Overview and prospects of LHCb results

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2022年12月9号

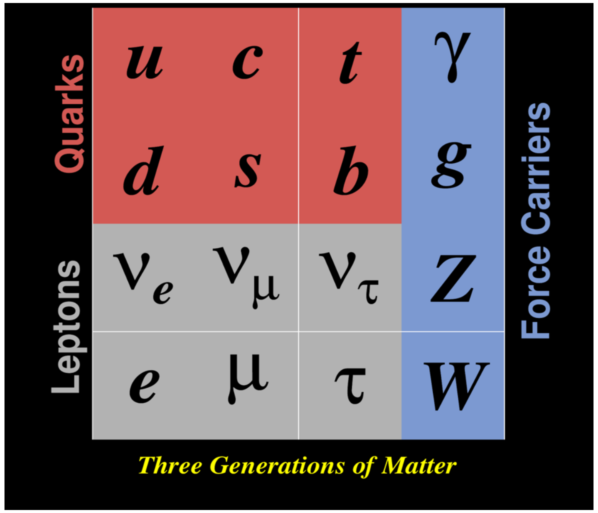
第19届重味物理和CP破坏研讨会
南京师范大学 2022年12月9-11号

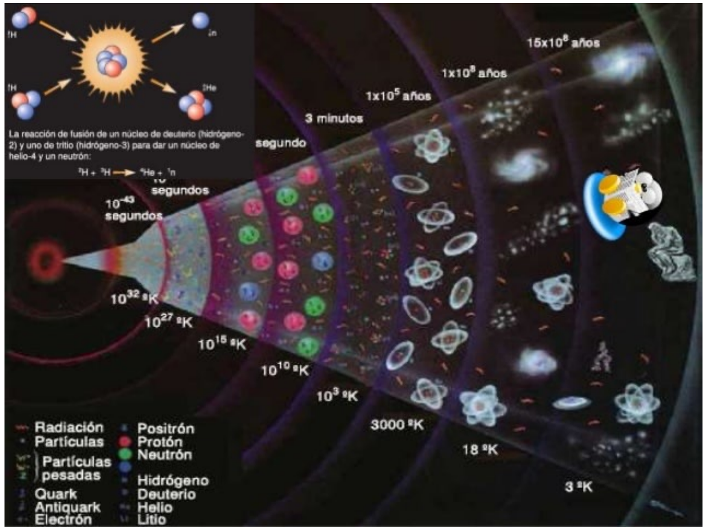
Flavor physics

- Flavor structure/symmetry reveals fundamental laws of Nature

Why three generations?
Do they behave equally?

How anti-matter disappears ?





- Test of SM and probing BSM through precision measurements
  - ➢ CP violation: test CKM mechanism and search for new sources
  - ➢ SM rare/forbidden decays: new interactions/particles

CKM mechanism

- CKM mechanism

Quark eigenstates interacting with Higgs different from eigenstates interacting with W bosons

Higgs — Weak

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

Three generations of quarks:

- ✓ Unitary matrix
- ✓ 3 rotation angles
- ✓ 1 phase: only known source of CPV in SM

Test of CKM mechanism:

- More than three quarks?
- Breaking of unitarity?
- New source of CPV?

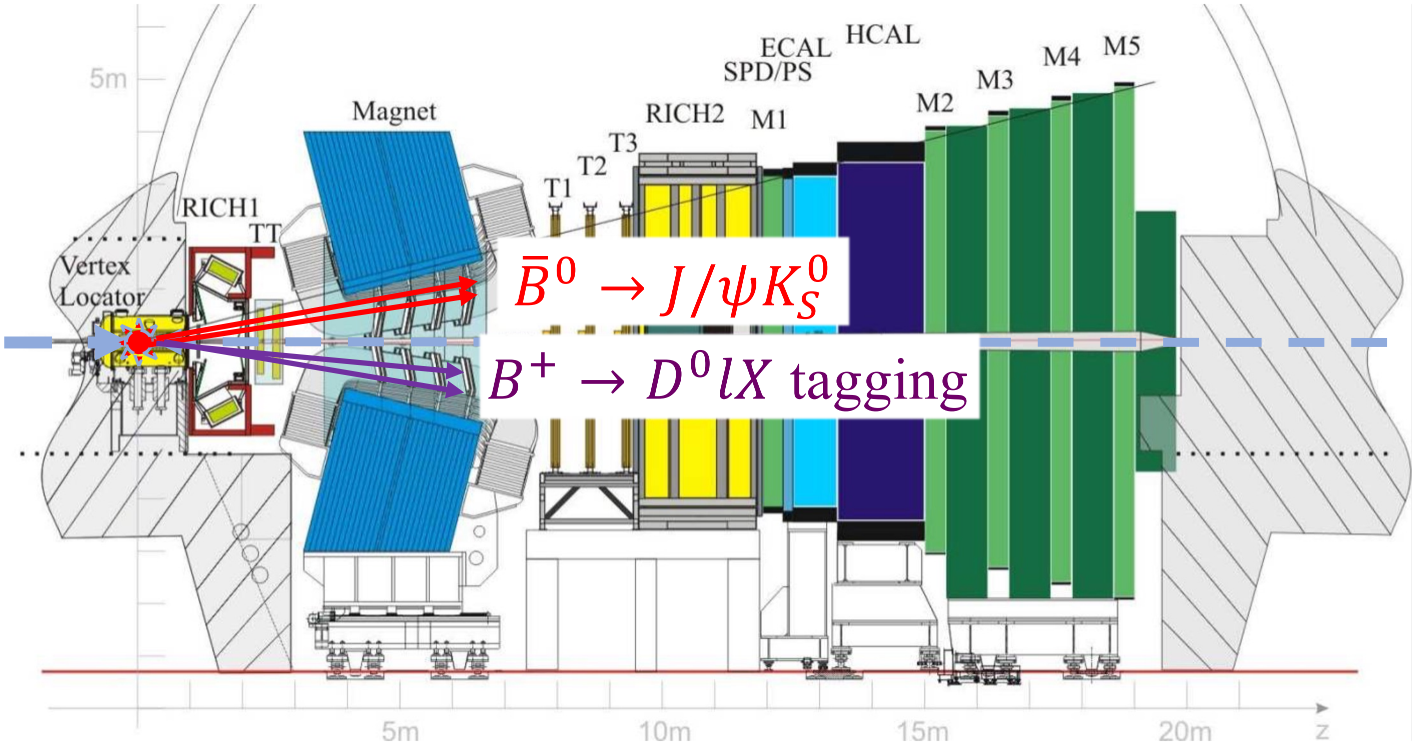
Overconstrain (3×3) CKM matrix with independent measurement of each element

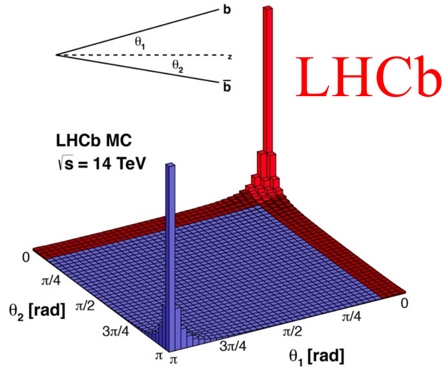
Actually, CKM insufficient to explain baryon asymmetry in Universe, must there be new CPV

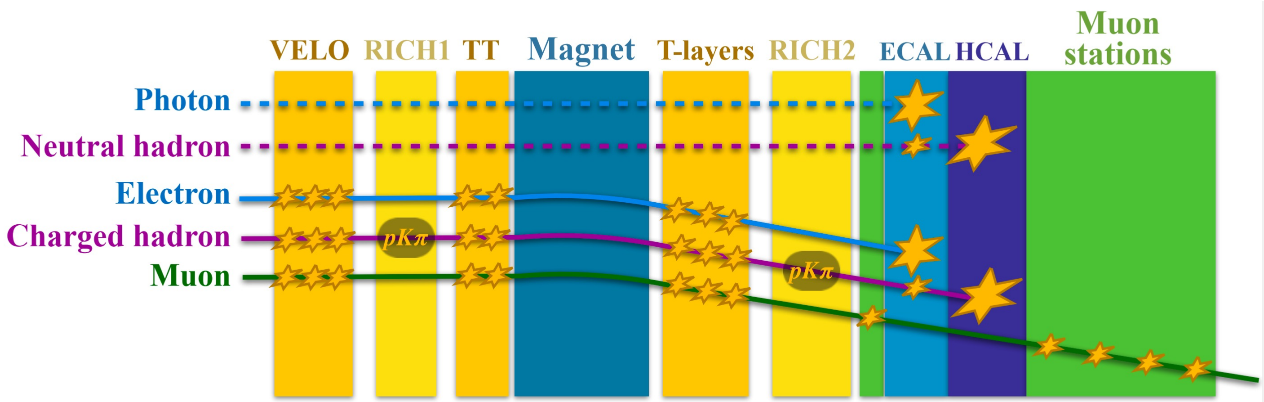
LHCb

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

- Dedicated flavor experiment for b, c hadrons







- ✓ Excellent vertexing
  $\sigma_\tau \sim 45$ fs
- ✓ Hadron PID
  $\epsilon(K \to K), \epsilon(p \to p) > 90\%$
- ✓ Momentum resolution
  $\delta m_{B \to K\pi} / m_B \sim 0.005$

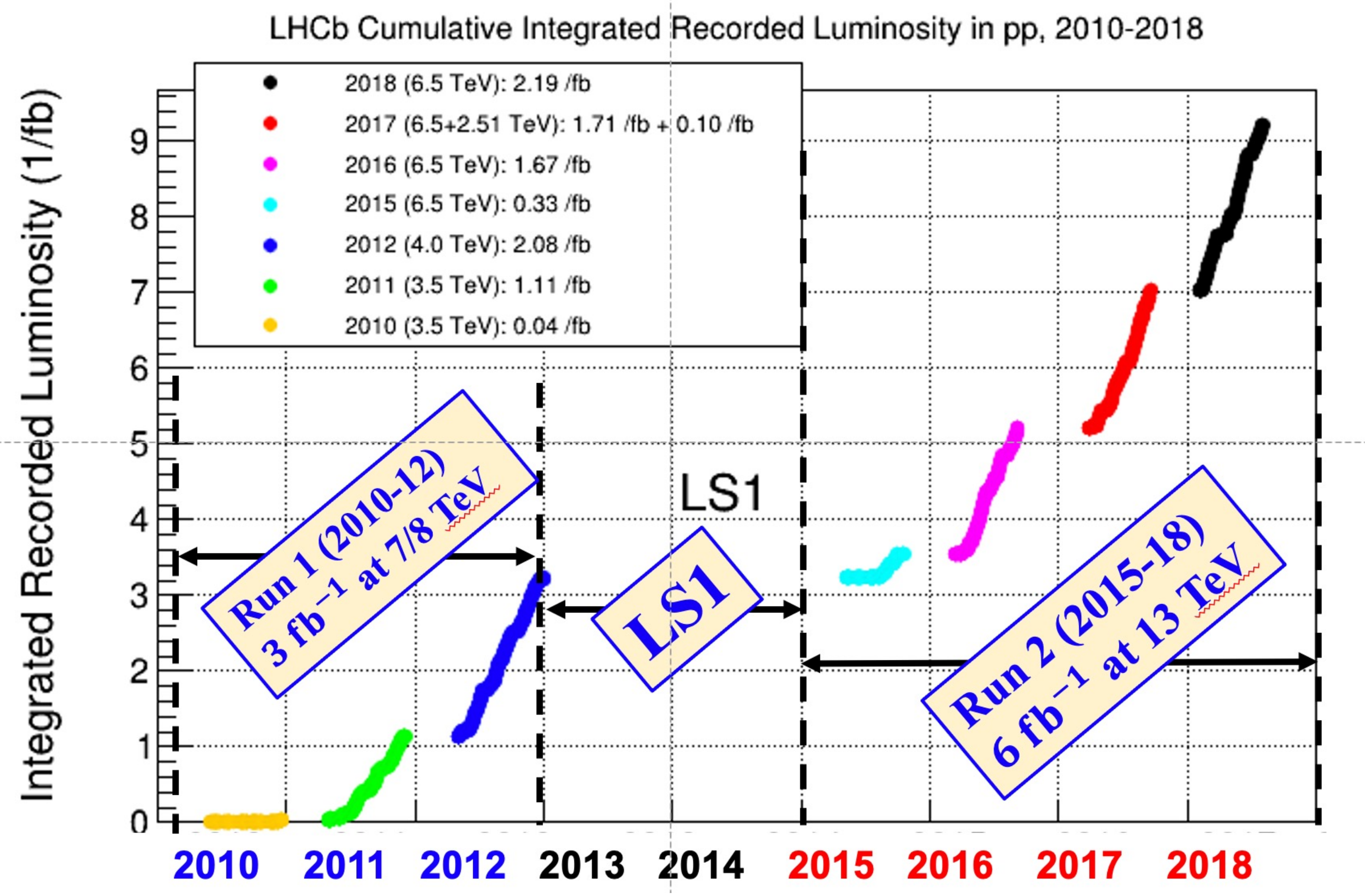
LHCb data

- pp collisions at $\sqrt{s} = 7, 8, 13$ TeV, $\int \mathcal{L} = 9\ \mathrm{fb}^{-1}$
- All species produced with large rates

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

$$\sigma\left(pp \to b\bar{b}X, \mathrm{LHCb}, 13\ \mathrm{TeV}\right) \approx 0.14\ \mathrm{mb}$$

$$\boldsymbol{B^+ : B^0 : B_s^0 : \Lambda_b^0 \approx 4 : 4 : 1 : 2}$$

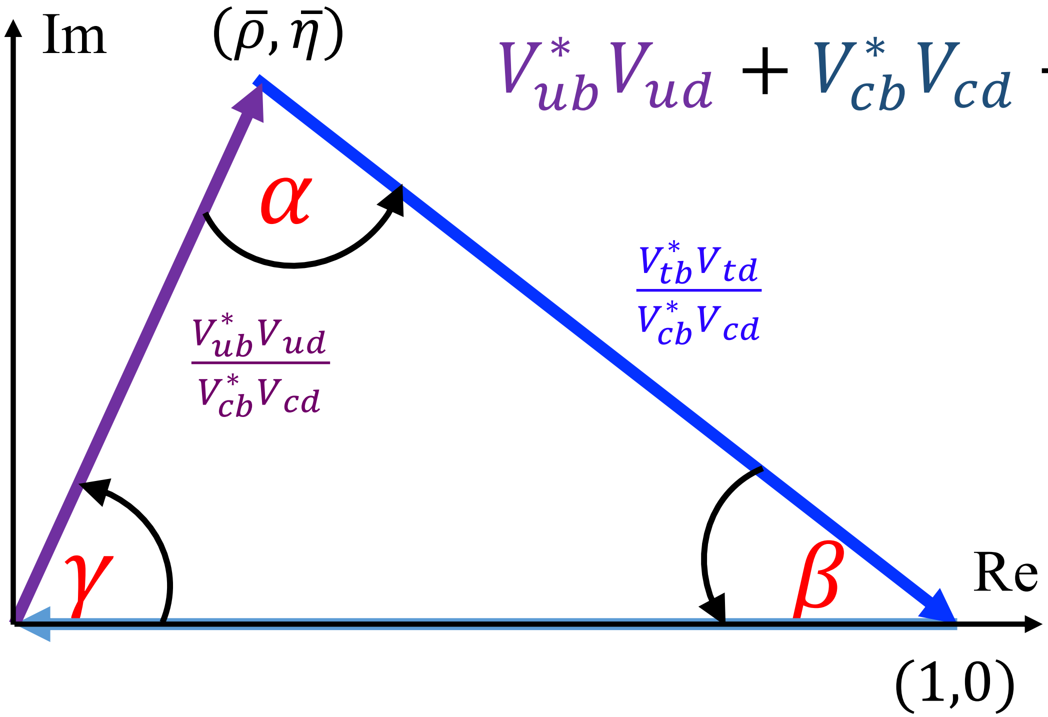


CKM angle measurements

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

The Unitarity Triangle

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



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

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

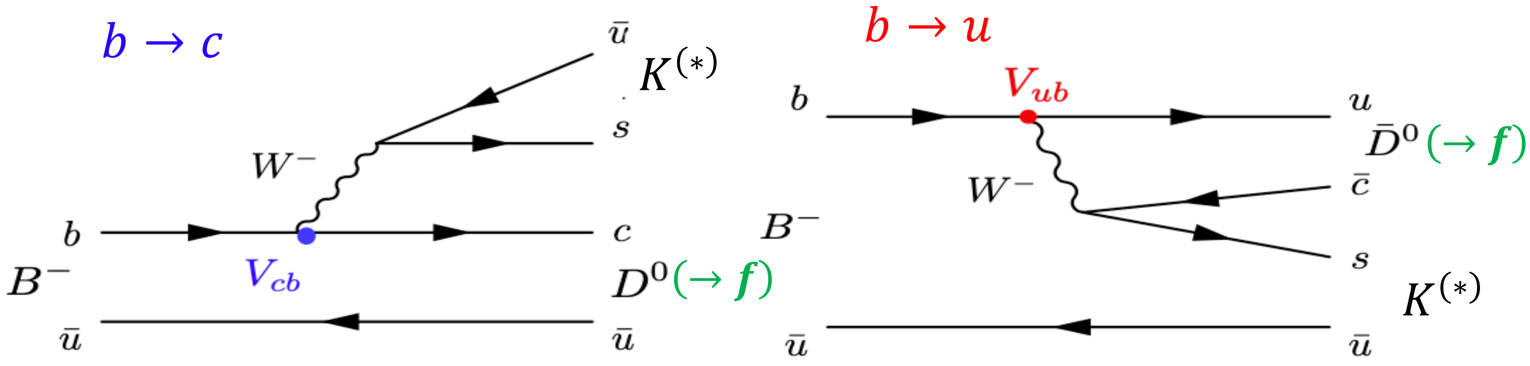
$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$

$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

Independent measurements of sides and angles, cross the same $(\bar{\rho}, \bar{\eta})$ point?

