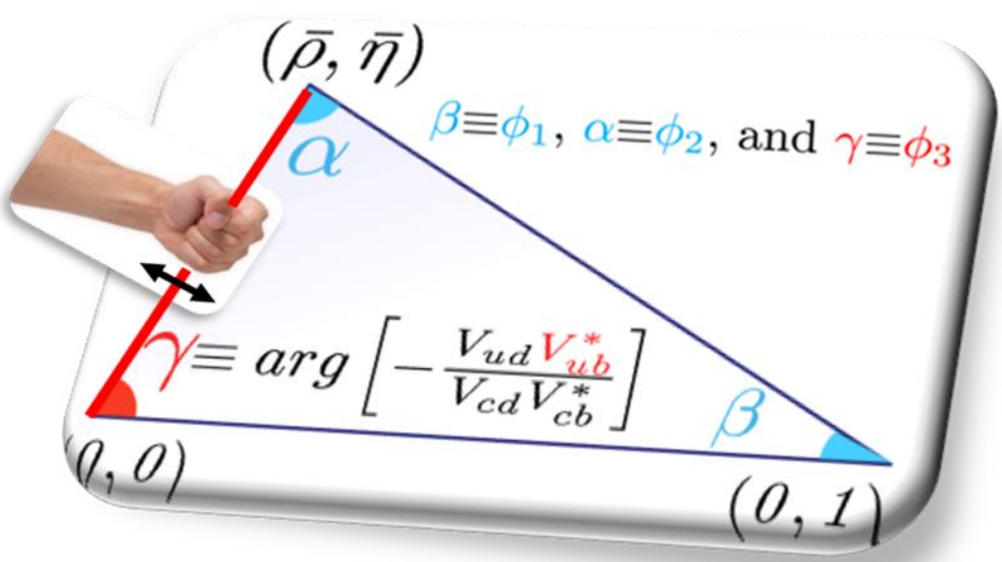
Recent CPV measurements in LHCb and Belle II

V. Tisserand, LPC-Clermont Ferrand, France

Mont Sainte Odile, Nov. 8th 2023



INTENSITY frontier

GDR-InF

GDR-InF Annual Workshop 2023

CNRS IN2P3 Les deux infinis

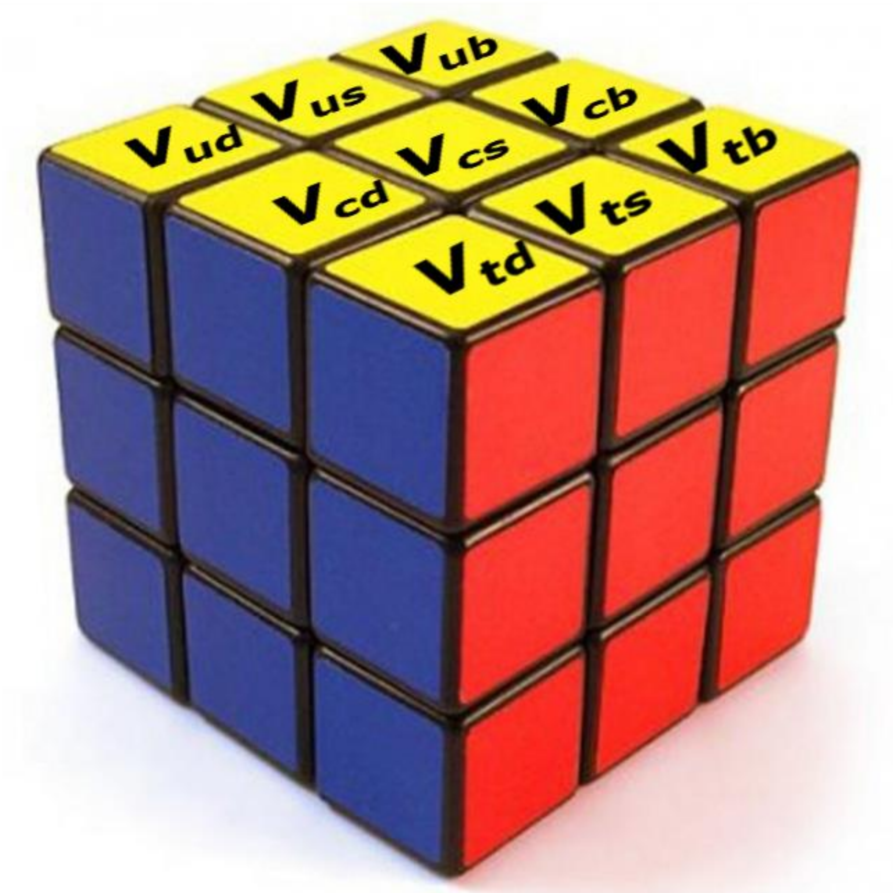
LPC Laboratoire de Physique de Clermont

Université Clermont Auvergne

Blaise Pascal 400 years

"After all, what are humans in Nature? A nothingness with respect to infinity, a whole with respect to nothingness, a middle ground between nothing and everything. Infinitely far from comprehending extremes, the end of things and their principle are for him invincibly hidden in an impenetrable secret, equally incapable of seeing the nothingness from which he is drawn, and the infinity into which he is engulfed." Blaise Pascal (Thoughts, 1669)

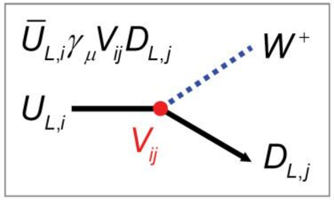
The CKM MATRIX
Cabibbo-Kobayashi-Maskawa



The Standard Model (SM) & the Unitary CKM Matrix
➔ mixing of the 3 quarks families & CP violation

• the Higgs boson gives mass to elementary bosons & fermions (quarks, leptons) through Yukawa couplings, but there is not only that ! :

$$\mathcal{L}_{cc}^{\rm quarks} = \frac{g}{2\sqrt{2}} W_\mu^\dagger [\sum_{ij} \bar{u}_i(q_2)\gamma^\mu(1-\gamma^5) V_{ij} d_j] + \text{h.c}$$



charged currents (EW) imply transitions between quark families : quarks decays [there are no neutral current changing flavour (FCNC) at tree level (i.e., GIM mechanism)].

V_{CKM} =

	d	s	b
u	$1-\lambda^2/2$	λ	$A\lambda^3(\rho-i\eta)$
c	$-\lambda$	$1-\lambda^2/2$	$A\lambda^2$
t	$A\lambda^3(1-\rho-i\eta)$	$-A\lambda^2$	1

$+ \mathcal{O}(\lambda^4)$ **$(VV^\dagger=1)$**

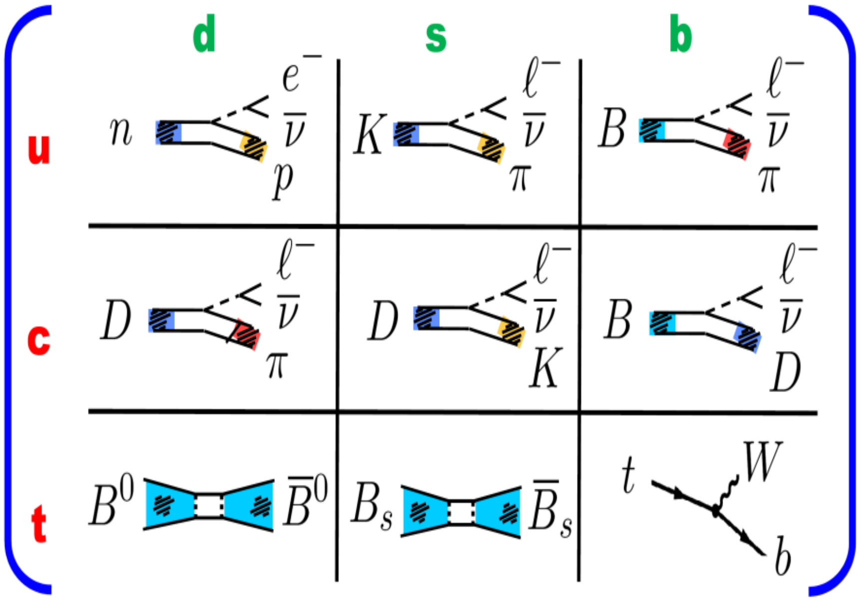
• **strong hierarchy** in EW V_{ij} couplings for the 3 families (wrt diagonal couplings $\propto\lambda^N \approx (0.225)^N$:

➔ Cabibbo angle).

• **KM** (Kobayashi-Maskawa) **mechanism :**
3 generations ➔ <u>4 params</u>:
A, λ, ρ & 1 complex part η which phase is the unique source of CPV in SM.

The CKM Matrix, the unitary triangle & the very rich phenomenolgy of quark flavors

V_{CKM} =



➔4 parameters (A, λ, ρ & η) to be obtained/tested wrt. data: nucleons, K, D, $B_{(s)}$ & top quark physics.

➔ unitarity relation in B_d system (1[rst] line/3[rd] column):

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$
$$O(1) + O(1) + O(1)$$

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

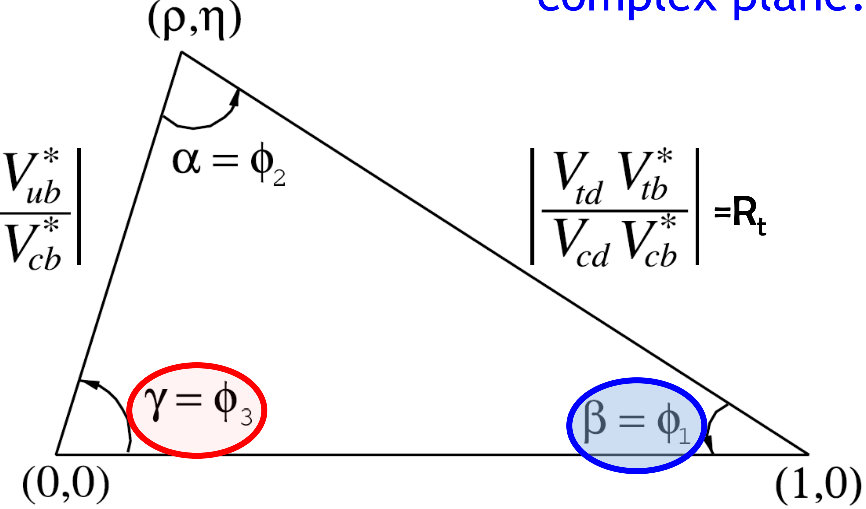
Parametrisation « à la Wolfenstein » phase invariant & valid at any orders in λ @ CKMfitter

(EPJ C41, 1-131, 2005) :

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| \qquad \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| = R_t$$



CPV means asymmetries
Typical performances drivers

- Large integrated luminosity
- Large σ(bb)
- Good detector acceptance
- Good trigger efficiency
- Good reconstruction efficiency

- Different B species: B^0, B_s^0, baryons

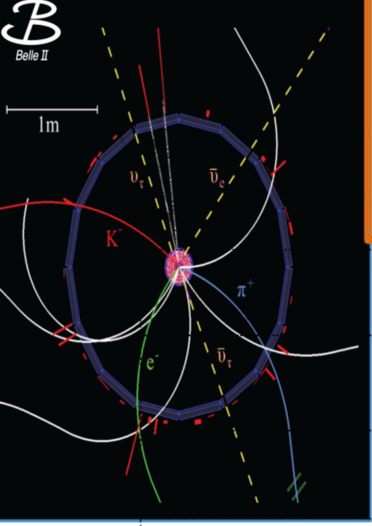
- Good flavour tagging (B or anti-B)

$$\mathcal{A}_{CP}(t) = \frac{N(B^0(t) \to f_{CP}) - N(\bar{B}^0(t) \to f_{CP})}{N(B^0(t) \to f_{CP}) + N(\bar{B}^0(t) \to f_{CP})}$$

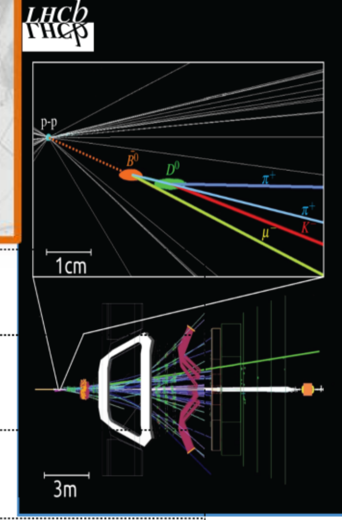
- Large B boost
- Good vertex resolution

- Good particle identification, K/π separation.
- Reconstruction of γ, π^0, η, K_S^0
- Presence of ν: good hermeticity
- Good S/N (physics, combinatorial, pile-up, beam bkg)

