Measurements of CP violation at LHCb

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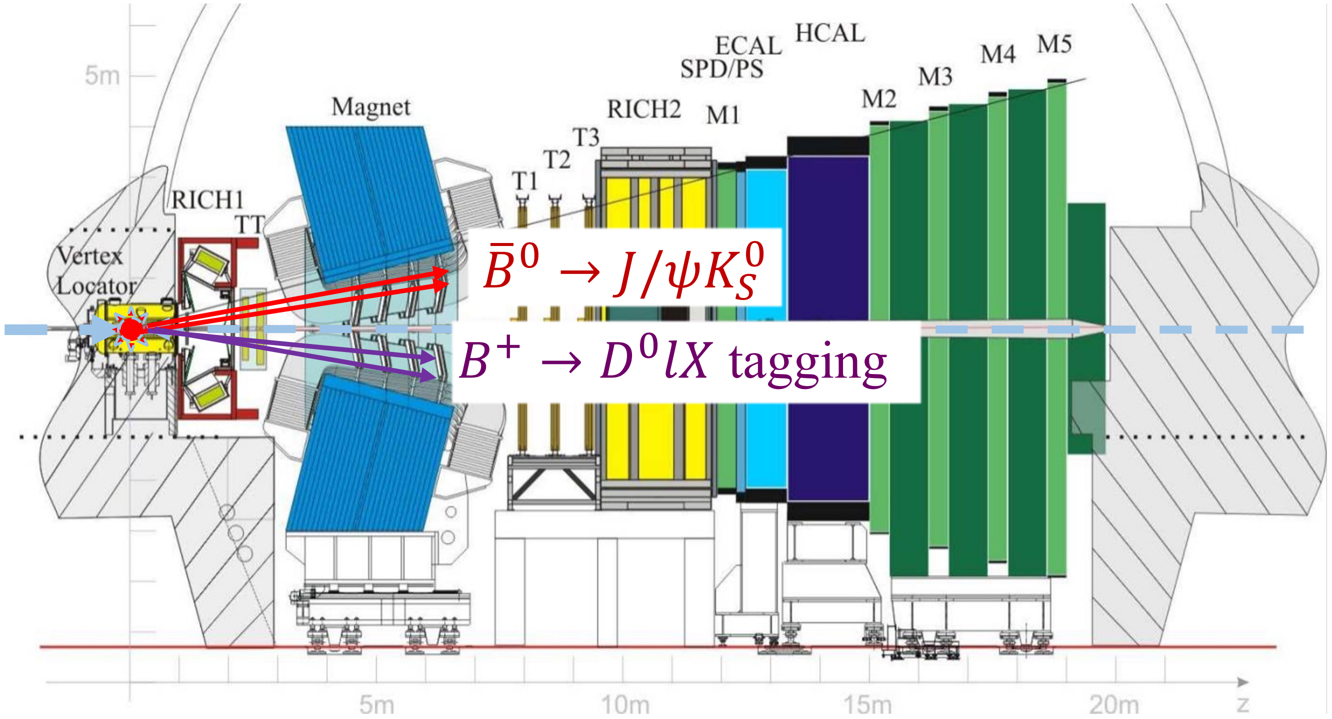
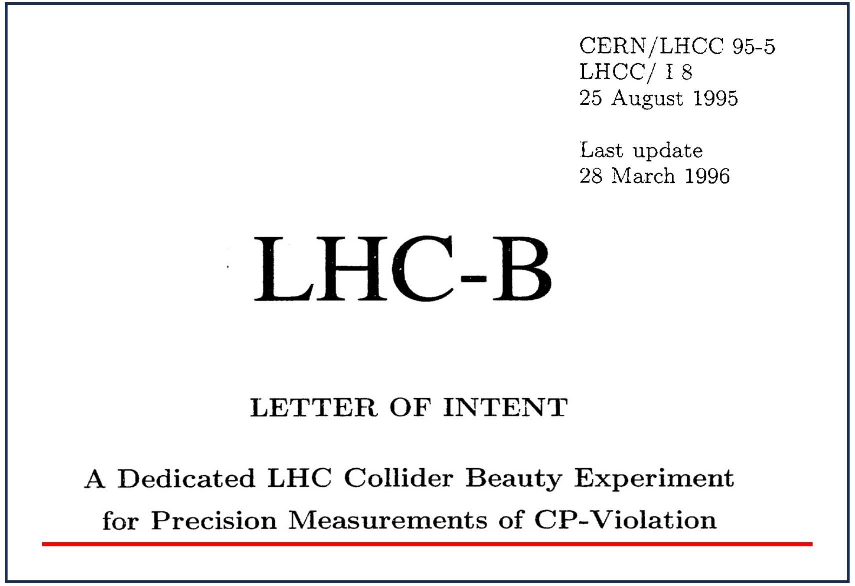
2024.4.19 – 23, 青岛

LHCb

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- Dedicated flavor experiment at CERN for *b*, *c* hadrons



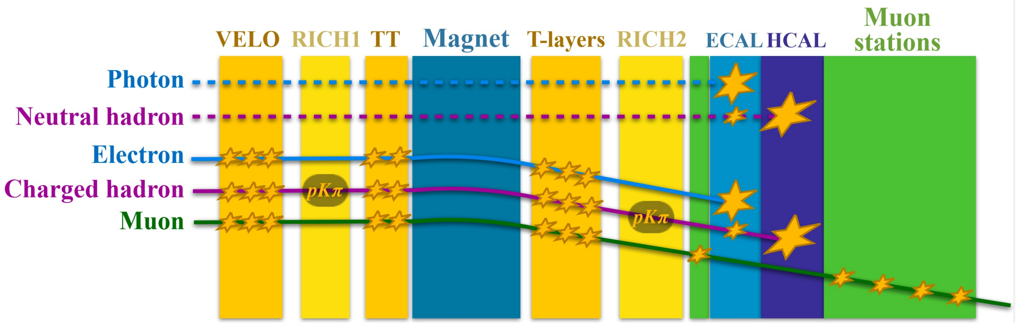

CERN/LHCC 95-5
LHCC/ I 8
25 August 1995

Last update
28 March 1996

LHC-B

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment
for Precision Measurements of CP-Violation



✓ Excellent vertexing
$\sigma_\tau \sim 45$ fs

✓ Hadron PID
$\epsilon(K \to K), \epsilon(p \to p) > 90\%$

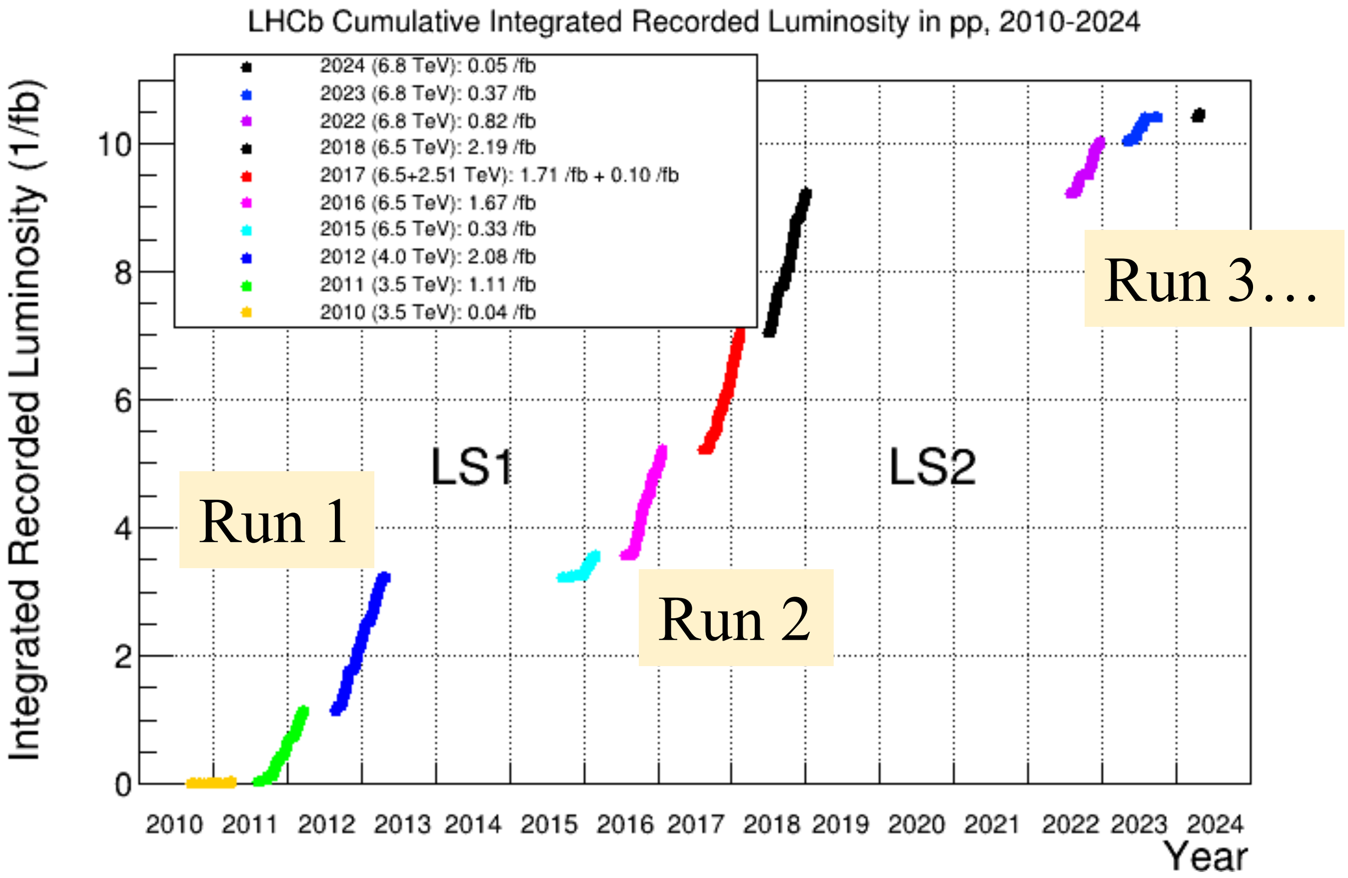
✓ Momentum resolution
$\delta m_{B \to K\pi}/m_B \sim 0.005$

LHCb data

- pp collisions at $\sqrt{s} = 7,\ 8, 13, 13.6\text{TeV}, \int \mathcal{L} = 10\ \text{fb}^{-1}$
- All species produced with large rates

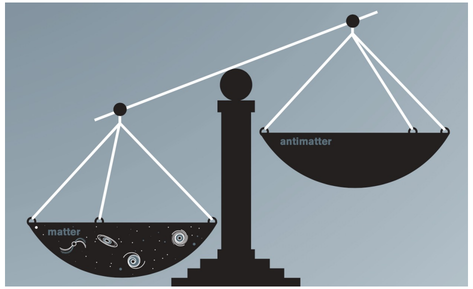
JHEP 05 (2017) 074
PRL 118 (2017) 052002
PRD 100 (2019) 031102(R)

$\sigma(pp \to b\bar{b}X, 13\ \text{TeV}) \approx 0.5\ \mu\text{b}$ $\quad B^+ : B^0 : B_s^0 : \Lambda_b^0 \approx 4 : 4 : 1 : 2$



CP violation in the SM and beyond

- Origin of matter and antimatter asymmetry in Universe



Matter   Anti-matter

Sakharov:
- Baryon-violation
- C and CP violation
- Out of thermal equilibrium

- CKM mechanism

Mass eigenstates (to Higgs) ⟷ flavor eigenstates (to EW bosons)

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(10^{-3})$$

Weak phases → CP violation

Four independent parameters due to unitarity
3 rotation angles + 1 phase

The only established CPV source, but insufficient

Measurement of direct CP violation

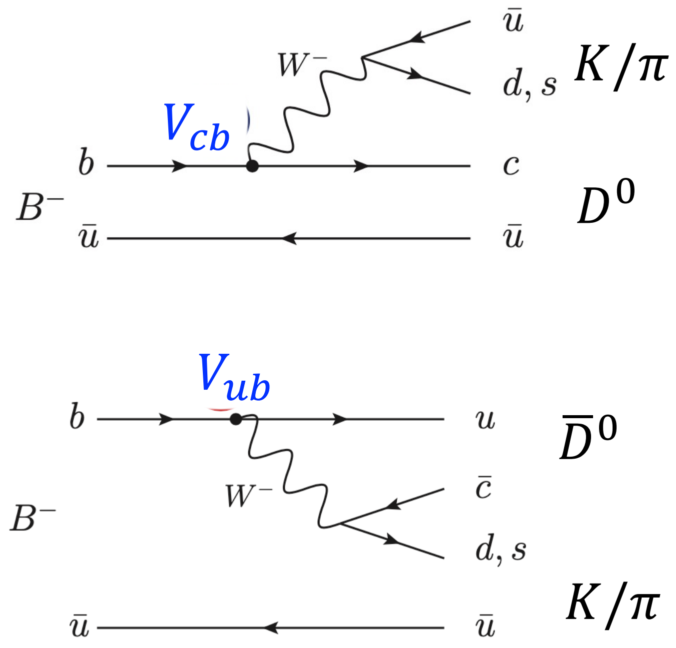
- Interference to probe phases

Strong phase difference — Weak phase difference

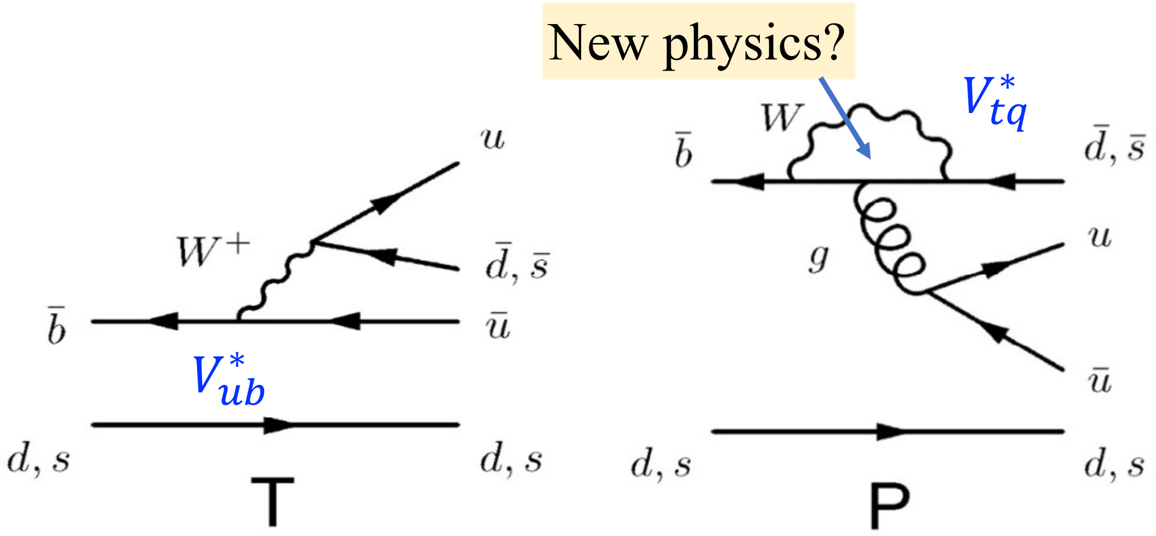
$$A_{CP} = \frac{2|\mathcal{A}_2/\mathcal{A}_1|\sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)}{1+|\mathcal{A}_2/\mathcal{A}_1|^2+2|\mathcal{A}_2/\mathcal{A}_1|\cos(\delta_1-\delta_2)\cos(\phi_1-\phi_2)}$$

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

➢ Tree diagrams (γ-measurements)

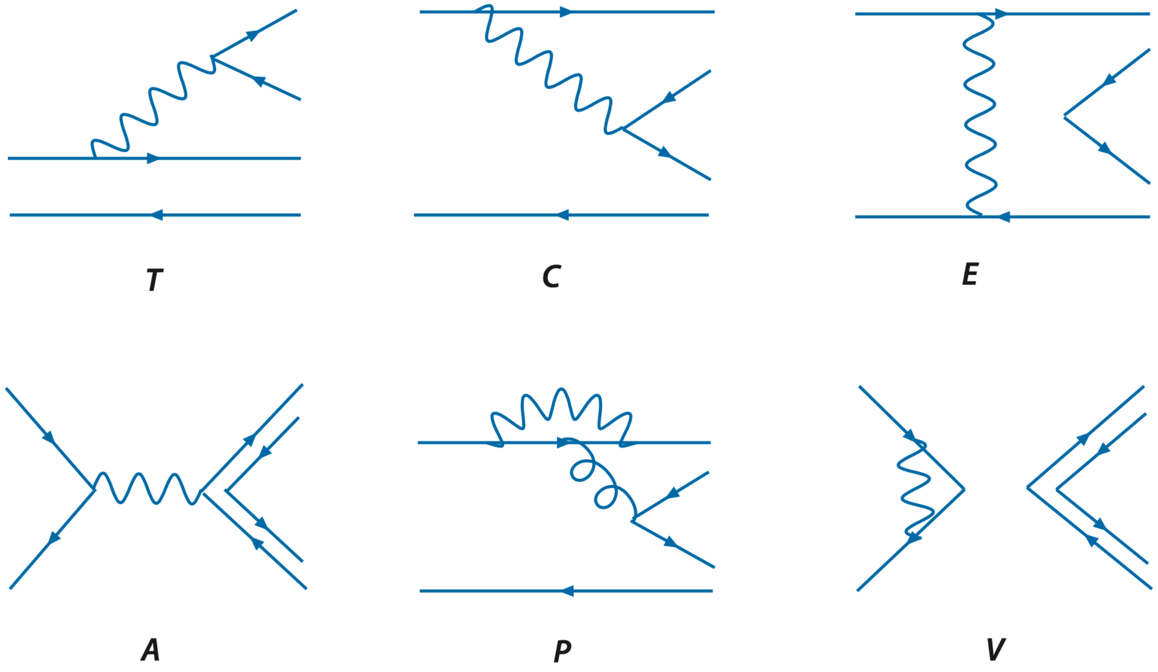


➢ Tree + loop diagrams (CKM, new physics)



