CP violation measurements at LHCb

Wenbin Qian (钱文斌)
University of Chinese Academy of Sciences
(中国科学院大学)

FIND论坛系列学术研讨会
FIND CP Violation at Electroweak Scale and Beyond
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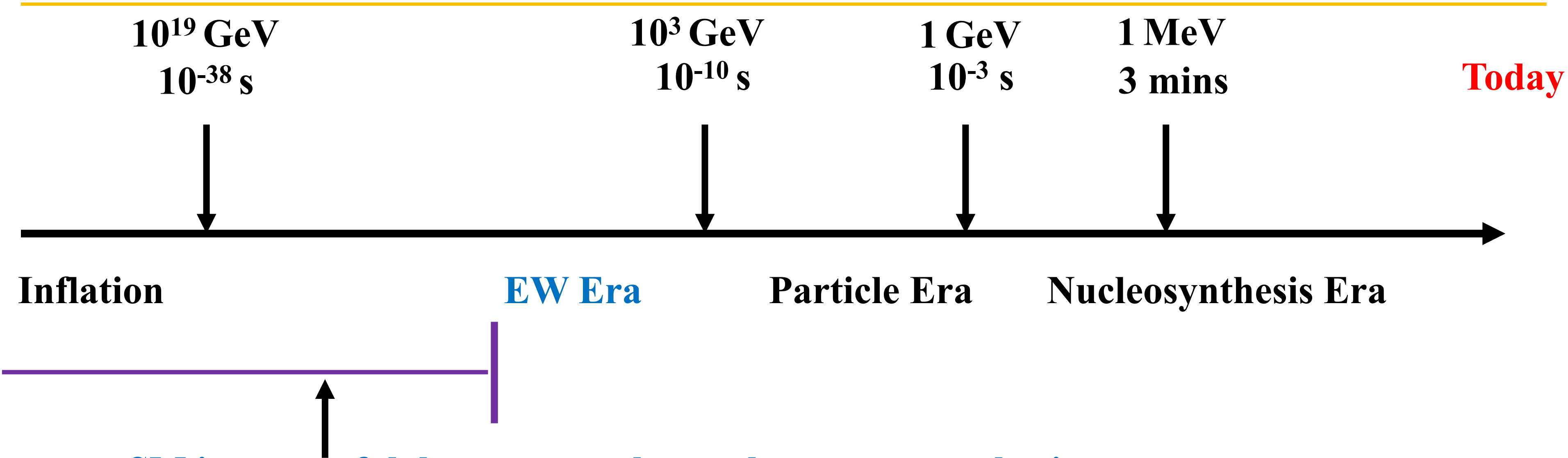
Outline

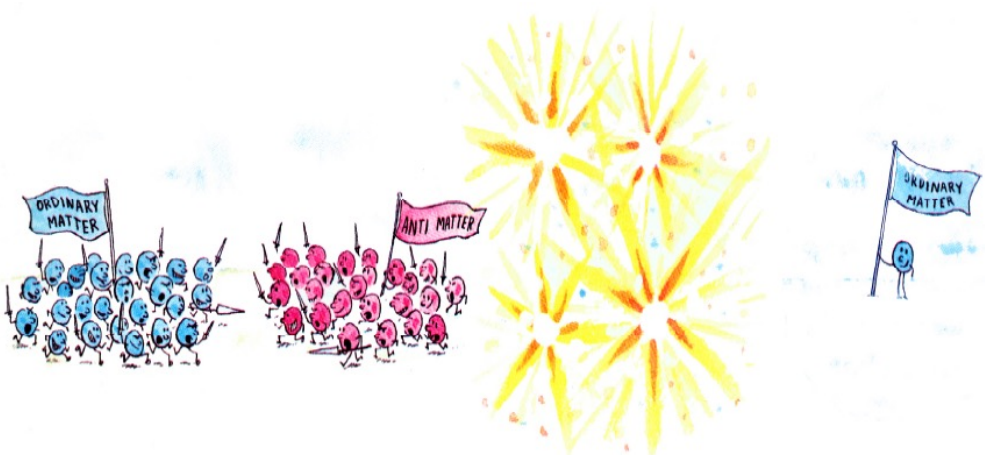
- Introduction
- CKM angle measurements
- Other CP violation measurements in b-sector
- CP violation measurements in c-sector
- Conclusions

New Physics



- SM is successful, however, we know there are new physics
- Matter dominated universe

$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \sim 10^{-10}$$



- SM model gives 10^{-17}, not enough
- Need extra sources of CP violation

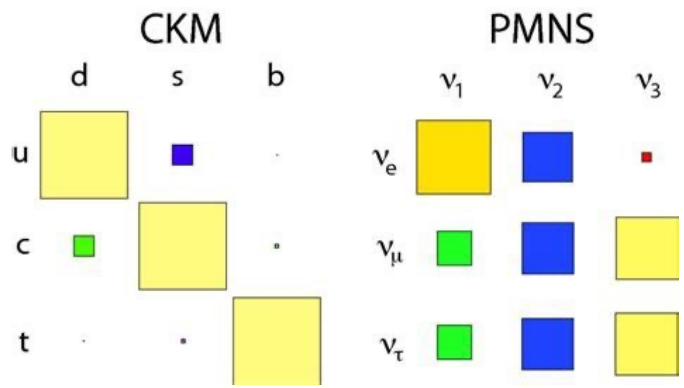
CP violation in SM

- **Complex phases in CKM matrix and PMNS matrix**
- **CKM matrix：unitary matrix connecting interaction and mass eigenstates**

Unitary condition, only requirement in SM

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

Interaction eigenstates **Mass eigenstates**



- **Matrix pattern very different**
- **Jarlskog invariant:**

$J_{exp} \sim 3\text{x}10^{-5}$ $J_{max} = 1/6\sqrt{3} \sim 0.1$

$$\begin{pmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} e^{\pm i\pi} \\ -\frac{1}{\sqrt{3}} e^{i\pi/6} & \frac{1}{\sqrt{3}} e^{-i\pi/6} & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} e^{-i\pi/6} & -\frac{1}{\sqrt{3}} e^{i\pi/6} & \frac{1}{\sqrt{3}} \end{pmatrix}$$

matrix with maximum CPV

- **Related to mass hierarchy? Forth generation?**

CP violation in SM

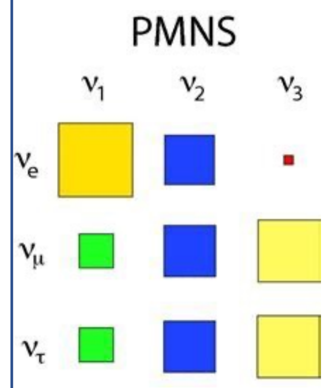
- Complex phases in CKM matrix and PMNS matrix
- CKM matrix： unitary matrix connecting interaction and mass eigenstates

Uni

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix}$$

Interaction eige

Mysterious and suspicious
The more we know, the more we don't know



- Matri
- Jarlsk

$$\frac{1}{\sqrt{3}} \quad \frac{1}{\sqrt{3}}e^{\pm i\pi}$$
$$\frac{1}{\sqrt{3}}e^{-i\pi/6} \quad \frac{1}{\sqrt{3}}$$
$$\frac{1}{\sqrt{3}}e^{-i\pi/6} \quad -\frac{1}{\sqrt{3}}e^{i\pi/6} \quad \frac{1}{\sqrt{3}}$$

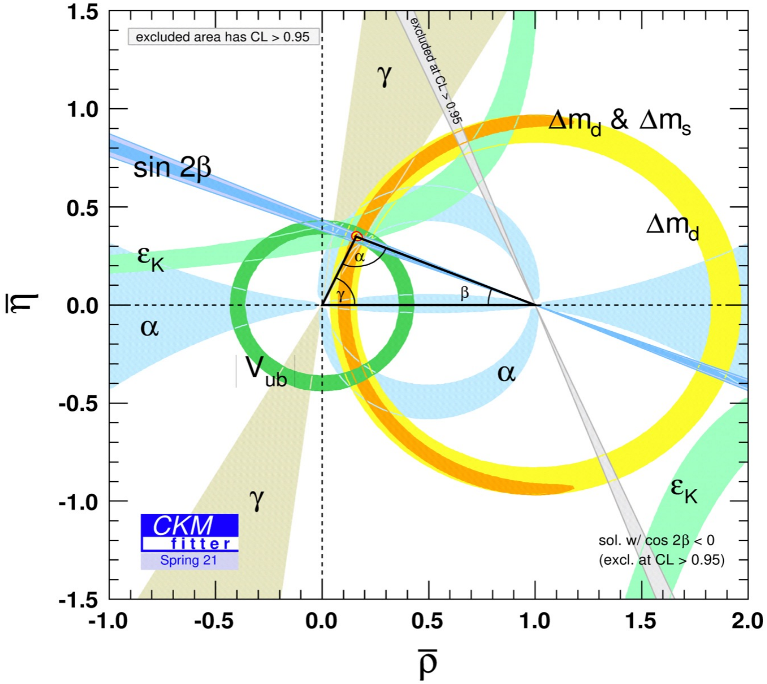
$J_{exp} \sim 3x10^{-5}$ $\quad J_{max} = 1/6\sqrt{3} \sim 0.1$

matrix with maximum CPV

- Related to mass hierarchy? Forth generation?

Unitary test

- **Closure test of unitary triangle etc** $\sum_i V_{ij}^* V_{ij} = 1$ $\sum_i V_{ij}^* V_{ik} = 0$
- **All measurements consistent with each other? Yes**
- **Is current precision enough? No**



10^{-5}

$$V_{ud}V_{ud}^* + V_{us}V_{us}^* + V_{ub}V_{ub}^* - 1$$

$$= -0.00230^{+0.00218}_{-0.00023}\ (1\sigma)$$
$$-0.00230^{+0.00237}_{-0.00044}\ (2\sigma)$$
$$-0.00230^{+0.00242}_{-0.00065}\ (3\sigma)$$

Direct measurements:

$$\boldsymbol{\alpha + \beta + \gamma = (179^{+7}_{-6})^\circ}$$

Global fits:

