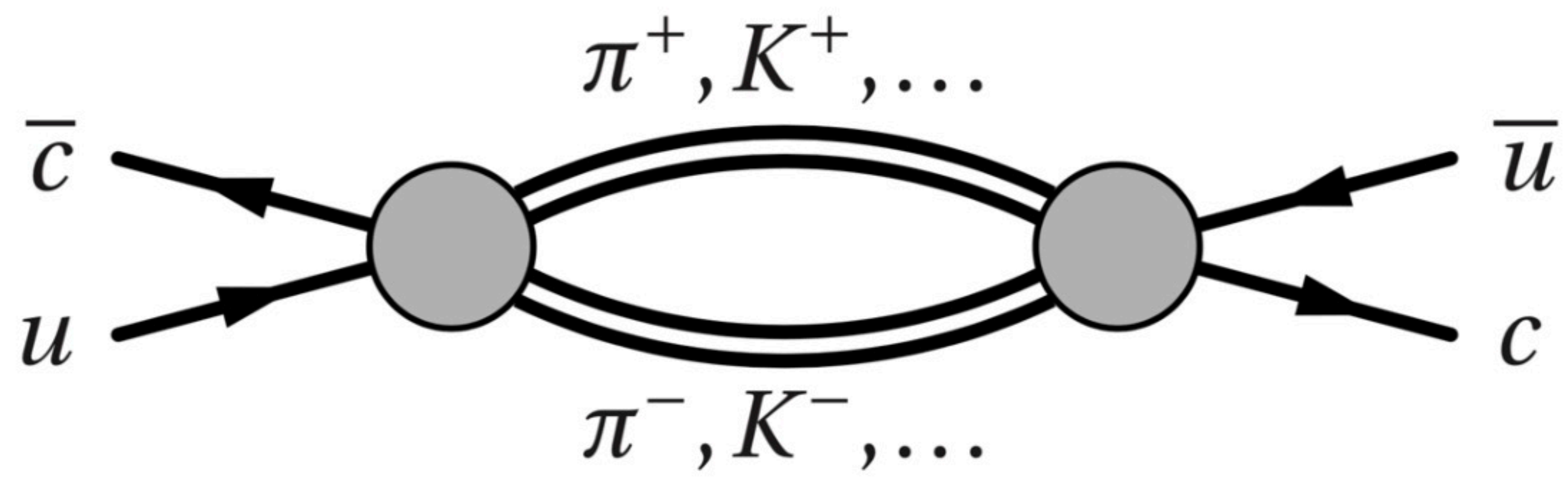
$$\boxed{\begin{aligned} S_{D^+D^-} &= -0.549 \pm 0.085\,(\text{stat}) \pm 0.015\,(\text{syst}) \\ C_{D^+D^-} &= \quad 0.162 \pm 0.088\,(\text{stat}) \pm 0.009\,(\text{syst}) \end{aligned}}$$



# CP violation in charm sector

- GIM mechanism very effective for charm decays, SM loops highly suppressed
- Tiny weak phases in first two generations of CKM matrix
- Oscillation and CPV ( $\leq 10^{-3}$)
- Long distance contribution comparable/larger than short distance



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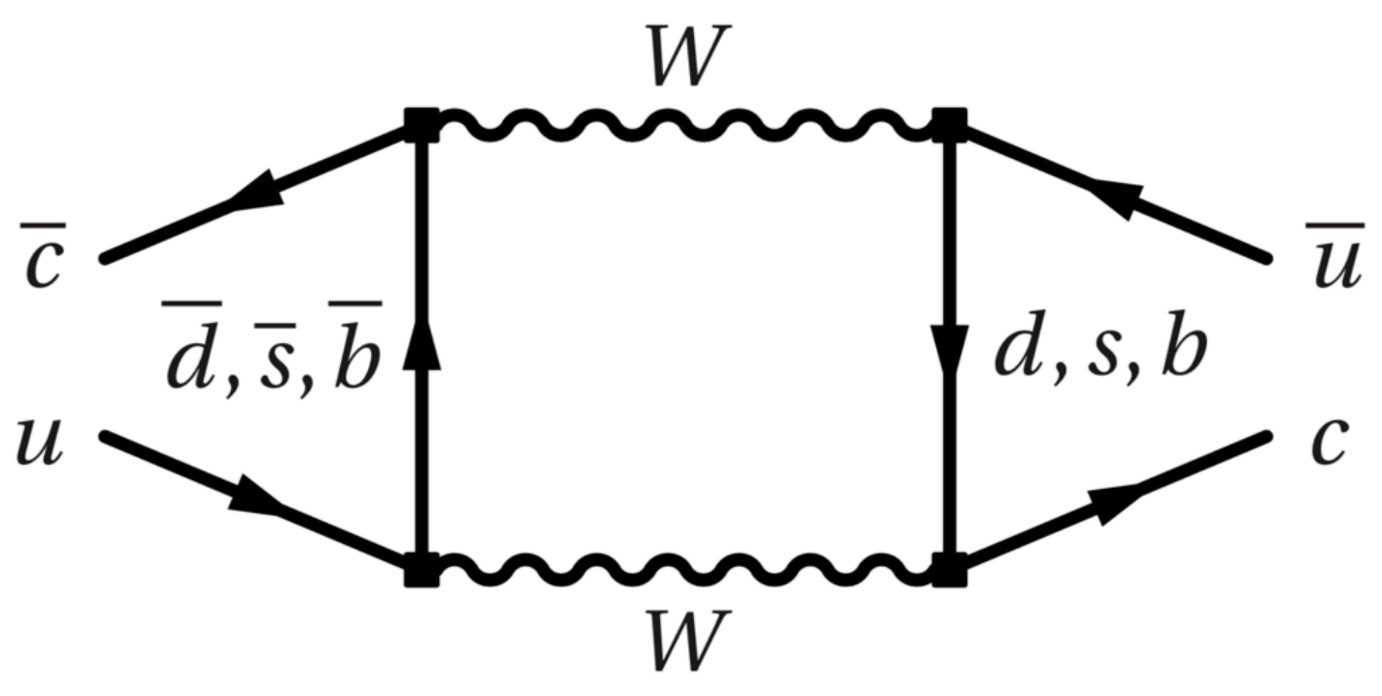
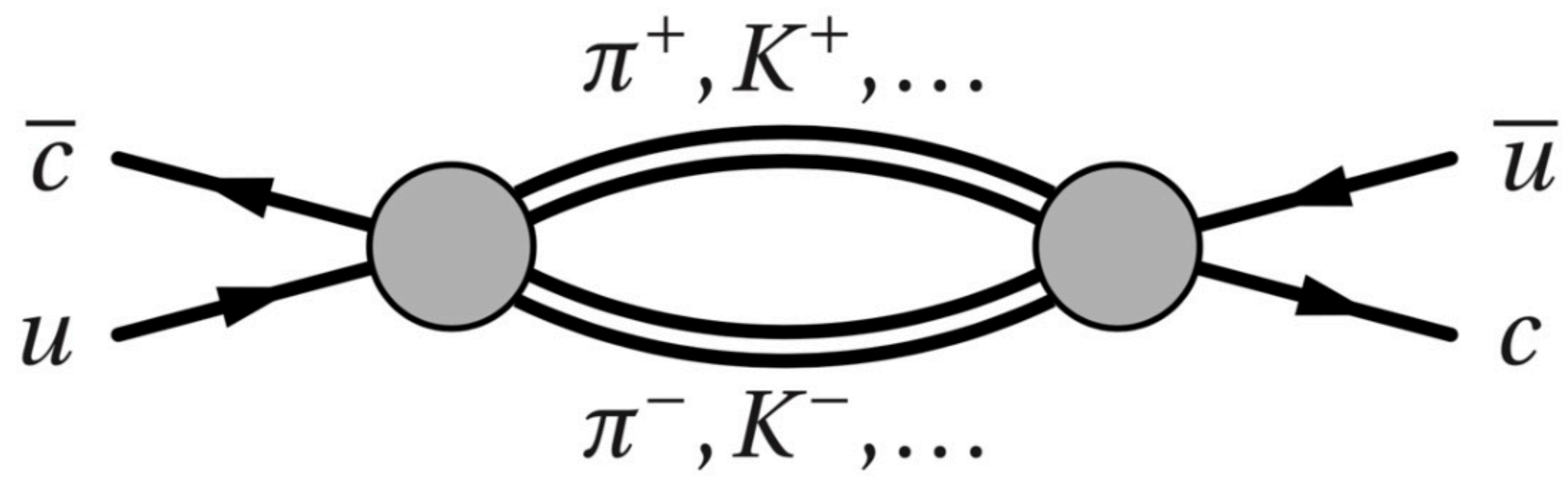



