(Selected) highlights from LHCb experiment

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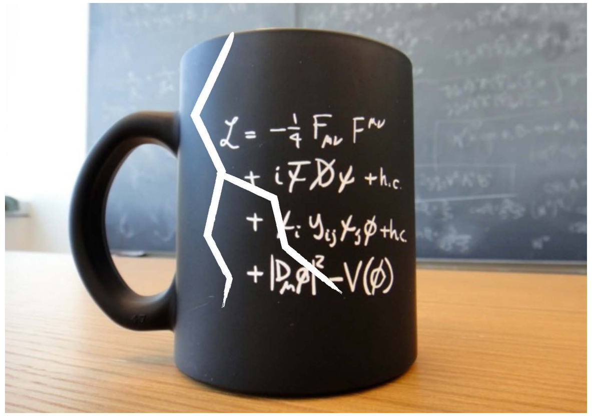
Mini-Workshop at IAS Program on High Energy Physics

Feb 12-13, 2023

Role of flavour physics

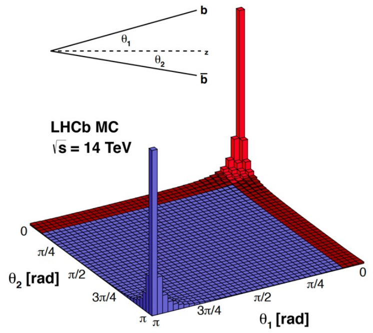
- **Key open HEP questions**
  - Why antimatter disappear?
  - Any BSM physics and what is the form?

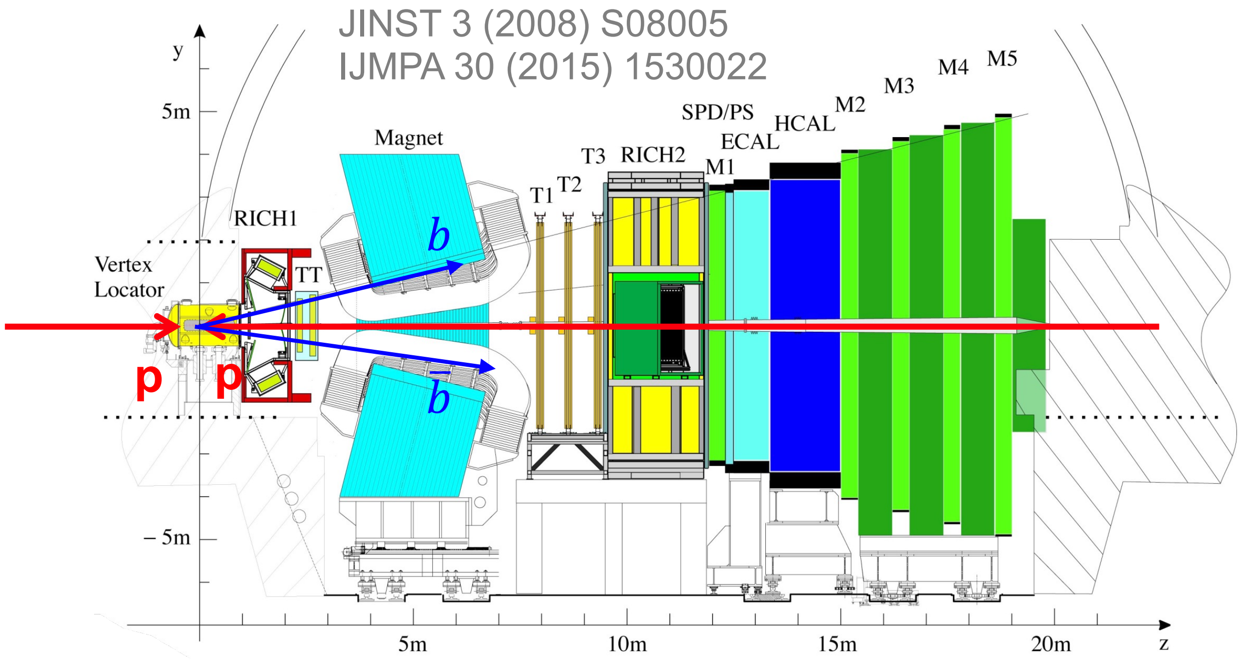


- **Precision study of flavour and CP violation can probe BSM physics**
  - Looking for new sources of CP violation
    - Precision flavour measurements to overconstrain CKM matrix
  - Looking for new phenomena in rare or forbidden decays
    - Flavour changing neutral current
    - Lepton flavour universality violation
    - Lepton flavour number violation

LHCb experiment

- **LHCb is a dedicated flavour physics experiment at the LHC**
  - >10⁴ $\times$ larger b production rate than the B factories @ Υ(4S)
  - Access to all b-hadrons: B^+, B^0, B_s^0, B_c^+, b-baryons
- **Can also study hadron spectroscopy and exotic states**
- **Acceptance optimised for forward $b\bar{b}$ production**





$\Delta p/p$=0.4-0.6%
$\varepsilon(\mu\to\mu)$~95%, $\varepsilon(\pi\to\mu)$~1%
$\varepsilon(K\to K)$~95%, $\varepsilon(\pi\to K)$~5%
$\varepsilon(e\to e)$~90%, misID~5%

Run-1 (2011-12) : 3.0 fb^{-1}
Run-2 (2015-18) : 6.0 fb^{-1}

CKM matrix

CKM mechanism

CKM matrix elements are fundamental SM parameters

- **Only known source for CPV in SM**
- **But insufficient to explain baryon asymmetry in Universe**

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

Three generations of quarks:

- ✓ **Unitary matrix**
- ✓ **3 rotation angles**
- ✓ **1 phase**

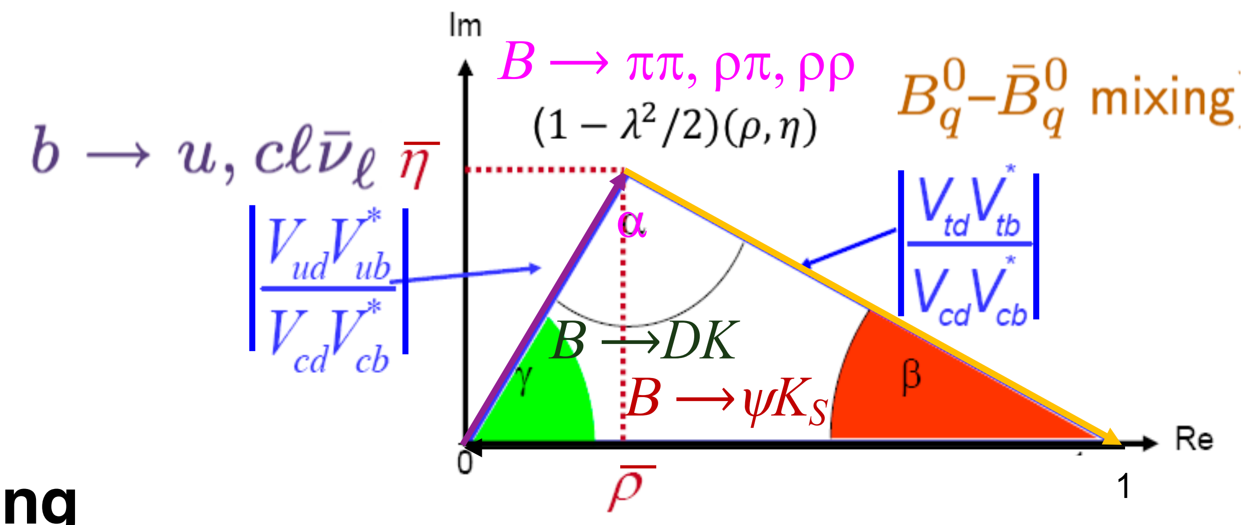
Test of CKM unitarity is a key test of SM:

- **New physics (NP) beyond SM?**
- **More than three quarks?**
- **New source of CPV?**

How to measure

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

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

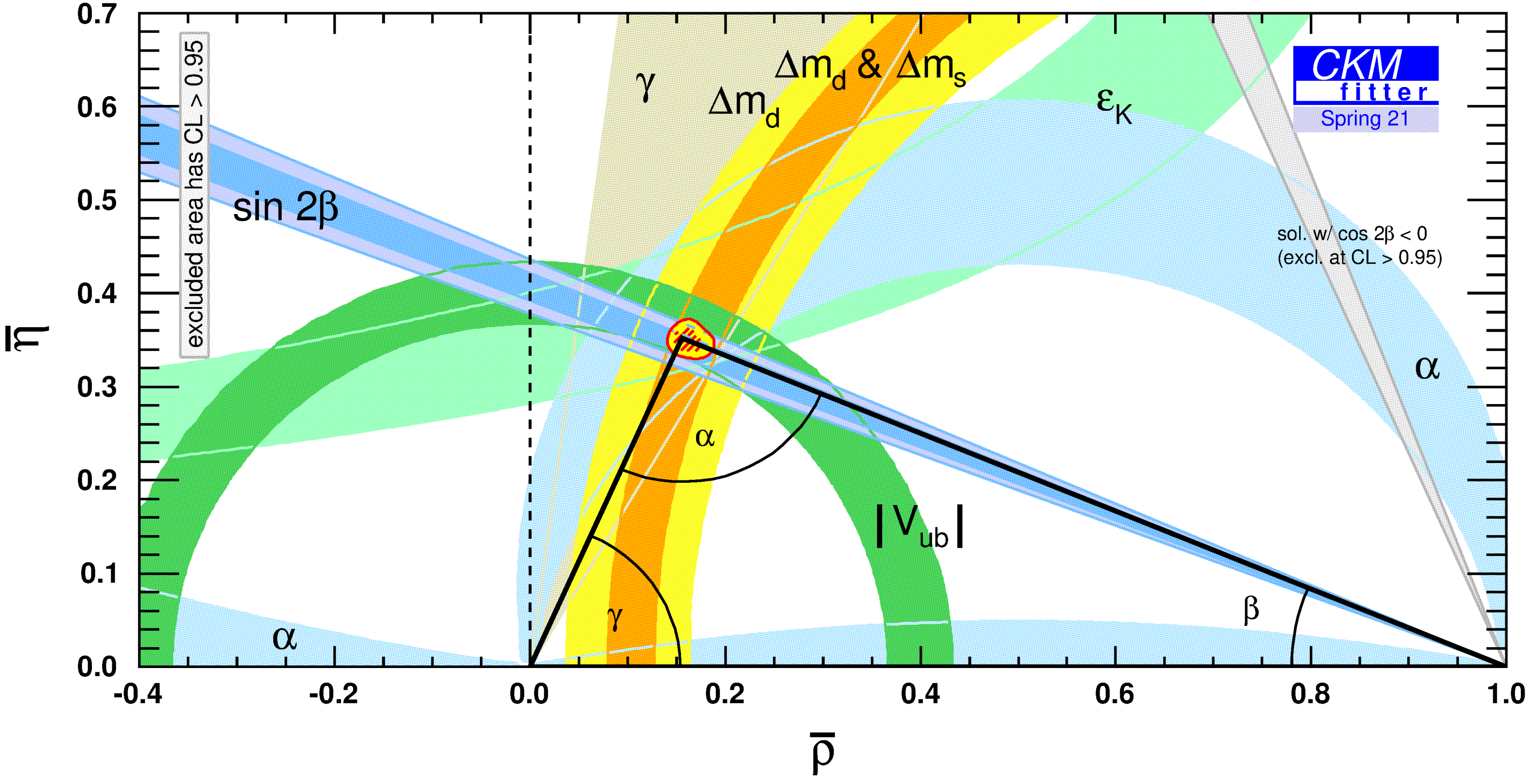


- **Test of Unitarity by measuring**
  - Angles (CP violating) and sides (CP conserving)

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \qquad \alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \qquad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