$$\boldsymbol{\alpha + \beta + \gamma = (179.9^{+1.9}_{-1.7})^\circ}$$

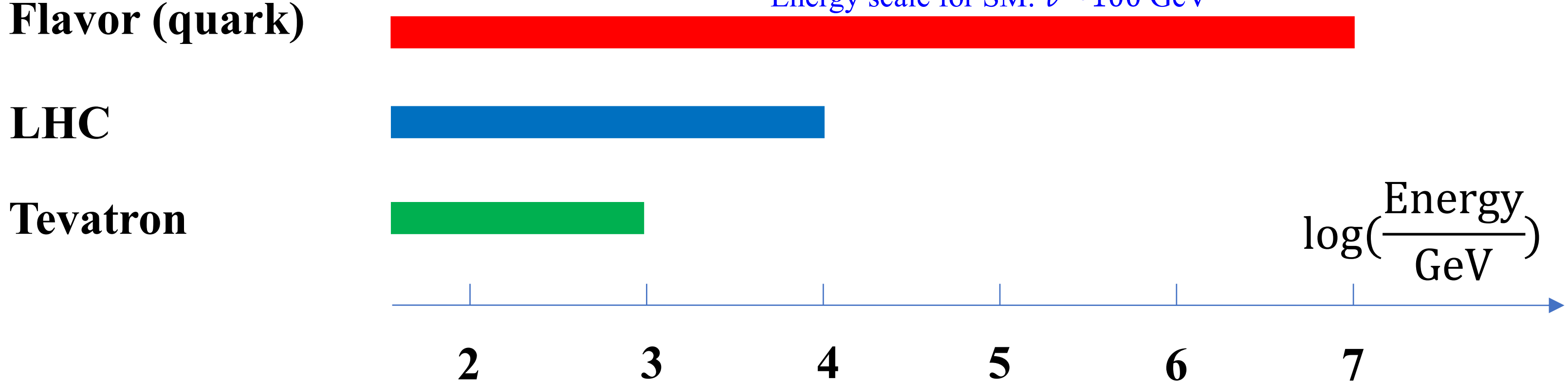
Energy scale

- Sensitive to New Physics scale much higher than direct search: 1-10^4 TeV

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

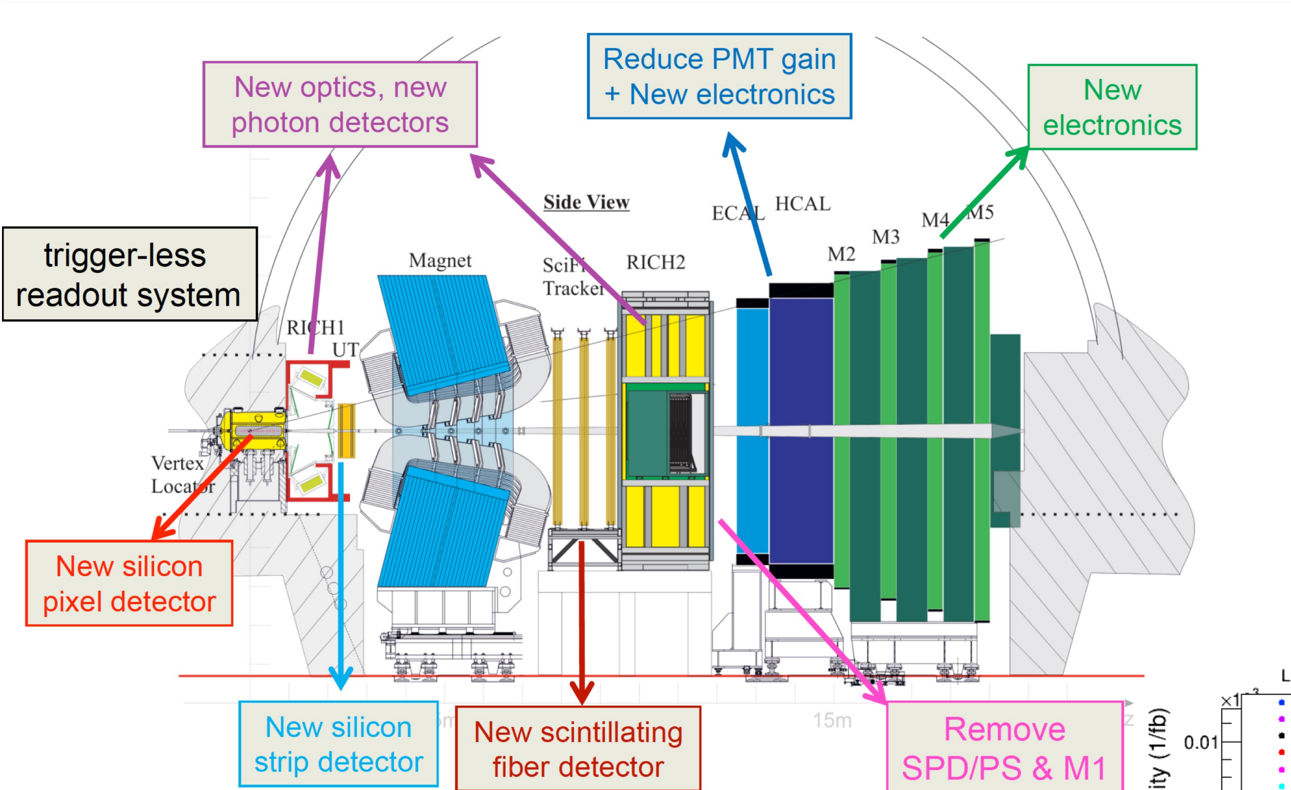
NP scale: Λ

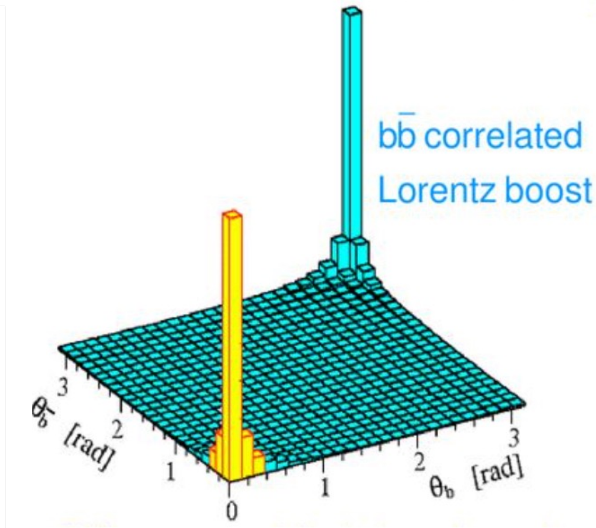
Energy scale for SM: v ~100 GeV



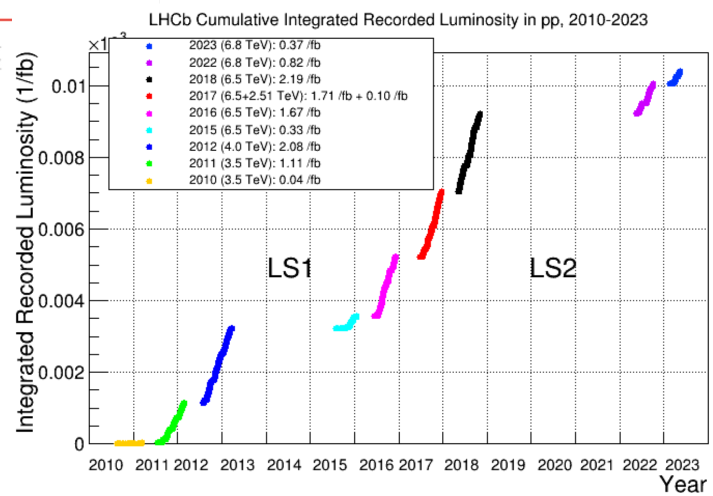
- **Statistics or precision** is key for flavor program: New Physics scale, i.e., Dim = 6, proportional to $\sqrt[4]{\text{statistics}}$ or $1/\sqrt{\text{Uncertainty}}$
- Also "tasteful", not only can tell there is New Physics, but also tell properties of New Physics based on flavor it couples to
- LHCb plays a key role in flavor and CP programs

LHCb

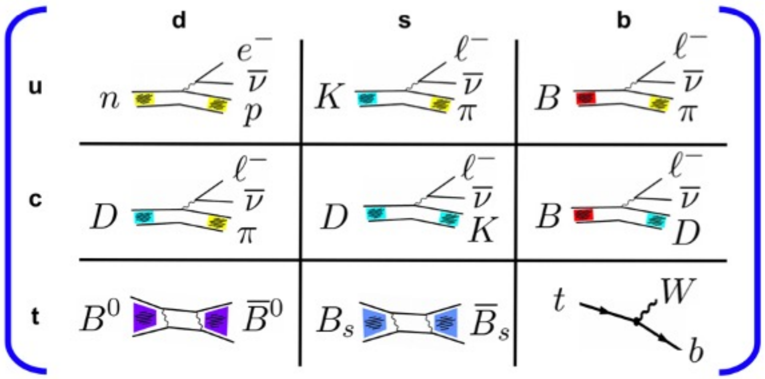




- **A new forward spectrometer**
- **Around 9 fb^{-1} for physics**
- **Data in 2022 and 2023 for understanding new detector (calibration etc.)**

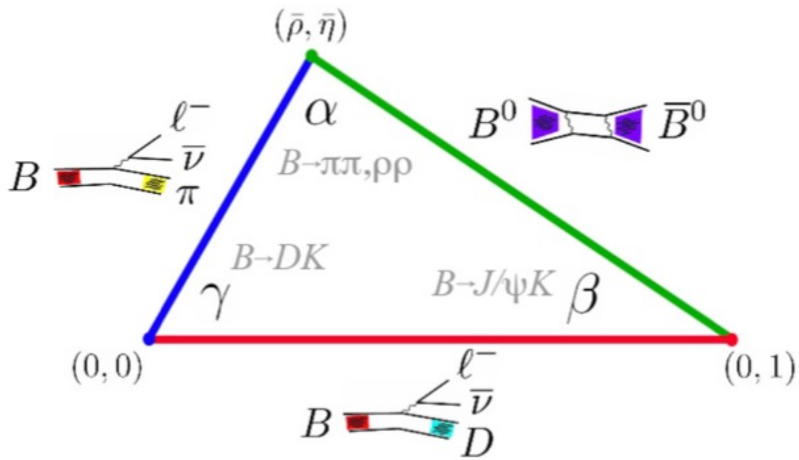


A glance of LHCb contribution



From S. Descotes-Genon

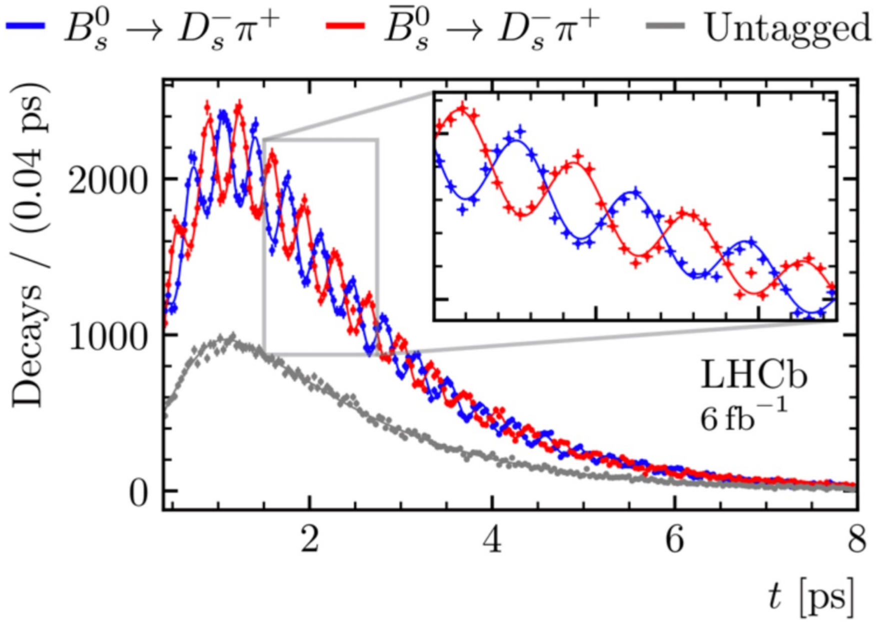
- $|V_{cs}|, |V_{cd}|$: (semi-)leptonic charm decays (can be done and should be done, but none has done anything yet)
- $|V_{ub}|, |V_{cb}|$: (semi-)leptonic B decays
- $|V_{td}|, |V_{ts}|$: $\Delta m_d, \Delta m_s$



- α: $B \to \pi\pi, B \to \rho\pi, B \to \rho\rho$, isospin analyses
- β: $B \to (\bar{c}c)K, B \to Dh^0$, time-dependent CP violation
- γ: $B \to DK$, ADS/GLW/GGSZ
- ϕ_s: $B_s^0 \to (c\bar{c})(KK, \pi\pi)$, time-dependent CP violation
- $-2\beta_s + \gamma$: $B_s \to D_s K$

Measurements of Δm_q

Nature Physics 18 (2022) 1-5



- **Measured using $B_S^0 \to D_S^- \pi^+$, $B^0 \to D^{(*)} \mu \nu X$**

$$\Delta m_d = 0.5065(19)\mathrm{ps}^{-1}$$
$$\Delta m_s = 17.7656(57)\mathrm{ps}^{-1}$$