Measurement of γ

- $\gamma = \arg\left[-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right] \approx -\arg V_{ub}$ measured via interference of $b \to c$ and $b \to u$ tree-level diagrams



V_{cb} favored, $\mathcal{A}_c \propto r_D e^{-i\delta_D}$ V_{ub} suppressed, $\mathcal{A}_u \propto r_B e^{-i\gamma+i\delta_B}$

Decay rates: $\Gamma(B^\pm \to f_D h^\pm) \propto r_B^2 + r_D^2 + 2 r_B r_D \kappa_D \cos(\delta_B + \delta_D \pm \gamma)$ giving direct A_{CP}

κ_D: dilution for multibody D decays

- Independent measurements with various D modes

$f_D =$
- $KK, \pi\pi$ (GLW) PLB 253 (1991) 483, PLB 265 (1991) 172
- $K\pi, K3\pi$ (ADS) PRL 78 (1997) 3257
- $K_S hh$ (GPGGSZ) PRD 68 (2003) 054018
- $B_s \to D_s K$ time dependent PLB 253 (1991) 483

JHEP 12 (2021) 141

LHCb combination:
$\gamma = (65.4^{+3.8}_{-4.2})^\circ$

Indirect constraints
$\gamma_{\mathrm{CKMFitter}} = (65.5^{+1.1}_{-2.7})^\circ$

γ with $B^{\pm} \to D(h^{\pm}h'^{\mp}\pi^0)h^{\pm}$

JHEP 07 (2022) 099

- Quasi-ADS modes $B^- \to D(K^{\pm}\pi^{\mp}\pi^0)h^-$

  Charm decay parameters r_D, δ_D and κ_D from BESIII data

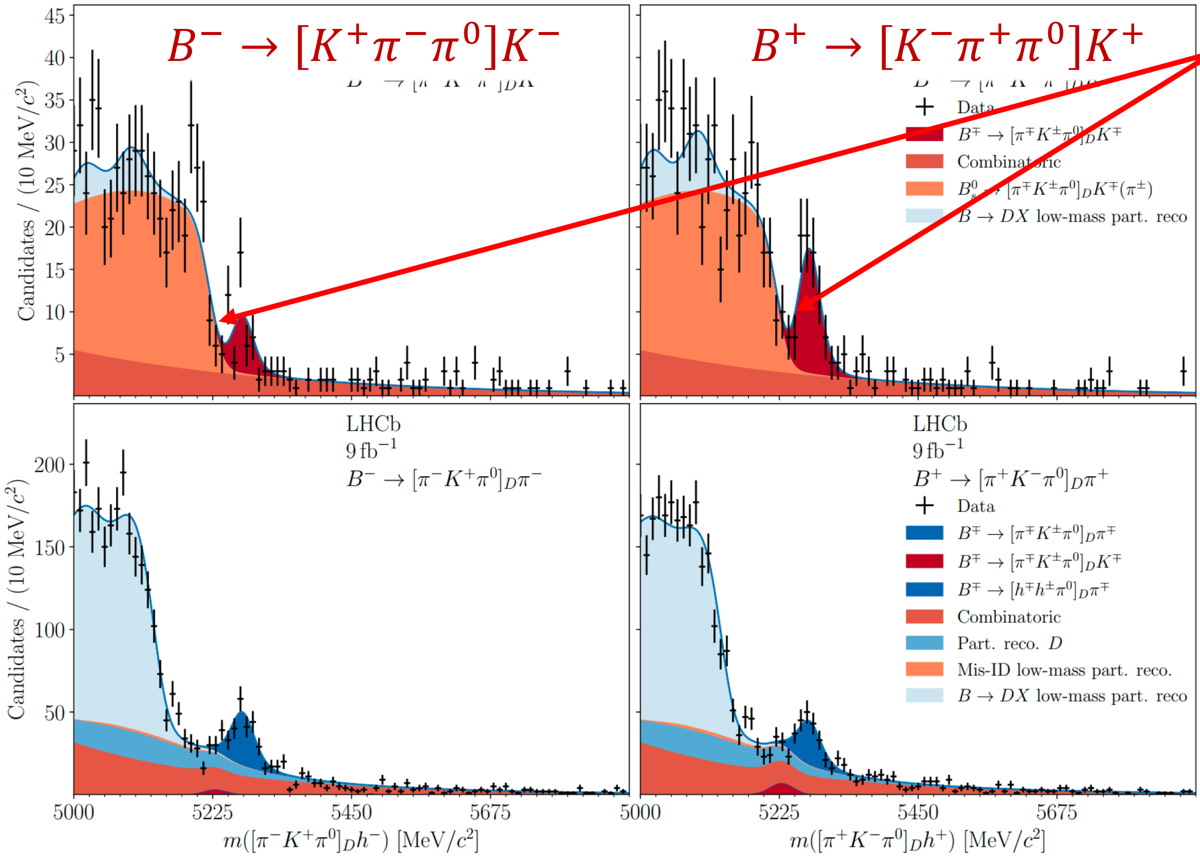
  PRD 68 (2003) 033003

  JHEP 05 (2021) 164

- Quasi-GLW modes $B^- \to D(K^+K^-\pi^0)h^-$, $B^- \to D(\pi^+\pi^-\pi^0)h^-$

  Both CP-even and CP-odd of D decays, CP even fraction from CLEO-c data

  PLB 747 (2015) 9; PLB 740 (2015) 1

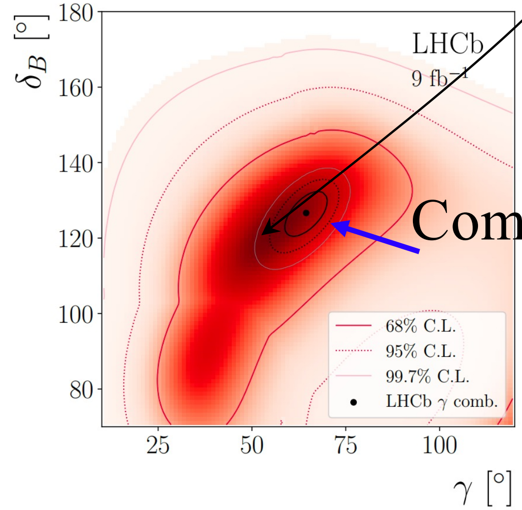


$A_{CP} = (-0.38 \pm 0.12 \pm 0.02)$

$\gamma = (56^{+24}_{-19})^{\circ}$

$\delta_B = (122^{+19}_{-23})^{\circ}$

$r_B = (9.3^{+1.0}_{-0.9}) \times 10^{-2}$

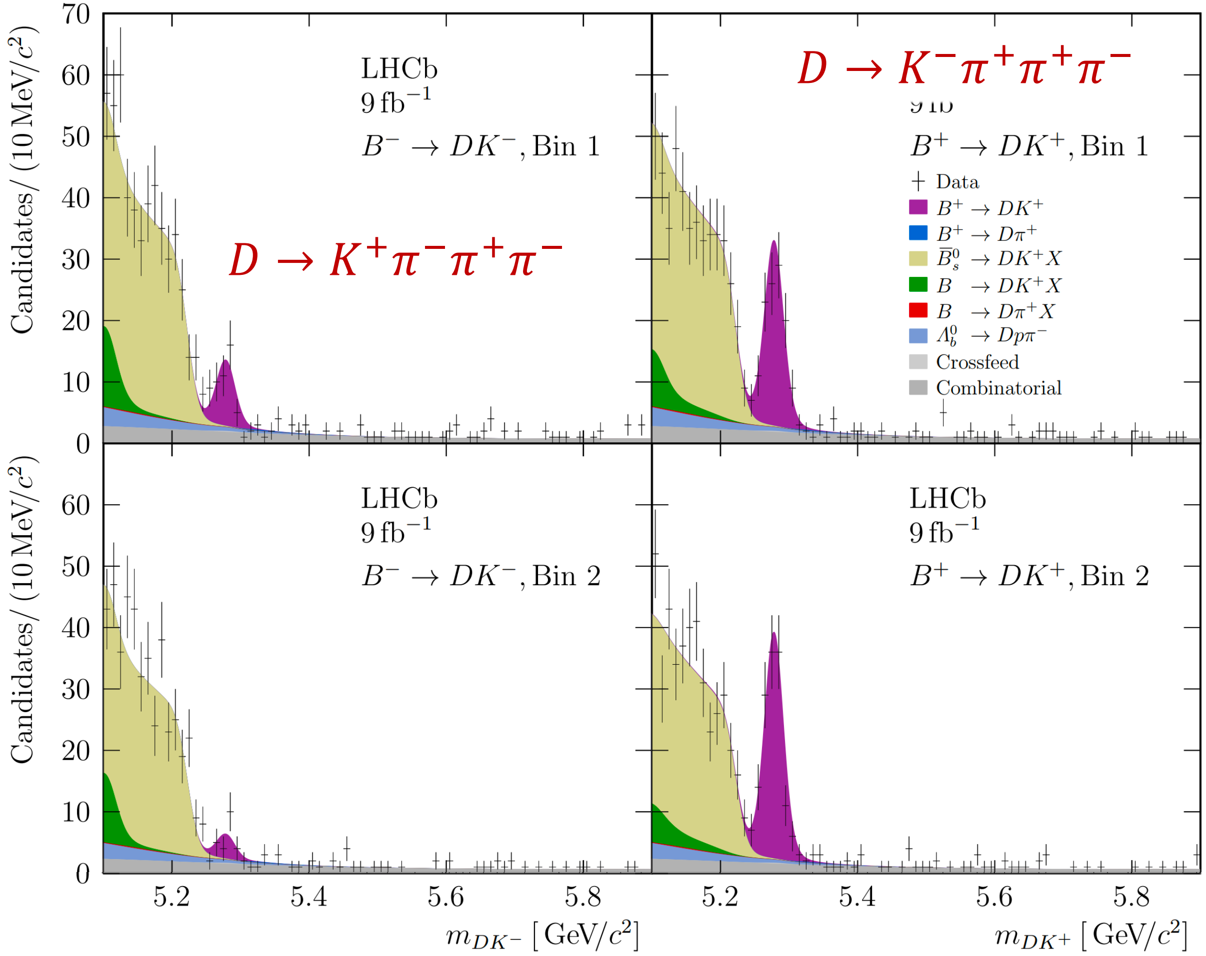


γ with $B^{\pm} \to D(K^{\pm}\pi^{\mp}\pi^{+}\pi^{-})h^{\pm}$

arXiv:2209.03692

- Phasespace split into 4 regions to improve D- $\overline{D}$ coherence, based on BESIII

JHEP 05 (2021) 164



A_{CP} in 4 regions

$$\mathcal{A}_K^1 = -0.469 \pm 0.088 \pm 0.009$$
$$\mathcal{A}_K^2 = -0.852 \pm 0.077 \pm 0.012$$
$$\mathcal{A}_K^3 = -0.284 \pm 0.080 \pm 0.009$$
$$\mathcal{A}_K^4 = +0.107 \pm 0.083 \pm 0.009$$

$$\gamma = \left(54.8^{+6.0}_{-5.8} \pm 0.6\ ^{+6.7}_{-4.3}\right)^{\circ}$$

stat. syst.

$r_{K3\pi}, \delta_{K3\pi}$

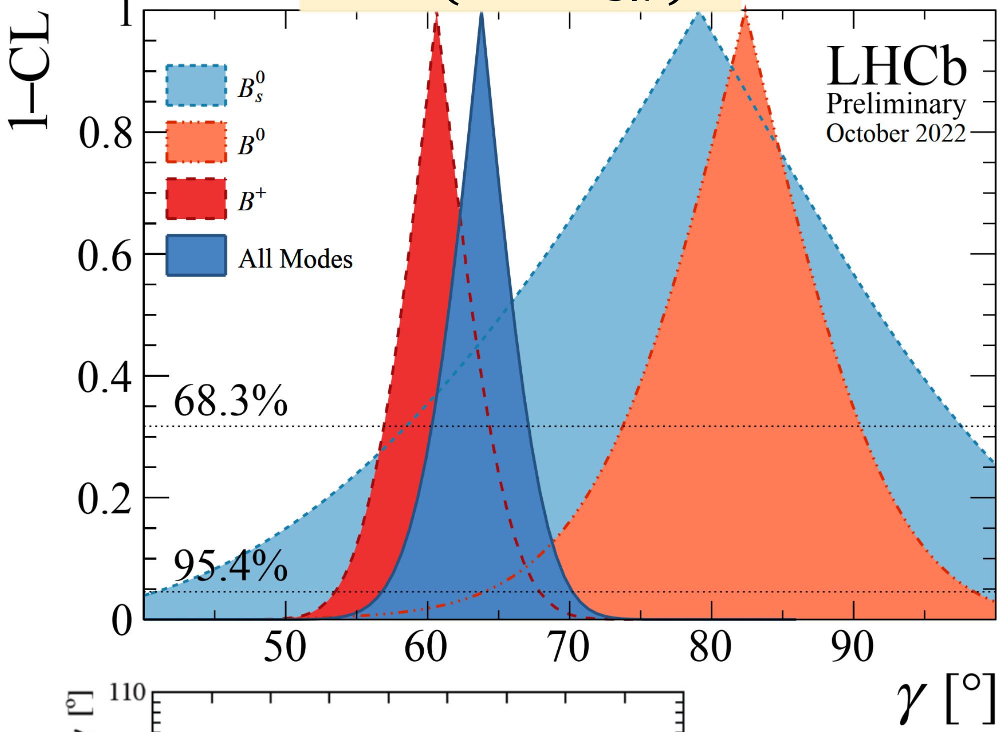
Second most precise result in a single channel

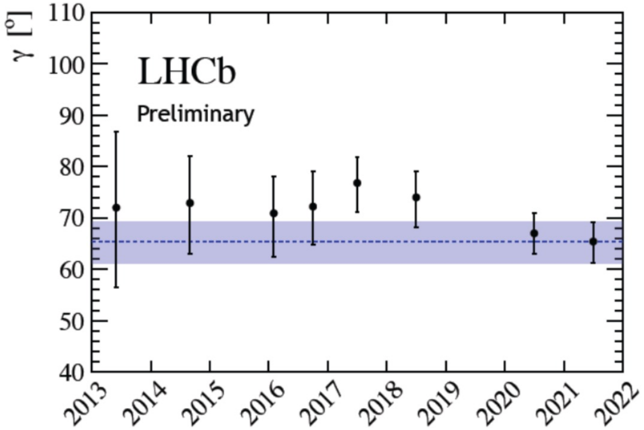
New γ combination

LHCb-CONF-2022-003

- Simultaneous determination of γ and D^0 mixing&CPV parameters

$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^{\circ}$

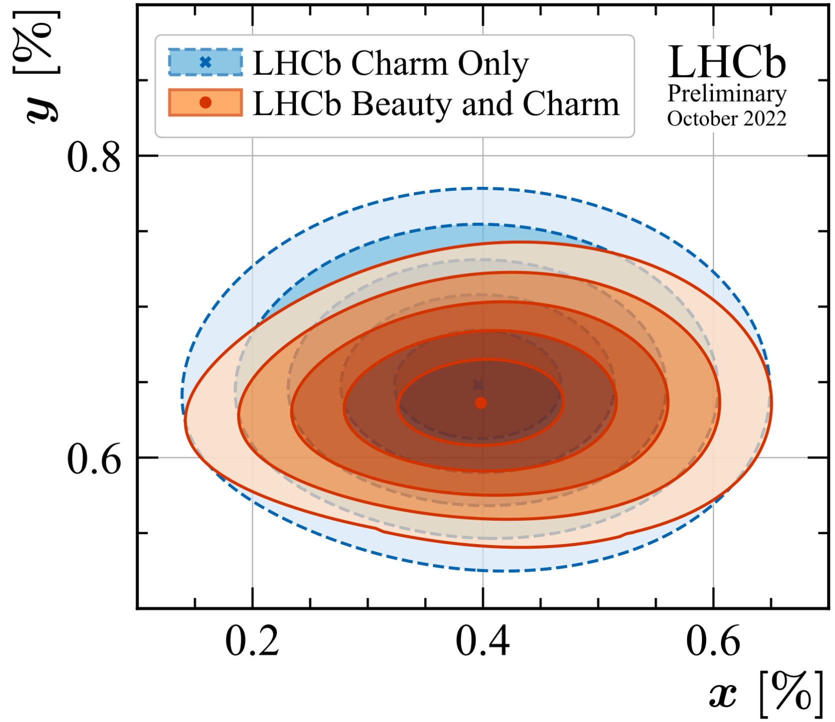




$$x_D = \frac{\Delta M_D}{M_D} = \left(0.398^{+0.050}_{-0.049}\right)\%$$

$$y_D = \frac{\Delta\Gamma_D}{2\Gamma_D} = \left(0.636^{+0.020}_{-0.019}\right)\%$$

Improved on y_D w.r.t charm only results



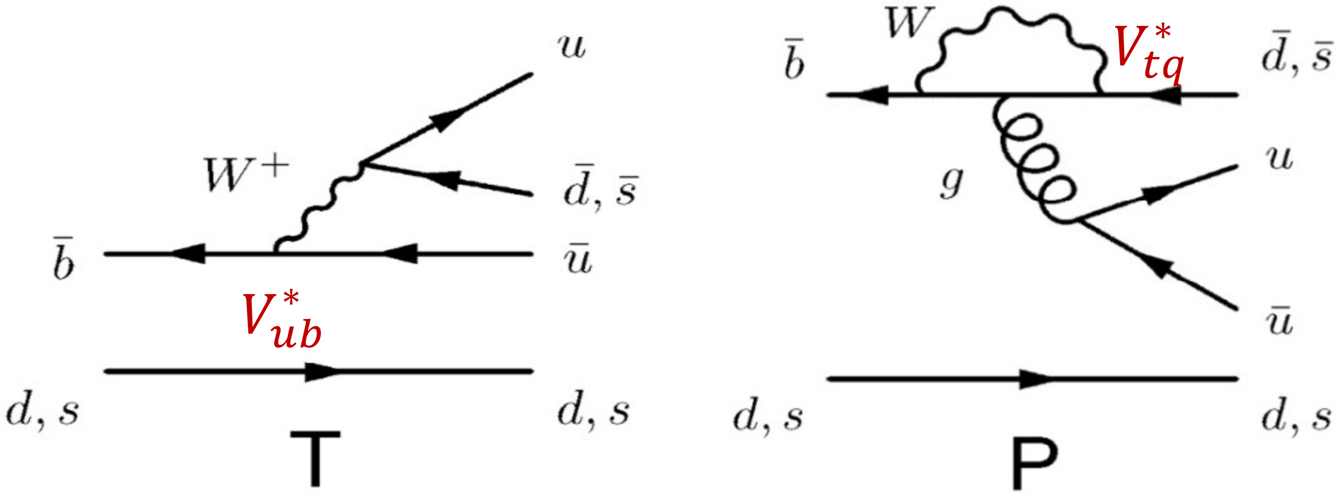
More on γ from LHCb by Shunan ZHANG [9:20, Sat.]

CPV in charmless decays

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

Charmless b-hadron decays

- Tree $b \to u$ and penguin $b \to d(s)$ diagrams: comparable magnitude and large weak phases → expecting direct CPV



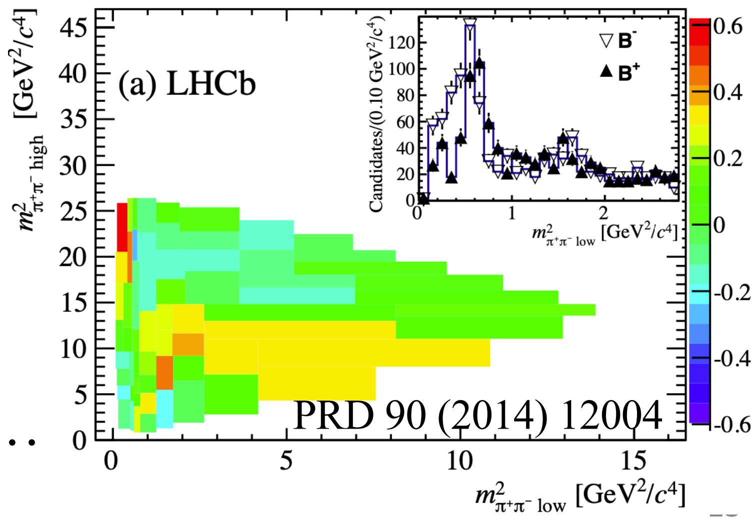
- Large asymmetry detected

$$A_{CP}(B_s^0 \to K^-\pi^+) = +0.236 \pm 0.017$$

$$A_{CP}(B^0 \to K^+\pi^-) = -0.0824 \pm 0.0047$$

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

Patterns of CPV in 3-body PHSP



Roughly described by models: pQCD, QCDF, SR …

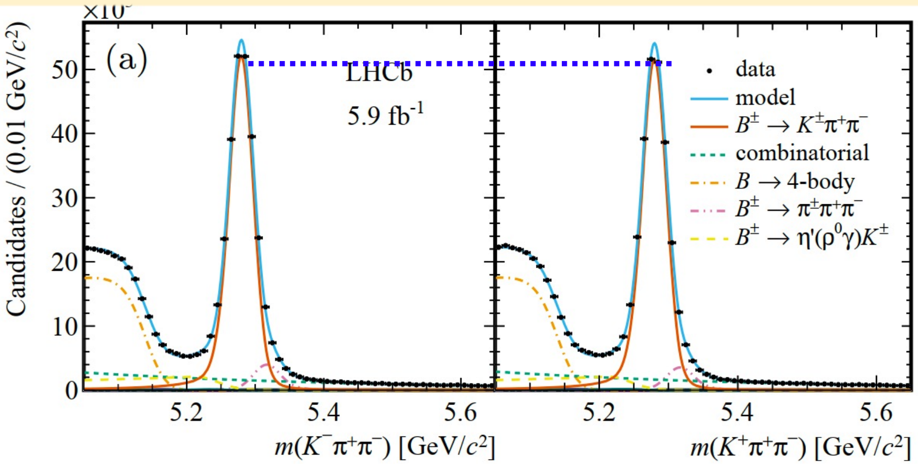
CPV in $B^{\pm} \to h_1^{\pm} h_2^{\mp} h_3^{\pm}$ in Run2

arXiv:2206.07622

Global CPV

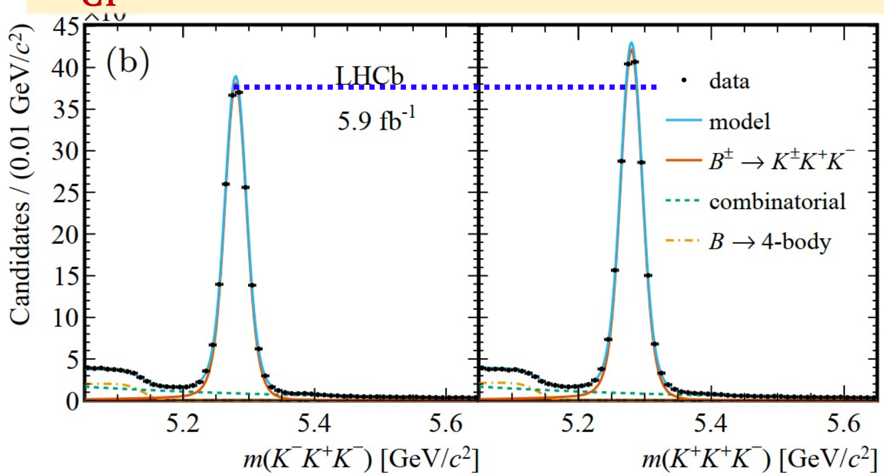
$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ 2.4σ

