

CPV studies of b hadrons at LHCb

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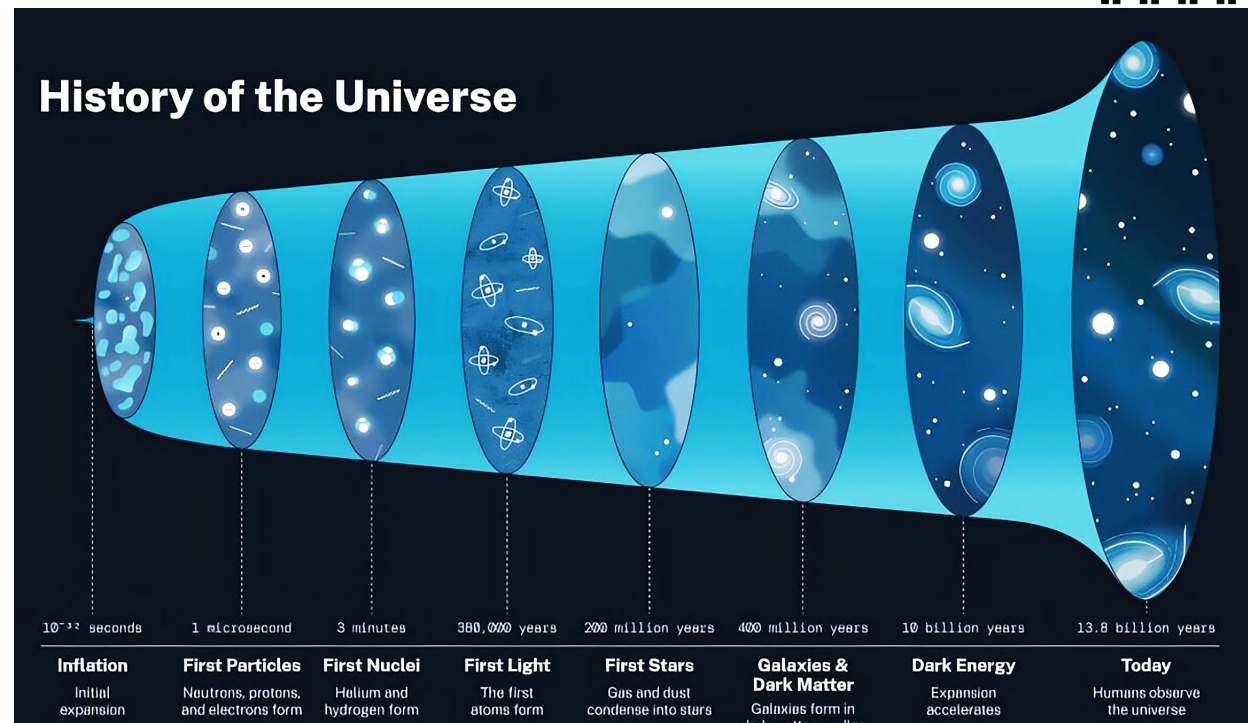
Outline

- Physics background
- CP violation
- LHCb experiment
- Measurements of CP violation at LHCb
- Summary



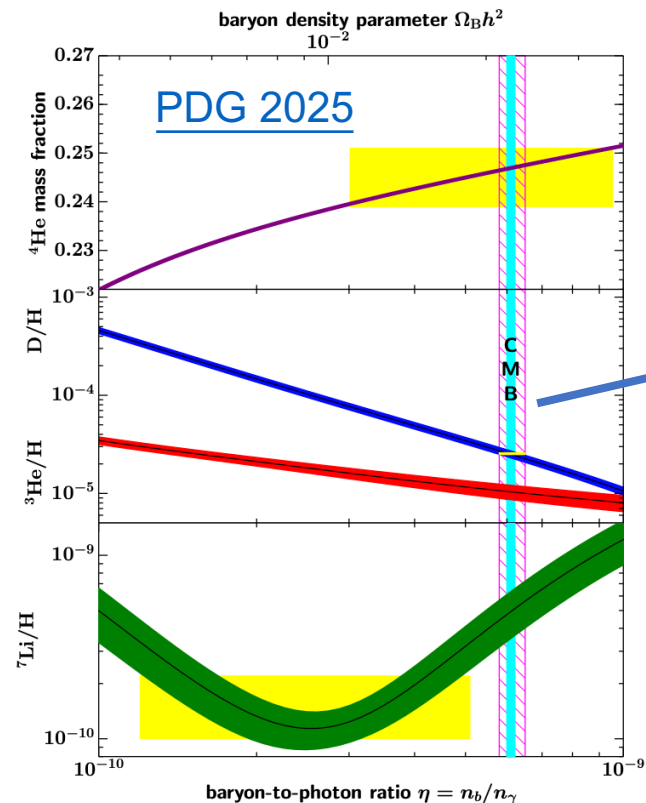
Unsolved physics problems

- Fundamental force, gravity
- Dark matter and energy
- Neutrino mass and oscillations
- Quark generation
- **Matter-antimatter asymmetry**
-

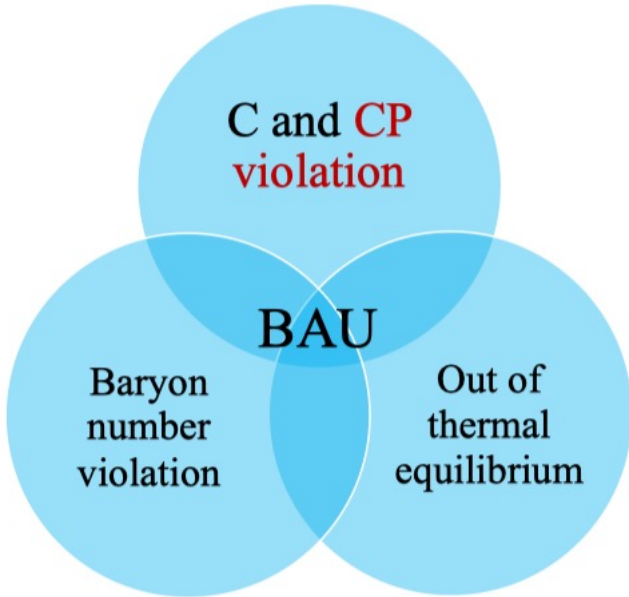
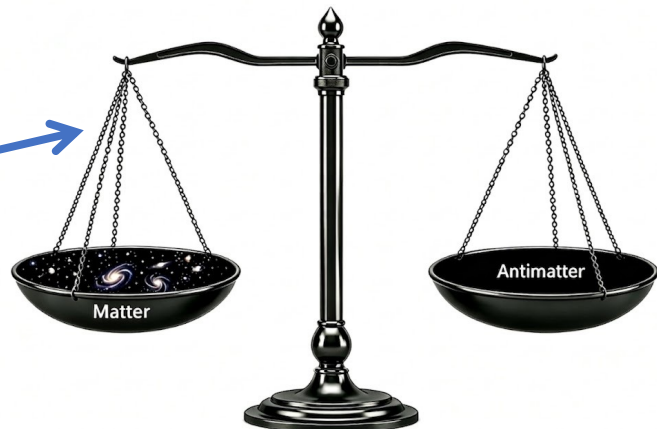


Matter-antimatter asymmetry

- Observed asymmetry
- Sakharov conditions



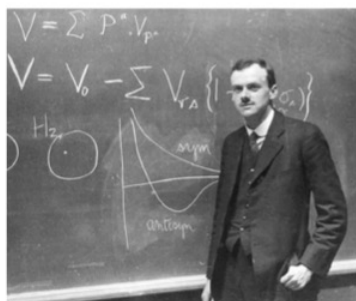
$$\eta = (n_B - n_{\bar{B}})/n_\gamma \sim 6 \times 10^{-10}$$



CP violation

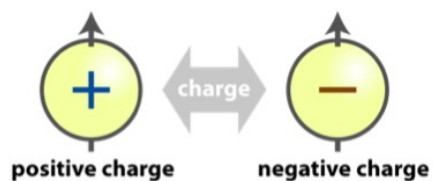
- Particle and antiparticle follow different laws

Prediction of antimatter
 $(i\partial_\mu\gamma^\mu - m)\psi = 0$

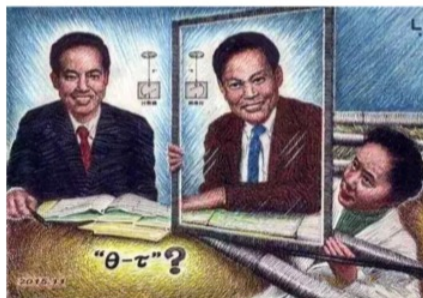


1928

Charge conjugation

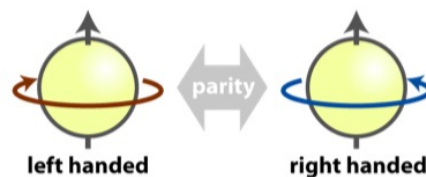


Parity violation
 $^{60}\text{Co} \rightarrow ^{60}\text{Ni} + \beta + \bar{\nu}_e$



1957

Parity

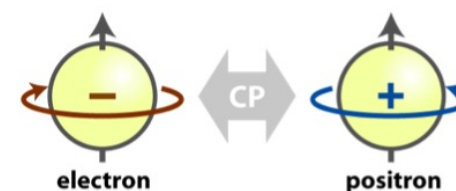


Charge-Parity violation
 $K_L^0 \rightarrow \pi^+ + \pi^-$



1964

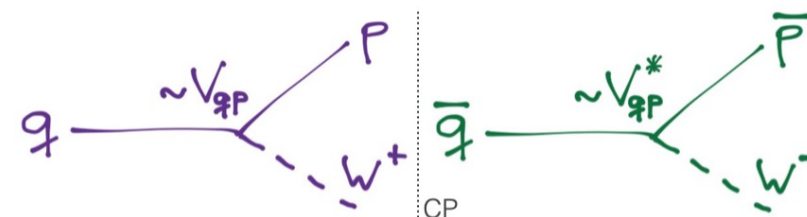
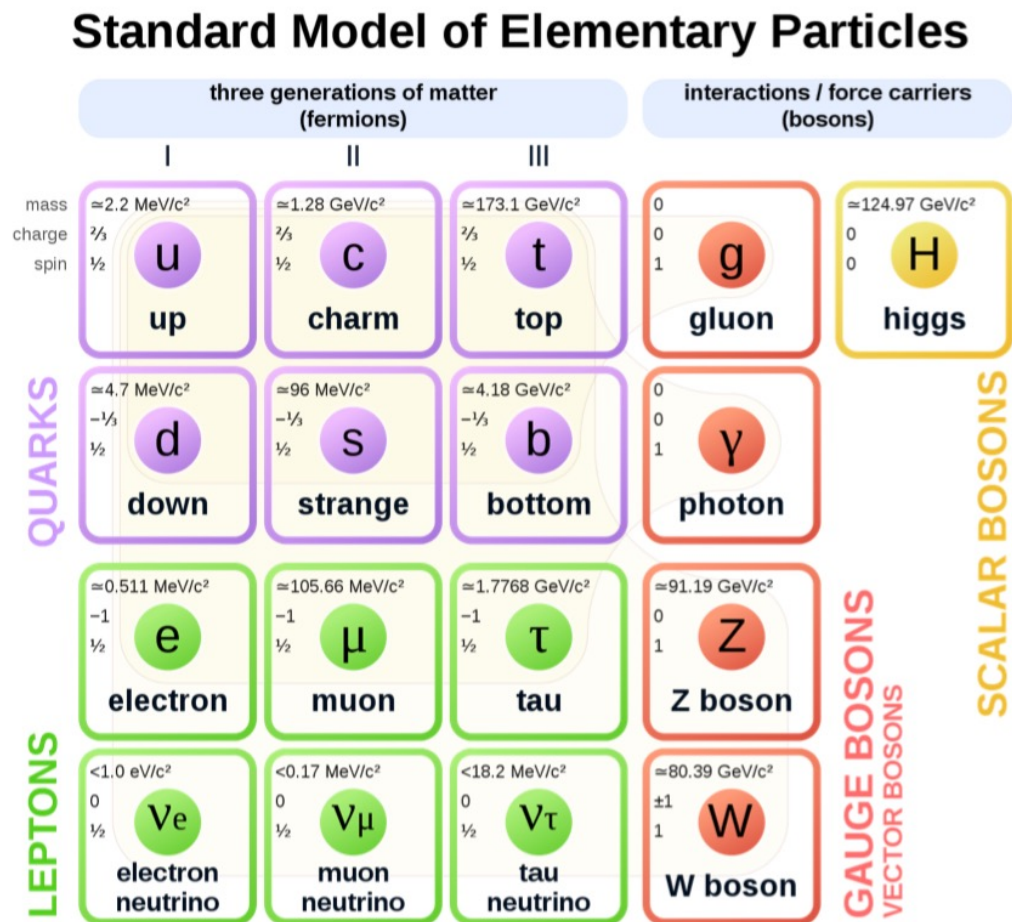
Charge-parity



Slide from Yanxi Zhang

CP violation in the Standard Model

- Cabibbo-Kobayashi-Maskawa (CKM) mechanism



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

flavour eigenstates
 V_{CKM}
mass eigenstates

CKM matrix

- Unitary matrix

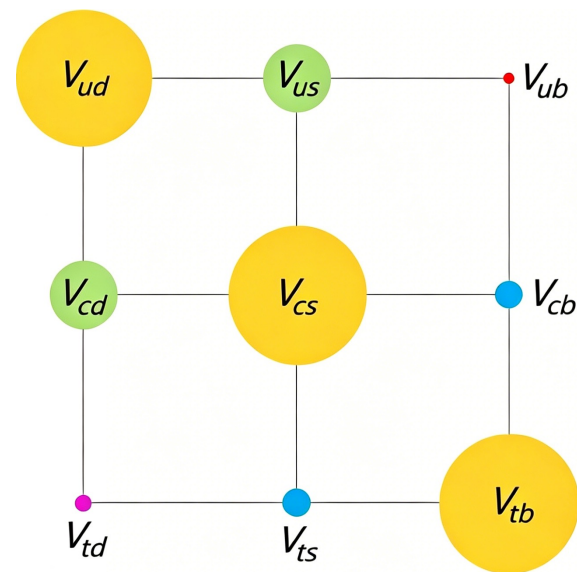
- ✓ $\sum_i V_{ij} V_{jk}^* = \delta_{jk}$, e.g. $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- ✓ $\sum_j V_{ij} V_{jk}^* = \delta_{ik}$, e.g. $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$

- Clear hierarchy in magnitudes
- Only source of CP violation in SM
- η in SM $\sim 10^{-17} \ll 10^{-10}$

New source of CPV is to be discovered!

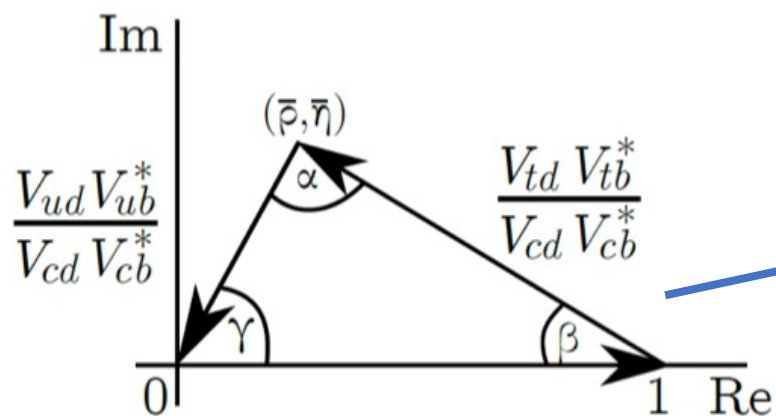
Wolfenstein parameterization, $\lambda = 0.225$

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

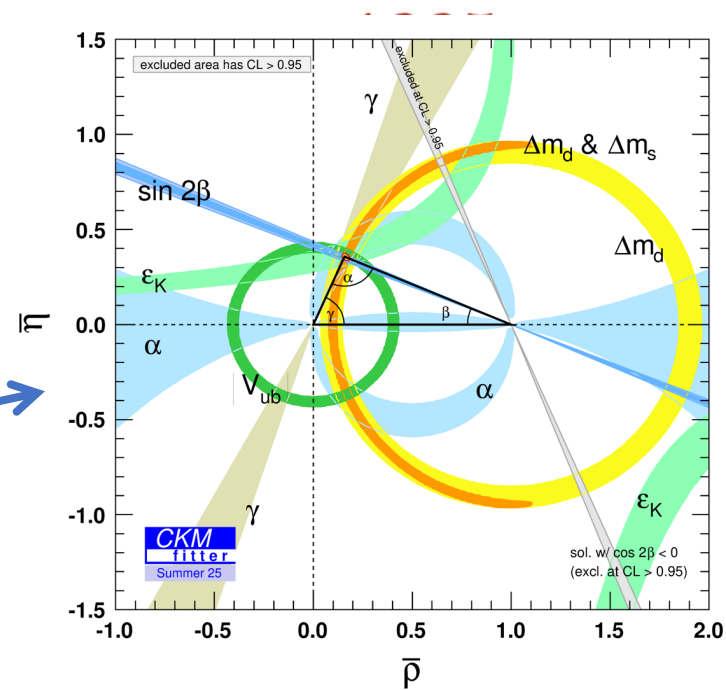


CKM matrix

- **Test of unitarity** (PDG 2025)
 - ✓ $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0007$
 - ✓ $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.001 \pm 0.012$
 - ✓ $\alpha + \beta + \gamma = (172 \pm 5)^\circ$

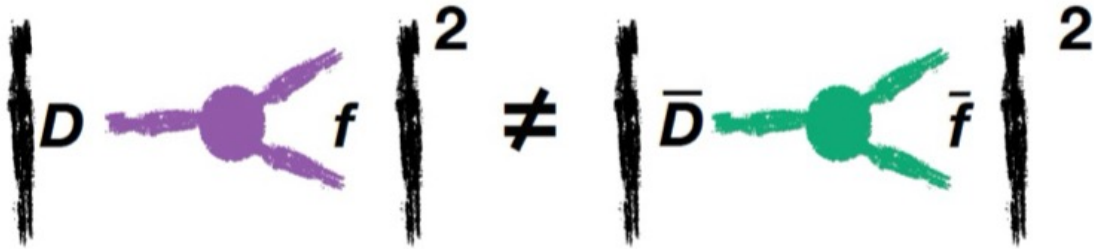


Rigorously tested in the past decades!