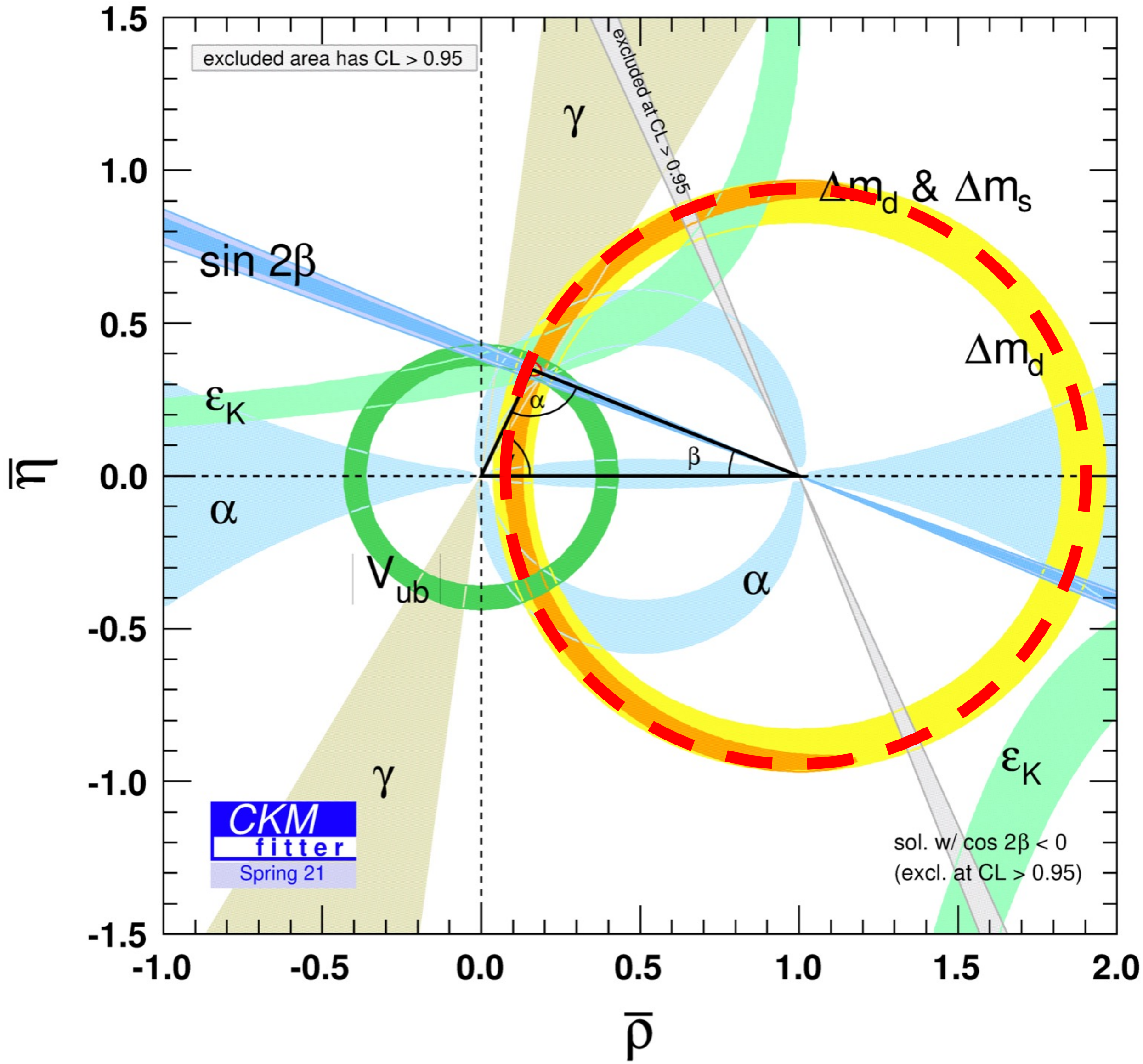
Precision of 0.38% and 0.03%!!!

$$\Delta \mathrm{m_q} = \frac{G_F^2}{6\pi^2} \left| V_{tq}^* V_{tb} \right|^2 M_W^2 S_0(x_t) B_q f_{Bq}^2 M_{Bq} \widehat{\eta_B}, \quad x_t = \frac{m_t^2}{M_W^2}$$

$$S_0(x) = x\left[\frac{1}{4} + \frac{9}{4}\frac{1}{1-x} - \frac{3}{2}\frac{1}{(1-x)^2}\right] - \frac{3}{2}\left[\frac{x}{1-x}\right]^3 \ln x$$

- **Uncertainties mainly from Bag parameters (3%) obtained from lattice**
- **Large reduction of uncertainties by making ratios of the two**

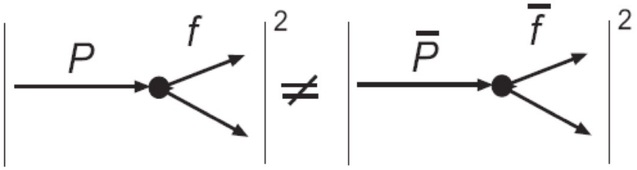
Contribution of Δm_q to CKM fit



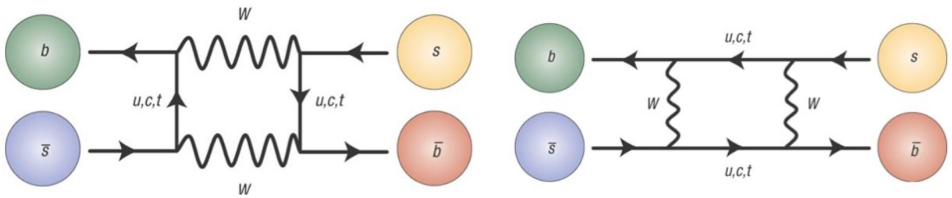
Types of CP violation

- **Direct CP violation**

$$|A_f| = |< f|H|P >| \neq |\bar{A}_{\bar{f}}| = | < \bar{f}|H|\bar{P} > |$$



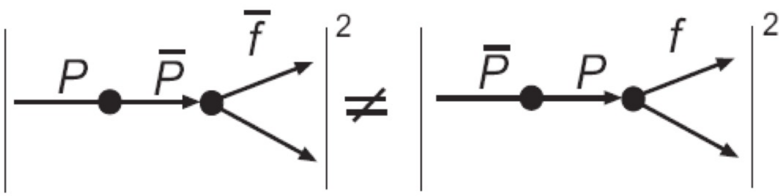
- **Neutral meson mixing**



$$B_L = p|B_q\rangle + q|\bar{B}_q\rangle$$
$$B_H = p|B_q\rangle - q|\bar{B}_q\rangle$$
$$\boldsymbol{\Delta m_q = m_H - m_L,\ \Delta\Gamma_q = \Gamma_L - \Gamma_H}$$

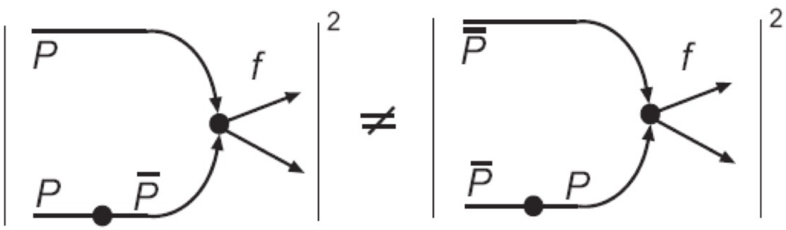
- **CP violation in mixing**

$$\left|\frac{q}{p}\right| ! = 1$$



- **CP violation in mixing and decay**

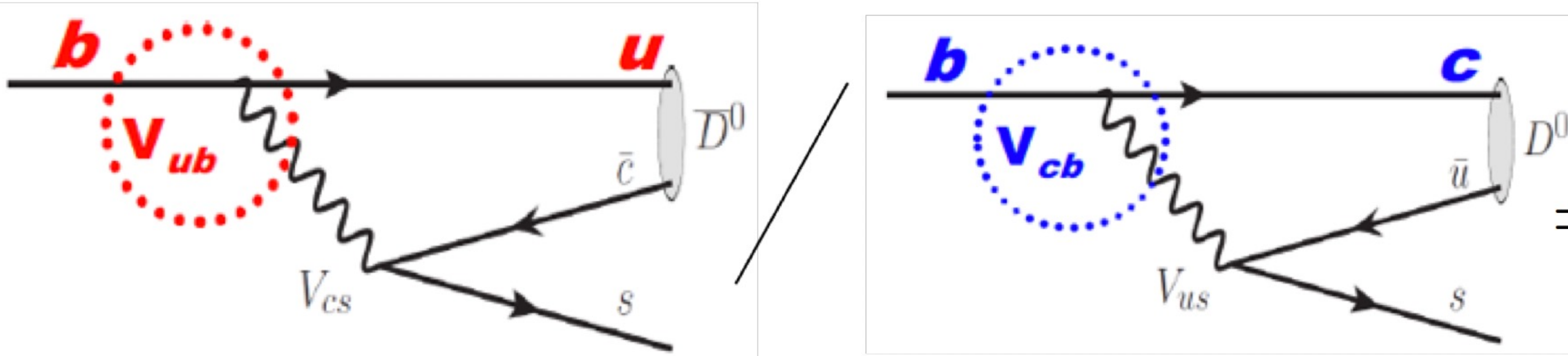
$$\arg(\lambda_f) + \arg(\lambda_{\bar{f}}) \neq 0\ , \qquad \text{with} \qquad \lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}\ .$$



CKM angle γ

- **Measured through $b \to c$ and $b \to u$ interference**

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



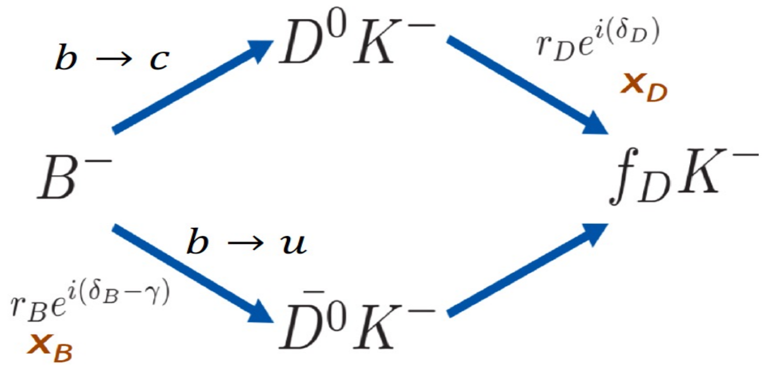
$$= r_B e^{i\delta_B}$$

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

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

- **Tree level processes → SM candle, NP normally enters loop diagrams**
- **Loop level processes suppressed, theoretically clean, $\delta\gamma/\gamma \sim 10^{-7}$** JHEP 1401 (2014) 051
- **All QCD parameters (hard to calculate) obtained from experimental measurements (global fit)**

Probe γ in different methods



D^0 and $\overline{D}^0$ decay to same final states to interference

GLW: D = CP eigenstates, e.g. KK, ππ — PLB 253 (1991) 483, PLB 265 (1991) 172

ADS: D = quasi-flavour-specific states e.g. Kπ — PRL 78 (1997) 3257

GGSZ: D = self-conjugate multi(3)-body states e.g. $K_s\pi\pi$ — PRD 68 (2003) 054018

GLS: ADS variant with singly Cabbibo-suppressed decay $D \to K_s K\pi$ — PRD 67 (2003) 071301

time-dependent $B_s \to D_s K$, $B^0 \to D\pi$ etc — Nucl. phys. B 672 (2003) 459

Dalitz (GW) method: $B^0 \to DK\pi$ — PRD 79 (2009) 051301

Sensitivities of γ from many channels, important to measure as many as possible

Global combination

B decay	D decay	Ref.
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-$	[29]
$B^{\pm} \to Dh^{\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[30]
$B^{\pm} \to Dh^{\pm}$	$D \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	[18]
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^0$	[19]
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^+h^-$	[31]
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S K^{\pm}\pi^{\mp}$	[32]
$B^{\pm} \to D^*h^{\pm}$	$D \to h^+h^-$	[29]
$B^{\pm} \to DK^{*\pm}$	$D \to h^+h^-$	[33]
$B^{\pm} \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]
$B^{\pm} \to Dh^{\pm}\pi^+\pi^-$	$D \to h^+h^-$	[34]
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	[37]
$B^0_s \to D^{\mp}_s K^{\pm}$	$D^+_s \to h^+h^-\pi^+$	[38]
$B^0_s \to D^{\mp}_s K^{\pm}\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[39]