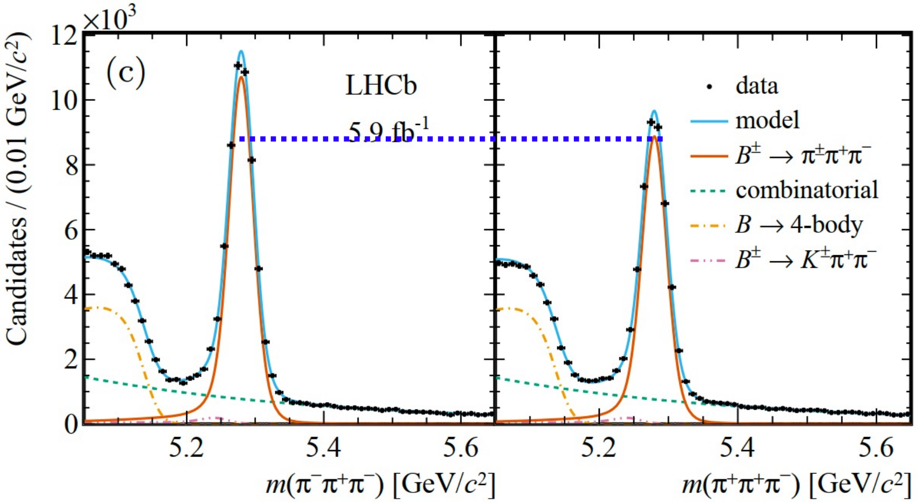
$A_{\rm CP} = +0.011 \pm 0.002 \pm 0.003 \pm 0.003$



$B^{\pm} \to K^{\pm}K^{+}K^{-}$ 8.5σ

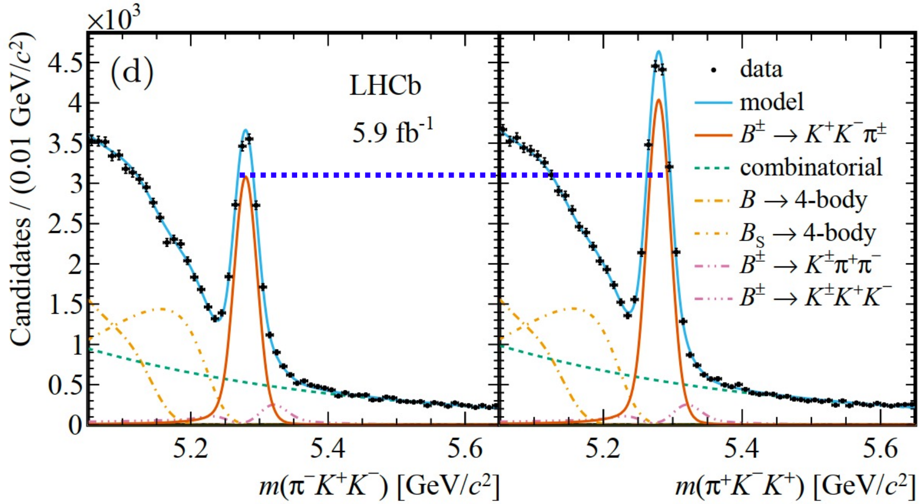
$A_{\rm CP} = -0.037 \pm 0.002 \pm 0.002 \pm 0.003$





$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ 14.1σ

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

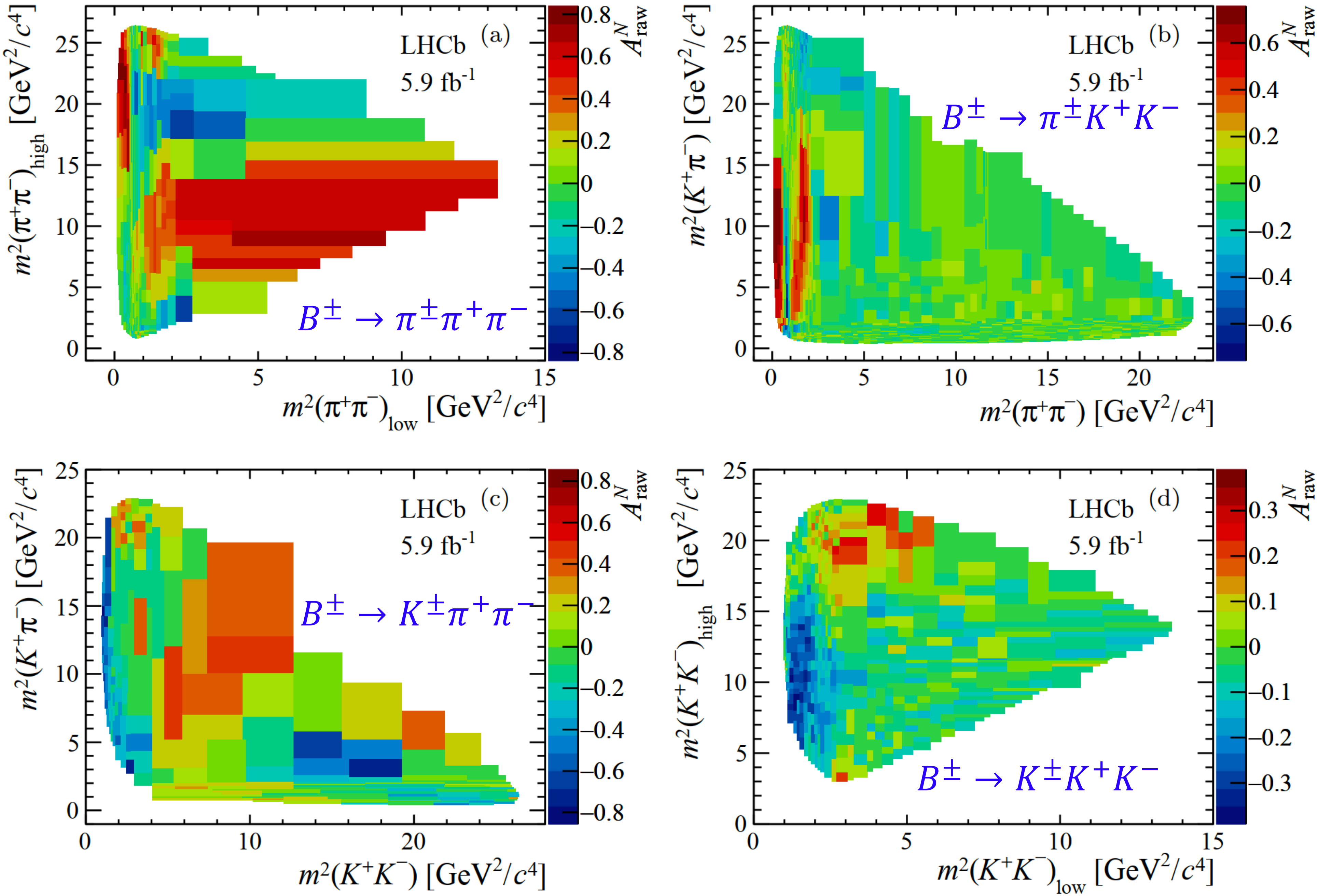


$B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ 13.6σ

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

Large localized CPV: patterns

arXiv:2206.07622

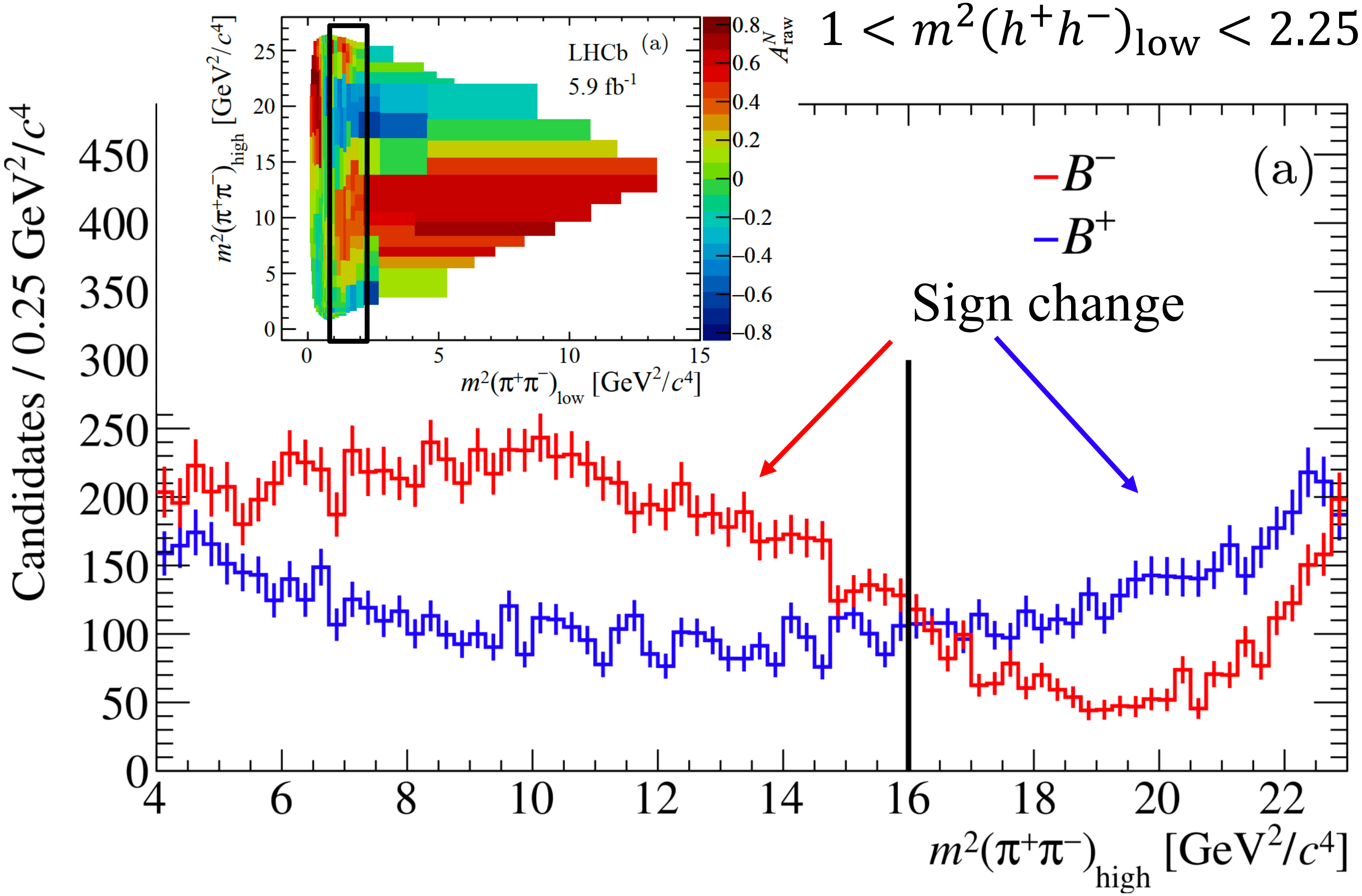


Localized CPV: dynamics

arXiv:2206.07622

- A_{CP} arise due to $\pi^+\pi^- \leftrightarrow K^+K^-$ rescattering

$1 < m^2(h^+h^-)_{\mathrm{low}} < 2.25\ \mathrm{GeV}^2$



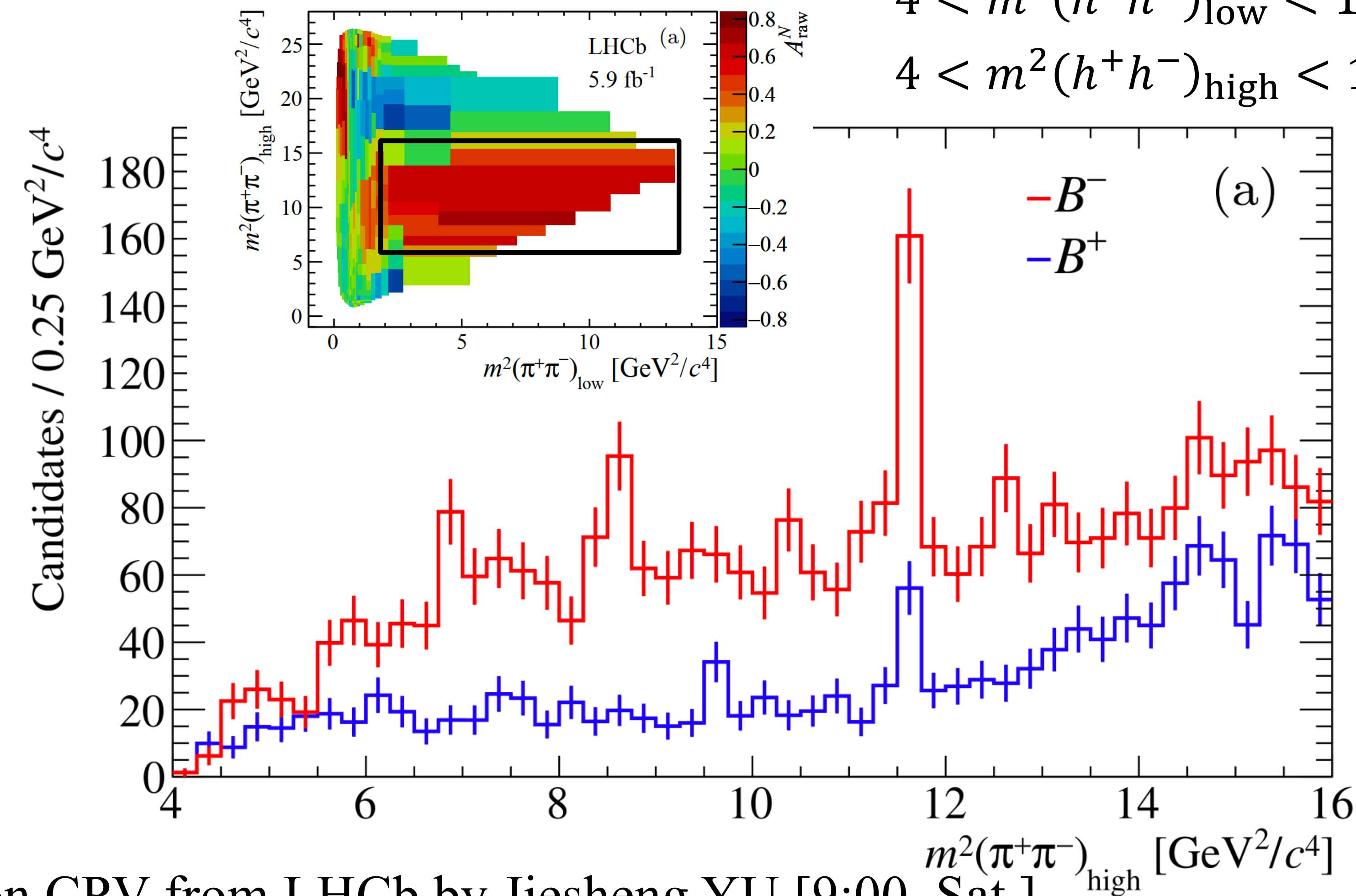
Localized CPV: dynamics

arXiv:2206.07622

- A_{CP} in charmonium region
  - Interference of $b \to c\bar{c}d$ with non-resonant?
  - Significant contribution of $b \to dc\bar{c}$ penguins?
  - S-wave $D\bar{D} \leftrightarrow \pi^+\pi^-$ rescattering?

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

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



More on CPV from LHCb by Jiesheng YU [9:00, Sat.]

What we are doing now?

Stolen from Ying LI in "Flavor Physics Lectures (2021.12.16)"

- Higher-Order Corrections
  - QCDF Two-loop calculations are almost completed

    M.Beneke, et.al, X-Q LI (CCNU)
  - PQCD One-loop calculations are partly completed

    H-N Li, Z-J Xiao (NJNU), C-D Lu (IHEP), Y L(YTU)
- Higher-Power Corrections
  - Form Factor

    Y-M Wang (NKU), Y-L Shen (OU), C-D Lu (IHEP)
  - light-Meson Distribution Amplitudes

    A. Khodjamirian, X-G Wu(CQU), S Cheng (HNU)
  - Heavy-Meson Distribution Amplitudes

    Y-M Wang(NKU), W WANG(SJTU),..
- Application

  Z-J Xiao (NJNU), C-D Lu (IHEP), W Wang (SJTU), Y-D Yang (CCNU), X-H Guo, F-S Yu (LZU), Q Chang (HNNU) Y L(YTU),…

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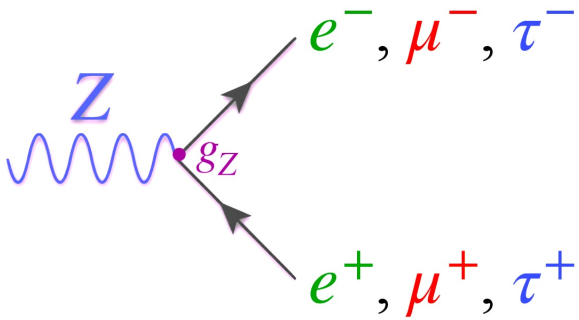
Flavor anomalies

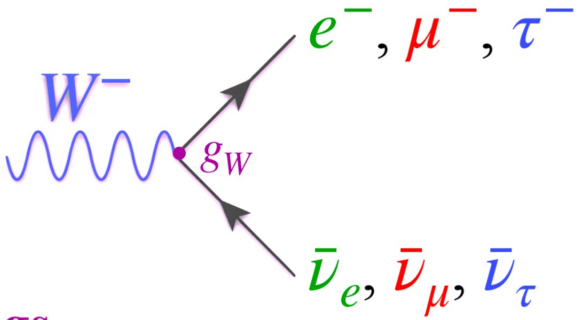
Lepton flavor universality (LFU)

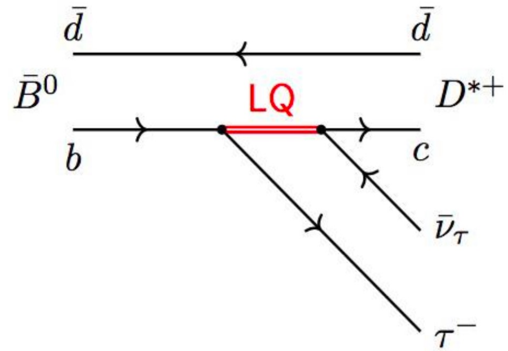
- Three lepton generations couple to EW bosons couple identically

But not in new physics



LFU couplings

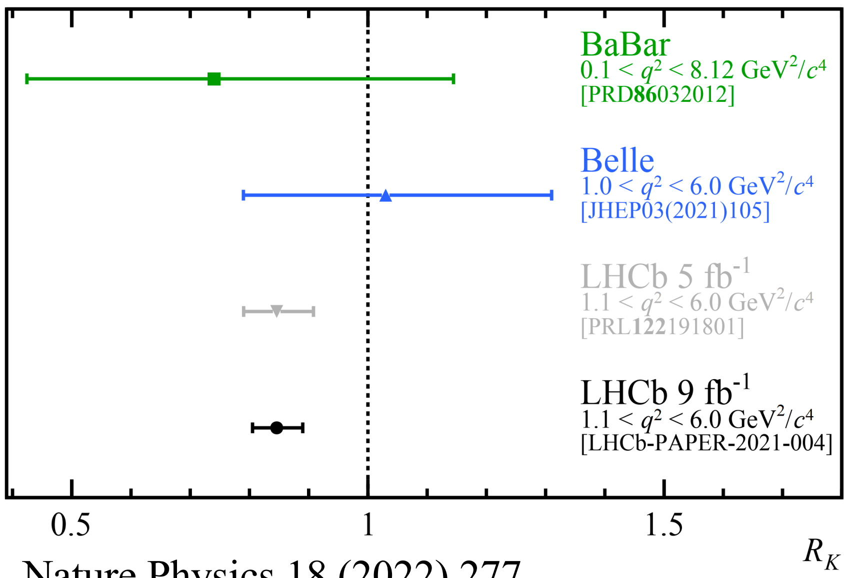




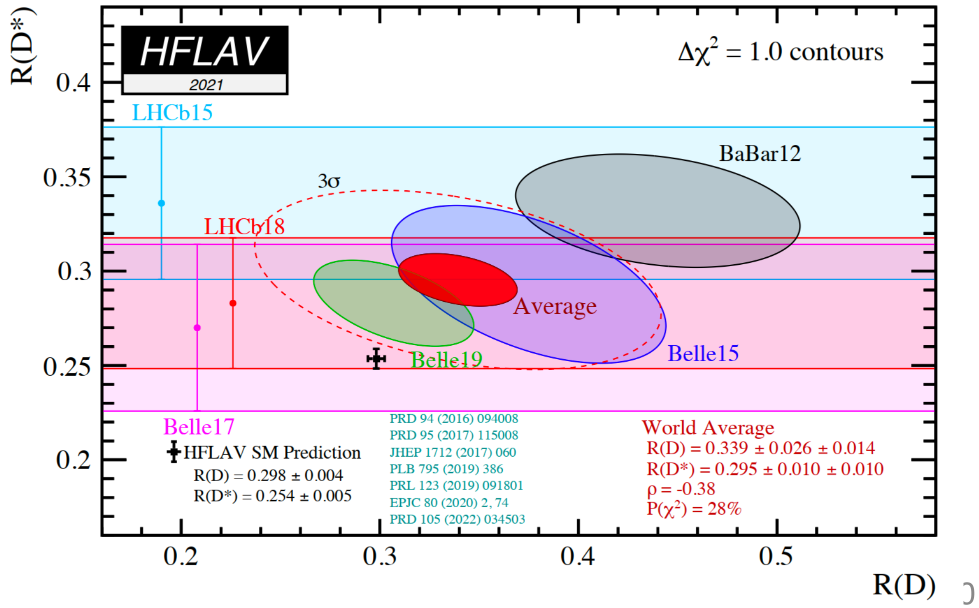
- Experimental hints of LFU violation

$$R_{X_s} = \frac{\mathcal{B}(H_b \to X_s \mu^+ \mu^-)}{\mathcal{B}(H_b \to X_s e^+ e^-)}$$