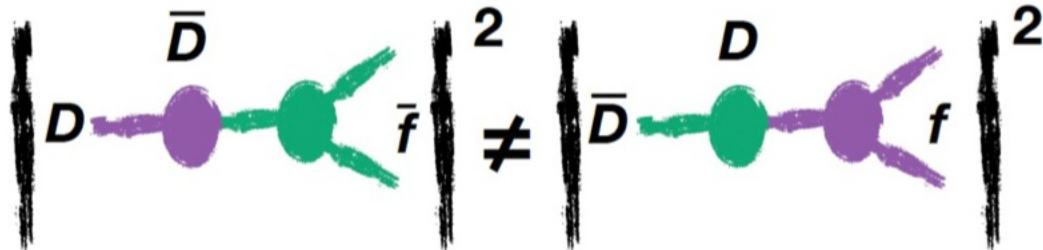


Types of CP violation

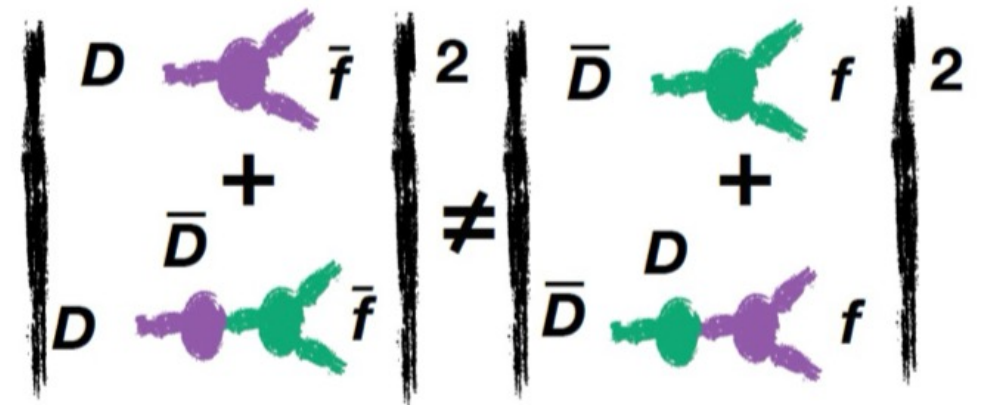
- Direct CPV in **decay**



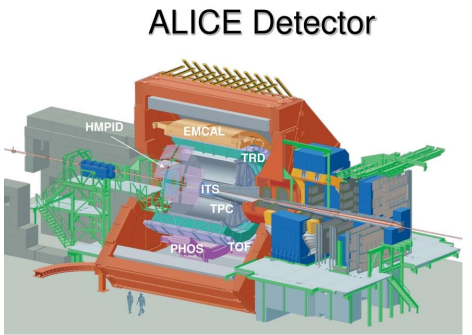
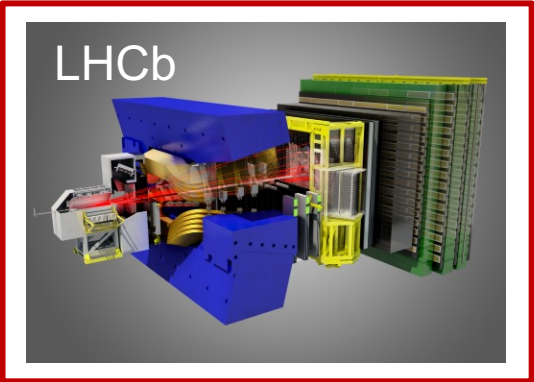
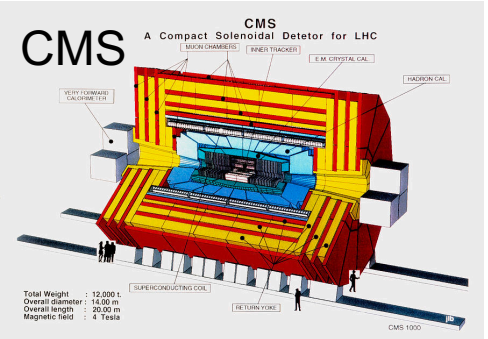
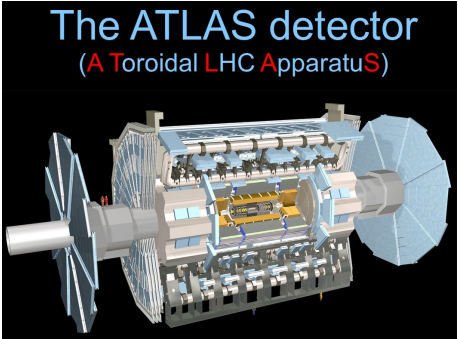
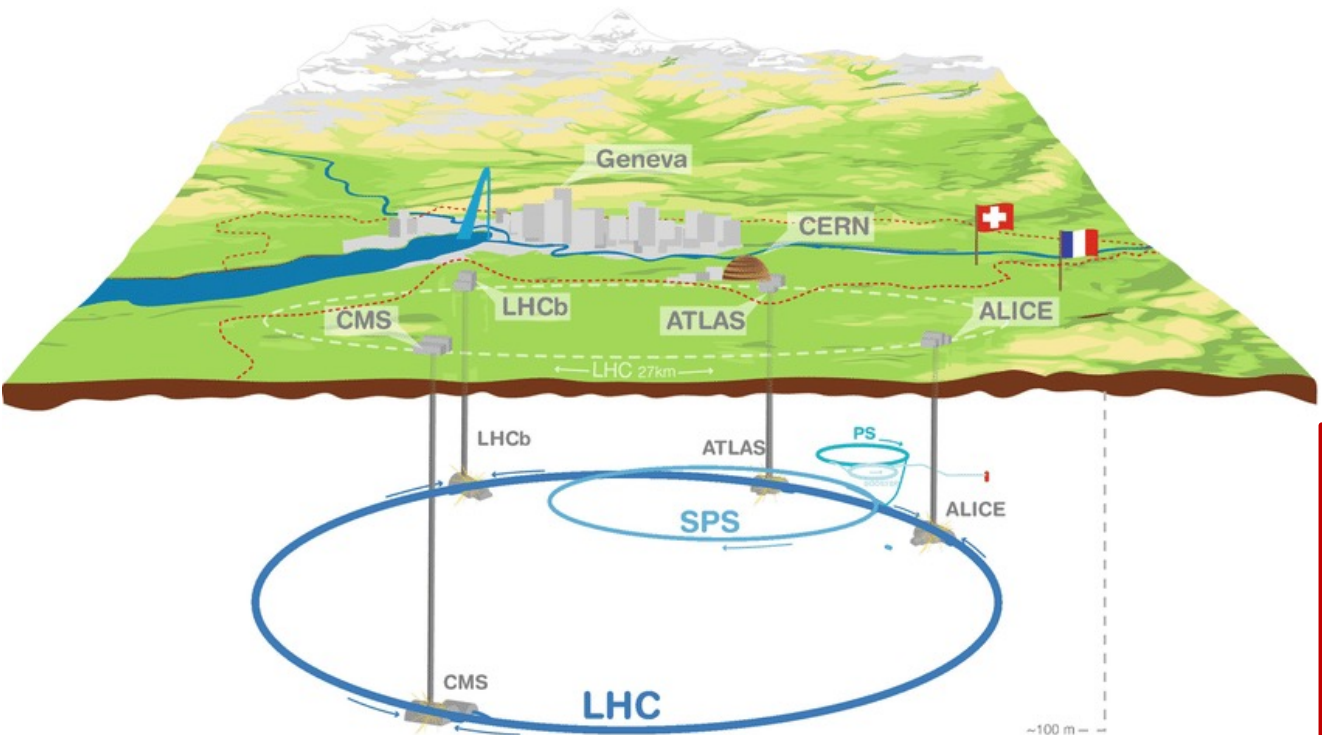
- Induced CPV in **mixing**



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

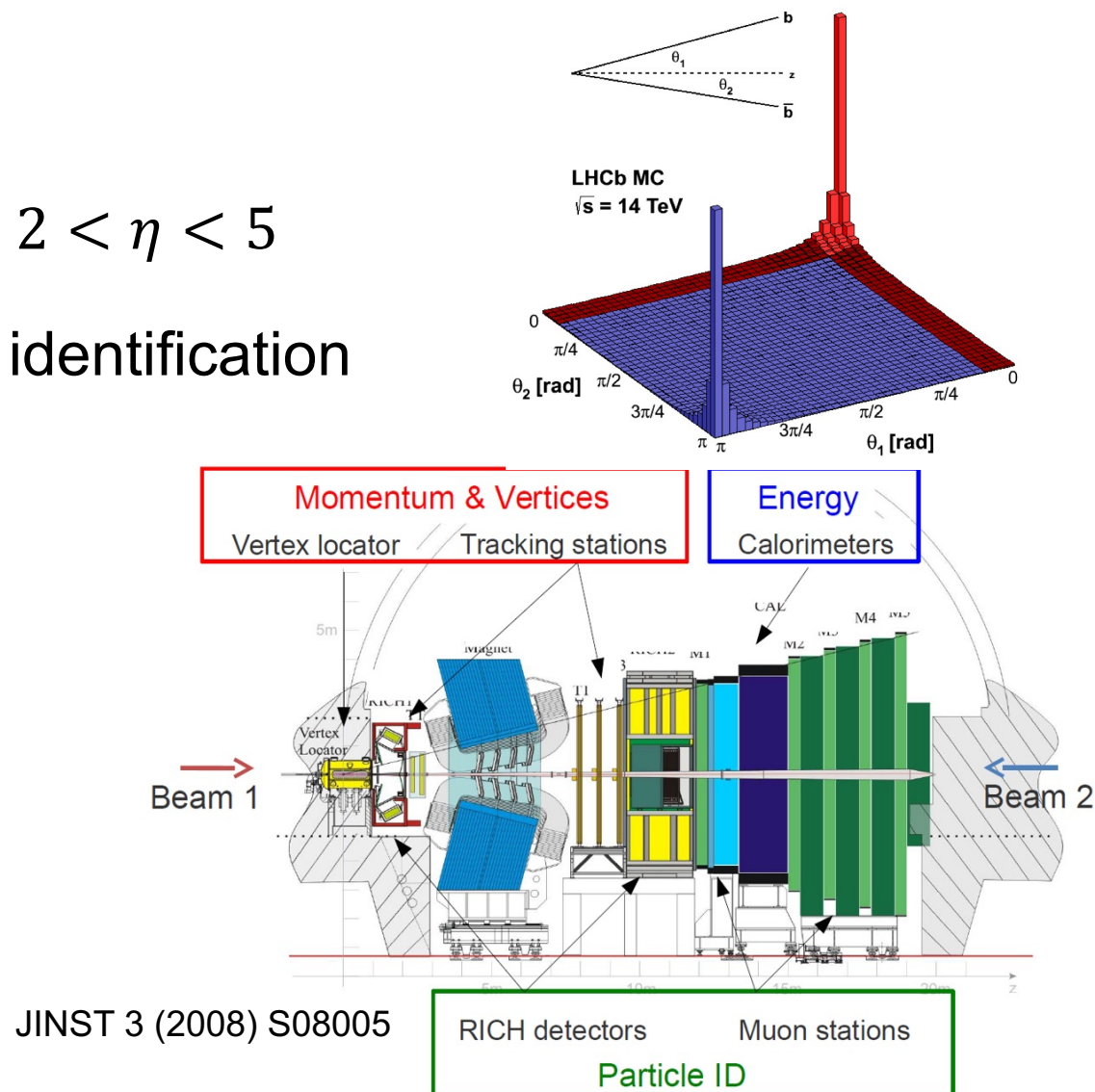


Large Hadron Collider



LHCb detector

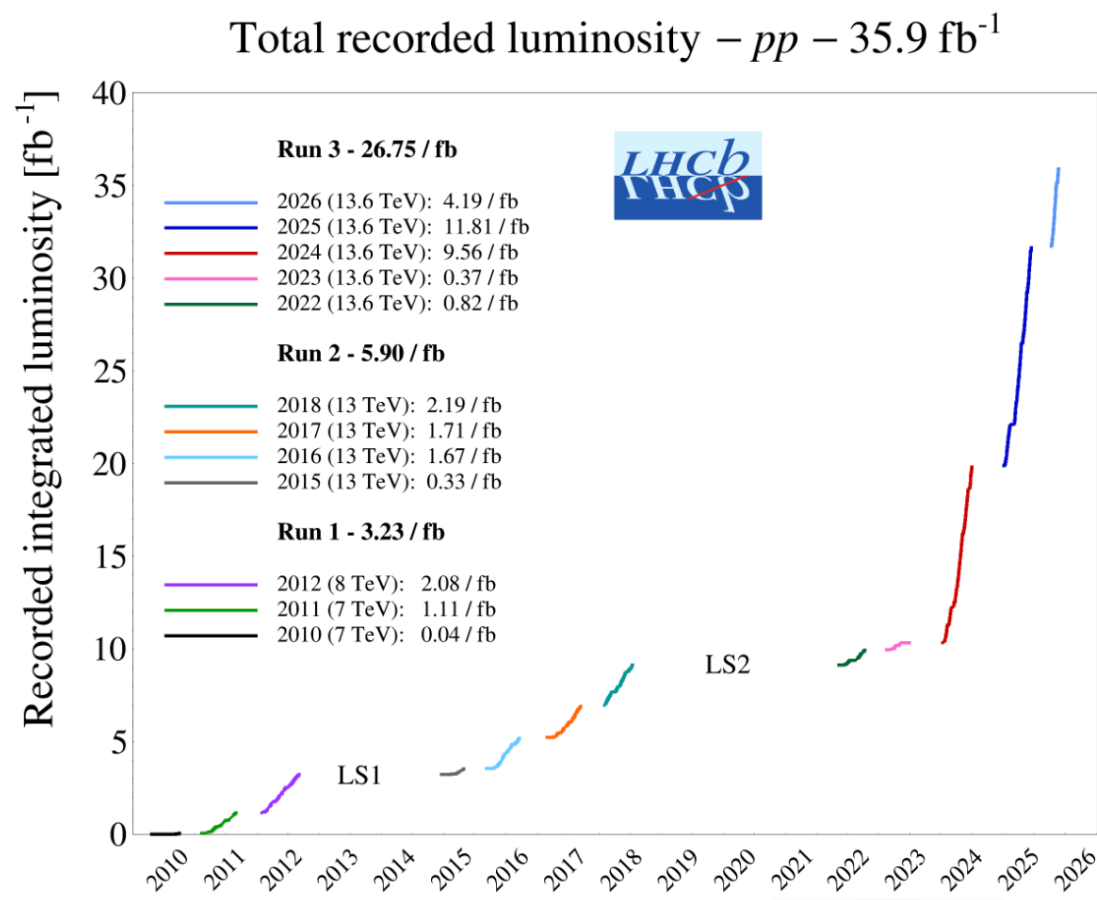
- Designed for beauty & charm physics, $2 < \eta < 5$
- Excellent tracking system and particle identification
 - ✓ momentum resolution, $\delta p/p \sim 0.5\%$
 - ✓ precise vertex reconstruction, $\delta(IP_x) \sim 35 \mu m$
 - ✓ reconstruction efficiency, $\sim 96\%$ for long tracks
 - ✓ PID efficiency, $\epsilon(\mu) \sim 97\%, \epsilon(K) \sim 95\%$
 - ✓ misID probability ($\pi \rightarrow K$) $\sim 5\%$
 - ✓ time resolution, ~ 45 fs



LHCb data

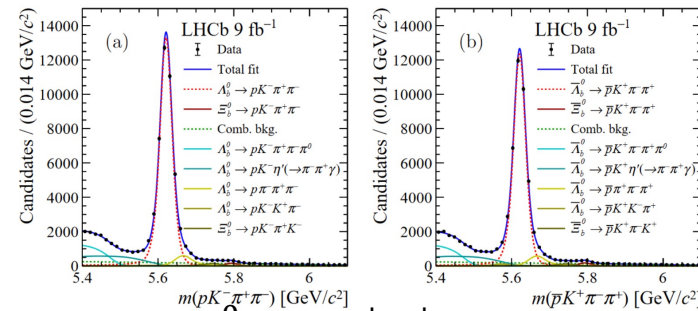
- Recorded data for analysis
 - ✓ Run 1 (2011-2012), $\sqrt{s} = 7, 8$ TeV, 3 fb^{-1}
 - ✓ Run 2 (2015-2018), $\sqrt{s} = 13$ TeV, 6 fb^{-1}
 - ✓ Run 3 (2024-2026), $\sqrt{s} = 13.6$ TeV
- Production cross section
 - ✓ $\sigma(pp \rightarrow b\bar{b}) \sim 72 \mu\text{b}$ at 7 TeV
 - ✓ $\sigma(pp \rightarrow b\bar{b}) \sim 144 \mu\text{b}$ @13 TeV
Phys.Rev.Lett. 118 (2017) 5

Large data sample for b physics



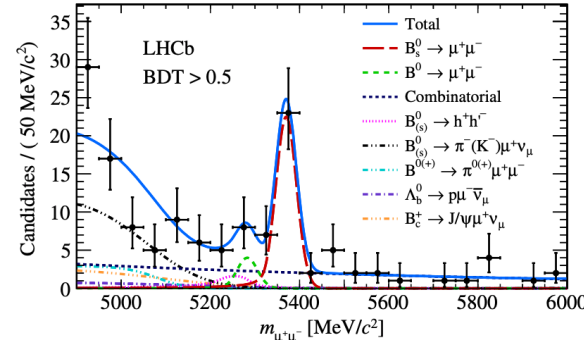
LHCb physics

- CP violation



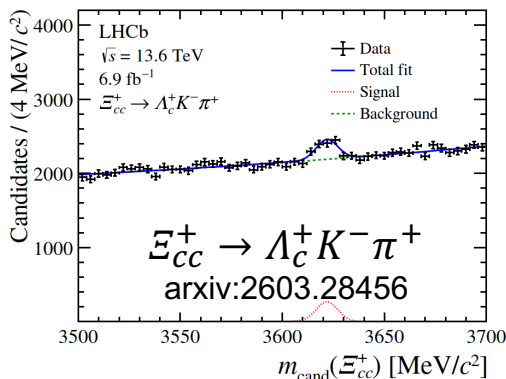
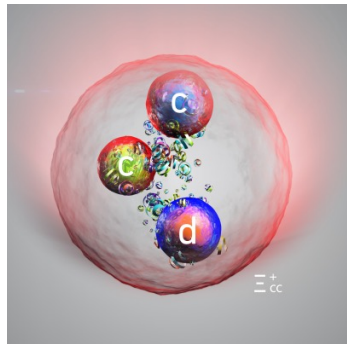
$\Lambda_b^0 \rightarrow pK^+\pi^+\pi^-$
Nature 643 (2025) 8074

- Rare decays



$B_{(s)}^0 \rightarrow \mu^+\mu^-$
PhysRevLett.118.191801

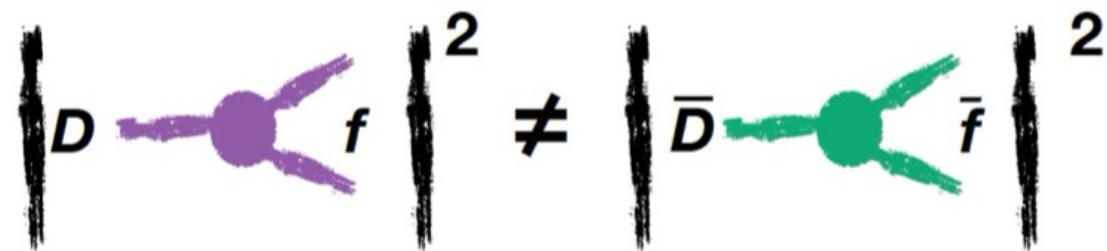
- Hadronic spectrum



- Lepton universality
- Electroweak
-

Abundant physics at LHCb

Direct CP violation



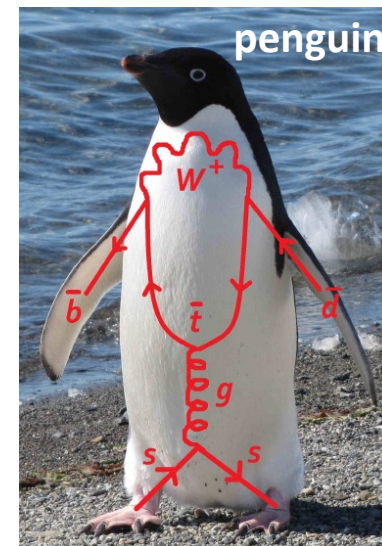
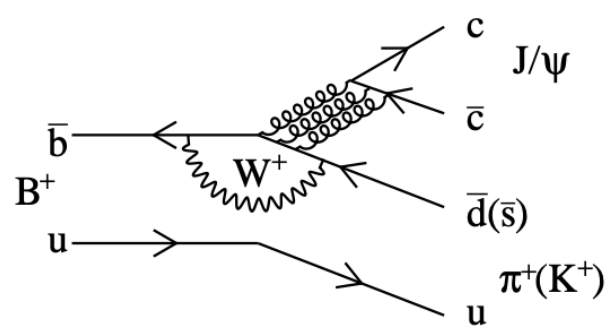
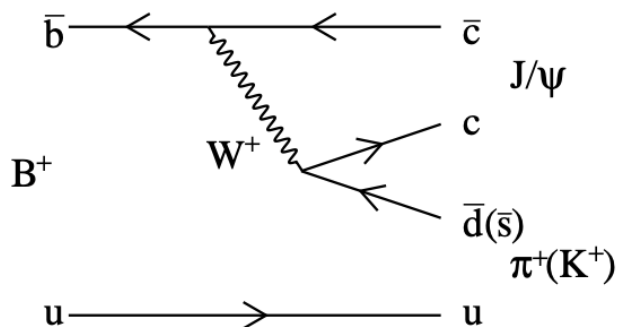
- CPV from the interference between at least two decay paths

$$\Gamma_f = |A_f|^2, \quad A_f = |A_1| e^{i(\delta_1 + \phi_1)} + |A_2| e^{i(\delta_2 + \phi_2)} + \dots$$

$$\bar{\Gamma}_{\bar{f}} = |\bar{A}_{\bar{f}}|^2, \quad \bar{A}_{\bar{f}} = |A_1| e^{i(\delta_1 - \phi_1)} + |A_2| e^{i(\delta_2 - \phi_2)} + \dots$$

$$\mathcal{A}_{CP} \equiv \frac{\Gamma_f - \bar{\Gamma}_{\bar{f}}}{\Gamma_f + \bar{\Gamma}_{\bar{f}}} = \frac{-2 |A_1| |A_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)}{|A_1|^2 + |A_2|^2 + 2 |A_1| |A_2| \cos(\delta_2 - \delta_1) \cos(\phi_2 - \phi_1)}$$