Measurements from b-decays

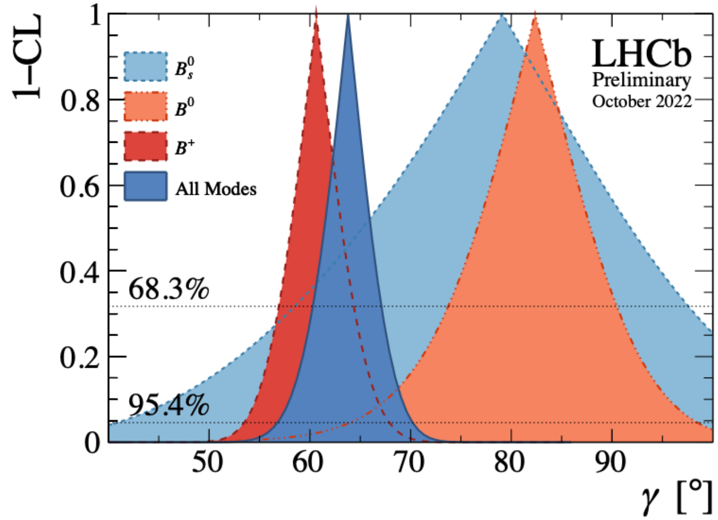
Now can also constrain D parameters

Decay	Parameters	Source
$B^{\pm} \to DK^{*\pm}$	$\kappa_{B^{\pm}}^{DK^{*\pm}}$	LHCb
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb
$B^0 \to D^{\mp}\pi^{\pm}$	β	HFLAV
$B^0_s \to D^{\mp}_s K^{\pm}(\pi\pi)$	ϕ_s	HFLAV
$D \to K^+\pi^-$	$\cos\delta_D^{K\pi}$, $\sin\delta_D^{K\pi}$, $(r_D^{K\pi})^2$, x^2, y	CLEO-c
$D \to K^+\pi^-$	$A_{K\pi}$, $A_{K\pi}^{\pi\pi\pi^0}$, $r_D^{K\pi}\cos\delta_D^{K\pi}$, $r_D^{K\pi}\sin\delta_D^{K\pi}$	BESIII
$D \to h^+h^-\pi^0$	$F^+_{\pi\pi\pi^0}$, $F^+_{KK\pi^0}$	CLEO-c
$D \to \pi^+\pi^-\pi^+\pi^-$	$F^+_{4\pi}$	CLEO-c+BESIII
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII
$D \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII
$D \to K^0_S K^{\pm}\pi^{\mp}$	$r_D^{K^0_S K\pi}$, $\delta_D^{K^0_S K\pi}$, $\kappa_D^{K^0_S K\pi}$	CLEO
$D \to K^0_S K^{\pm}\pi^{\mp}$	$r_D^{K^0_S K\pi}$	LHCb

Charm (and b) inputs

D decay	Observable(s)	Ref.
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]
$D^0 \to h^+h^-$	ΔY	[43–46]
$D^0 \to K^+\pi^-$ (Single Tag)	$R^{\pm}$, $(x'^{\pm})^2$, $y'^{\pm}$	[47]
$D^0 \to K^+\pi^-$ (Double Tag)	$R^{\pm}$, $(x'^{\pm})^2$, $y'^{\pm}$	[48]
$D^0 \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	$(x^2+y^2)/4$	[49]
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[50]
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]

Global combination results

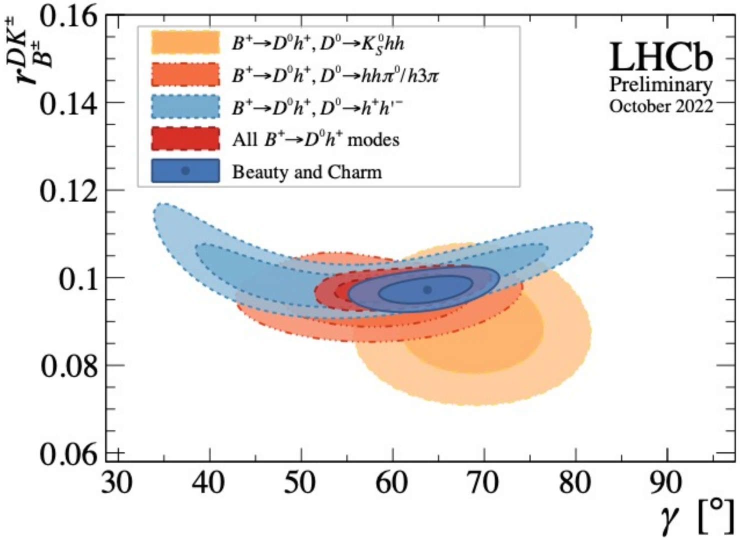


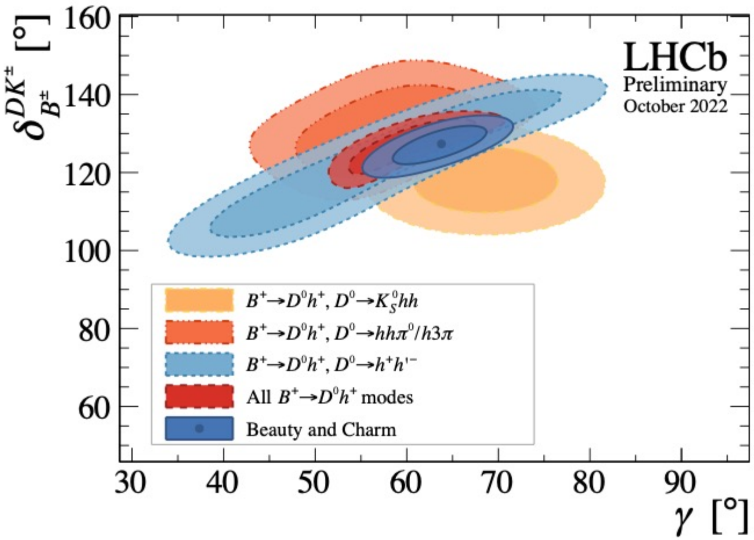
$\gamma = (63.8^{+3.5}_{-3.7})°$

- **Compatible with indirect determination**

$\gamma = (65.5^{+1.1}_{-2.7})°$ CKMfitter

- **Dominant by B^+ decays**
- **Different decays contribute differently, global combination gives best sensitivity**

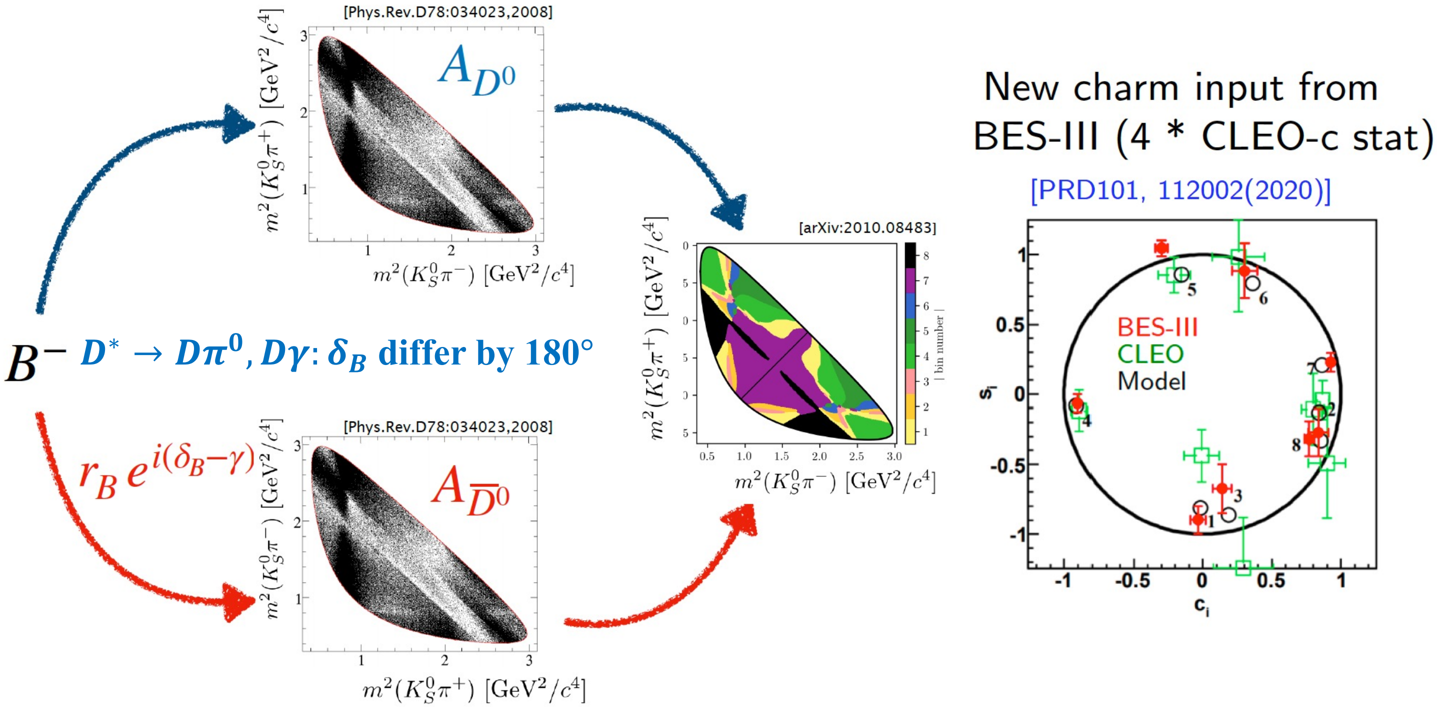




CKM angle γ : results

LHCb-PAPER-2023-012

- **Binned method (BPGGSZ) for $B^+ \to D^* K^+, D^* \to D\pi^0, D\gamma$, $D \to K_S^0 h^+ h^-$**
- **Uncertainties from BaBar and Belle around 26°**
- **First measurements from LHCb, using fully reconstructed method**



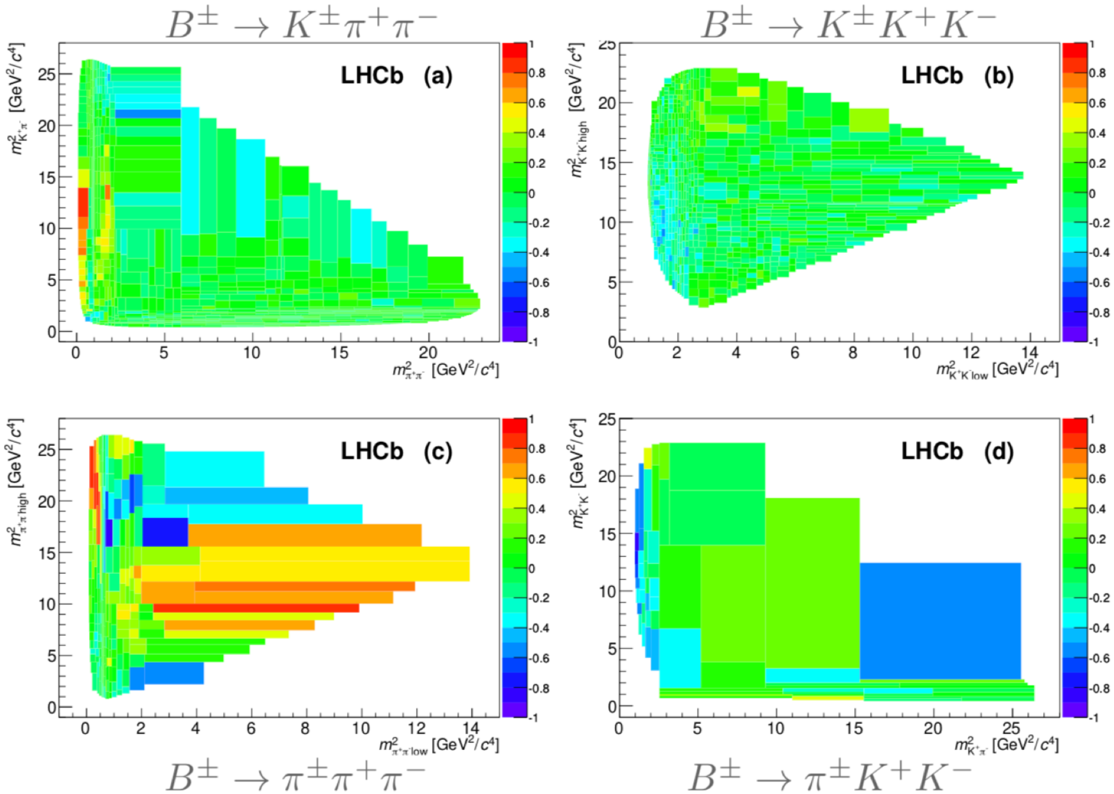
$$\gamma = 69 \pm 14\ ^\circ$$

Results consistent with previous measurements, but more precise

CPV in three-body charmless B decays

PRL 112 (2014) 011081
PRL 111 (2013) 101801
PRD 90 (2014) 112004

- Interesting CPV pattern seen on Dalitz plot of $B^+ \to h^+h^-h'^+, h^{(\prime)} = K, \pi$
- Dalitz plot analysis needed to shed more light on understanding nature of these CPV