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu \bar{\nu}_\mu)}$$



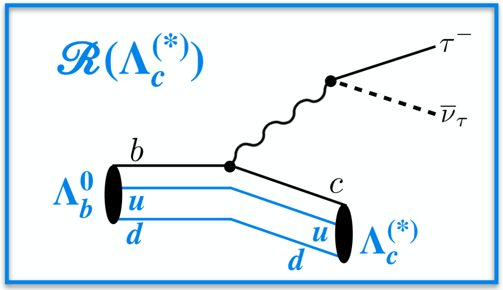
Nature Physics 18 (2022) 277

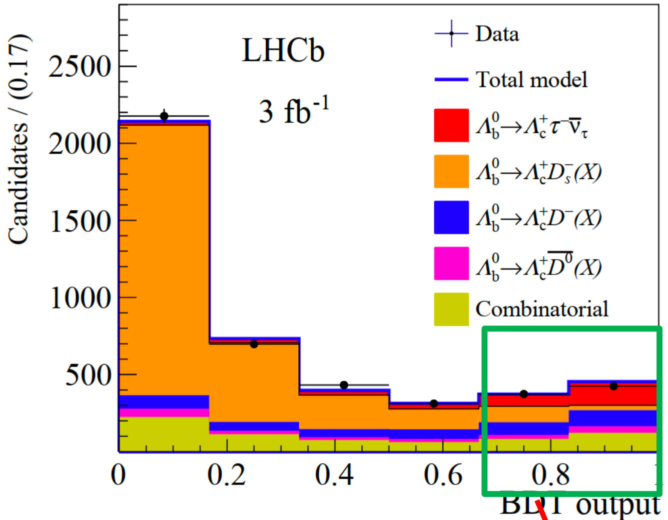


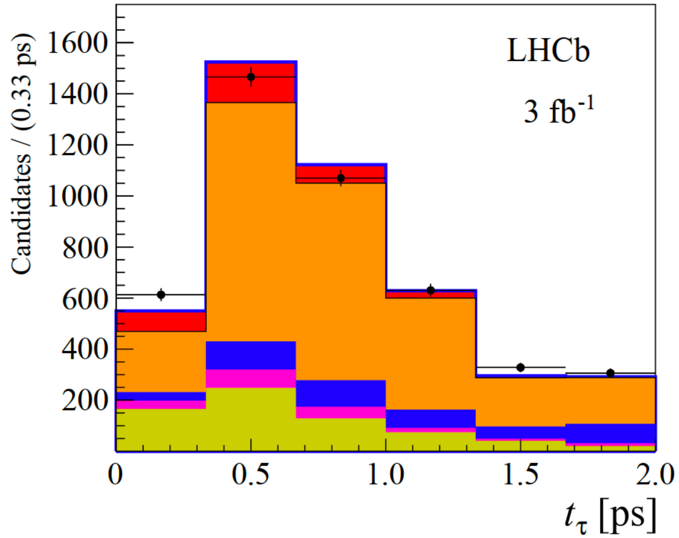
$R(\Lambda_c^+)$ from $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$

PRL 128 (2022) 191803

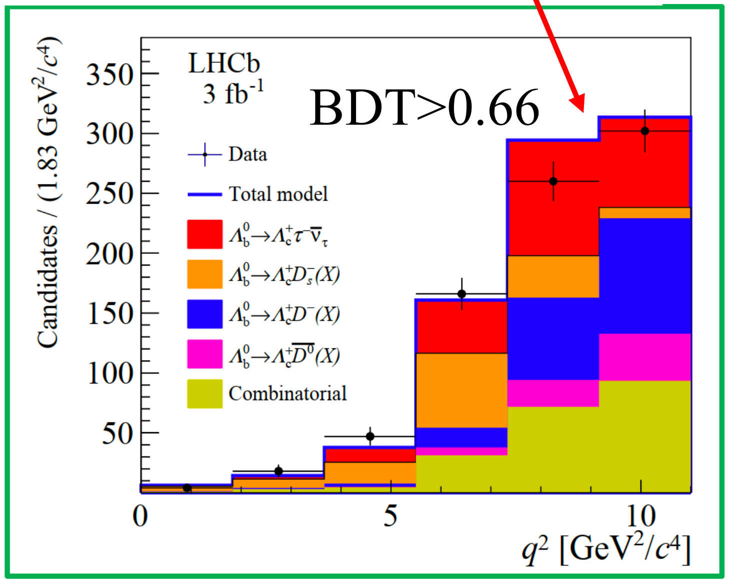
- First observation of $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ decays







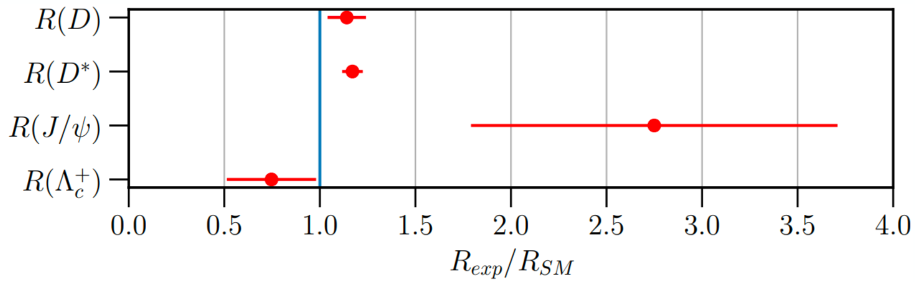
[Only Run1 data]



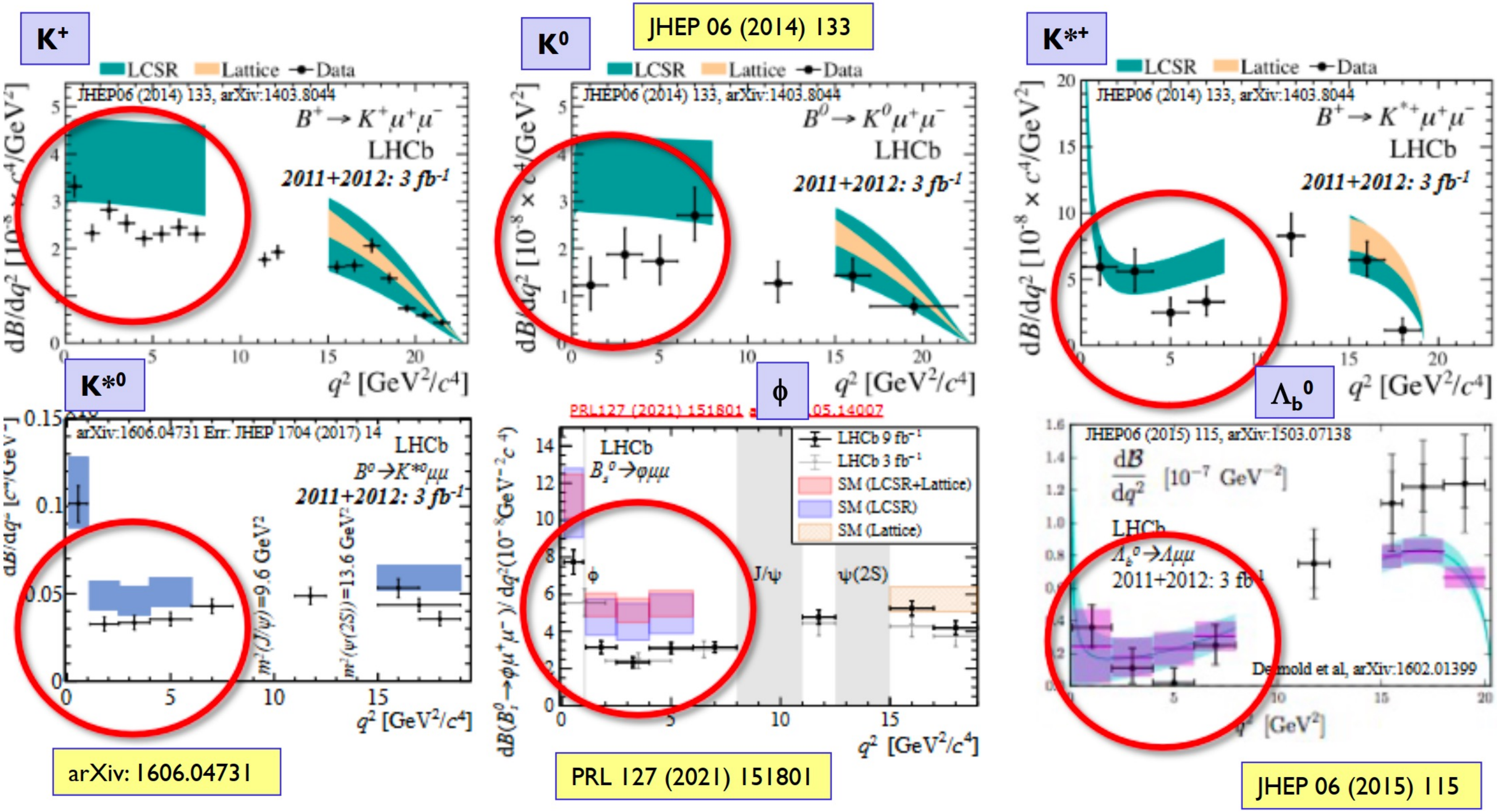
$$R(\Lambda_c^+) = 0.242 \pm 0.076$$

Consistent with SM prediction

$$R_{\mathrm{SM}}(\Lambda_c^+) = 0.340 \pm 0.004$$



More anomalies in SL decays



- All semi-leptonic BF's lower than SM expectations at low q^2 (~1 to 4σ) [comparison limited due to large theory uncertainties from form factors]

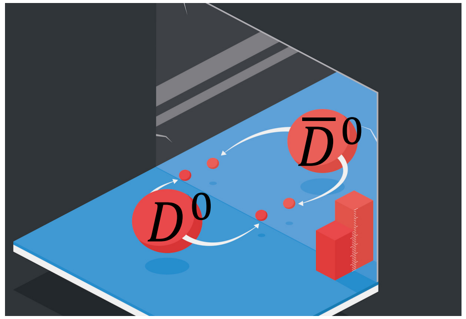
More on LHCb anomalies by Jibo HE [14:00, Fri.]

Charm physics

Direct CPV in charm decays

- First charm CPV observed by LHCb in 2019

PRL 122 (2019) 211803



$$\Delta A_{\rm CP}^{D^0} = A_{\rm CP}(K^+K^-) - A_{\rm CP}(\pi^+\pi^-) = (-15.4 \pm 2.9)\times 10^{-4}$$

- New measurement of time-integrated CP asymmetry

$$A_{\rm CP}^{D^0}(K^+K^-) = a_{KK}^d + \frac{\langle t \rangle_{KK}}{\tau_D}\Delta Y_{KK}$$

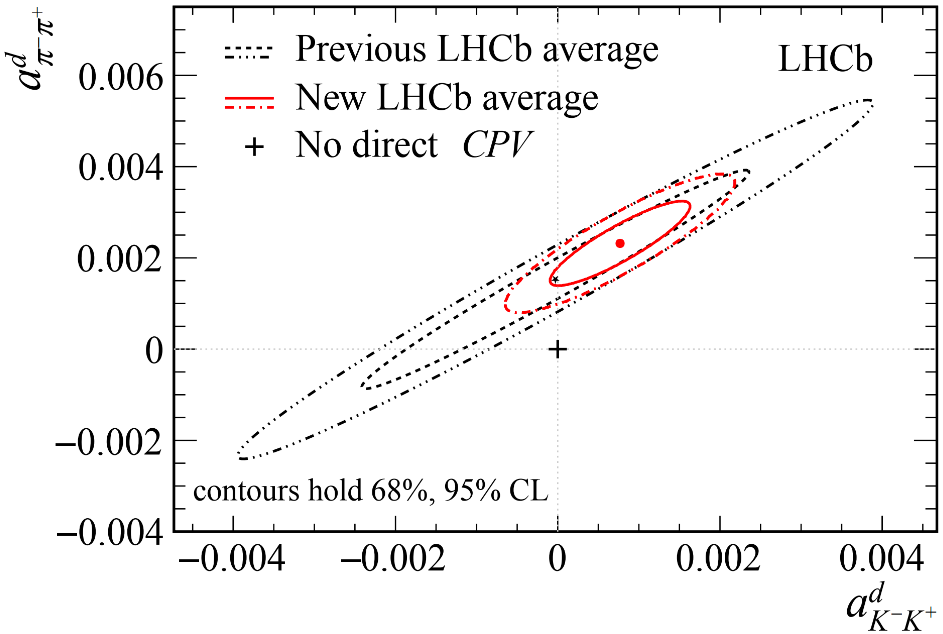
arXiv:2209.03179

$$= [6.8 \pm 5.4({\rm stat}) \pm 1.6({\rm syst})]\times 10^{-4}$$

To obtain:

$$a_{KK}^d = (7.7 \pm 5.7)\times 10^{-4}$$
$$a_{\pi\pi}^d = (23.2 \pm 6.1)\times 10^{-4}$$

First evidence of CPV in $D^0 \to \pi^+\pi^-$ decays (3.8σ)



D^0 mixing parameters

PRL 127 (2021) 111801

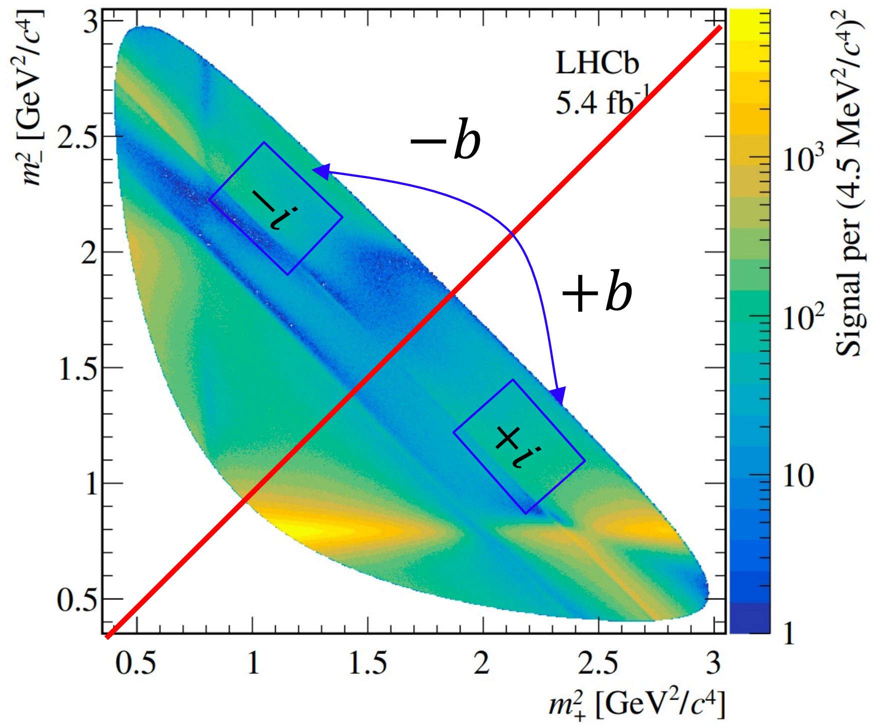
- $D^0 - \bar{D}^0$ mixing to form mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

  Observables: $x_D \equiv \Delta M/\Gamma$, $y_D \equiv \Delta\Gamma/2\Gamma$, $|q/p|$, $\phi_f \equiv \arg(q\bar{A}_f/pA_f)$

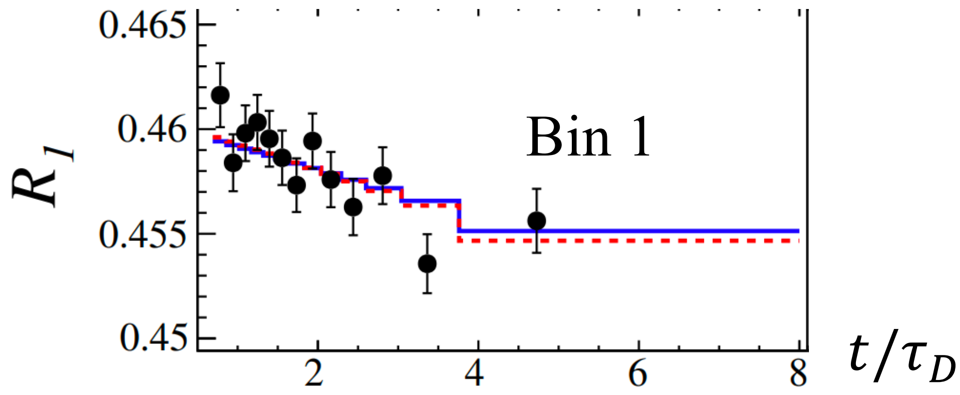
- Measurement using bin flip method with $D^0 \to K_S^0\pi^+\pi^-$ decays

PRD 99 (2019) 012007

$$\mathcal{A}^{D^0}\left(m^2_{K_S^0\pi^+}, m^2_{K_S^0\pi^-}, t\right) = g_+(t; x, y)\mathcal{A}^{D^0}(m_+^2, m_-^2) + \frac{q}{p} g_-(t; x, y)\mathcal{A}^{\bar{D}^0}(m_+^2, m_-^2)$$



- Dalitz density varies with decay time t
- Model independent approach: ratios between two symmetric bins



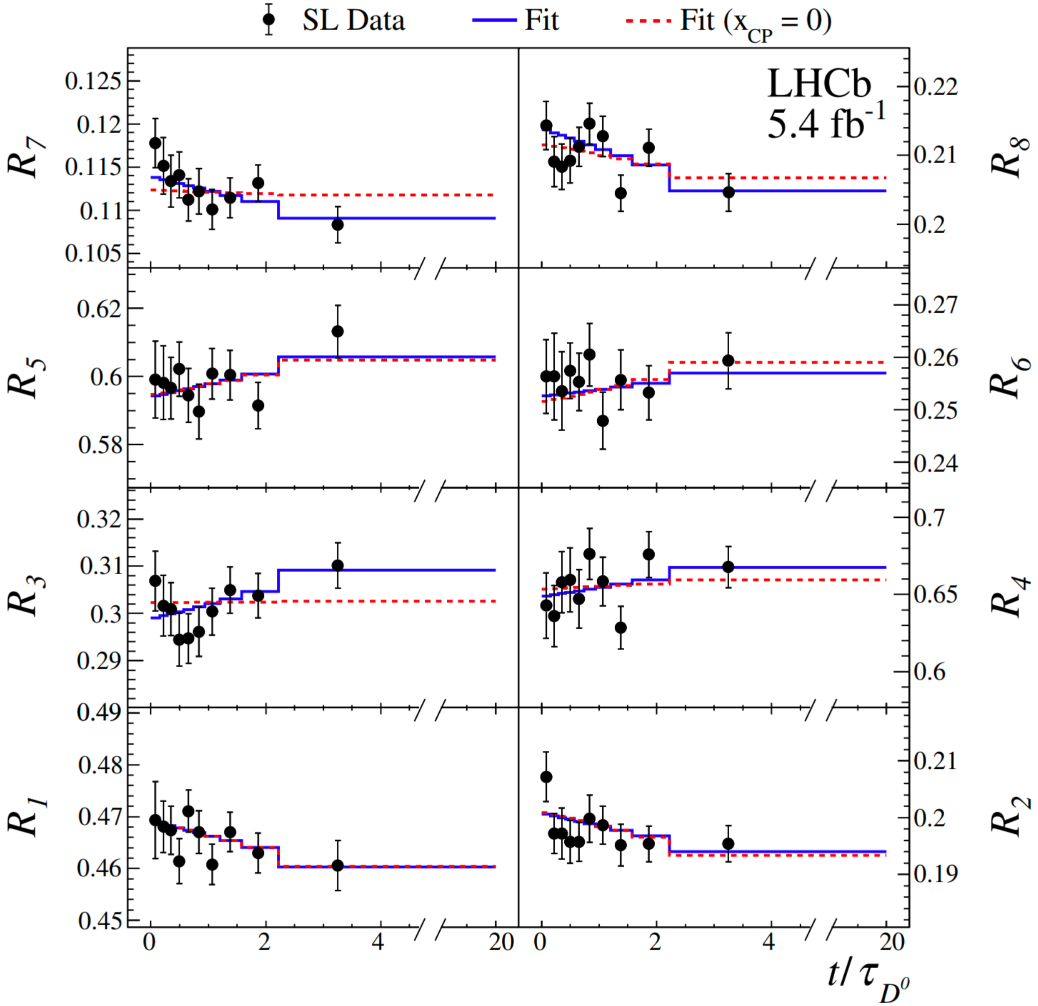
$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3}$$
$$y = (4.6^{+1.5}_{-1.4}) \times 10^{-3}$$