Strong phase difference Weak phase difference



Direct CP violation

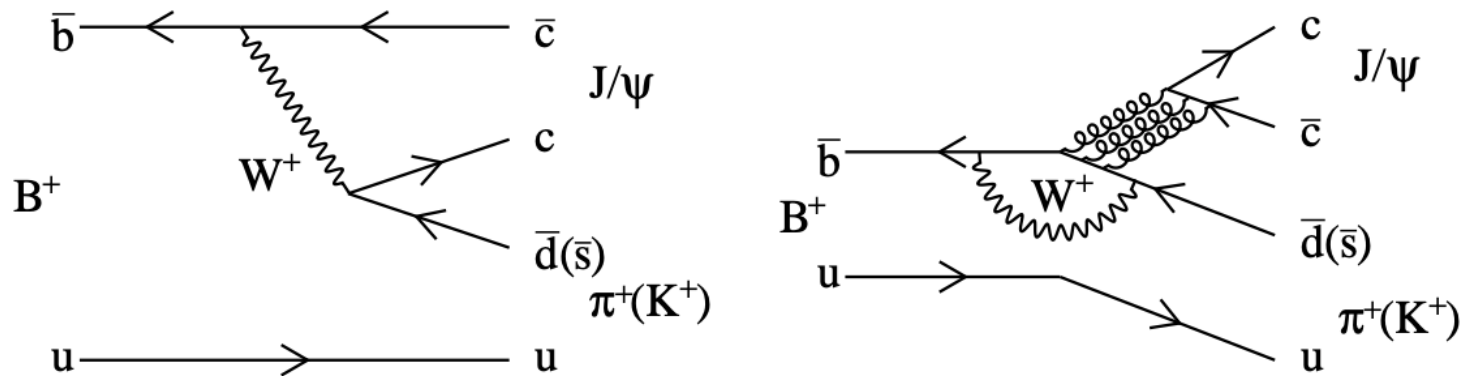
$$\begin{aligned} A_{CP} &= A_{\text{raw}} - A_{\text{prod}} - A_{\text{det}} \\ A_{\text{raw}} &= (\mathbf{n}_B - \mathbf{n}_{\bar{B}}) / (\mathbf{n}_B + \mathbf{n}_{\bar{B}}) \\ A_{\text{det}} &= A_{\text{trigger}} + A_{\text{track}} + A_{\text{PID}} + \dots \end{aligned}$$

- Measurement of A_{CP} in $B^+ \rightarrow J/\psi \pi^+$ decays [Phys. Rev. Lett. 134 (2025) 101801]
- Measurement of A_{CP} in $B^+ \rightarrow \rho^0 K^{*+}$ decays [Phys.Rev.Lett. 136 (2026) 2, 021803]
- Measurement of A_{CP} in $\Lambda_b^0 / \Xi_b^0 \rightarrow \Lambda h^+ h'^-$ decays [Phys.Rev.Lett. 134 (2025) 10, 101802]
- Measurement of A_{CP} in $\Lambda_b^0 \rightarrow p K^+ \pi^+ \pi^-$ decays [Nature 643 (2025) 8074]

Measurement of A_{CP} in $B^+ \rightarrow J/\psi \pi^+$ decays

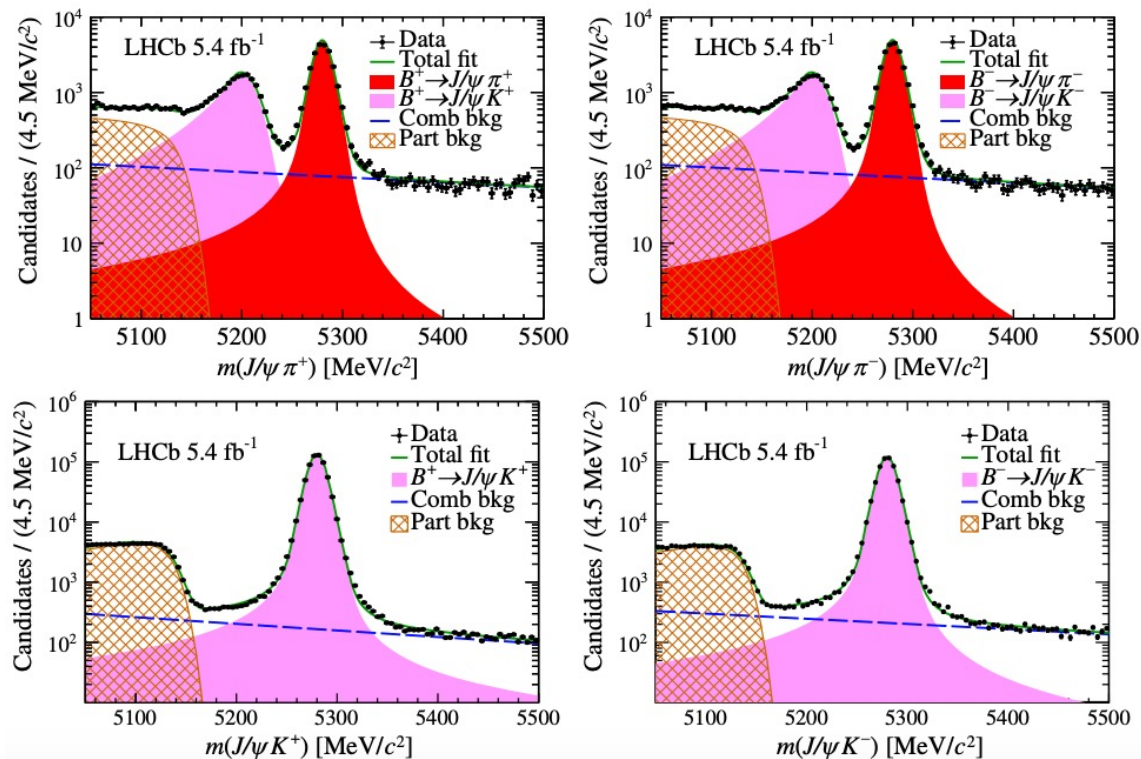
- Expected CPV at $\mathcal{O}(1\%)$ for $J/\psi \pi^+$ and negligible CPV for $J/\psi K^+$
[PRD 49 (1994) 5904, PRD 52 (1995) 242]
- Ideal decay to search for direct CPV in b decays to charmonium

$$\Delta A_{CP} = A_{CP}^{J/\psi \pi} - A_{CP}^{J/\psi K} = (A_{\text{raw}}^{J/\psi \pi} - A_{\text{raw}}^{J/\psi K}) - (A_{\text{det}}^{J/\psi \pi} - A_{\text{det}}^{J/\psi K})$$



Measurement of A_{CP} in $B^+ \rightarrow J/\psi \pi^+$ decays

- Measured results



$$\Delta A_{CP} = (1.29 \pm 0.49 \pm 0.08) \times 10^{-2} \text{ (Run 2)}$$

$$\Delta A_{CP} = (1.42 \pm 0.43 \pm 0.08) \times 10^{-2} \text{ (Run 1+2)}$$

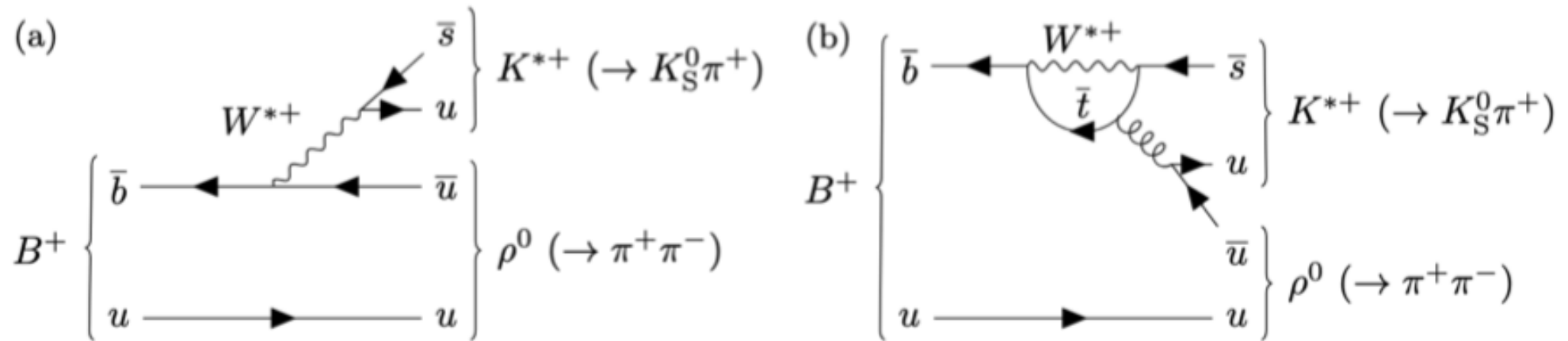
1st evidence (3.2 σ) for direct CPV
in the beauty decays to charmonium
final states.

Measurement of A_{CP} in $B^+ \rightarrow \rho^0 K^{*+}$ decays

- Longitudinal polarization fraction in $B \rightarrow VV$ decays

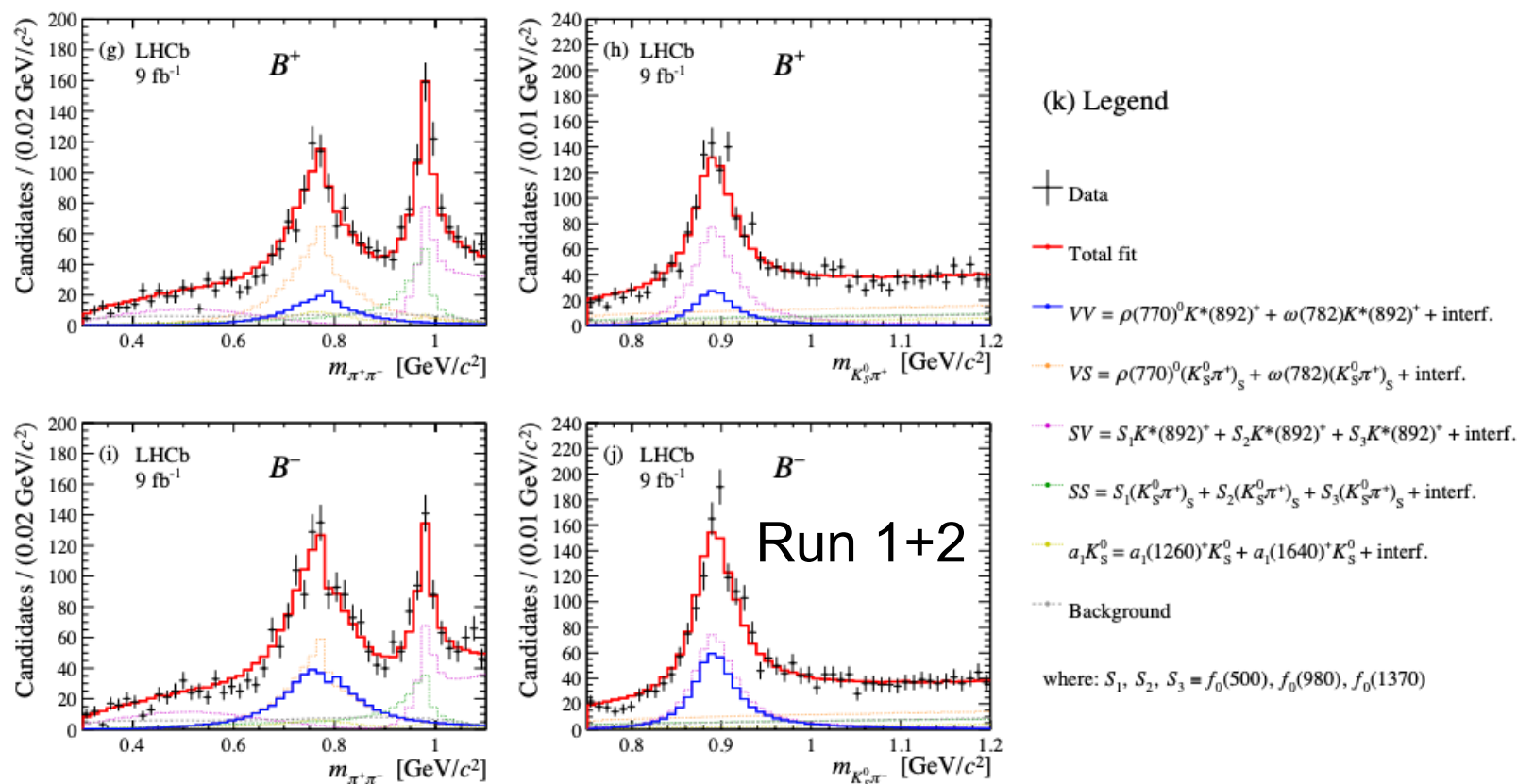
$$f_L \equiv |A_0|^2 / (|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2)$$

- $f_L \sim 1$ in SM, measured to be 10% to almost 100% across different decays



Measurement of A_{CP} in $B^+ \rightarrow \rho^0 K^{*+}$ decays

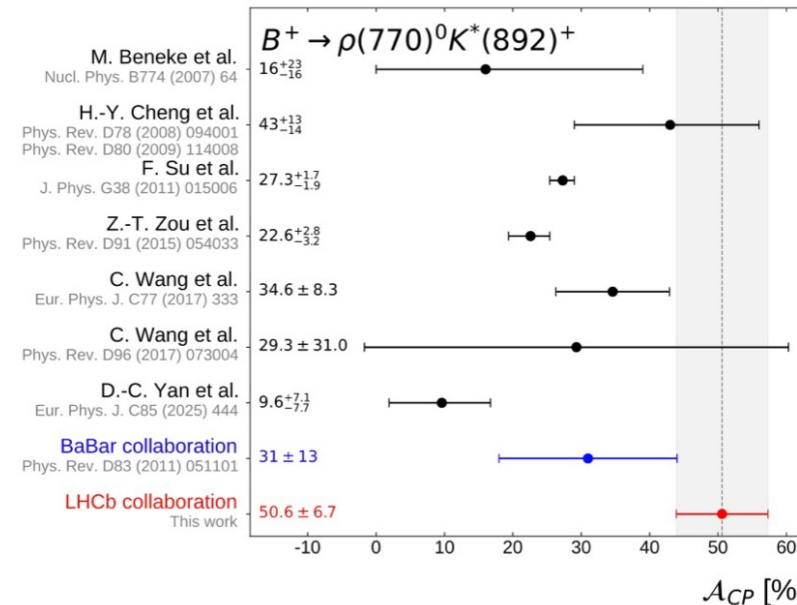
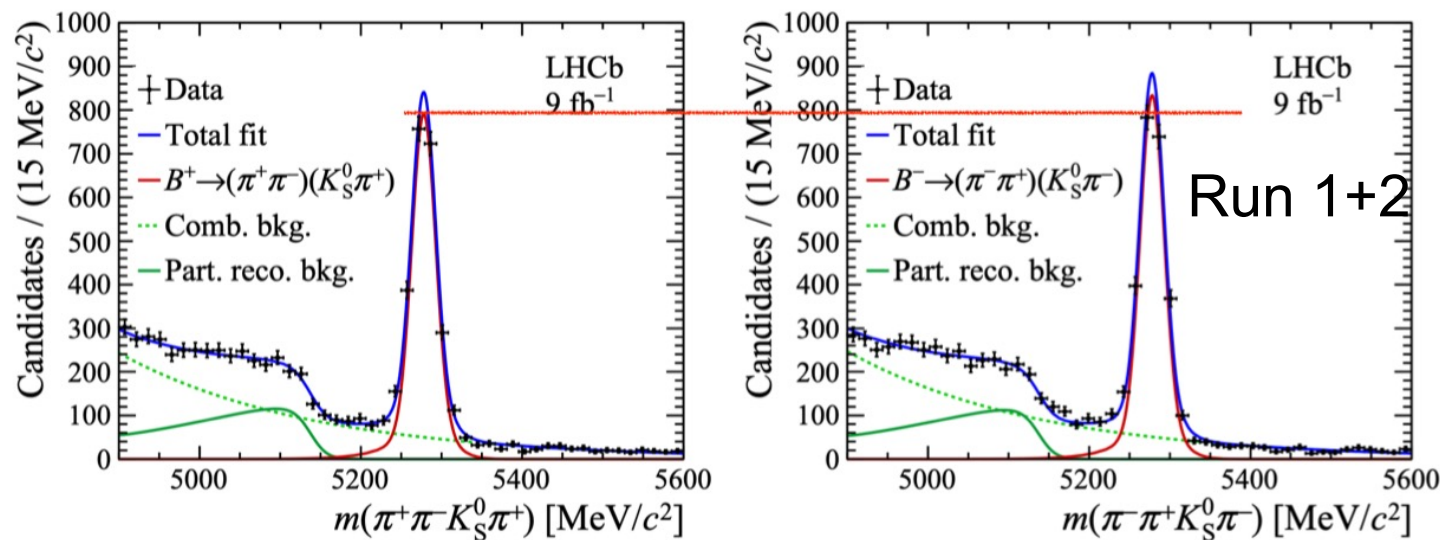
- Separate different resonances by an amplitude analysis



Measurement of A_{CP} in $B^+ \rightarrow \rho^0 K^{*+}$ decays

- First **observation** of CPV, exceeding 9σ
- Help to shed light on the polarization puzzle

$$A_{CP} = 0.507 \pm 0.062 \pm 0.024, f_L = 0.720 \pm 0.028 \pm 0.09$$



A long list of searches in b baryons at LHCb

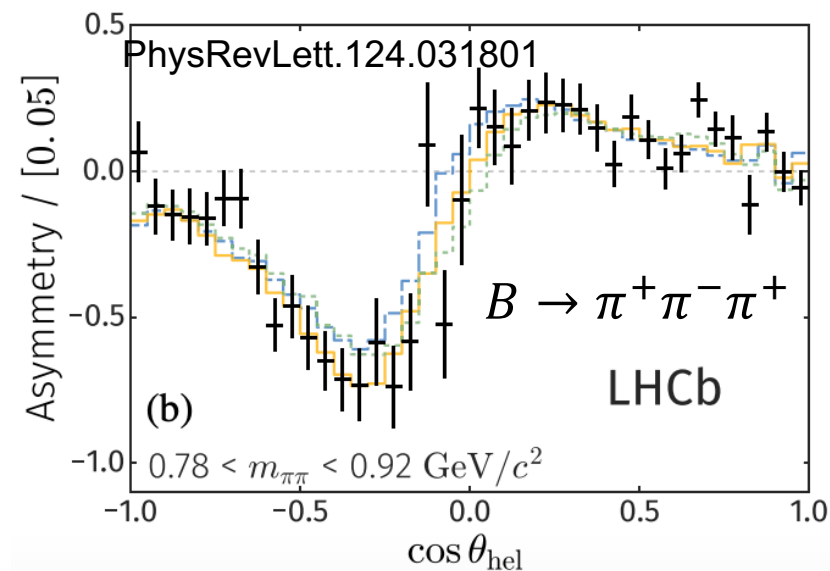
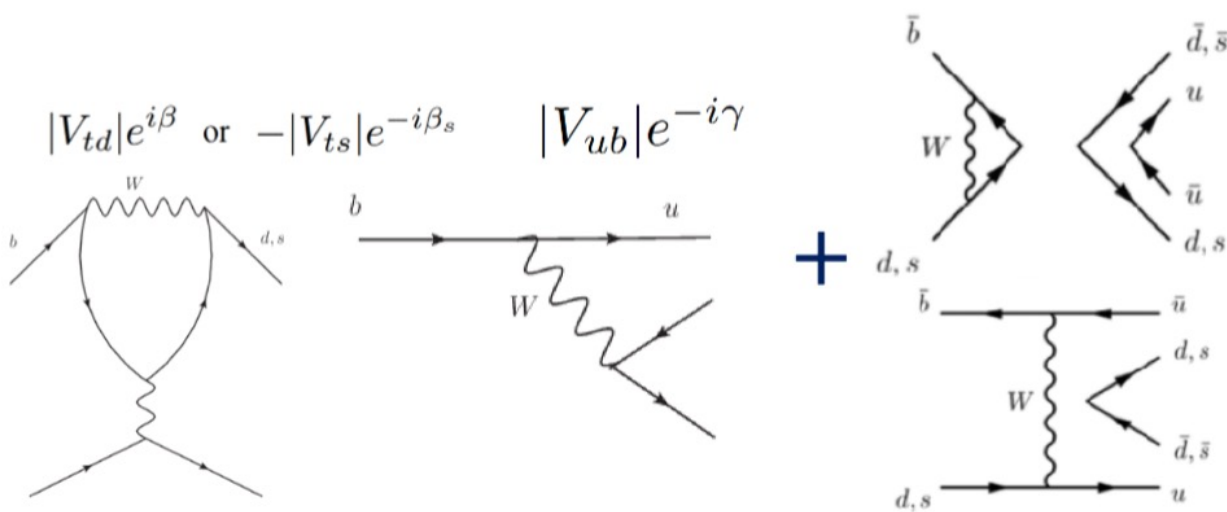
- Help to understand the dynamics of weak in the baryon decays
- Provide a better picture of CPV originating from quark transitions