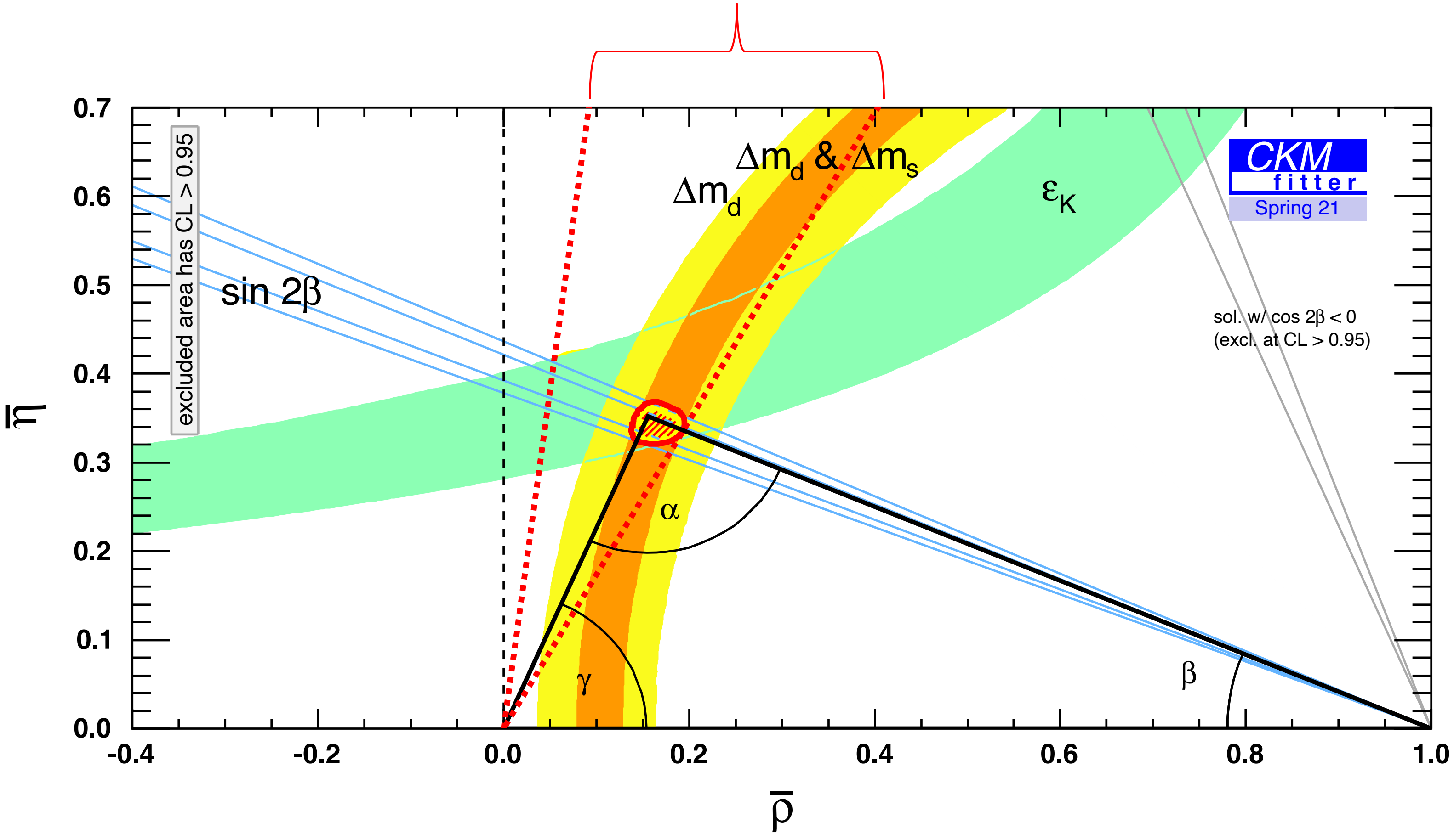
CKM unitarity triangle

- All measurements are consistent with CKM unitarity
- More precision measurements needed



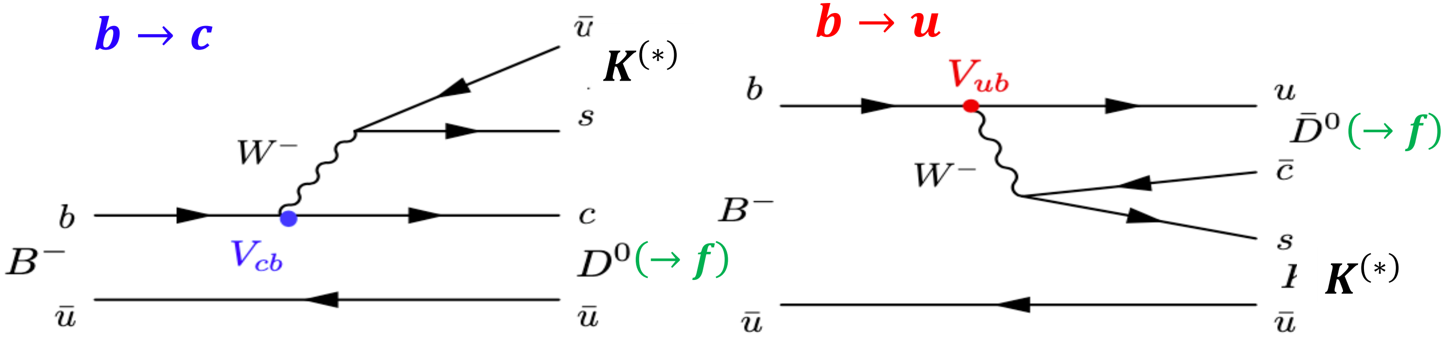
Loop vs tree to probe NP

- **CKM triangle determined from loop processes**
- **Compared with tree-level determination for γ**



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}

Coherent factor κ_D: dilution for multibody D decays

- Independent measurements with various D modes

$f_D = \begin{cases} KK, \pi\pi \text{ (GLW)} \\ K\pi, K3\pi \text{ (ADS)} \\ K_S hh \text{ (GPGGSZ)} \\ B_s \to D_s K \text{ time dependent} \end{cases}$

- $KK, \pi\pi$ (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

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

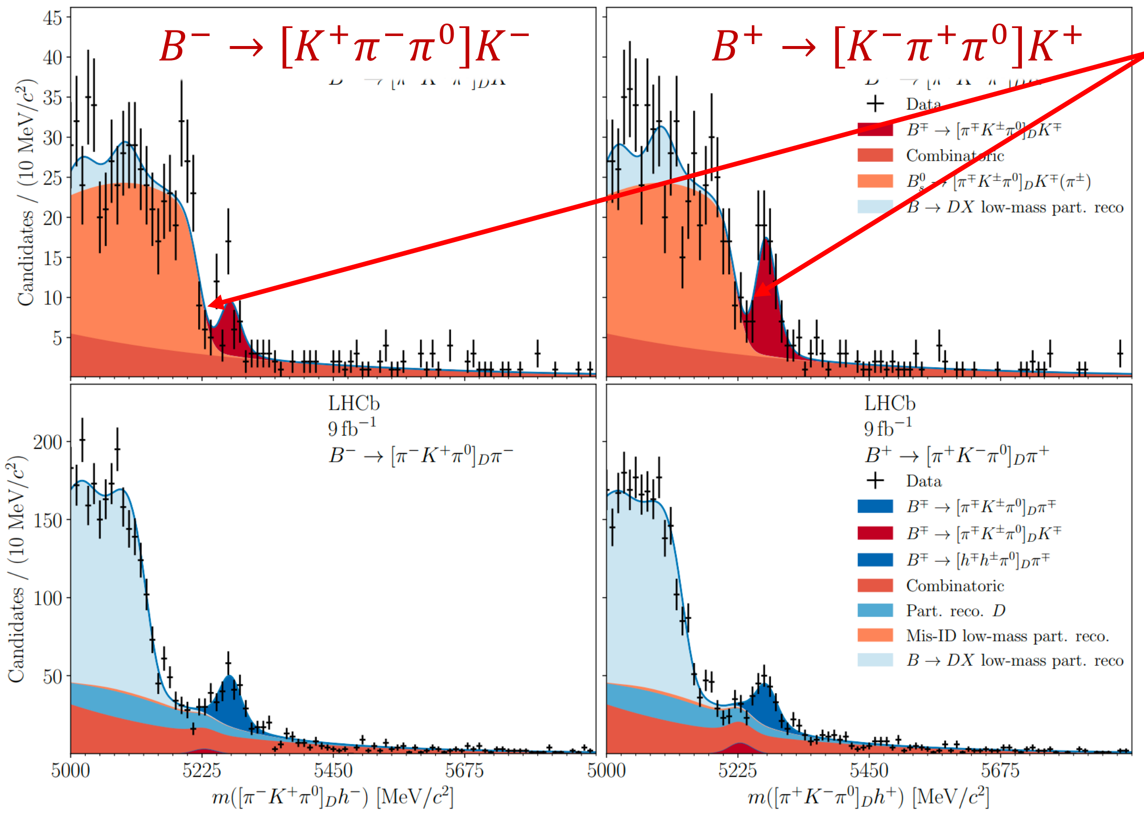
  PRD 68 (2003) 033003

  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

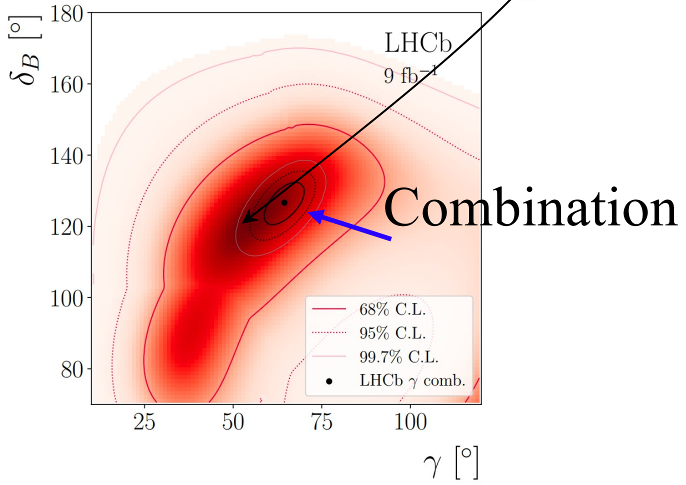


$A_{CP} = (-0.38 \pm 0.12 \pm 0.02)$

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

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

$r_B = (9.3^{+1.0}_{-0.9})\times10^{-2}$

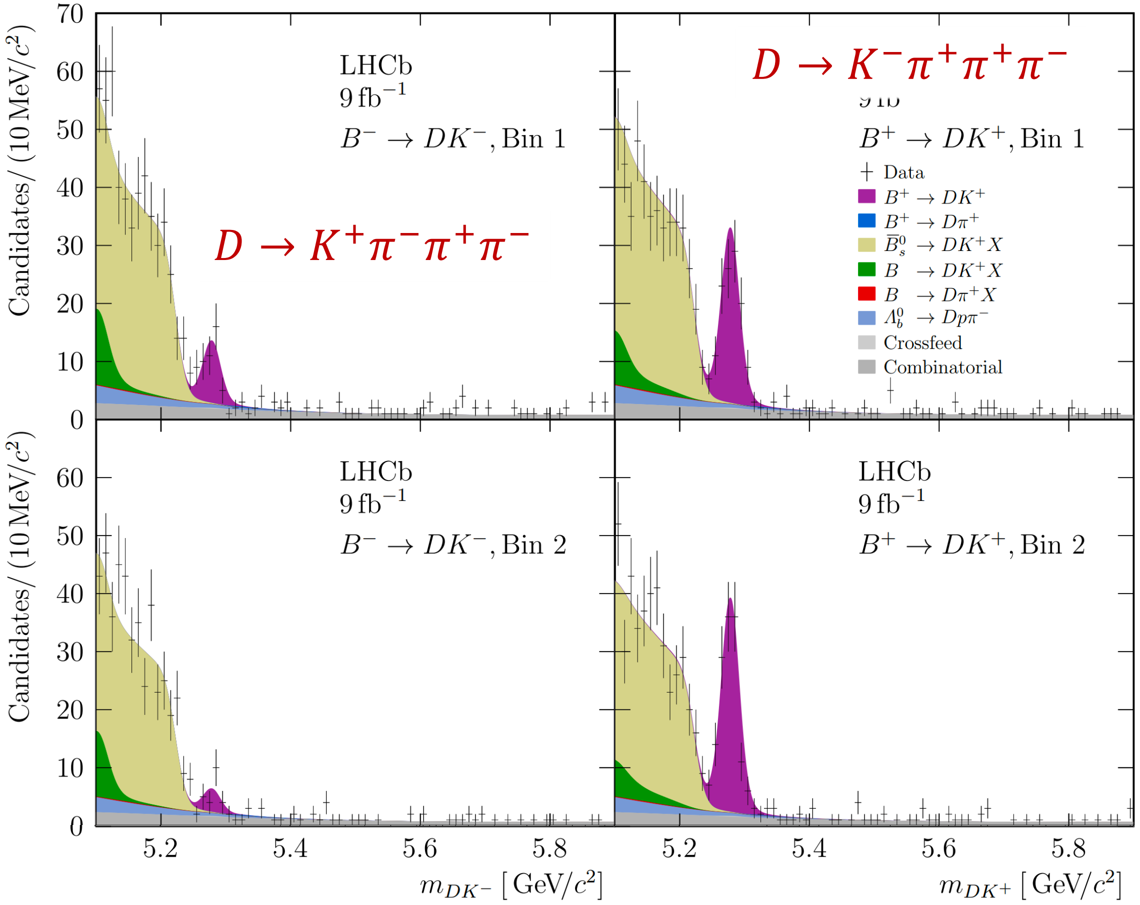


γ with $B^{\pm} \to D(K^{\pm}\pi^{\mp}\pi^{+}\pi^{-})h^{\pm}$

arXiv:2209.03692

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

JHEP 05 (2021) 164



A_{CP} in 4 regions

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

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

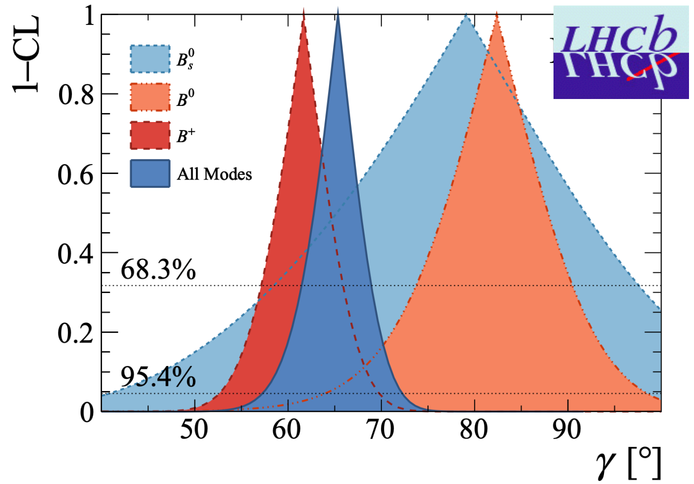
stat. syst.