Test CKM mechanism and search for new physics (CP sources)

(Quasi)Two body decays



Understanding the amplitudes

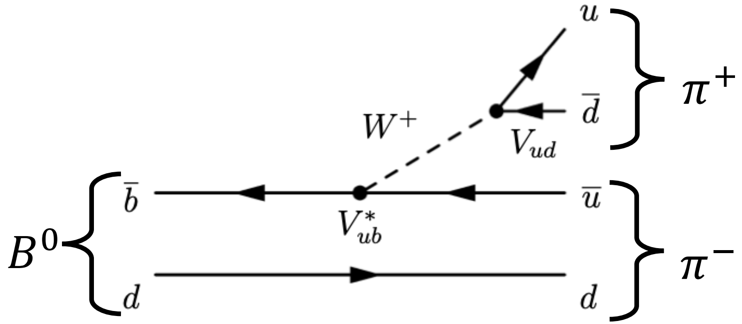
The $B^0 \to \pi^+\pi^-$ decay

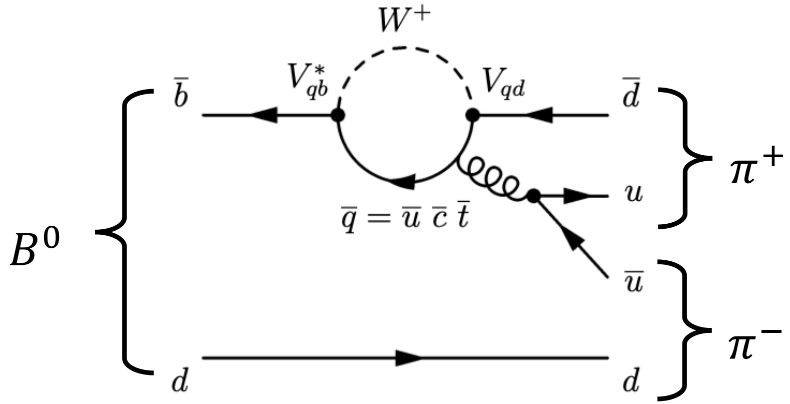
- Time dependent asymmetry

$$A_{CP}(t) = \frac{-C_f \cos(\Delta M t) + S_f \sin(\Delta M t)}{\cosh(\Delta\Gamma t/2) + A_f^{\Delta\Gamma} \sinh(\Delta\Gamma t/2)}$$

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f \equiv \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2} \qquad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

Direct CPV | Mixing induced CPV | $f \equiv \pi^+\pi^-$

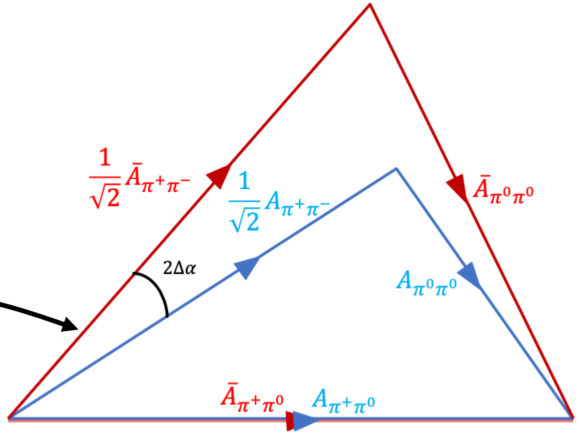




- Penguin polluting to $\alpha(\phi_2)$ angle measurement

$$2\alpha'(T+P) = \arg\lambda_f \neq 2\alpha(T)$$

$$\alpha = \alpha' + \Delta\alpha$$



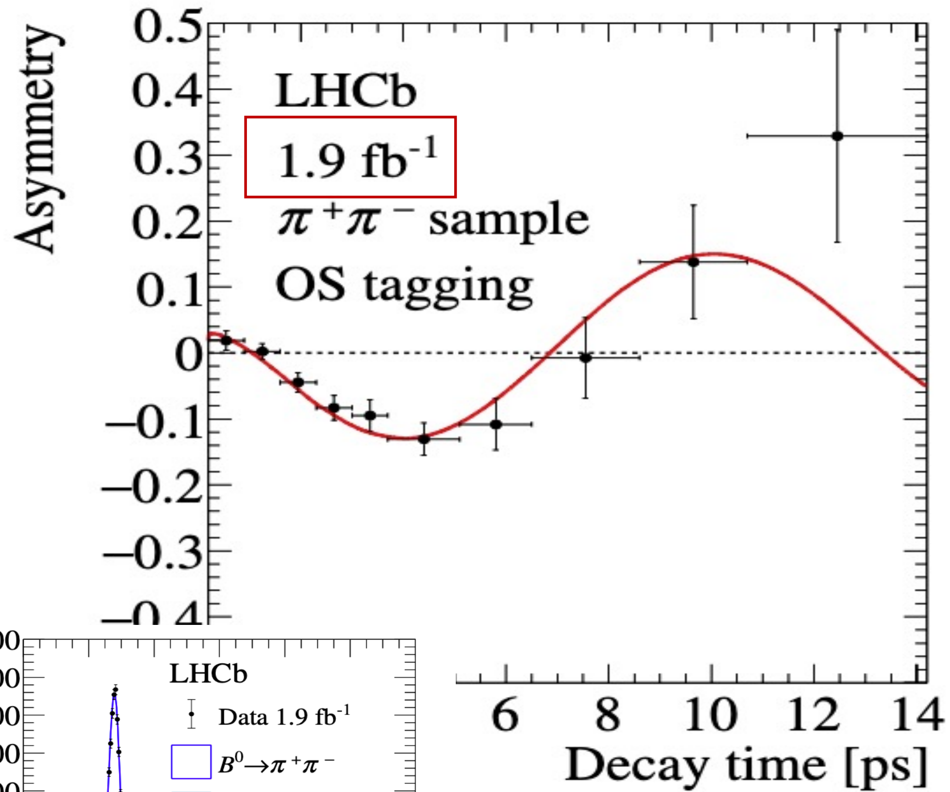
Isospin relation

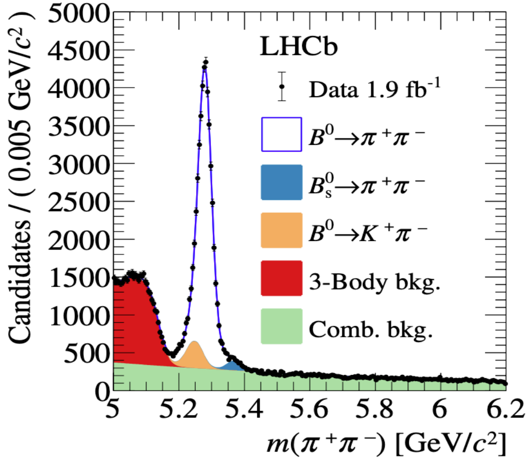
PRL 65 (1990) 3381

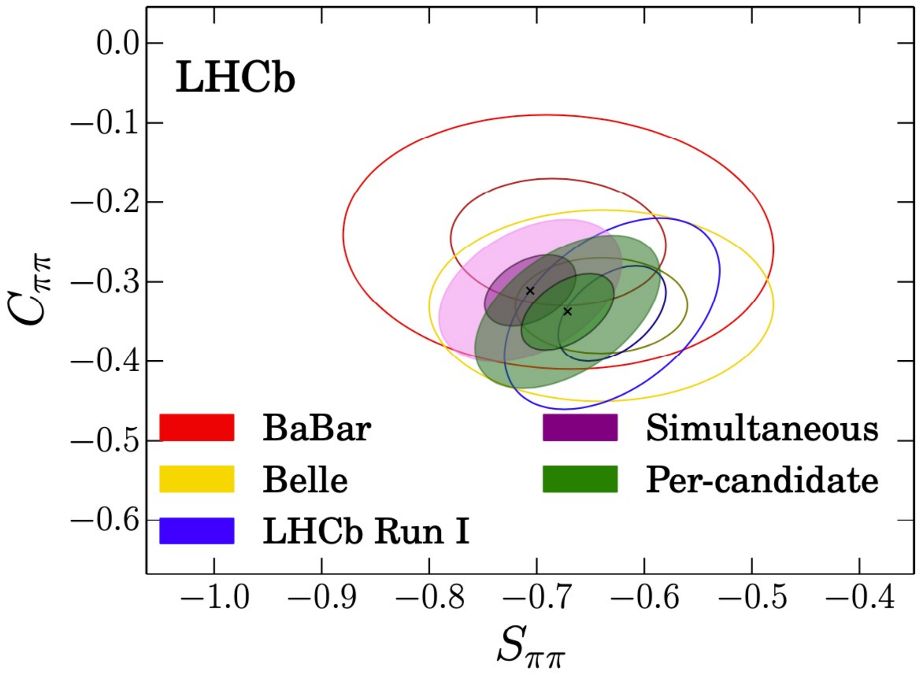
CPV in $B^0 \to \pi^+\pi^-$ decay

JHEP 03 (2021) 075

Time dependent asymmetry







$$C_{\pi^+\pi^-} = -0.311 \pm 0.045 \pm 0.15$$

$$S_{\pi^+\pi^-} = -0.706 \pm 0.042 \pm 0.13$$

$$C_{\pi^+\pi^-} = -0.31 \pm 0.03$$
$$S_{\pi^+\pi^-} = -0.67 \pm 0.03$$

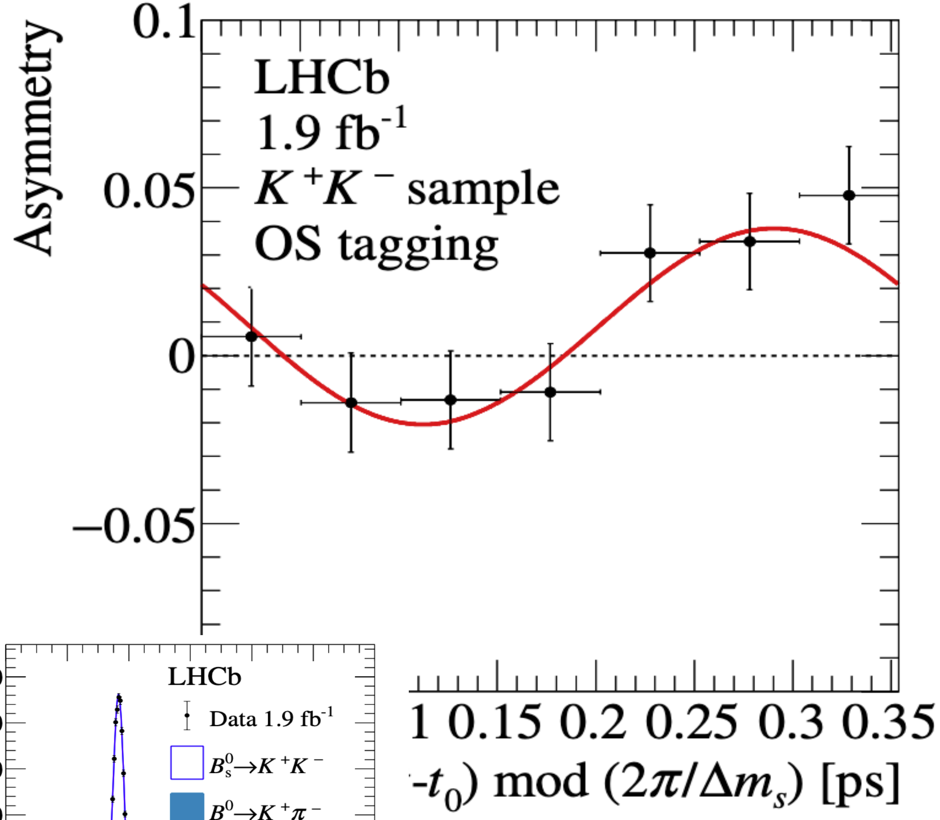
HFLAV [PRD107(2023)052008]

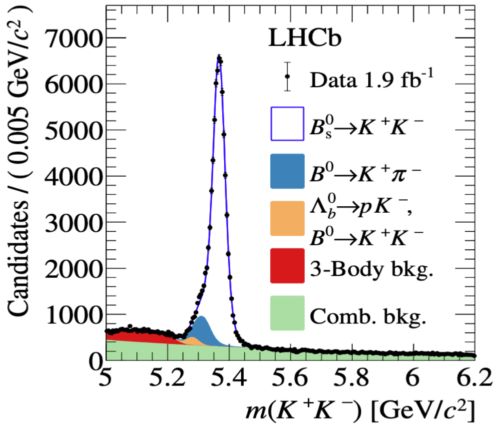
Direct and mixing induced CP violation

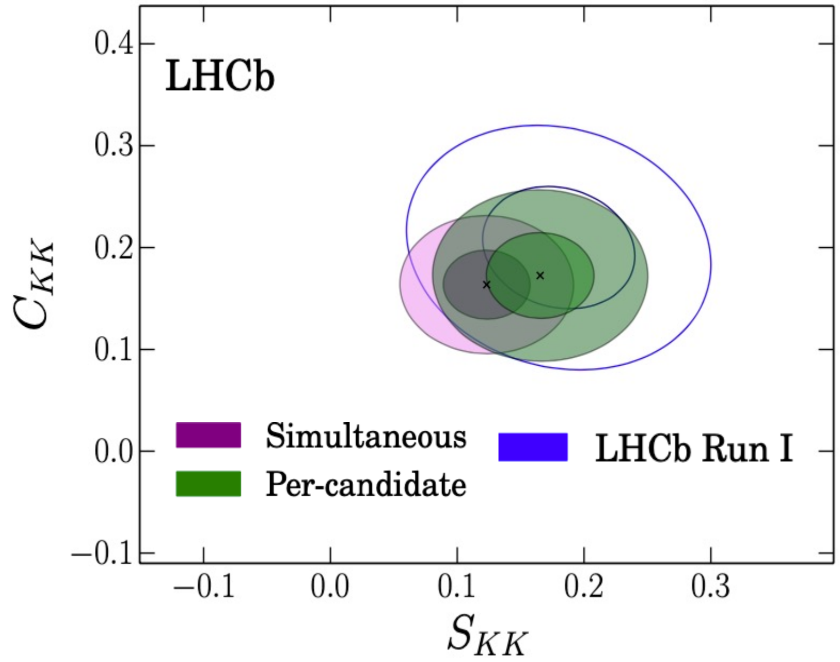
CPV in $B_s^0 \to K^+K^-$ decay

JHEP 03 (2021) 075

Time dependent asymmetry







$C_{K^+K^-} = 0.172 \pm 0.031$

$S_{K^+K^-} = 0.139 \pm 0.032$

LHCb unique

Direct and mixing induced CP violation

Used to test SU(3) flavor symmetry

Direct CPV in $B \to K\pi$ system

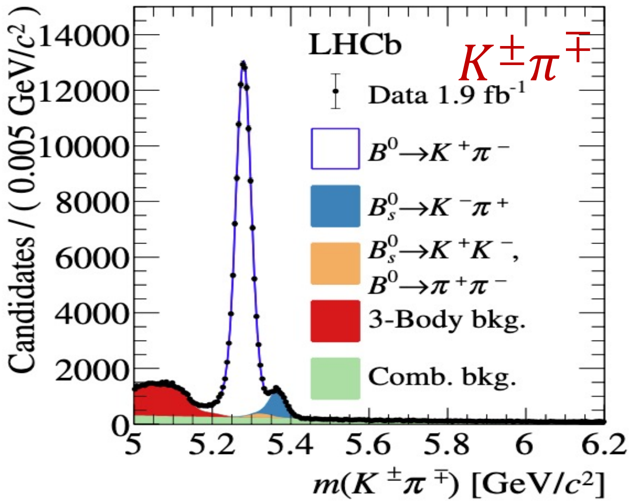
JHEP 03 (2021) 075
PRL 126 (2021) 091802

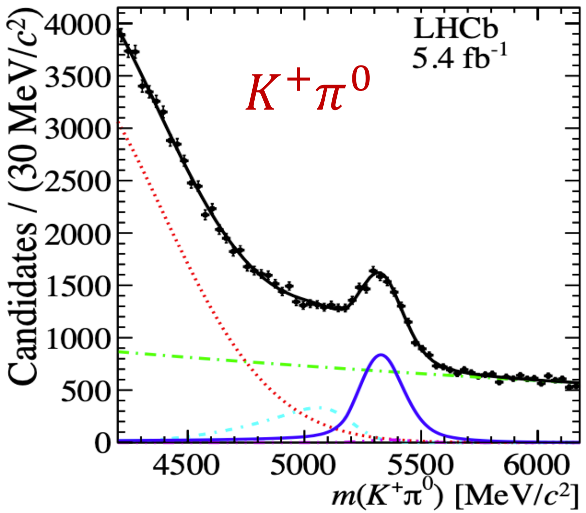
- Isospin symmetry and neglecting "sub-leading" diagrams implies

$$\Delta A_{CP}^{K\pi} = A_{CP}(B^0 \to K^+\pi^-) - A_{CP}(B^+ \to K^+\pi^0) \approx 0$$

Experiment: $\Delta A_{CP}^{K\pi} \neq 0$ at 5.5σ, so called "$K\pi$" puzzle

- Inputs from LHCb





$$A_{CP}(B^+ \to K^+\pi^0) = +0.025 \pm 0.015 \pm 0.006 \pm 0.003$$
$$A_{CP}(B^0 \to K^+\pi^-) = -0.0824 \pm 0.0033 \pm 0.0033$$