Decay	Methods	Data	References
$\Lambda_b^0 \rightarrow p K_S^0 \pi^-$	A_{CP}	1 fb ⁻¹	JHEP 04 (2014) 087
$\Lambda_b^0 \rightarrow \Lambda h h'$	A_{CP}	3 fb ⁻¹	JHEP 05 (2016) 081
$\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$	TPA, energy test	3 fb ⁻¹ 6.6 fb ⁻¹	Nature Physics 13 (2017) 391 PRD 102 (2020) 051101
$\Lambda_b^0 \rightarrow p K^- \mu^+ \mu^-$	A_{CP}	3 fb ⁻¹	JHEP 06 (2017) 108
$\Lambda_c^+ \rightarrow p h^- h^+$	A_{CP}	3 fb ⁻¹	JHEP 03 (2018) 182
$\Lambda_b^0 \rightarrow p K^- / p \pi^-$	A_{CP}	3 fb ⁻¹	PLB 787 (2018) 124
$\Lambda_b^0 \rightarrow p h^- h^+ h^-$	TPA	3 fb ⁻¹	JHEP 08 (2018) 039
$\Lambda_b^0 \rightarrow p h^- h^+ h^-$	A_{CP}	3 fb ⁻¹	EPJC 79 (2019) 745
$\Xi_b^- \rightarrow p K^- K^-$	Amplitude	5 fb ⁻¹	PRD 104 (2020) 052010
$\Xi_c^+ \rightarrow p K^- \pi^+$	<u>kNN</u>	3 fb ⁻¹	EPJC 80 (2020) 986
$\Lambda_b^0 \rightarrow p D^0 K^-$	Miranda S_{CP}^i	9 fb ⁻¹	PRD104 (2021) 112008
$\Lambda_b^0 \rightarrow \Lambda \gamma$	photon polarization	3 fb ⁻¹	PRD105 (2022) L051104
$\Lambda_b^0 \rightarrow \Lambda_c^+ h^-$	Decay parameter	9 fb ⁻¹	PRL 133 (2024) 261804
$\Lambda_b^0 \rightarrow p h^-$	A_{CP}	9 fb ⁻¹	PRD 111(2025) 092004
$\Lambda_b^0 \rightarrow \Lambda h h'$	A_{CP}	9 fb ⁻¹	PRL 134 (2025) 101802
$\Lambda_b^0 \rightarrow p K^- \pi^+ \pi^-$	A_{CP}	9 fb ⁻¹	Nature 643 (2025) 1223
$\Lambda_b^0, \Xi_b^0 \rightarrow p K_S^0 h^-$	A_{CP}	9 fb ⁻¹	JHEP 10 (2025) 169
$\Lambda_b^0 \rightarrow J/\psi p h^-$	A_{CP}, TPA	6 fb ⁻¹	LHCb-PAPER-2025-021

Credit : Shanzhen Chen

Measurement of A_{CP} in $\Lambda_b^0/\Xi_b^0 \rightarrow \Lambda h^+ h'^- \text{ decays}$

- Large CPV up to 75% is observed in $B \rightarrow h^+ h'^- h''^+$ ($h = K, \pi$) decays
- Interesting to search CPV in $\Lambda_b^0/\Xi_b^0 \rightarrow \Lambda h^+ h'^-$ decays
- Use $\Lambda_b^0 \rightarrow \Lambda_c^+(\Lambda\pi^+)\pi^-$ decays as the control channel



Measurement of A_{CP} in $\Lambda_b^0/\Xi_b^0 \rightarrow \Lambda h^+ h'^-$ decays

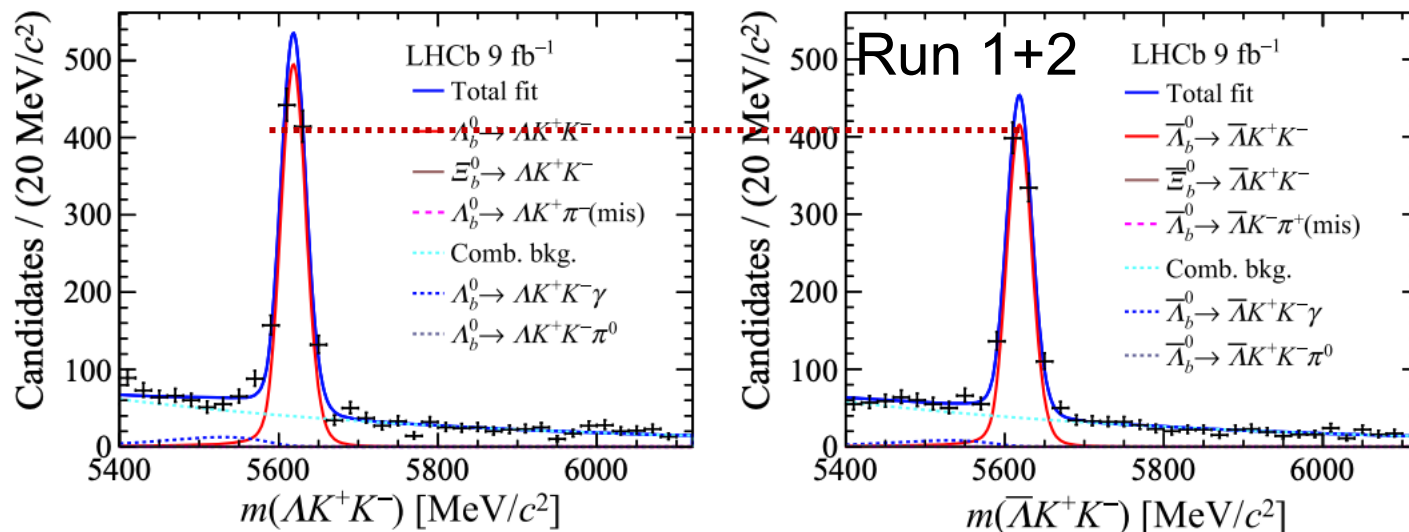
- First **evidence** of CPV in $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$ decays, 3.1σ

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \rightarrow \Lambda\pi^+\pi^-) = -0.013 \pm 0.053 \pm 0.018,$$

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \rightarrow \Lambda K^+\pi^-) = -0.118 \pm 0.045 \pm 0.021,$$

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \rightarrow \Lambda K^+ K^-) = 0.083 \pm 0.023 \pm 0.016,$$

$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \rightarrow \Lambda K^-\pi^+) = 0.27 \pm 0.12 \pm 0.05,$$

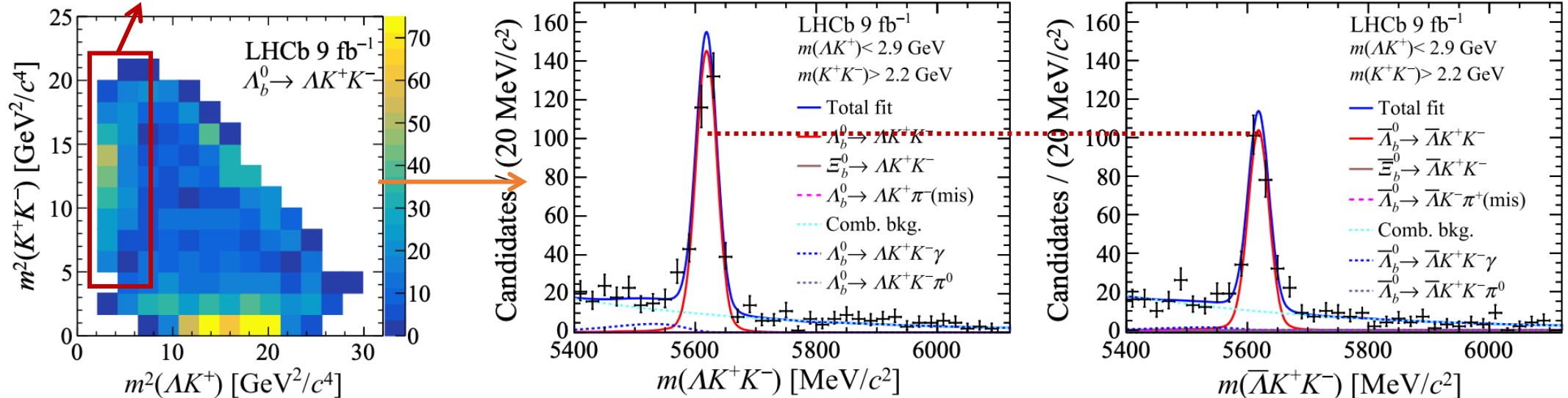


Measurement of A_{CP} in $\Lambda_b^0/\Xi_b^0 \rightarrow \Lambda h^+ h'^-$ decays

- First **evidence** of CPV in $\Lambda_b^0 \rightarrow N^{*+} K^-$ decays, 3.2σ

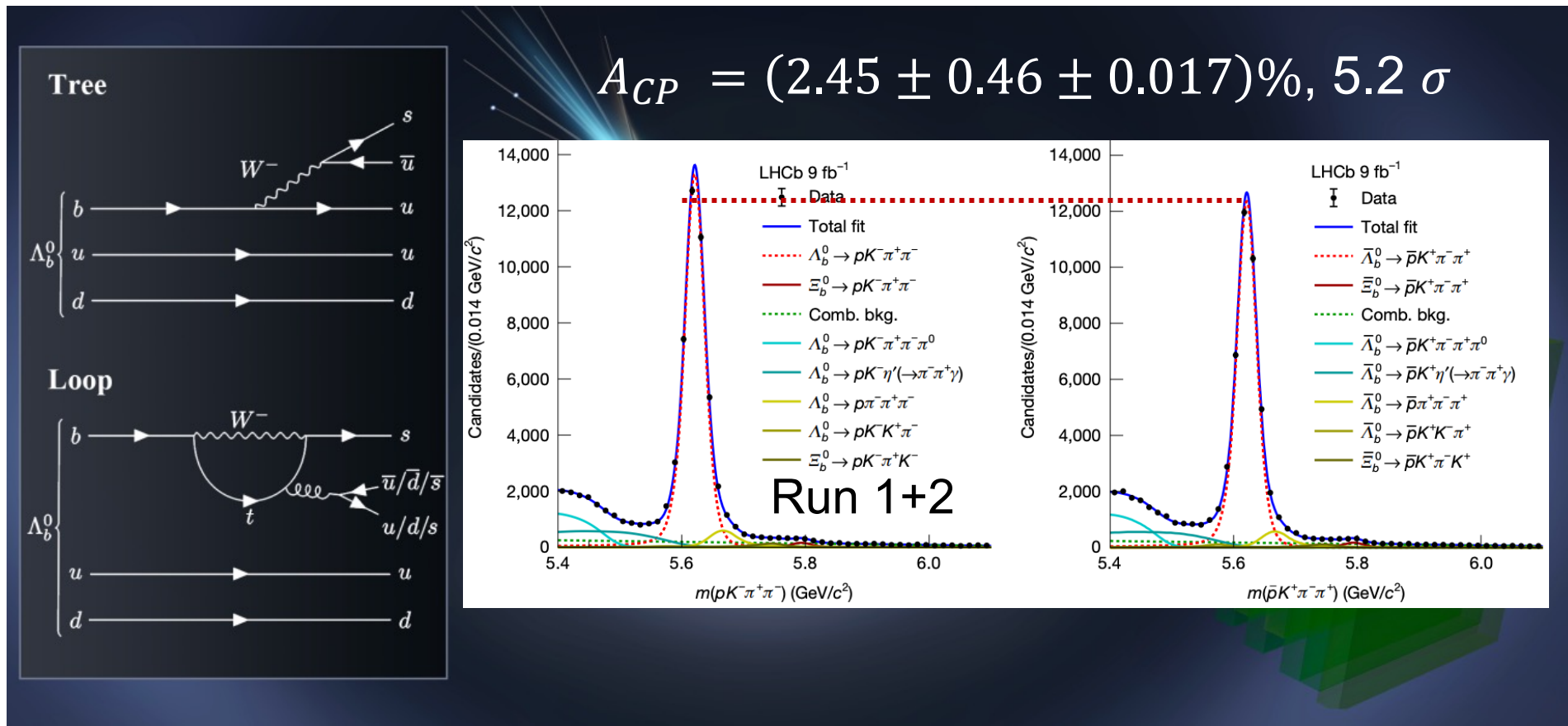
$$\Delta A_{CP} = 0.165 \pm 0.048 \pm 0.017$$

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



Measurement of A_{CP} in $\Lambda_b^0 \rightarrow pK^+\pi^+\pi^-$ decays

- First **observation** of CPV in baryon, a **milestone** in CPV

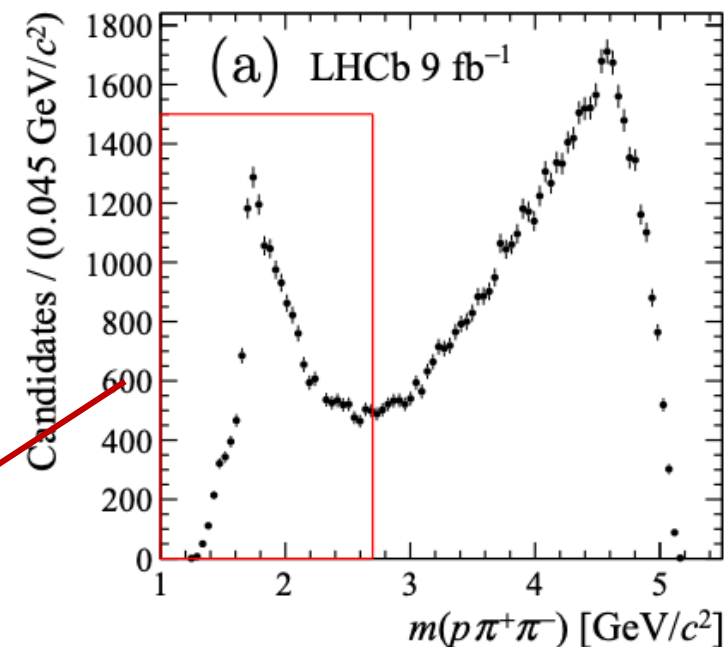


Measurement of A_{CP} in $\Lambda_b^0 \rightarrow pK^+\pi^+\pi^-$ decays

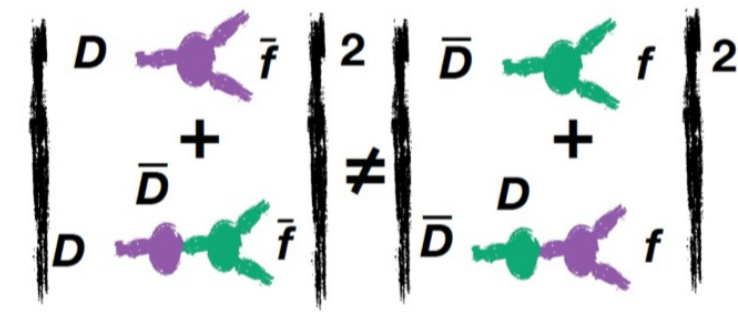
- CPV in local phase-space regions

Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \rightarrow R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$
$\Lambda_b^0 \rightarrow R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$
$\Lambda_b^0 \rightarrow R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$
$\Lambda_b^0 \rightarrow R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$

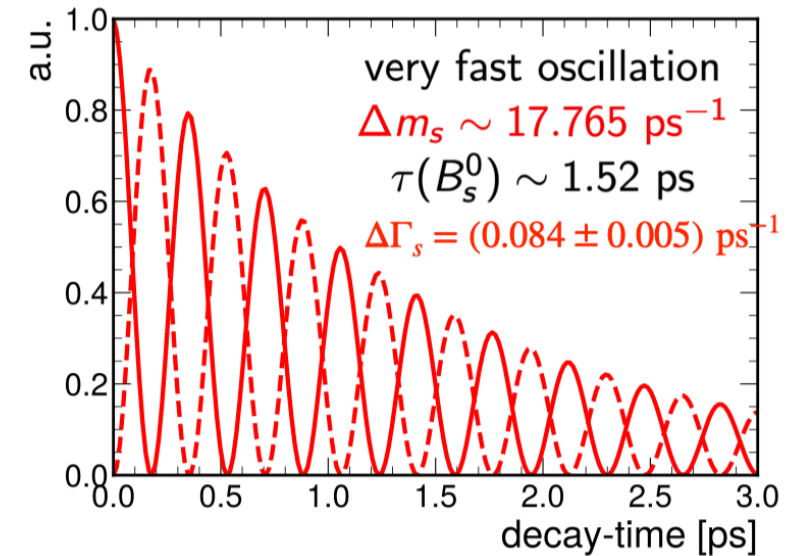
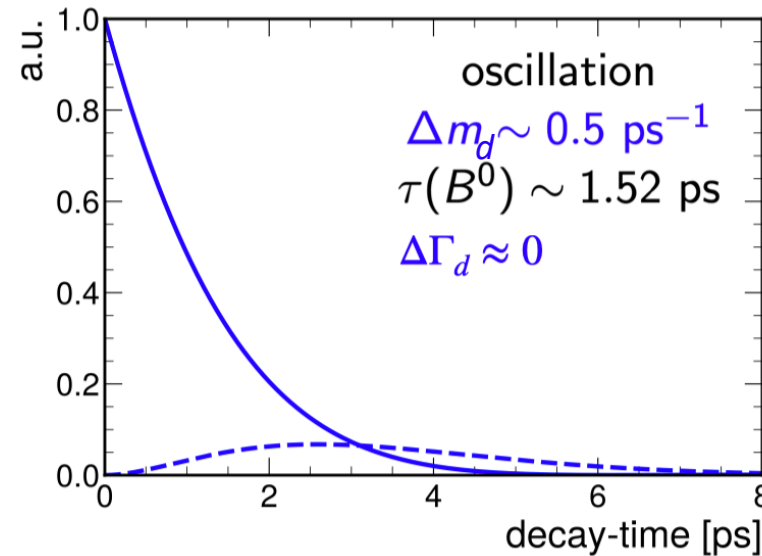
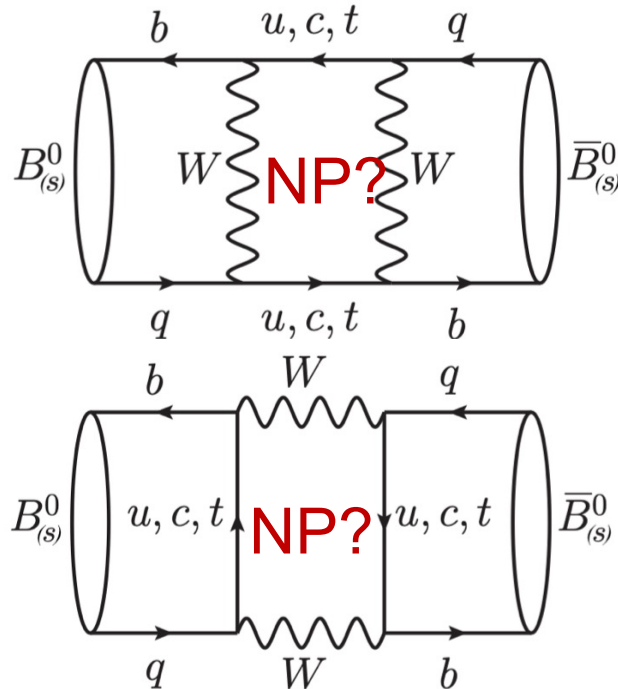
6 σ



$B_{d,s}^0 - \bar{B}_{d,s}^0$ mixing



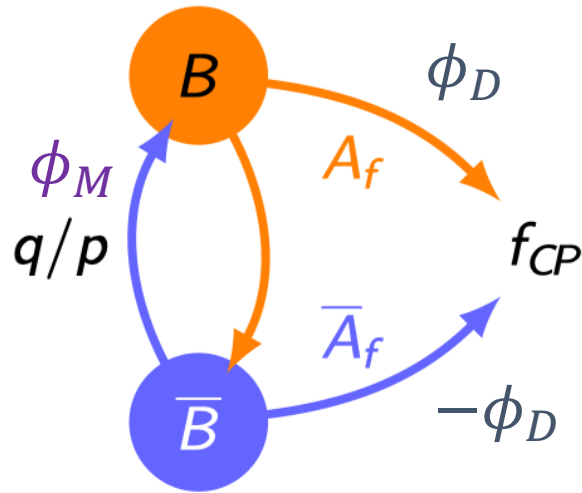
- $|B_{L,H}^0\rangle = p|B_{d,s}^0\rangle \pm q|\bar{B}_{d,s}^0\rangle$, p & $q \in \mathbb{C}$ with $|p|^2 + |q|^2 = 1$
- Abundant physics $\Delta m_{d,s} = m_H - m_L, \tau$, $\Delta\Gamma_{d,s} = \Gamma_L - \Gamma_H$



CKM angles $\beta_{(s)}$

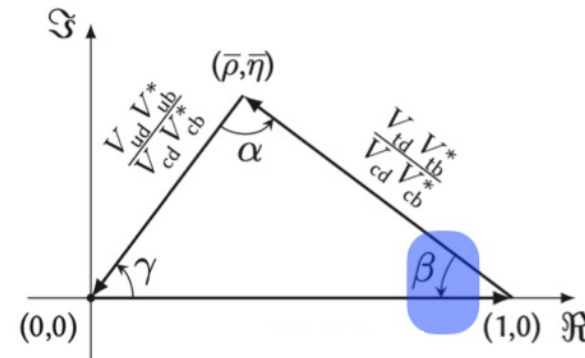
- CPV phases from the interference between mixing and decay
- Related to $B_{d,s}^0$ normalised triangles

CPV phase $\phi_q = \phi_M - 2\phi_D$



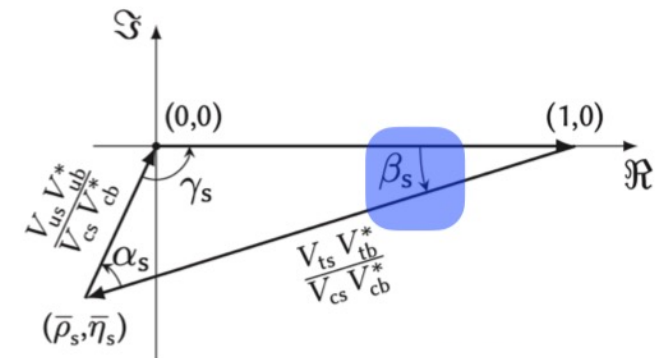
$$\phi_d = 2\beta = 2\arg\left(\frac{V_{td}V_{tb}^*}{V_{cb}V_{cb}^*}\right)$$