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

Second most precise result in a single channel

LHCb: pushing the frontier

And significant improvements in γ



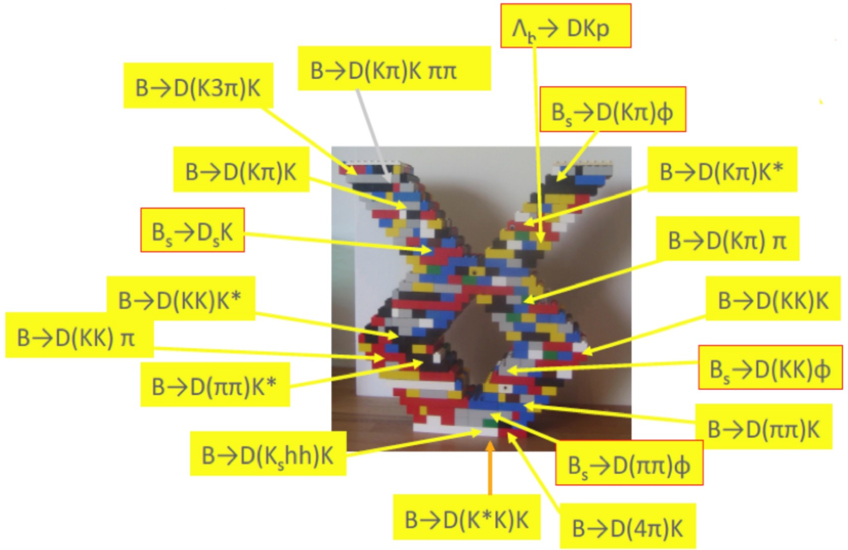
LHCb-CONF-2022-003

LHCb:

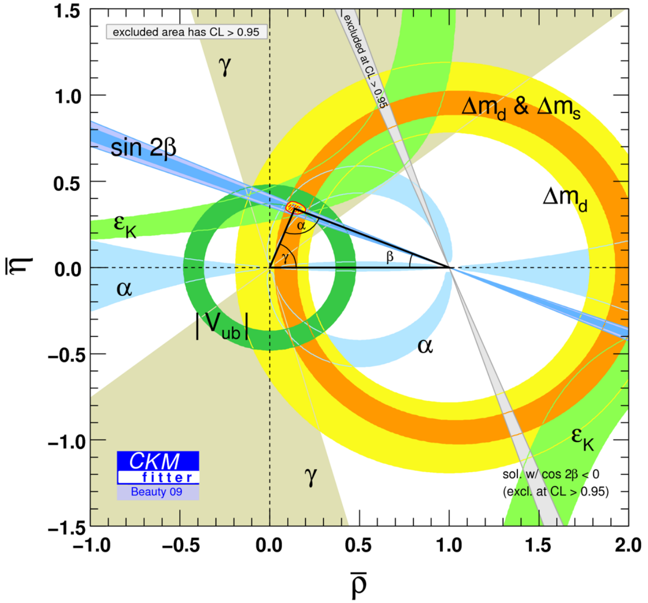
$\gamma = (63.8^{+3.5}_{-3.7})^\circ$

Previous WA:

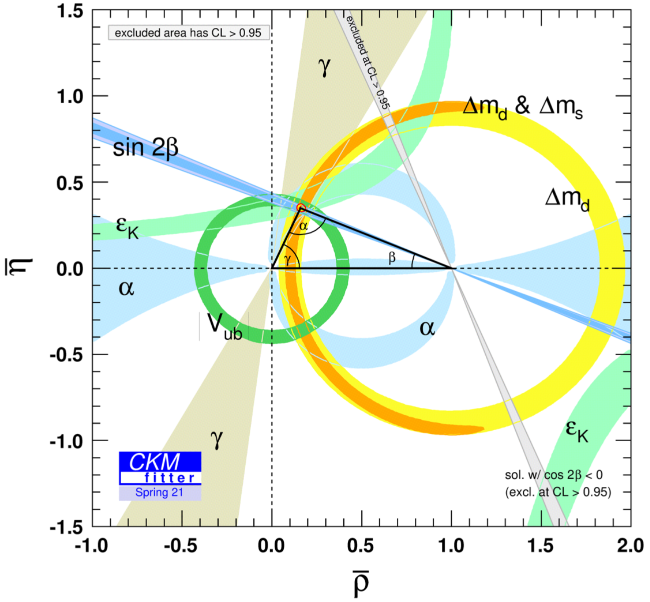
$\gamma = (73.5^{+4.2}_{-5.1})^\circ$



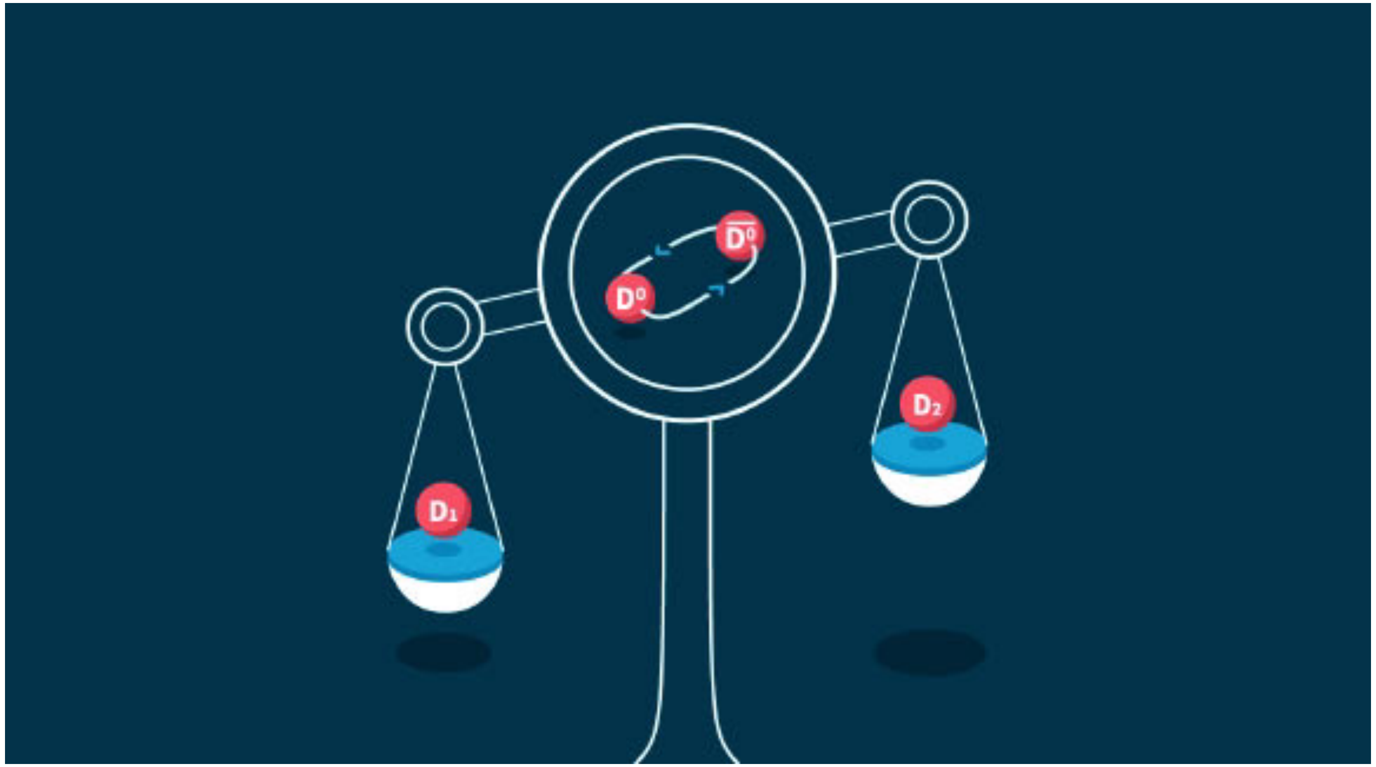
When LHC started



Current status



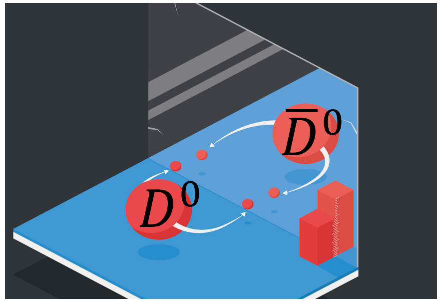
Charm physics



Direct CPV in charm decays

- **First charm CPV observed by LHCb in 2019**

PRL 122 (2019) 211803



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

- **New measurement of time-integrated CP asymmetry**

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

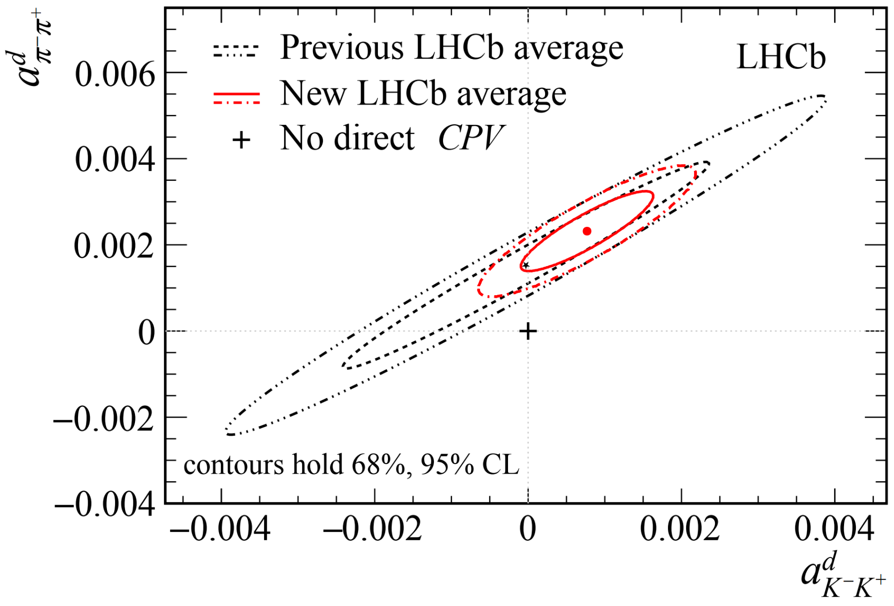
arXiv:2209.03179

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

To obtain:

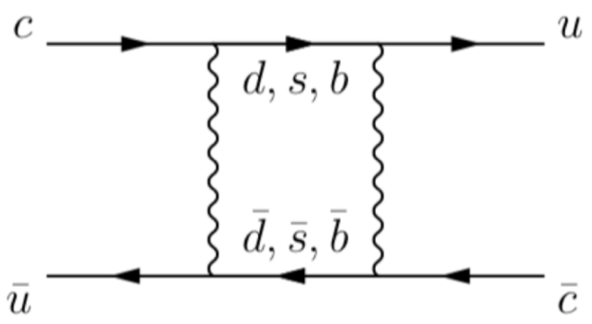
$$a_{KK}^d = (7.7 \pm 5.7)\times 10^{-4}$$
$$a_{\pi\pi}^d = (23.2 \pm 6.1)\times 10^{-4}$$

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



$D^0 - \bar{D}^0$ mixing

- **After many effort, D^0-$\bar{D}^0$ oscillation was observed**
- **But mass difference and CP-violation poorly known**

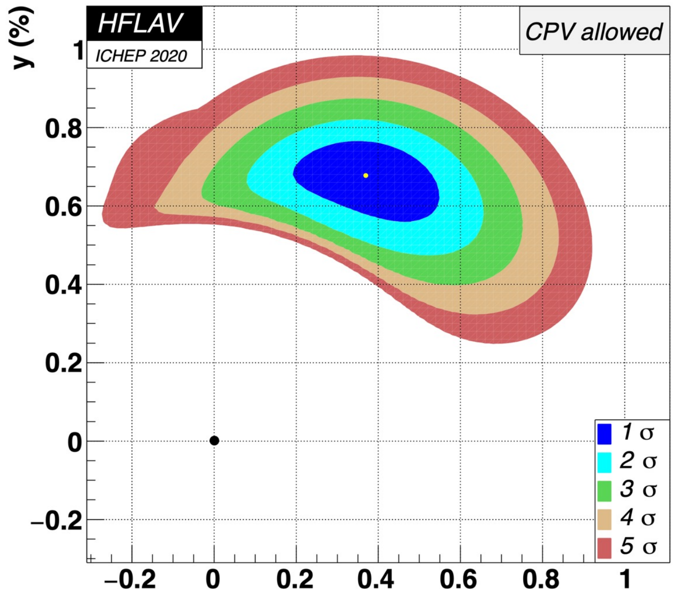


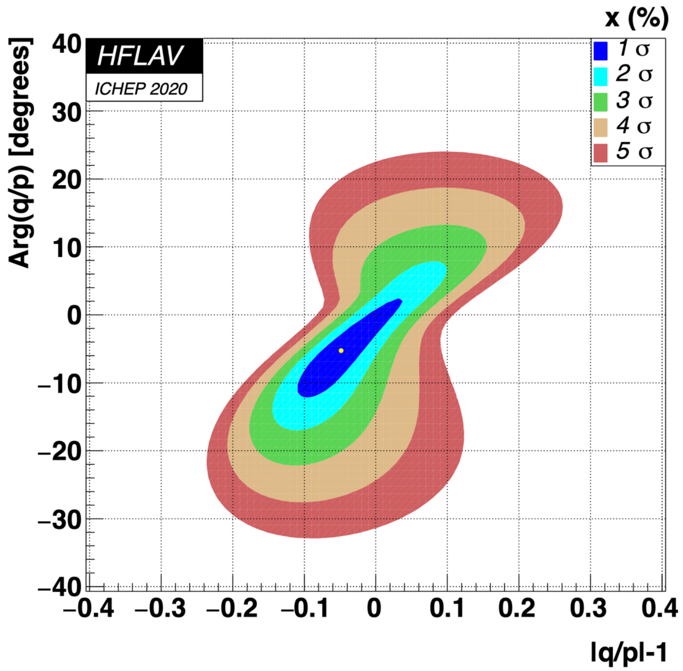
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} = (0.68^{+0.06}_{-0.07})\% \neq 0$$

$$x = \frac{m_1 - m_2}{\Gamma} = (0.37 \pm 0.12)\%$$

World average (WA)