**Breakthroughs by LHCb thanks to huge statistics:**

First observation of CPV in $D^0 \to h^+h^-$ decays

$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$ [PRL(2019)211803]

Evidence of CPV in $D^0 \to \pi^+\pi^-$ decay

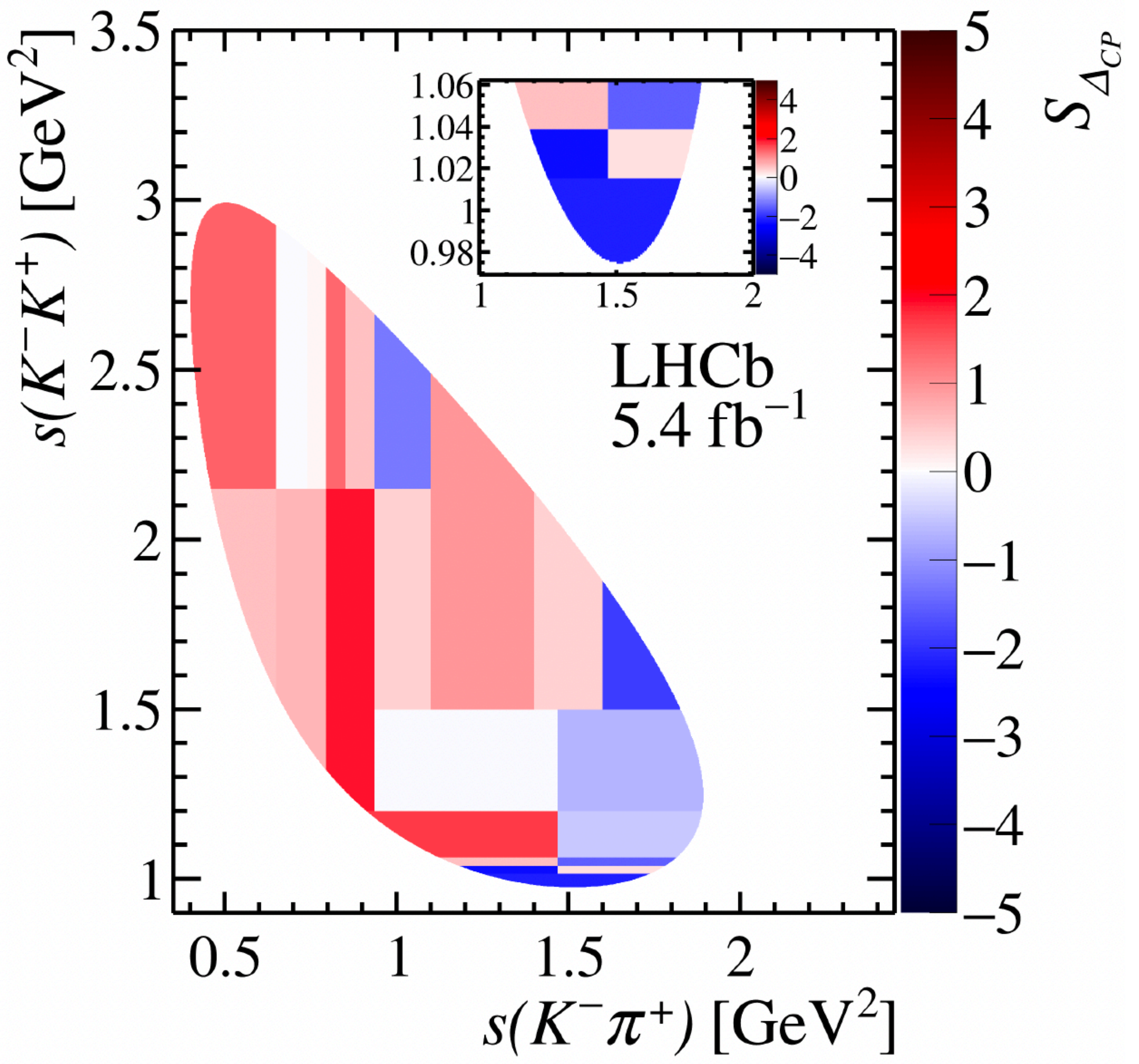
$A_{CP}(\pi^+\pi^-) = (23.2 \pm 6.1) \times 10^{-4}$ $(3.8\sigma)$ [PRL(2023)211803]

# Direct CP violation in $D^+ \to K^+K^-\pi^+$

**New** arXiv:2409.01414

- Search for localised CP violation in the phase space of $D^+ \to K^+K^-\pi^+$ $(S)$ decay
- Control channel $D_s^+ \to K^+K^-\pi^+$ $(C)$ to subtract nuisance asymmetries

$$\boxed{\Delta A_{CP}^{i} = A_{\mathrm{raw}}^{i,S} - A_{\mathrm{raw}}^{i,C} - \Delta A_{\mathrm{raw}}^{\mathrm{global}}}$$