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



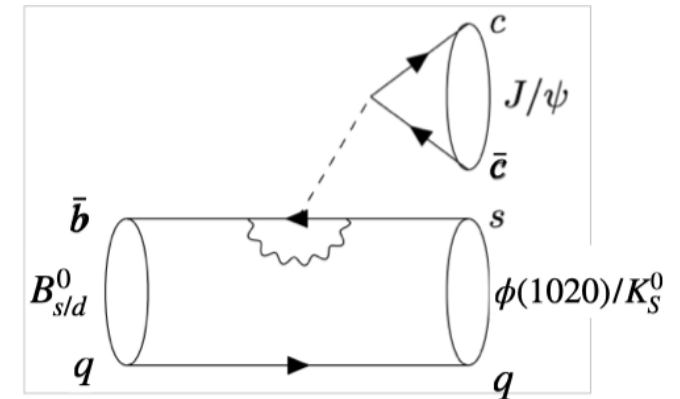
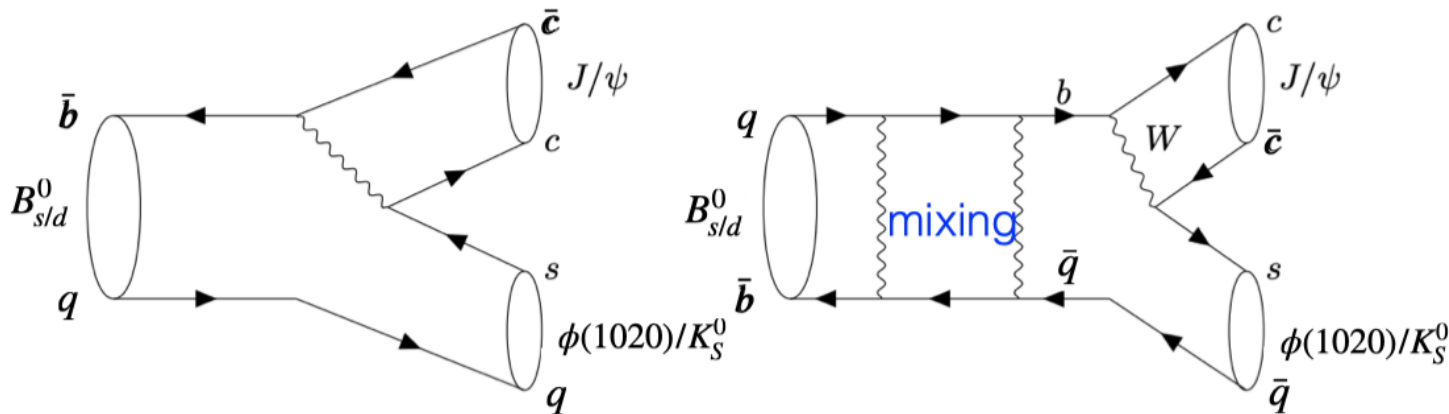
$$\phi_s = -2\beta_s = 2\arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



CKM angles $\beta_{(s)}$

- Accessed by tree dominated transition $b \rightarrow c\bar{c}s$, e.g. $B^0 \rightarrow J/\psi K_S^0$ & $B_s^0 \rightarrow J/\psi \phi$
- Measured $\phi_q = \phi_q^{\text{tree}} + \Delta\phi_q^{\text{penguin}} + \Delta\phi_q^{\text{NP}}$
- Stringent test of SM and sensitive to New Physics in mixing



Time-dependent Decay rate

- It is all about $\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f}$, $\phi_q = -\arg(\lambda_f)$
 - ✓ q & p , mixing parameters; A_f & $\bar{A}_f$, decay amplitudes; η_f , CP eigenstate value
 - ✓ Γ_q , decay width; $\Delta\Gamma_q$, decay width difference; Δm_q , oscillation frequency

$$\Gamma(B_q^0(t) \rightarrow f) \equiv |A_f|^2 (1 + |\lambda_f|^2) e^{-\Gamma_q t} \left[\cosh \frac{\Delta\Gamma_q t}{2} + \textcolor{brown}{A}^{\Delta\Gamma} \sinh \left(\frac{\Delta\Gamma_q t}{2} \right) + \textcolor{violet}{C} \cos(\Delta m_q t) - \textcolor{red}{S} \sin(\Delta m_q t) \right]$$

$$\Gamma(\bar{B}_q^0(t) \rightarrow f) \equiv \left| \frac{p}{q} \right|^2 |A_f|^2 (1 + |\lambda_f|^2) e^{-\Gamma_q t} \left[\cosh \frac{\Delta\Gamma_q t}{2} + \textcolor{brown}{A}^{\Delta\Gamma} \sinh \left(\frac{\Delta\Gamma_q t}{2} \right) - \textcolor{violet}{C} \cos(\Delta m_q t) + \textcolor{red}{S} \sin(\Delta m_q t) \right]$$

$$\textcolor{brown}{A}^{\Delta\Gamma} = \frac{2\text{Re}(\lambda_f)}{1 + |\lambda_f|^2}, \quad \textcolor{violet}{C} = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \text{ (Direct)}, \quad \textcolor{red}{S} = \frac{2\text{Im}(\lambda_f)}{1 + |\lambda_f|^2} \text{ (Interf.)}$$

$$\Rightarrow A_{CP}(t) = \frac{\Gamma_{\bar{B}_q^0 \rightarrow f}(t) - \Gamma_{B_q^0 \rightarrow f}(t)}{\Gamma_{\bar{B}_q^0 \rightarrow f}(t) + \Gamma_{B_q^0 \rightarrow f}(t)} \cong \eta_f \sin(\textcolor{red}{\phi}_q) \sin(\Delta m_q t)$$

Experimental measurement

→ Experimentally

$$A_{CP}(t) \propto e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \cdot (1 - 2\omega) \cdot (C_f \cos(\Delta m_{(s)}t) + \eta_f \cdot S_f \sin(\Delta m_{(s)}t))$$

Dilution of Flavour tagging

$$\eta_f = (-1)^L$$

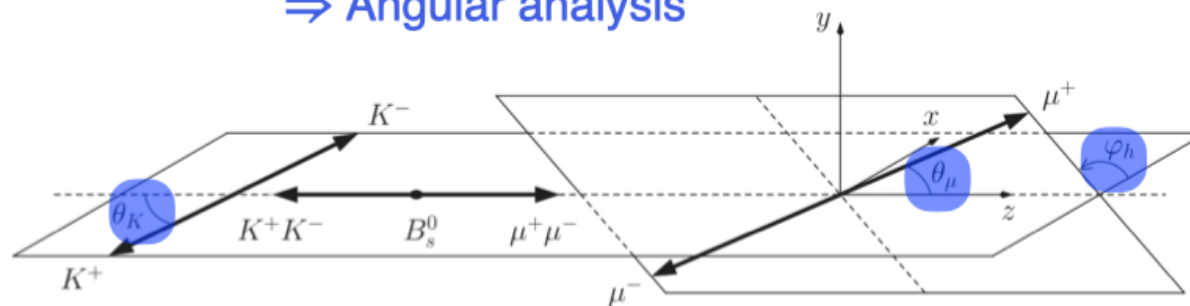
Dilution of decay time resolution

$$\sigma_{eff}^{B_s^0} \sim 42(3) \text{ fs} \rightarrow \mathcal{D} = 0.757$$

$$\sigma_{eff}^{B_s^0} \sim 60 \text{ fs} \rightarrow \mathcal{D} \sim 1$$

Disentangle CP-even ($L = 0, 2$) & CP-odd ($L = 1 + K^+K^-$ S-wave) components

⇒ Angular analysis



$$B_s^0 \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$$

Slide from Peilian Li

Time-dependent CP violation

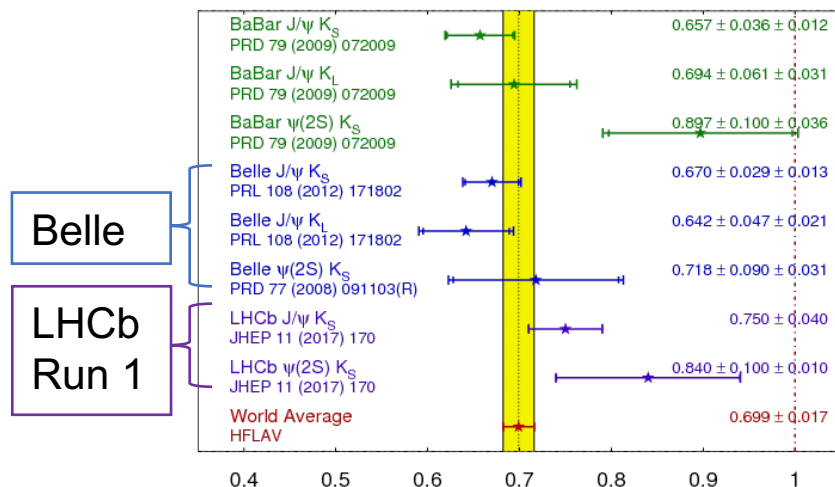
- Measurement of $\sin 2\beta$ in $B^0 \rightarrow \psi K_S^0$ decays [Phys. Rev. Lett. 132 (2024) 021801]
- Measurement of ϕ_s in $B_s^0 \rightarrow J/\psi \phi$ decays [Phys. Rev. Lett. 132 (2024) 051802]
- Measurement of ϕ_s in $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ decays [Physics Letters B 797 (2019) 134789]
- Measurement of CPV in $B^0 \rightarrow J/\psi \pi^+ \pi^-$ decays [arXiv:2601.15646]
- Measurement of ϕ_s in $B_s^0 \rightarrow \phi \phi$ decays [Phys. Rev. Lett. 131 (2023) 171802]

Measurement of $\sin 2\beta$ in $B^0 \rightarrow \psi K_S^0$ decays

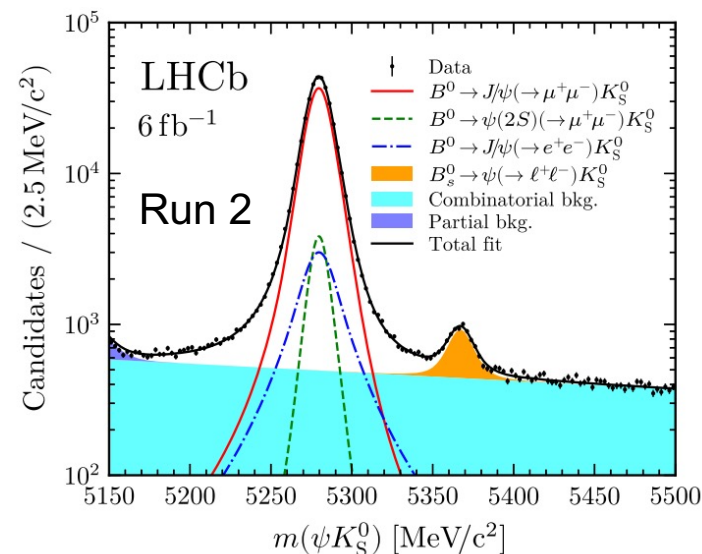
- Precise prediction $\sin 2\beta^{\text{tree}} = 0.7155_{-0.0071}^{+0.0079}$ [CKM fitter]
- Golden channel to measure $\sin 2\beta = \sin(2\beta^{\text{tree}} + \Delta\phi_d^{\text{penguin}} + \Delta\phi_d^{\text{NP}})$
- Previous average $\sin 2\beta = 0.699 \pm 0.017$ [HFLAV 2021]

Dominated by Belle

$\sin(2\beta) \equiv \sin(2\phi_1)$ **HFLAV** 2021



Update with 3 channels

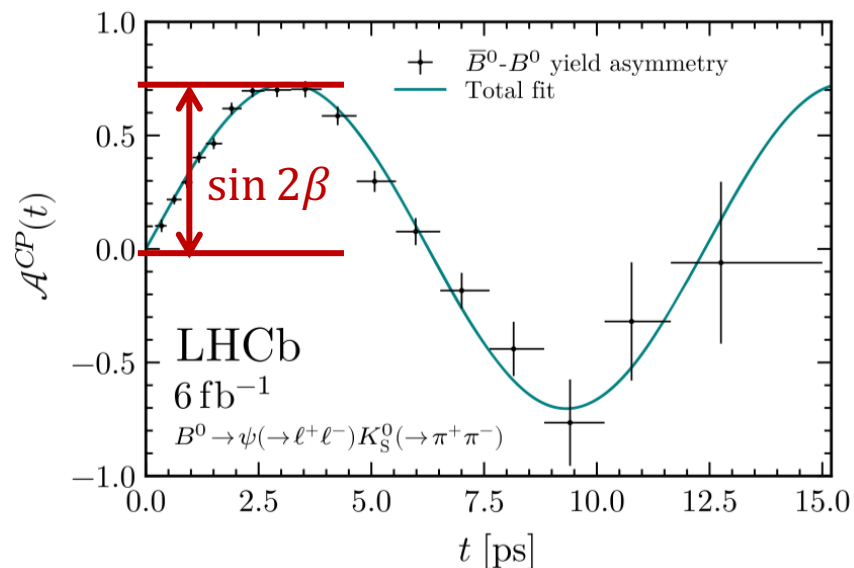


Measurement of $\sin 2\beta$ in $B^0 \rightarrow \psi K_S^0$ decays

- Consistent with SM results and **1st time to dominate** this measurement

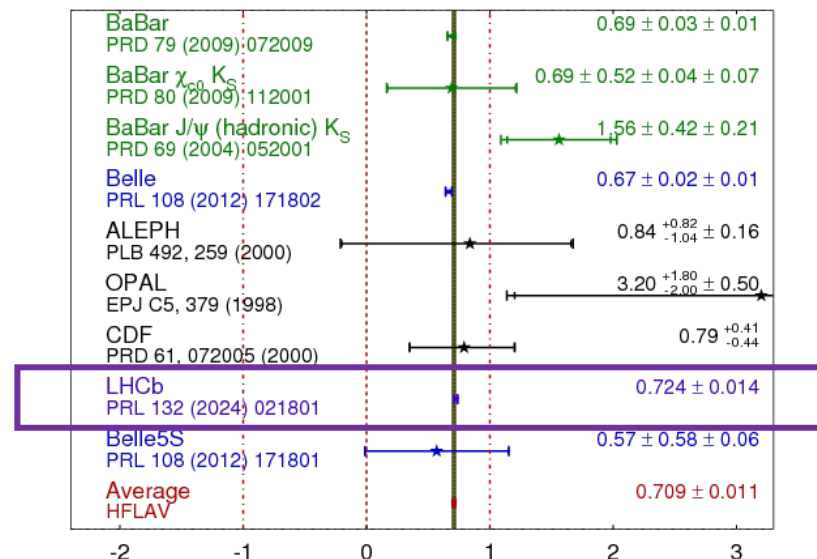
$$\sin 2\beta = 0.717 \pm 0.013 \pm 0.008 \text{ (Run 2)}$$

$$\sin 2\beta = 0.724 \pm 0.014 \text{ (Run 1+2)}$$



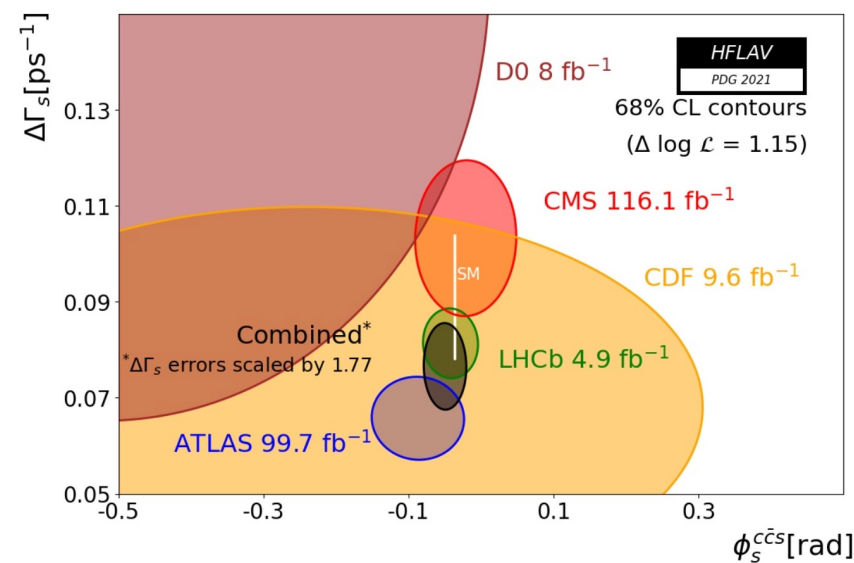
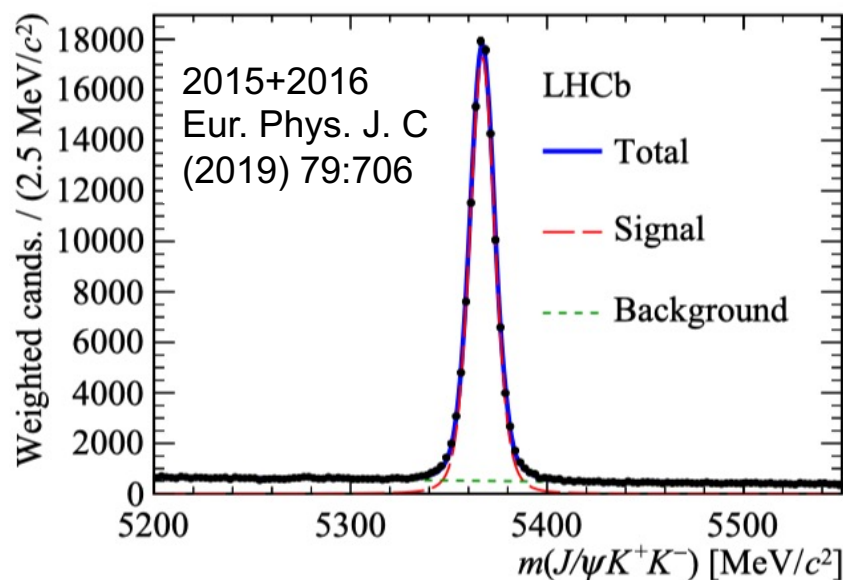
$$\sin(2\beta) \equiv \sin(2\phi_1)$$

HFLAV
Moriond 2024
PRELIMINARY

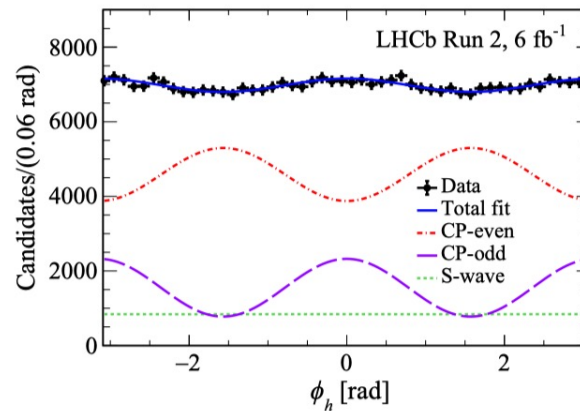
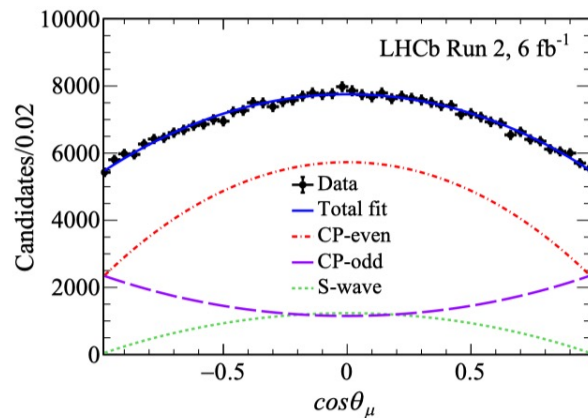
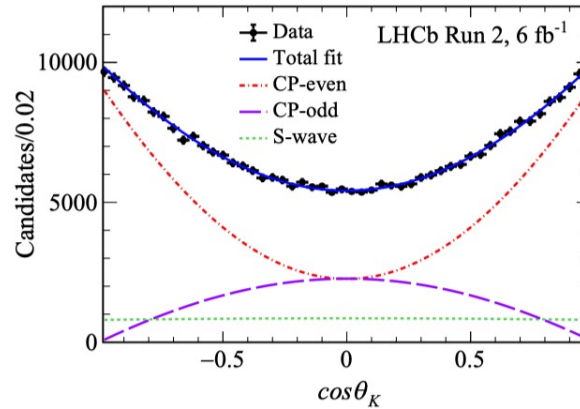
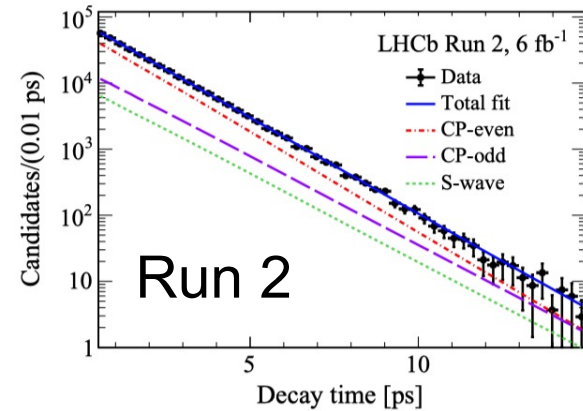