- **Mainly used for new physics search**

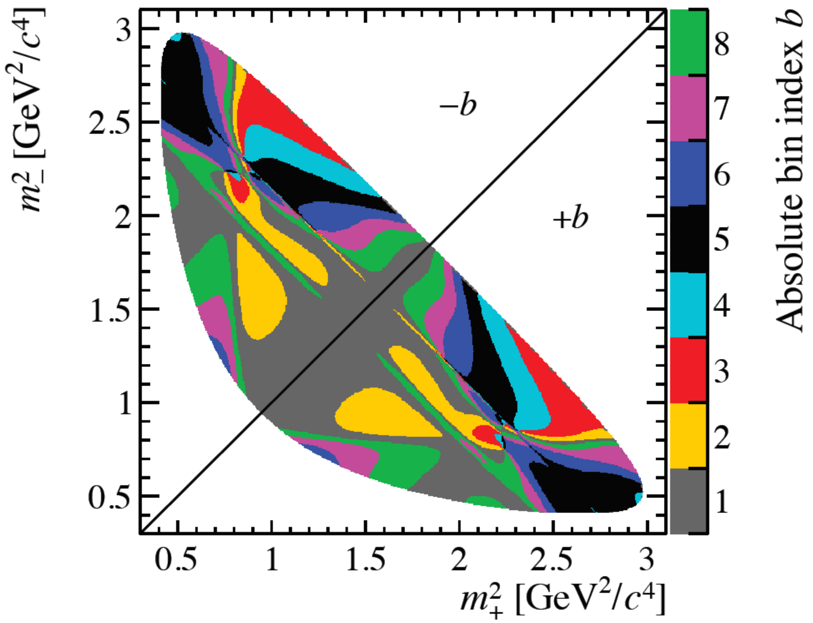
Expect in SM: $|x| \lesssim |y| \sim$ $10^{-6} - 10^{-3}$ (short distance), $10^{-3} - 10^{-2}$ (long distance)

- If obtain $|x| >> |y|$ or *CPV* $\Rightarrow$ New Physics

Bin-Flip with $D^0 \to K_s^0\pi^+\pi^-$

PRD 99, 012007 (2019)

- **"Bin-Flip" method: yield ratio between –b and b bin as a function of time**
  - Most detector effects cancel
  - Fix $X_b = (C_b, S_b)$ parameters from CLEO+BESIII



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

Fit parameters:
4 mixing+CPV + r_b

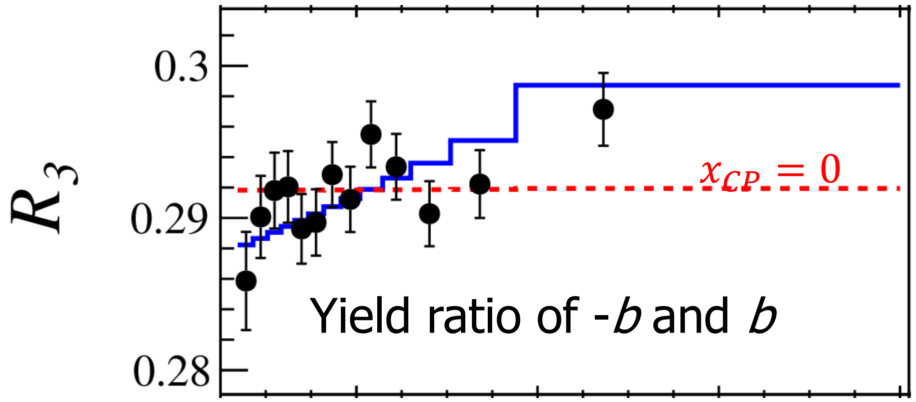
$z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y + ix)$
$x_{CP} \equiv -\mathrm{Im}(z_{CP})$
$y_{CP} \equiv -\mathrm{Re}(z_{CP})$
$\Delta x \equiv -Im(\Delta z)$
$\Delta y \equiv -\mathrm{Re}(\Delta z)$
If CP-conservation, q/p=1
$\Delta x = \Delta y = \Delta z = 0$
$x_{CP} = x \quad y_{CP} = y$

Results with prompt D^0 and WA

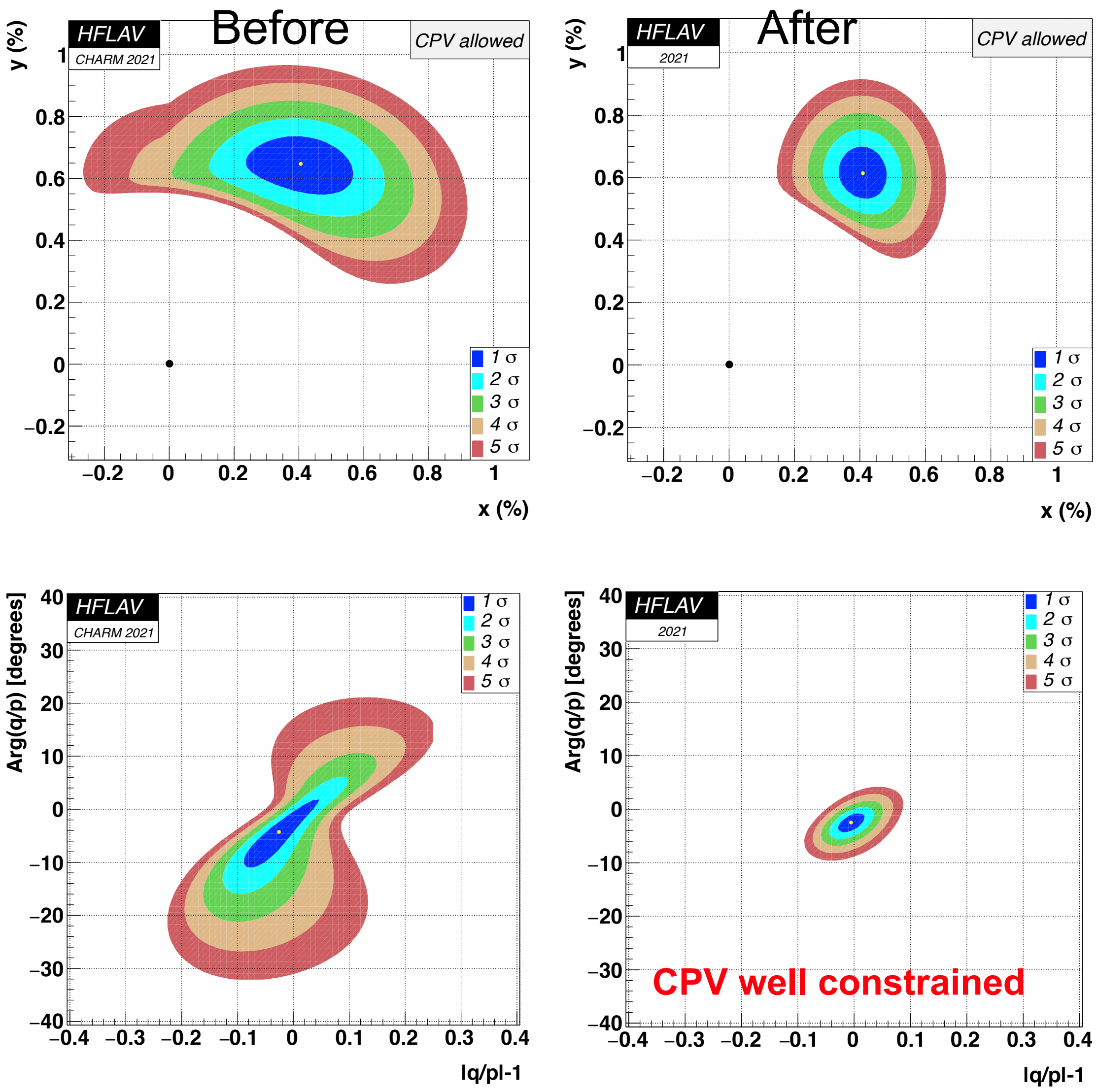
- **Bin-Flip method** PRD 99, 012007 (2019)
- **First measurement of $x > 0$ for 7σ**
  PRL 127 (2021) 111801

$$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$
$$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$

30.6M signal events



Huge impact on WA of x and CPV !