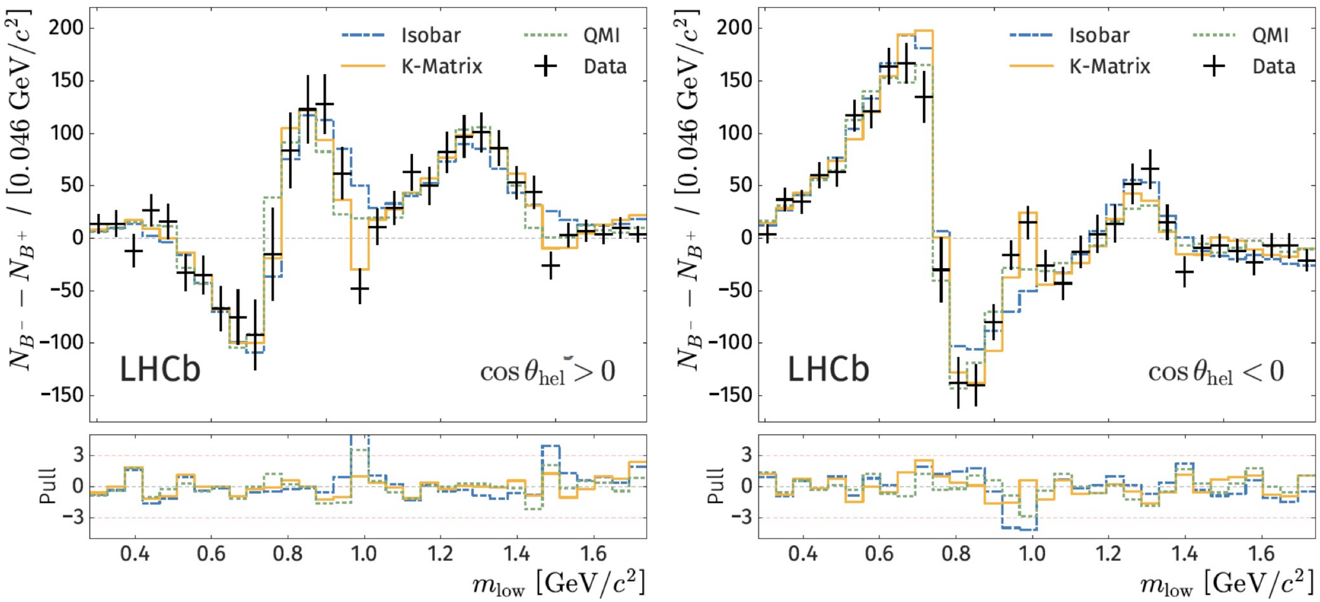


- Now, amplitude analyses of $B^+ \to \pi^+\pi^-\pi^+$ and $B^+ \to K^+K^-\pi^+$, with much larger statistics than previous B-factory analyses, has been performed

New CP violation patterns

LHCb-PAPER-2019-017
LHCb-PAPER-2019-018

- CP violation around $\rho(770)$ pole well described by the three S-wave models

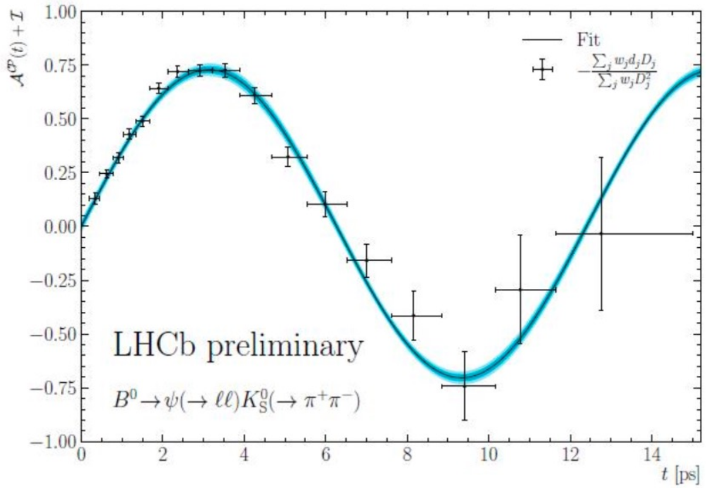


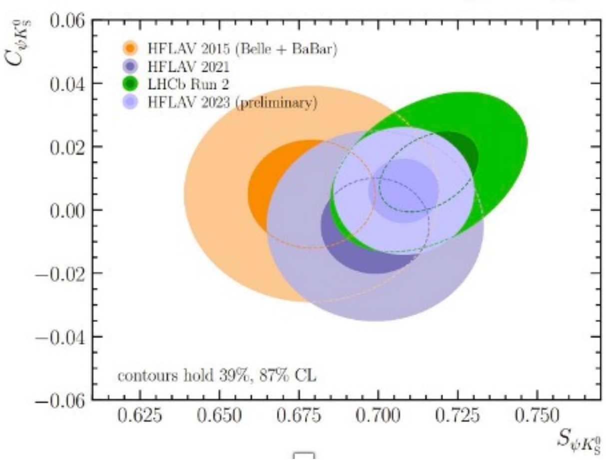
- Over 25σ significance for CPV due to S-P interference, first observation
- CP violation sign flips around $\rho(770)$ pole and over helicity angle
- Crucial object next: any new physics inside?

CKM angle β

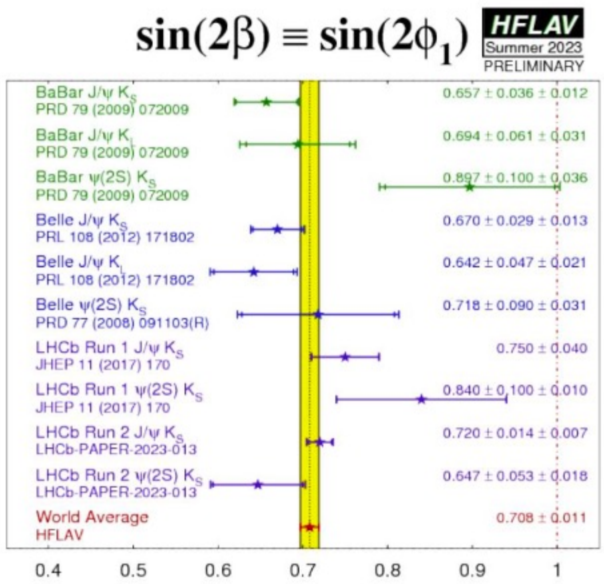
$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\overline{B}^0(t)\to\psi K^0_S) - \Gamma(B^0(t)\to\psi K^0_S)}{\Gamma(\overline{B}^0(t)\to\psi K^0_S) + \Gamma(B^0(t)\to\psi K^0_S)} \approx \underbrace{D_{\Delta t} D_{FT}}_{\text{Experimental dilution factors}} S \sin(\Delta m_d t)$$

$$S^{\text{Run 2}}_{\psi K^0_S} = 0.716 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$C^{\text{Run 2}}_{\psi K^0_S} = 0.012 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})$$





[HFLAV to update]



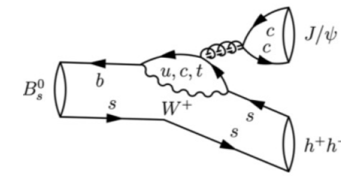
See talk from Peilian

CKM angle $\phi_s^{c\bar{c}s}$

- **Using predictions with CKM parameters, probe new physics in sensitive decays**

$B_s^0 \rightarrow J/\psi\phi$

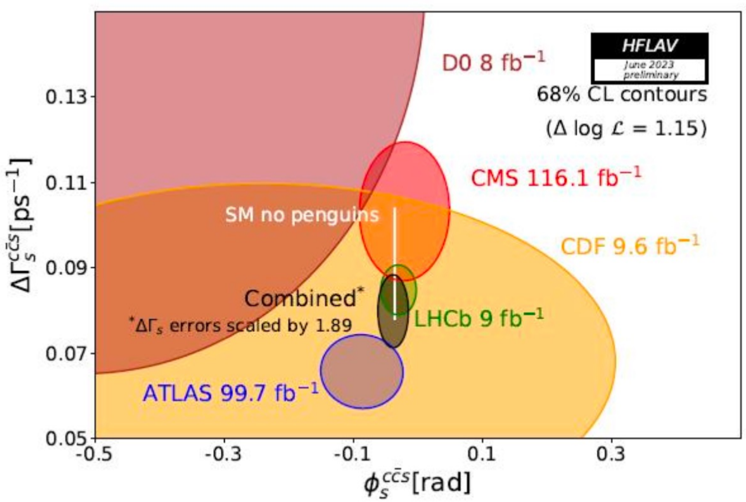
$+2\beta_s$: $B_s^0 \rightarrow \bar{B}_s^0 \rightarrow J/\psi\phi$



Penguin pollution: Data-driven method

$$\phi_s^{meas.} = -2\beta_s + \delta\phi_s^{peng} + \delta\phi_s^{NP}$$

Very small value | **Very small value**



$+2\beta_s$:

$36.8^{+0.9}_{-0.6}$ mrad [CKMfitter]

(37 ± 1) mrad [UTFIT]