I. Ripp-Baudot @ Moriond QCD 23



The Actors
Belle II vs LHCb



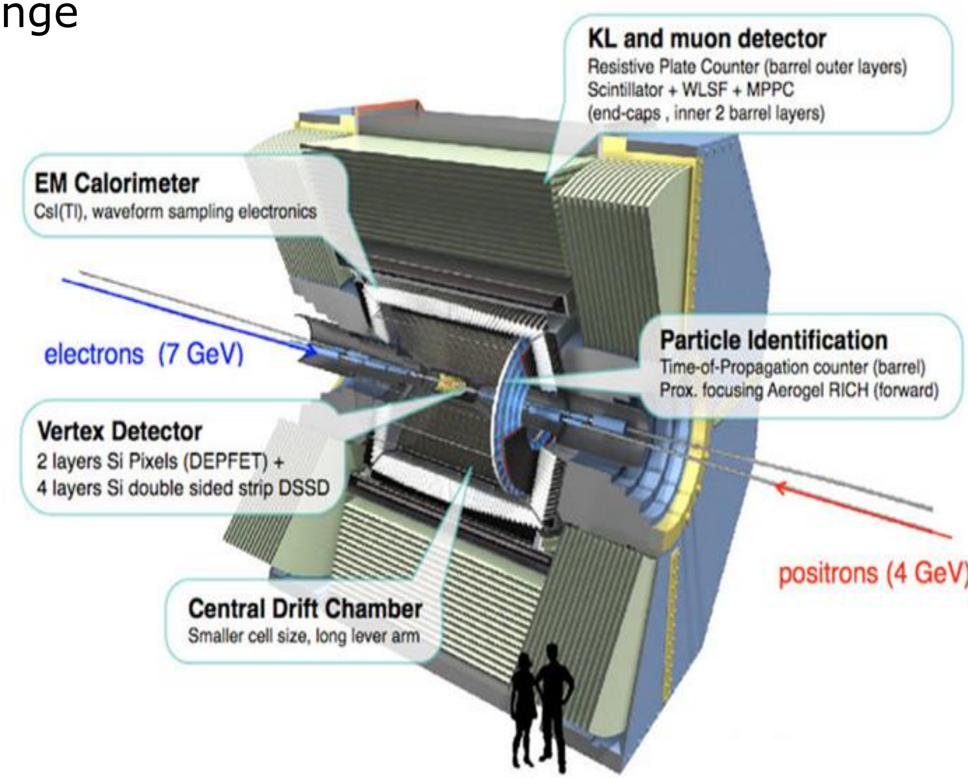
Belle II		LHCb
2019	Start	2011
428 (target: 50 000)	Current dataset (fb^{-1})	9 (target: 300)
4.7 (target: 60)	Instantaneous lumi. ($\times 10^{34}$ cm^{-2} s^{-1})	0.04 (target: 1.5)
1	bb cross-section (nb)	500 000 (@13 TeV) 😀
Good 😀	Selection efficiency	0.3-acceptance & trigger & background
B^0, few B_s^0 in the future?	B species	all: B^0, B_s^0, B_c^+, B-baryons 😀
130	B boost (μm)	10 000 😀
> 33% 😀	B-flavour tagging power	typically 5%
• Unique measurements: D* polarisation, inclusive measurements, … • Excellent τ physics capability • Good reco of γ, π^0, η, K_S^0 😀	Collision setup	Hadronisation and large occupancy

→ **Good complementarity between Belle II and LHCb**

Belle II @ SuperKEKB

- General-purpose detector successor of Belle @ KEKB
- Beams of electrons and positrons with asymmetric energy (7 and 4 GeV): boost $\beta\gamma = 0.28$
- Collisions at the $\Upsilon(4S)$ mass (10.58 GeV)

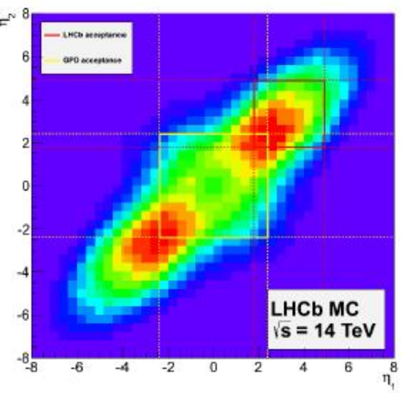
Highest e^+e^- luminosity machine ever (sub-μbeams + intensity + crab crossing)
Machine background remains a challenge

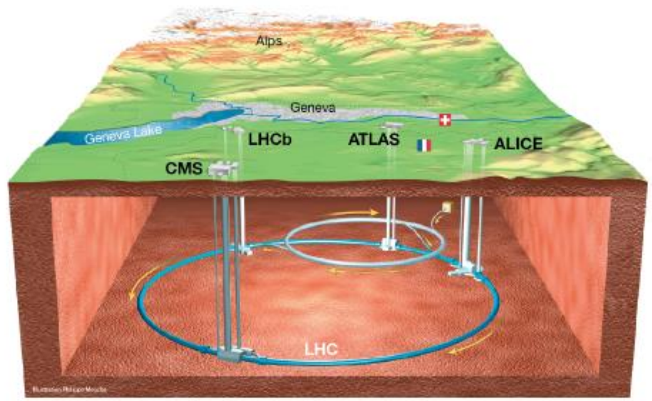


The initial momentum of the b or c hadron is known
Excellent reconstruction efficiency, vertexing, PID, invisible decays

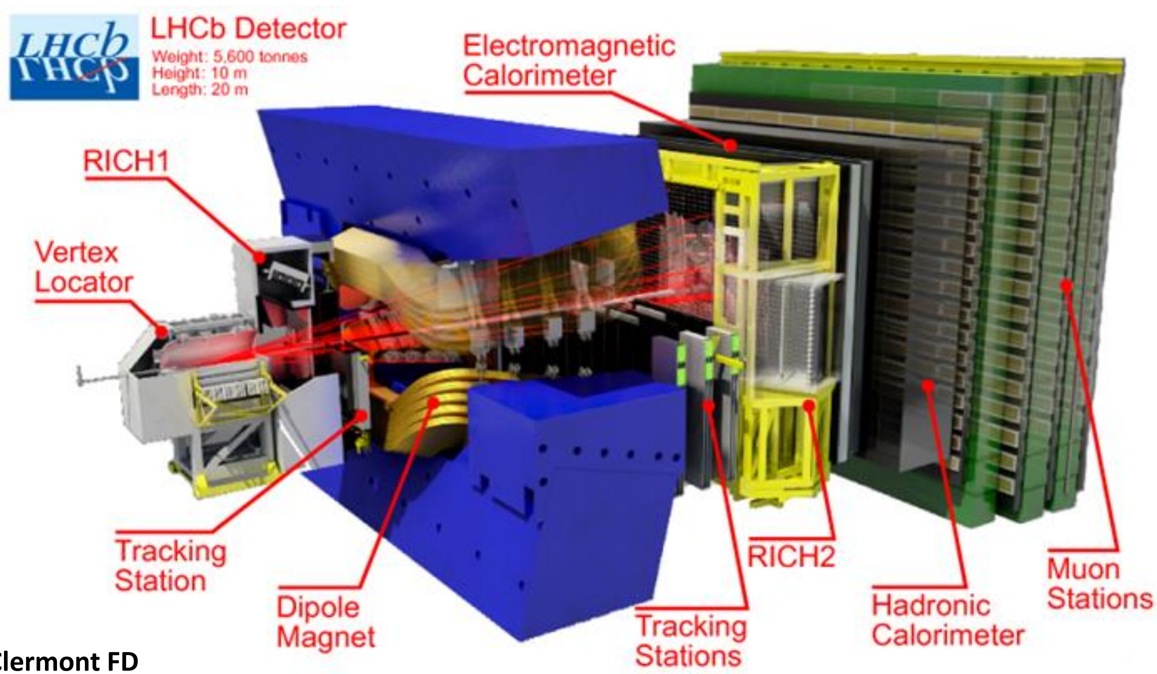
LHCb @ LHC

- General purpose detector in the forward region
- proton-proton collisions at $\sqrt{s} = 7 - 14$ TeV

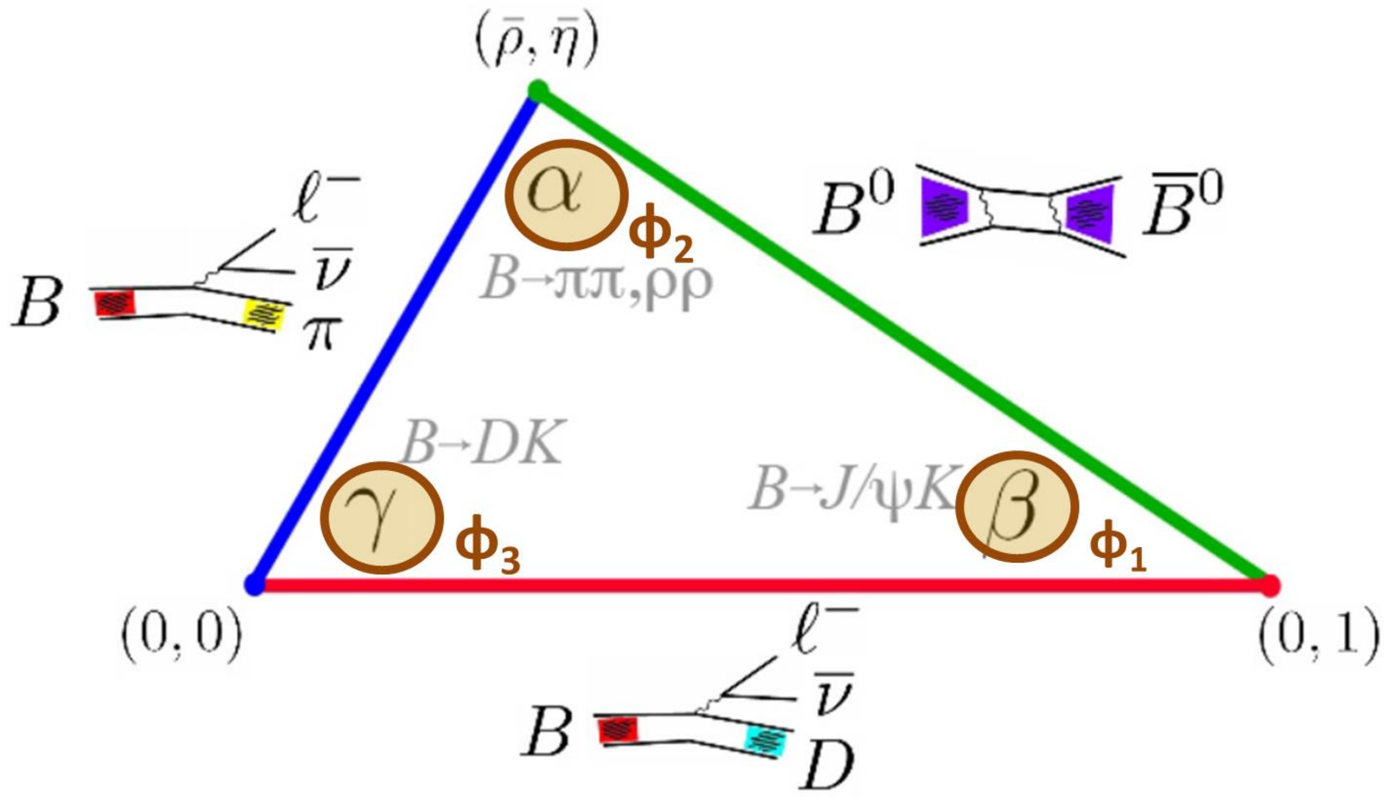




Few 10 billions of b and c hadrons produced/year
flying more than few 10 mm
Lorentz $\beta\gamma$>20
Excellent vertexing, tracking and PID
Software & topological based adaptative trigger

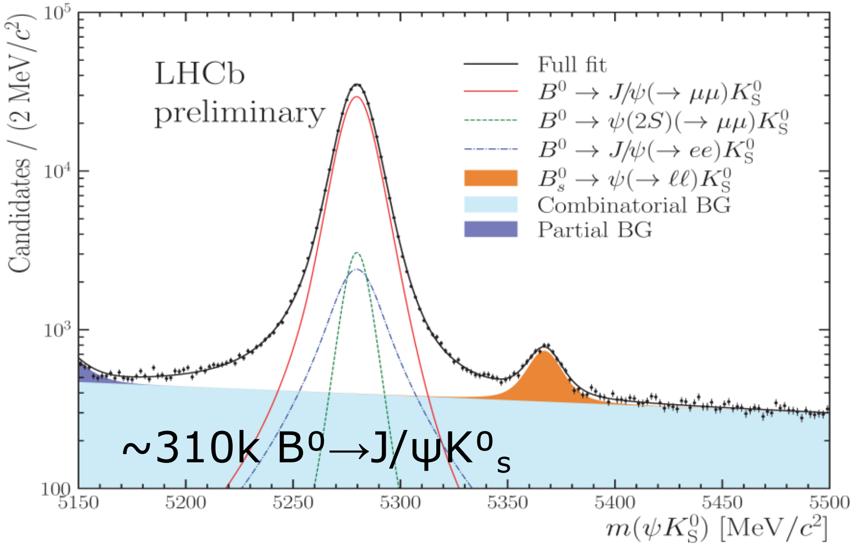


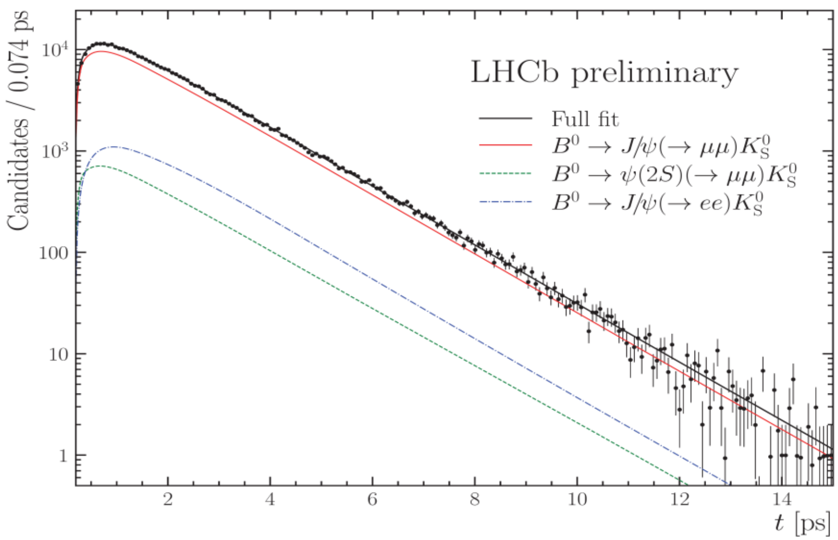
The angles

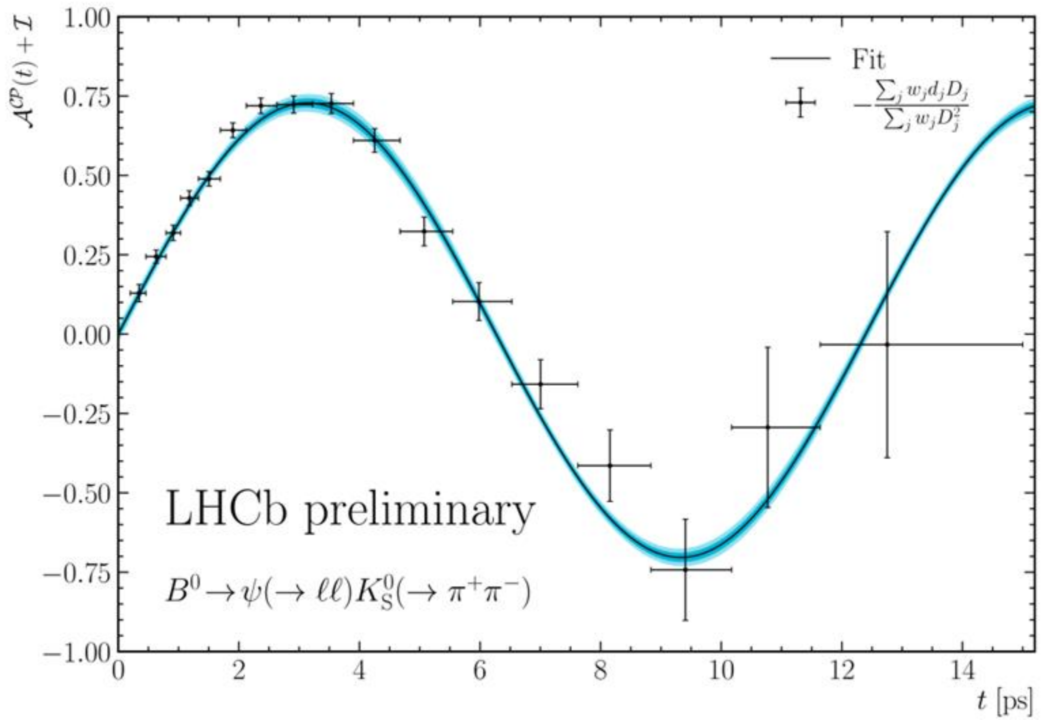


EXTREMELY ACTIVE FIELD
MANY NEW RESULTS !