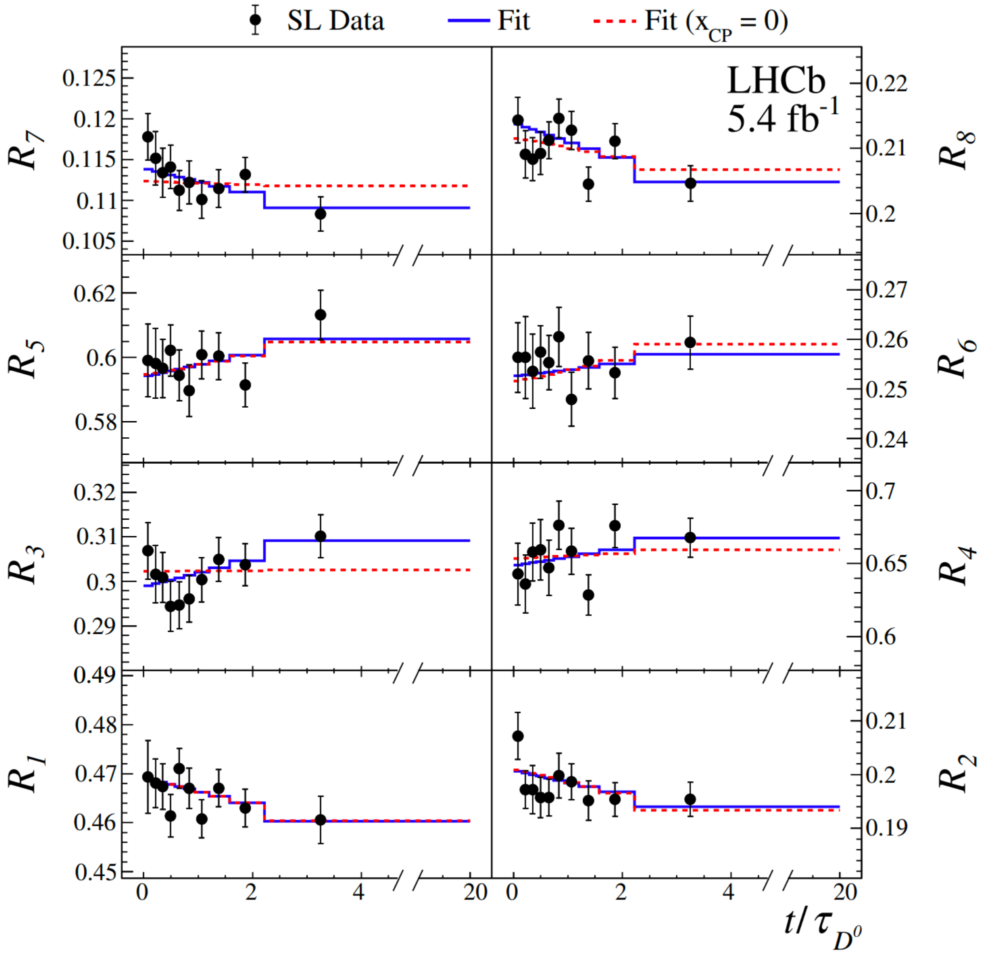


Update with SL decays

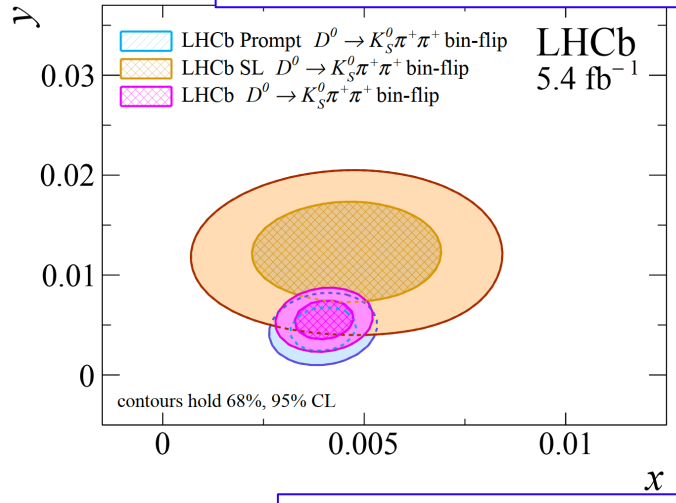
arXiv:2208.06512

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

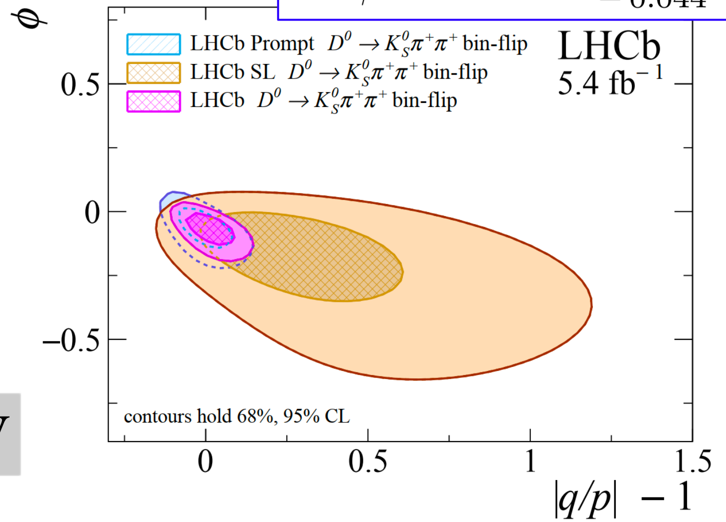
3.7M signal events



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



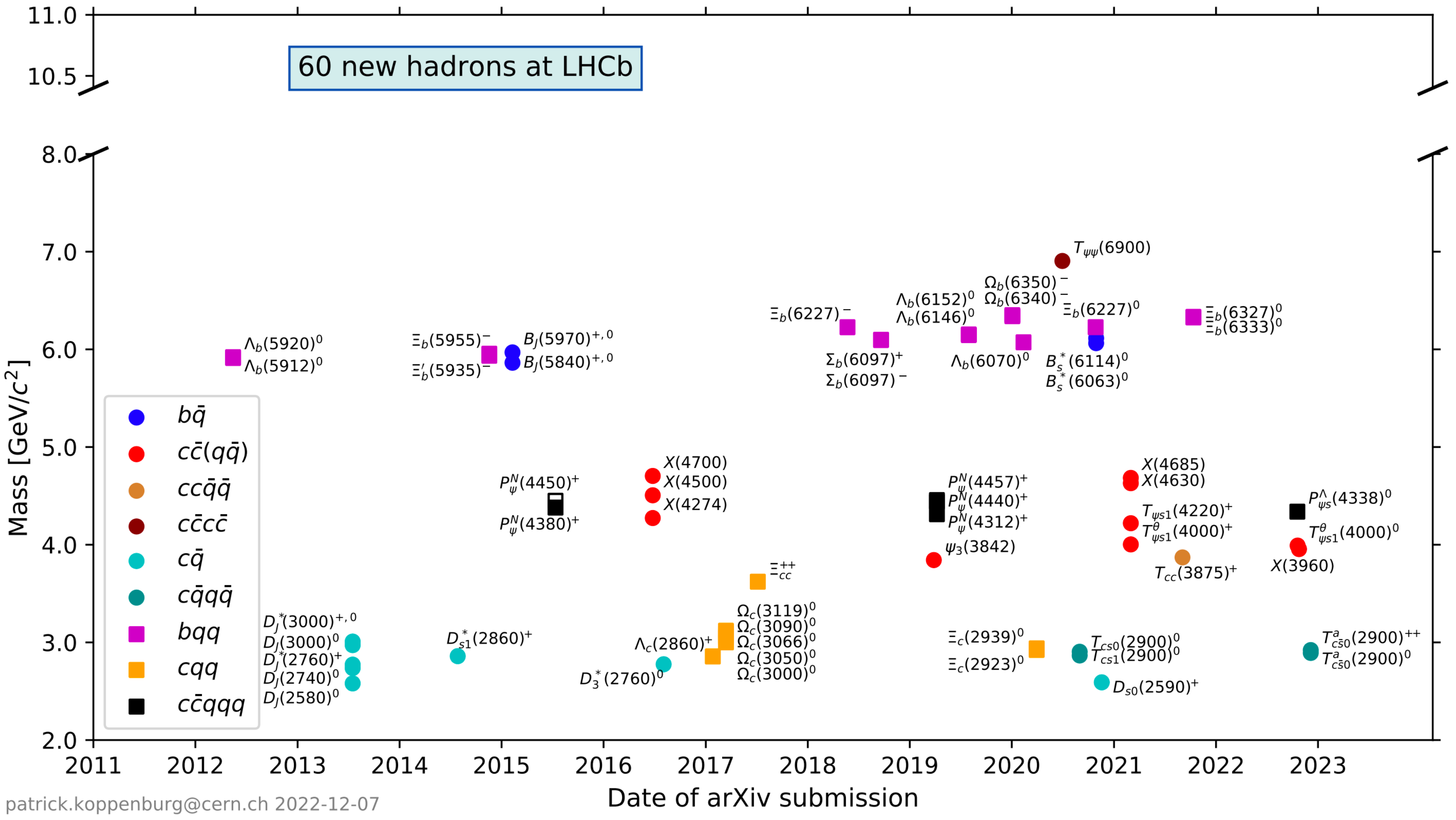
Average: $|q/p| = 1.012^{+0.050}_{-0.048}$, $\phi = -0.061^{+0.037}_{-0.044}$ rad



No sign of CPV

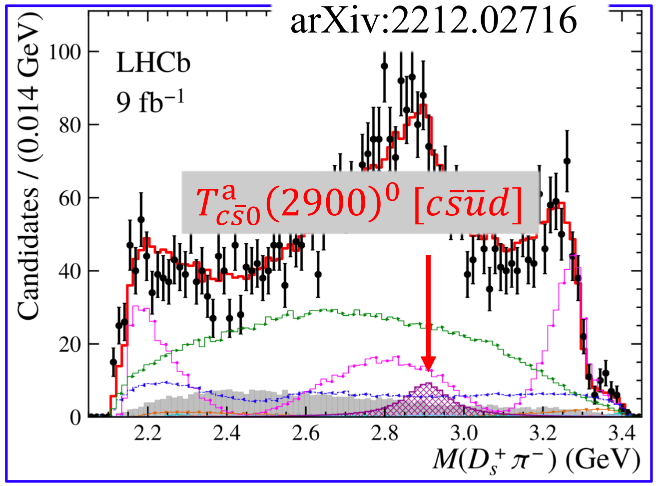
Hadron spectroscopy

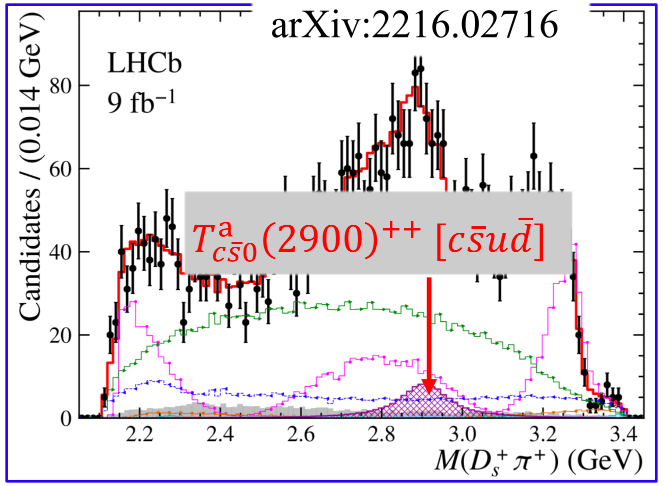
List of new hadrons keep growing



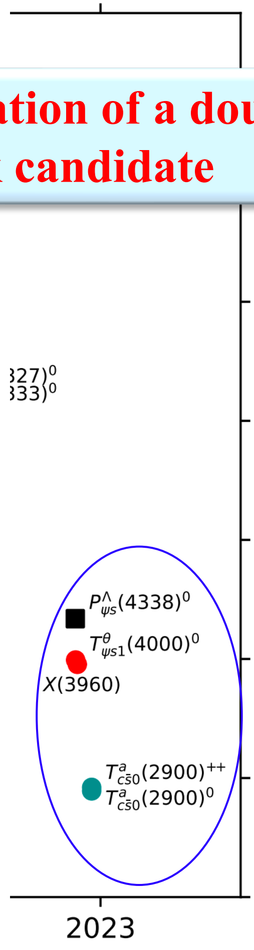
New naming conventions:
arXiv:2206.15233

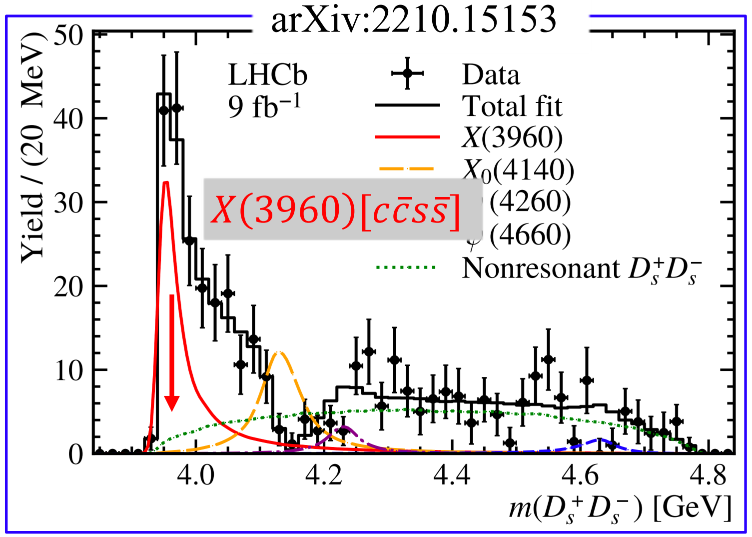
List of new hadrons keep growing

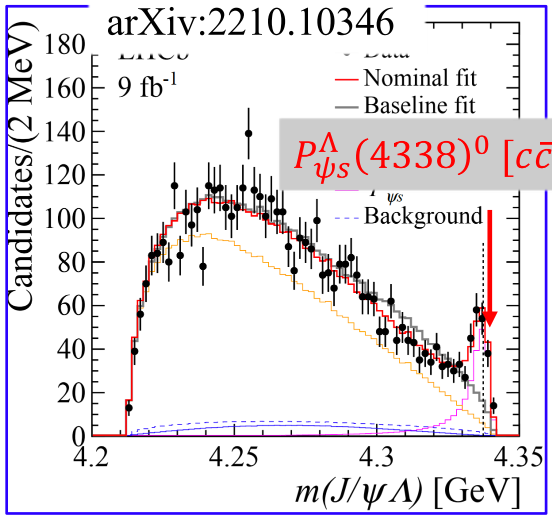




1st observation of a doubly charged tetraquark candidate





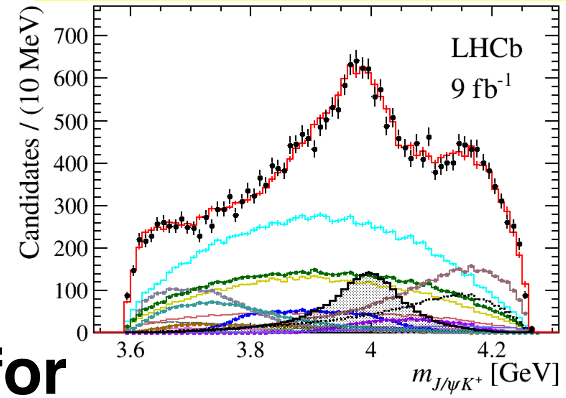


1st observation of a pentaquark candidate with strangeness

Z_{cs} $[c\bar{c}u\bar{s}]$ states

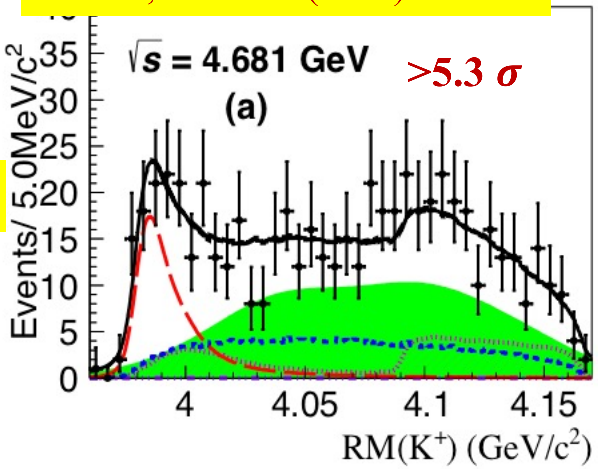
- **Charged Z_{cs} states observed at BESIII and LHCb:** $Z_{cs}(3985)$, $Z_{cs}(4000)$, $Z_{cs}(4220)$
- $Z_{cs}(3985)$, $Z_{cs}(4000)$ **have similar mass but very different widths**
- **BESIII also find an evidence for the neutral isospin partner**