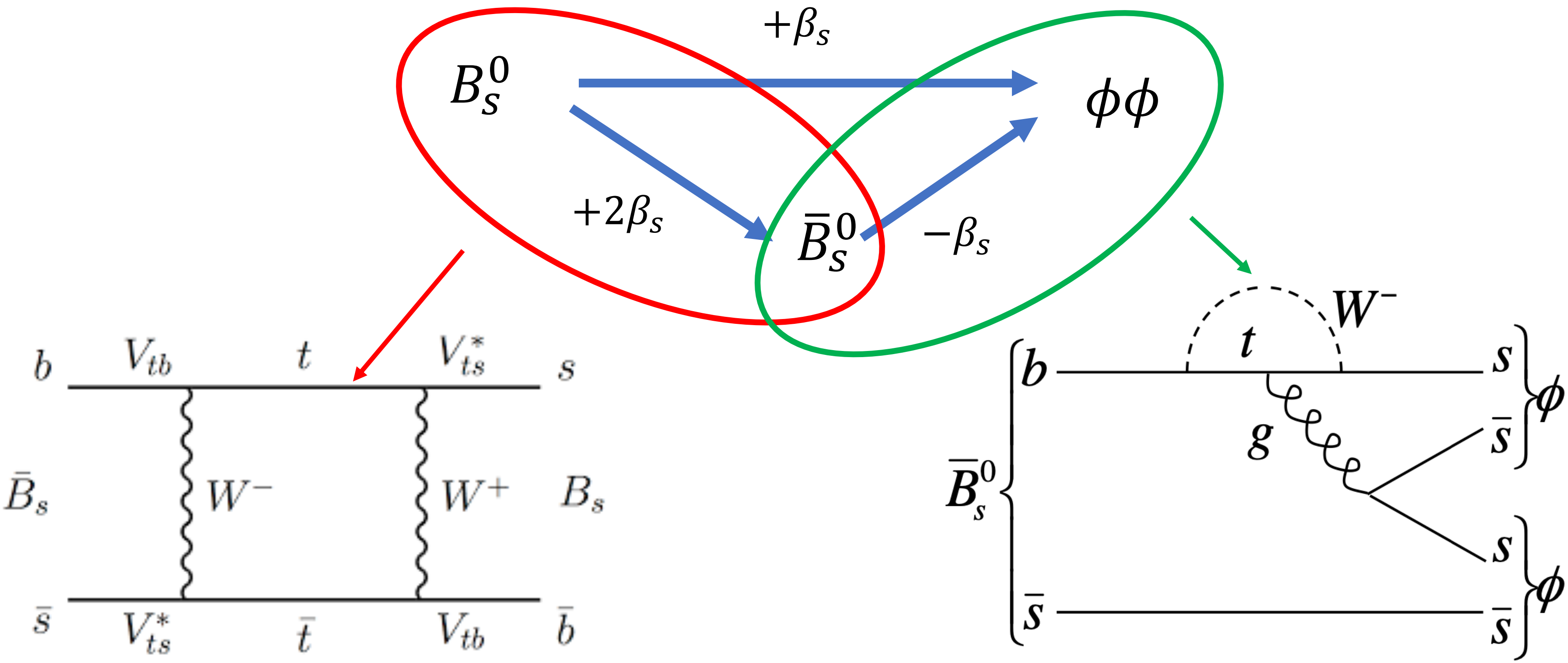
Global combination

$\phi_s^{c\bar{c}s} = -49 \pm 19$ mrad

See talk from Peilian

CKM angle $\phi_s^{s\bar{s}s}$

- **Very sensitive to new physics in B_s mixing and in penguin**

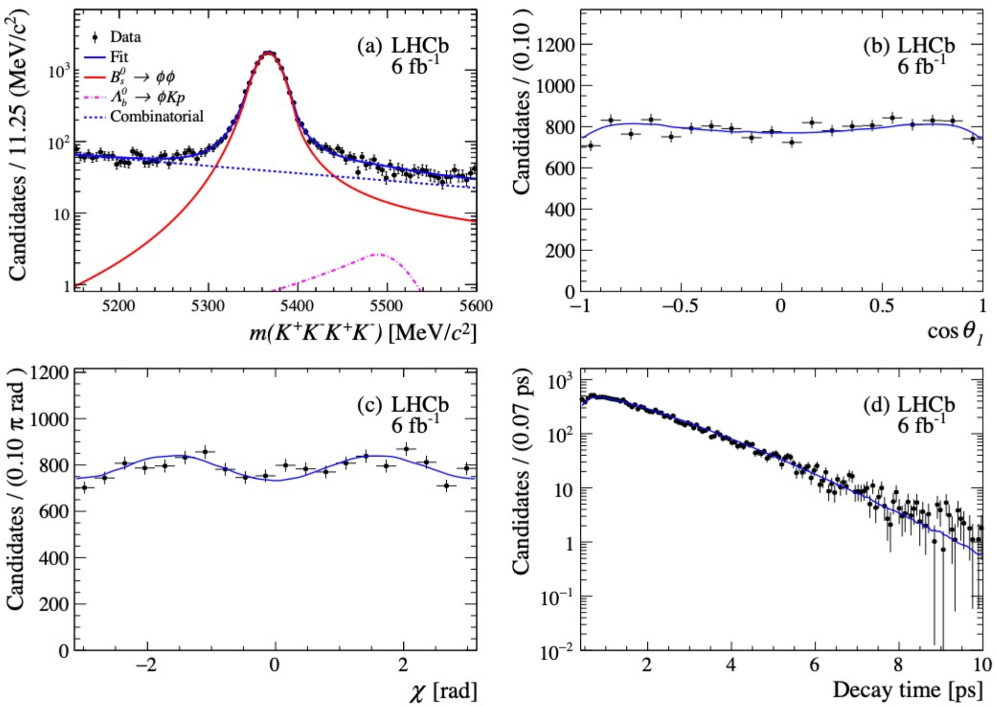


$$\phi_s^{s\bar{s}s} \sim 0 \quad \text{(SM)}$$

See talk from Peilian

CKM angle $\phi_s^{s\bar{s}s}$

- Very sensitive to new physics in B_s mixing and in penguin
- Time-dependent angular analysis to probe CP violation： distinguish flavor, resonant contributions



See talk from Peilian

Mixing angle:

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad},$$

Direct CP violation parameter:

$$|\lambda| = 1.004 \pm 0.030 \pm 0.009,$$

CP violation in weak decays

LHCb-PAPER-2019-006

1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1964
Strange particles:
***CP* violation in K meson decays**
J. W. Cronin,
V. L. Fitch *et al.*

2001
Beauty particles:
***CP* violation in B^0 meson decays**
BaBar and Belle collaborations

March 2019

1963
Cabibbo Mixing
N. Cabibbo

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

2019
Charm particles:
***CP* violation in D^0 meson decays**
LHCb collaboration

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

A. Carbone, CERN seminar, March 19, 2019

CP violation in charm observed at 5.3σ

- **The only place where CPV is not found is in baryon decays, closely related to baryon number asymmetry**

First evidence of CPV in $D^0 \to \pi^+\pi^-$

- **Previous CP violation discovery in charmed mesons:**

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

- **Now we measure**

$$A_{CP}(K^+K^-) = (6.8 \pm 5.4 \pm 1.6)\times 10^{-4}$$

- **Interpretation:**

$$A_{CP}(f) = a_f^d + \frac{\langle t \rangle_f}{\tau_D} \Delta Y_f$$

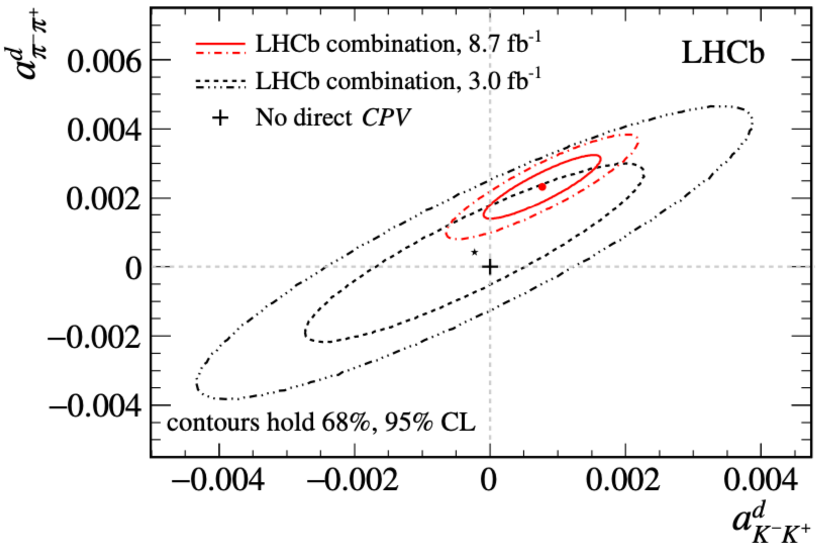
Related to CPV in mixing and decay

Determined by LHCb

- **Direct CP violation:**

$$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4},$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4},$$

3.8σ



Discovery of a non-zero x

LHCb-PAPER-2022-020
LHCb-PAPER-2021-009

- **Mixing parameters: $x = (3.7 \pm 1.2)\times10^{-3}, y = (6.8^{+0.6}_{-0.7})\times10^{-3}$**
- **CP violation in mixing: $\left|\frac{q}{p}\right| \neq 1$**
- **CPV in mixing and decay: $\phi \neq 0$**

  (assume no direct CPV)

$$x_{CP} = -\operatorname{Im}(z_{CP}) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right],$$

$$\Delta x = -\operatorname{Im}(\Delta z) = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right],$$

$$y_{CP} = -\operatorname{Re}(z_{CP}) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right],$$

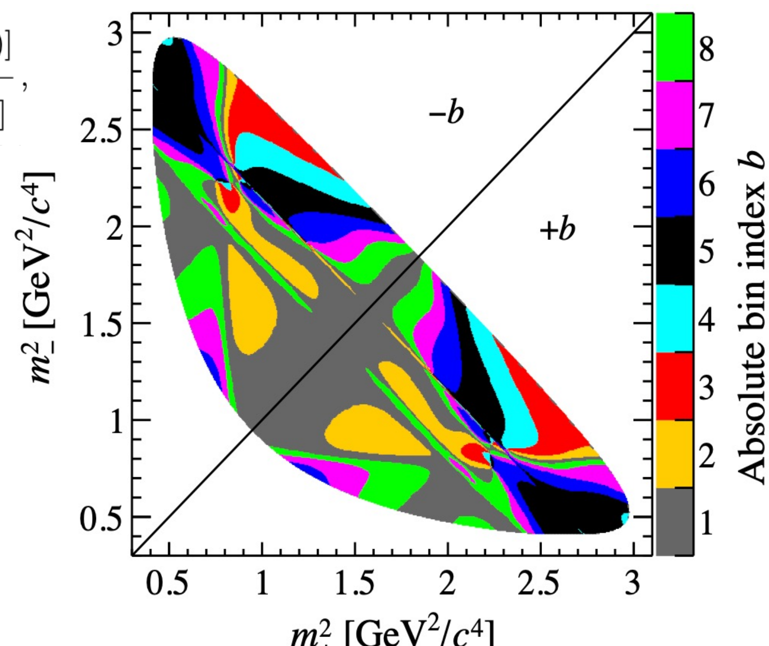
$$\Delta y = -\operatorname{Re}(\Delta z) = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right].$$

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

$$x_{CP} = -\operatorname{Im}(z_{CP}), \quad \Delta x = -\operatorname{Im}(\Delta z),$$
$$y_{CP} = -\operatorname{Re}(z_{CP}), \quad \Delta y = -\operatorname{Re}(\Delta z).$$

$$X_b \equiv c_b - i s_b,$$

- **Measured using prompt $D^{*+} \to D^0\pi^+, D^0 \to K_S^0\pi^+\pi^-$ and secondary $\overline{B} \to D^0\mu^-\overline{\nu_\mu}X$**