First time for $x \neq 0$

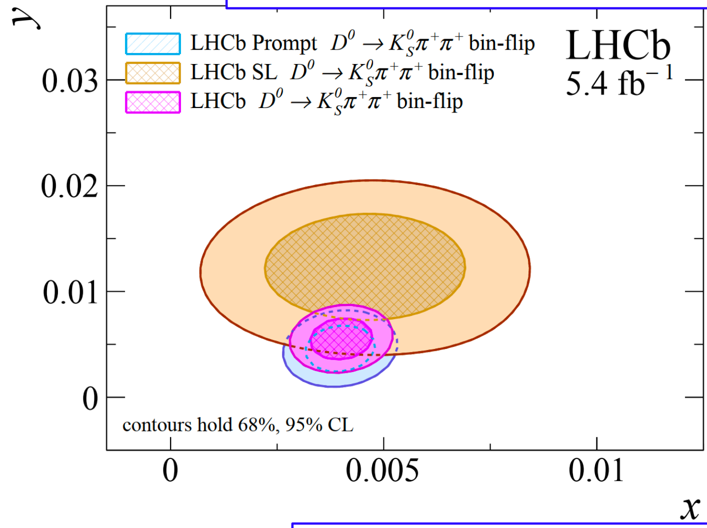
Update with SL decays

arXiv:2208.06512

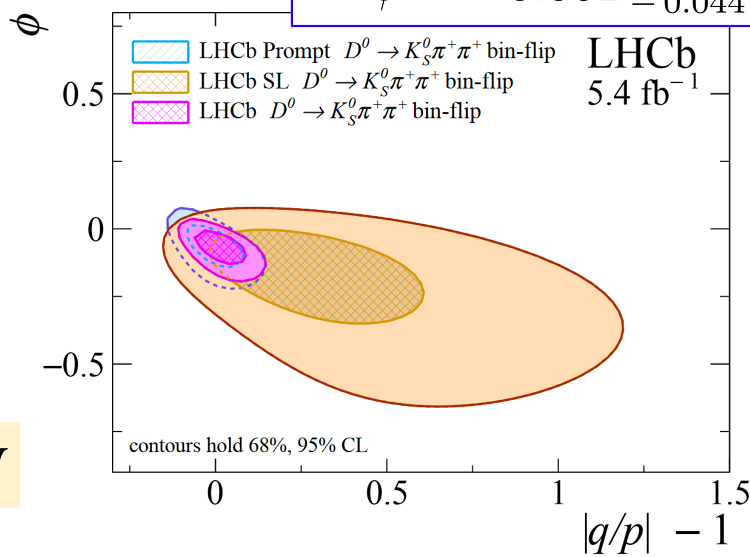
- $\bar{B} \to D^0(K_s^0\pi^+\pi^-)\mu^- X$



Average: $x = (4.01 \pm 0.49) \times 10^{-3}$
$y = (5.5 \pm 1.3) \times 10^{-3}$



Average: $|q/p| = 1.012\,^{+0.050}_{-0.048}$,
$\phi = -0.061\,^{+0.037}_{-0.044}$ rad



No sign of CPV

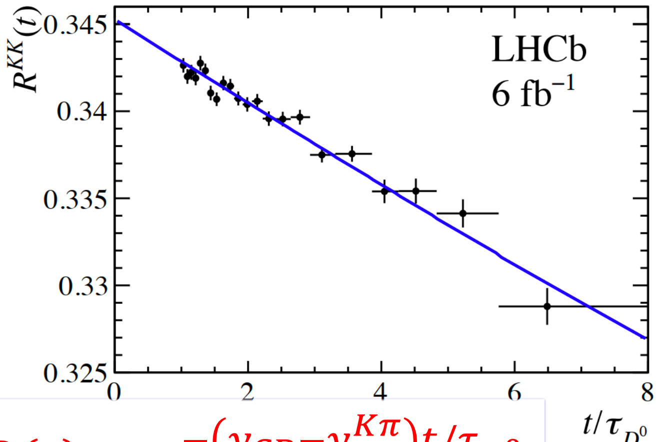
$y_{\mathrm{CP}} - y_{\mathrm{CP}}^{K\pi}$ in D^0 two-body decays

PRD 105 (2022) 092013

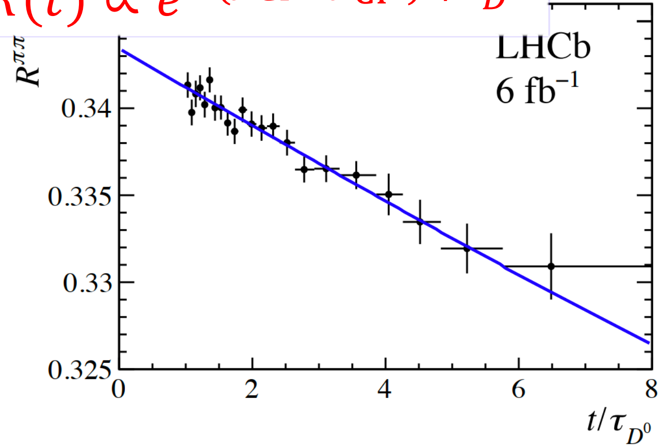
- $y_{\mathrm{CP}} = \frac{\hat{\Gamma}(D^0\to f)+\hat{\Gamma}(\bar{D}^0\to f)}{2\Gamma} - 1$: measuring CP averaged (effective) decay width
- $y_{\mathrm{CP}} - y_{\mathrm{CP}}^{K\pi} = \frac{\hat{\Gamma}(D^0\to f)+\hat{\Gamma}(\bar{D}^0\to f)}{\hat{\Gamma}(D^0\to K^-\pi)+\hat{\Gamma}(\bar{D}^0\to K^+\pi^-)} - 1 \approx y_D\left(1+\sqrt{R_{K\pi}}\right)$
- For $f = K^+K^-$ and $\pi^+\pi^-$

$y_D = \frac{\Delta\Gamma}{\Gamma} \approx 0.6\%$

$R_{K\pi} = \sqrt{\frac{\mathrm{DCS}}{\mathrm{CF}}(t=0)} \approx 6\%$

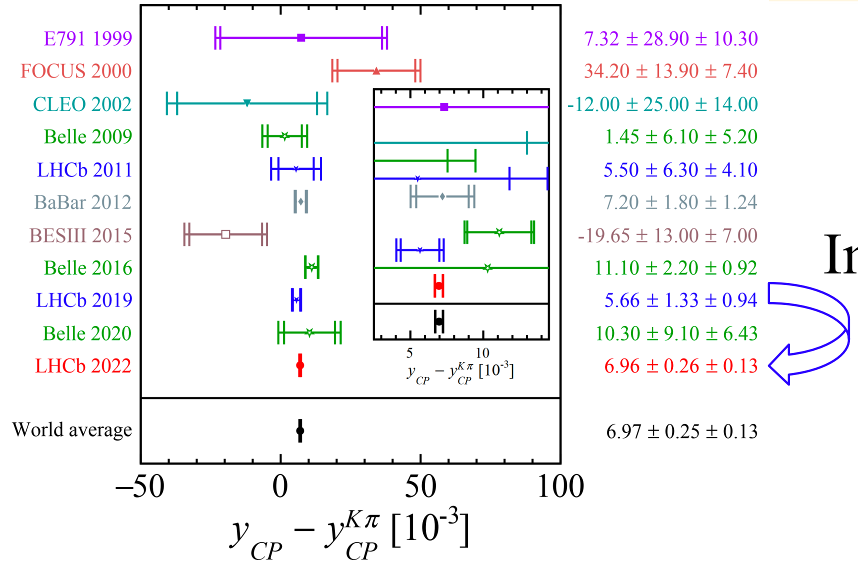


$R(t) \propto e^{-(y_{\mathrm{CP}}-y_{\mathrm{CP}}^{K\pi})t/\tau_{D^0}}$



Average K^+K^- and $\pi^+\pi^-$:

$y_{CP} - y_{\mathrm{CP}}^{K\pi} = (6.96 \pm 0.26 \pm 0.13)\times 10^{-3}$



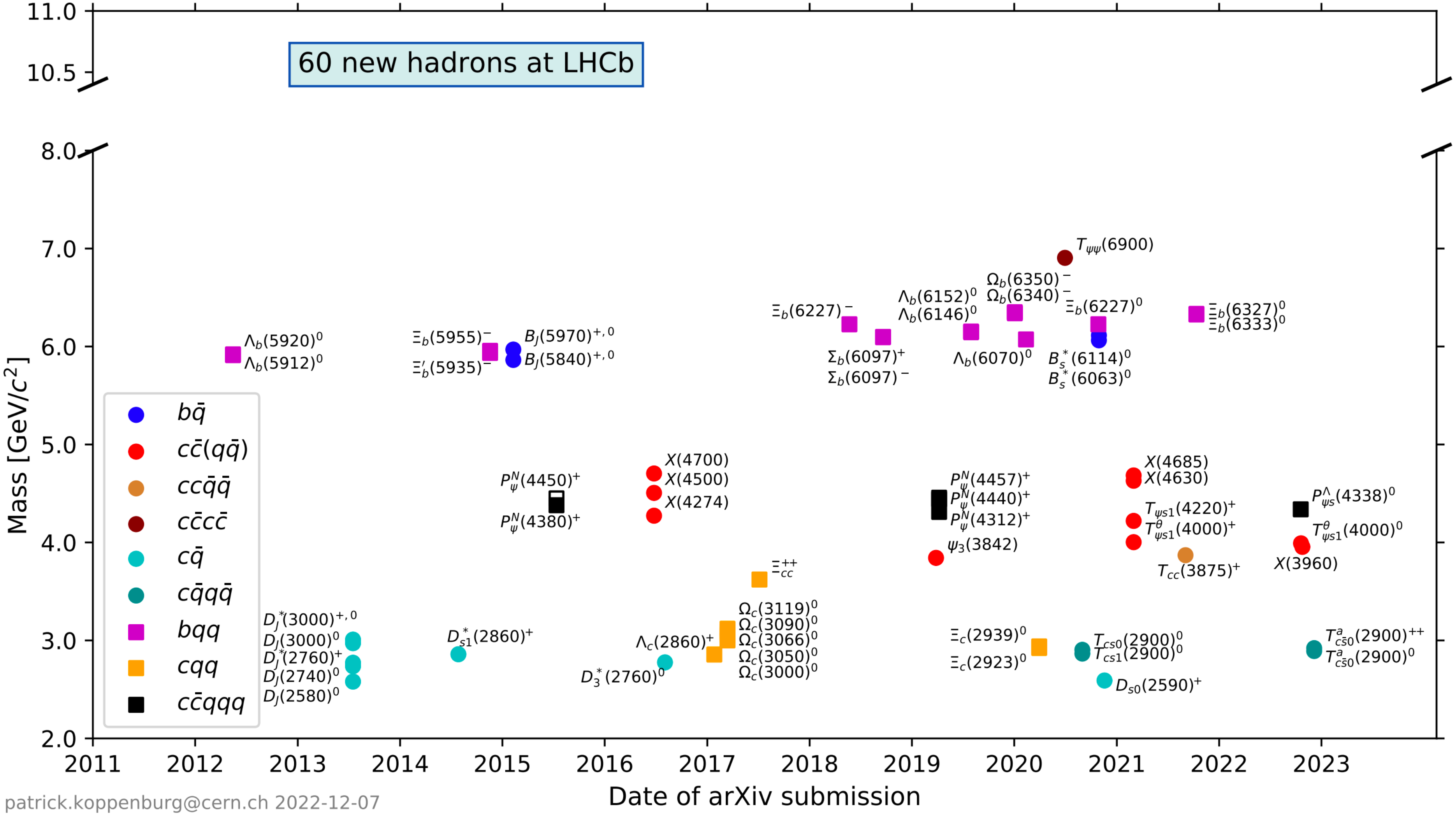
Improved by ×4

Improve δy_D by ×2: $y_D = (6.46^{+0.24}_{-0.25})\times 10^{-3}$

More on LHCb Charm by Liang SUN [14:20, Sat.]

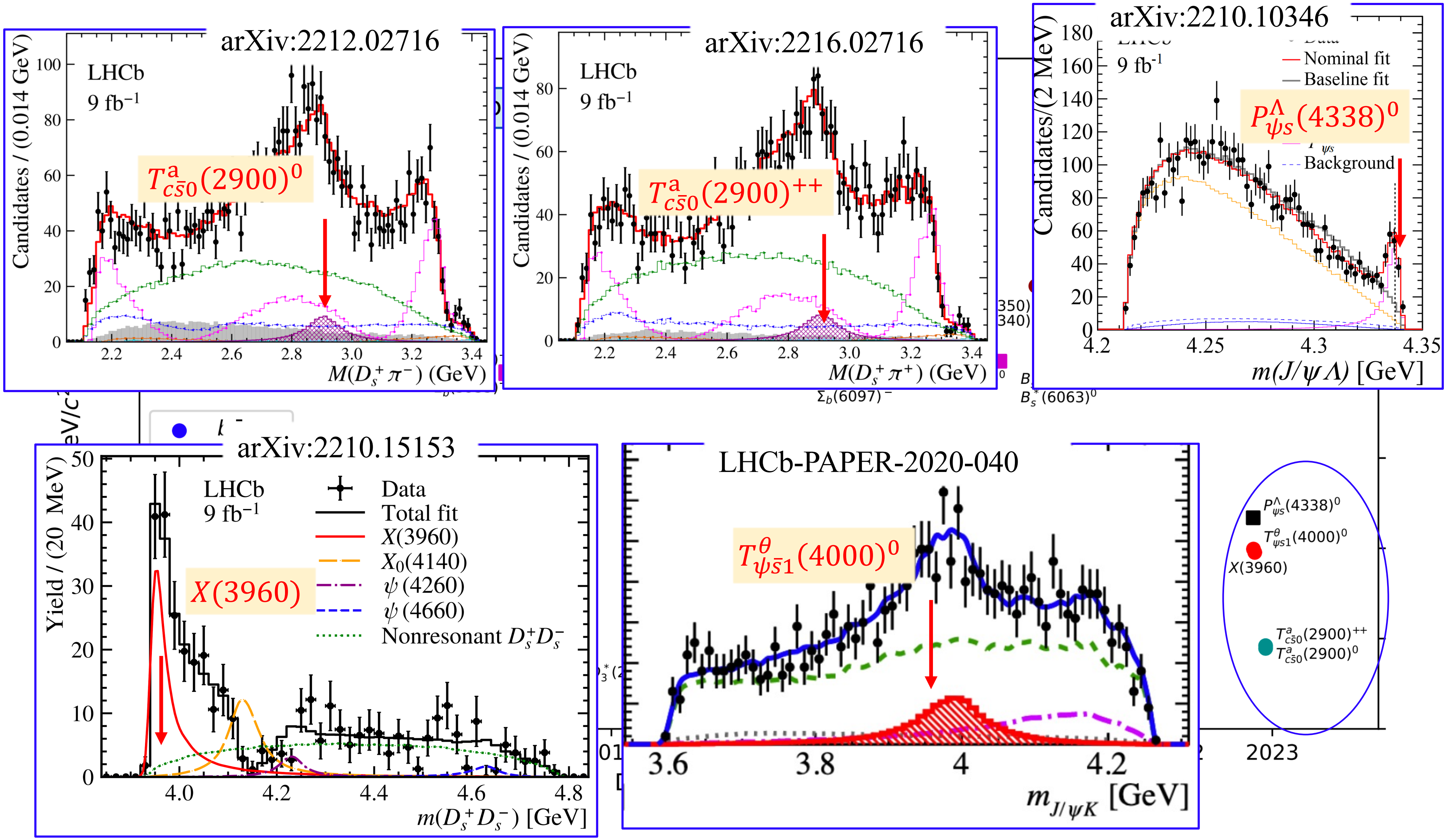
Hadron spectroscopy

List of new hadrons keep growing



New naming conventions:
arXiv:2206.15233

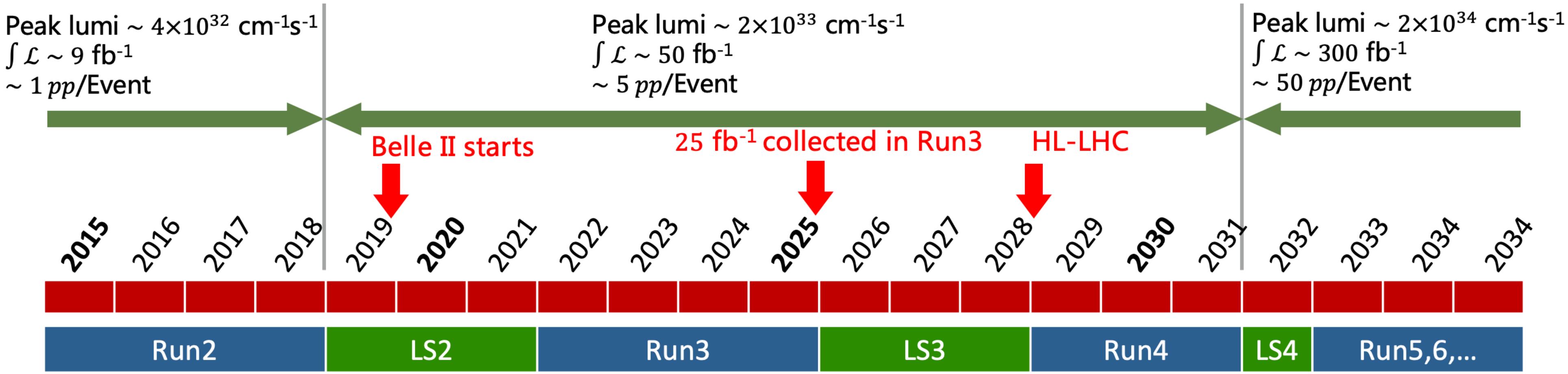
List of new hadrons keep growing



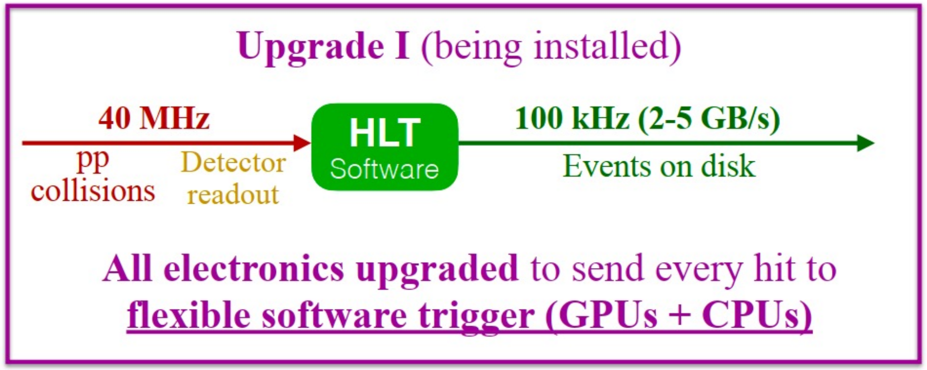
More on LHCb hadrons by Yiming LI [14:20, Sun.]