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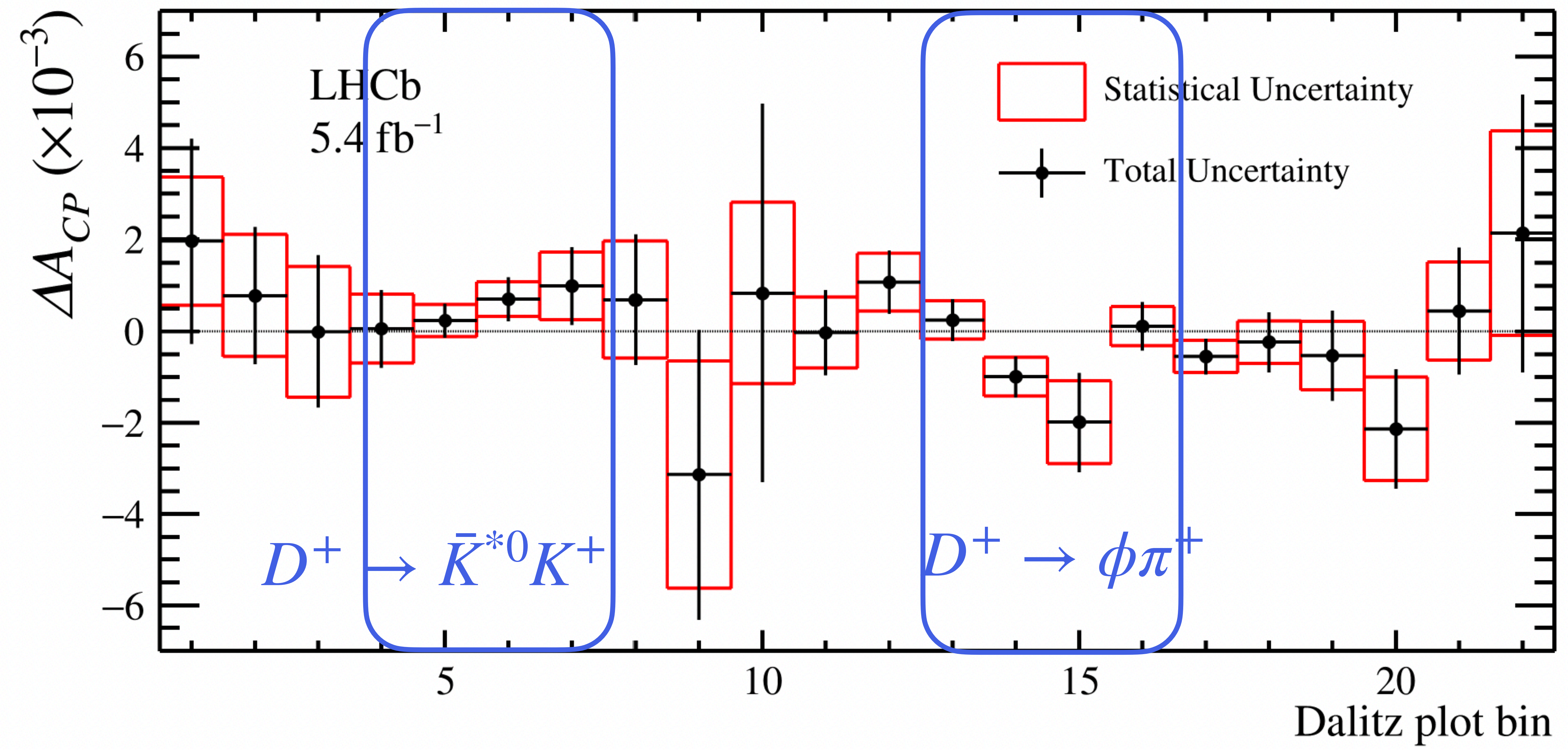
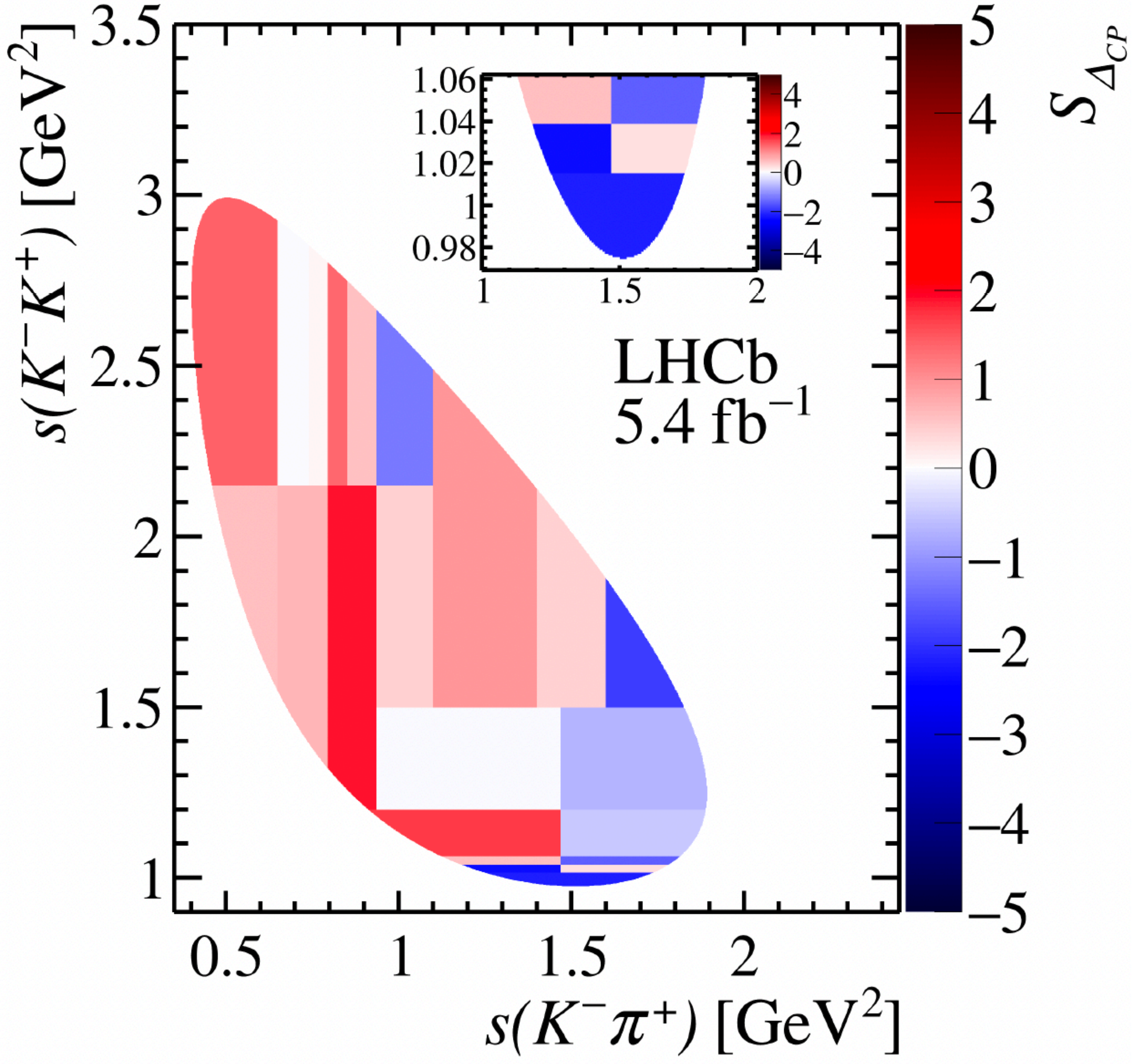
$$A^{\phi\pi^+}_{CP|S} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3}$$
$$A^{\bar{K}^{*0}K^+}_{CP|S} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3}$$