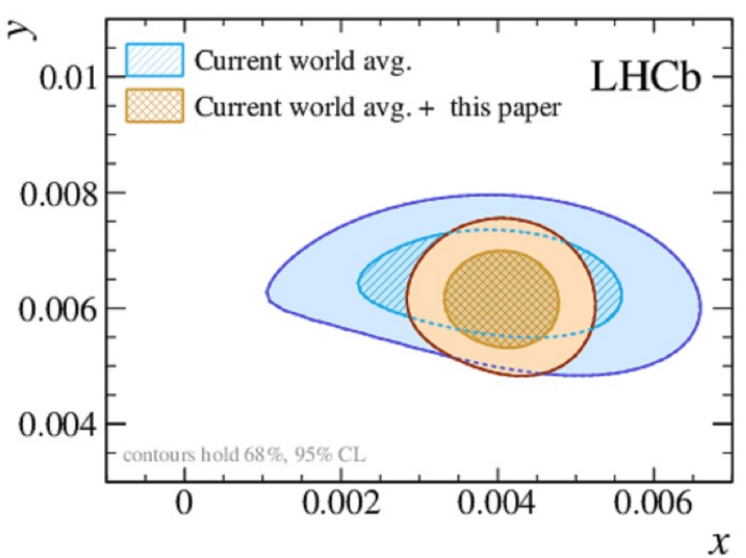
Discovery of a non-zero x

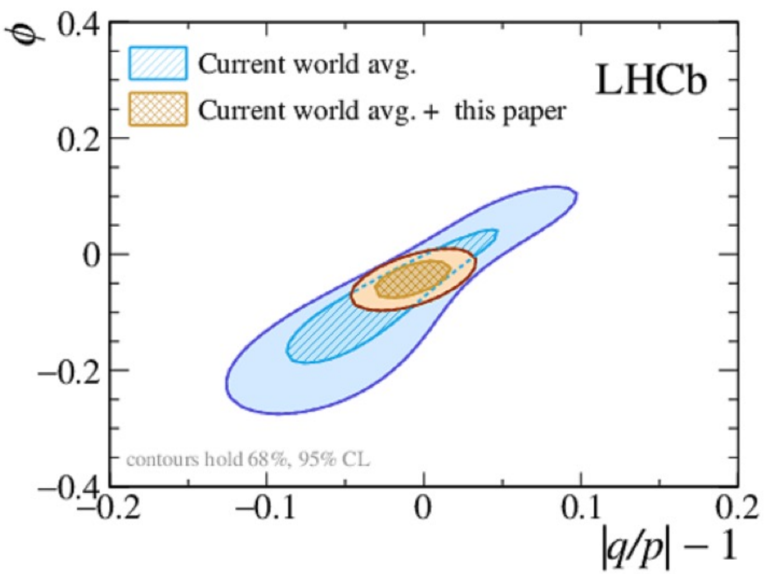
- **Results and constrain on CP violation parameters**

$$x_{CP} = [\ \ 4.01 \pm 0.45\,(\text{stat}) \pm 0.20\,(\text{syst})] \times 10^{-3}\,,$$
$$y_{CP} = [\ \ 5.51 \pm 1.16\,(\text{stat}) \pm 0.59\,(\text{syst})] \times 10^{-3}\,,$$
$$\Delta x = [-0.29 \pm 0.18\,(\text{stat}) \pm 0.01\,(\text{syst})] \times 10^{-3}\,,$$
$$\Delta y = [\ \ 0.31 \pm 0.35\,(\text{stat}) \pm 0.13\,(\text{syst})] \times 10^{-3}\,.$$

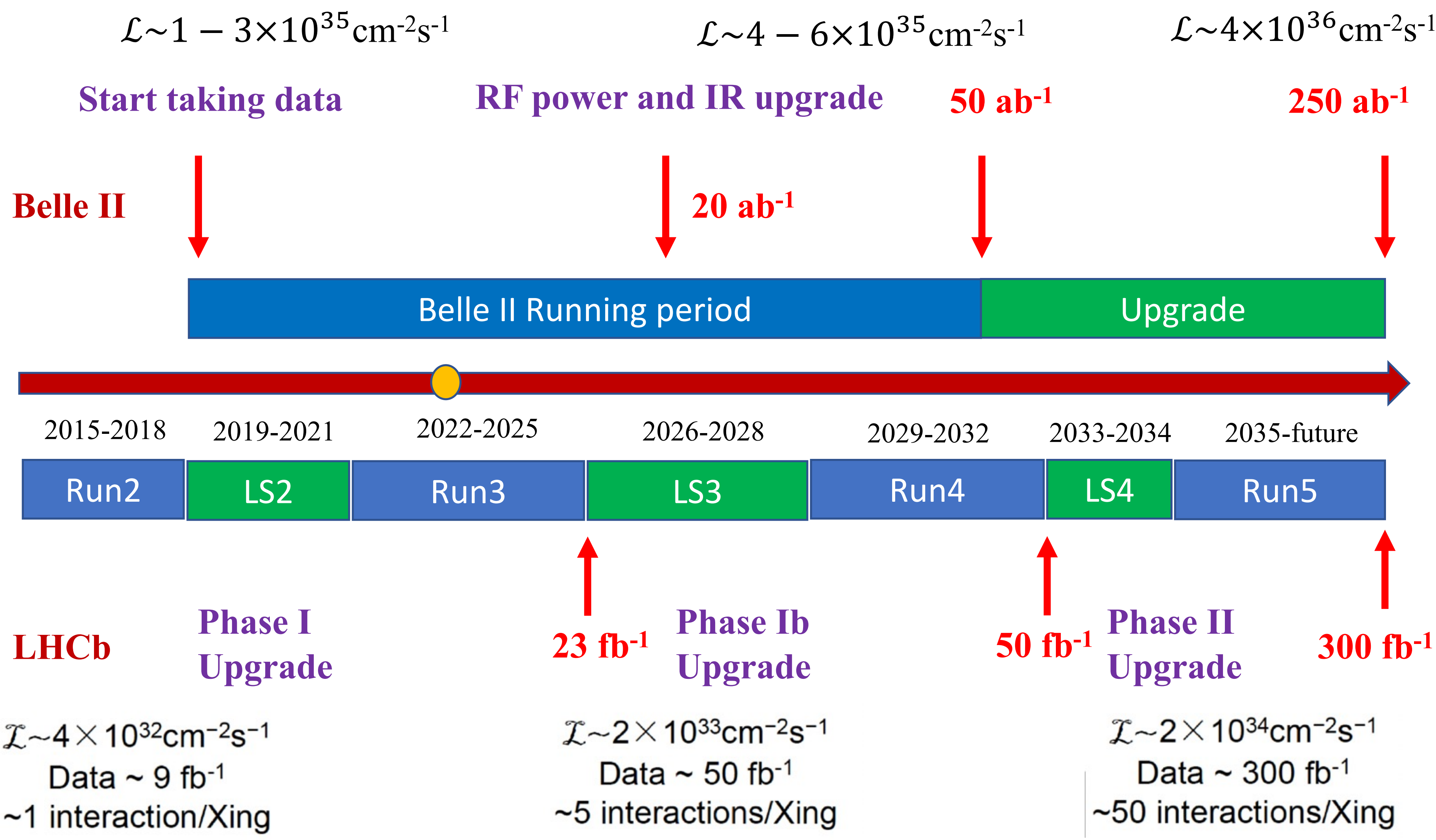
$$x = (4.01 \pm 0.49) \times 10^{-3}\,,$$
$$y = (\ 5.5 \pm 1.3\ ) \times 10^{-3}\,,$$
$$|q/p| = 1.012\,^{+0.050}_{-0.048}\,,$$
$$\phi = -0.061\,^{+0.037}_{-0.044}\ \text{rad.}$$

- **Significant improvement on our understanding of D mixing and CPV**





Future data taking plans

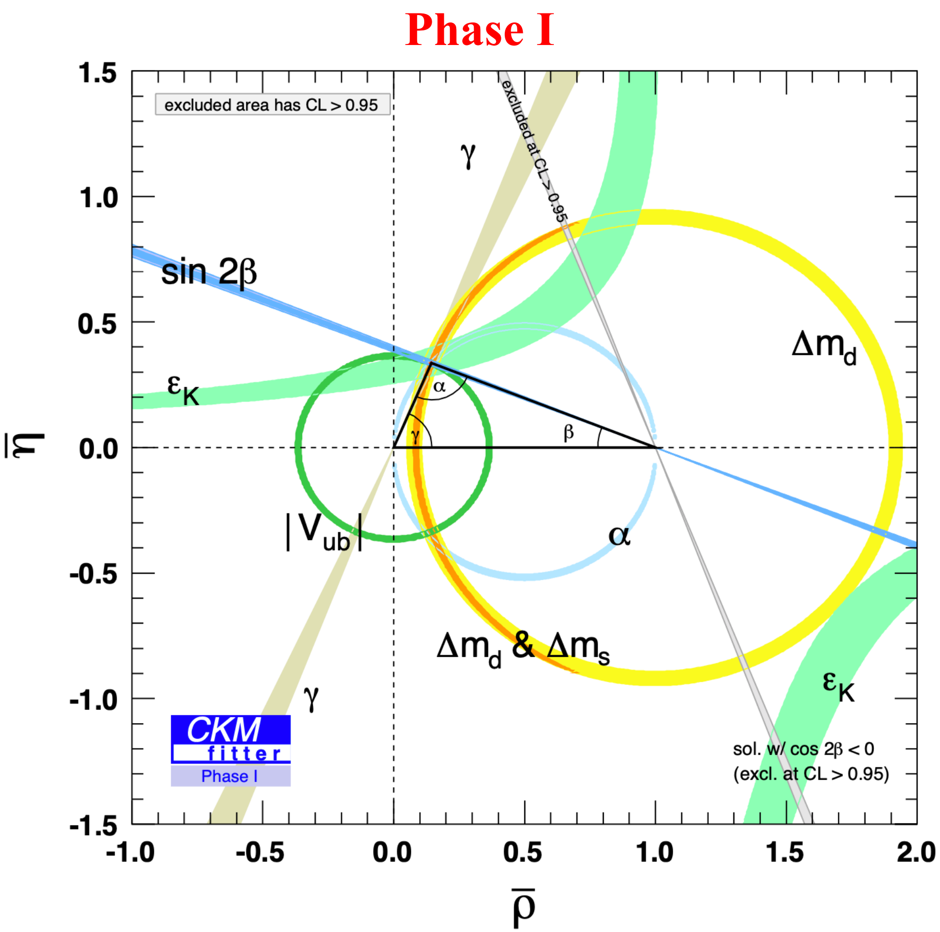


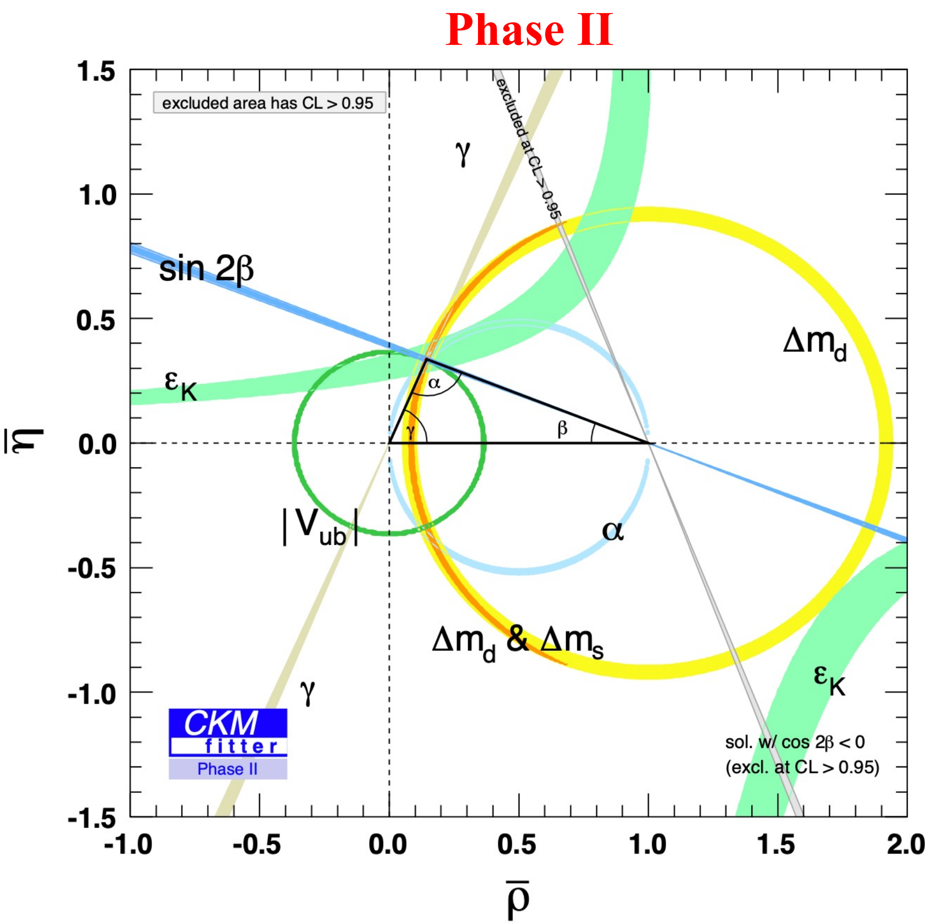
Physics potential

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	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}	–