$B^0 \to \psi K^0_S$ Run2 sin(2 β/ϕ_1)





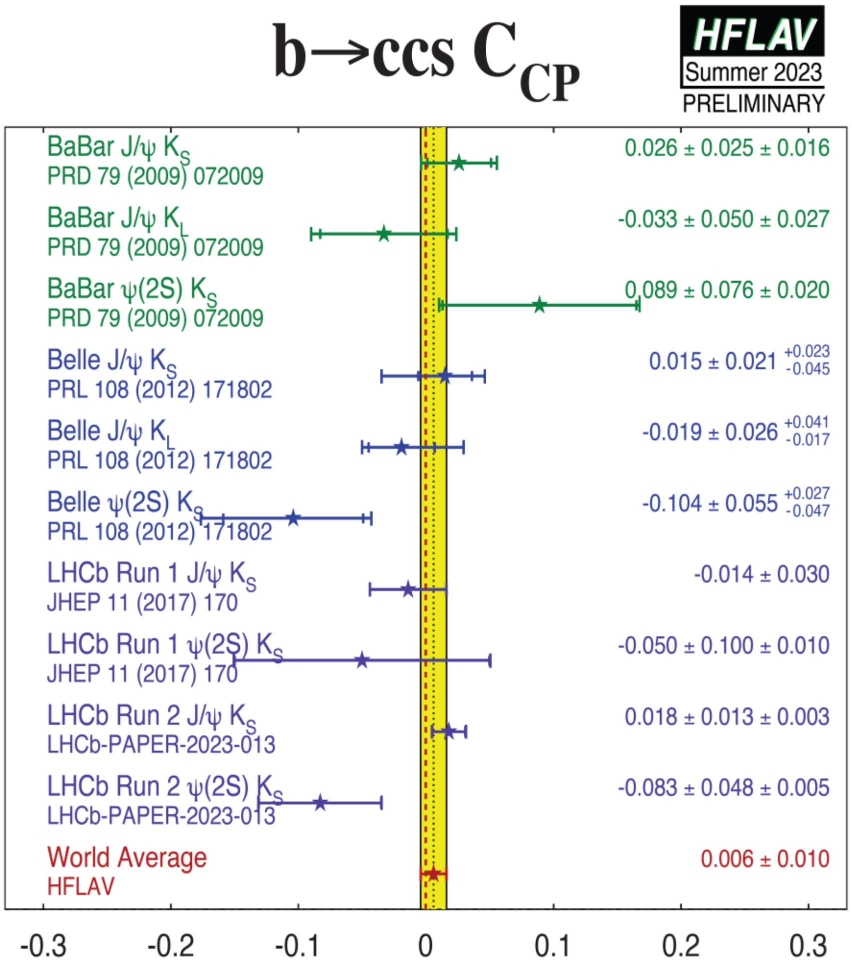


New total LHCb combination

$$S^{\text{Run 1+2}}_{\psi K^0_S} = 0.723 \pm 0.014\,(\text{stat+syst})$$
$$C^{\text{Run 1+2}}_{\psi K^0_S} = 0.007 \pm 0.012\,(\text{stat+syst})$$

See for more details the LHCb CERN June 2023 Seminar

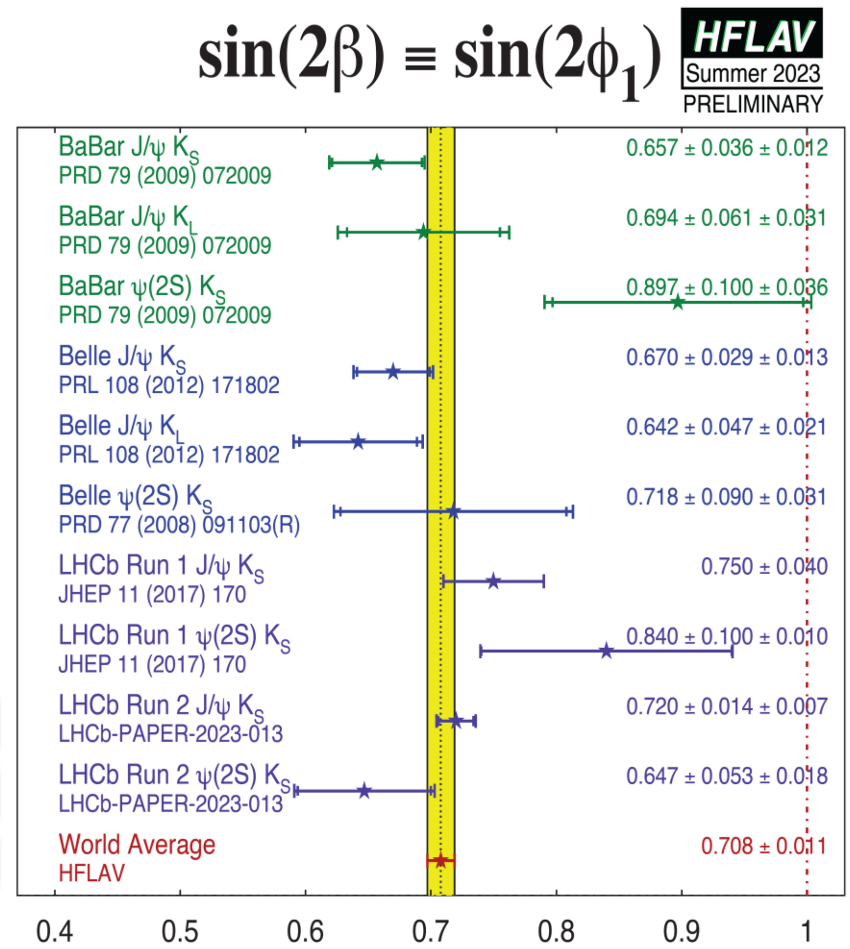
World Average of sin(2 β/ϕ_1)



NEW!!

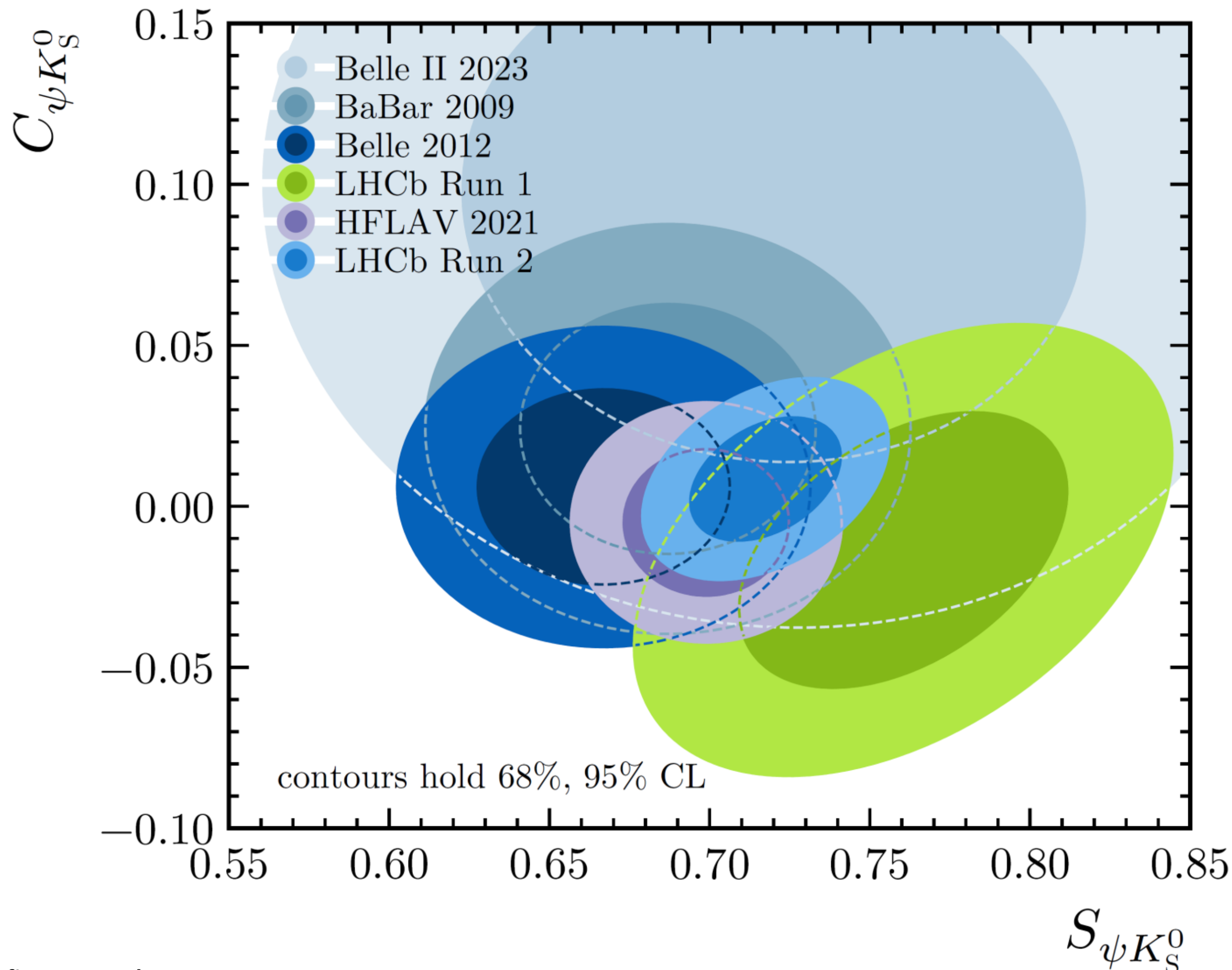
NEW!!

NEW!!



β/ϕ_1 = (22.54±0.31)°

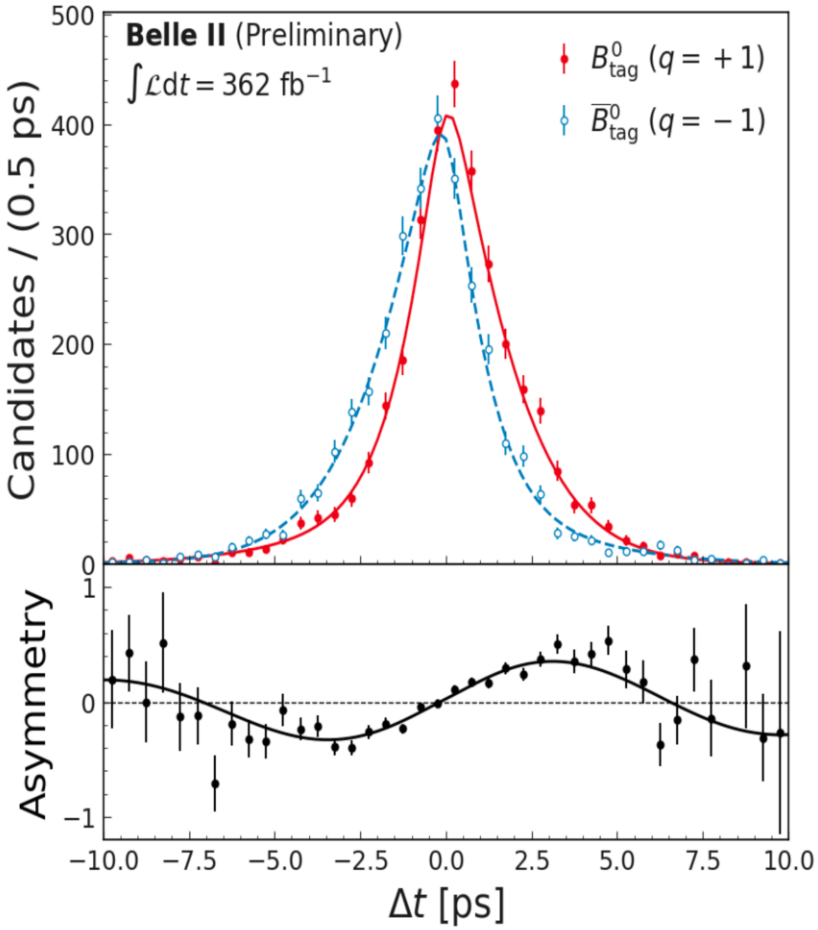
Comparison with other experiments



Does not include latest result from Belle II

Latest news from Belle II on sin(2 $\beta\phi_1$)

TDCPV in $B^0 \to J/\psi\, K_S^0$



- τ_{B^0} and Δm_d (PRD107(2023)9,L091102)
  - Measured in $B^0 \to D^{(*)-}\pi^+$
  - $\tau_{B^0} = 1.499 \pm 0.013 \pm 0.008$ ps
  - $\Delta m_d = 0.516 \pm 0.008 \pm 0.005$ ps^{-1}
- S and C fit
  - Δt resolution considered in PDF
  - remove background from the fit (sFit)
  - $S = 0.724 \pm 0.035 \pm 0.014$
  - $C = 0.035 \pm 0.026 \pm 0.012$
    - HFLAV: $S = 0.695 \pm 0.019$ $C = 0.000 \pm 0.020$
    - LHCb: $S = 0.716 \pm 0.015$ $C = 0.012 \pm 0.012$