p-values (2.3-14.1%) compatible with no CPV



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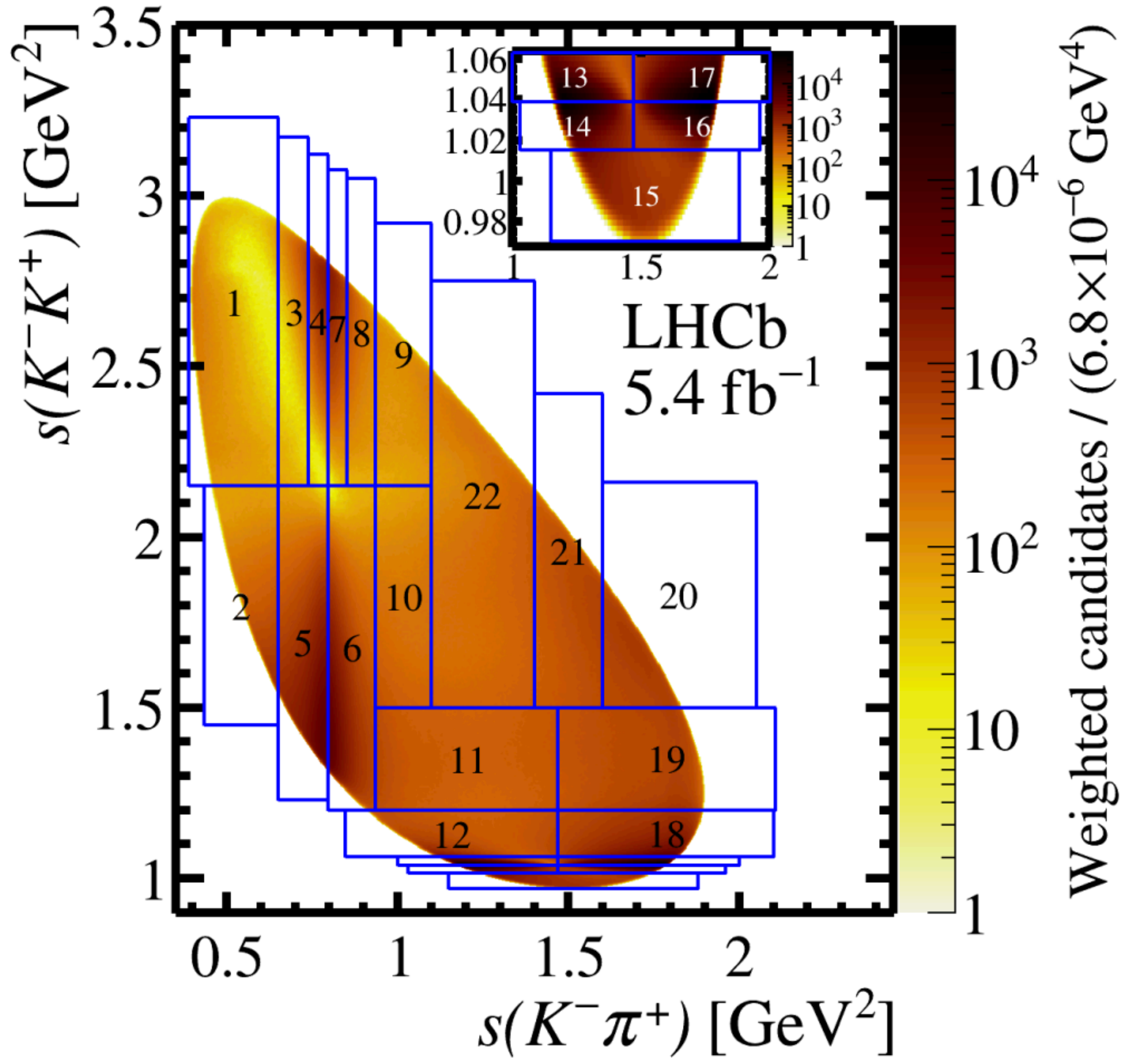
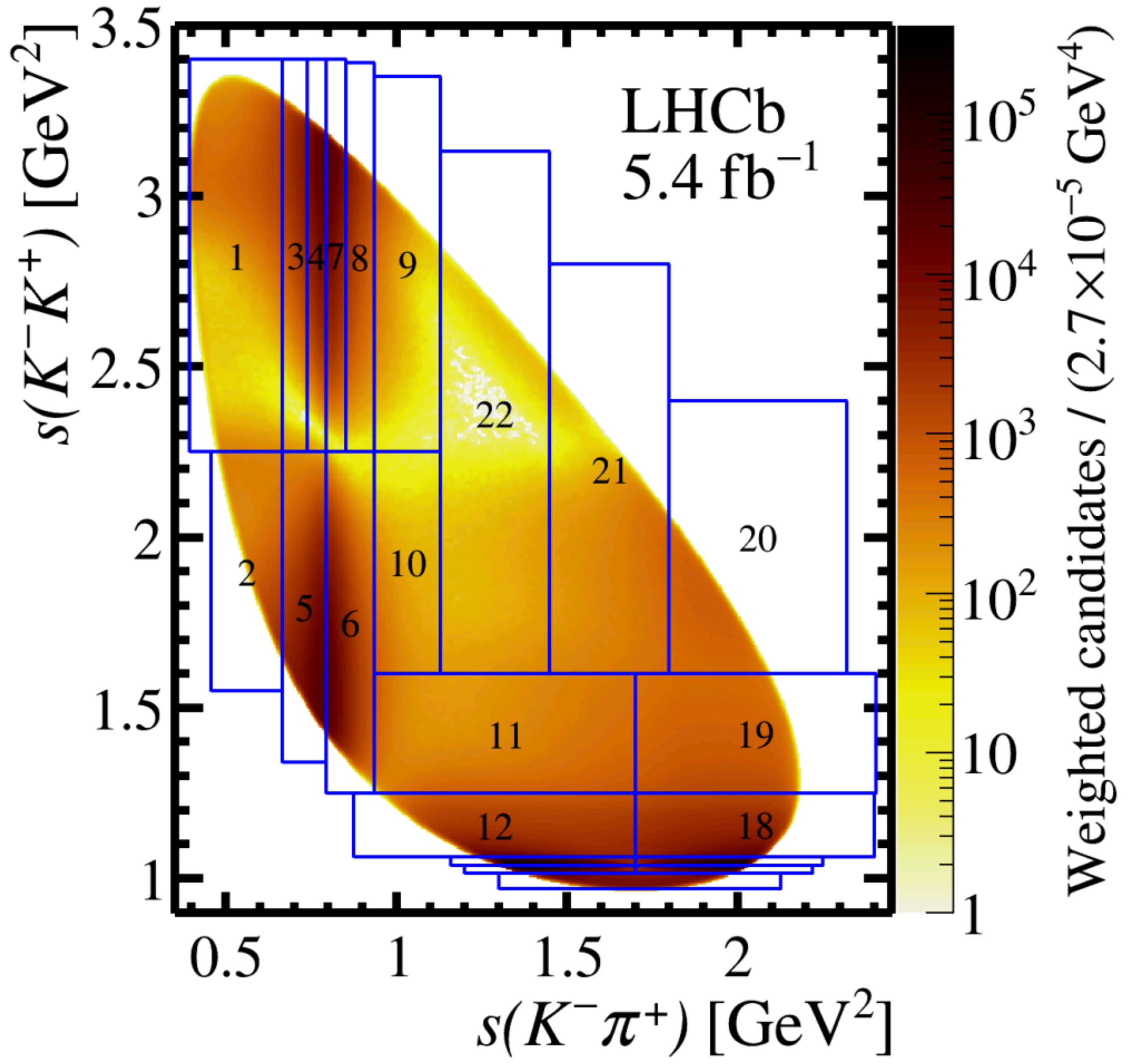
- Test-statistic to extract a p-value for the hypothesis of no localised CP violation

$$\chi^2(\mathcal{S}_{\Delta_{CP}}) = \sum_{i}^{N_{\text{bins}}} (\mathcal{S}_{\Delta_{CP}}^{i})^2, \qquad \mathcal{S}_{\Delta_{CP}}^{i} = \frac{\Delta A_{CP}^{i}}{\sigma_{\Delta A_{CP}^{i}}}$$