LHCb, PRL127 (2021) 082001



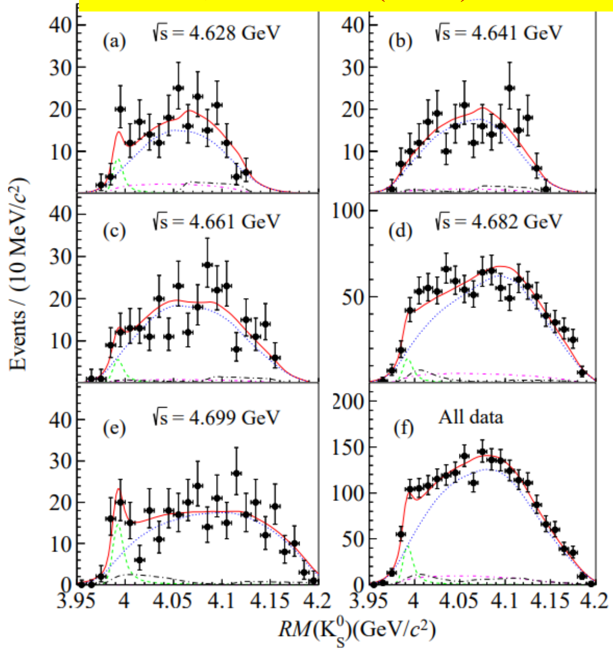
$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

BESIII, PRL 126 (2021) 102001



$e^+e^- \to K_S^0(D_s^- D^{*+} + D_s^{*-} D^+)$

BESIII, PRL 129 (2022) 112003



LHCb

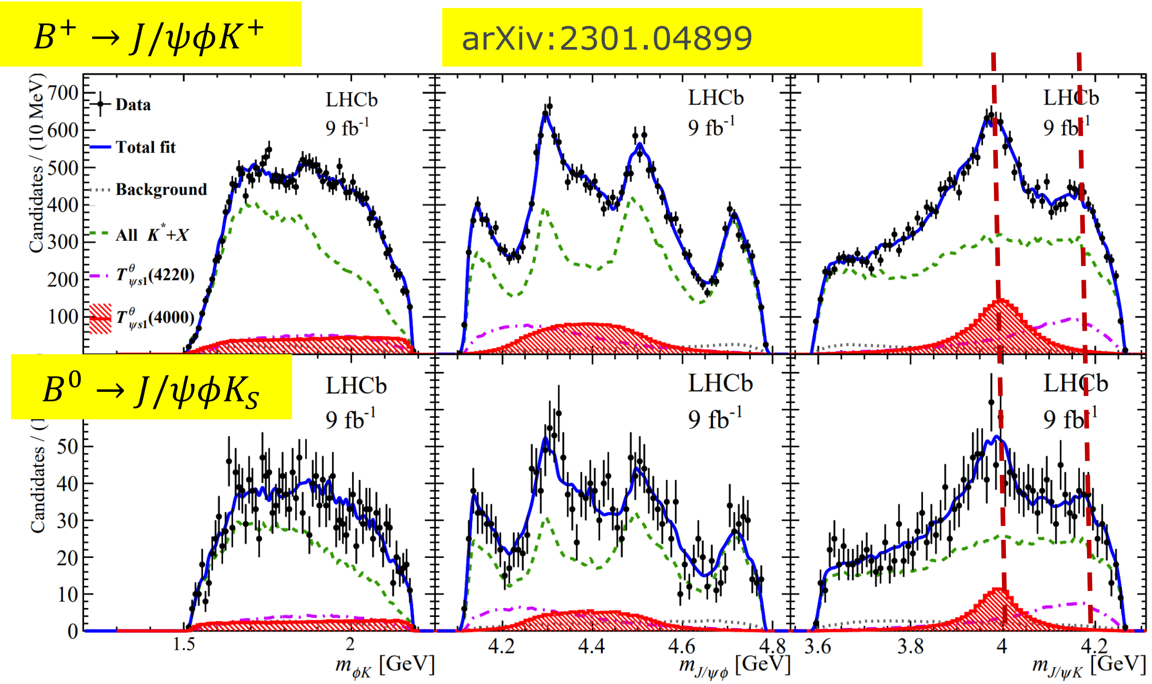
All $Z_{cs}(1^+)$		Mass [MeV]	width [MeV]	$25 \pm 5\,^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

BESIII

	Mass (MeV/c^2)	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$

$T_{\psi s1}^{\theta}(4000)^0$ in $B^0 \to J/\psi\phi K_S^0$

- **Simultaneous fit to $B^0 \to J/\psi\phi K_S$ and $B^+ \to J/\psi\phi K^+$, assuming isospin symmetry for all the intermediate states, except for the charged and neutral $T_{\psi s1}^{\theta}(4000)$ states**



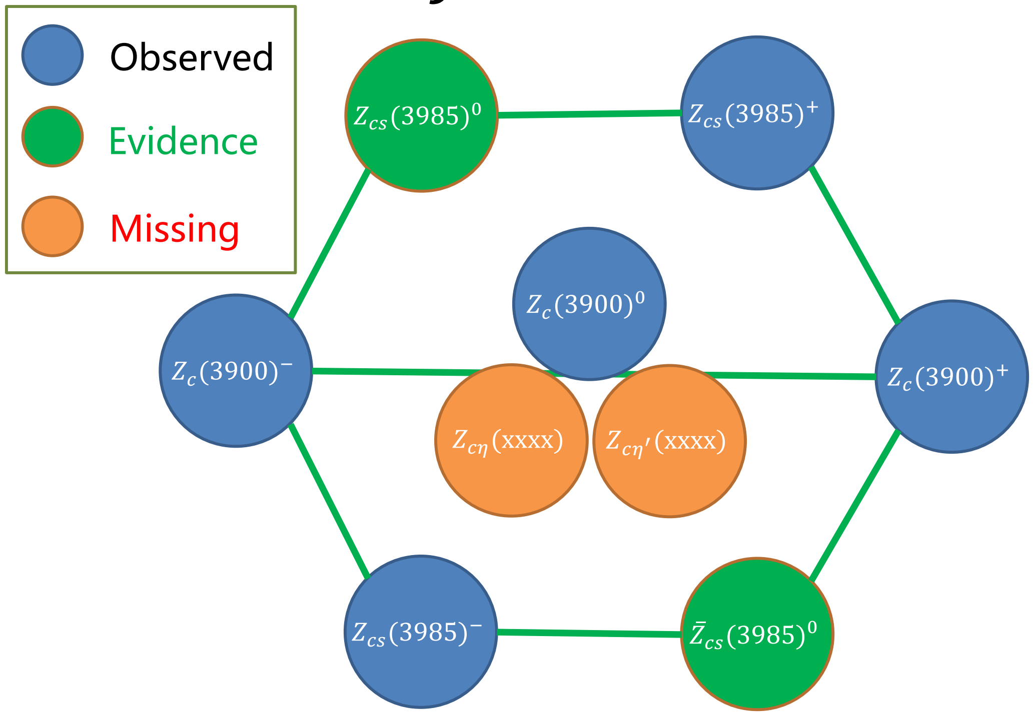
- **Consistent with being isospin partners: $\Delta m = -12.1^{+11.1+6.0}_{-10.2-4.2}$ MeV**
- **Significance is 4.0σ without isospin symmetry for $T_{\psi s1}^{\theta}(4000)$, while 5.4σ with isospin symmetry constrain**

	J^P	Mass (MeV/c^2)	Width (MeV)	Fit fraction
$T_{\psi s1}^{\theta}(4000)^0 \to J/\psi K_S^0$	1^+	$3991.3^{+11.7+8.5}_{-10.4-16.7}$	$104.8^{+29.3+17.1}_{-25.3-23.3}$	$7.9 \pm 2.5^{+3.0}_{-2.8}$
$Z_{cs}^+ / T_{\psi s1}^{\theta}(4000)^+ \to J/\psi K^+$	1^+	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$

Possible emergence of two SU(3) flavour tetrquark nonets

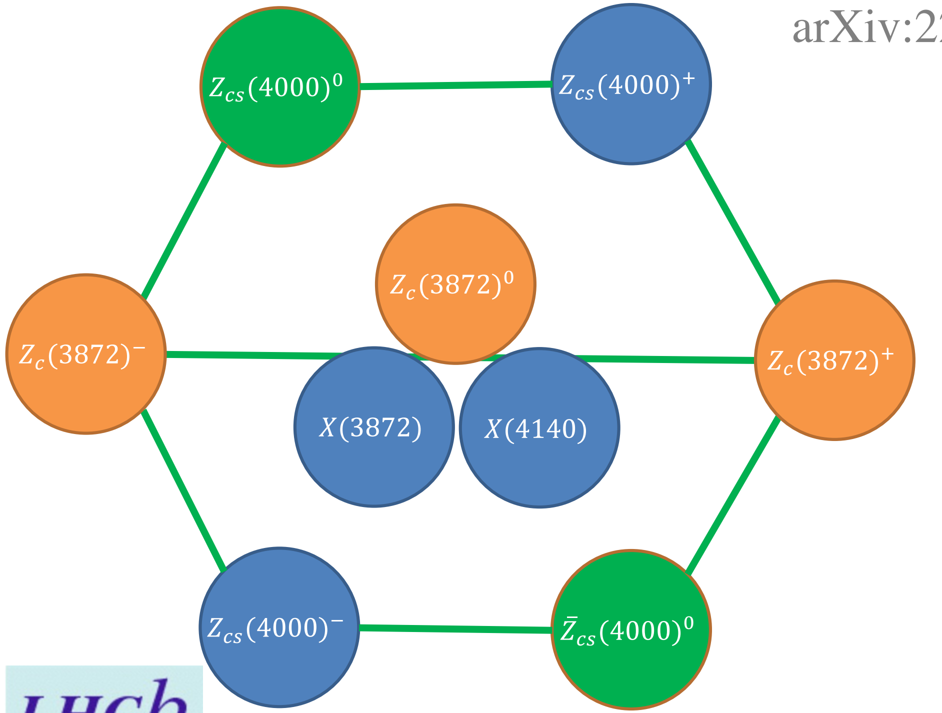
arXiv:2103.08331
arXiv:2111.08650
arXiv:2207.08563

$J^{P(C)} = 1^{+(-)}$



BESIII arXiv:2211.07217

$J^{P(C)} = 1^{+(+)}$

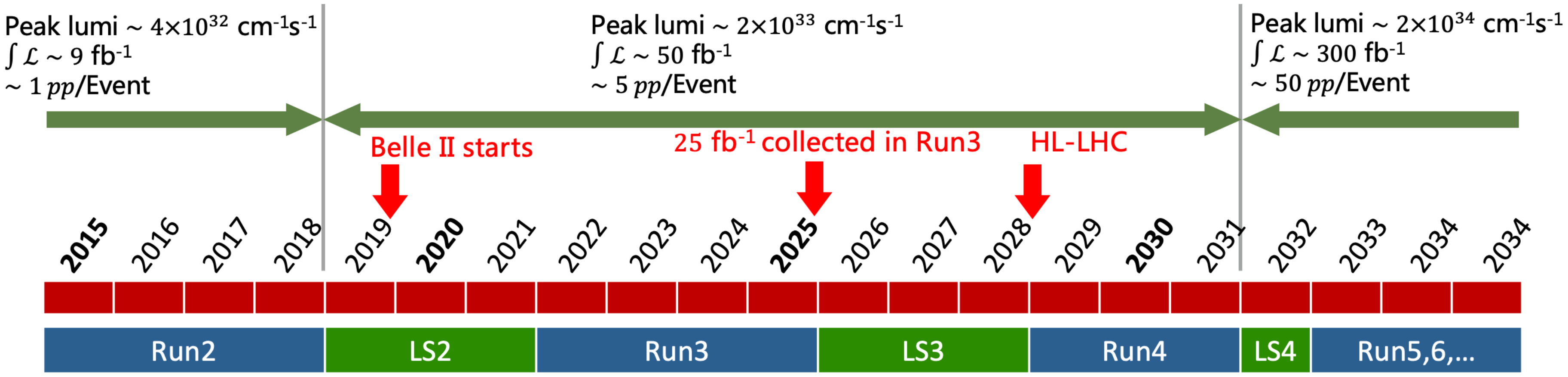


LHCb

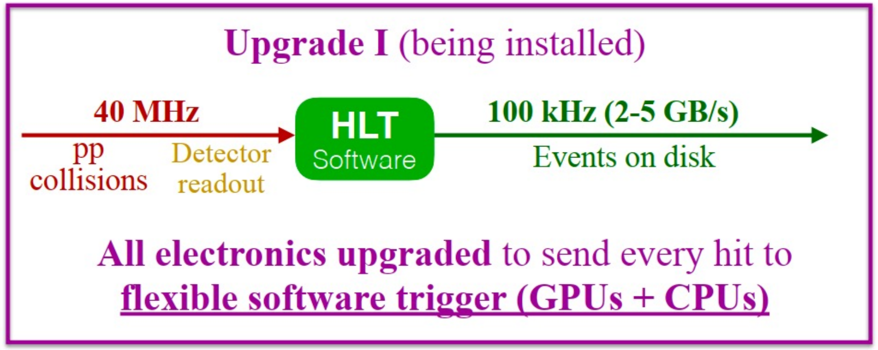
Two multiplets could exist in both molecular and compact tetrquark models, however not all of the states exist in the molecular model

LHCb upgrade(d)