Measurement of ϕ_s in $B_s^0 \rightarrow J/\psi\phi$ decays

- Precise prediction for $b \rightarrow c\bar{c}s$ decays, $\phi_s^{\text{tree}} = -37.0^{+0.6}_{-0.5}$ mrad [CKM fitter]
- Golden channel to measure $\phi_s = \phi_s^{\text{tree}} + \Delta\phi_s^{\text{penguin}} + \Delta\phi_s^{\text{NP}}$
- Previous average $\phi_s^{c\bar{c}s} = -50 \pm 19$ mrad [HFLAV 2021]



Measurement of ϕ_s in $B_s^0 \rightarrow J/\psi\phi$ decays



$$\phi_s^{J/\psi\phi} = -39 \pm 22 \pm 6 \text{ mrad}$$

$$\Delta\Gamma_s^{J/\psi\phi} = 0.085 \pm 0.004 \pm 0.002 \text{ ps}^{-1}$$

✓ **Most precise** measurement

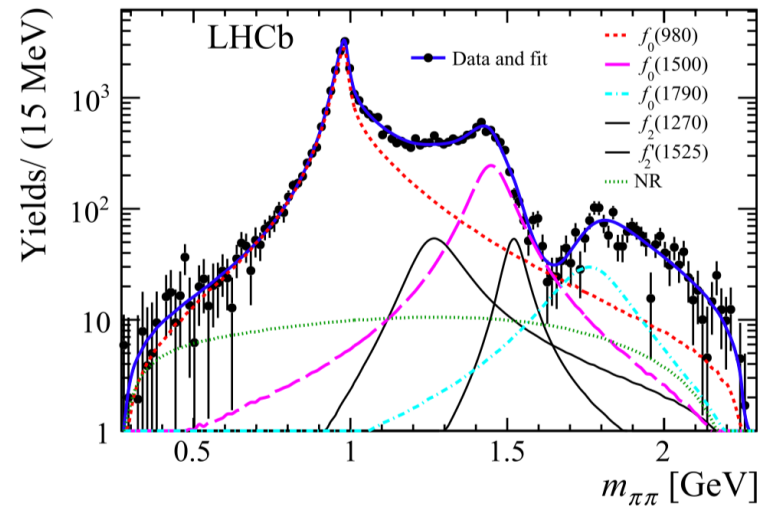
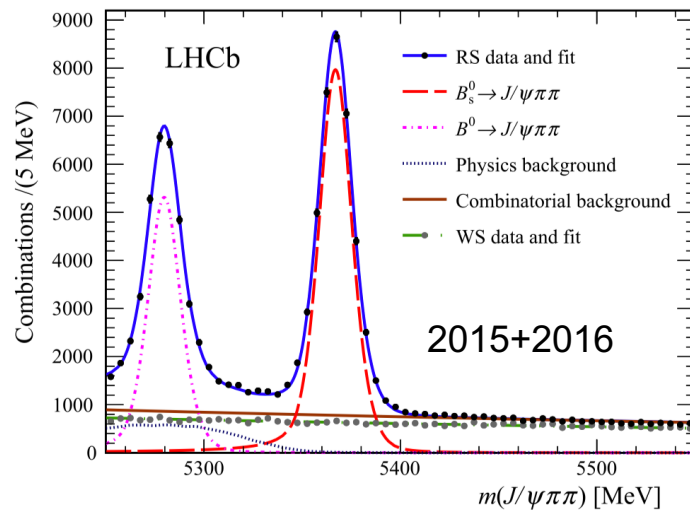
✓ Consistent with SM

✓ No CPV observed

Measurement of ϕ_s in $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ decays

- Second good choice to measure ϕ_s
- Contributions in the $\pi^+ \pi^-$ mass spectrum need to be separated

$$\phi_s^{J/\psi \pi^+ \pi^-} = 75 \pm 65 \pm 14 \text{ mrad (2015+2016)}$$



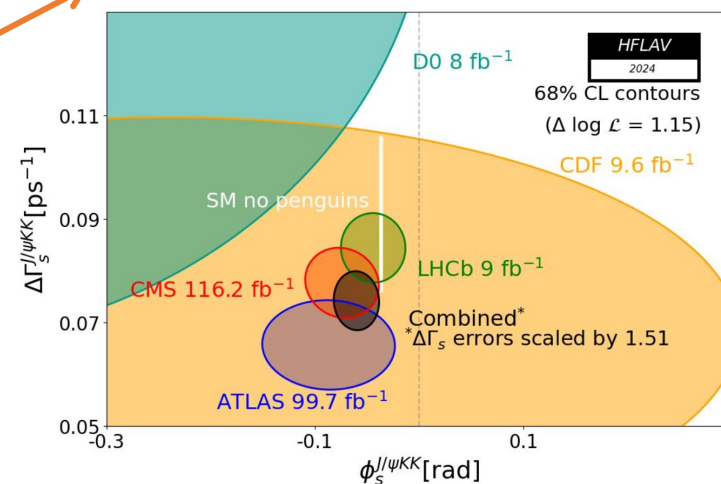
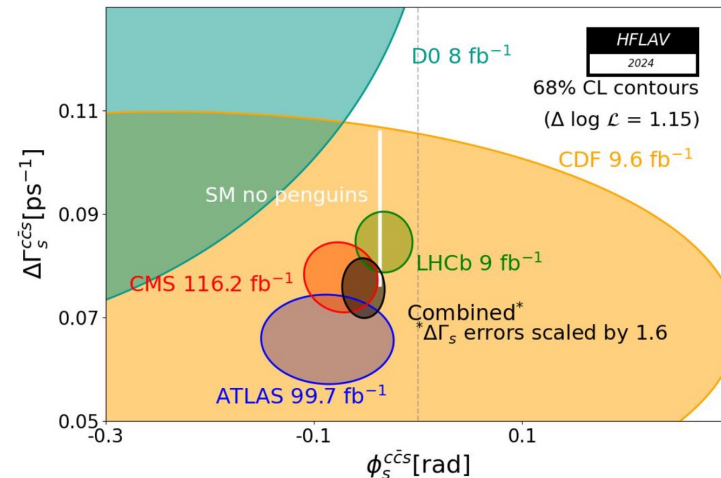
World average ϕ_s

- $\phi_s^{c\bar{c}s} = -52 \pm 13 \text{ mrad}$
- $\phi_s^{J/\psi\phi} = -60 \pm 14 \text{ mrad}$
- **1st evidence for CPV**

Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s} \text{ (rad)}$	$\Delta\Gamma_s \text{ (ps}^{-1}\text{)}$	Ref.
CDF	$J/\psi K^+ K^-$	9.6 fb^{-1}	$[-0.60, +0.12], 68\% \text{ C.L.}$	$+0.068 \pm 0.026 \pm 0.009$	[2]
D0	$J/\psi K^+ K^-$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	[3]
ATLAS	$J/\psi K^+ K^-$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	[4]
ATLAS	$J/\psi K^+ K^-$	14.3 fb^{-1}	$-0.110 \pm 0.082 \pm 0.042$	$+0.101 \pm 0.013 \pm 0.007$	[5]
ATLAS	$J/\psi K^+ K^-$	80.5 fb^{-1}	$-0.081 \pm 0.041 \pm 0.022$	$+0.0607 \pm 0.0047 \pm 0.0043$	[1]
ATLAS	above 3 combined		$-0.087 \pm 0.036 \pm 0.021$	$+0.0657 \pm 0.0043 \pm 0.0037$	[1]
CMS	$J/\psi K^+ K^-$	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	[6]
CMS	$J/\psi K^+ K^-$	96.5 fb^{-1}	$-0.073 \pm 0.023 \pm 0.007$	$+0.0761 \pm 0.0043 \pm 0.0019$	[7]
CMS	above 2 combined		-0.074 ± 0.023	$+0.078 \pm 0.004$	[7]
LHCb	$J/\psi K^+ K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0032$	[8]
LHCb	$J/\psi \pi^+ \pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—	[9]
LHCb	$J/\psi K^+ K^-^a$	3.0 fb^{-1}	$+0.119 \pm 0.107 \pm 0.034$	$+0.066 \pm 0.018 \pm 0.010$	[10]
LHCb	$\psi(2S) K^+ K^-$	3.0 fb^{-1}	$+0.23^{+0.29}_{-0.28} \pm 0.02$	$+0.066^{+0.41}_{-0.44} \pm 0.007$	[11]
LHCb	$D_s^+ D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—	[12]
LHCb	$D_s^+ D_s^-$	6.0 fb^{-1}	$-0.09 \pm 0.11 \pm 0.03$	—	[13]
LHCb	$J/\psi \pi^+ \pi^-$	1.9 fb^{-1}	$-0.057 \pm 0.060 \pm 0.011$	—	[14]
LHCb	$J/\psi K^+ K^-$	6 fb^{-1}	$-0.039 \pm 0.022 \pm 0.006$	$+0.0845 \pm 0.0044 \pm 0.0024$	[15]
LHCb	$J/\psi K^+ K^-^c$	3.0 fb^{-1}	$+0.00 \pm 0.28 \pm 0.07$	$+0.115 \pm 0.045 \pm 0.011$	[16]
LHCb	above 9 combined		-0.033 ± 0.018	$+0.085 \pm 0.004$	
$B_s^0 \rightarrow J/\psi K^+ K^-$ combined			-0.060 ± 0.014	$+0.074 \pm 0.004$	
All combined			-0.052 ± 0.013	$+0.076 \pm 0.004$	

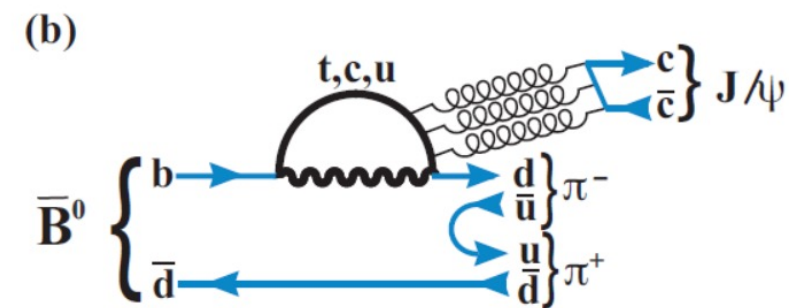
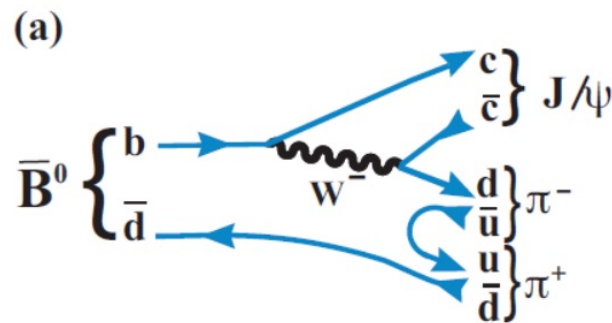
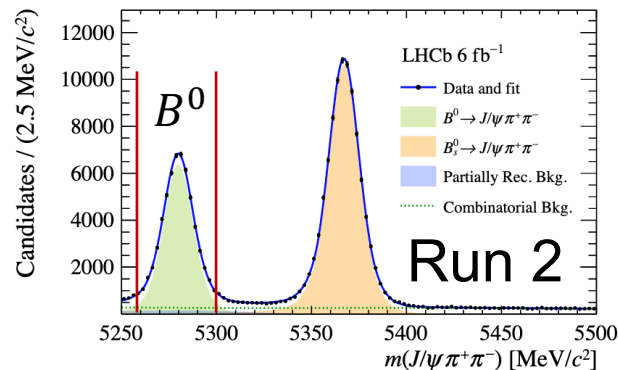
^a $m(K^+ K^-) > 1.05 \text{ GeV}/c^2$ ^b Run 2 ^c $J/\psi \rightarrow e^+ e^-$

HFLAV 2024



CPV study in $B^0 \rightarrow J/\psi \pi^+ \pi^-$ decays

- Average $\phi_s^{J/\psi\phi} = -60 \pm 14$ mrad, neglected $\Delta\phi_s$ at $\mathcal{O}(10)$ mrad [PhysRevLett.115.061802]
- Primary control channel $B^0 \rightarrow J/\psi \rho^0(770)$ decay
- Enhanced penguin contributions in $B^0 \rightarrow J/\psi \rho^0(770)$ relative to $B^0 \rightarrow J/\psi K_S^0$



CPV study in $B^0 \rightarrow J/\psi \pi^+ \pi^-$ decays

- Estimate $\Delta\phi_s$ assuming SU(3) flavour symmetry
 - ✓ assume identical penguin parameters $a'e^{i\theta'}$ in $B^0 \rightarrow J/\psi \rho^0$ and $ae^{i\theta}$ in $B_s^0 \rightarrow J/\psi \phi$
 - ✓ $[\gamma, \epsilon]$ from PDG, $|\lambda|$ and $2\beta^{\text{eff}}$ from this analysis
 - ✓ 2β from $B^0 \rightarrow J/\psi K_S^0$ Run 2 analysis [Phys. Rev. Lett. 132 (2024) 021801]

$$\Delta\phi_s = -\arg \left(\frac{(\xi e^{2i\gamma} - 1) + \epsilon(\xi - 1)}{(\xi e^{2i\gamma} - 1) + \epsilon(\xi - 1)e^{2i\gamma}} \right),$$
$$\xi \equiv |\lambda| e^{-i(2\beta^{\text{eff}} - 2\beta)} = \frac{1 - ae^{i\theta} e^{-i\gamma}}{1 - ae^{i\theta} e^{i\gamma}}$$

$$\Delta\phi_s = 0.9 \pm 9.8 \text{ mrad in Run 1}$$

[Phys. Lett. B742 (2015) 38]

Run 3 analysis is ongoing, particularly important to improve $\Delta\phi_s$ precision

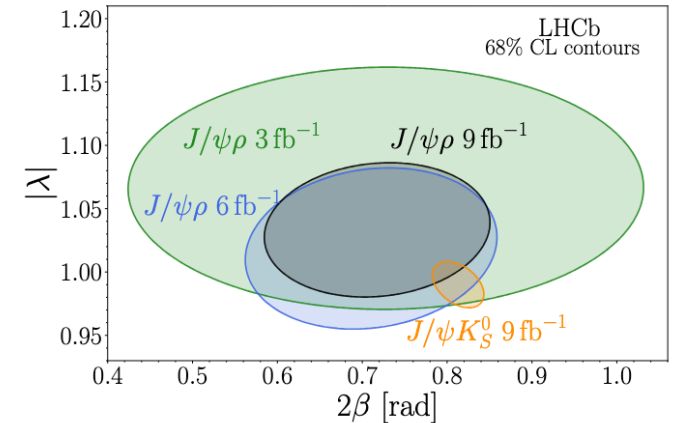
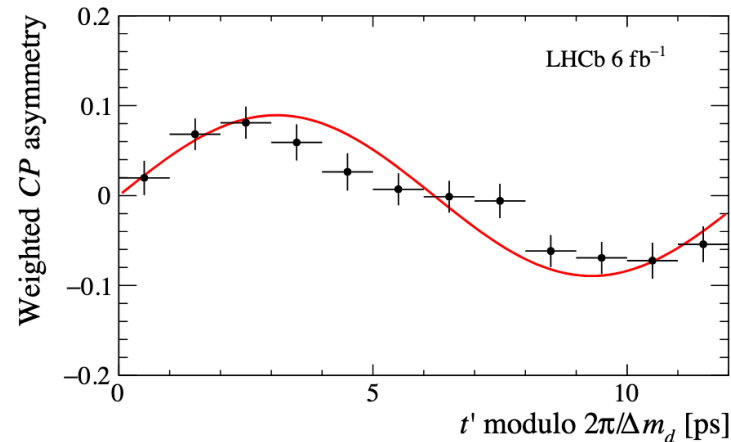
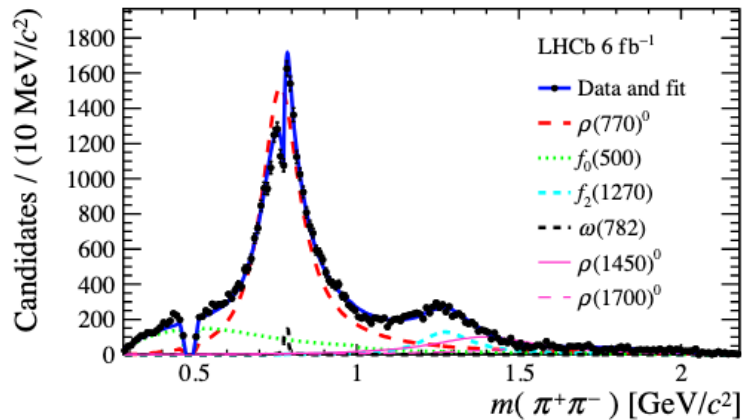
CPV study in $B^0 \rightarrow J/\psi \pi^+ \pi^-$ decays

- Most precise estimate of $\Delta\phi_s$

$$2\beta^{eff} = 0.710 \pm 0.084 \pm 0.051 \text{ rad}, |\lambda| = 1.019 \pm 0.034 \pm 0.024 \text{ (Run 2)}$$

$$2\beta^{eff} = 0.718 \pm 0.088 \text{ rad}, |\lambda| = 1.033 \pm 0.035 \text{ (Run 1+2)}$$

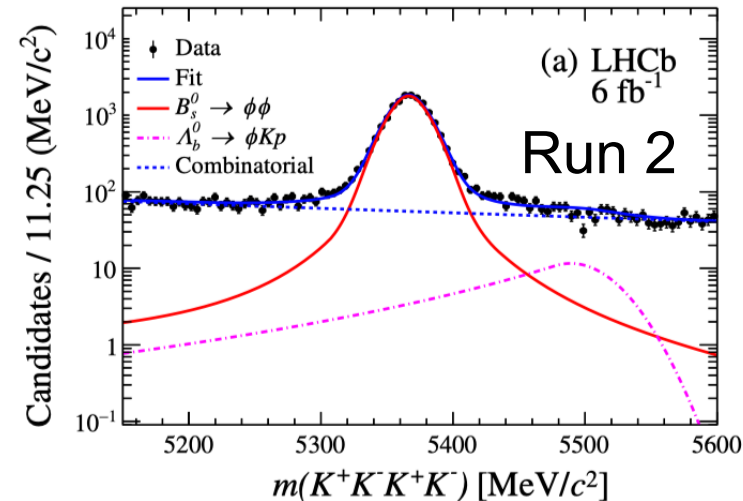
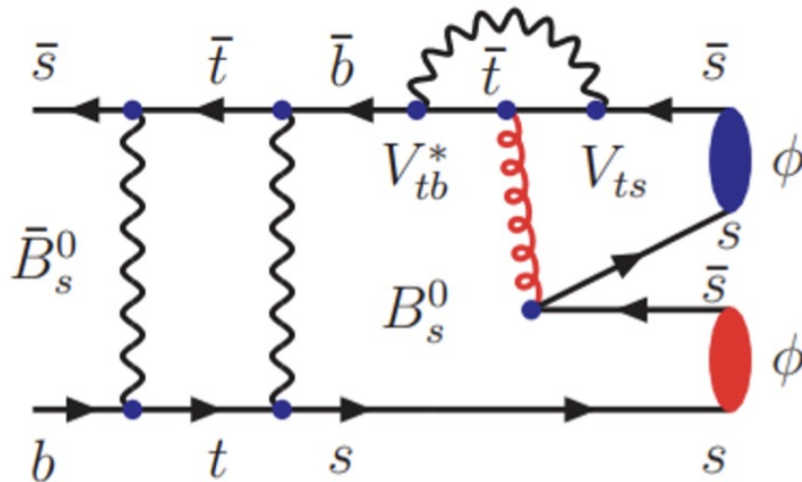
$$\Delta\phi_s = 5.0 \pm 4.6 \text{ mrad} \ll \phi_s \text{ uncertainty of 14 mrad}$$



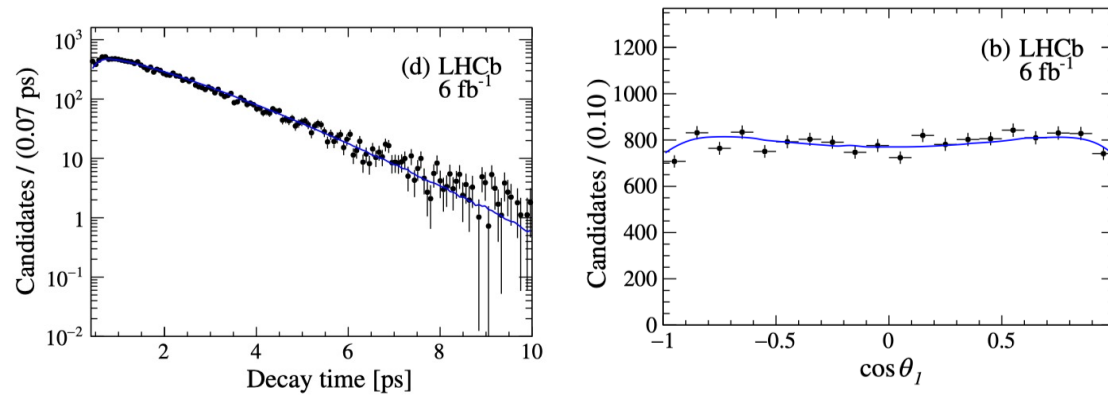
Measurement of ϕ_s in $B_s^0 \rightarrow \phi\phi$ decays