$D^+ \to K^+K^-\pi^+$ $(S)$

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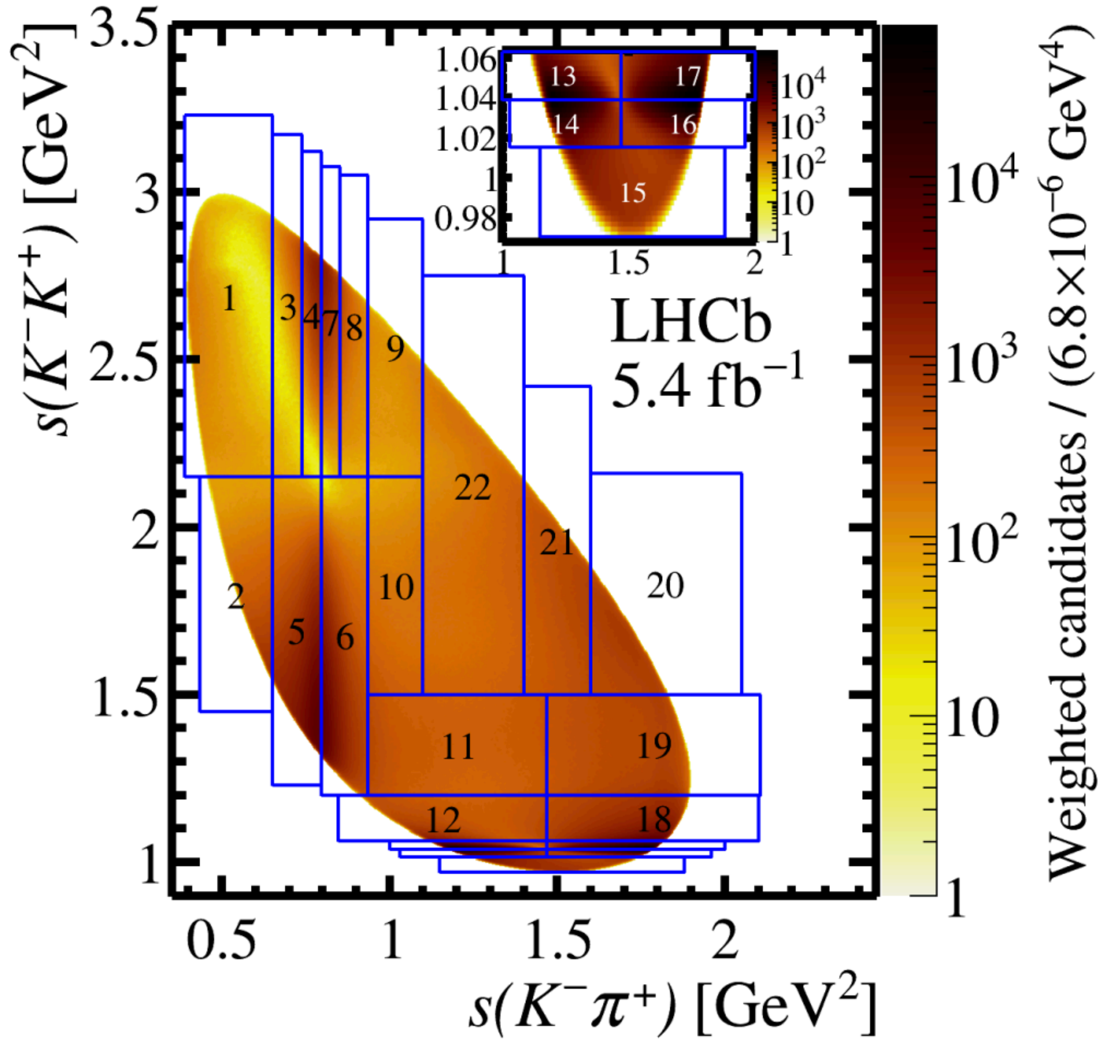
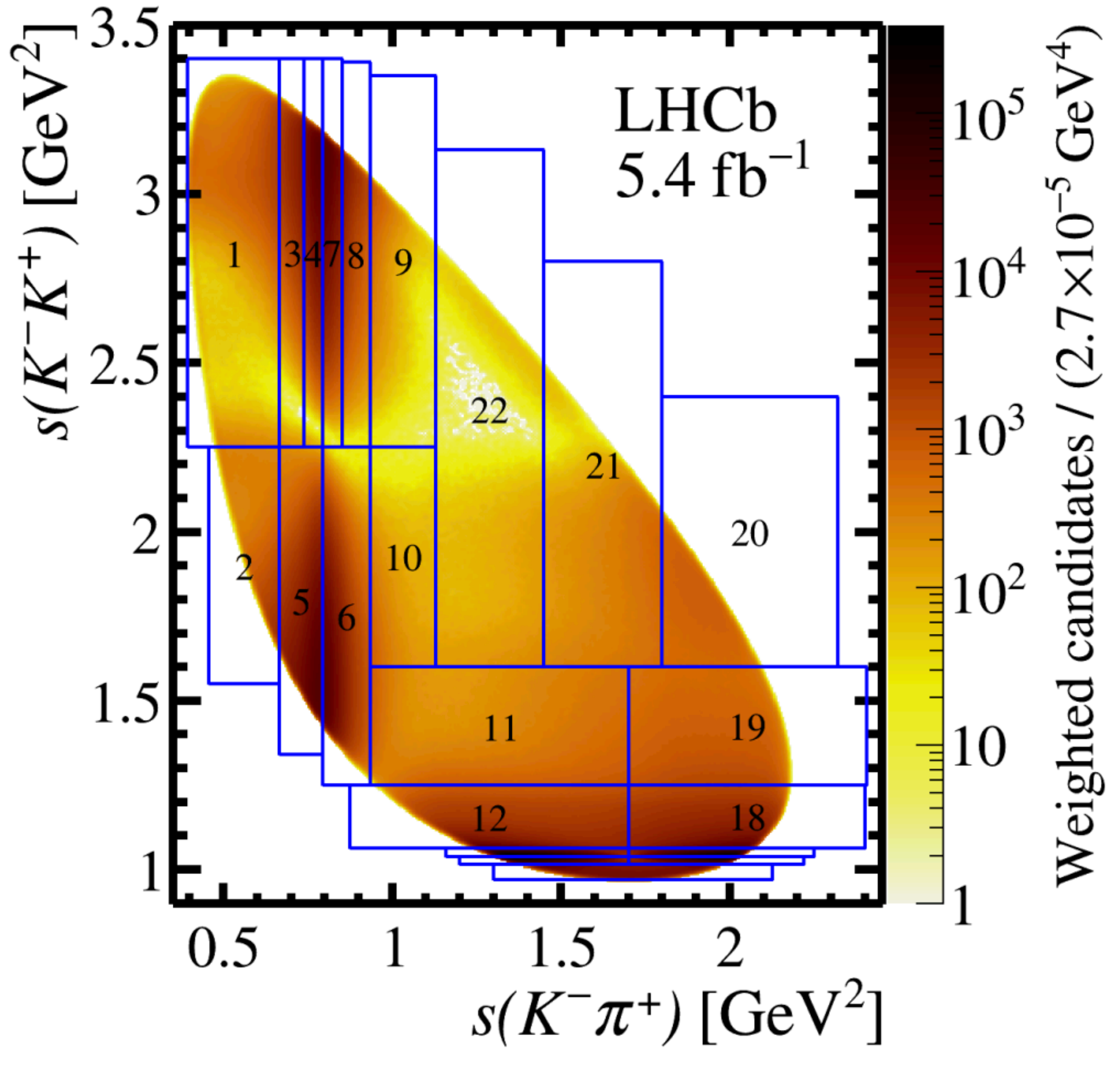
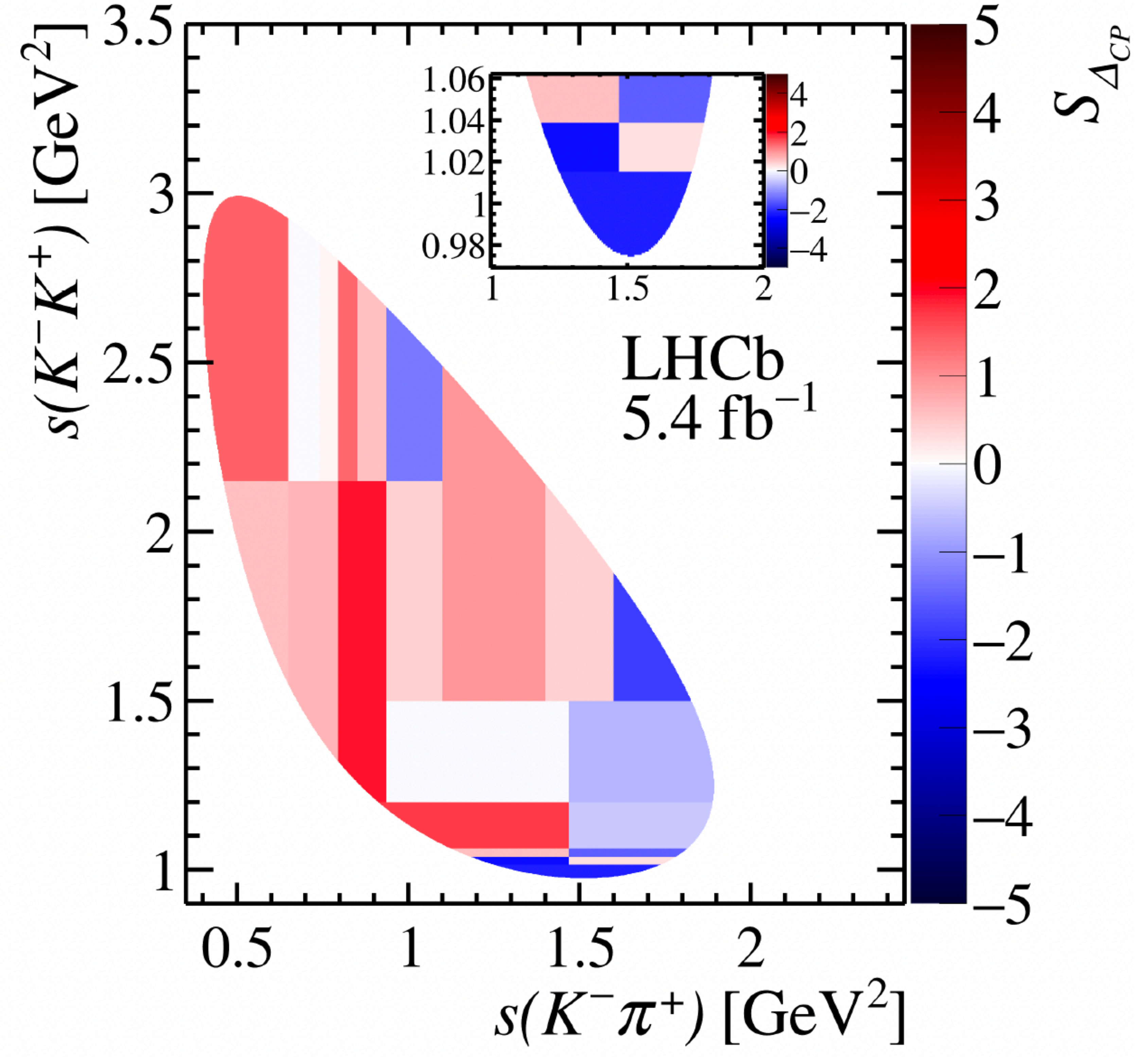