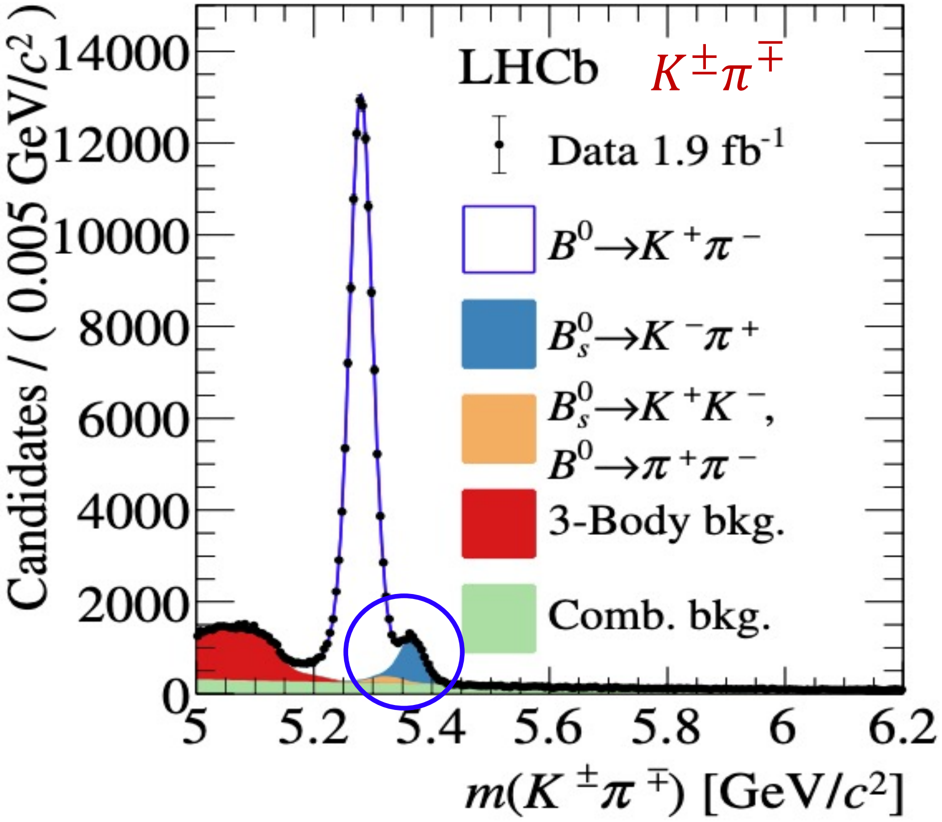
$\Delta A_{CP}^{K\pi} \neq 0$ at $> 8\sigma$

- More complex relation, required combined results from LHCb and BelleII

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

Direct CPV in $B_s^0 \to K^- \pi^+$

JHEP 03 (2021) 075



$b \to d$ decay, large CPV observed

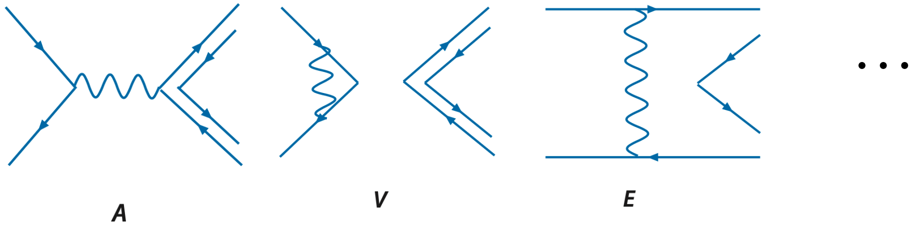
$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.236 \pm 0.013 \pm 0.011$$

Test the U-spin (d-s) symmetry: PLB621(2005)126

$$\Delta \equiv \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} \frac{\Gamma_s}{\Gamma_d} = -0.085 \pm 0.043$$

Nonzero at 2σ

Violation of SU(3) and/or underestimated contributions ?

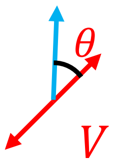


Reanalysis in Chin.Phys.C 46 (2022) 12

CPV in quasi $B \to V(\to PP)P$ decays

- Interference between $B \to VP$ and $B \to SP$

$$\cos\theta = \frac{2m^2_{\mathrm{high}} - (m^2_{\mathrm{high}})_{\mathrm{max}} + (m^2_{\mathrm{high}})_{\mathrm{min}}}{(m^2_{\mathrm{high}})_{\mathrm{max}} - (m^2_{\mathrm{high}})_{\mathrm{min}}}$$

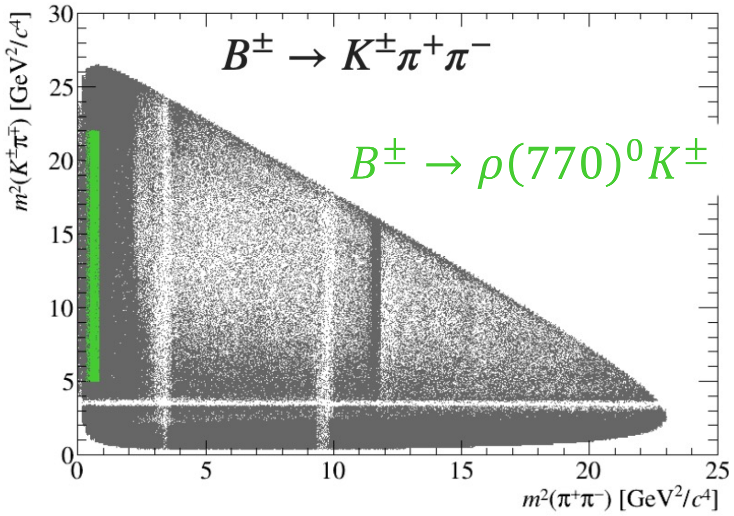


$$\mathcal{M}_{\pm} = a^V_{\pm} f^V(m_{\mathrm{low}}) \cos\theta + a^S_{\pm} f^S(m_{\mathrm{low}})$$

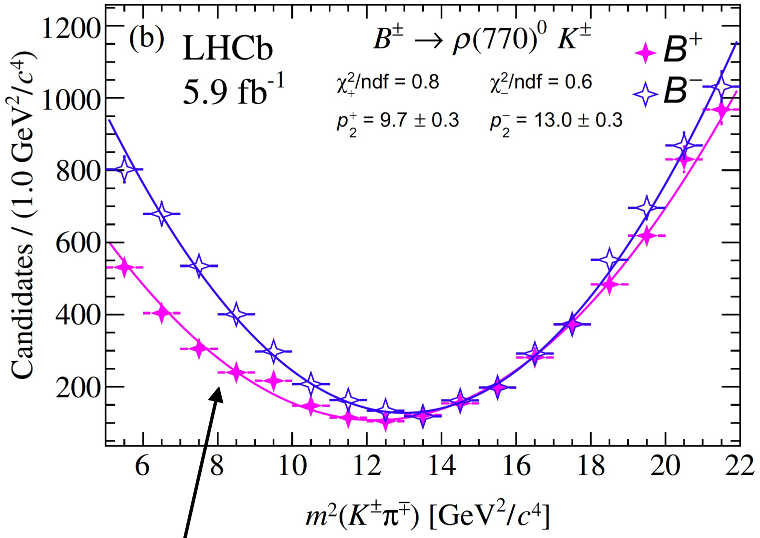
$$\to \quad \frac{d\Gamma_{\pm}}{d\cos\theta} \propto \left|a^V_{\pm}\right|^2 \cos^2\theta + 2p^{SV}_{\pm}\cos\theta + p^S_{\pm}$$

May be polluted by higher waves

- Extraction of $\left|a^V_{\pm}\right|^2$ through angle analysis of resonance region PRD106(2022)113002



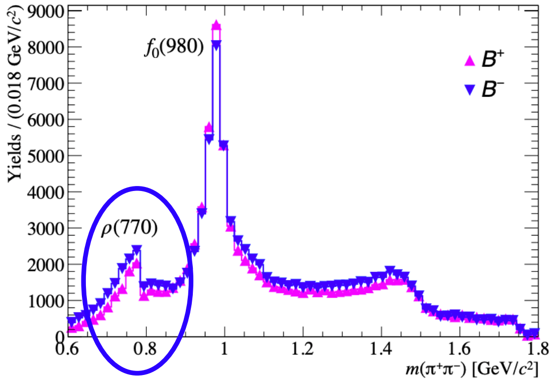
PRD108(2023)012013



Interference between S and P waves

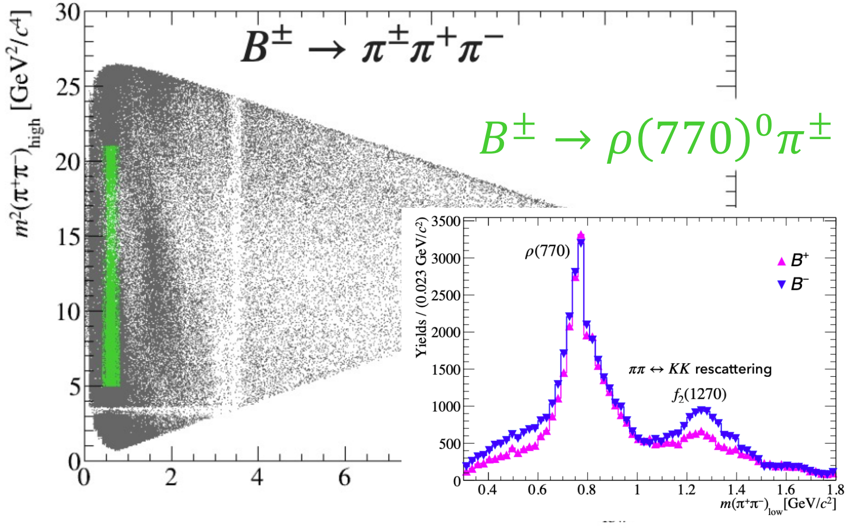
$$A_{CP}[B^{\pm} \to \rho(770)^0 K^{\pm}] = 0.150 \pm 0.021$$