- Penguin-dominated decay via $b \rightarrow s\bar{s}s$
- Sensitive probe to NP in mixing and decay
- Cancellation of mixing and decay weak phases

$$\phi_s^{s\bar{s}s} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{tb}V_{ts}^*}\frac{V_{tb}V_{ts}^*}{V_{ts}V_{tb}^*}\right) \sim 0$$

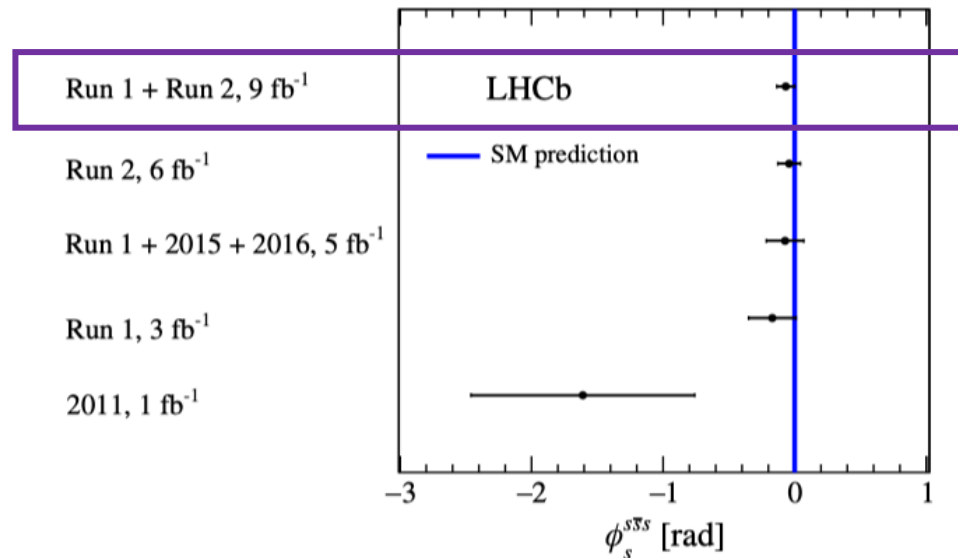


Measurement of ϕ_s in $B_s^0 \rightarrow \phi\phi$ decays



$$\phi_s^{s\bar{s}s} = -42 \pm 75 \pm 9 \text{ mrad (Run 2)}$$

$$\phi_s^{s\bar{s}s} = -74 \pm 69 \text{ mrad (Run 1+2)}$$



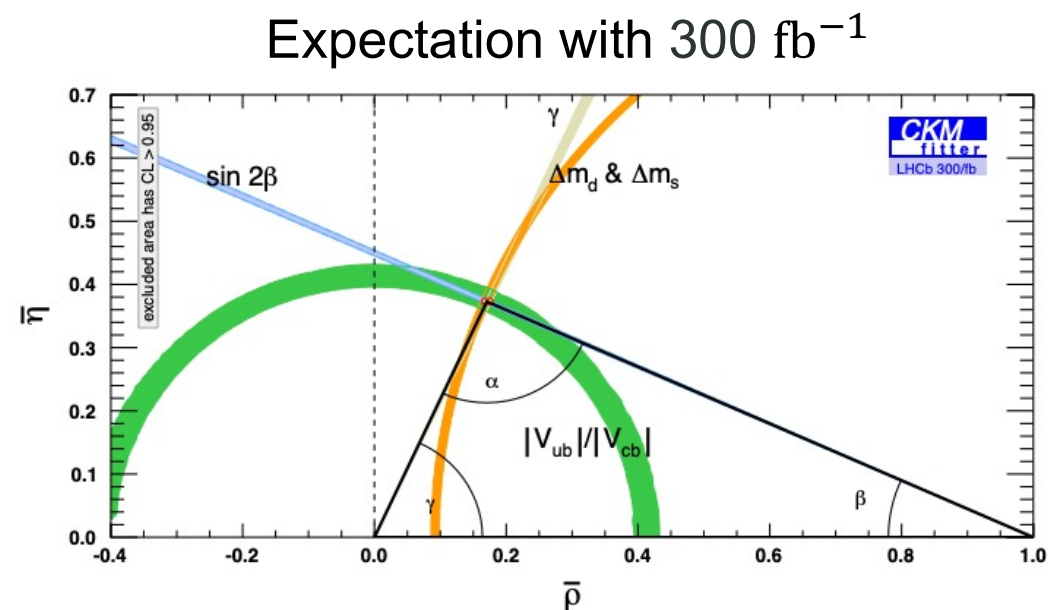
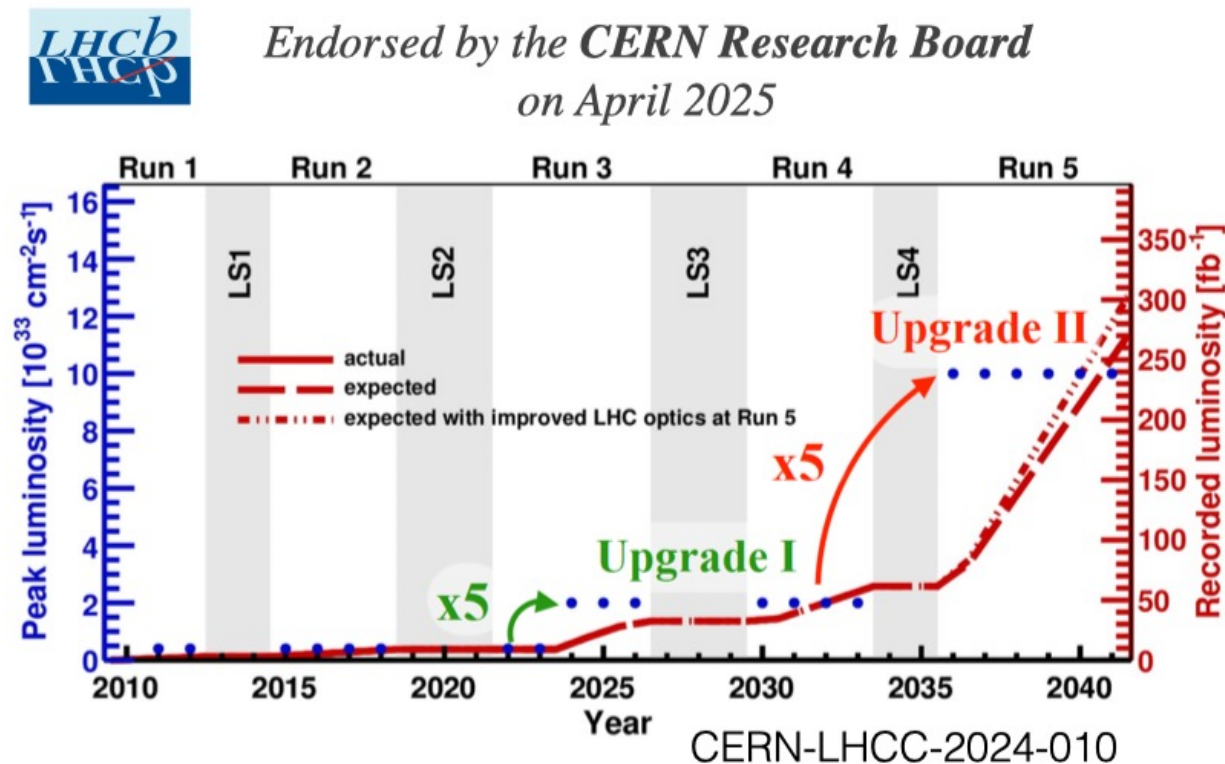
✓ **Most precise** measurement

✓ Consistent with SM

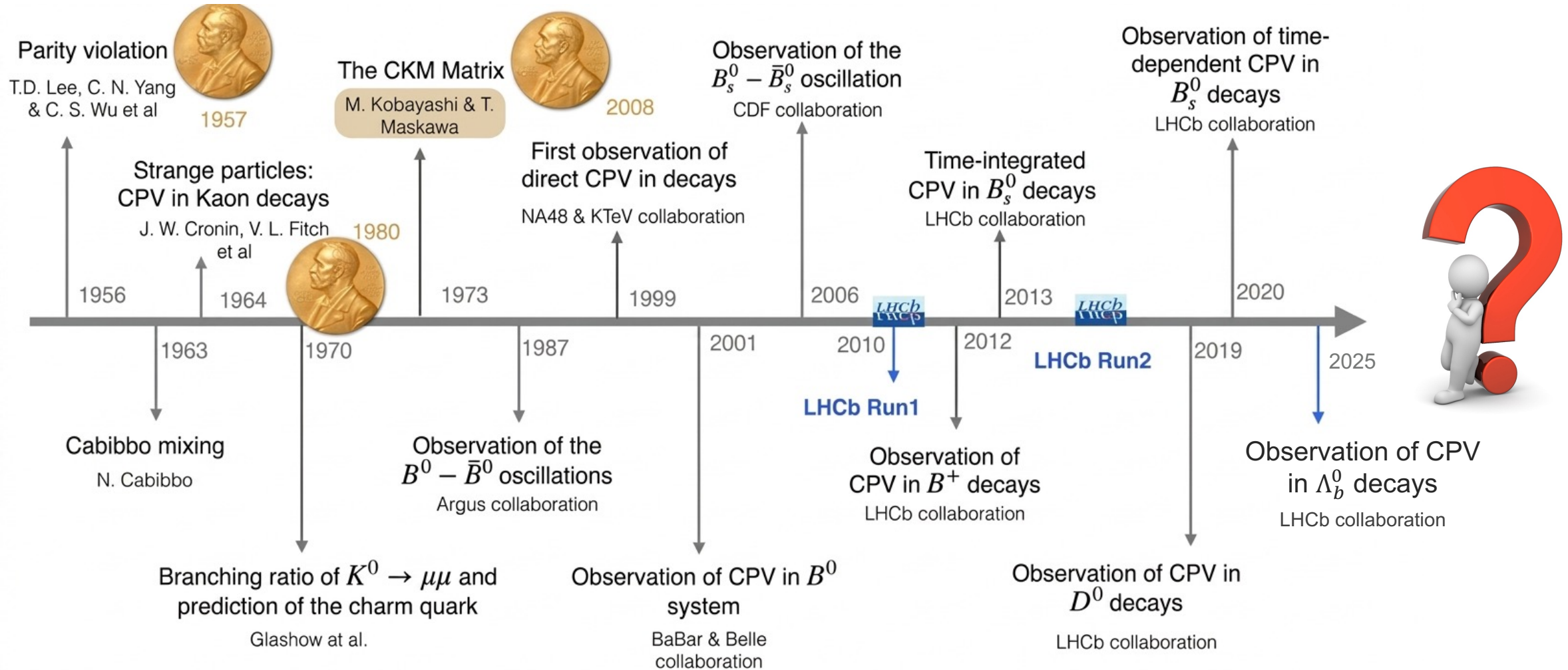
✓ No CPV observed

Prospects

- Target to record 300 fb⁻¹ at the end of Run 5



A brief history of CP violation



Summary

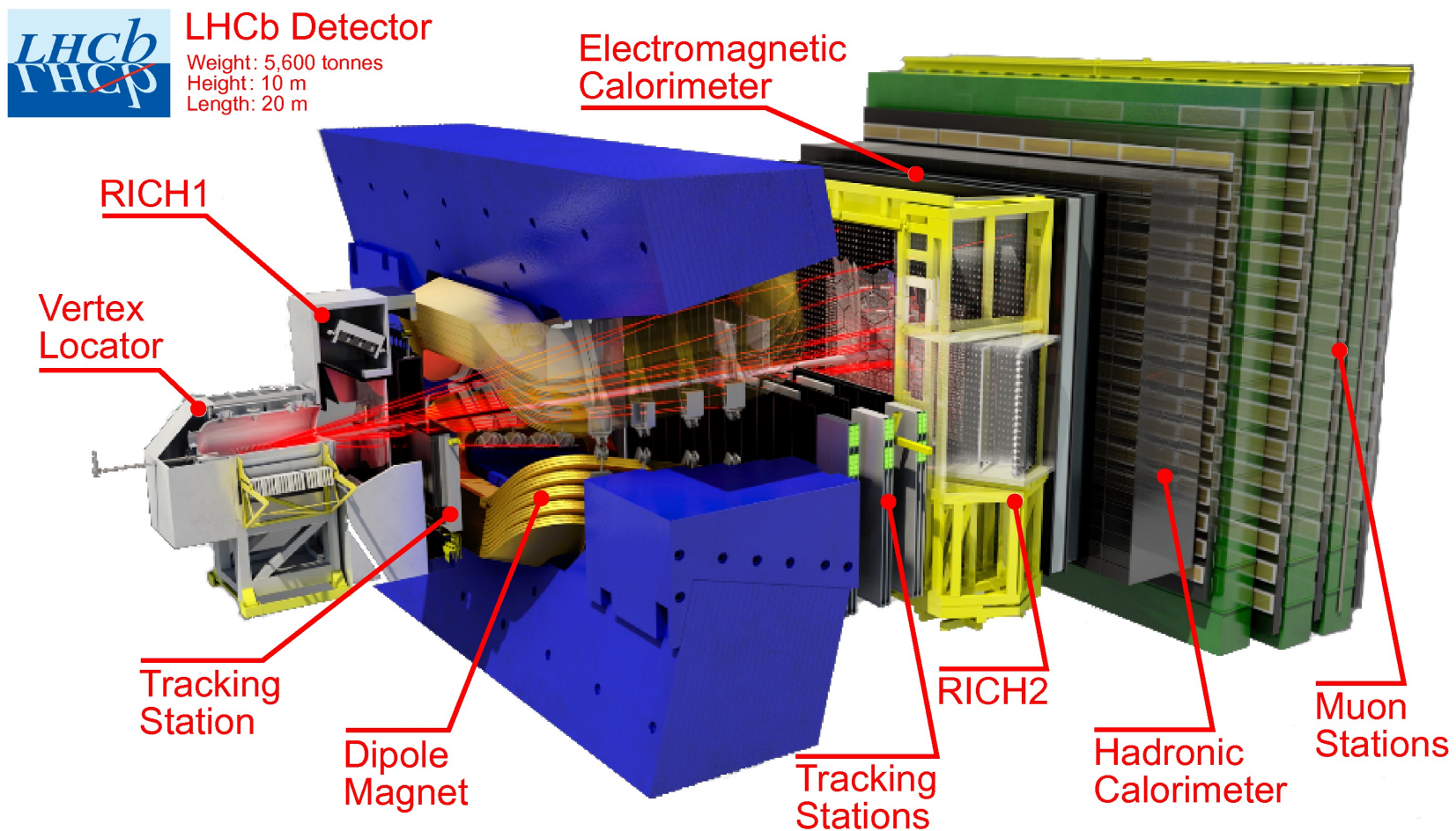
- CPV studies are important to understand matter-antimatter asymmetry
- LHCb experiment is an ideal platform to study CPV
- Huge efforts in the last decades, no physics beyond SM is observed

Stay tuned for Run 3 results!

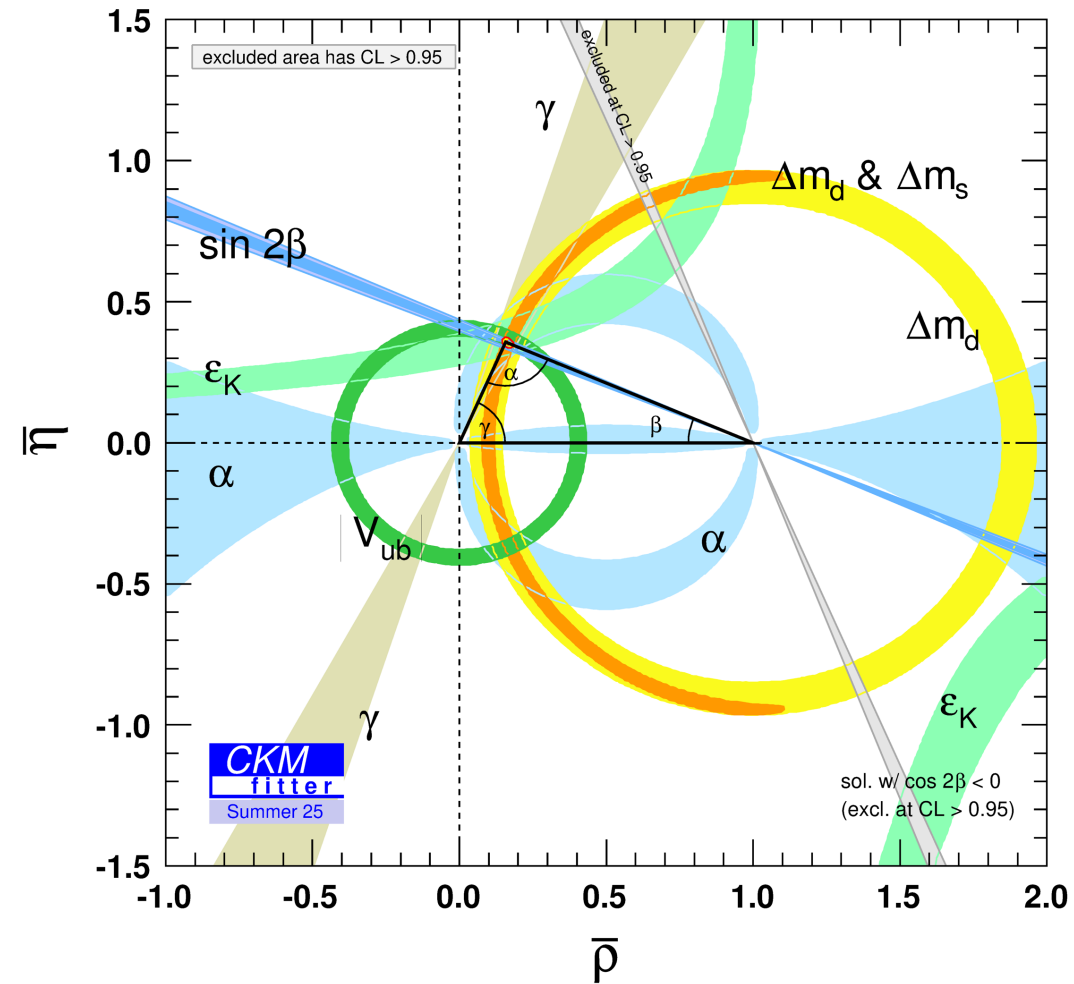


Backup

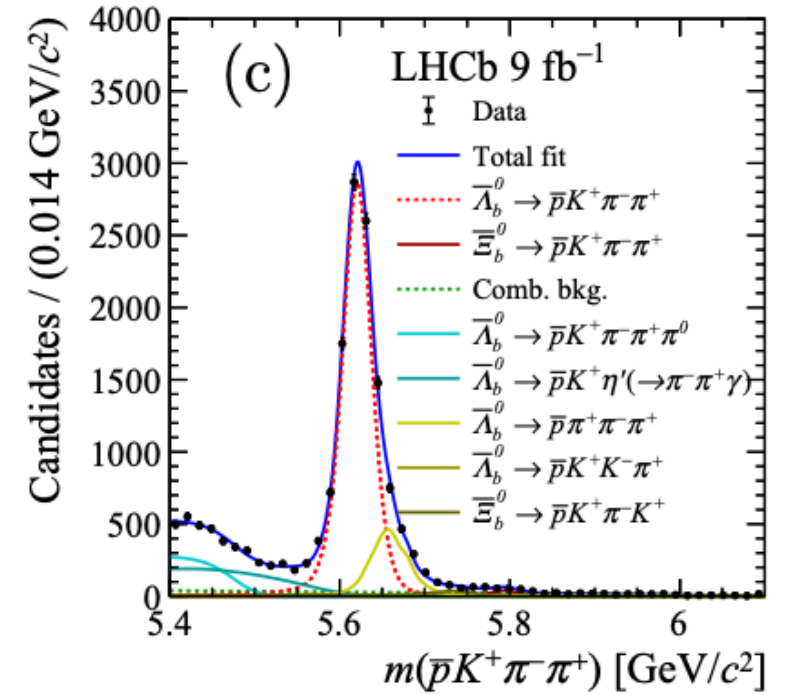
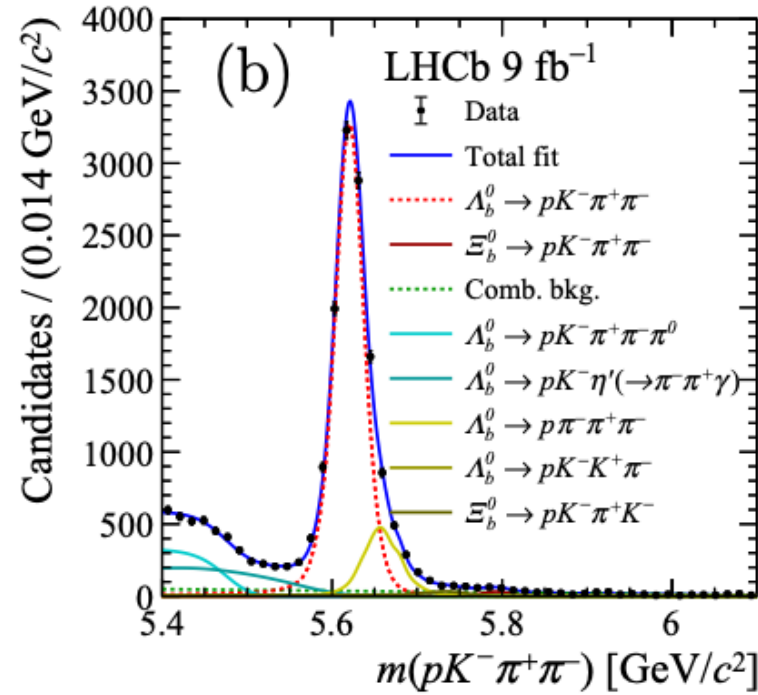
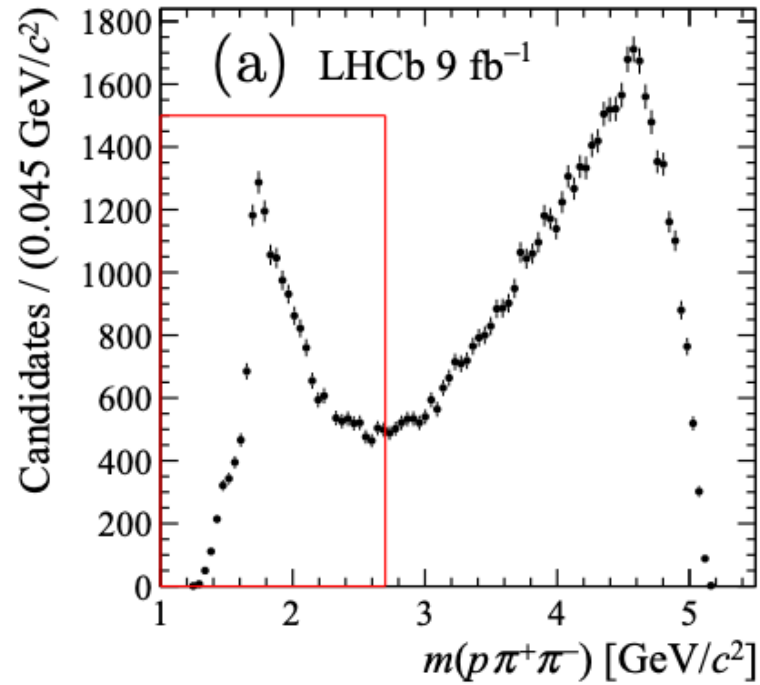
LHCb detector