$D^+ \to K^+K^-\pi^+$ $(S)$




$D_s^+ \to K^+K^-\pi^+$ $(C)$

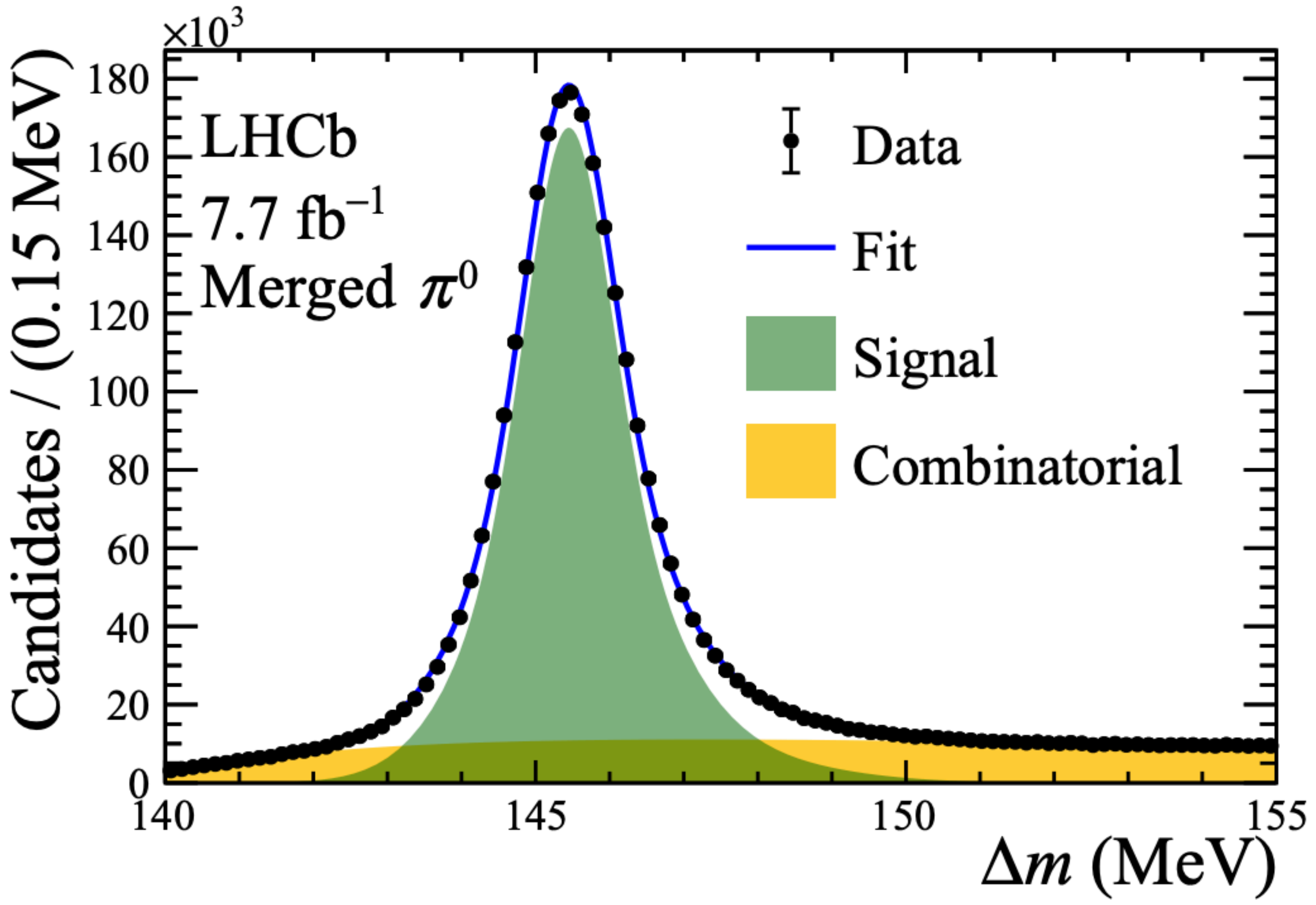
- p-values (2.3-14.1%) compatible with absence of localised CP violation in Dalitz plot