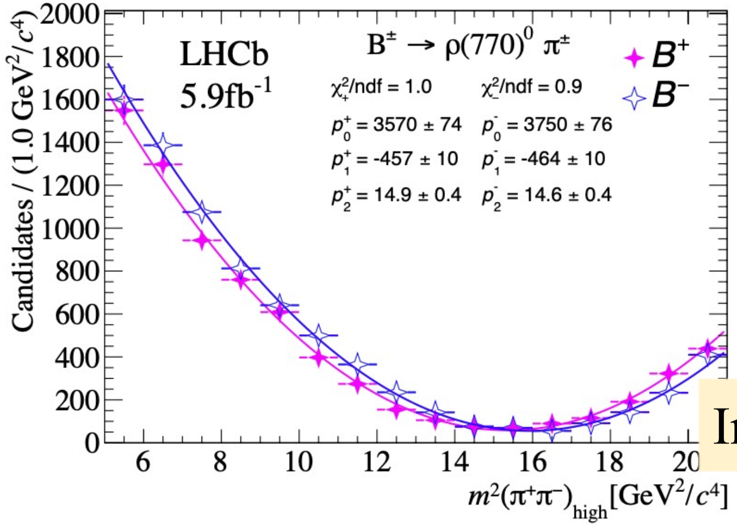
Hinted by mass projections



Quasi $B^\pm \to P^\pm V$ decays: one diagram dominating

PRD108(2023)012013

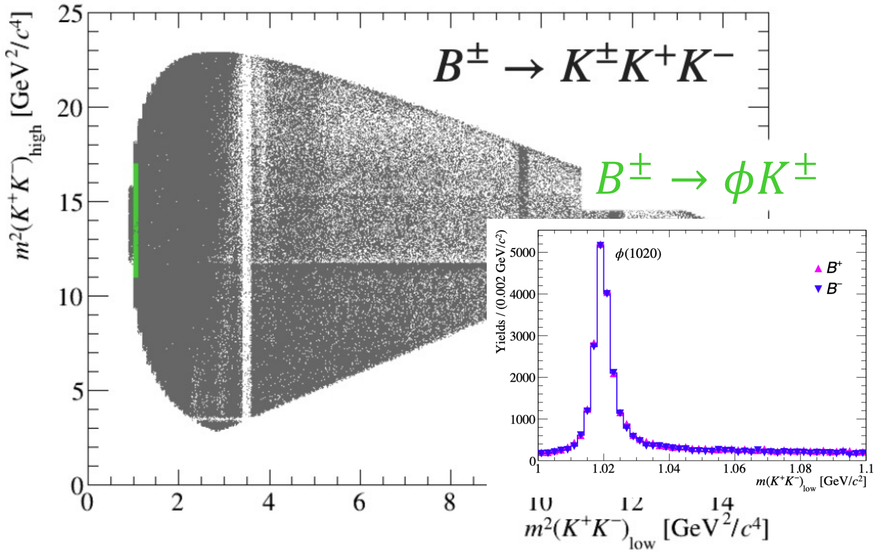


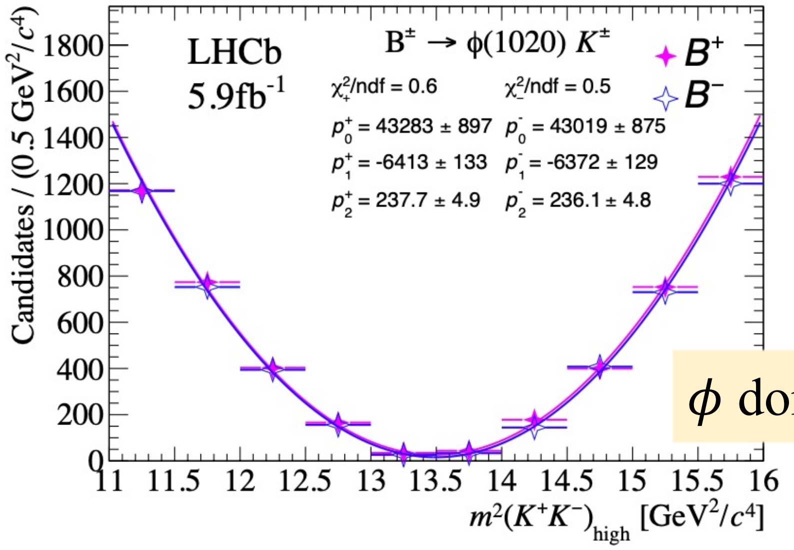


$A_{CP}[B^\pm \to \rho(770)^0\pi^\pm]$
$= -0.004 \pm 0.019$

Mainly tree diagram

Interference of S and P waves





$A_{CP}[B^\pm \to \phi K^\pm]$
$= 0.004 \pm 0.016$

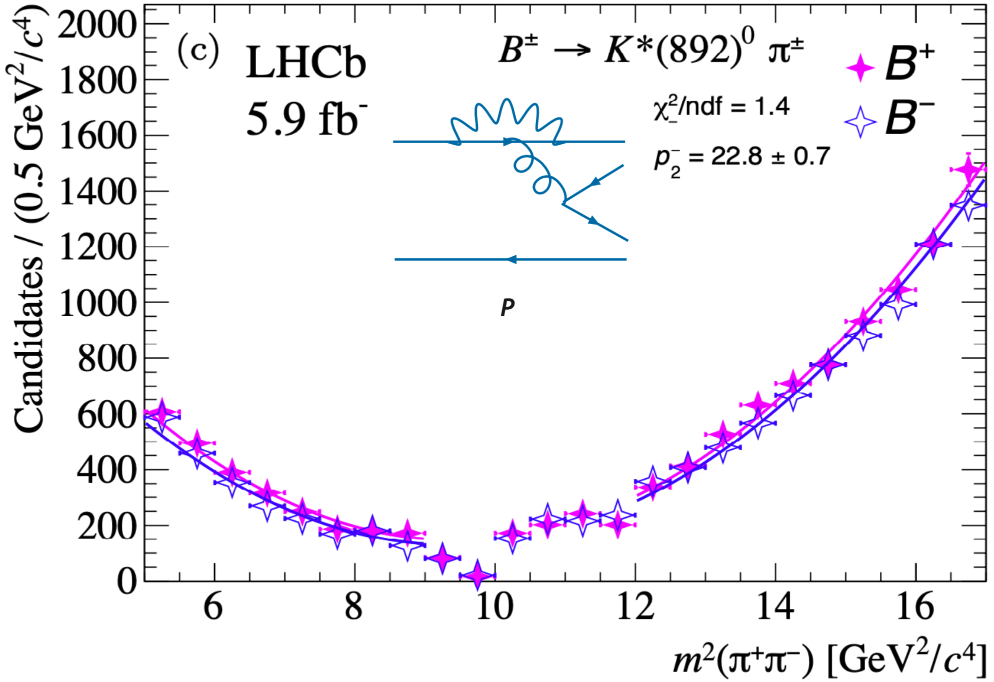
Mainly loop diagram

ϕ dominating

Quasi $B^{\pm} \to P^{\pm}V$ decays: one diagram dominating

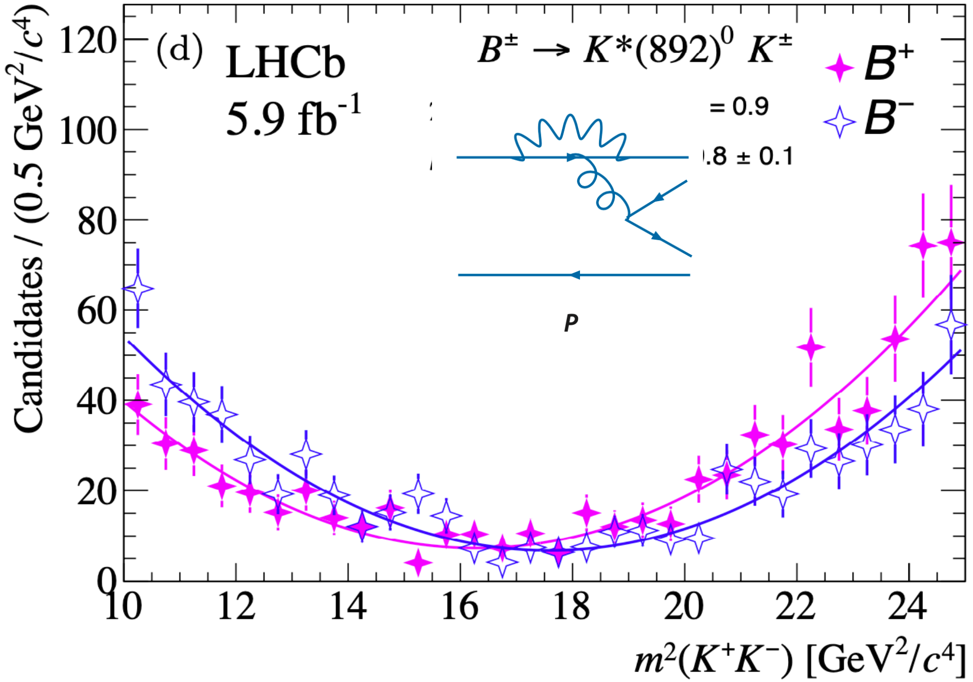
PRD108(2023)012013

$B^{\pm} \to K^{*}(892)^{0}\pi^{\pm}$



$A_{CP} = -0.015 \pm 0.024$

$B^{\pm} \to K^{*}(892)^{0}K^{\pm}$



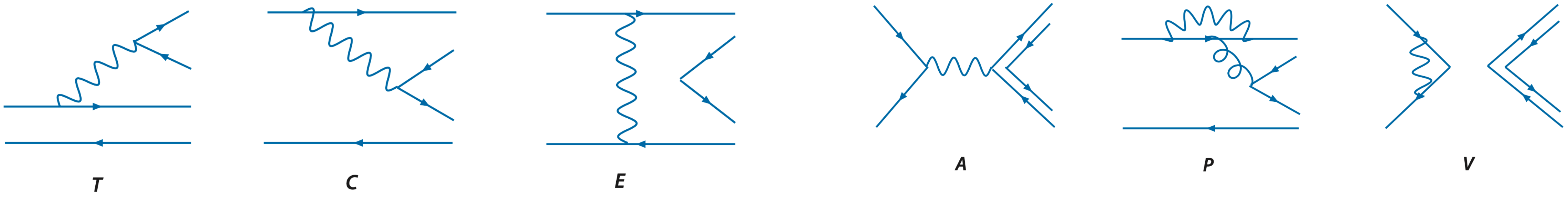
$A_{CP} = 0.007 \pm 0.063$

$K-\pi$ puzzle for PP, VP, PV decays

PDG

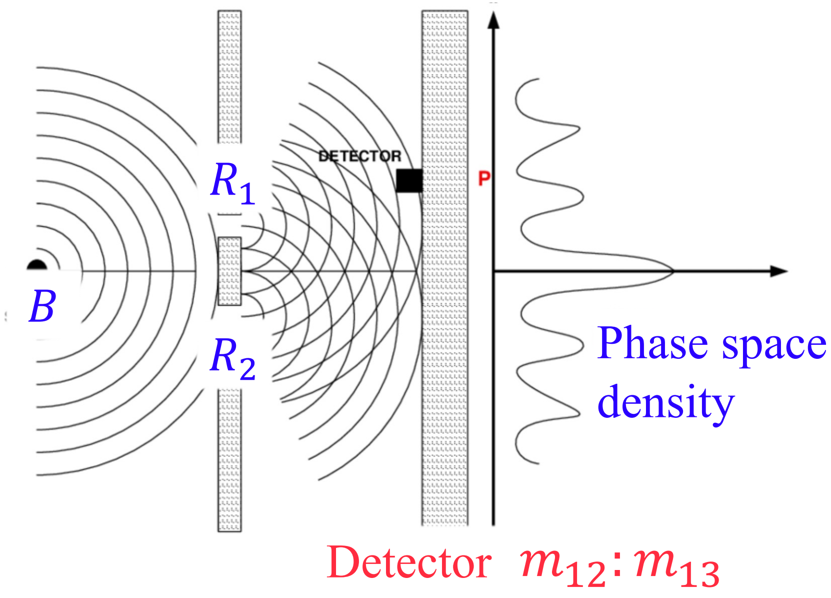
	$B \to K\pi$	$B \to K^*\pi$	$B \to K\rho$	Main diagrams
$\bar{B}^0 \to K^{(*)-}\pi^{(*)+}$	-0.0834 ± 0.0032	-0.27 ± 0.04	0.21 ± 0.11	$b \to u\bar{u}s$, T,P, E
$\bar{B}^0 \to \bar{K}^{(*)0}\pi^{(*)0}$	0.00 ± 0.13	-0.15 ± 0.13	-0.04 ± 0.20	$b \to q\bar{q}s$, T,P,C,E
$B^- \to \bar{K}^{(*)0}\pi^{(*)+}$	-0.017 ± 0.016	-0.04 ± 0.09	-0.03 ± 0.15	$b \to d\bar{d}s$, P
$B^- \to K^{(*)-}\pi^{(*)0}$	0.030 ± 0.013	-0.39 ± 0.21	0.37 ± 0.10	$b \to u\bar{u}s$, T,P,C,A

Precision to be improved (LHCb and BelleII)



Three body decays

$$B \to h_1 h_2 h_3$$



Importance of strong phase

$$A_{CP} = \frac{2|\mathcal{A}_2/\mathcal{A}_1|\sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)}{1+|\mathcal{A}_2/\mathcal{A}_1|^2+2|\mathcal{A}_2/\mathcal{A}_1|\cos(\delta_1-\delta_2)\cos(\phi_1-\phi_2)}$$

CPV in $B^{\pm} \to h_1^{\pm} h_2^{\mp} h_3^{\pm}$

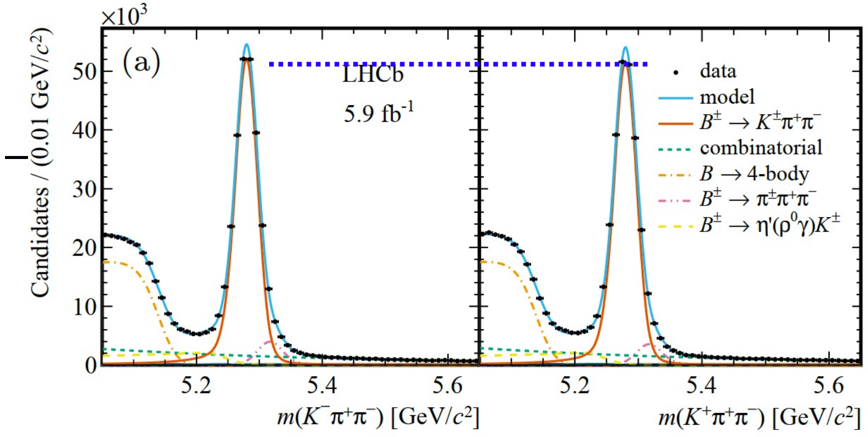
PRD108(2023)012008

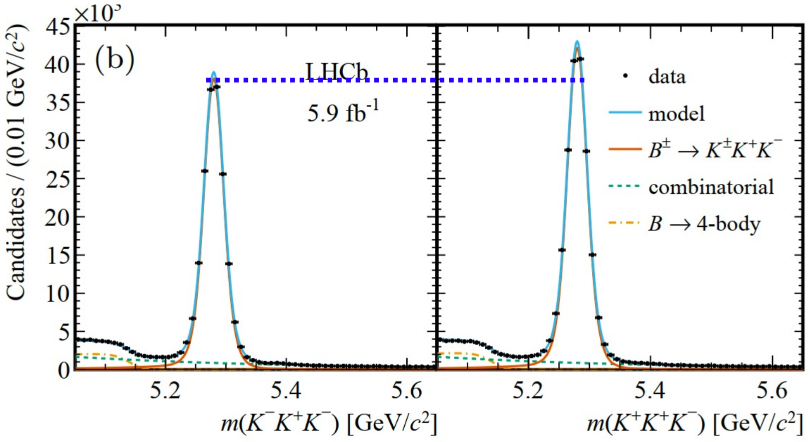
Global CPV

$A_{CP} = +0.011 \pm 0.002 \pm 0.003 \pm 0.003$ 2.4σ

$A_{CP} = -0.037 \pm 0.002 \pm 0.002 \pm 0.003$ 8.5σ

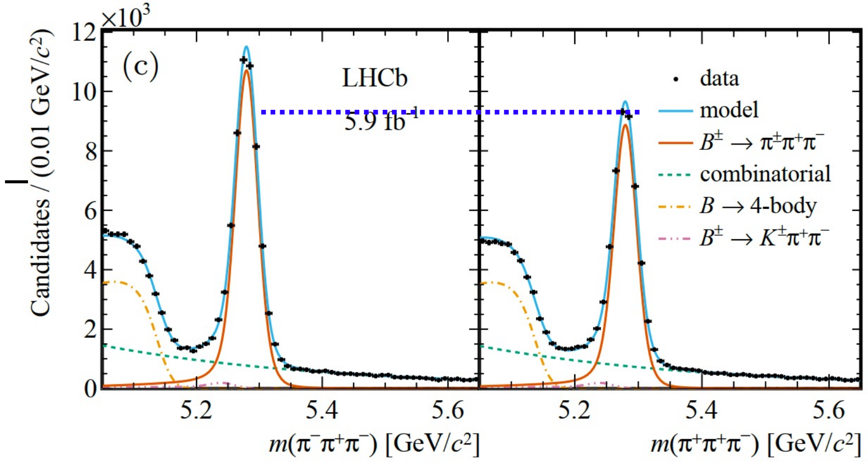
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

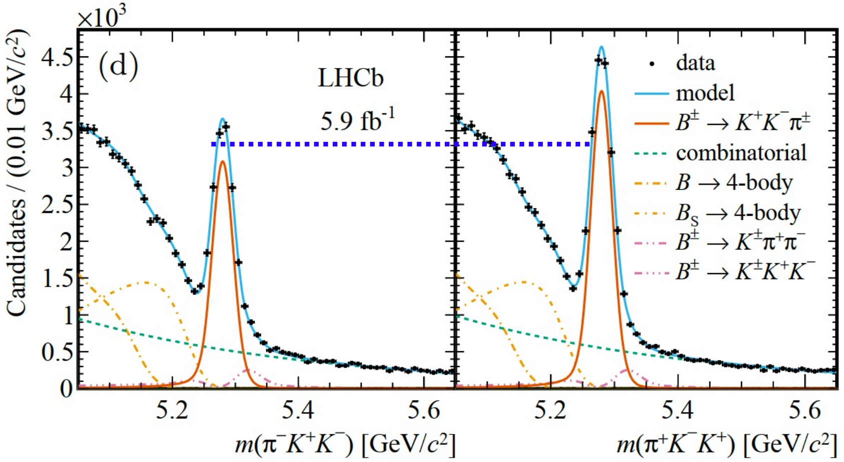




$B^{\pm} \to K^{\pm}K^{+}K^{-}$

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$





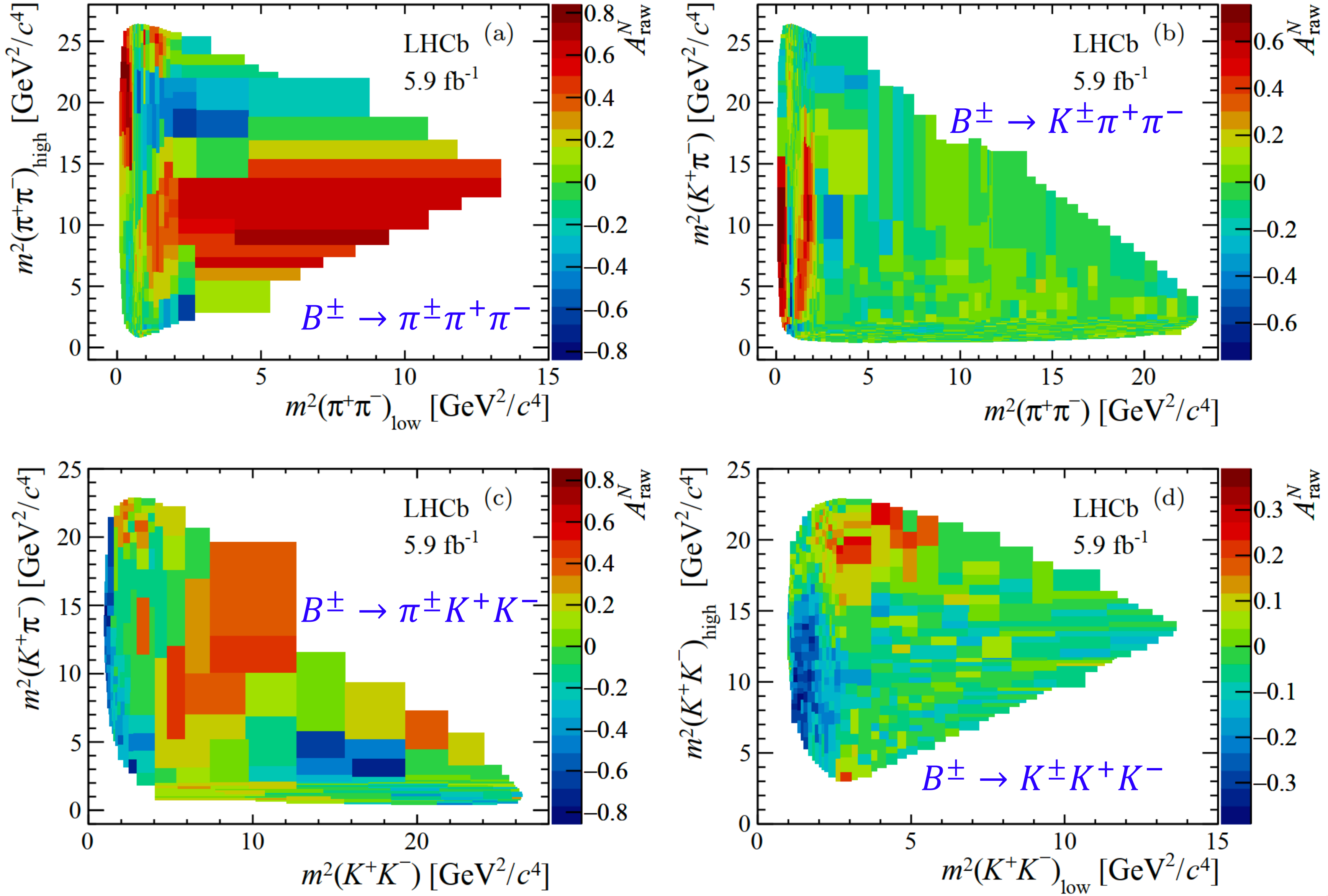
$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$