LHCb upgrade(d)

Long term plan beyond 2035

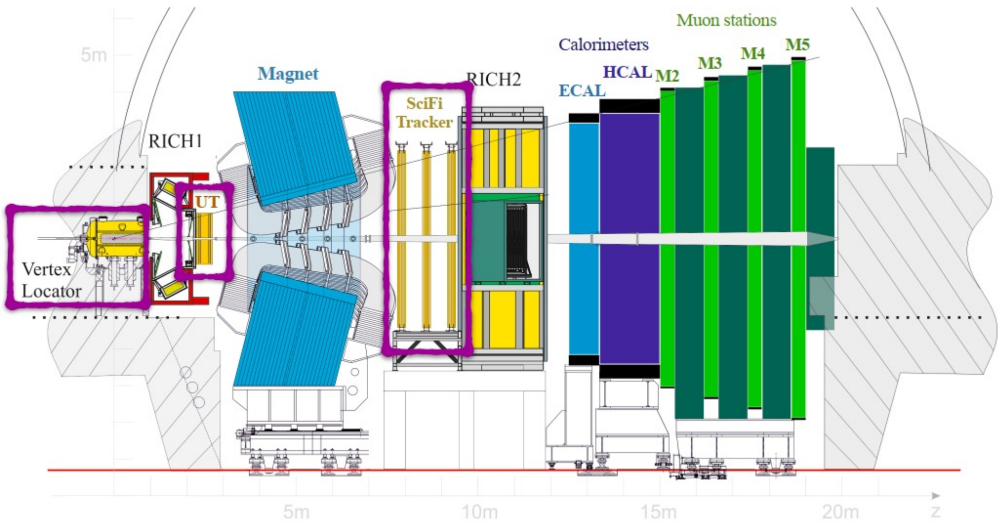


- Starts to accumulate data for Run3

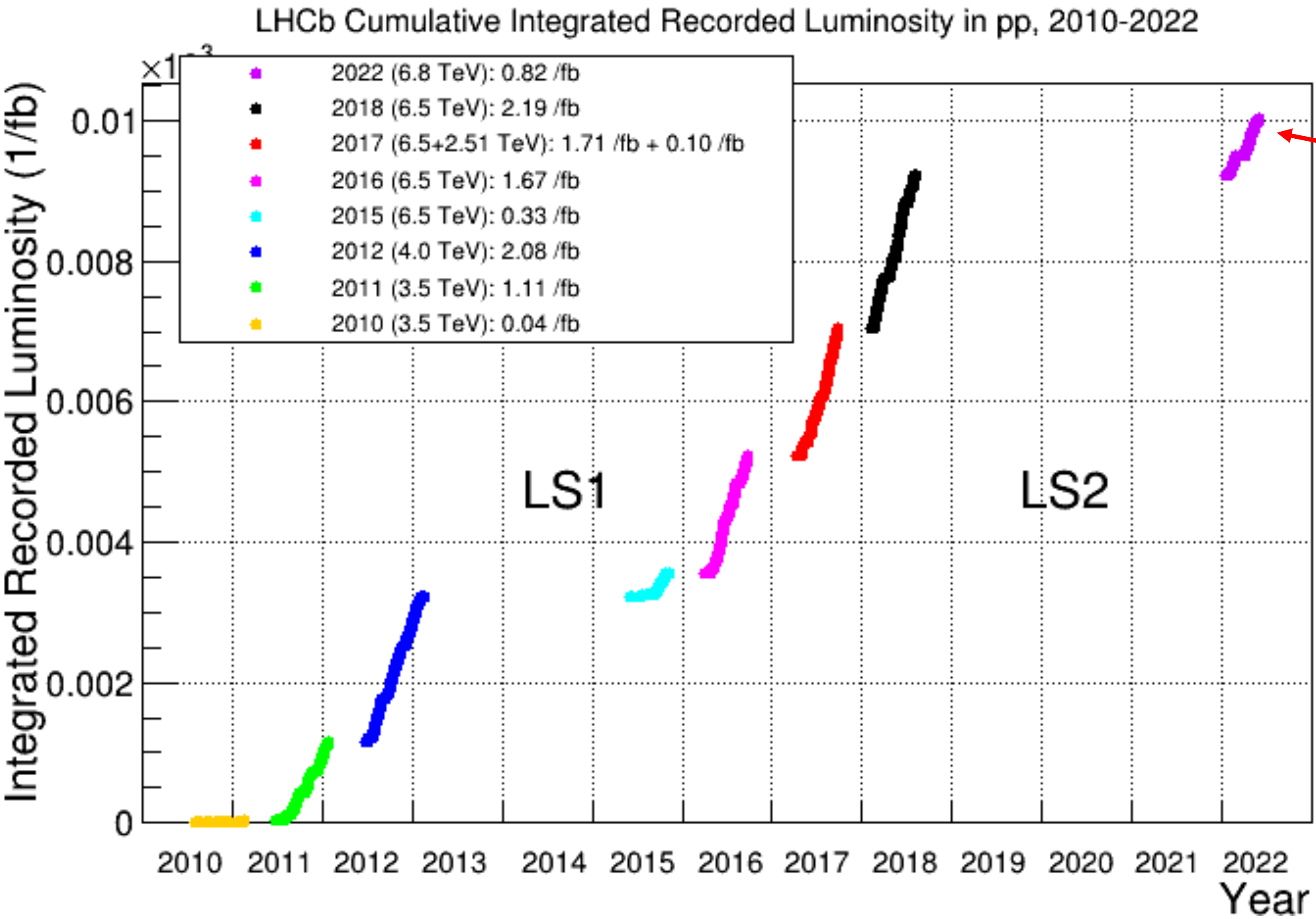


CERN-LHCC-2012-007

Increase granularity and longevity of **3 new trackers**



5x higher inst. lumi. to 2×10^{33} cm$^{-2}s^{-1}$,
5 visible interactions/crossing



LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2022
2022 (6.8 TeV): 0.82 /fb
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
LS1
LS2
Integrated Recorded Luminosity (1/fb)
0.01
0.008
0.006
0.004
0.002
0
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022
Year

This is Run3

LHCb upgrades

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].

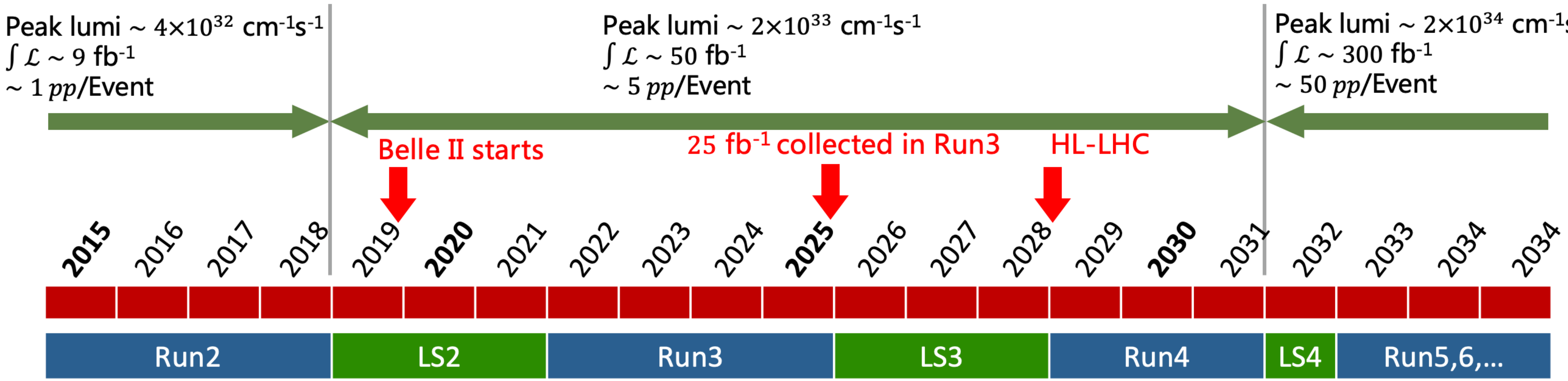
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, with $B^0_s \to D^+_s K^-$	$(^{+17}_{-22})^\circ$ [123]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [152]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [569]	0.011	0.005	0.003	–
ϕ_s, with $B^0_s \to J/\psi\phi$	49 mrad [32]	14 mrad	–	4 mrad	22 mrad [570]
ϕ_s, with $B^0_s \to D^+_s D^-_s$	170 mrad [37]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B^0_s \to \phi\phi$	150 mrad [571]	60 mrad	–	17 mrad	Under study [572]
a^s_{sl}	33×10^{-4} [193]	10×10^{-4}	–	3×10^{-4}	–

- **CKM tests**: match precision from indirect determination
  $\sigma_{\phi_s} \sim 4$ mrad, $\sigma_\gamma \sim 0.35^\circ$, $\sigma_{\sin 2\beta} \sim 0.003$

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
$b \to c l^- \bar{\nu}_l$ 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}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

- Studies of flavor towards new physics
- LHCb: a wide range of flavor physics, new results since HFCPV2021
  - Precision measurement of CKM matrix: $\gamma < 4°$
  - CPV in bottom hadrons: pattern in $B \to 3h$ decays
  - Flavor symmetries among leptons: $R(\Lambda_c^+)$
  - Charm mixing and CPV: precision on x_D, y_D, evidence of $A_{CP}(\pi^+\pi^-) \neq 0$
  - Hadron structure: more exotic hadrons
- LHCb plans for upgrade from 10 fb^{-1} to 300 fb^{-1}
  - New physics?



Don't miss other LHCb talks for details

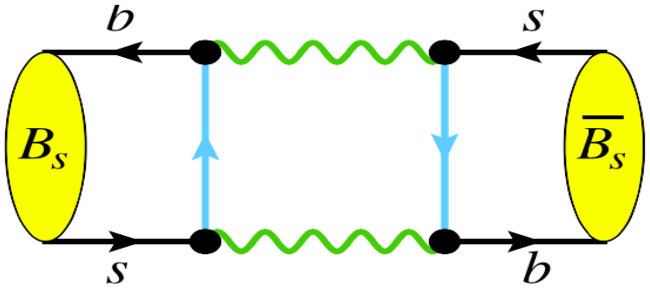
backups

Three types of CPV

- Mixing

$$\mathcal{P}(\bar{B}_s^0 \to B_s^0) \neq \mathcal{P}(B_s^0 \to \bar{B}_s^0)$$

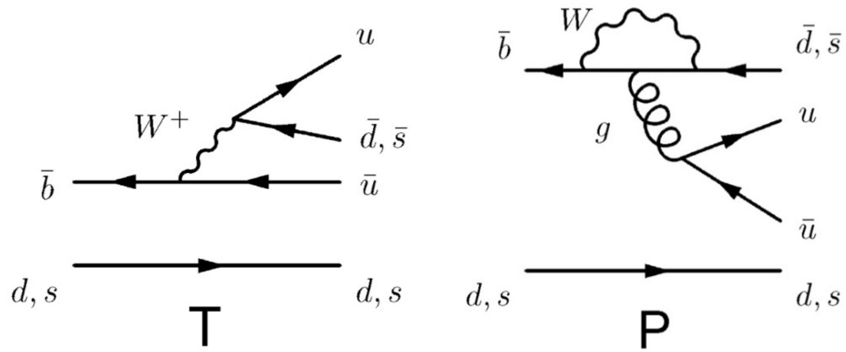
Off shell $\mathrm{Arg}(M_{12}) \neq \mathrm{Arg}(\Gamma_{12})$ On shell



- Decay

$$\mathcal{P}(B \to f) \neq \mathcal{P}(\bar{B} \to \bar{f})$$

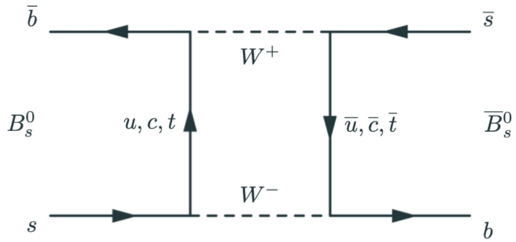
At least two interfering amplitudes with different strong and different weak phases



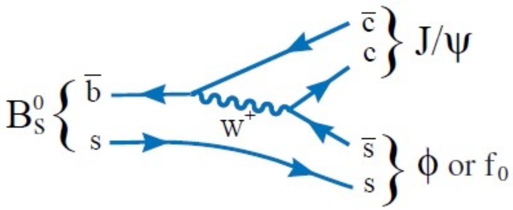
- Mixing and decay

$$\mathcal{P}(B \to \bar{B} \to f) \neq \mathcal{P}(\bar{B} \to B \to \bar{f})$$

Different weak phases in mixing and decay



$\propto (V_{tb}^* V_{ts})^2$



$\propto V_{cb}^* V_{cs}$

Constraining CKM matrix elements in SM and probing NP

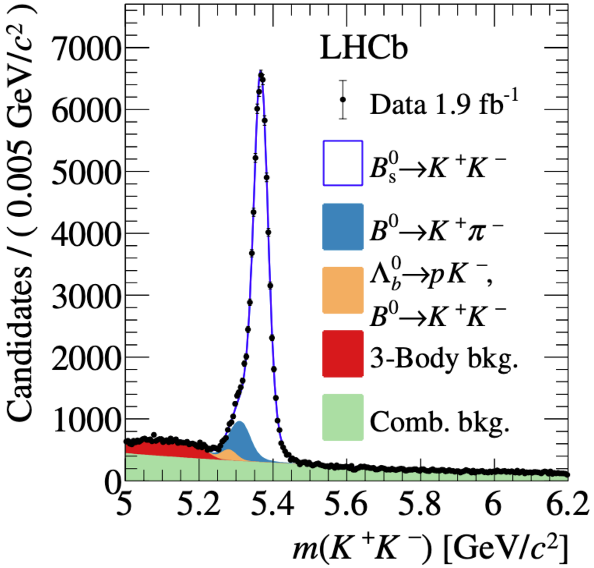
CPV in charmless decays

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

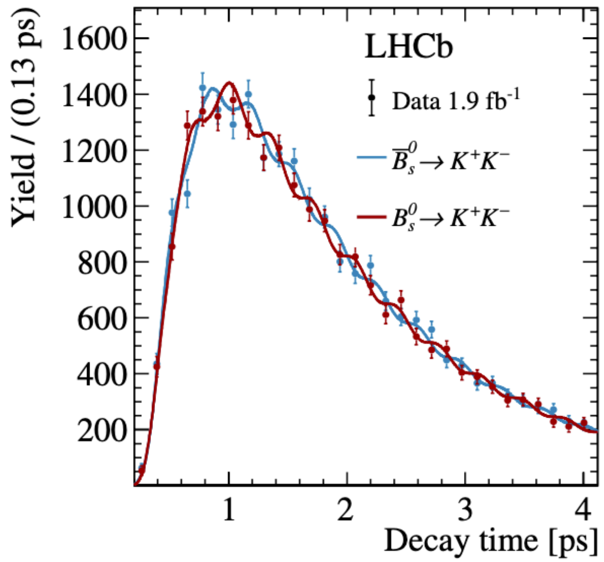
CPV in $B_s^0 \to K^+K^-$ decays

JHEP 03 (2021) 075

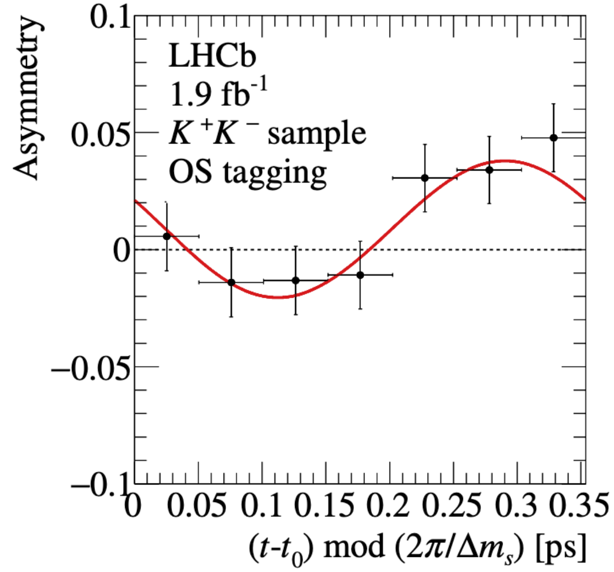
Mass distribution



Decay time distribution



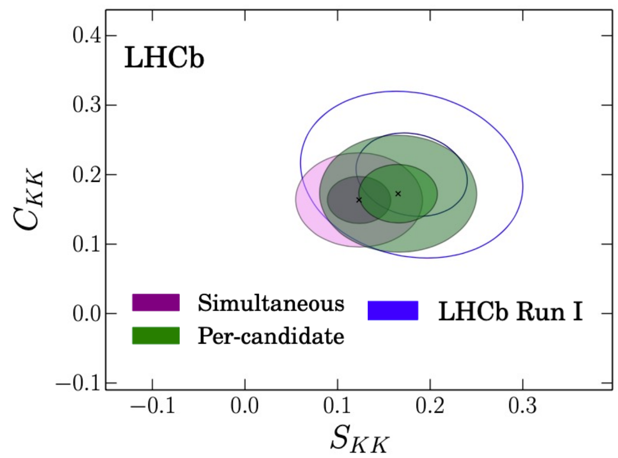
Time dependent asymmetry



$$C_{K^+K^-} = 0.164 \pm 0.034 \pm 0.14$$
$$S_{K^+K^-} = 0.123 \pm 0.034 \pm 0.15$$
$$A_{KK}^{\Delta\Gamma} = -0.83 \pm 0.05 \pm 0.09$$

$$\sqrt{C_{K^+K^-}^2 + S_{K^+K^-}^2 + \left(A_{KK}^{\Delta\Gamma}\right)^2} = 0.93 \pm 0.08$$

Consistent with Run I results



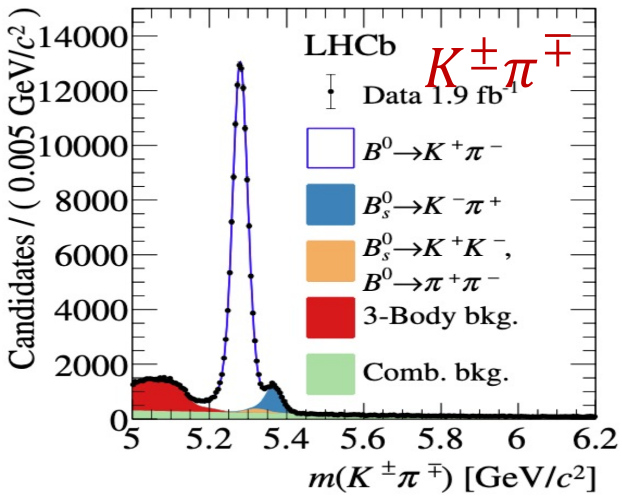
Direct CPV in $B \to K\pi$ system

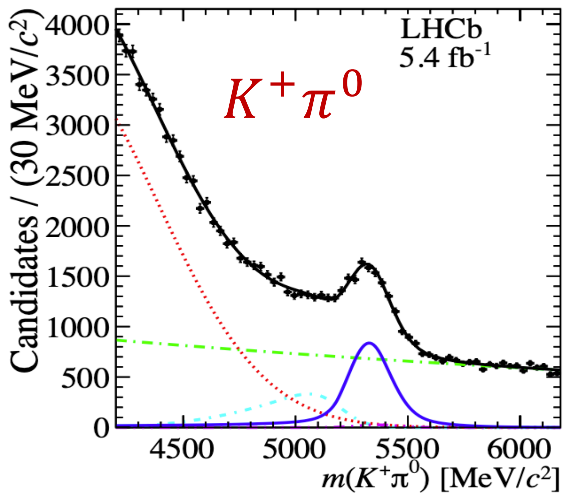
JHEP 03 (2021) 075
PRL 126 (2021) 091802

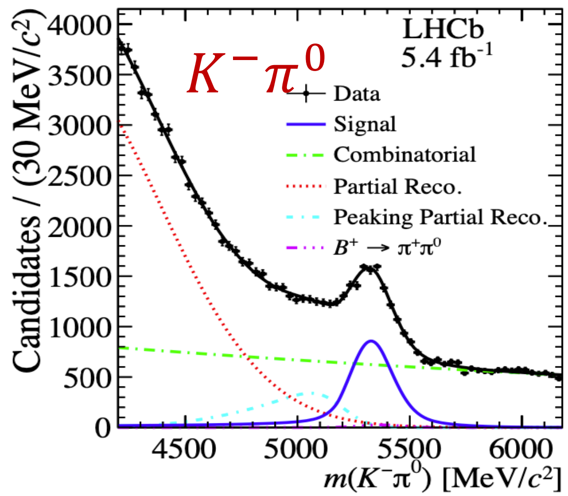
- Isospin symmetry implies $A_{\rm CP}(B^0 \to K^+\pi^-) \approx A_{\rm CP}(B^+ \to K^+\pi^0)$

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

- New measurements







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

New value of $\Delta A_{\rm CP}^{K\pi} = 0.115 \pm 0.014$, nonzero at $> 8\sigma$

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

$$\Delta \equiv \frac{A_{\rm CP}(B^0 \to K^+\pi^-)}{A_{\rm CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B \to K^+\pi^-)}\frac{\Gamma_s}{\Gamma_d} = -0.085 \pm 0.043$$, nonzero at 2σ