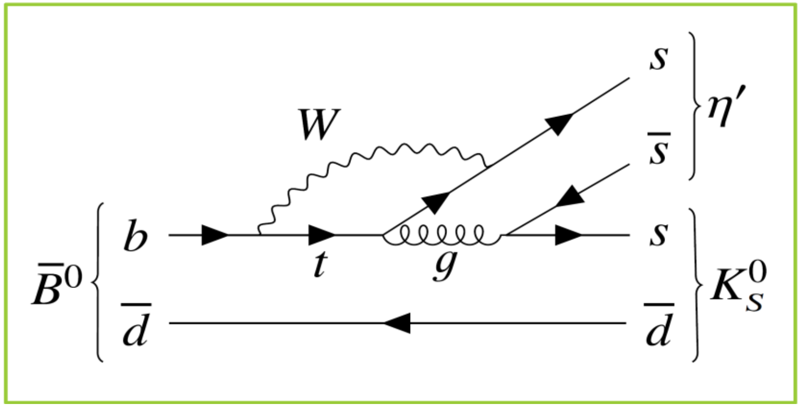
GFlaT reduces statistical uncertainty by ~8%

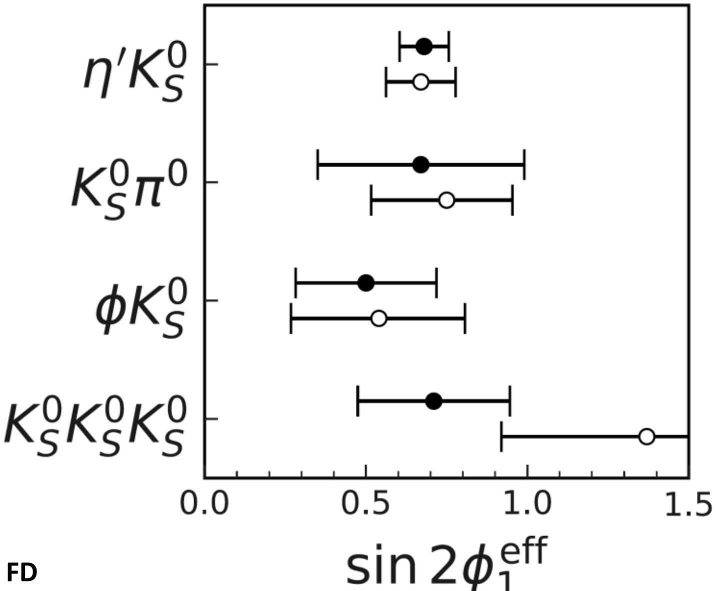
Y. Uemastu @ CKM 2023

$\sin 2\phi_1^{\rm eff}$ measurement in $B^0 \to \eta' K_S^0$

$b \to qqs$ (penguin) transitions

- $B^0 \to \eta' K_S^0$
  - $b \to s q\bar{q}$: loop-suppressed transition
    → Deviation of $S = \sin 2\phi_1^{\rm eff}$ from $\sin 2\phi_1$ indicates BSM effect
  - relatively high BF w.r.t. other gluonic penguins





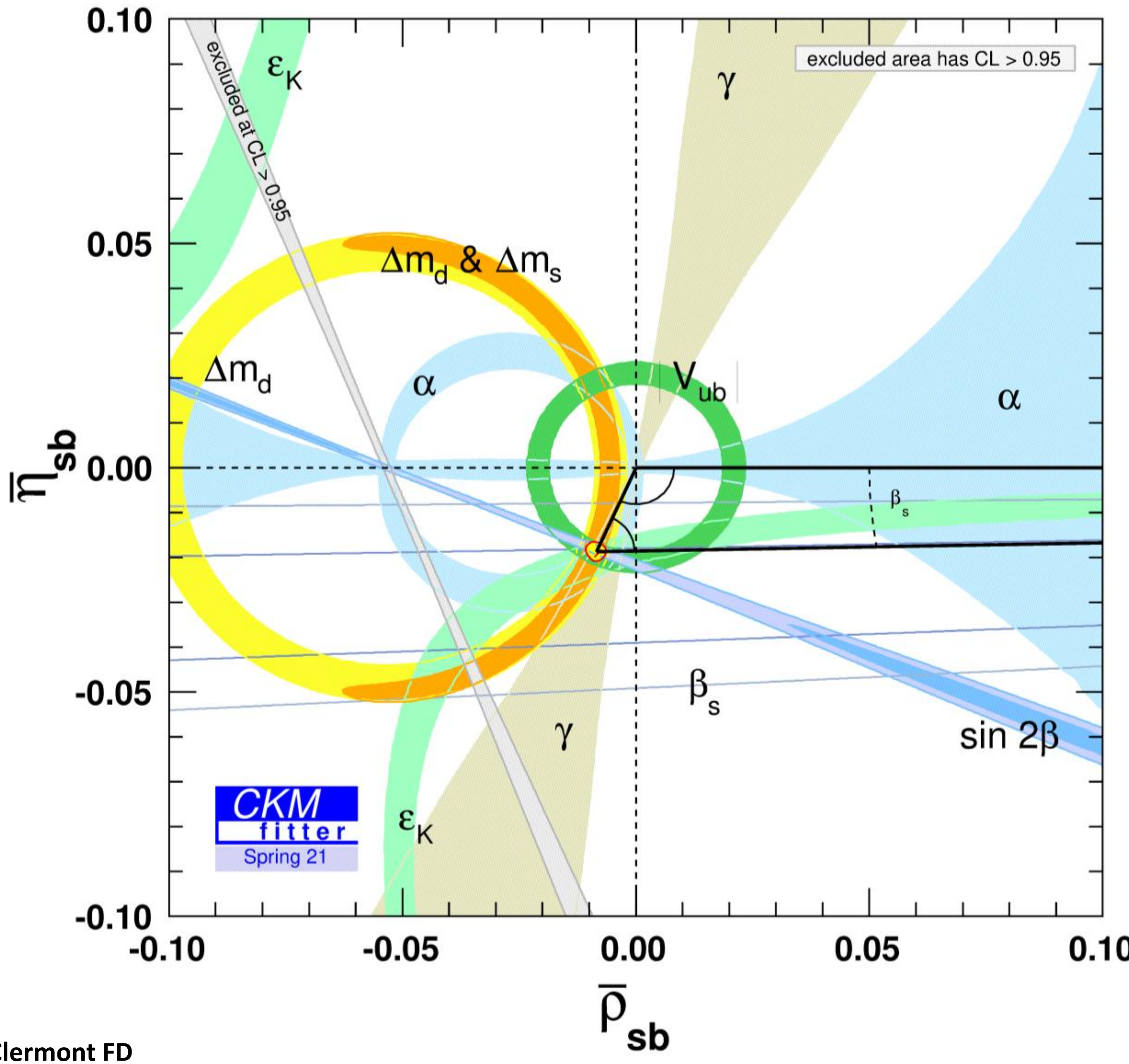
Belle II with 360/fb does almost same as or better than Belle 711/fb !!!!

Y. Uemastu @ CKM 2023

Reminder CKM global fit: $\sin 2\beta_s$ ($-\sin 2\phi_s$)

Unitarity condition from 2nd and 3rd columns:

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

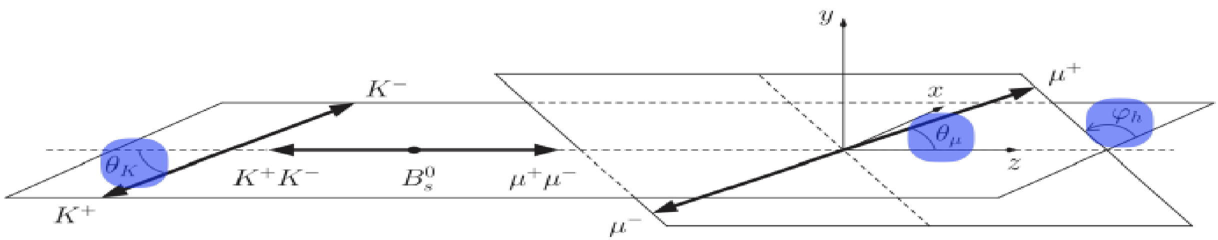


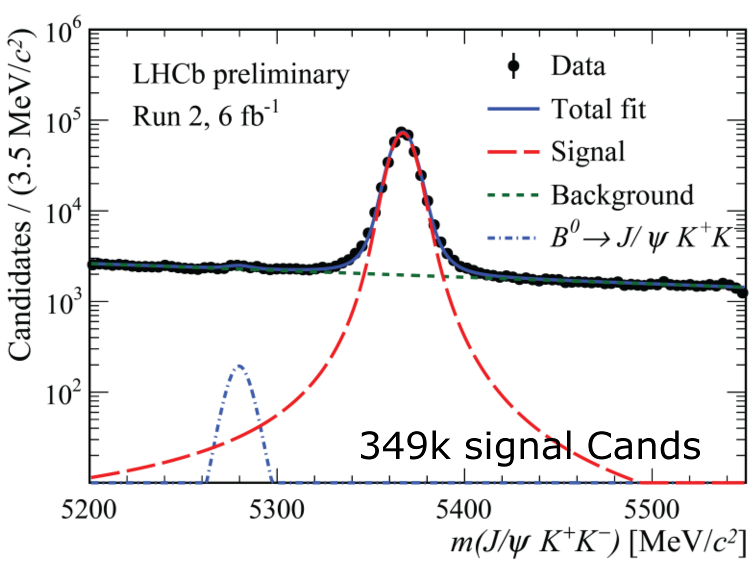
β_s

$B_s^0 \to J/\psi K^+K^-$ Run2 sin(-2$\beta_s \equiv \phi_s$)

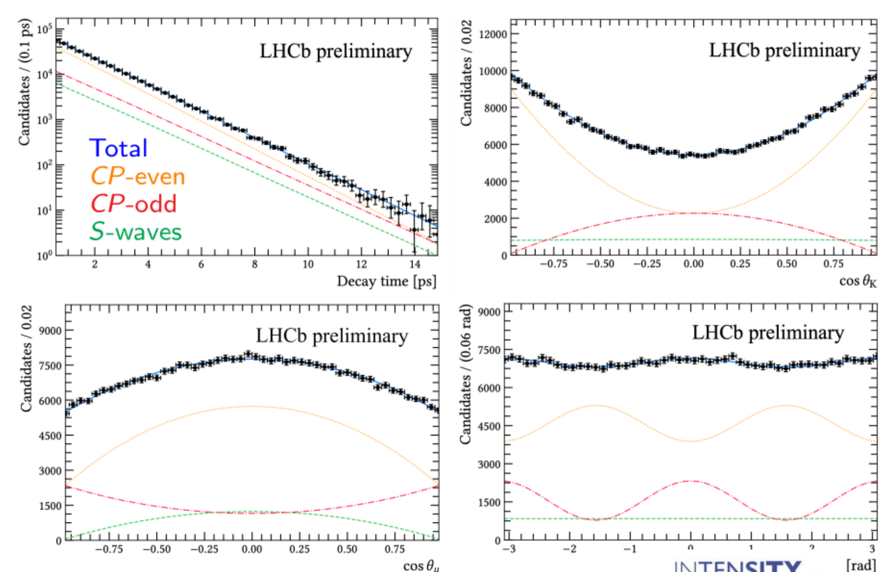
$$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to J/\psi KK) - \Gamma(B_s^0 \to J/\psi KK)}{\Gamma(\bar{B}_s^0 \to J/\psi KK) + \Gamma(B_s^0 \to J/\psi KK)} = \eta_f \cdot \sin\phi_s^{\text{obs}} \cdot \sin(\Delta m_s t)$$

- CP eigenvalue of the final state $\eta_f = (-1)^L$
- A mixture of CP-even & CP-odd components → angular analysis





Extract physics parameters: ϕ_s, λ, $\Delta\Gamma_s, \Gamma_s - \Gamma_d$, Δm_s



$\sin(-2\beta_s \equiv \phi_s)$

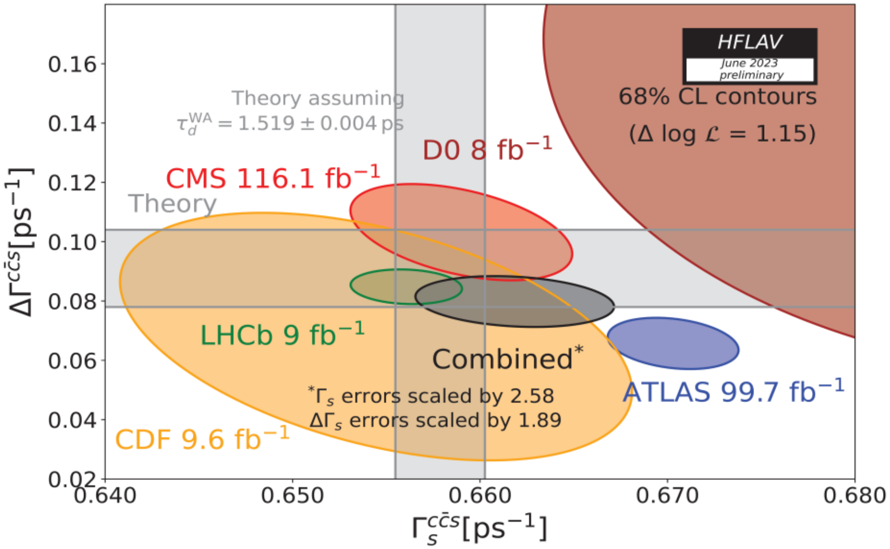
Combination with all measurements

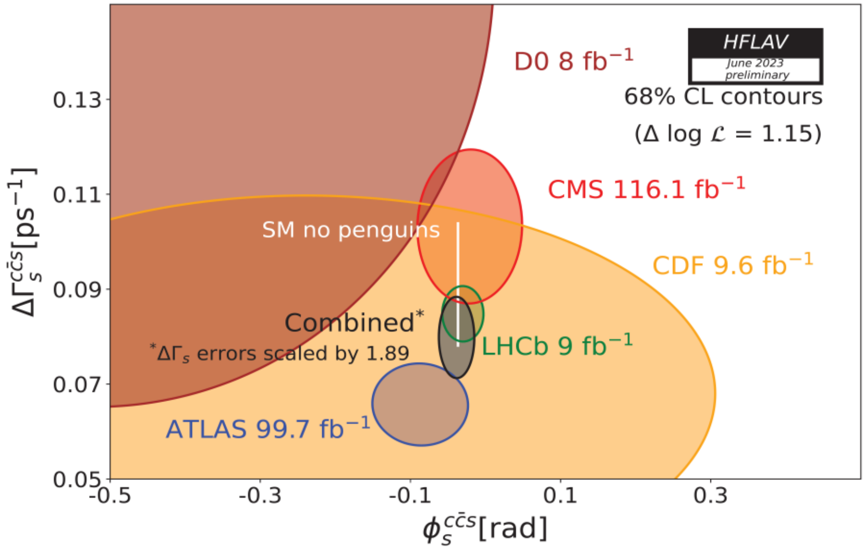
$\phi_s^{s\bar{s}s}$ FROM $B_s \to \phi\phi$ [PAPER-2023-001]

- $\phi_s^{J/\psi KK} = -0.050 \pm 0.017$ rad $\to$ improved by 23%
- $\phi_s^{c\bar{c}s} = -0.039 \pm 0.016$ rad $\to$ improved by 15%
- Consistent with the prediction of Global fits assuming SM:[3]

$$\phi_s^{\text{CKMfitter}} \approx (-0.0368^{+0.0006}_{-0.0009})\ \text{rad},\ \phi_s^{\text{UTfitter}} = -0.0370 \pm 0.0010\ \text{rad}$$

[3] Ignoring penguin contribution.