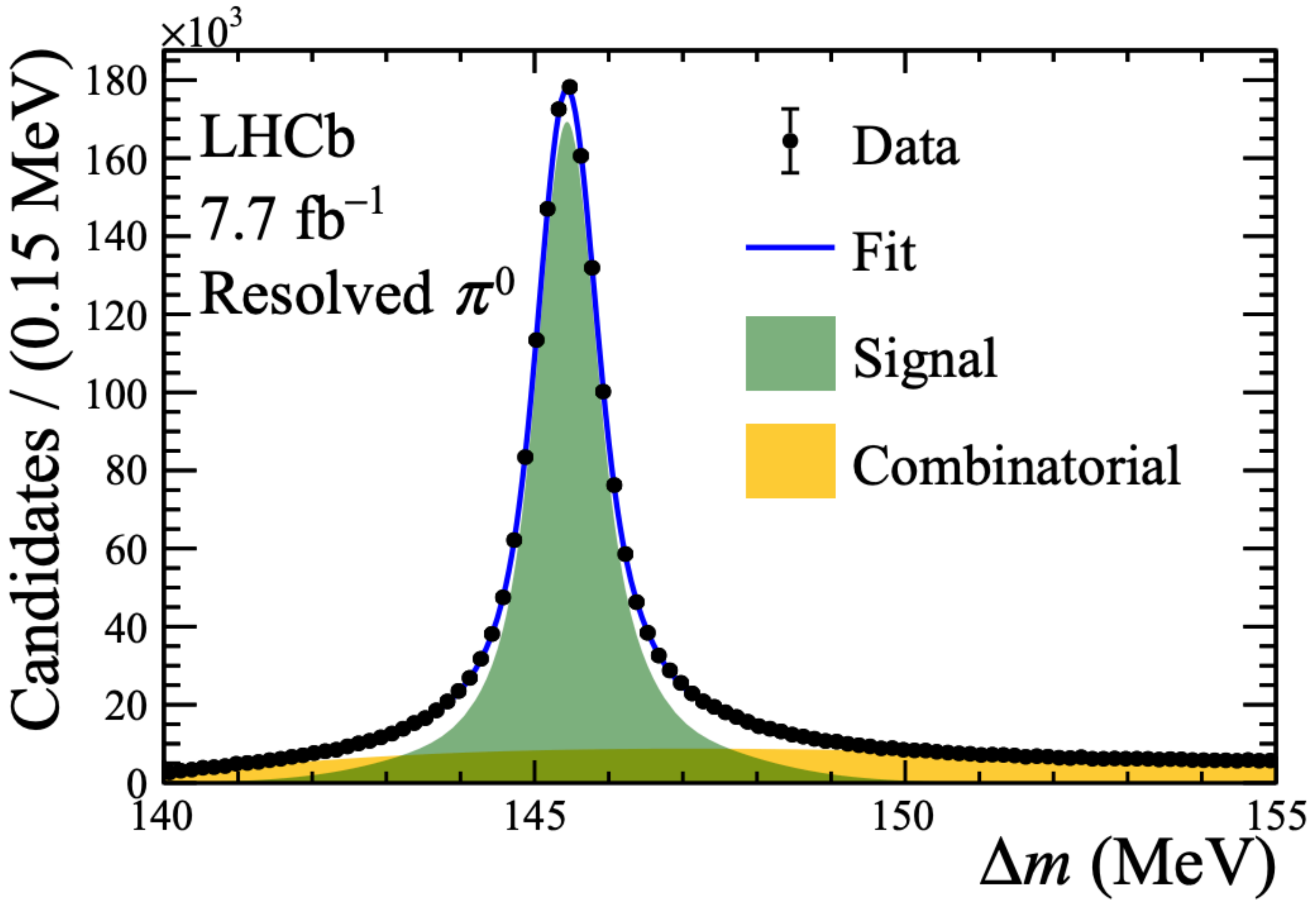


# Time-dependent CP violation in $D^0 \to \pi^+\pi^-\pi^0$

Phys. Rev. Lett. 133 (2024) 101803

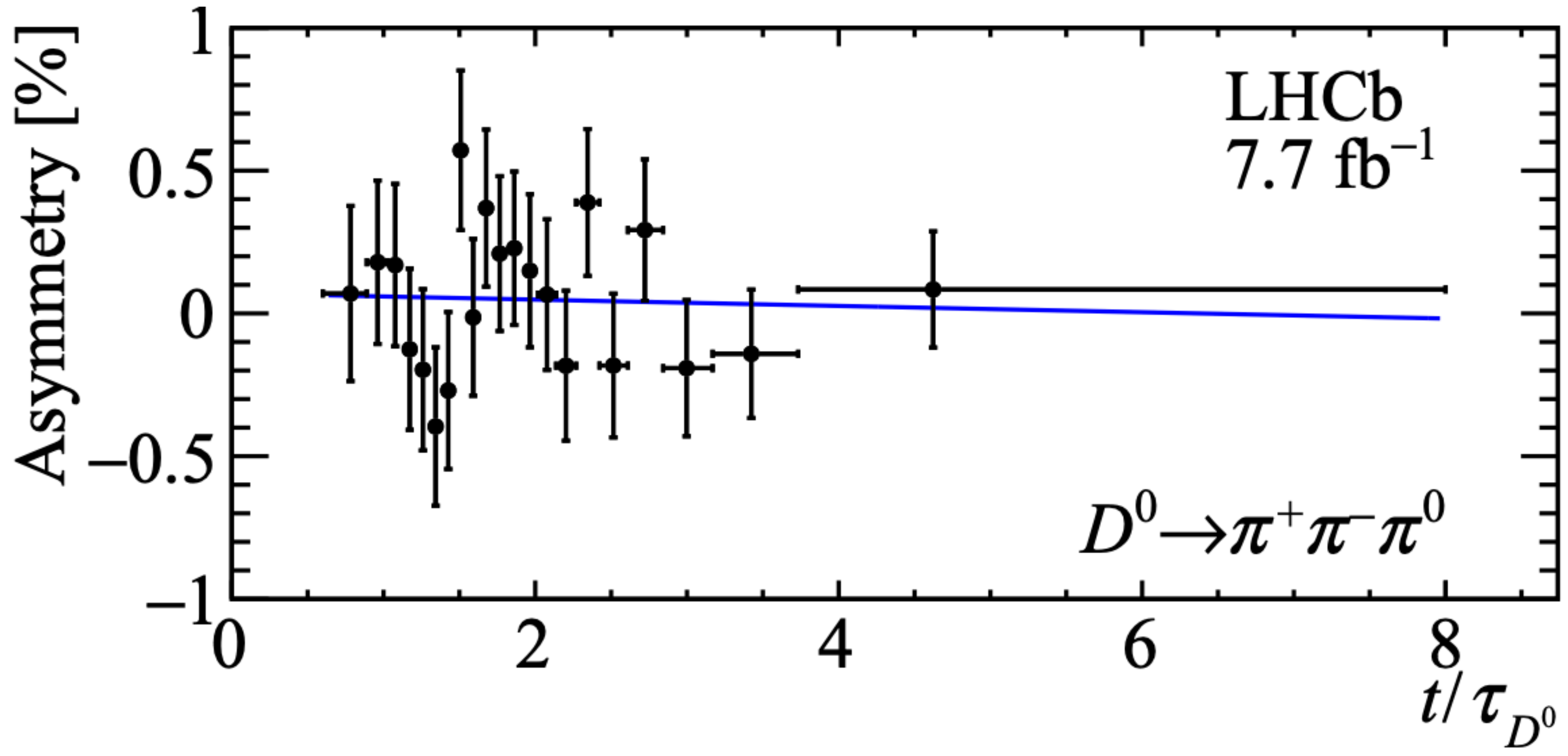
- First measurement of time-dependent CP violation in SCS mode




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

$$A_{\rm meas}(\langle t/\tau_{D^0}\rangle_i) \equiv \frac{N^i_{D^0} - N^i_{\bar{D}^0}}{N^i_{D^0} + N^i_{\bar{D}^0}}$$




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

- No evidence for time-dependent CP violation, constant with world average

$$\Delta Y \equiv \eta_{CP}\Delta Y_{f_{CP}} = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$$