$A_{CP} = +0.080 \pm 0.004 \pm 0.003 \pm 0.003$ 14.1σ

$A_{CP} = -0.114 \pm 0.007 \pm 0.003 \pm 0.003$ 13.6σ

Large localized CPV: patterns

PRD108(2023)012008

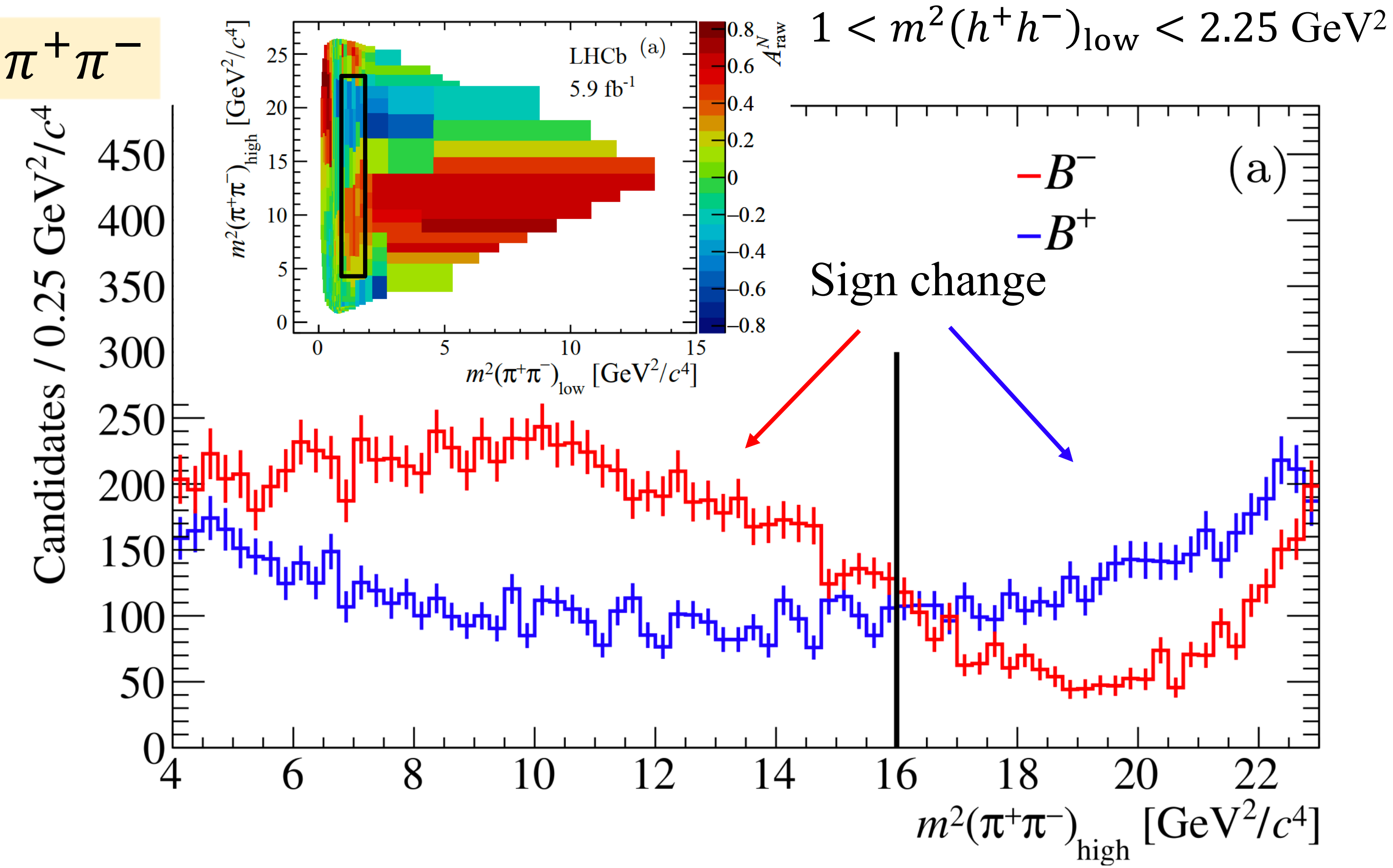


Localized CPV: dynamics

PRD108(2023)012008

- A_{CP} in $\pi^+\pi^- \leftrightarrow K^+K^-$ rescattering region

$B^+ \to \pi^+\pi^+\pi^-$



Localized CPV: dynamics

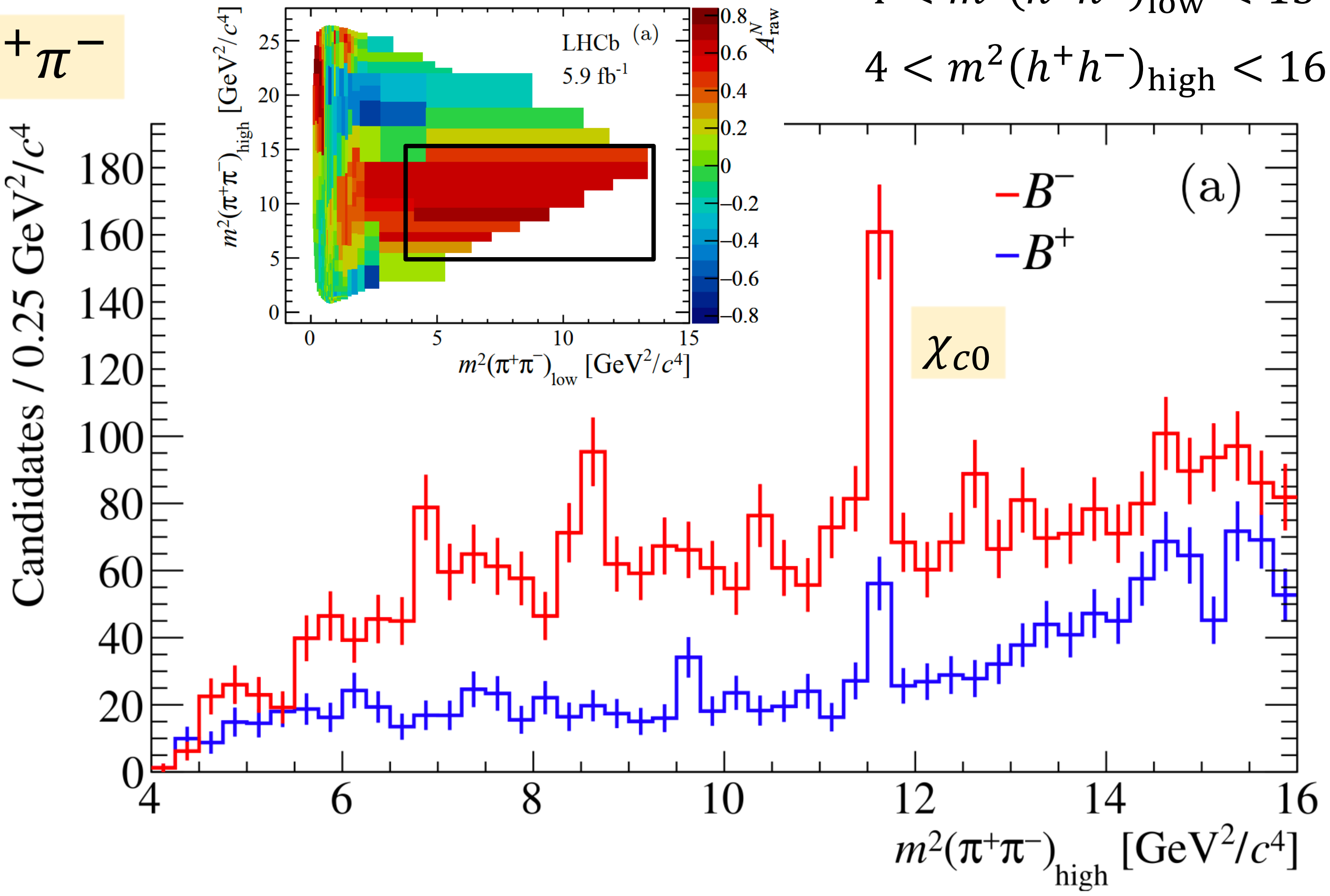
PRD108(2023)012008

- A_{CP} in charmonium region
  - ➢ Interference of χ_{c0} with $b \to u\bar{u}d$ amplitudes

$B^+ \to \pi^+\pi^+\pi^-$

$4 < m^2(h^+h^-)_{\text{low}} < 15$ GeV²

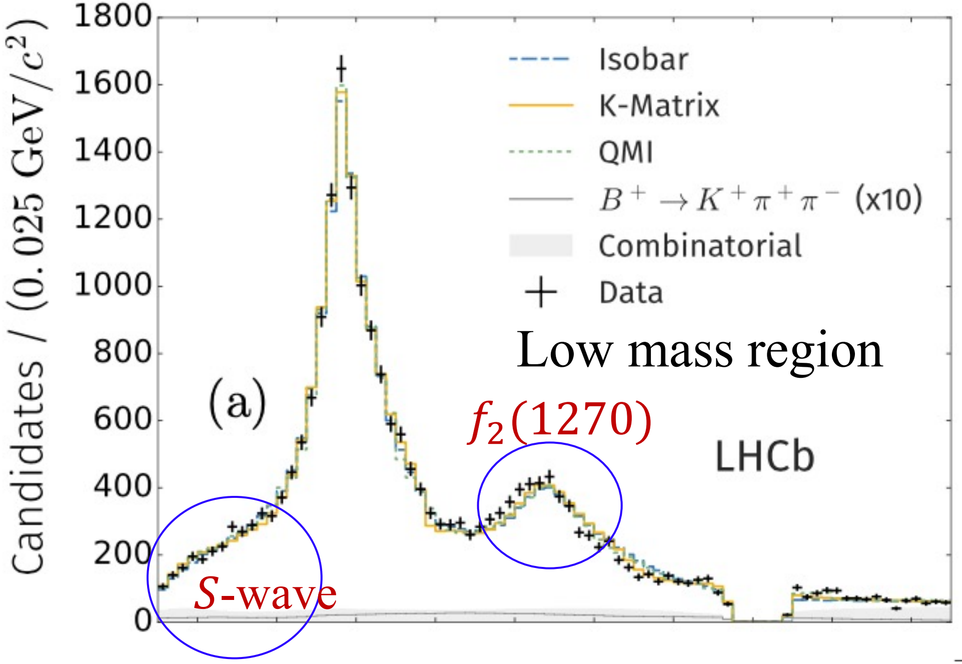
$4 < m^2(h^+h^-)_{\text{high}} < 16$ GeV²

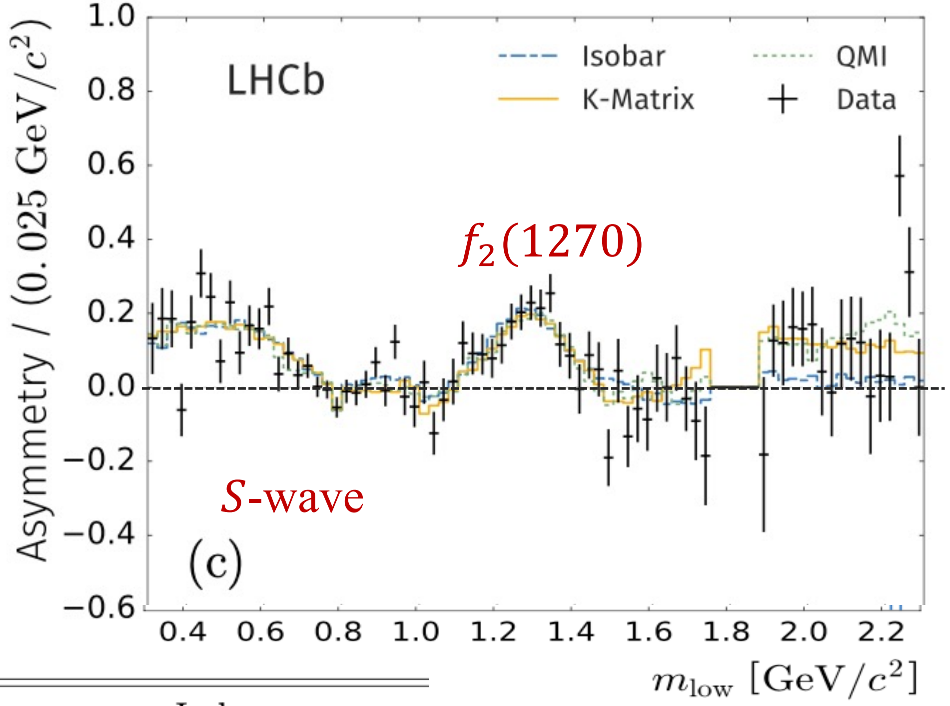


$B^+ \to \pi^+\pi^-\pi^+$ amplitude analysis

PRL 124 (2020) 031801
PRD 101 (2020) 012006

Sum of amplitudes: $A^{\pm}(m_{13}^2, m_{23}^2) = \sum_{j=1}^{N} c_j^{\pm} F_j(m_{13}^2, m_{23}^2)$





Components and $A_{CP}(c_j)$

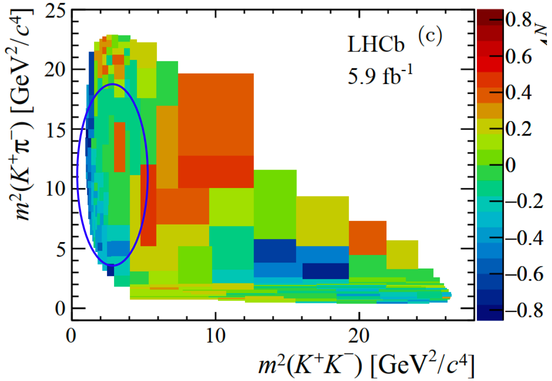
Component	Isobar
$\rho(770)^0$	$+0.7 \pm 1.1 \pm 0.6 \pm 1.5$
$\omega(782)$	$-4.8 \pm 6.5 \pm 1.3 \pm 3.5$
$f_2(1270)$	$+46.8 \pm 6.1 \pm 1.5 \pm 4.4$
$\rho(1450)^0$	$-12.9 \pm 3.3 \pm 3.6 \pm 35.7$
$\rho_3(1690)^0$	$-80.1 \pm 11.4 \pm 7.8 \pm 24.1$
S-wave	$+14.4 \pm 1.8 \pm 1.0 \pm 1.9$

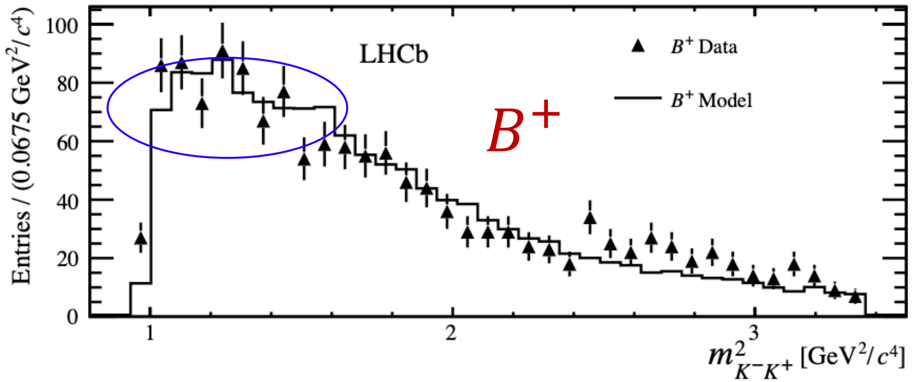
$B^+ \to \pi^+ K^- K^+$ amplitude analysis

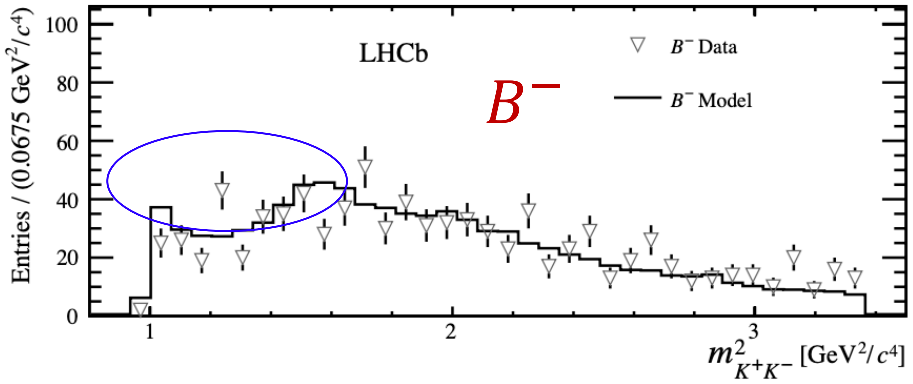
PRL 123 (2019) 231802

- large S-wave contribution: modeled by non-resonant single pole and $\pi^+\pi^- \to K^+K^-$ rescattering

Large asymmetry observed in rescattering region $0.95 < m_{K^+K^-} < 1.42$ GeV





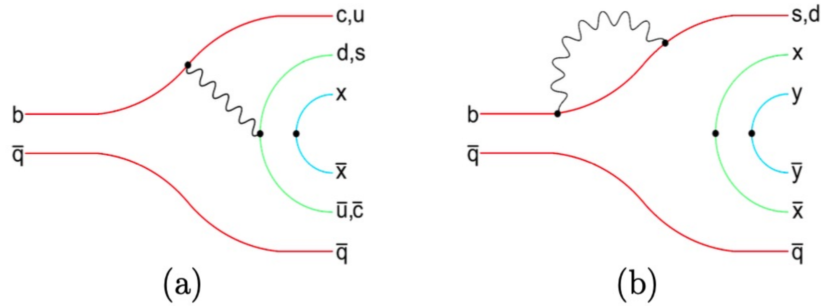


Contribution	Fit Fraction(%)	A_{CP}(%)
$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$+12.3 \pm 8.7 \pm 4.5$
$K_0^*(1430)^0$	$4.5 \pm 0.7 \pm 1.2$	$+10.4 \pm 14.9 \pm 8.8$
Single pole	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$
$\rho(1450)^0$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$
$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$+26.7 \pm 10.2 \pm 4.8$
Rescattering	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$

Baryonic B decays

Charmless baryonic decays

- A few interesting properties
  - ➢ Two-body suppressed compared to $B \to MM$ decays
  - ➢ Threshold enhancement
  - ➢ Forward-backward asymmetry

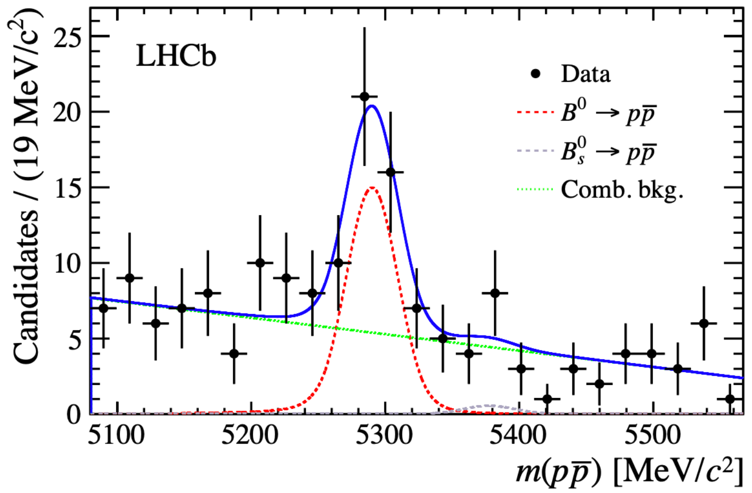


$\mathcal{B}(B^0 \to p\bar{p}) = (1.25 \pm 0.32)\times 10^{-8}$

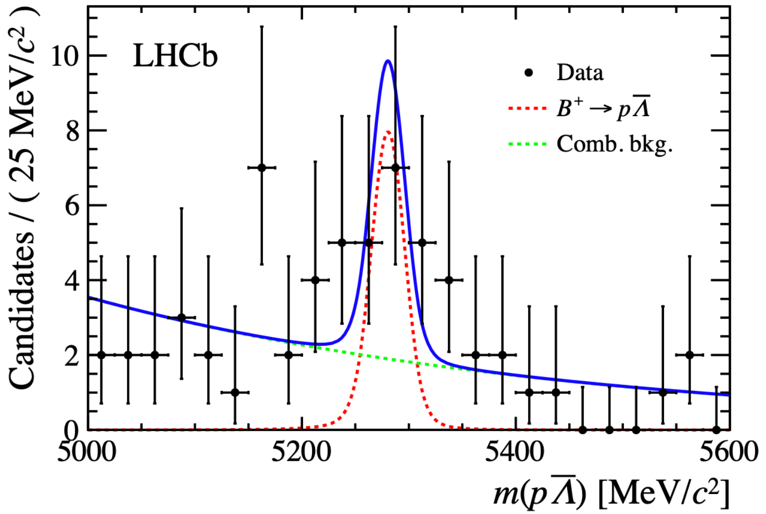
$\sim 0.01\times\mathcal{B}(B \to \pi\pi)$