Long term plan beyond 2035

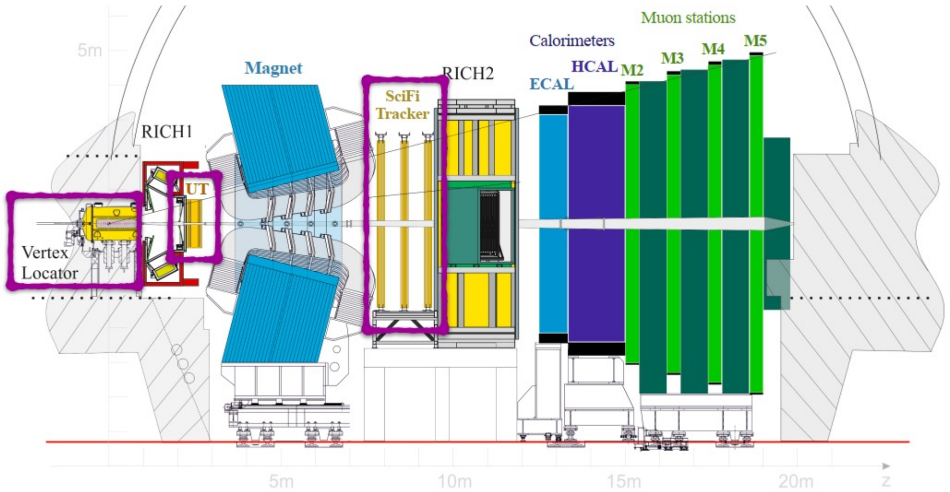


- Starts to accumulate data for Run3

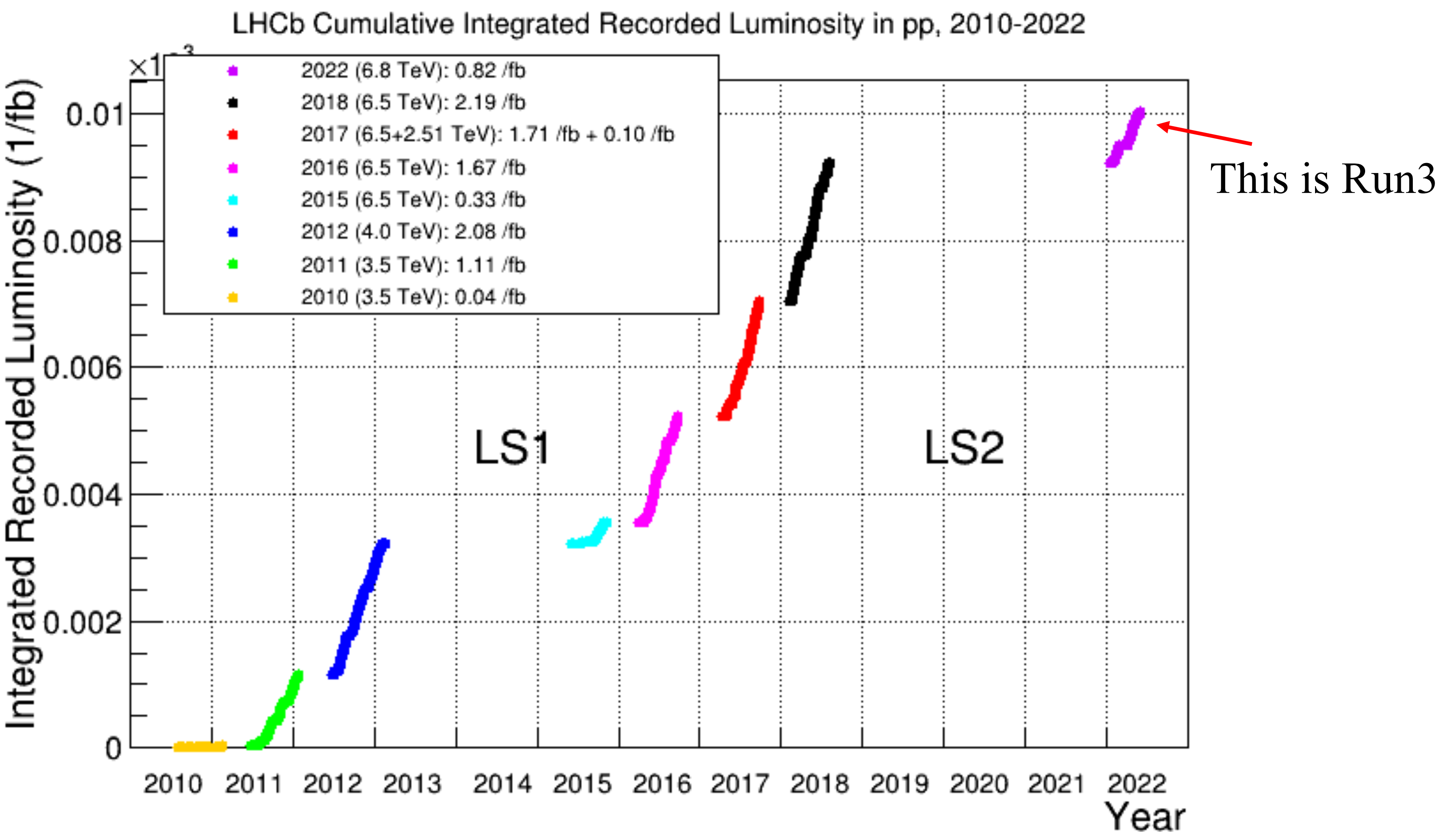


CERN-LHCC-2012-007

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
Integrated Recorded Luminosity (1/fb)
0.01
0.008
0.006
0.004
0.002
0
LS1
LS2
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].

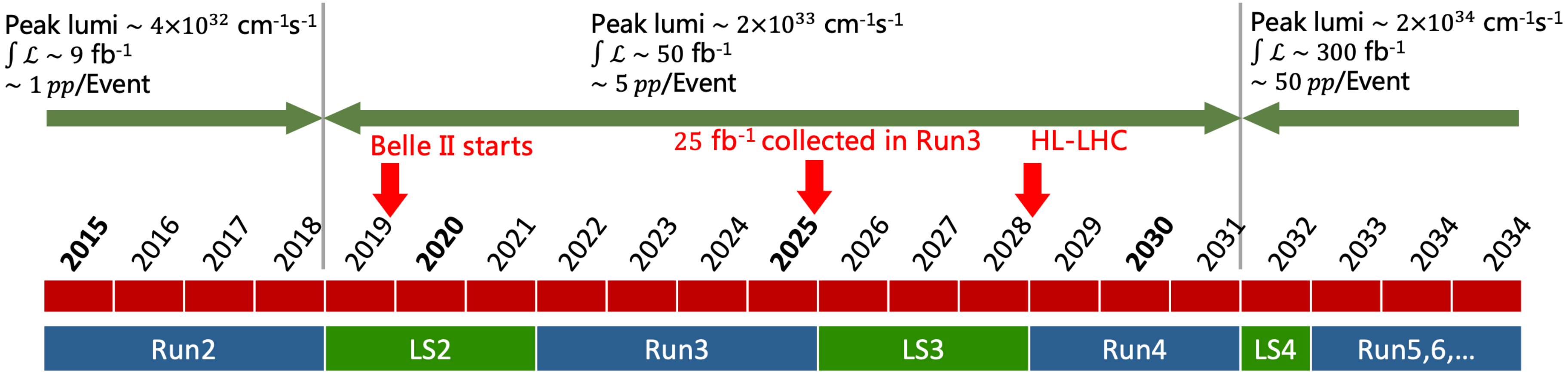
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	GPDs Phase II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [255]	0.022	0.036	0.006	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [254]	0.029	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.07, 0.04, 0.11	–	0.02, 0.01, 0.03	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [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}	–

- 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}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

- **Studies of flavor towards new physics**
- **LHCb: a wide range of flavor physics**
  - Precision measurement of CKM matrix: $\gamma < 4^{\circ}$
  - 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 9 $\mathbf{fb^{-1}}$ to 300 $\mathbf{fb^{-1}}$**
  - New physics?