# Time-dependent CP violation in $D^0 \to K\pi$

LHCb-PAPER-2024-008

- Interference between mixing and decay for favoured RS and suppressed WS decays


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

DCS over CF amplitude

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

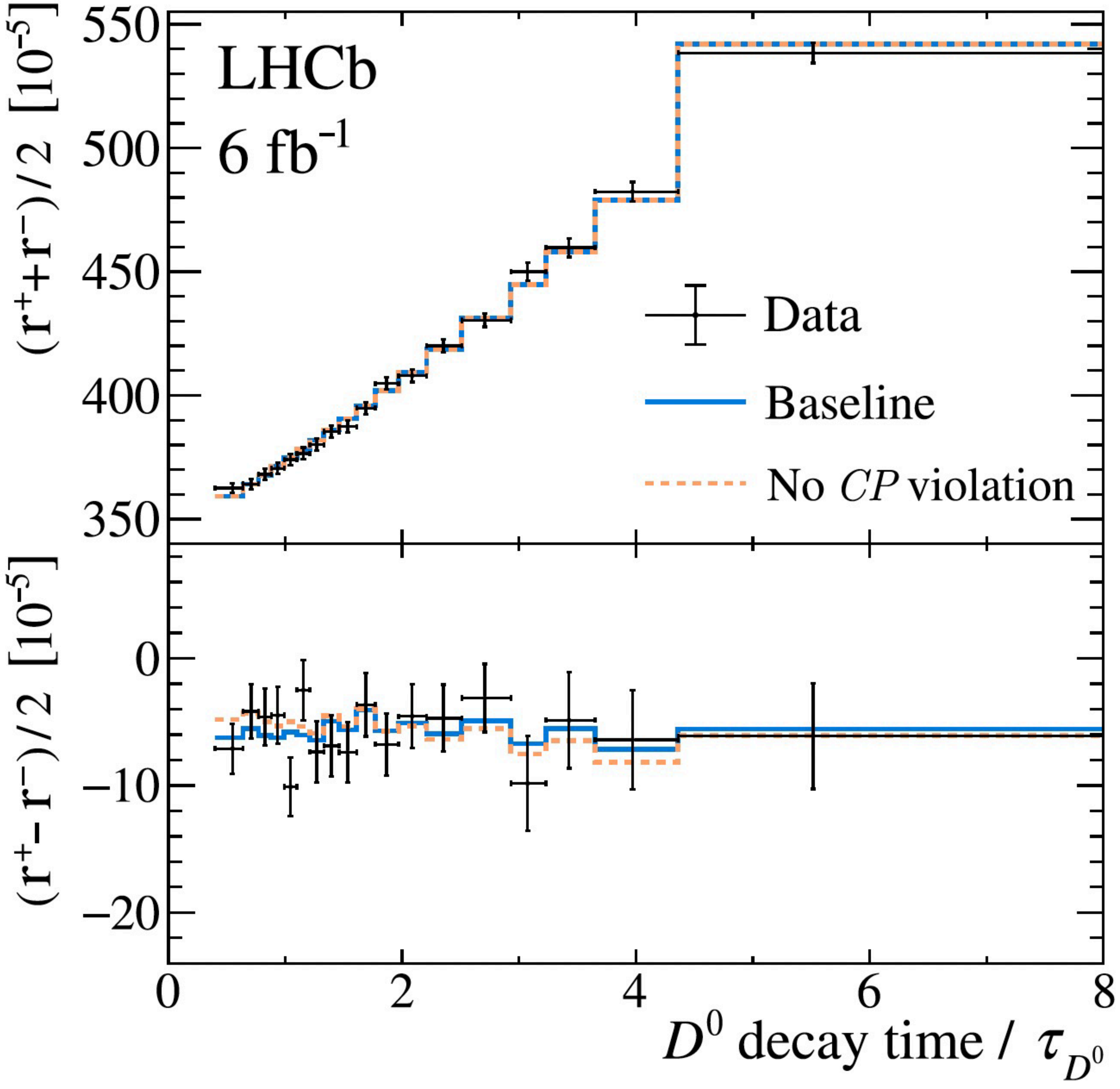
CPV observables: $A_{K\pi}$ (in decays), $\Delta c_{K\pi}$ (in interference), $\Delta c'_{K\pi}$ (in mixing).

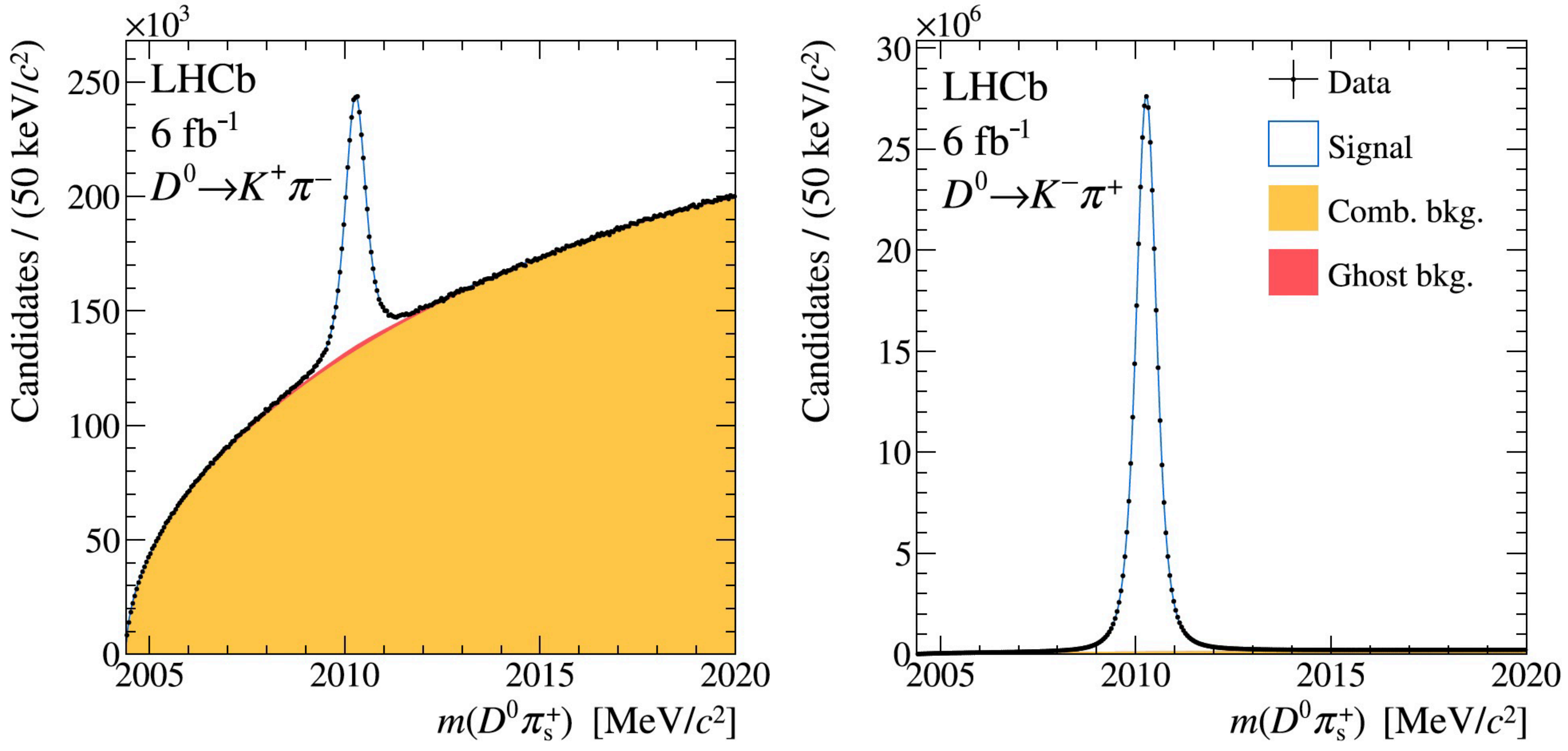
Mixing observables: $c_{K\pi}$, $c'_{K\pi}$

# Time-dependent CP violation in $D^0 \to K\pi$

arXiv:2407.18001

- Measured with yields: RS ~400 M, WS ~1.6 M




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

Mixing parameter

Evidence of non 0

No CPV

$$c_{K\pi} \approx y_{12} \cos\phi_f^{\Gamma} \cos\Delta_f + x_{12} \cos\phi_f^{M} \sin\Delta_f$$