See for more details the LHCb CERN June 2023 Seminar

$\sin(-2\beta_s \equiv \phi_s)$

- CP violation measurements in the penguin-mediated decay $B_s^0 \to \phi\phi$
  - $\mathcal{L}$ = 6 fb^{-1}, Run 2 data from 2015 to 2018, arXiv:2304.06198

- A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays
  - $\mathcal{L}$ = 9 fb^{-1}, Run 1 2011 + 2012 and Run 2 2015 to 2018 data, LHCb-PAPER-2023-025

M. Cruz Torres @CKM 2023

CKM global fit: the angle α / ϕ_2

→ Branching ratios and $\mathcal{CP}$ asymmetries for $B \to \pi\pi, \rho\pi, \rho\rho$

→ Isospin analysis constrains hadronic penguin and tree amplitudes

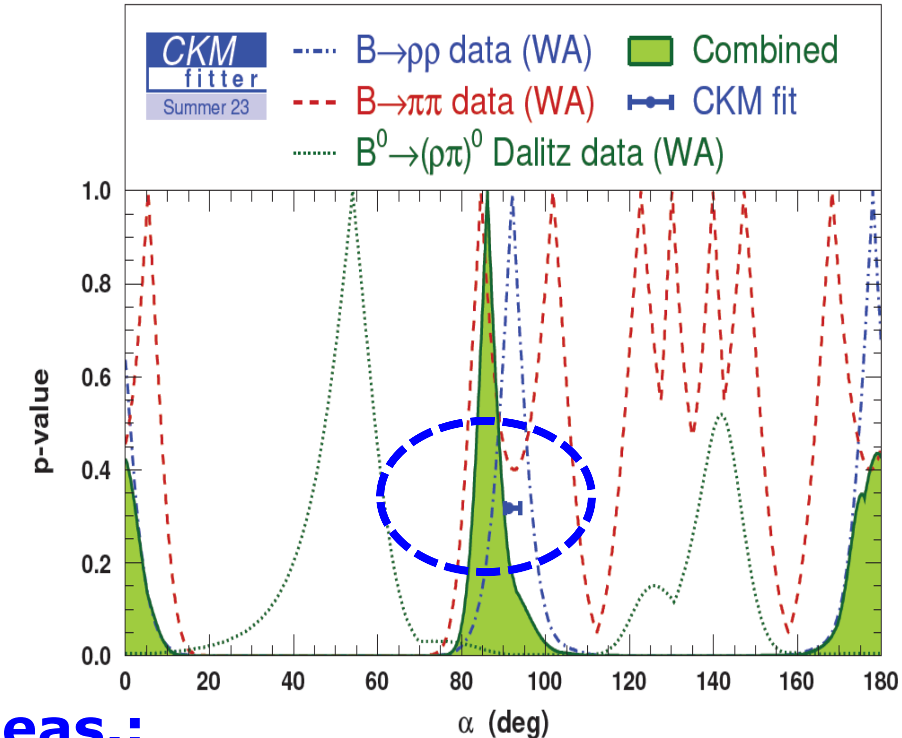
[$B^{0,+} \to \pi^{0,+}\pi^0, \rho^+\rho^{-,0}$ updates: Belle II] [Detailed discussion: Charles, Deschamps, Descotes-G., Niess '17]

As in previous editions:

→ Average dominated by $B \to \pi\pi$ and $B \to \rho\rho$

→ $B \to \pi\pi, \rho\rho$ agree w/ α [ind.]

→ $B \to \rho\pi$ is in tension [Charles+'17]

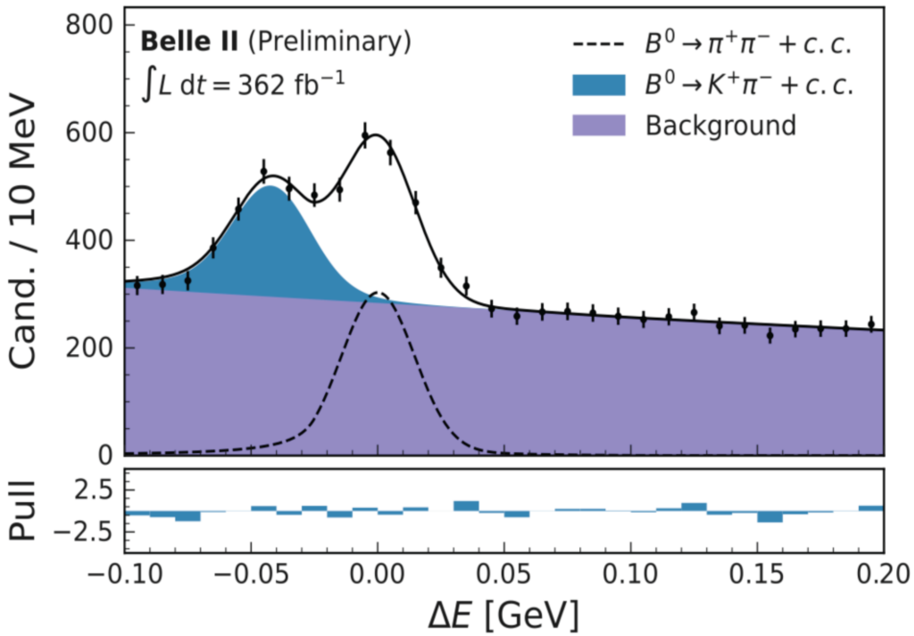


Global CKMfit+ meas.:

α [°]	$91.06^{+1.43}_{-0.75}$
α [°] (meas. not in the fit)	$91.28^{+2.73}_{-0.88}$
α [°] (dir. meas.)	$86.2^{+3.9}_{-3.5}$ || $-1.0^{+3.3}_{-4.9}$

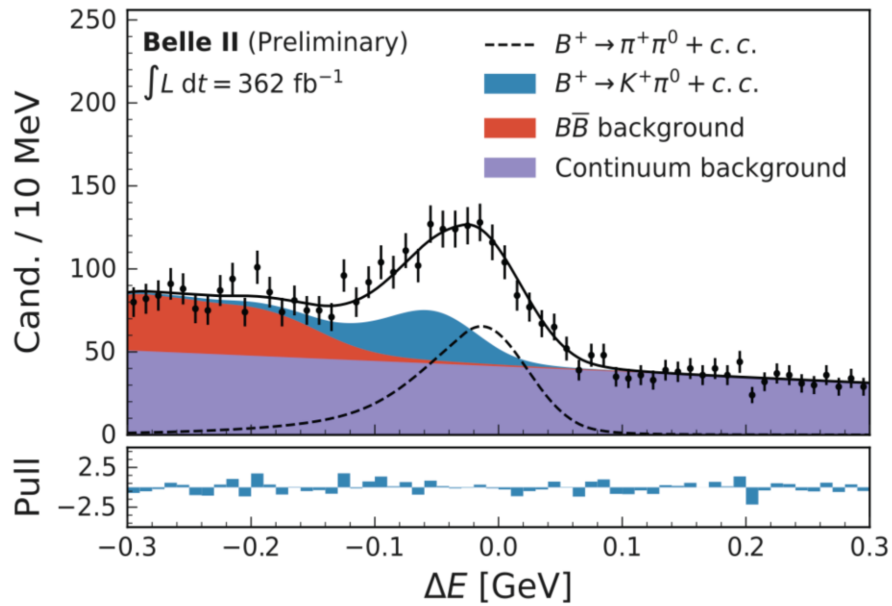
$B \to \pi\pi$ decays

~1500 $B^0 \to \pi^+\pi^-$



$$\mathcal{B}(\pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$$

~900 $B^+ \to \pi^+\pi^0$



$$\mathcal{B}(\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$$

$$\mathcal{A}(\pi^+\pi^0) = -\,0.081 \pm 0.54 \pm 0.008$$

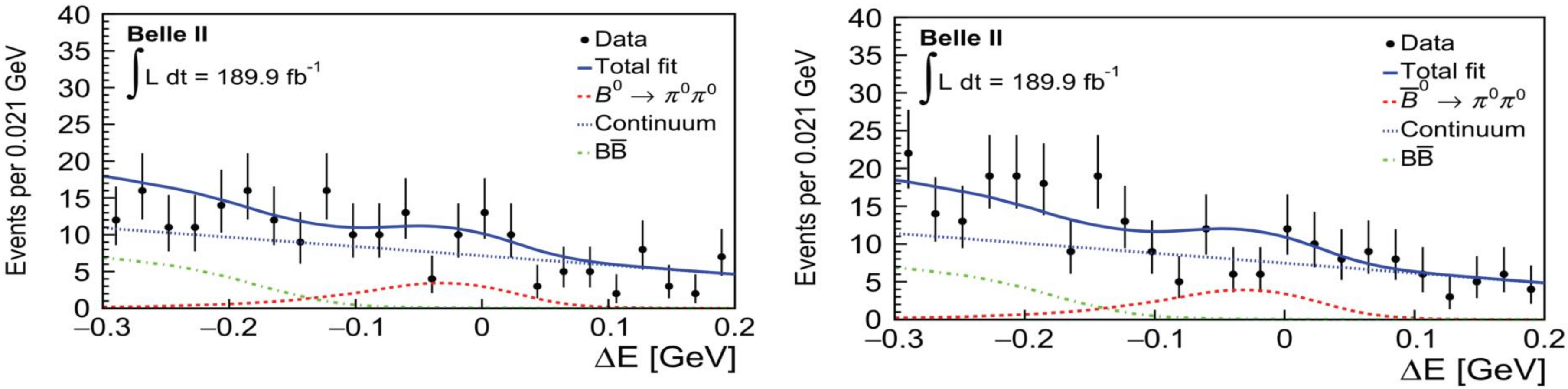
Competitive with world's best results.
Major systematic uncertainty on BR($B^+ \to \pi^+\pi^0$) from π^0 efficiency.

M. Dorigo @ CKM 2023

Belle II

$B^0 \rightarrow \pi^0\pi^0$

Most challenging charmless decay. Only photons in the final state, completely swamped by continuum from real π^0.
With a 4D fit we find 90 signal candidates [PRD107 (2023) 112009]



$$\mathcal{B}(B^0 \rightarrow \pi^0\pi^0) = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$$

$$\mathcal{A}_{CP}(B^0 \rightarrow \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07$$

Achieved Belle precision on BF with 1/3 of Belle sample size thanks to improved photon selection and continuum suppression