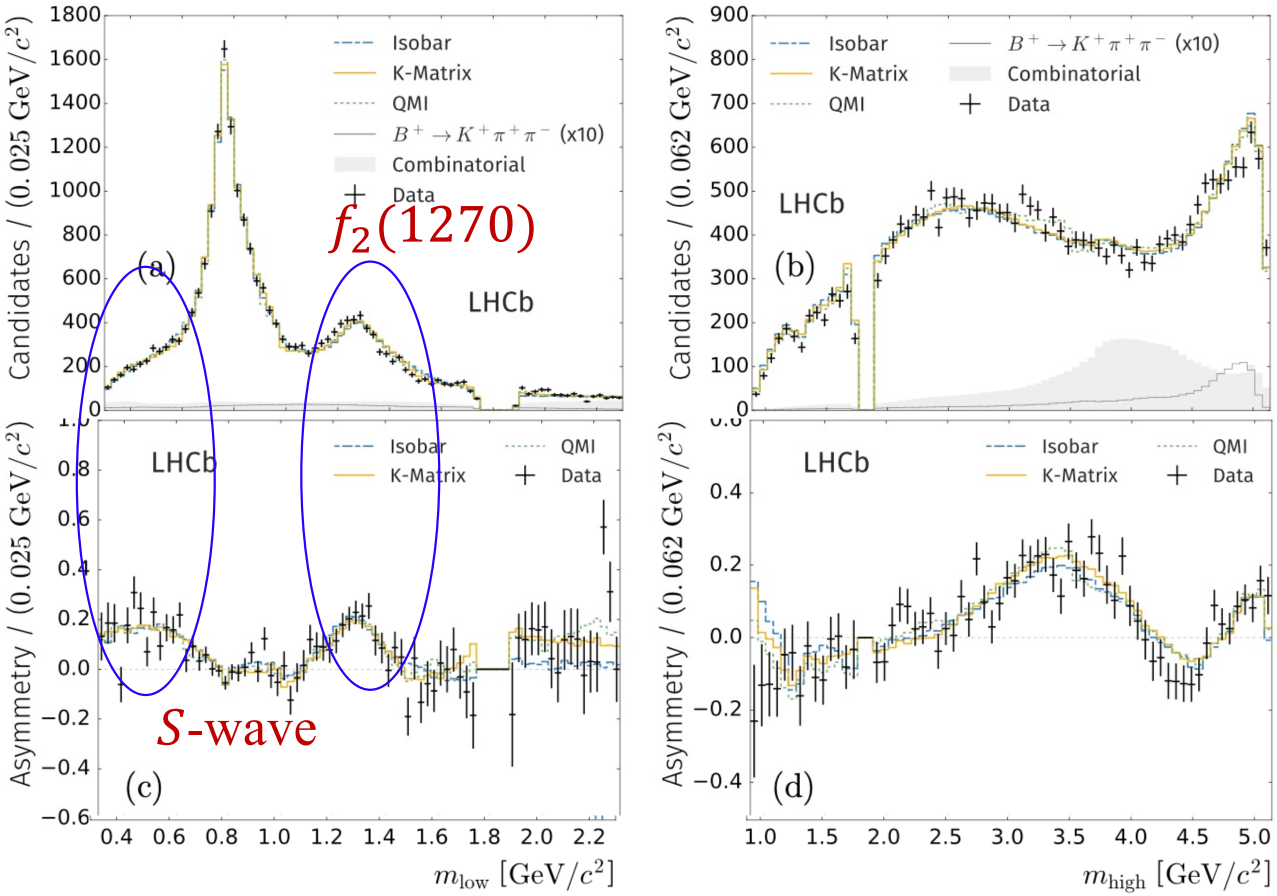
Direct CPV in $B^+ \to \pi^+\pi^-\pi^+$

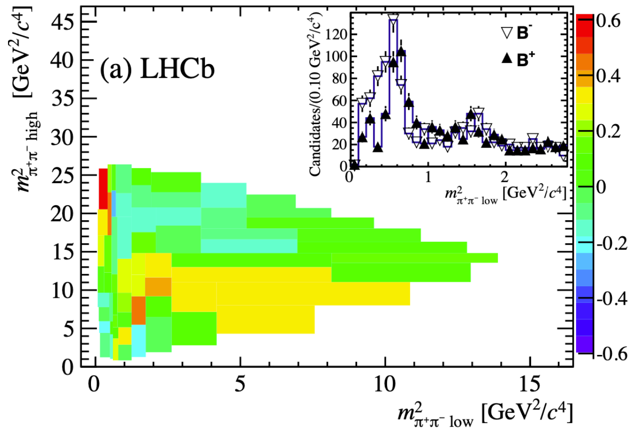
PRL 124 (2020) 031081
PRD 101 (2020) 012006

- CPV observed in phase space of $B \to hhh$ decays, better understanding with Dalitz plot analysis

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

Mass projections and CP





Components and quasi-two-body $A_{\rm CP}$

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	$+14.4 \pm 1.8 \pm 1.0 \pm 1.9$

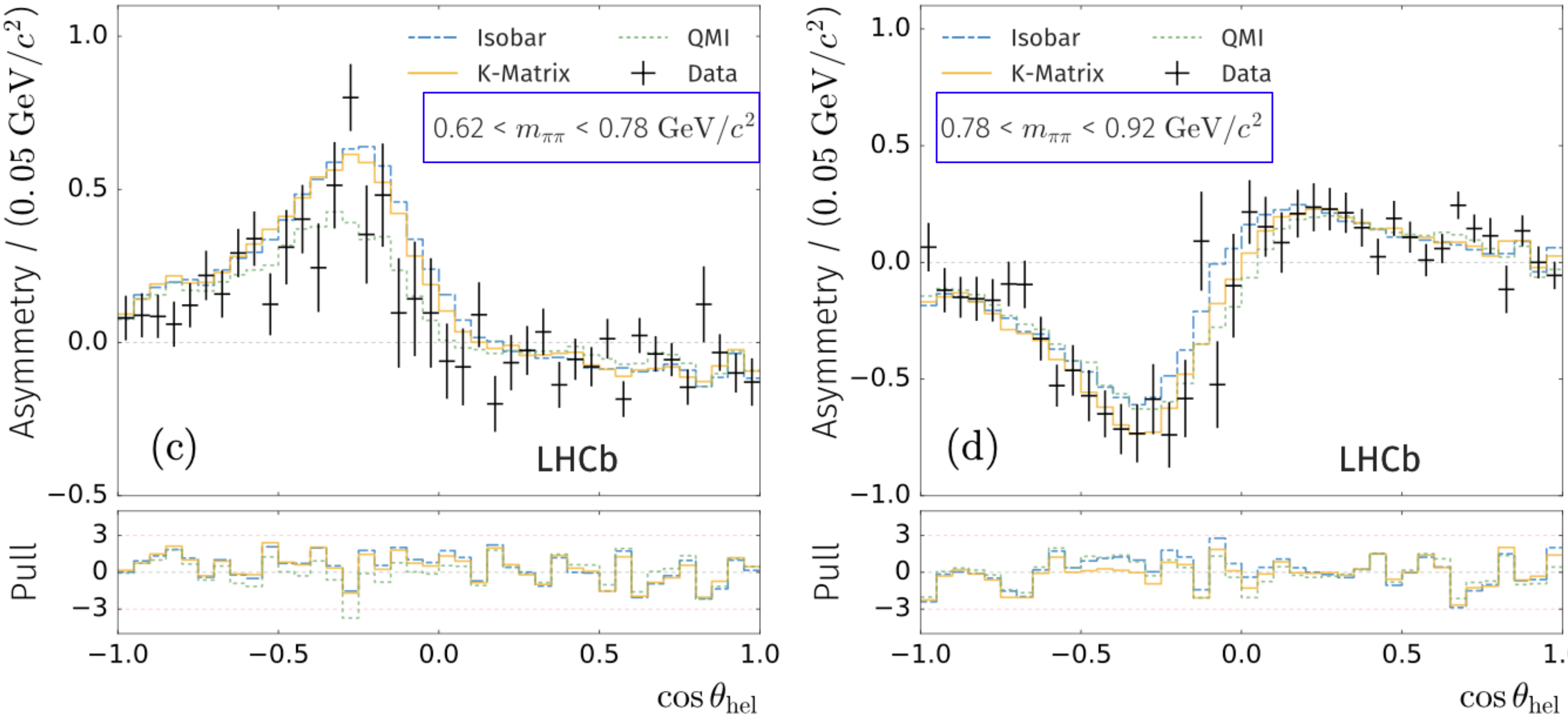
$S - P$ wave interference

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

$$A_{\mathrm{CP}} \propto \cos\theta \times (m_S^2 - S) \times (m_P^2 - S) + \cdots$$

A_{CP} in bins of helicity angle

Below $\rho(770)^0$ mass   Above $\rho(770)^0$ mass



Direct CPV in $B^+ \to \pi^+ K^- K^+$

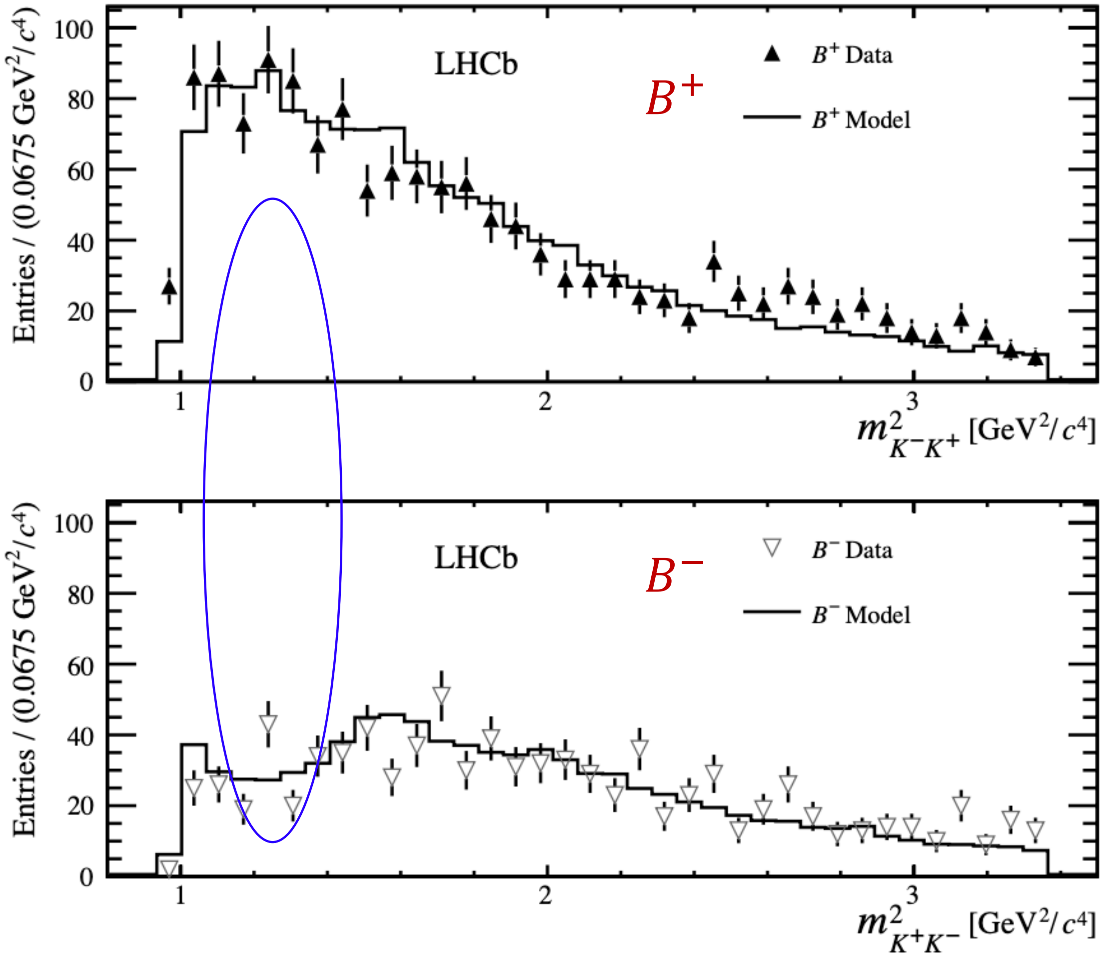
PRL 123 (2019) 231802

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

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

Mass and fit projections

$A_{CP} = (-66 \pm 4 \pm 2)\%$



Quasi-two-body A_{CP}

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	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$

CPV in beauty baryons

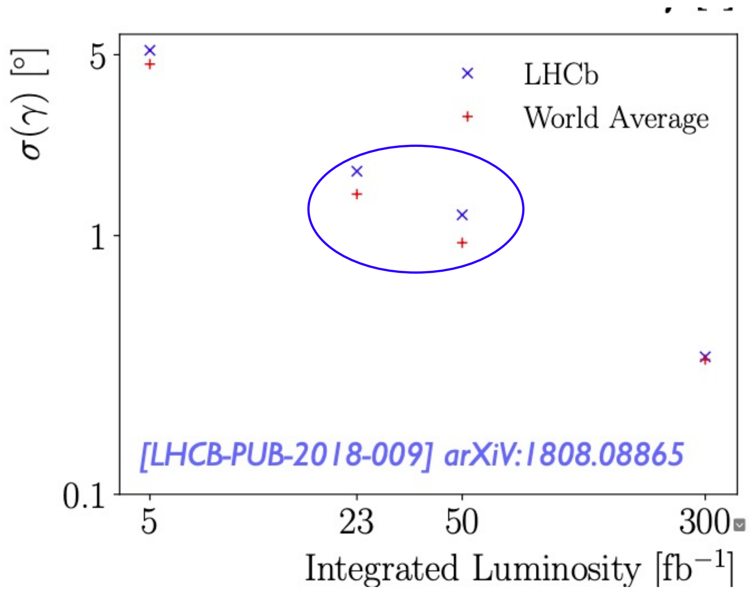
A new terrain for CPV and CKM matrix

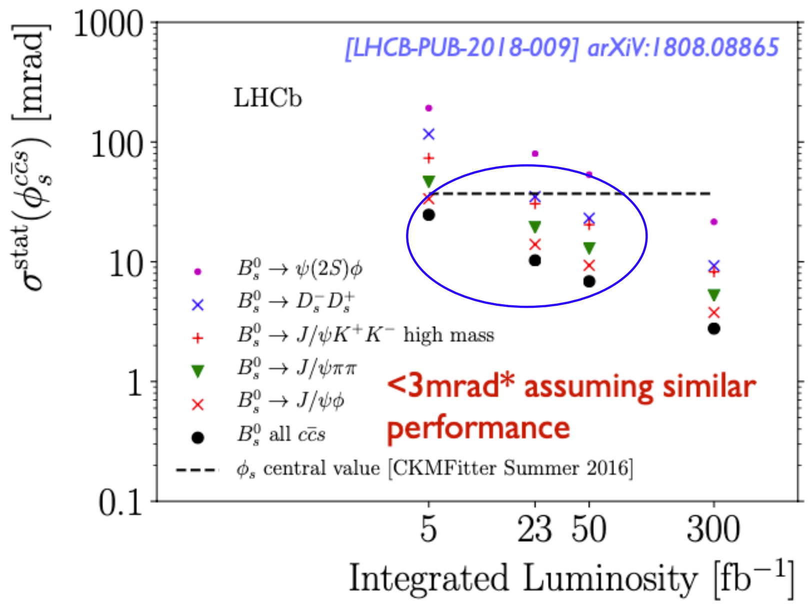
Summary

- New results on mixing parameters, direct CPV in $b \to D$ and charmless decays

  $\Delta M_s = 17.7656 \pm 0.0057\ \text{ps}^{-1}, \phi_s = -42 \pm 25\ \text{mrad}, \gamma = (65.4^{+3.8}_{-4.2})^{\circ}, A_{CP}(hh(h))\ldots$

  Even new ones are coming with full run 1+ run 2data
- No CPV in beauty baryons observed, but started to be sensitive at % level
- The future:





And baryon CPV

LHCb上味物理中的反常	何吉波
Hadron spectroscopy and exotics at LHCb	张黎明
gamma measurements at LHCb	张舒楠
Recent charm physics results at LHCb	孙亮
Recent CPV measurements at LHCb	俞洁晟

Backup slides

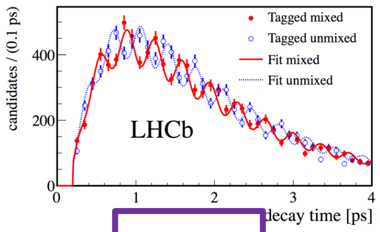
CKM matrix up to λ^6

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

LHCb

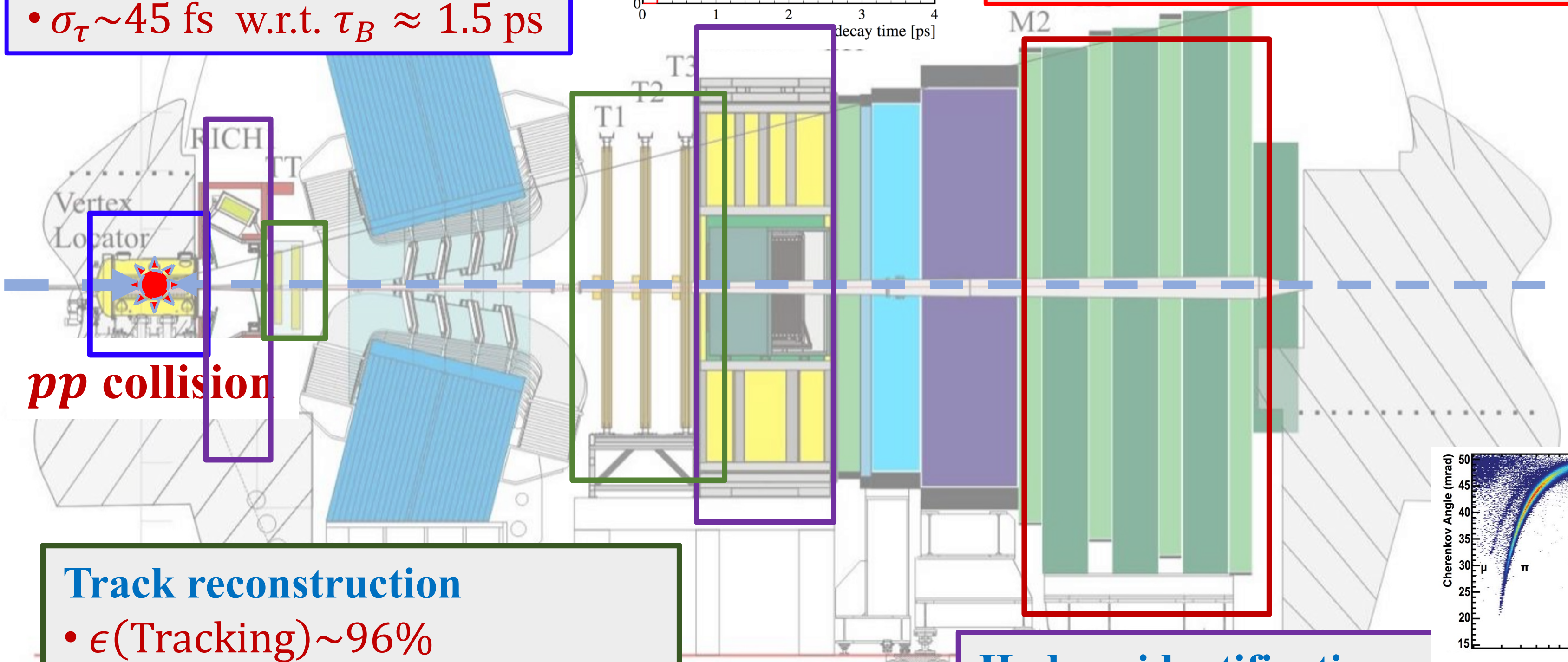
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- Dedicated flavor experiment for b, c hadrons



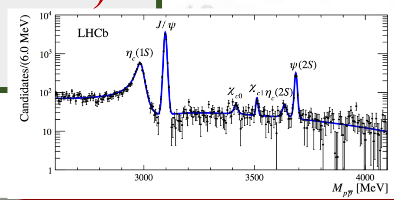
Vertex reconstruction
- σ_{IP}~20 μm
- σ_τ~45 fs w.r.t. $\tau_B \approx 1.5$ ps

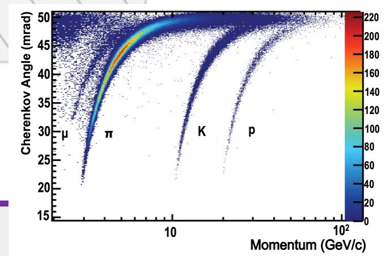
Muon identification
- $\epsilon(\mu \to \mu)$~97%
- MisID rate $(\pi \to \mu)$~$1-3\%$



***pp* collision**

Track reconstruction
- ϵ(Tracking)~96%
- $\delta p/p$ ~0.5%-1% (5-200 GeV)
- $\epsilon(m_{J/\psi}) \approx 15$ MeV





Hadron identification
- $\epsilon(K \to K), \epsilon(p \to p) > 90\%$
- MisID rate $(\pi \to K/p) < 5\%$