- **Great experimental potential ahead, need lattice to accompany**

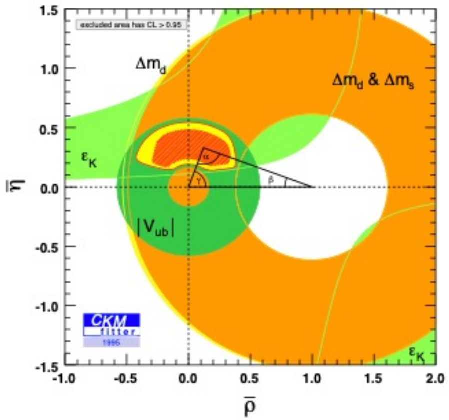
CKM fit in a near future



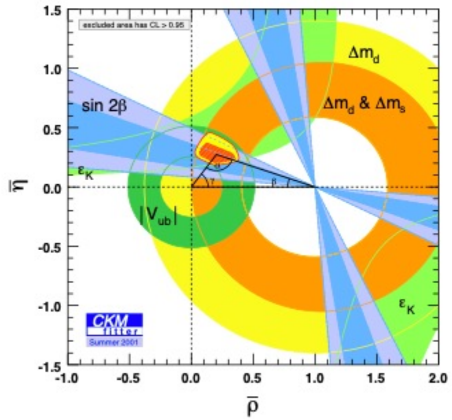


- With assumptions on improvements on lattice (mostly factor of 2)
- Central values at current fit values

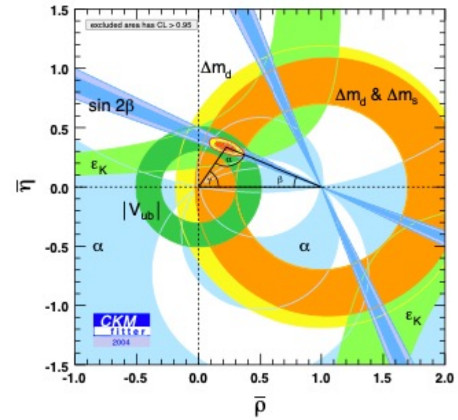
Summary: CKM status over years



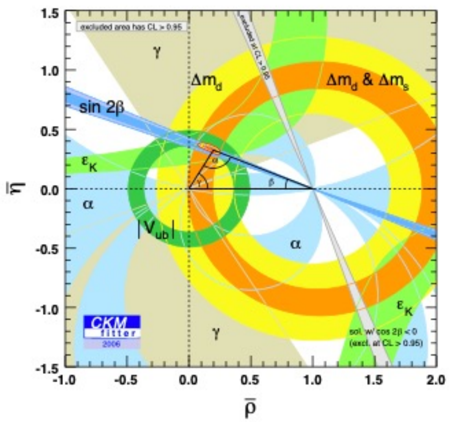
1995



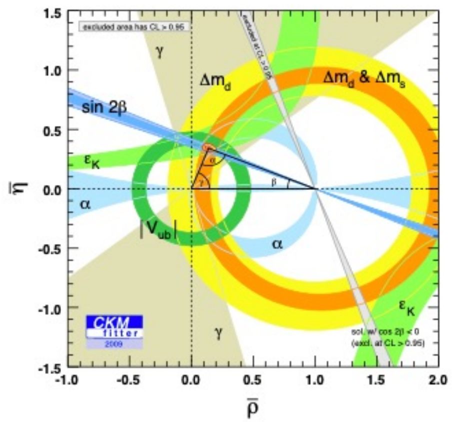
2001



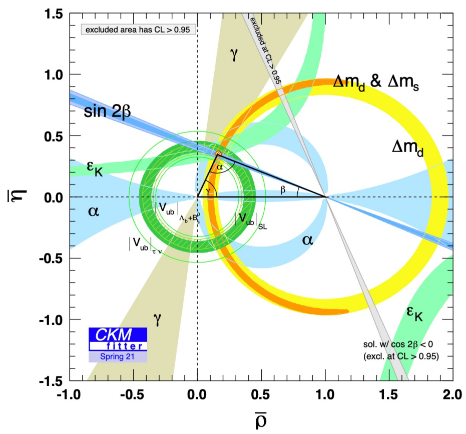
2004



2006

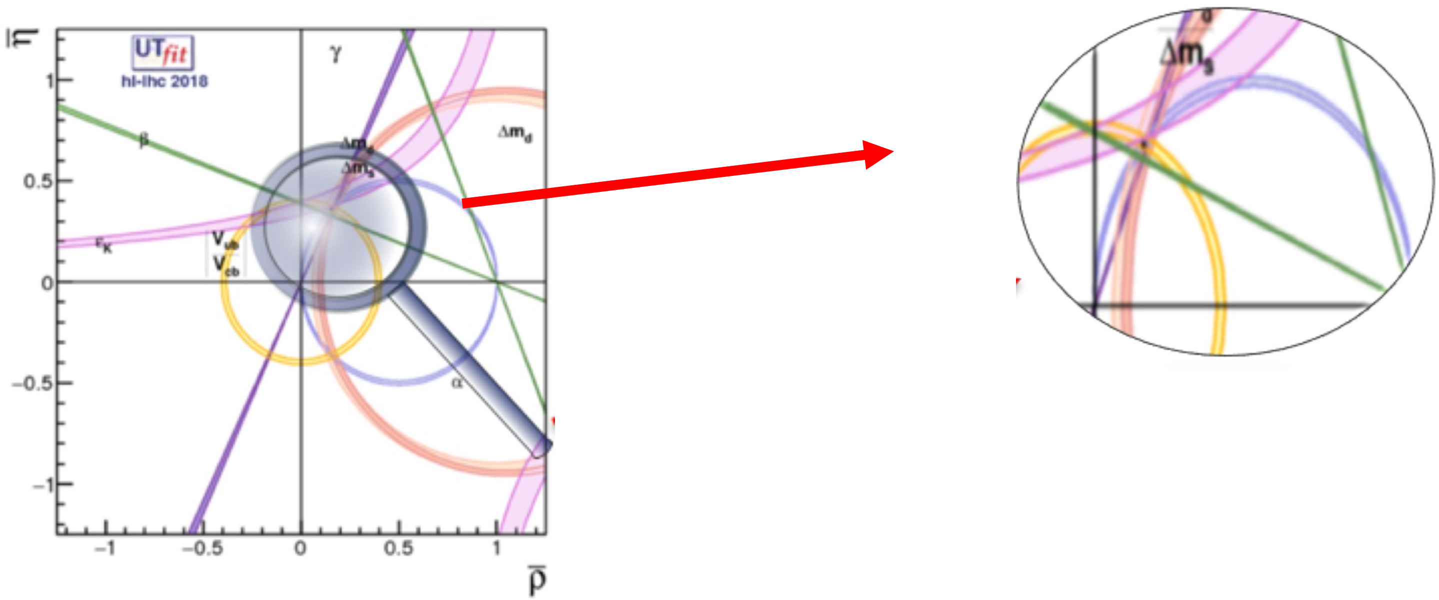


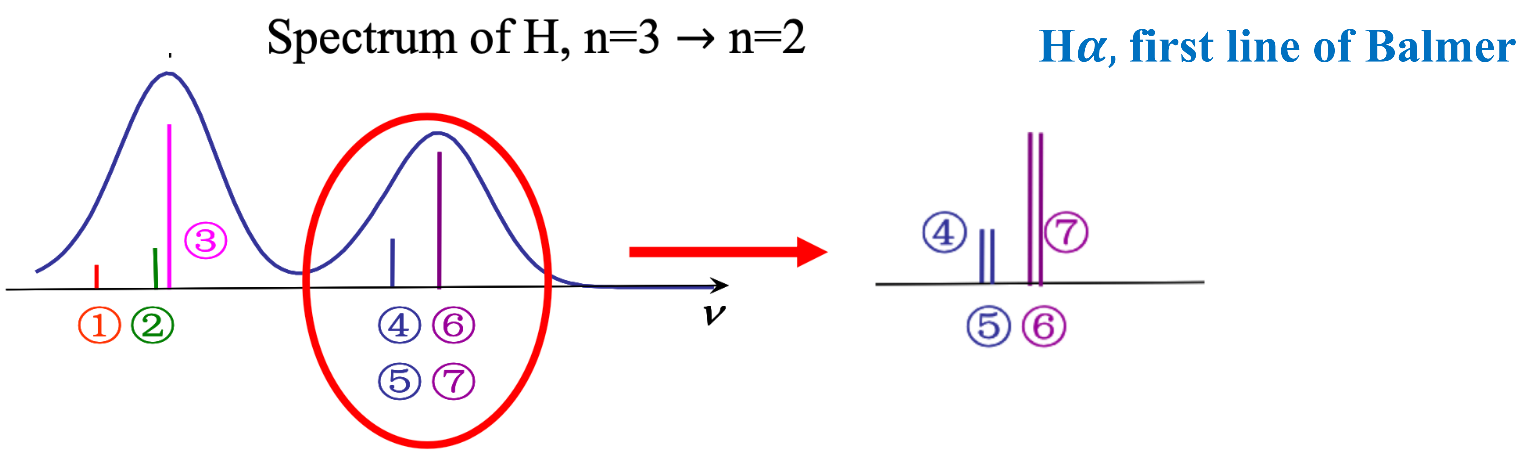
2009



2021

Summary: Future of CKM



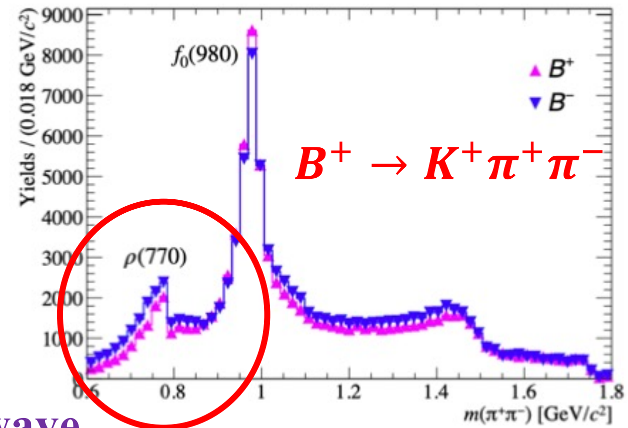


Thank You for Your Attention

CP violation in $B \to PV$

LHCb-PAPER-2021-050

- Resonant contributions in vector region: S, P waves and their interference
- CP violation can be measured by analyzing angular distributions

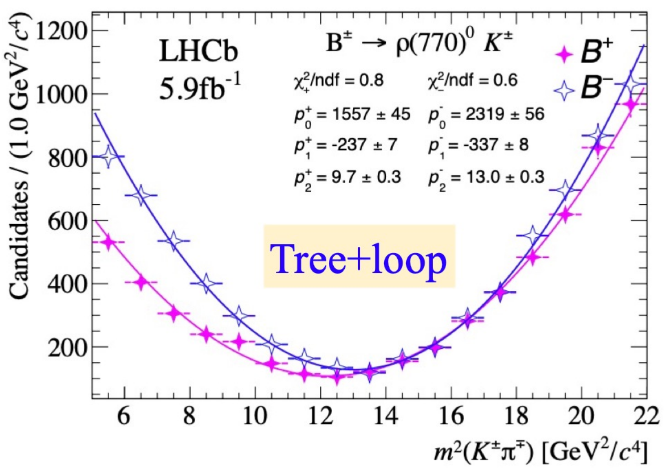


S-wave

S, P-wave interference

P-wave

$$|\mathcal{M}_\pm|^2 = f(\cos\theta(m_V^2, s_\perp)) = p_0^\pm + p_1^\pm \cos\theta(m_V^2, s_\perp) + p_2^\pm \cos^2\theta(m_V^2, s_\perp),$$



$$A_{CP}[B^\pm \to \rho(770)^0 K^\pm] = 0.150 \pm 0.019$$

Cautious when using the results!!!

It is not CP violation of $\rho(770)K^+$, but all vector contributions in the region, $\omega(782)$ may cause sizable effects