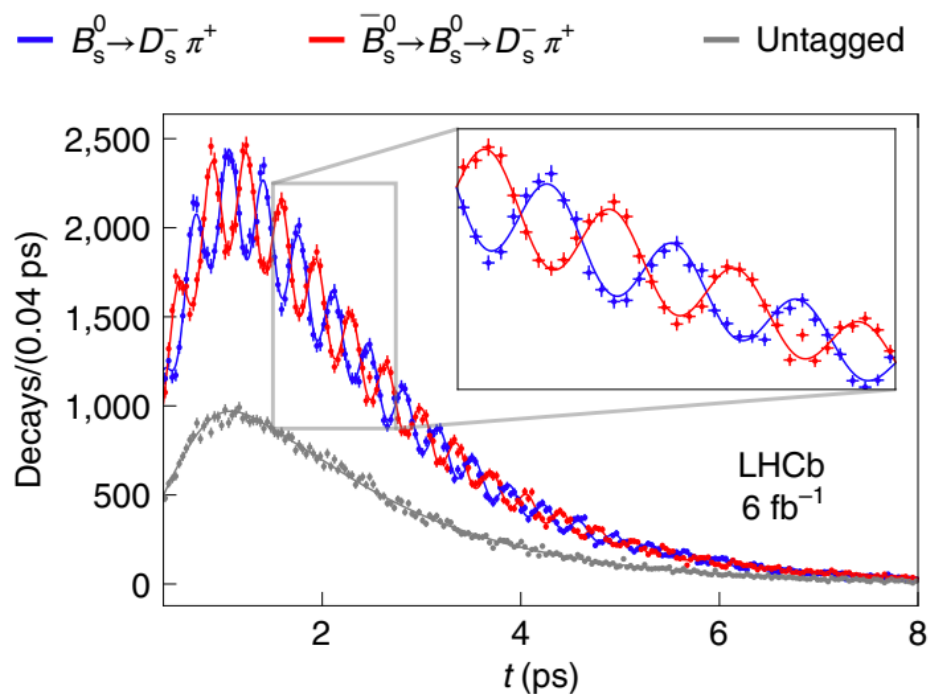
CKM fitter 2025



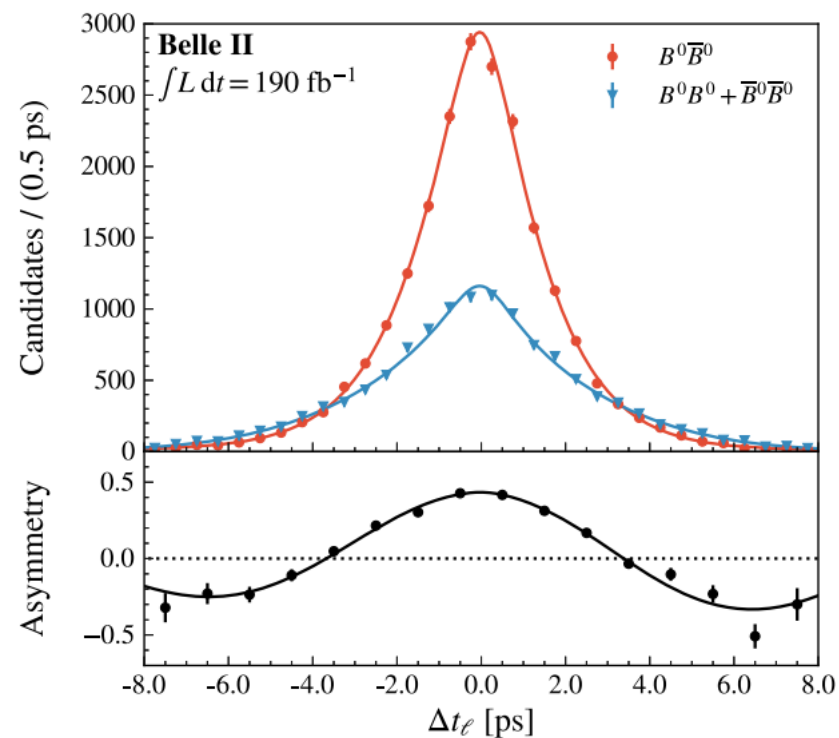
Measurement of A_{CP} in $\Lambda_b^0 \rightarrow pK^+\pi^+\pi^-$ decays



Oscillation frequency



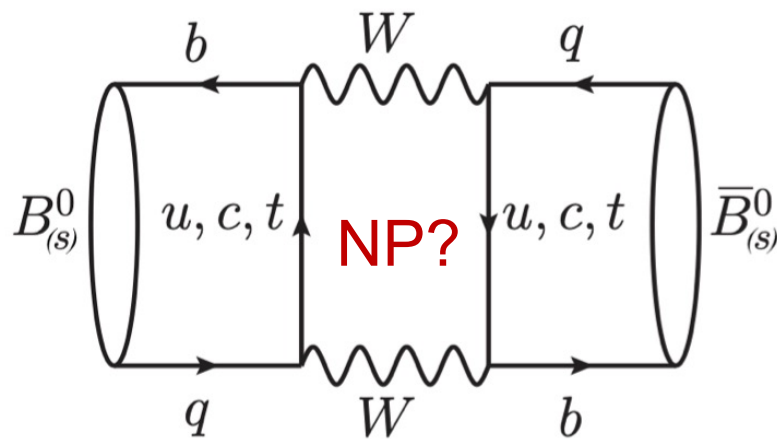
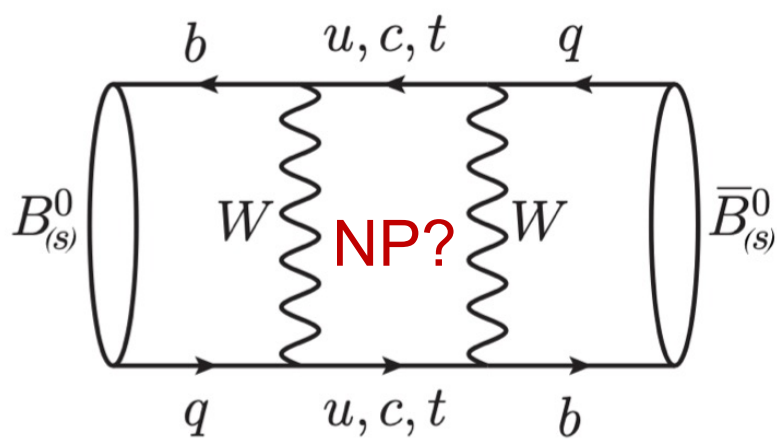
Nat. Phys. 18(2022)1-5



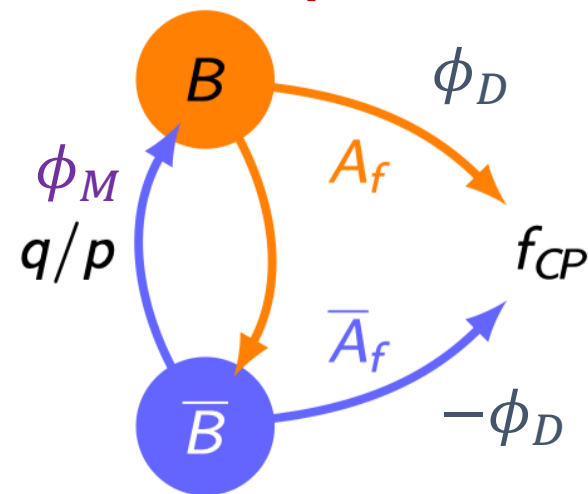
PhysRevD.107.L091102

CPV in neutral B mesons

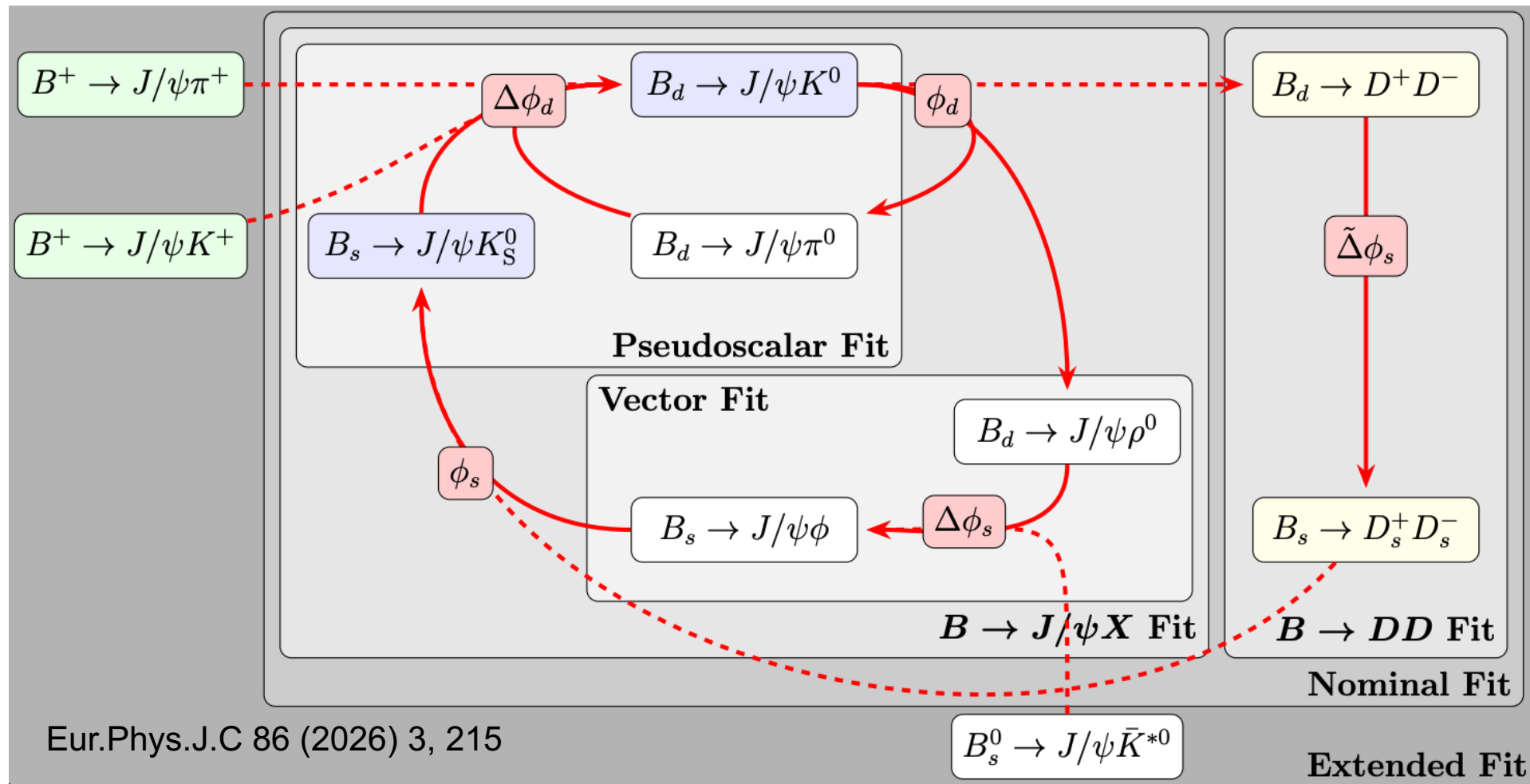
- CPV of interference between mixing and decay
- Abundant physics $\phi_s = -2\beta_s$, $\phi_d = 2\beta$, $\Delta m_q, \Gamma_q, \Delta\Gamma_q \dots$
- Stringent test of SM and sensitive to New Physics in mixing



CPV phase $\phi_q = \phi_M - 2\phi_D$

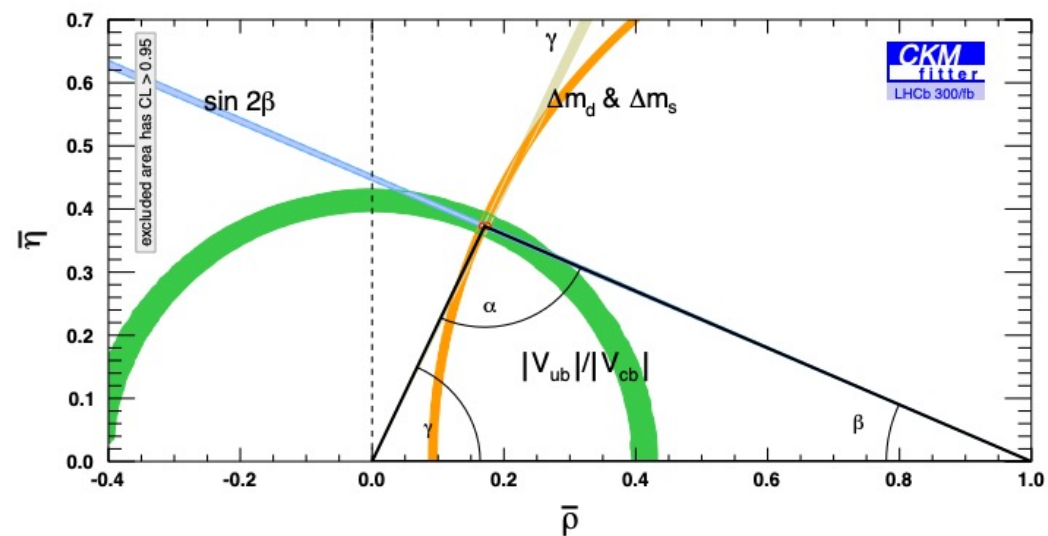
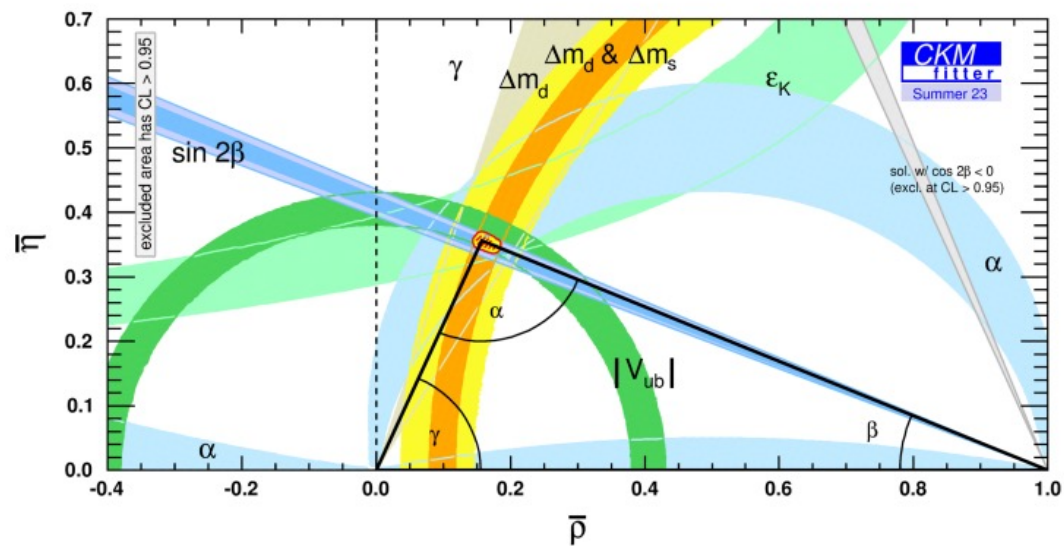


Control of penguin contribution



Propects

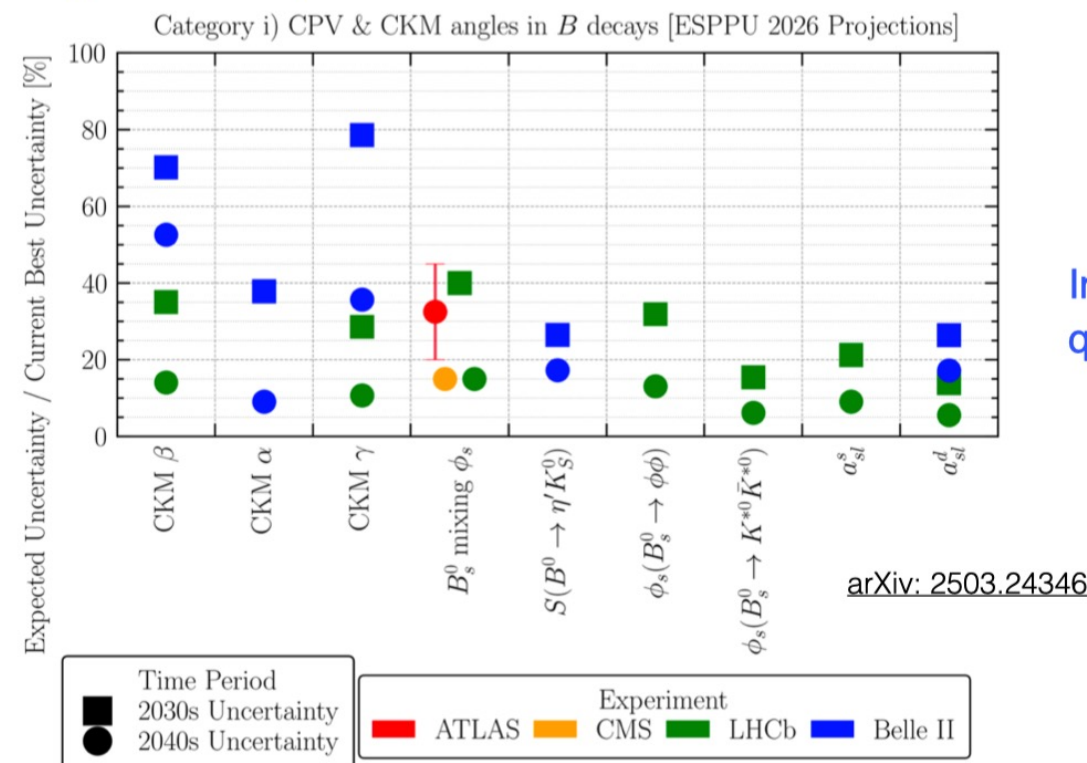
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Propects

Prospects

The next decades are poised to probe the nature of CP violation and the Standard Model with **unprecedented precision**, and potentially observe signatures of new physics



Input from theory to relate quarks to hadrons crucial!

Slide from Peilian Li