$\mathcal{B}(B^+ \to \overline{\Lambda}^0 p) = (2.4^{+1.0}_{-0.8} \pm 0.3)\times 10^{-7}$

$\sim 0.01\times\mathcal{B}(B \to K\pi)$



PRL119 (2017) 232001



JHEP 04 (2017) 162

Charmless baryonic decays

- A few interesting properties
  - Two-body suppressed compared to $B \to MM$ decays
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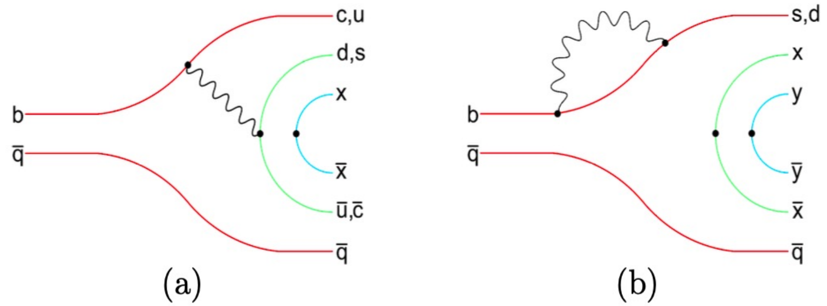
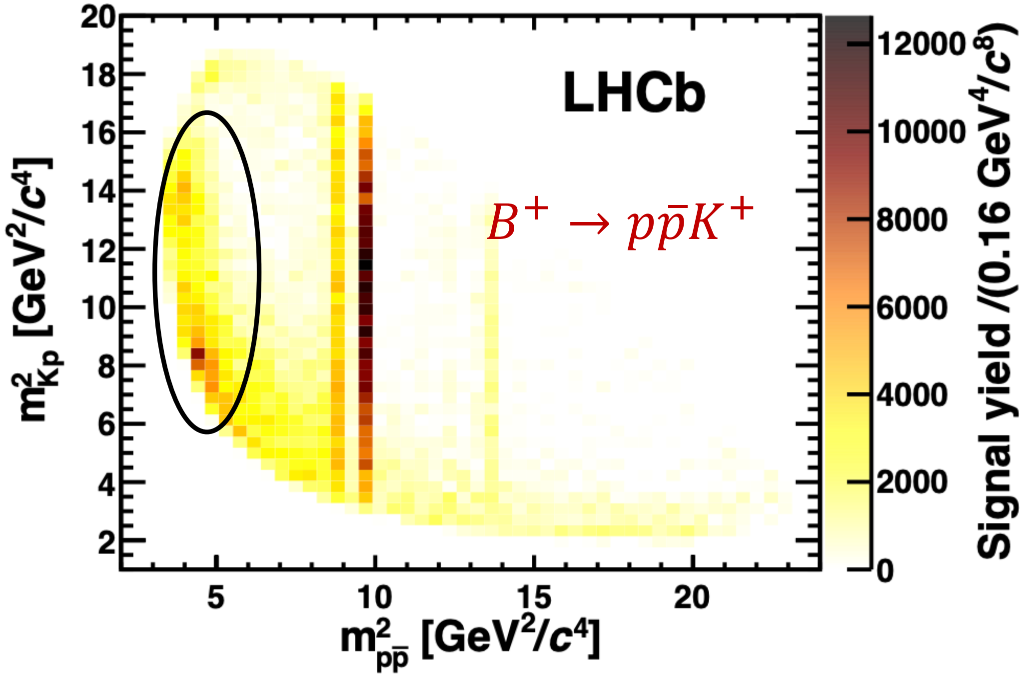
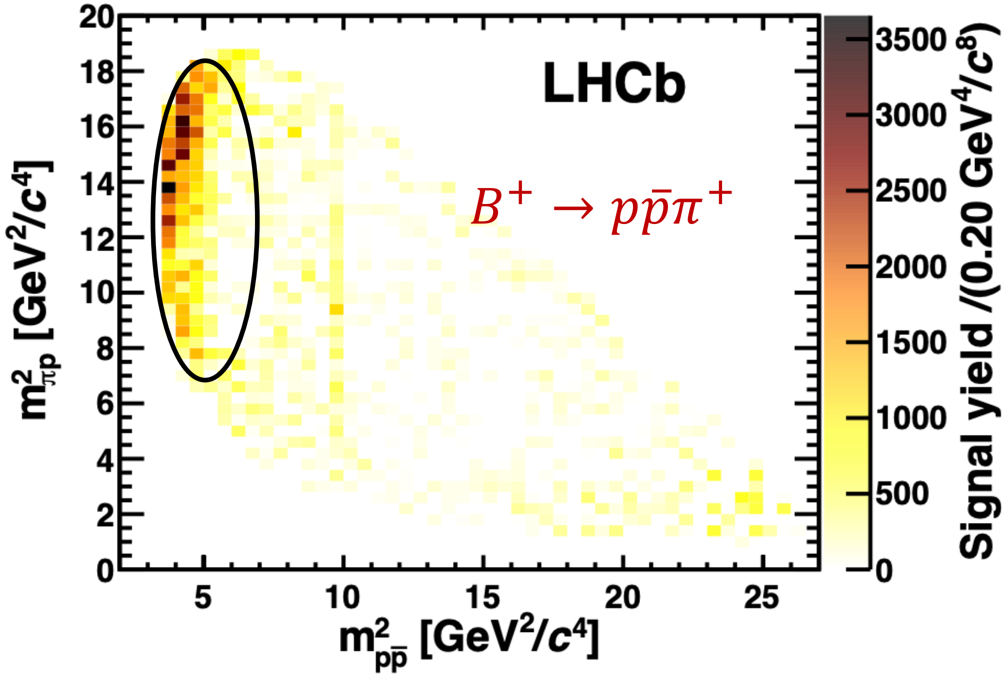




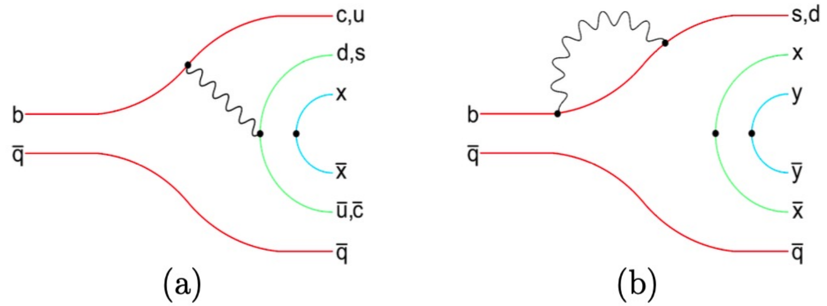


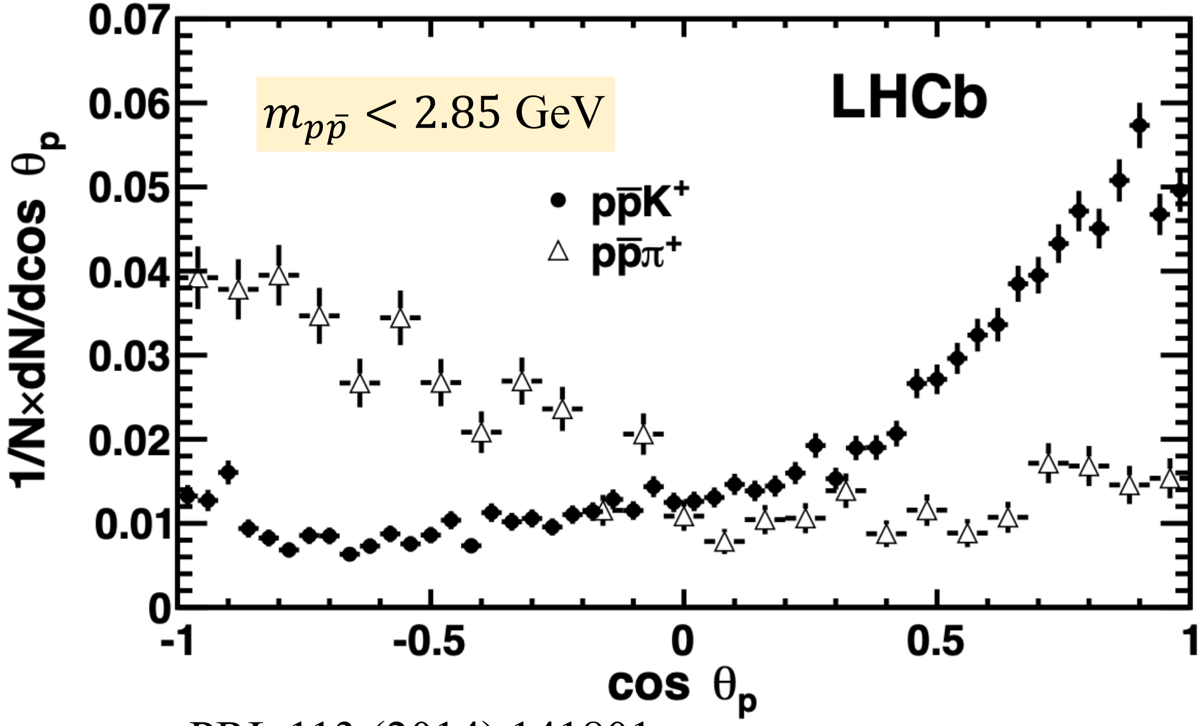
Similarly for $B \to p\bar{p}hh'$ decays

PRL 113 (2014) 141801

Charmless baryonic decays

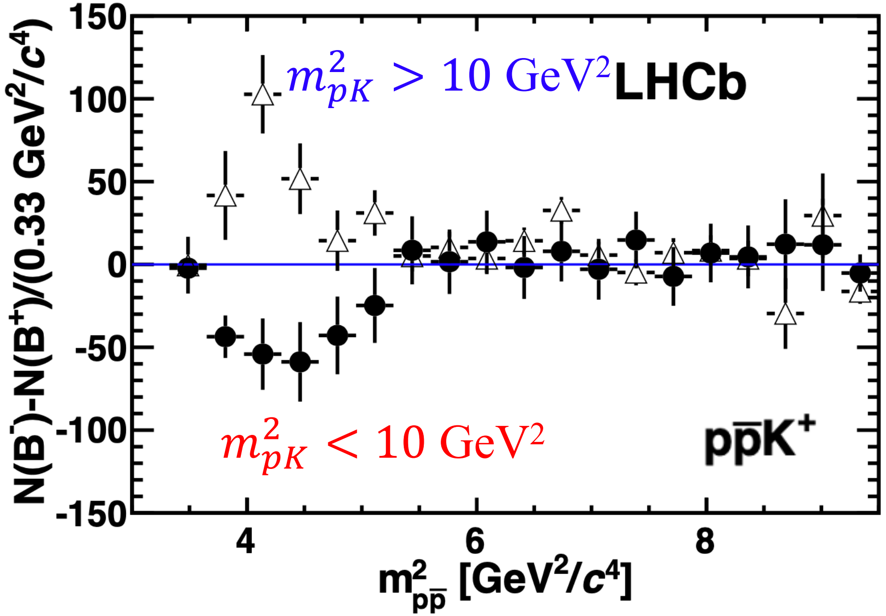
- A few interesting properties
  - Two-body suppressed compared to $B \to MM$ decays
  - Threshold enhancement
  - Forward-backward asymmetry





PRL 113 (2014) 141801

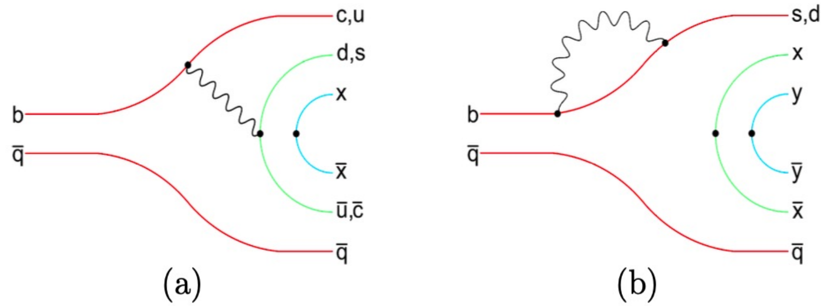
Hints at interferences, CP violation?



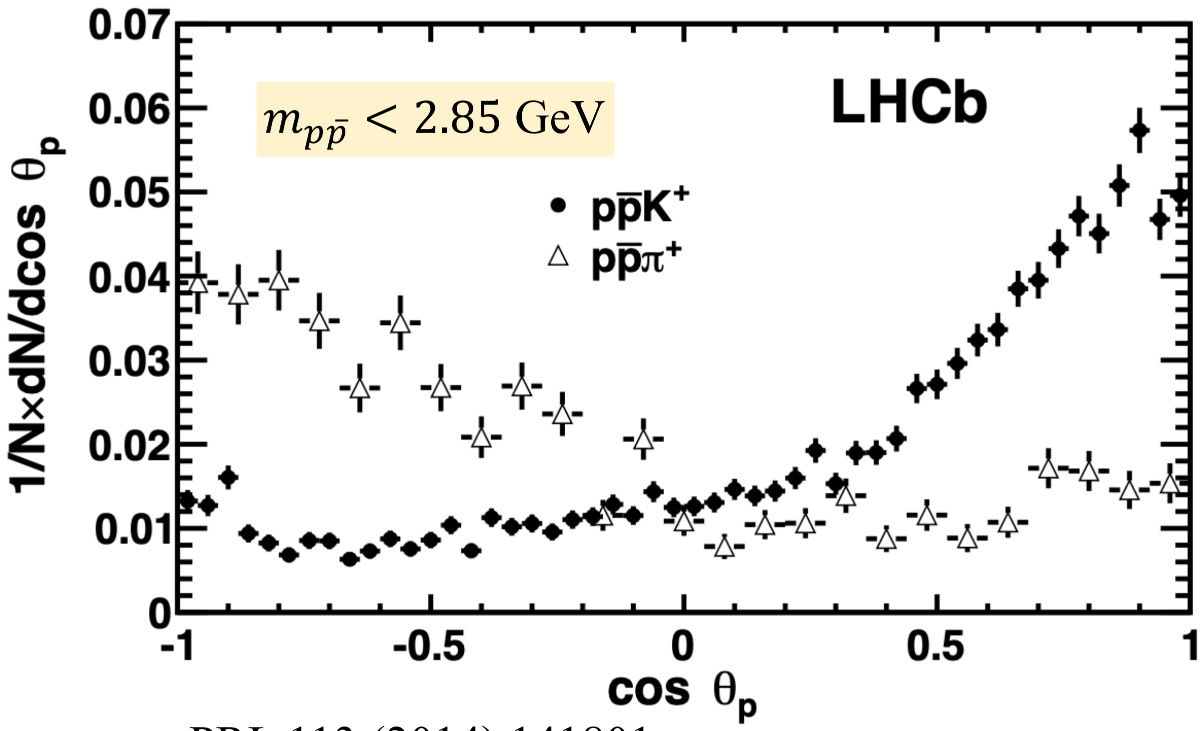
Evidence of local CPV

Charmless baryonic decays

- A few interesting properties
  - ➢ Two-body suppressed compared to $B \to MM$ decays
  - ➢ Threshold enhancement
  - ➢ Forward-backward asymmetry

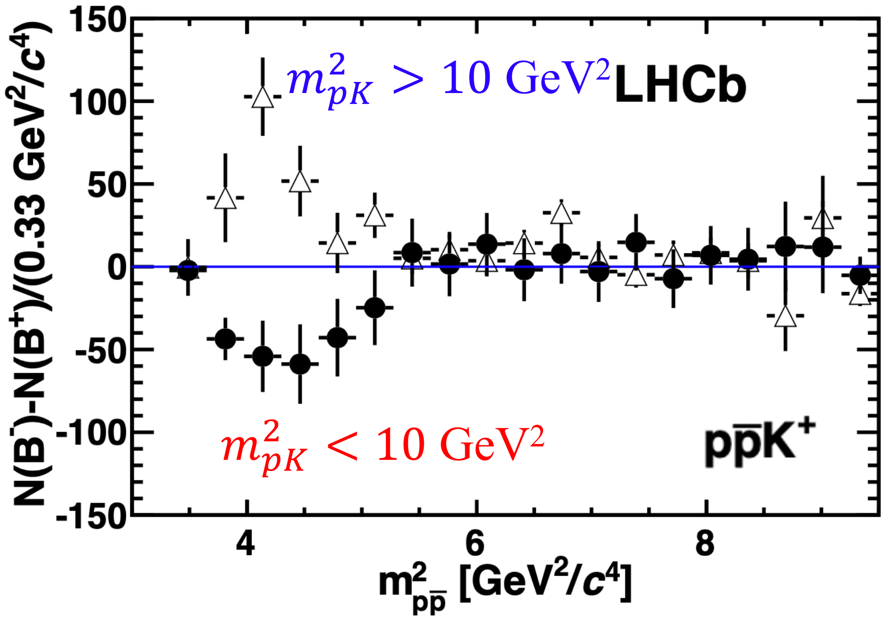


Predications very difficult



PRL 113 (2014) 141801

Hints at interferences, CP violation?