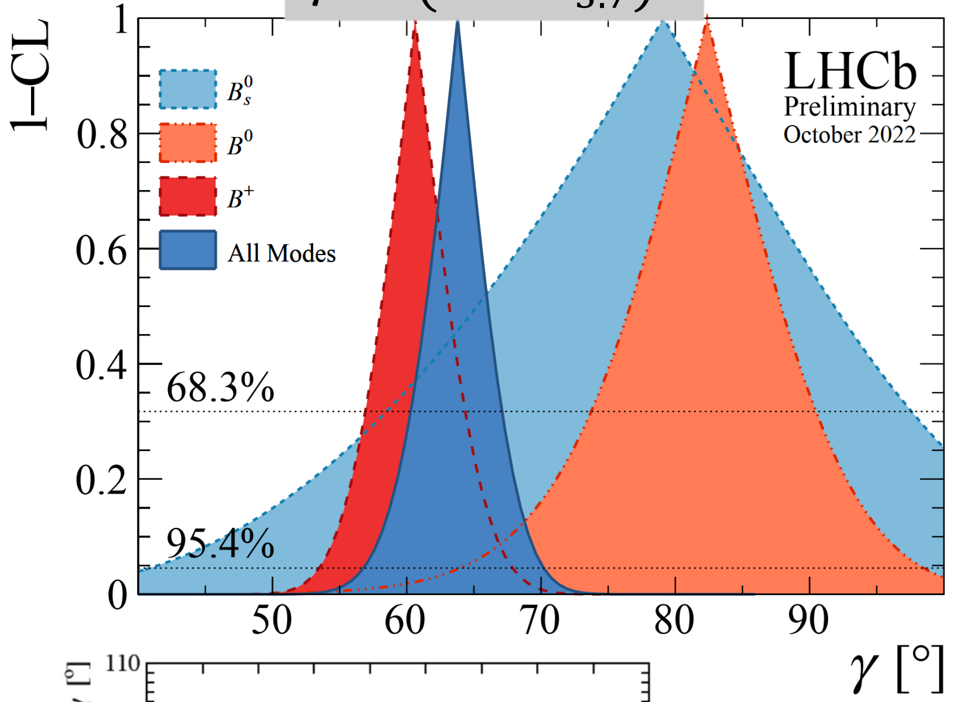
Backup

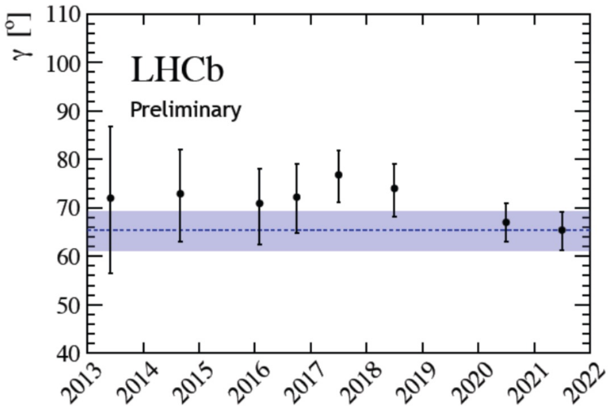
New γ combination

LHCb-CONF-2022-003

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

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

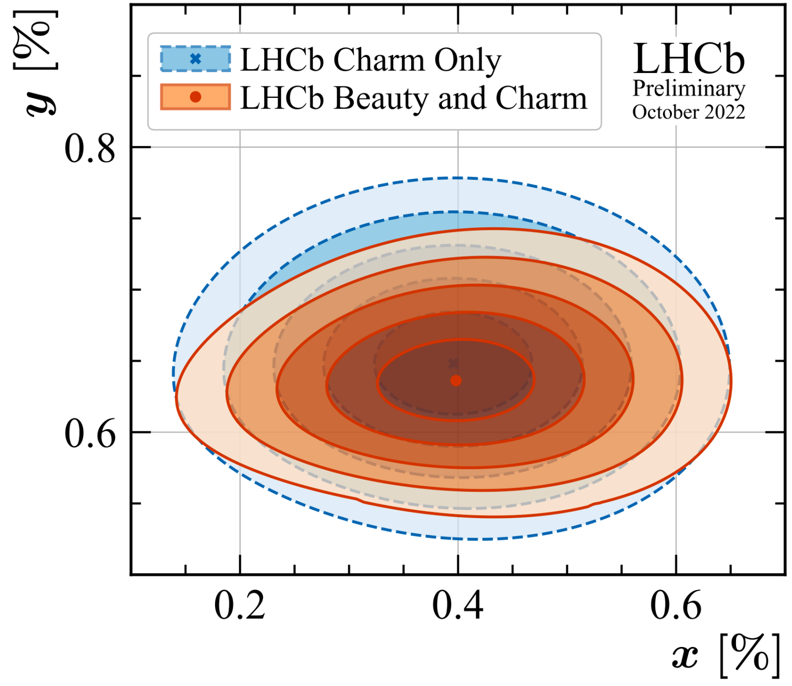




$$x_D = \frac{\Delta M_D}{M_D} = \left(0.398^{+0.050}_{-0.049}\right)\%$$

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

Improved on y_D w.r.t charm only results

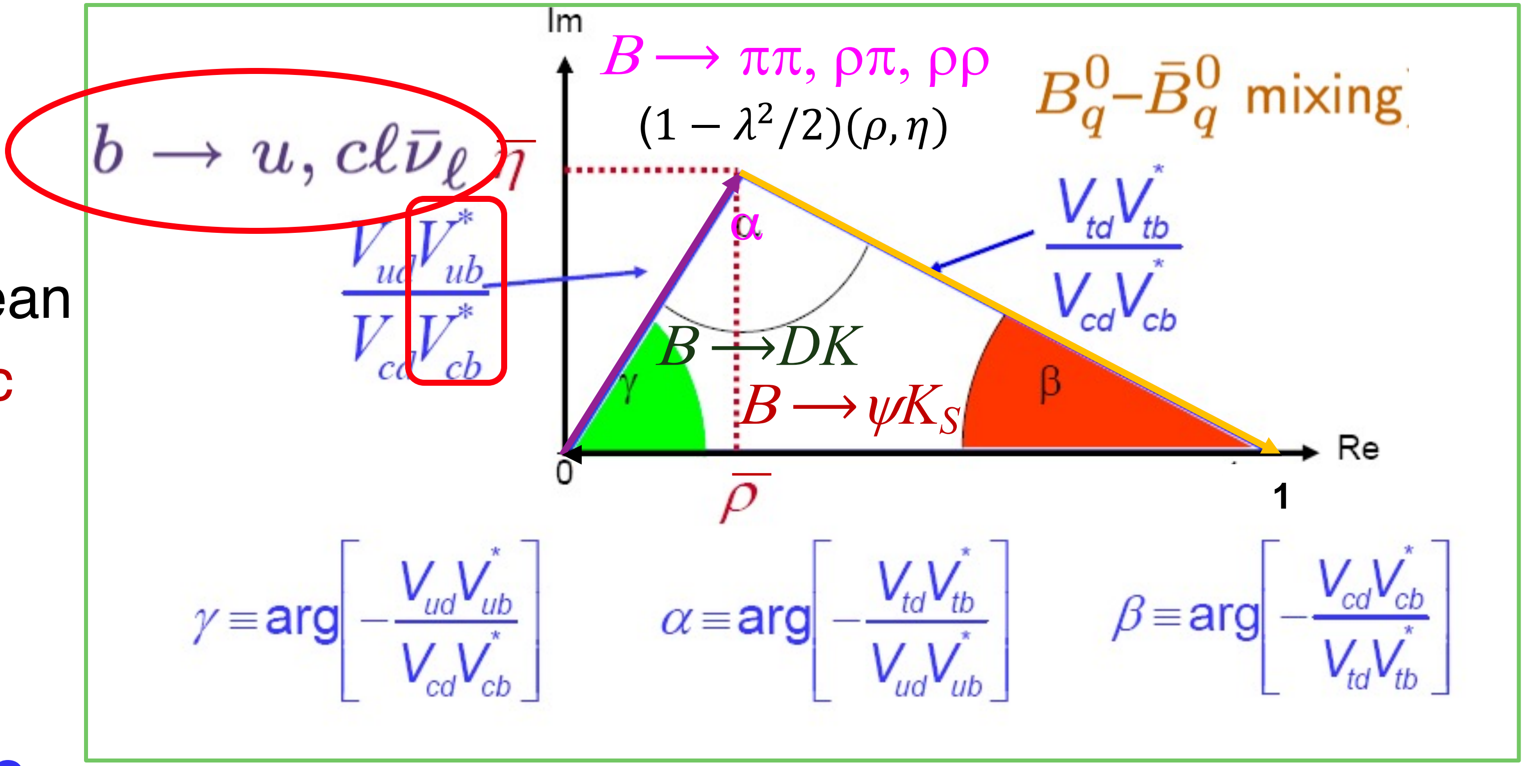


V_{ub}/V_{cb}

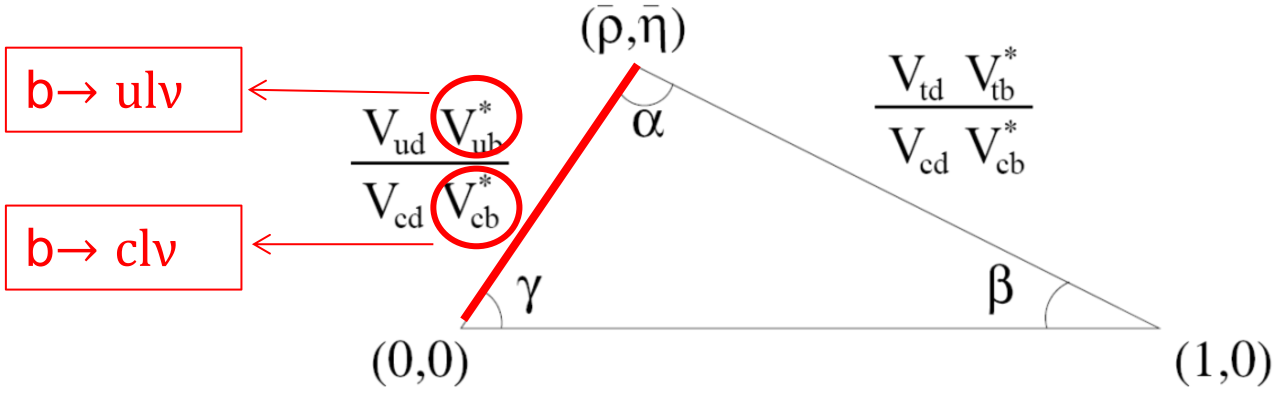
- V_{ub}/V_{cb} **is fundamental input to constrain SM**

- **Measure differential decay rates of:**
  - Inclusive semileptonic decays: theoretically clean
  - Exclusive (semi)leptonic decays: theoretical uncertainties

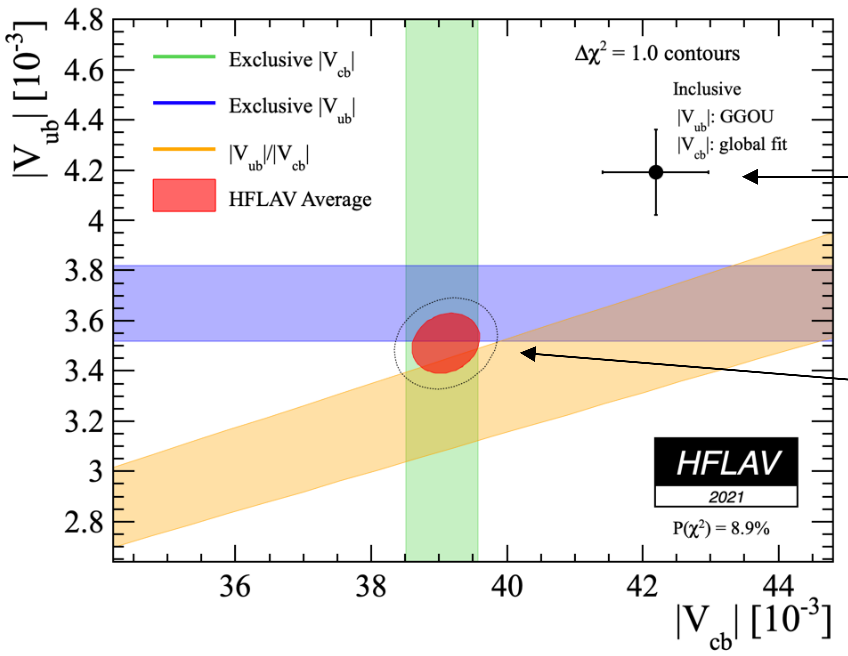
- **Large tenson between inclusive and exclusive determinations**



V_{ub}/V_{cb} puzzle

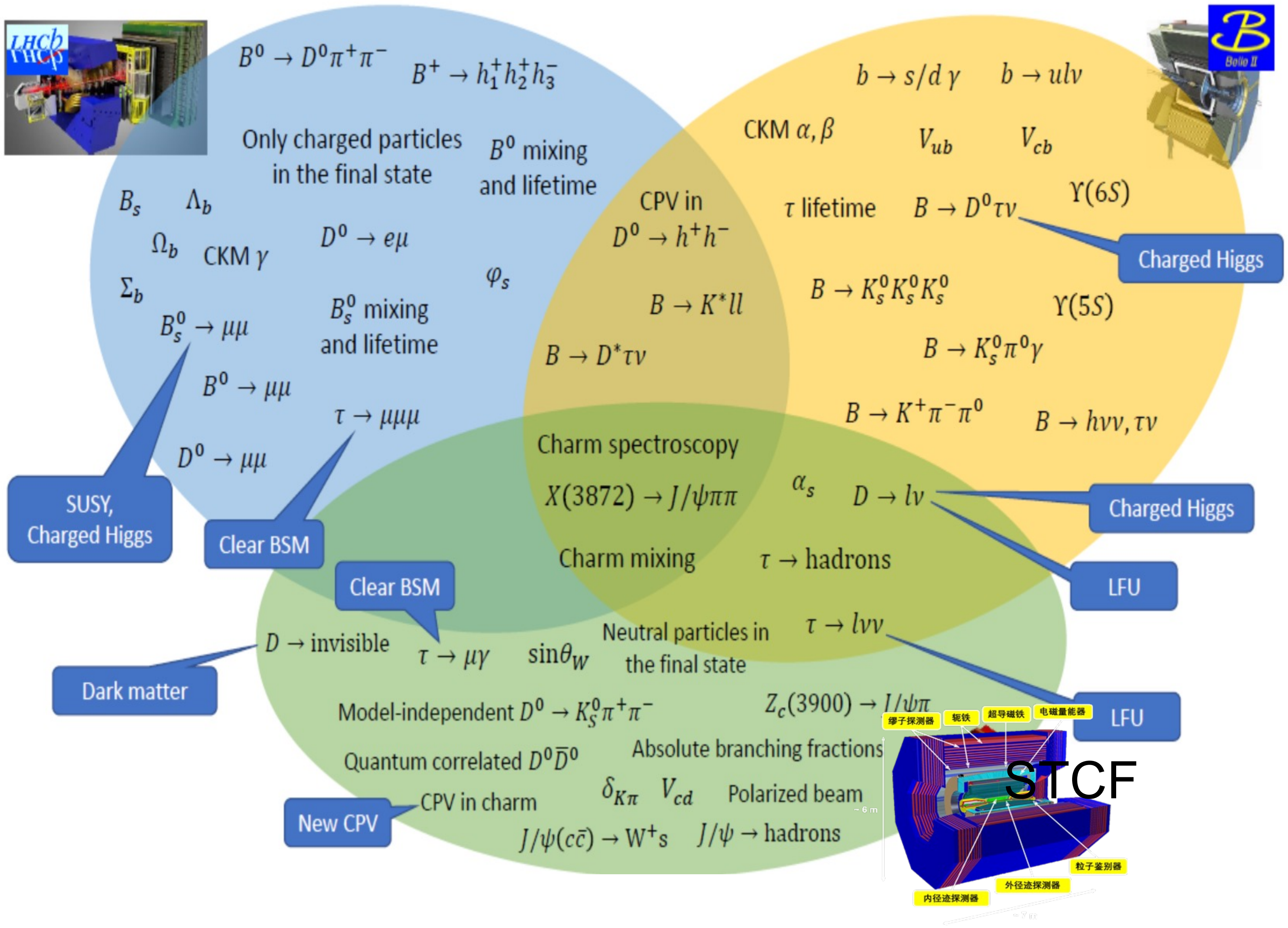


- **Tension between inclusive and exclusive determinations**



- **Inclusive: high background**
  - $|V_{ub}| = (4.19 \pm 0.17)\times10^{-3}$
  - $|V_{cb}| = (42.19 \pm 0.78)\times10^{-3}$
- **Exclusive: need LQCD inputs**
  - $|V_{ub}| = (3.51 \pm 0.12)\times10^{-3}$
  - $|V_{cb}| = (39.10 \pm 0.50)\times10^{-3}$

互补与协同


LHCb
$B^0 \to D^0\pi^+\pi^-$
$B^+ \to h_1^+ h_2^+ h_3^-$
Only charged particles in the final state
B^0 mixing and lifetime
B_s
Λ_b
Ω_b
CKM γ
$D^0 \to e\mu$
φ_s
Σ_b
$B_s^0 \to \mu\mu$
B_s^0 mixing and lifetime
$B^0 \to \mu\mu$
$\tau \to \mu\mu\mu$
$D^0 \to \mu\mu$
SUSY, Charged Higgs
Clear BSM
Belle II
$b \to s/d\,\gamma$
$b \to ul\nu$
CKM α, β
V_{ub}
V_{cb}
τ lifetime
$B \to D^0\tau\nu$
$\Upsilon(6S)$
Charged Higgs
CPV in $D^0 \to h^+h^-$
$B \to K^*ll$
$B \to K_S^0 K_S^0 K_S^0$
$\Upsilon(5S)$
$B \to K_S^0\pi^0\gamma$
$B \to D^*\tau\nu$
$B \to K^+\pi^-\pi^0$
$B \to h\nu\nu, \tau\nu$
Charm spectroscopy
$X(3872) \to J/\psi\pi\pi$
α_s
$D \to l\nu$
Charged Higgs
Charm mixing
$\tau \to$ hadrons
LFU
Clear BSM
$D \to$ invisible
$\tau \to \mu\gamma$
$\sin\theta_W$
Neutral particles in the final state
$\tau \to l\nu\nu$
LFU
Dark matter
Model-independent $D^0 \to K_S^0\pi^+\pi^-$
$Z_c(3900) \to J/\psi\pi$
Quantum correlated $D^0\bar{D}^0$
Absolute branching fractions
New CPV
CPV in charm
$\delta_{K\pi}$
V_{cd}
Polarized beam
$J/\psi(c\bar{c}) \to W^+s$
$J/\psi \to$ hadrons
STCF
缪子探测器
轭铁
超导磁铁
电磁量能器
粒子鉴别器
外径迹探测器
内径迹探测器