New γ combination

LHCb-CONF-2022-003

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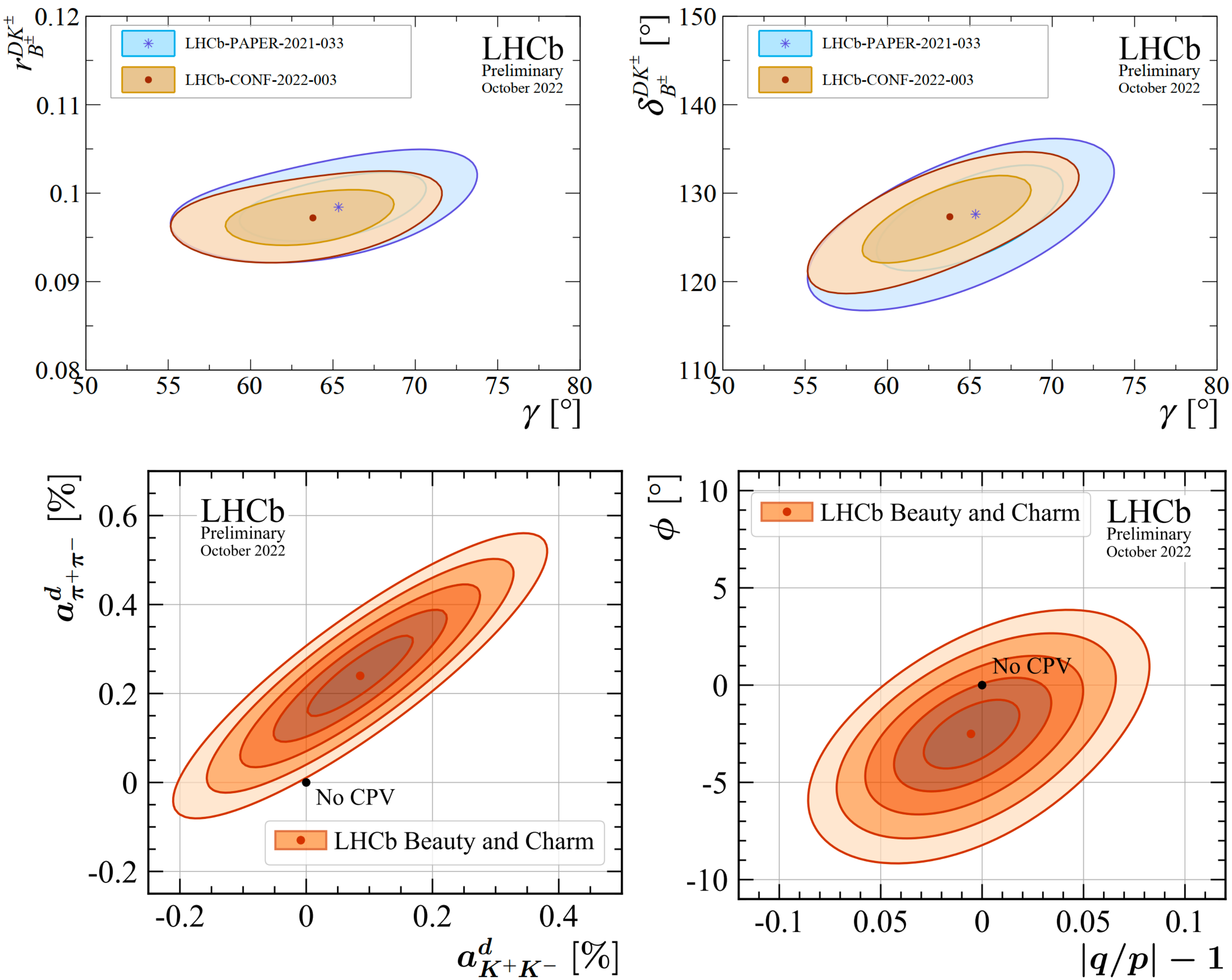


Mixing and CPV

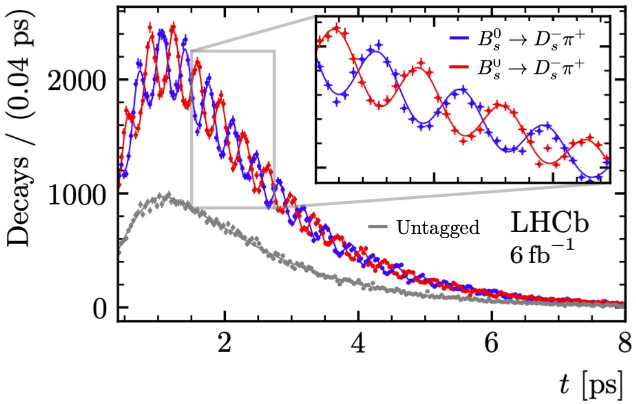
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

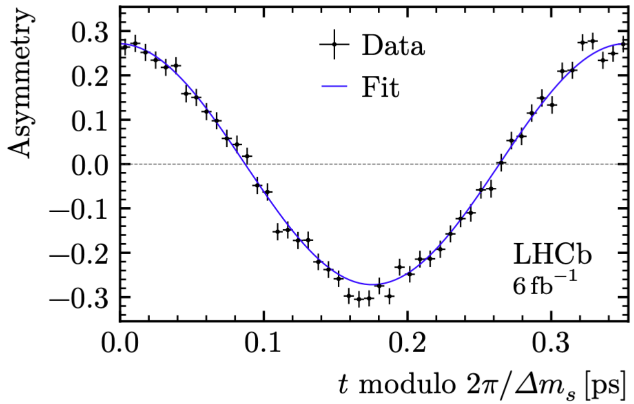
ΔM_s of $B_s^0 - \bar{B}_s^0$ oscillation

Time dependent rate of flavor specific decays

$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C \cdot \cos(\Delta m_s t)\right] \quad C = \begin{cases} -1 & \text{if mixing occurs} \\ 1 & \text{if not mixed} \end{cases}$$

Degraded by initial b-flavor tagging: $\epsilon(1-\omega)^2 \sim 6\%$

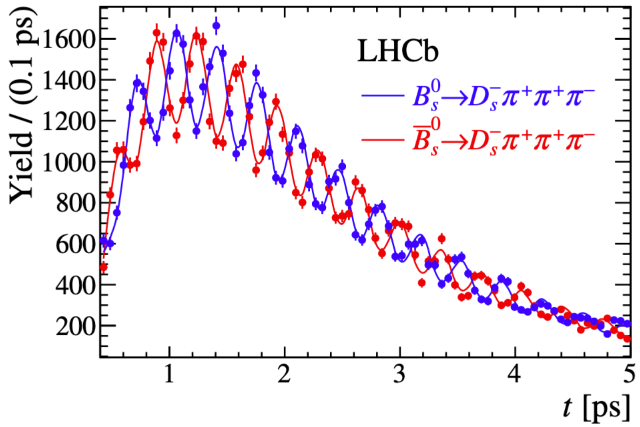


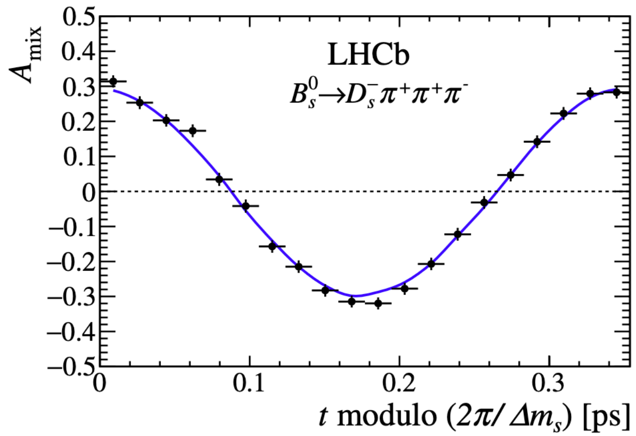


$B_s \to D_s^{\pm}\pi^{\mp}$

Giving most precise single measurement

arXiv:2104.04421





$B_s \to D_s^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$

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LHCb average: $\Delta M_s = 17.7656 \pm 0.0057\ \text{ps}^{-1}$

Lattice and sum rule Prediction: $18.4^{+0.7}_{-1.2}\ \text{ps}^{-1}$

B_s^0 mixing angle $\phi_s = -2\beta_s^{\text{eff}}$

- ϕ_s sensitive to new physics, SM prediction: $\phi_s = -37 \pm 1$ mrad
- Time dependent CP asymmetry:

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

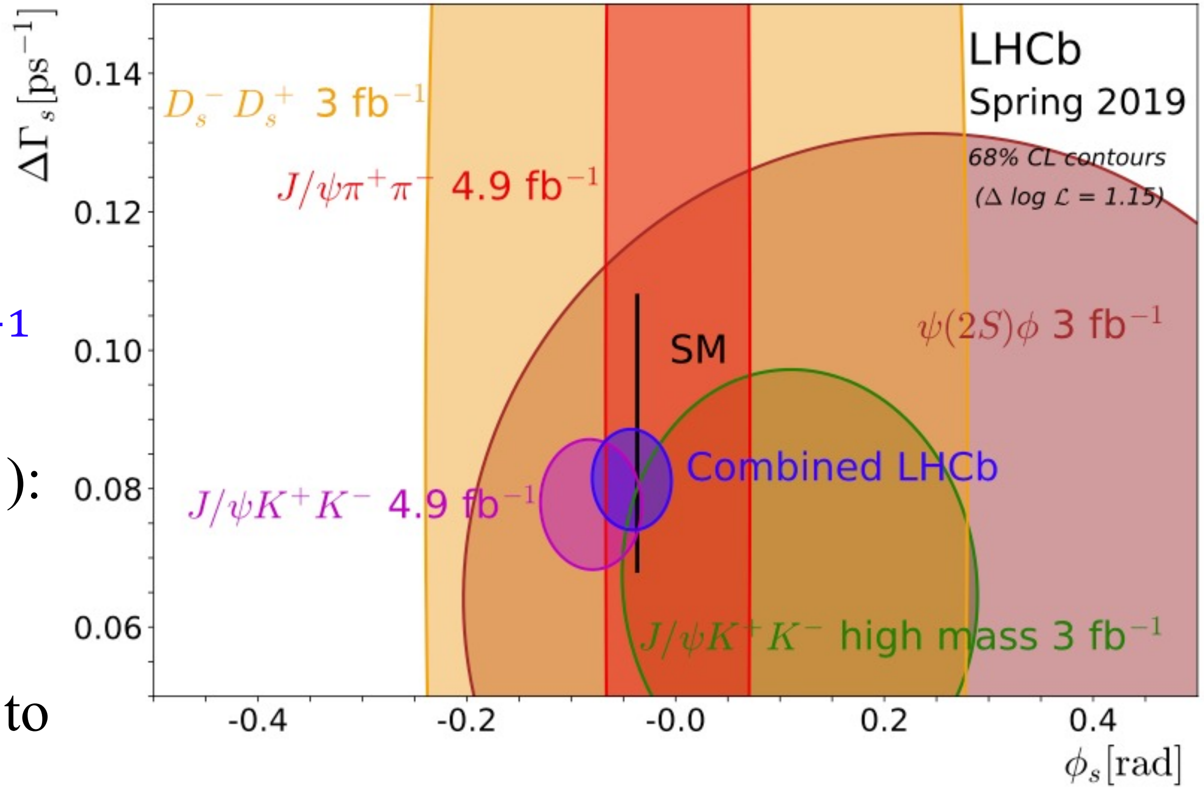
$$A_{\text{CP}}(t) = \frac{\Gamma_{\bar{B}_s^0\to f}(t) - \Gamma_{B_s^0\to f}(t)}{\Gamma_{\bar{B}_s^0\to f}(t) + \Gamma_{B_s^0\to f}(t)} \propto -\eta_f \sin\phi_s \sin(\Delta M_s t)$$

f: common final state

EPJC 79 (2019) 706

- LHCb combination of five measurements

$\phi_s = -42 \pm 25$ mrad
$\Delta\Gamma_s = 0.0813 \pm 0.0048\ \text{ps}^{-1}$



New world average (PDG 2021):

$\phi_s = -50 \pm 19$ mrad

Consistent with SM, but need to gain experimental precision

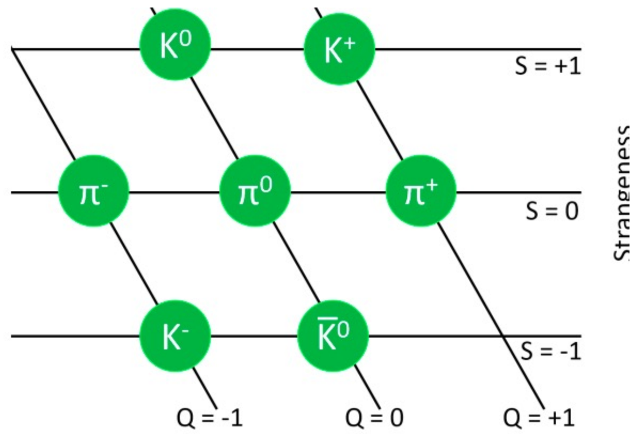
U-spin symmetry

- *CP* asymmetries of partial decay widths in $B^{\pm} \to h^{\pm}h^{+}h^{-}$ decays related to U-spin symmetry

Phys. Lett. B824 (2022) 136824

Phys. Lett. B726 (2013) 337

Phys. Lett. B564 (2003) 90



- Theoretical prediction:

$$\frac{\Delta\Gamma(B^{\pm} \to \pi^{\pm}K^{+}K^{-})}{\Delta\Gamma(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-})} = \frac{\Delta\Gamma(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-})}{\Delta\Gamma(B^{\pm} \to K^{\pm}K^{+}K^{-})} = -1$$

Phys. Rev. D102 (2020) 112010

$$\Delta\Gamma_{CP}(h_1^{\pm}h_2^{+}h_3^{-}) = \Gamma(h_1^{-}h_2^{+}h_3^{-}) - \Gamma(h_1^{+}h_2^{-}h_3^{+}) = \frac{A_{CP}(B^{\pm} \to h_1^{\pm}h_2^{+}h_3^{-})\mathcal{B}(B^{+} \to h_1^{+}h_2^{+}h_3^{-})}{\tau(B^{+})}$$

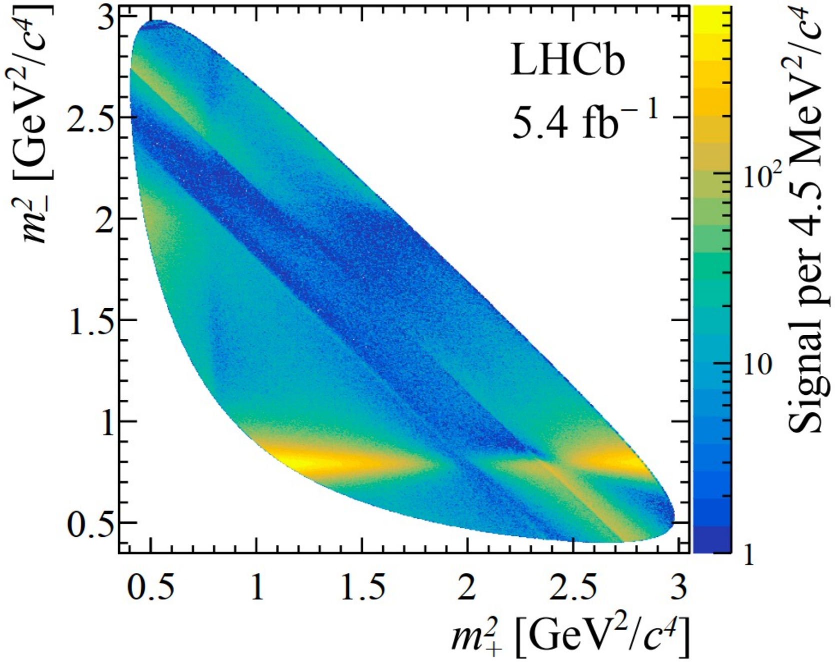
Results:

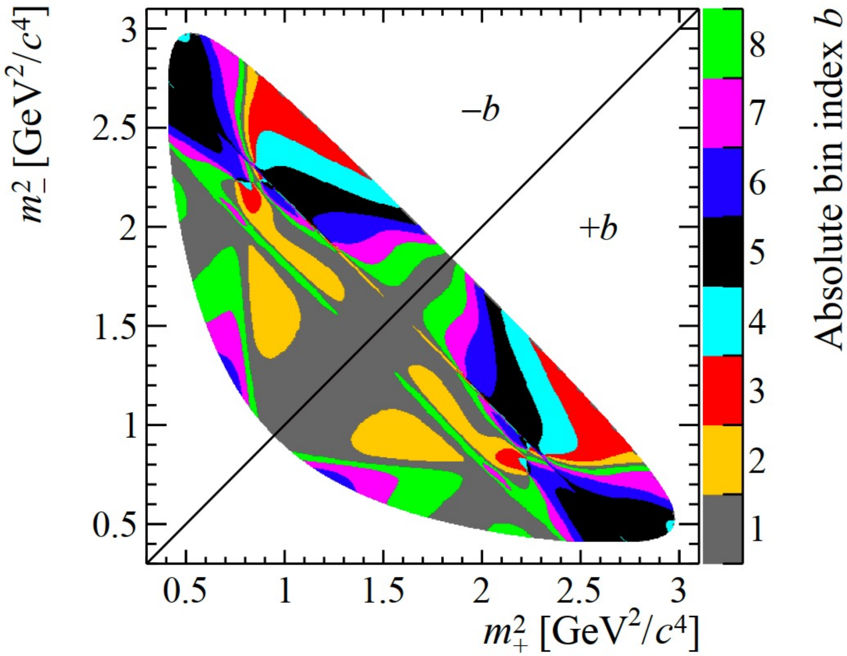
$$\frac{\Delta\Gamma(B^{\pm} \to \pi^{\pm}K^{+}K^{-})}{\Delta\Gamma(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-})} = \frac{A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-})\mathcal{B}(B^{+} \to \pi^{+}K^{+}K^{-})}{A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-})\mathcal{B}(B^{+} \to K^{+}\pi^{+}\pi^{-})} = -0.92 \pm 0.18$$

$$\frac{\Delta\Gamma(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-})}{\Delta\Gamma(B^{\pm} \to K^{\pm}K^{+}K^{-})} = \frac{A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-})\mathcal{B}(B^{+} \to \pi^{\pm}\pi^{+}\pi^{-})}{A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-})\mathcal{B}(B^{+} \to K^{+}K^{+}K^{-})} = -1.06 \pm 0.08$$

In agreement with the predictions

$D^0 \to K_S^0\pi^+\pi^-$ Dalitz binning



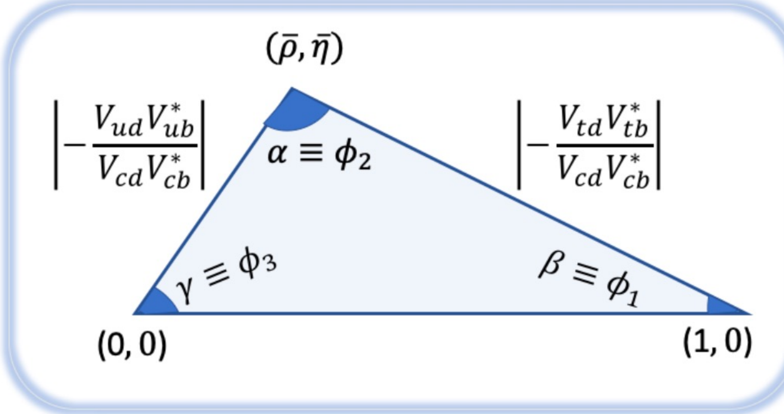


$$R_{bj}^{\pm} \approx \frac{r_b + \frac{1}{4} r_b \langle t^2\rangle_j \, \mathrm{Re}\left(z_{CP}^2 - \Delta z^2\right) + \frac{1}{4}\langle t^2\rangle_j \, |z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j \, \mathrm{Re}\left[X_b^*(z_{CP} \pm \Delta z)\right]}{1 + \frac{1}{4}\langle t^2\rangle_j \, \mathrm{Re}\left(z_{CP}^2 - \Delta z^2\right) + r_b \frac{1}{4}\langle t^2\rangle_j \, |z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j \, \mathrm{Re}\left[X_b(z_{CP} \pm \Delta z)\right]},$$

The rates of the decay processes are parametrized in different ways by CKM matrix elements

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

Unitarity triangle in the $(\bar{\rho}, \bar{\eta})$ complex plane



Overconstraint the CKM elements precisely is one of the key goal of the **Flavour Physics**

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

- 4 parameters: $A,\ \lambda,\ \rho, \eta$
  - 3 angles
  - 1 complex phase

- Parameters are obtained and tested wrt data (rich pheno and large mass range): Nucleons, K, D, $B_{(s)}$ and top quark physics

$V_{CKM} =$