Evidence of local CPV

CPV in beauty baryons

A new area for weak/strong dynamics

CPV in baryon decays

- Baryonic CPV not observed, despite similar quark-level process as meson decays

Two-body decays: $A_{CP}(\Lambda_b^0 \to pK^-) = -0.020 \pm 0.023$

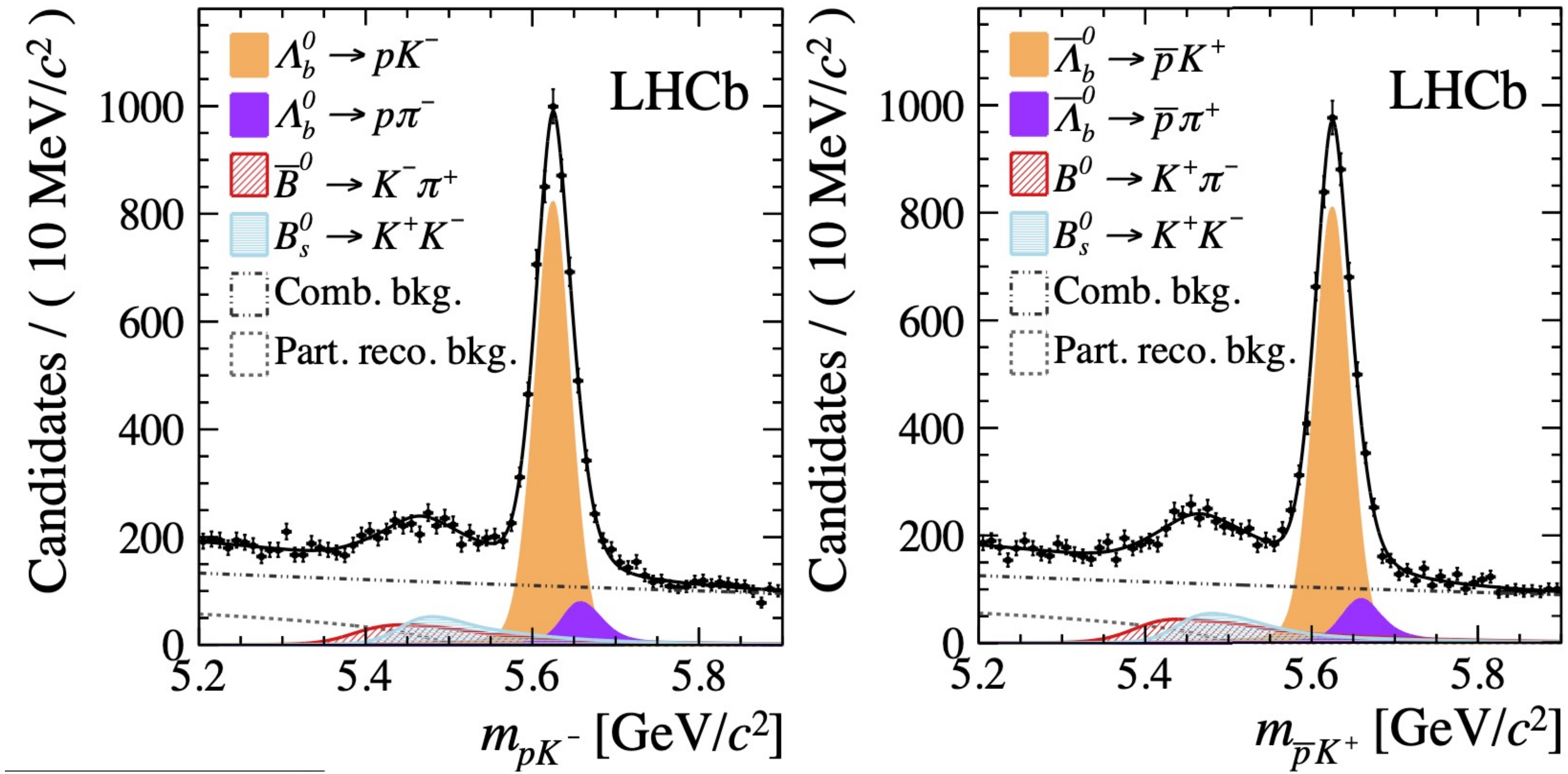
$A_{CP}(\Lambda_b^0 \to p\pi^-) = -0.035 \pm 0.029$

Mesons:

$A_{CP}(B^0 \to K^+\pi^-) = -0.0834$

$A_{CP}(B_s^0 \to K^-\pi^+) = 0.236$

Phys. Lett. B784 (2018) 124

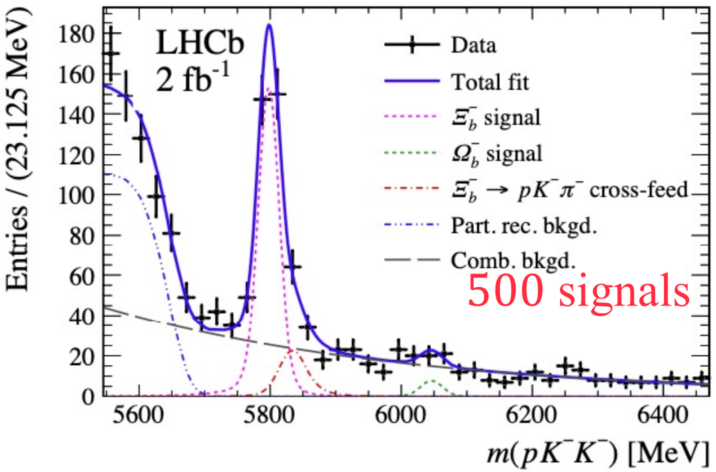


CPV in $\Xi_b^- \to pK^-K^-$ decays

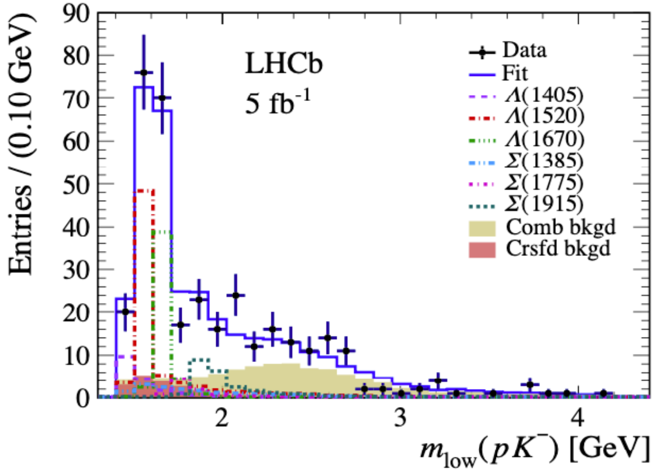
PRD 104 (2021) 052010

- Charmless $b \to s$ transition
- Amplitude analysis with 6 resonances

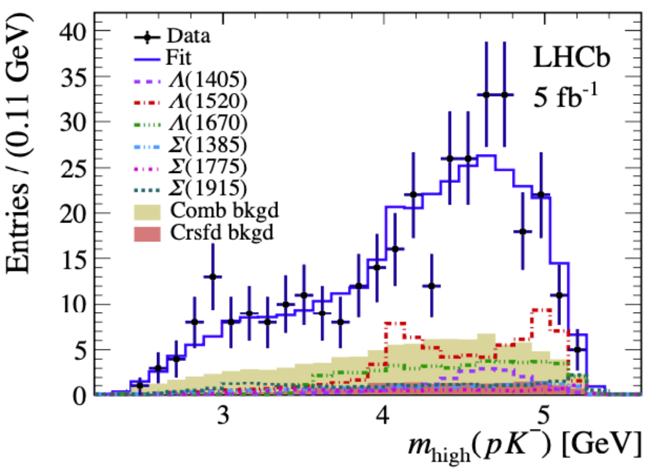
Ξ_b^- mass



$m_{\text{low}}(pK^-)$



$m_{\text{high}}(pK^-)$



Component	A^{CP} (10^{-2})
$\Sigma(1385)$	-27 ± 34 (stat) ± 73 (syst)
$\Lambda(1405)$	-1 ± 24 (stat) ± 32 (syst)
$\Lambda(1520)$	-5 ± 9 (stat) ± 8 (syst)
$\Lambda(1670)$	3 ± 14 (stat) ± 10 (syst)
$\Sigma(1775)$	-47 ± 26 (stat) ± 14 (syst)
$\Sigma(1915)$	11 ± 26 (stat) ± 22 (syst)

No evidence of CPV

$\mathcal{B}\left(\Xi_b^- \to pK^-K^-\right) = (2.3 \pm 0.9) \times 10^{-6}$

Magnitude similar to $\mathcal{B}(B \to 3h)$

CPV in $\Lambda_b^0, \Xi_b^0 \to phhh$ decays

EPJC 79 (2019) 745

- Six decay modes from 0.5-10K signals (3 fb^{-1})
- Abundant resonant structures

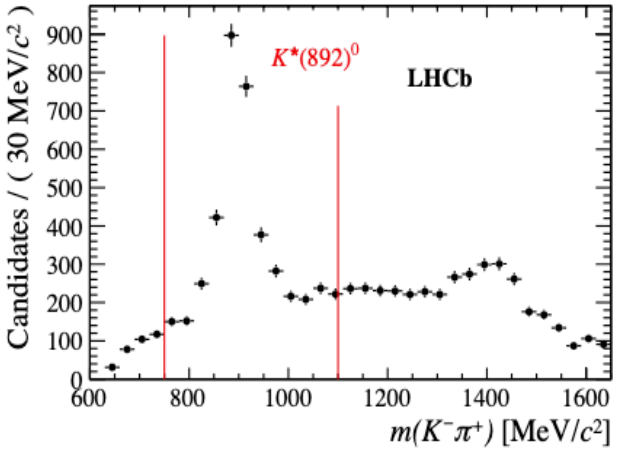
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

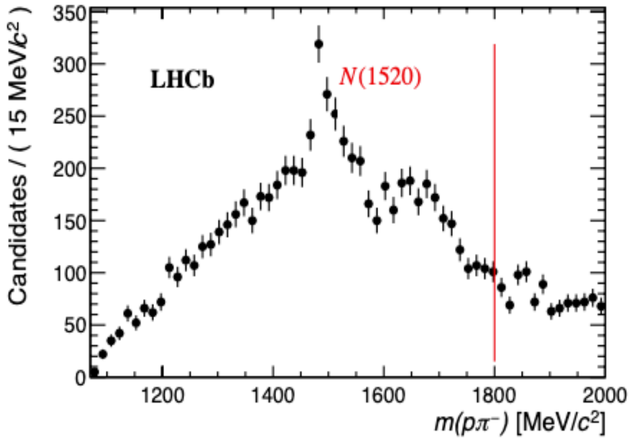
$\Xi_b^0 \to pK^-\pi^+\pi^-$ $\quad$ $\Lambda_b^0 \to pK^-\pi^+\pi^-$

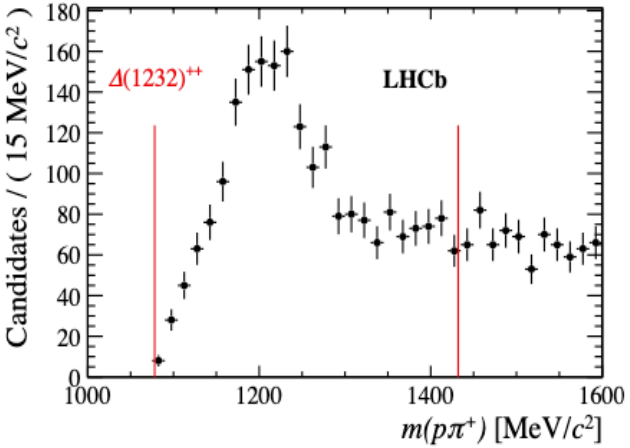
$\Xi_b^0 \to pK^-\pi^+K^-$ $\quad$ $\Lambda_b^0 \to pK^-K^+\pi^-$

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

Example: $\Lambda_b^0 \to pK^-\pi^+\pi^-$







- Global and local A_{CP} around resonances studied, relative to CKM favored modes

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (+1.1 \pm 2.5 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (+3.2 \pm 1.1 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-6.9 \pm 4.9 \pm 0.8)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (+0.2 \pm 1.8 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+\pi^-) = (-17 \pm 11 \pm 1)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+K^-) = (-6.8 \pm 8.0 \pm 0.8)\,\%$$

With ~ 1% experimental precision, no evidence of A_{CP}
Rule out CP violation ≫ 5%

- Strong phase too small?
- One diagram dominates?

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

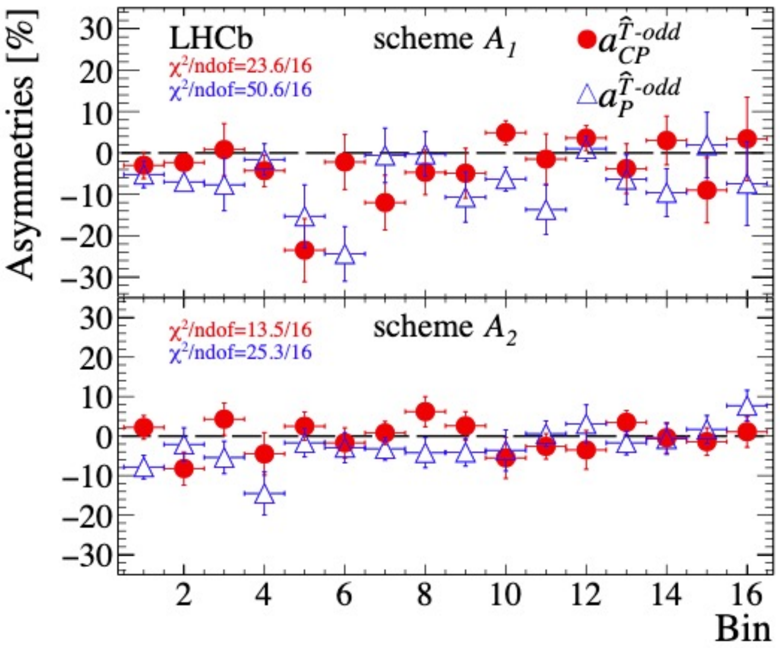
PRD 102 (2020) 051101

- Triple product $C_{\hat{T}} \equiv \vec{P}_p \cdot (\vec{p}_{\pi^-_{\text{fast}}} \times p_{\pi^+})$, $\bar{C}_{\hat{T}} \equiv \vec{P}_p \cdot \left(\vec{p}_{\pi^+_{\text{fast}}} \times p_{\pi^-}\right)$
- Triple product asymmetry: $A_{\hat{T}} = \langle C_{\hat{T}} \rangle$, $\bar{A}_{\hat{T}} = \langle -\bar{C}_{\hat{T}} \rangle$

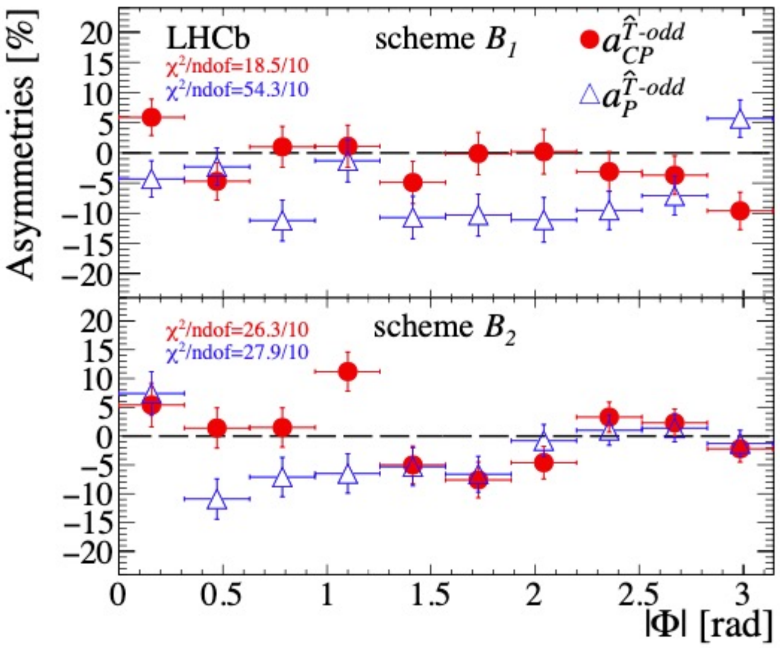
CP violating: $a_{CP} = (A_{\hat{T}} - \bar{A}_{\hat{T}})/2 = (-0.7 \pm 0.7 \pm 0.2)\%$

No strong CP violation globally or in local phase space

Binning according to N^{*+}/Δ^{++} resoances



Φ: angle between $\vec{p}_p \times \vec{p}_{\pi^-_{\text{fast}}}$ and $\vec{p}_{\pi^+} \times \vec{p}_{\pi^-_{\text{slow}}}$



Summary

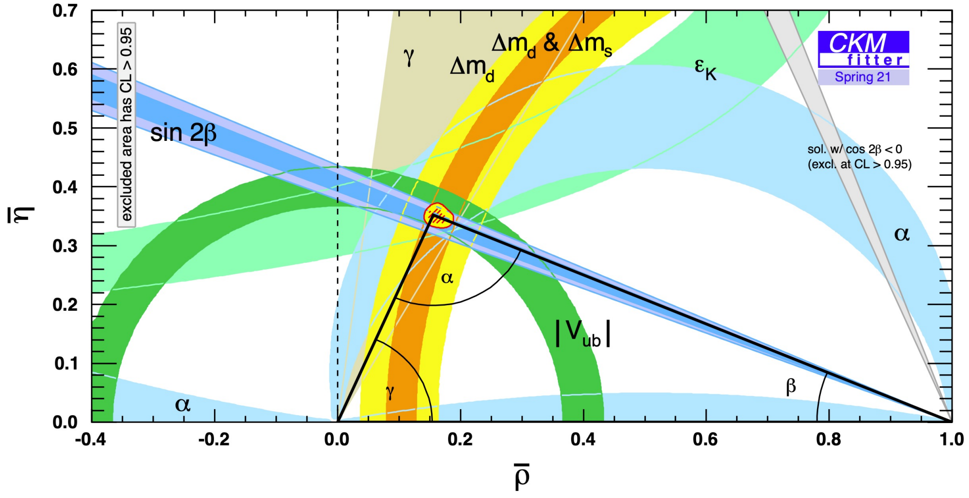
- **CP violation:** probing weak and strong dynamics of SM, sensitive to new physics
- LHCb pushes CP violation in *b*-decays to new frontier
  - **Two-body decays**: test of SU(3), studies of decay topologies
  - **Three-body decays**: CPV from hadronic interferences, extracting strong/weak phases
  - ***B* baryonic decays**: puzzles and opportunities
  - **CPV in baryon decays**: unique to LHCb, new information