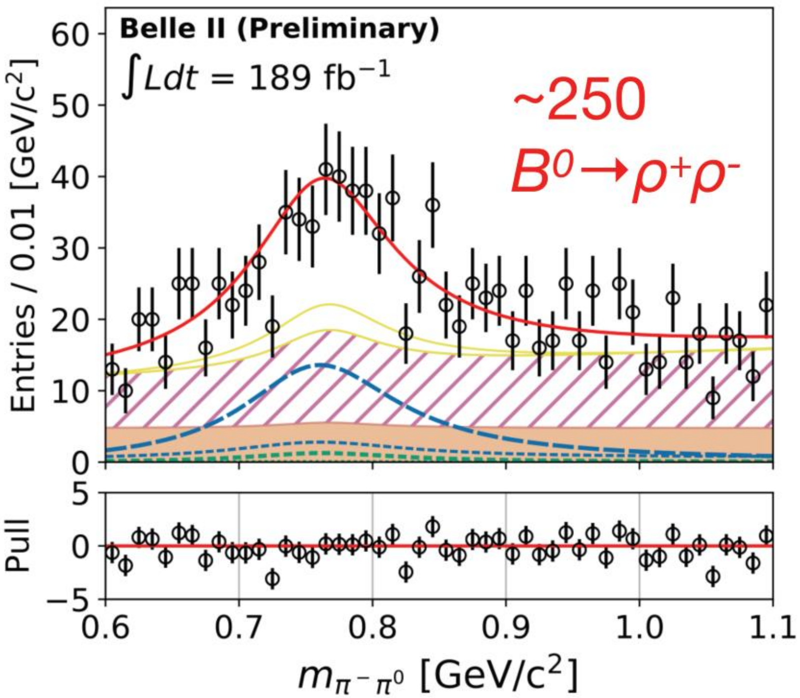
M. Dorigo @ CKM 2023

the angle α / ϕ_2

$B^0 \to \rho^+\rho^-$

$$\mathcal{B} = (26.7 \pm 2.8 \pm 2.8) \times 10^{-6}$$

$$f_L = 0.956 \pm 0.035 \pm 0.033$$

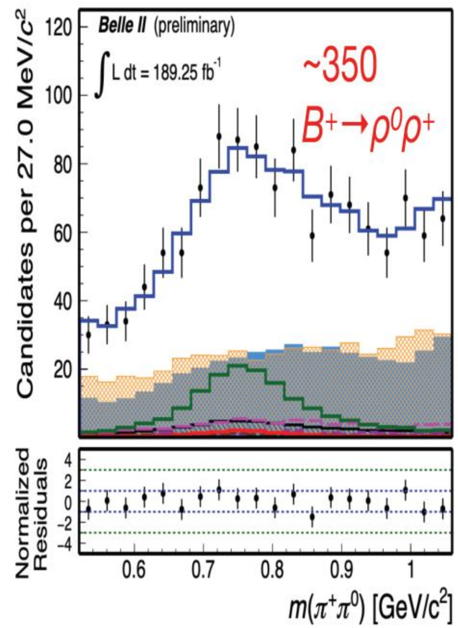


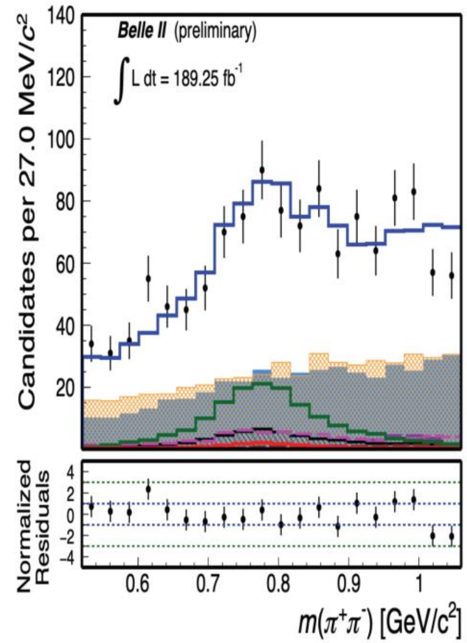
$B^+ \to \rho^0\rho^+$

$$\mathcal{B} = (23.2^{+2.2}_{-2.1} \pm 2.7) \times 10^{-6}$$

$$f_L = 0.943^{+0.035}_{-0.033} \pm 0.027$$

$$A_{CP} = -0.069 \pm 0.069 \pm 0.060$$





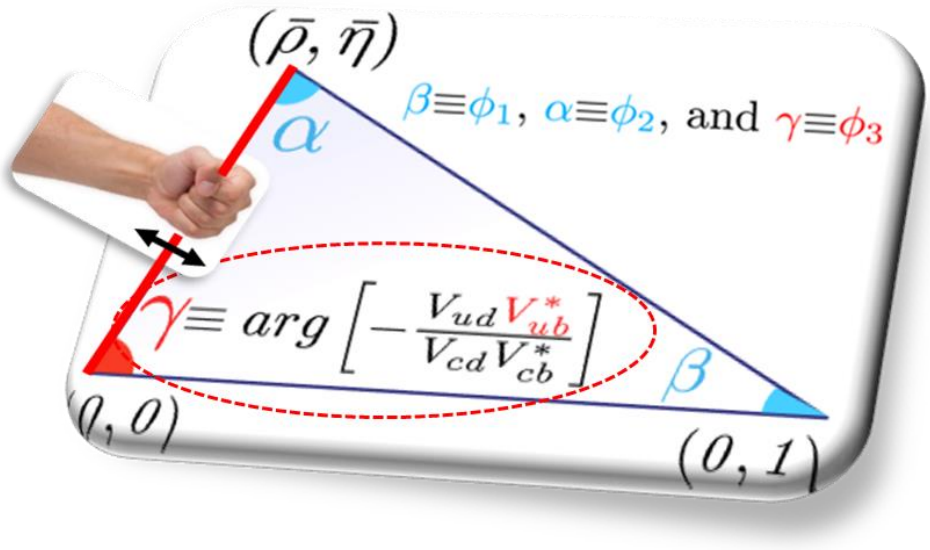
M. Dorigo @ CKM 2023

The CKM angle γ/ϕ_3 is special

It is a fundamental parameter of the SM related to the complex phase in the KM mechanism responsible for CP violation in quark sector.

In particular, γ/ϕ_3 is the phase of the complex number $(\bar{\rho}, \bar{\eta})$

Already ~12 years ago after the B factories BaBar@SLAC and Belle@KEK, we knew that!



M. Kobayashi & T. Masakwa, Nobel prize of physics 2008

The KM mechanism is the main source of CPV at EW scale (i.e. @ $m_{W/Z}$) But there is still room for BSM physics

The usefulness of measuring accurately γ/ϕ_3

CKM angle γ is the least well known CKM constraint (although now only just (i.e., similar to α)) and remains a unique CPV parameter:

- **SM benchmark or standard candle of the CKM Matrix in SM – The only CKM angle accessible at tree level**

- **Probes NP scales extremely far beyond direct searches in ((N)M)FV NP scenarios:** $\Lambda_{NP}^{\gamma} \sim \mathcal{O}\left(10^3 \text{ TeV}\right)$
  [arXiv:1101.0134]
  and at least 15-20 TeV in Model independent approach ! https://arxiv.org/pdf/1309.2293.pdf

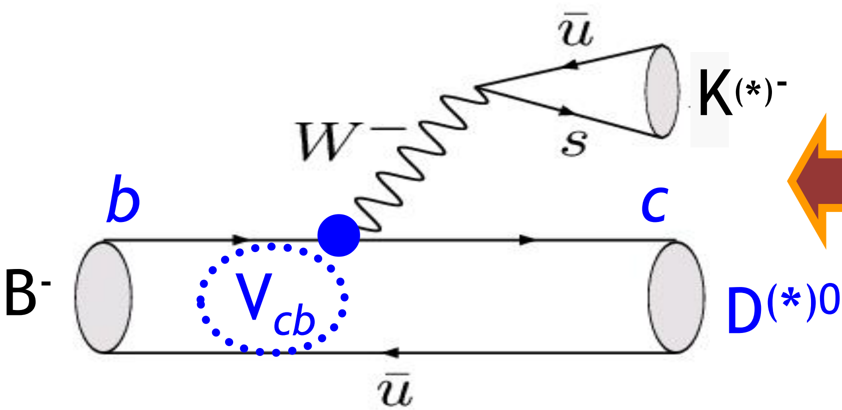
→ **Determination form tree B→DK decay theoretically extremely clean : [arXiv:1308.5663]** $\delta\gamma/\gamma \sim \mathcal{O}\left(10^{-7}\right)$

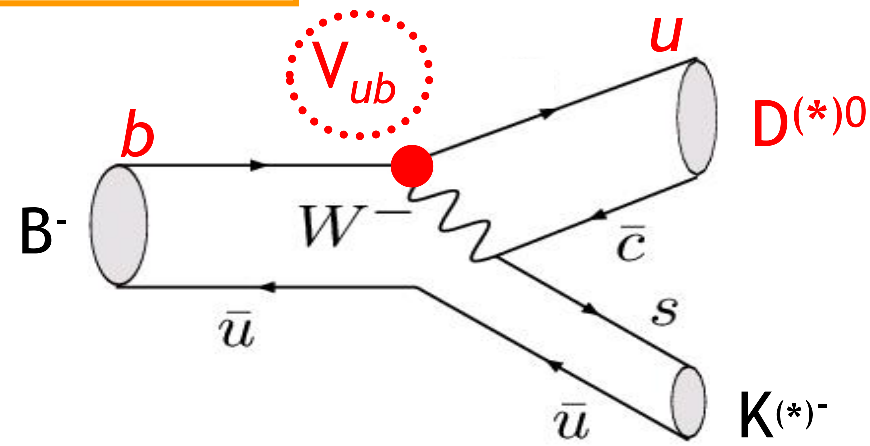
→ **Use for "direct" vs "indirect" (i.e., "tree" vs "loop" processes) disagreement in global CKM fit consistency test : - Tree level decays test the SM and are robust to New Physics** ("standard candle for the SM KM coherence tests"): ⊥ **constraint to sin(2β), need ideally precision of about ~1° and below**

- Loops (B to charmless decays) test for physics beyond the SM but require a clean measurement as input & precise understanding of theory assumptions (SU(3) breaking, U-spin…).

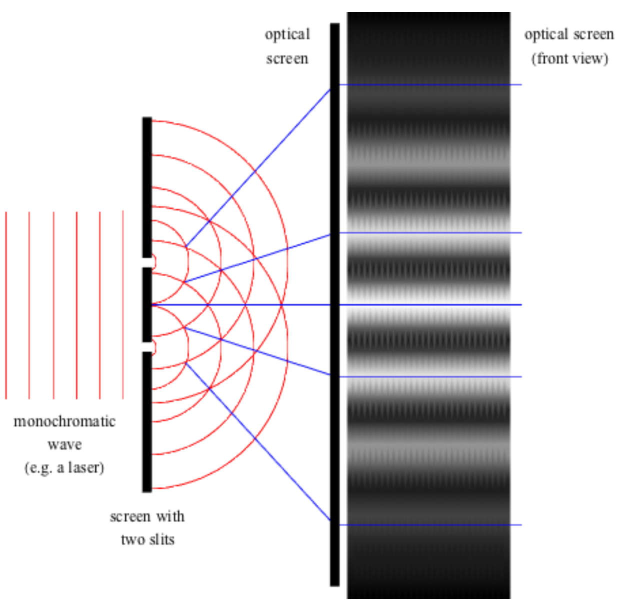
Measuring γ/ϕ_3 in open-charm B-decays: $B^- \to \tilde{D}^{(*)0}K^{(*)-}$

Same final state $\tilde{D}^0 \equiv [D^0/D^0]$





See Young's double slit experiment



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

Measuring γ/ϕ_3 in open-charm B-decays: $B^- \to \tilde{D}^{(*)0}K^{(*)-}$
Experimental aspects

➔ **measuring γ at tree level is difficult** (typical BFs $<10^{-6}$ and less, reconst. & selection efficiencies below %):

- **STATISTICS is THE NAME OF THE GAME** ⇒ efficient detection/ selection/ PID/ tracking/ vertexing and even neutrals
- **combining many measurements/methods + inputs** from charm factories (D parameters + mixing & CPV)

➔ **Many methods/modes to combine** for optimal & redundant determination of γ (+rigorous statistical treatment possibly matters !)

➔ **various charmed modes in B^0, B^+, B^0_s, Λ^0_b, B^+_c decays** are useful to understand/confirm possible sensitivity to BSM physics and its nature

✚ Very important experimental inputs from CPV and strong phases at BESIII

Y. Gao
@ CKM 2023

Measuring γ/ϕ_3 state of the art: world field yet dominated by LHCb

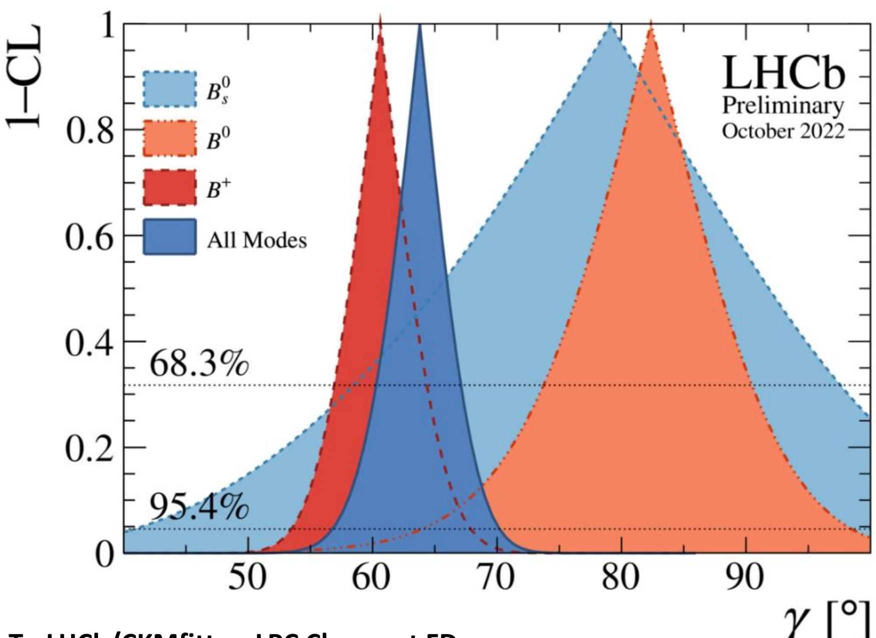
Update γ combination from LHCb measurements

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

- Improvement of about 10%
- Good compatibility with unitarity fits

  $$\gamma_{CKMFitter} = \left(65.5^{+1.1}_{-2.7}\right)^{\circ}$$

- Tension between different B categories remains ($\sim 2\sigma$)



Approaching the 1° accuracy !

LHCb-CONF-2022-002 [link] the LHCb fit combines dozens of LHCb papers

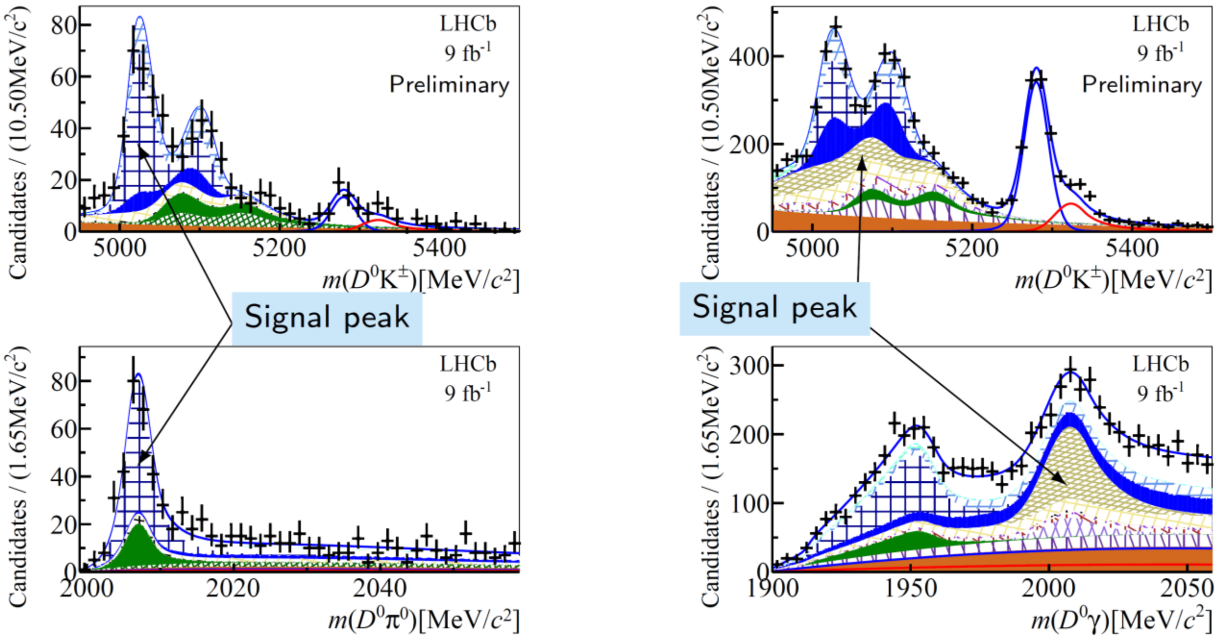
B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	New
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	Updated
$B^\pm \to Dh^\pm$	$D \to K_S^0 h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K_S^0 K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[39]	Run 1&2	As before

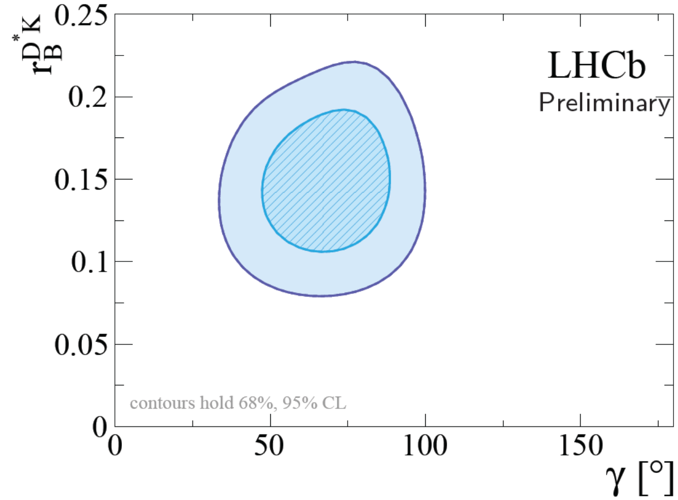
D decay	Observable(s)	Ref.	Dataset	Status since Ref. [14]
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]	Run 2	New
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]	Run 1	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]	Run 2	New
$D^0 \to h^+h^-$	ΔY	[43–46]	Run 1&2	As before
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[47]	Run 1	As before
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[48]	Run 1&2(*)	As before
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[49]	Run 1	As before
$D^0 \to K_S^0\pi^+\pi^-$	x, y	[50]	Run 1	As before
$D^0 \to K_S^0\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]	Run 1	As before
$D^0 \to K_S^0\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K_S^0\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]	Run 2	New

NEW LHCb γ/ϕ_3 in B^+

See CERN July seminar by M. Tat

$B^- \to D^* K^-$





- $\gamma = (69 \pm 14)^\circ$
- $\delta_B^{D^*K} = (311 \pm 15)^\circ$
- $r_B^{D^*K} = 0.15 \pm 0.03$

$D^* \to D\pi^0$ LHCb-PAPER-2023-012 $D^* \to D\gamma$

+ Partially reconstructed $B^\pm \to D^* K^\pm$ LHCb-PAPER-2023-029

I. Mackay
@ CKM 2023

Phase-space binned $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$

+ Binned four-body decay:
$D^0 \to K^+K^-\pi^+\pi^-$

A journey through five dimensions

From the phase-space binned asymmetries, we obtain:

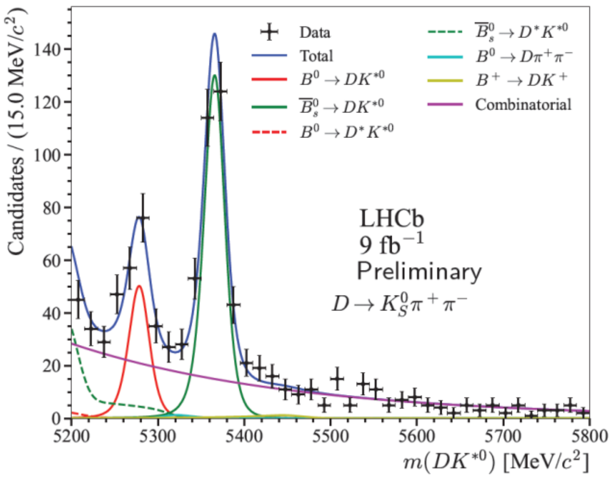
- $\gamma = (116^{+12}_{-14})^\circ$
- $\delta_D^{DK} = (81^{+12}_{-14})^\circ$
- $r_B^{DK} = 0.110 \pm 0.020$

NEW LHCb γ/ϕ_3 in B^0

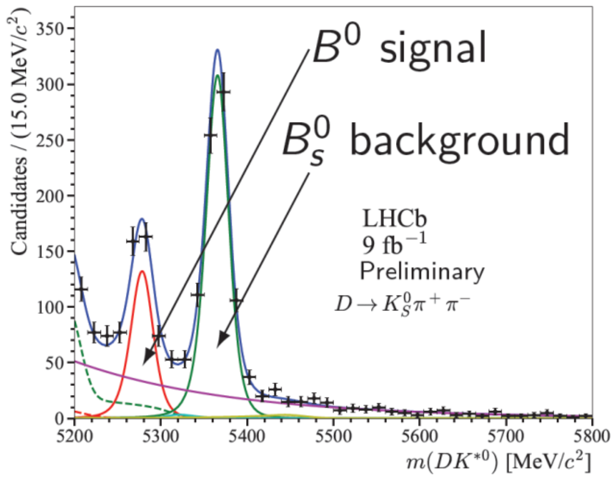
See CERN July seminar by M. Tat

$B^0 \to DK^{*0}$ candidates with $D \to K_S^0\pi^+\pi^-$ $(D \to K_S^0 K^+K^-)$

GGSZ
Self-tagging K*

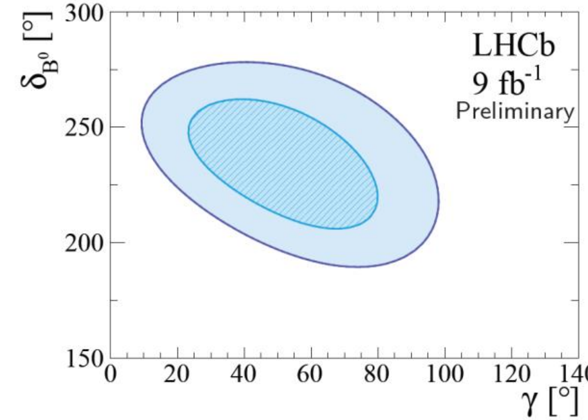


LL



DD

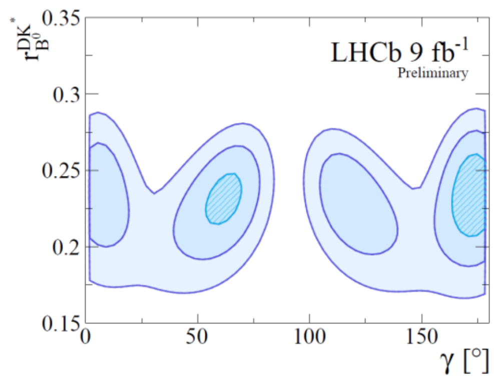
LHCb-PAPER-2023-009

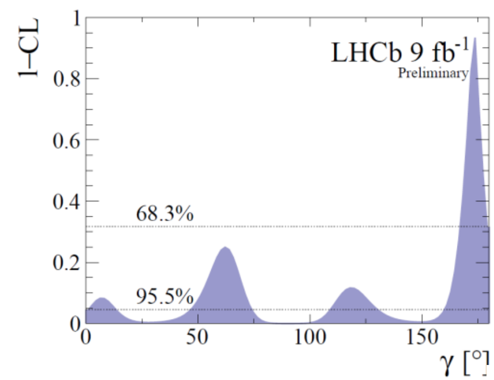


- $\gamma = (49 \pm 20)^\circ \leftarrow$
- $\delta_{B^0} = (236 \pm 19)^\circ$
- $r_{B^0} = 0.27 \pm 0.07$

+ ADS & GLW
for $B^0 \to DK^{*0}$

S. Stanislaus
@ CKM 2023





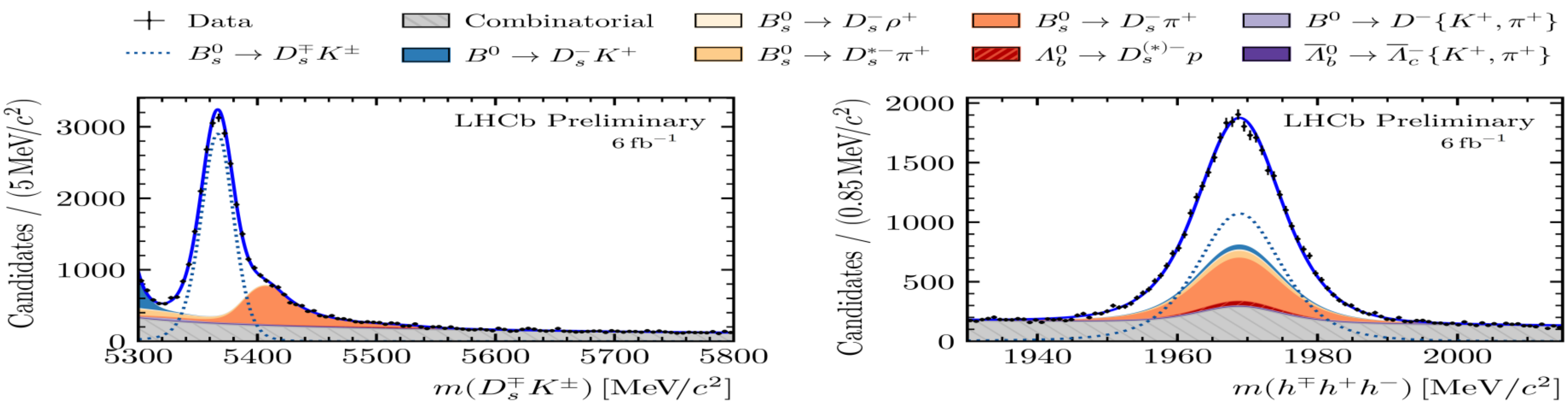
LHCb-CONF-2023-003

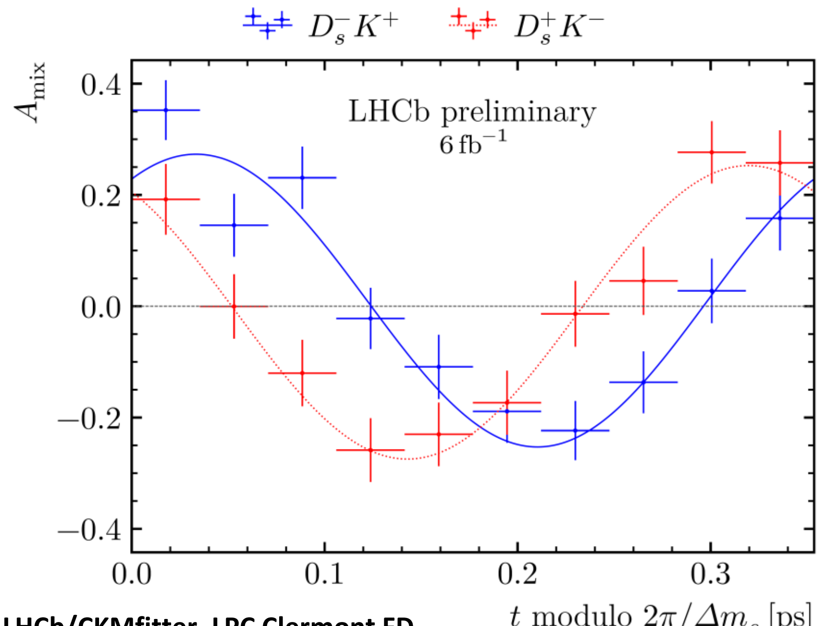
NEW LHCb γ/ϕ_3 in B_s

$B_s^0 \to D_s^{\mp} K^{\pm}$ - Run2

Q. Führing @ CKM 2023

20950 ± 180 candidates





- **Significant $C\!P$ violation in the interference $S_f \neq -S_{\bar{f}}$ at 8.8 σ**

$$C_f = 0.791 \pm 0.061 \pm 0.022$$
$$A_f^{\Delta\Gamma} = 0.051 \pm 0.134 \pm 0.037$$
$$S_f = -0.571 \pm 0.084 \pm 0.023$$
$$A_{\bar{f}}^{\Delta\Gamma} = 0.303 \pm 0.125 \pm 0.036$$
$$S_{\bar{f}} = -0.503 \pm 0.084 \pm 0.025$$

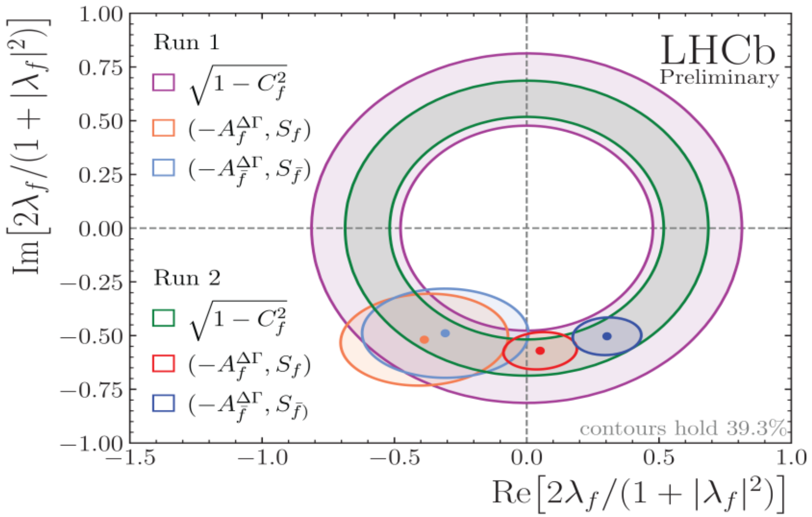
- **No systematic limitation expected in Run3**