Results with full Run1/2 data expected in coming year(s)

Precisions; 3/4-body amplitudes; baryonic decays; decays with neutrals $\pi^0/\eta/K_S\ldots$

Run3 data are accumulating

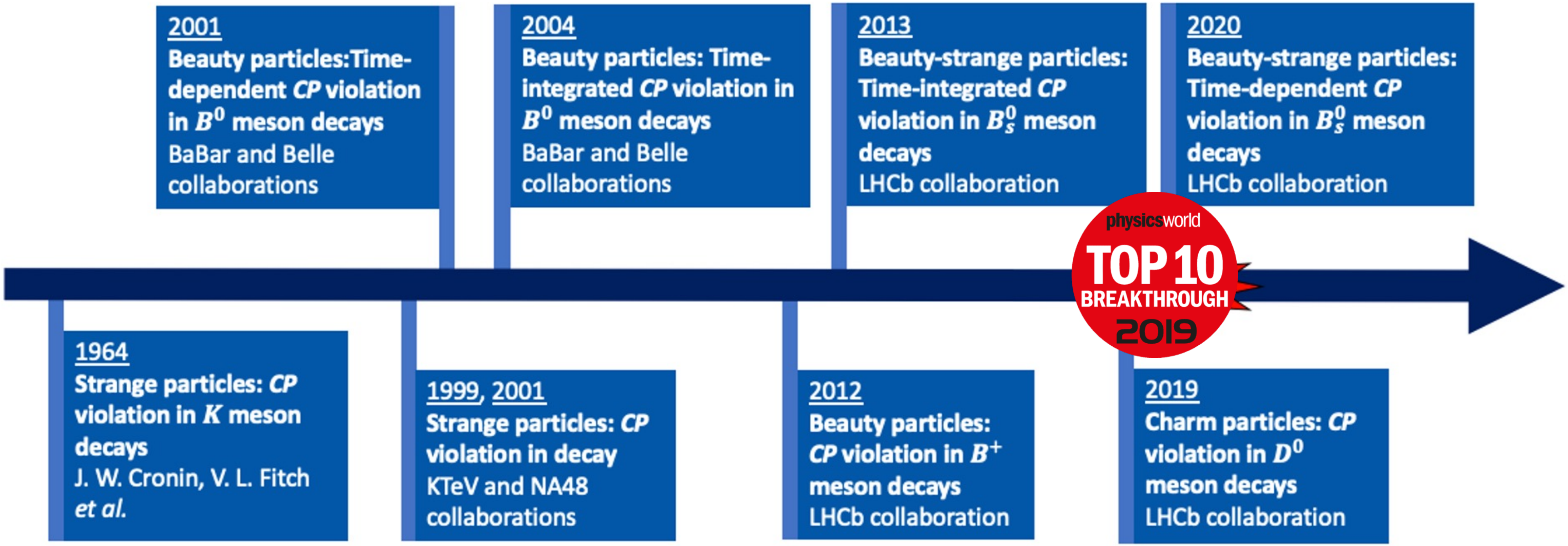
CKM global test/constraints
and
Search for new physics



Backup slides

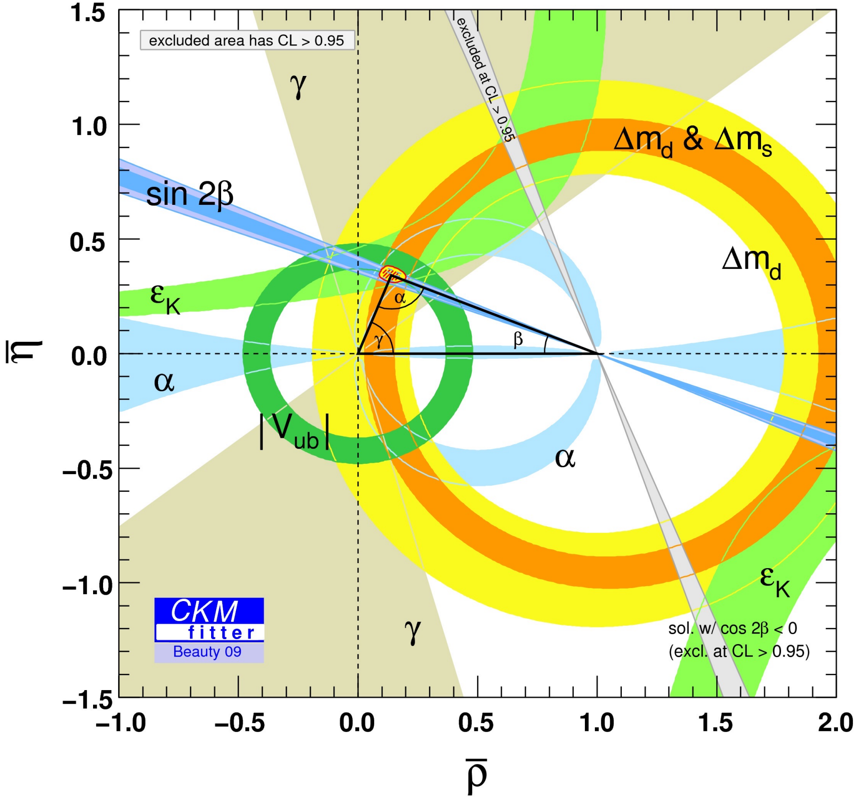
Histroy of CPV

LHC experiments

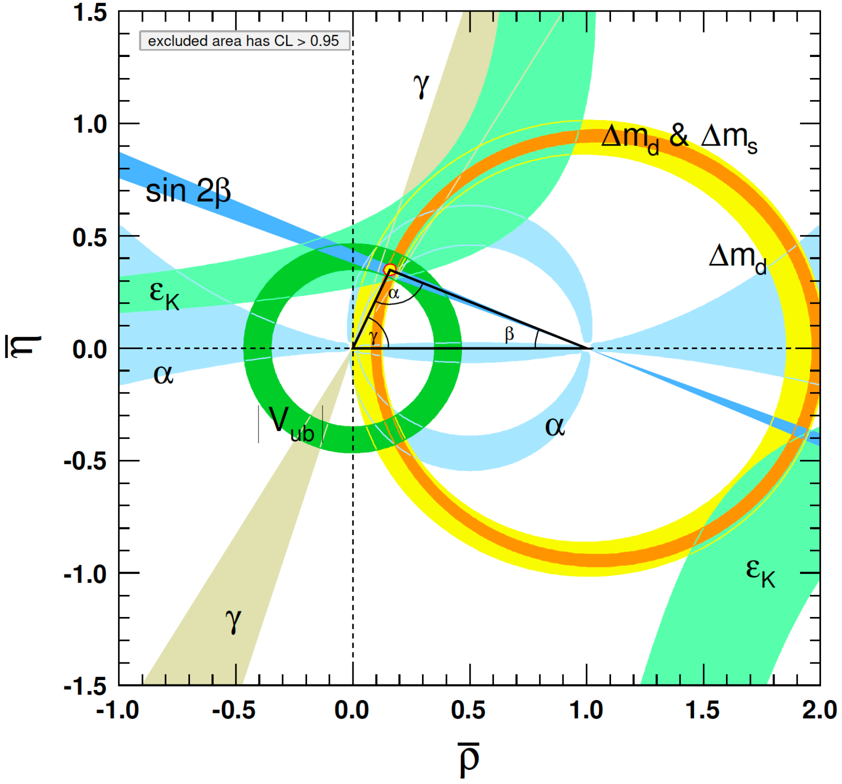


Global analysis of CKM mechanism (4 parameters)

When LHC started



Current status

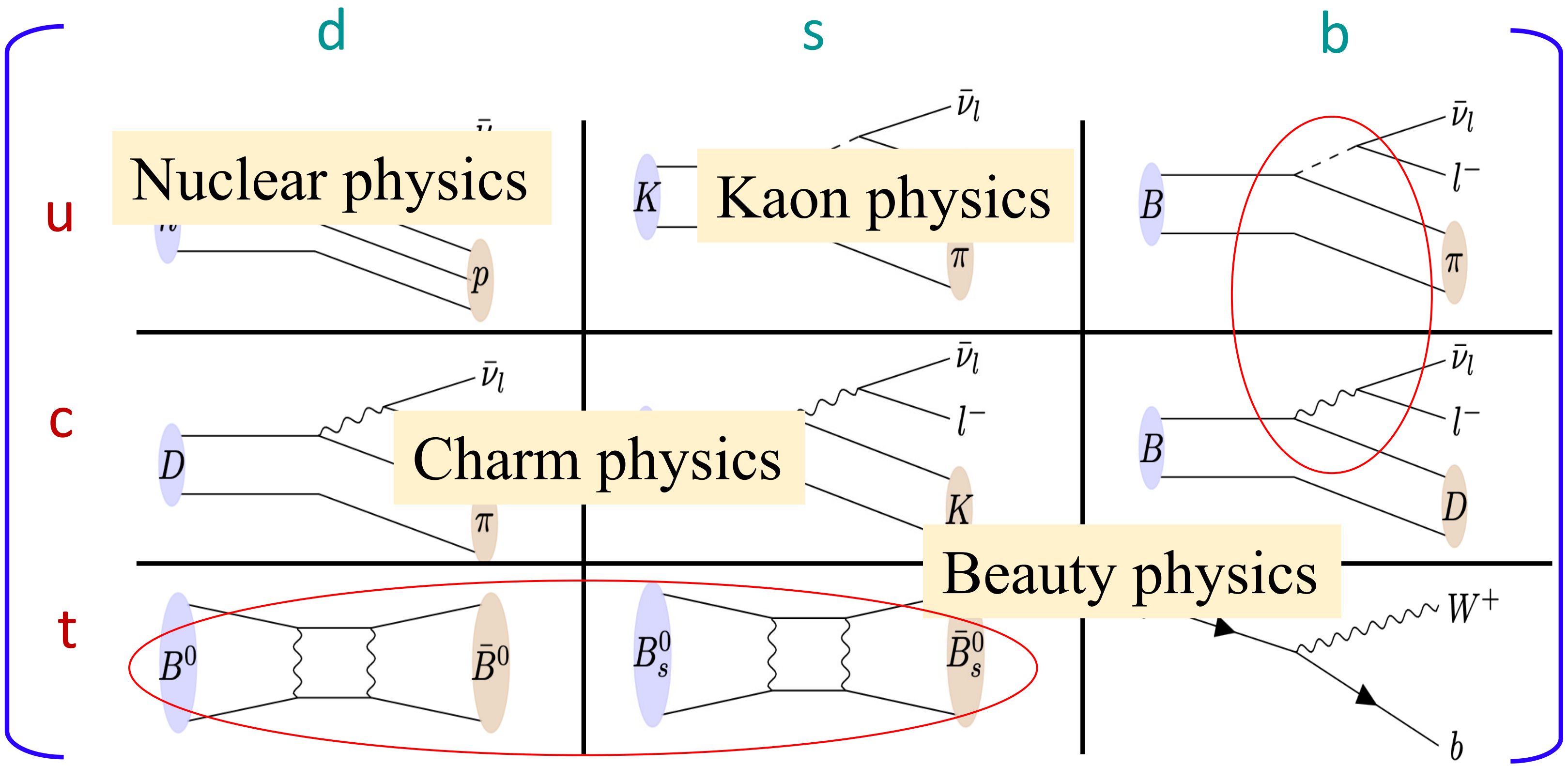


$A = 0.826^{+0.018}_{-0.015}$ $\lambda = 0.22500 \pm 0.00067$ $\bar{\rho} = 0.159 \pm 0.010$ $\bar{\eta} = 0.348 \pm 0.010$

$$\alpha + \beta + \gamma = (173 \pm 6)^\circ$$

Quark mixing matrix

$V_{CKM} =$



Standard parameterization: $\theta_{12}, \theta_{13}, \theta_{23}, \gamma$ Wolfenstein parameterization: ρ, η, λ, A

Fundamental parameters of SM, core to flavor physics

Test of universality: $V_{ji}^{*} V_{jk} = 0\ (i \neq k), 1(i = k)$

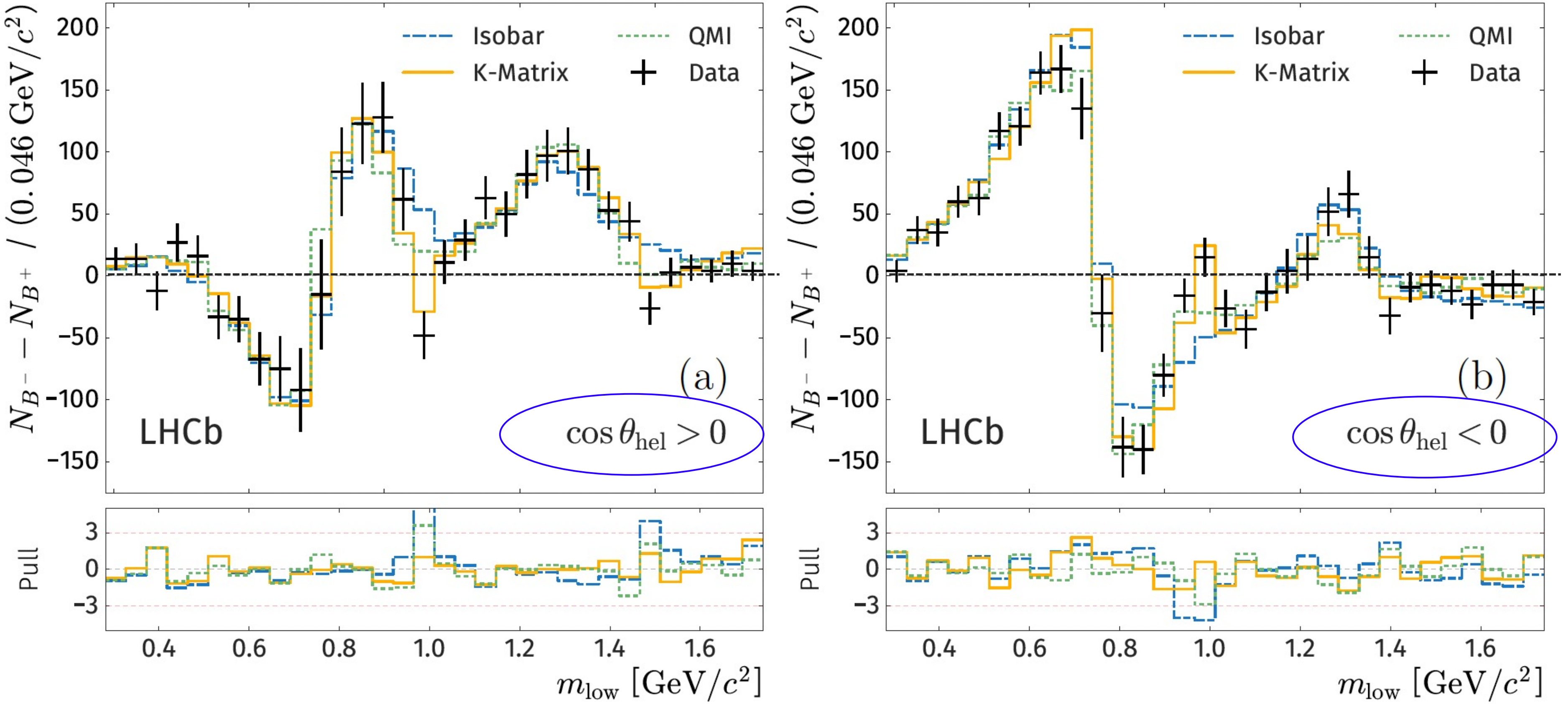
$S - P$ wave interference

PRL 124 (2020) 031081
PRD 101 (2020) 012006

- Evaluation of strong phase in Breit-Wigner with energy $\sqrt{s}$

$$A_{CP} \propto \cos\theta \times (m_S^2 - s) \times (m_P^2 - s) \ldots + |\mathrm{BW}_P|^2 \cos^2\theta + |\mathrm{BW}_S|^2$$

A_{CP} in bins of invariant mass



CKM matrix up to λ^6

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (1 - \lambda^2)(\rho + i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

LHCb Upgrade II sensitivities

CERN Yellow Rep.Monogr. 7 (2019) 867

Table 10.1: Summary of prospects for future measurements of selected flavour observables. The projected LHCb sensitivities take no account of potent detector improvements, apart from in the trigger. Unless indicated otherwise the Belle-II sensitivies are taken from Ref. [568].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [569]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [32]	14 mrad	–	4 mrad	22 mrad [570]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [37]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad	Under study [572]
a_{sl}^s	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [186]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [244]	34%	–	10%	21% [573]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [244]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c l^- \bar{\nu}_l$ LUV studies					
$R(D^*)$	9% [199, 202]	3%	2%	1%	–
$R(J/\psi)$	25% [202]	8%	–	2%	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [574]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [222]	4.3×10^{-5}	3.5×10^{-5}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [210]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

$\delta < 1\%$

Uncertainty reduced by factor ~10

1% level precision

High precision charm physics