NEW LHCb γ/ϕ_3 in B_s

[2] JHEP 03 (2018) 059
[4] LHCb-CONF-2023-004

Time-dependent measurements of γ

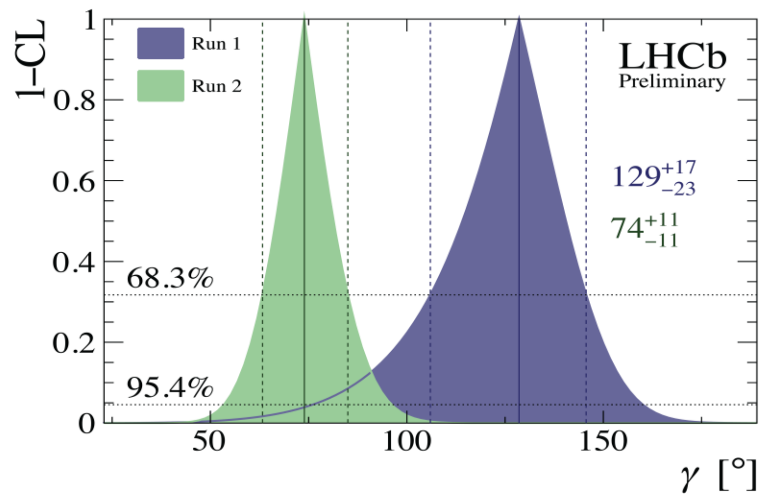
- $B^0 \to D^{\mp}\pi^{\pm}$ (Run1, 3 fb^{-1})
- $B_s^0 \to D_s^{\mp}K^{\pm}$ (Run1, 3 fb^{-1})
- $B_s^0 \to D_s^{\mp}K^{\pm}\pi^{\mp}\pi^{\pm}$ (Run1+2, 9 fb^{-1})
- $B_s^0 \to D_s^{\mp}K^{\pm}$ NEW! (Run2, 6 fb^{-1})



$B_s^0 \to D_s^{\mp}K^{\pm}$ - Run2

$$\gamma = (74 \pm 11)^{\circ}$$

Q. Führing @ CKM 2023

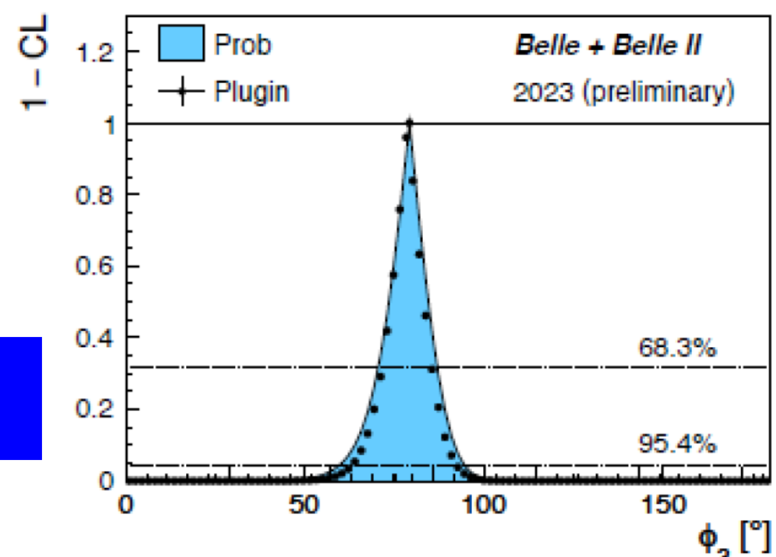


Belle+Belle II status γ/ϕ_3 in B^+

inputs: four different methods, 17 different final states

B decay	D decay	Method	Data set (Belle + Belle II) [fb^{-1}]	
$B^+ \to Dh^+$	$D \to K_S^0 h^- h^+$	BPGGSZ	$711 + 128$	[JHEP 02 063 (2022)]
$B^+ \to Dh^+$	$D \to K_S^0 \pi^- \pi^+ \pi^0$	BPGGSZ	$711 + 0$	[JHEP 10 178 (2019)]
$B^+ \to Dh^+$	$D \to K_S^0 \pi^0, K^- K^+$	GLW	$711 + 189$	[arxiv:2308.05048]
$B^+ \to Dh^+$	$D \to K^+ \pi^-, K^+ \pi^- \pi^0$	ADS	$711 + 0$	[PRL 106 231803 (2011)]
$B^+ \to Dh^+$	$D \to K_S^0 K^- \pi^+$	GLS	$711 + 362$	[arxiv:2306.02940]
$B^+ \to D^* K^+$	$D \to K_S^0 \pi^- \pi^+$	BPGGSZ	$605 + 0$	[PRD 81 112002 (2010)]
$B^+ \to D^* K^+$	$D \to K_S^0 \pi^0, K_S^0 \phi, K_S^0 \omega, K^- K^+, \pi^- \pi^+$	GLW	210+0	[PRD 73 051106 (2006)]

$B^0 \to D^{(*)} h^{(*)}$ decays are not included: minimal impact and introduce additional external parameters

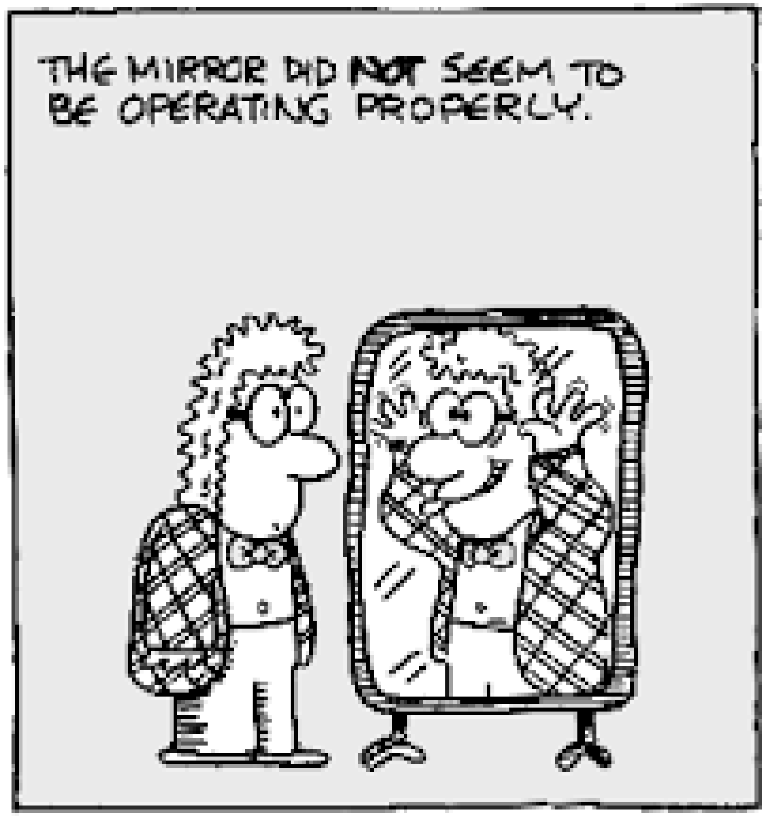


Combined fit from 60 Observables:

$\gamma/\phi_3 = (78.6 \pm 7.3)°$

K. Trabelsi @ CKM 2023

Other CP Violations



EXTREMELY ACTIVE FIELD
MANY NEW RESULTS !

CPV in 3-body charmless B decays

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

- Measurements of CP asymmetries in charmless three-body:
  - ☑ $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ (First Observation)
  - ☑ $B^{\pm} \to K^{\pm}K^{+}K^{-}$ (First Observation)
  - ☑ $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ (Confirmation)
  - ☑ $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ (No asymmetry)
- The phase space reveals non-uniform asymmetries
- Indication of CP violation involving the $\pi\pi \leftrightarrow KK$ rescattering
- Indication of CP violation involving the $\chi_{c0}(1P)$ resonance

$B \to PV$

- Measurements of CP asymmetries in $B \to PV$:
  - ☑ New method to measure CPV
  - ☑ $B^{\pm} \to \rho(770)K^{\pm}$ (First Observation)
  - ☑ All other channels (No asymmetry)

L. Falcão
@ CKM 2023

Direct CPV in D decays at LHCb

- First evidence in individual channel, $D^0 \to \pi^+\pi^-$

$$a^{dir}_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4} \quad (3.8\sigma)$$

- Recent searches in other two-body channels, $D^0 \to K^+K^-$ and $D_s^+ \to \eta^{(\prime)}\pi^+$

- Testing multibody decays for local CPV

  $D_{(s)}^+ \to K^-K^+K^+$, $D^0 \to \pi^+\pi^-\pi^0$ and $D^0 \to K_S K^{\pm}\pi^{\mp}$ All consistent with CP symmetry

- More to come with Run2 data

J. Brodzicka
@ CKM 2023

CPV in D decays at Belle II

Measurement of BR and search for CPV in $D^0 \to K^0_S K^0_S \pi^+ \pi^-$ decays

PRD 107, 052001 (2023)

Belle II

Search for CPV in $D^+_{(s)} \to K^+ K^0_S h^+ h^-$ decays and observation of $D^+_s \to K^+ K^- K^0_S \pi^+$

arXiv:2305.11405

Search for CPV using T-odd correlations in $D^+_{(s)} \to K^+ K^- \pi^+ \pi^0, K^+ \pi^- \pi^+ \pi^0$ and $D^+ \to K^- \pi^+ \pi^+ \pi^0$ decays

arXiv:2305.12806

M. Bertemes @ CKM 2023

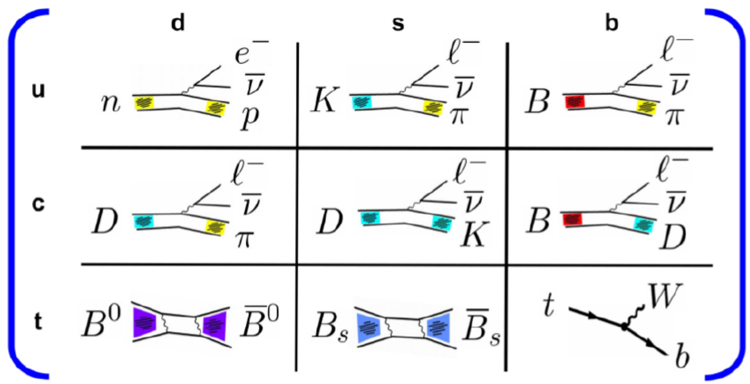
CKM global fit: Testing the consistency

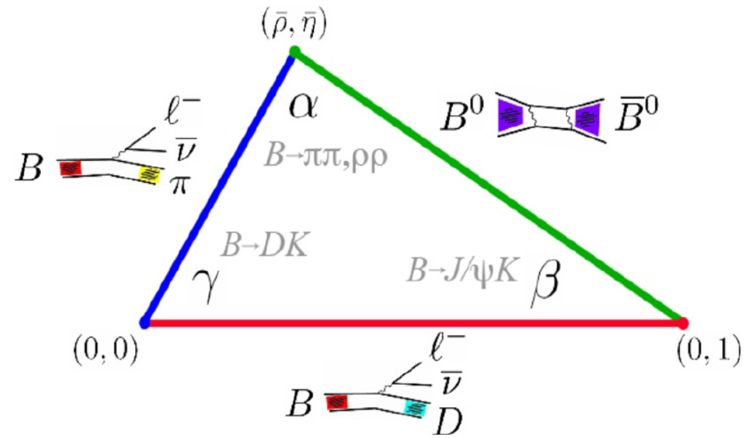
CKM fitter

Summer 23

CKM global fit: Testing the consistency

V =





→ Double requirement: precision in meas. and theo. prediction

→ Observables with **very different properties** are available:

- *Tree*: e.g., $|V_{ub}|$
- *Loop*: e.g., Δm_d, Δm_s, ϵ_K, $\sin(2\beta)$
- *$\mathcal{CP}$-conserving*: e.g., $|V_{ub}|$, Δm_d, Δm_s
- *$\mathcal{CP}$-violating*: e.g., γ, ϵ_K, $\sin(2\beta)$
- *Exp. uncs.*: e.g., α, $\sin(2\beta)$, γ
- *Syst. uncs.*: e.g., $|V_{ub}|$, $|V_{cb}|$, ϵ_K, Δm_d, Δm_s

CKM global fit: the experimental and theoretical inputs

New in 2023

CKM	Process	Observables	Non-perturbative theoretical inputs
$\|V_{ud}\|$	$0^+ \to 0^+\ \beta$	$\|V_{ud}\|_{\rm nucl} = 0.97373 \pm 0.00009 \pm 0.00053$	Nuclear matrix elements
$\|V_{us}\|$	$K \to \pi \ell \nu_\ell$	$\|V_{us}\|_{\rm SL} f_+^{K\to\pi}(0) = 0.21635 \pm 0.00038$	$f_+^{K\to\pi}(0) = 0.9675 \pm 0.0011 \pm 0.0023$
	$K \to e\nu_e$	$\mathcal{B}(K \to e\nu_e) = (1.582 \pm 0.007)\cdot 10^{-5}$	
	$K \to \mu\nu_\mu$	$\mathcal{B}(K \to \mu\nu_\mu) = 0.6356 \pm 0.0011$	$f_K = 155.57 \pm 0.17 \pm 0.57$ MeV
	$\tau \to K\nu_\tau$	$\mathcal{B}(\tau \to K\nu_\tau) = (0.6986 \pm 0.0085)\cdot 10^{-2}$	
$\frac{\|V_{us}\|}{\|V_{ud}\|}$	$K \to \mu\nu_\mu / \pi \to \mu\nu_\mu$	$\frac{\mathcal{B}(K\to\mu\nu_\mu)}{\mathcal{B}(\pi\to\mu\nu_\mu)} = 1.3367 \pm 0.0028$	$f_K/f_\pi = 1.1973 \pm 0.0007 \pm 0.0014$
	$\tau \to K\nu_\tau / \tau \to \pi\nu_\tau$	$\frac{\mathcal{B}(\tau\to K\nu_\tau)}{\mathcal{B}(\tau\to\pi\nu_\tau)} = (6.437 \pm 0.092)\cdot 10^{-2}$	
$\|V_{cd}\|$	νN	$\|V_{cd}\|_{\rm not\ lattice} = 0.230 \pm 0.011$	
	$D \to \tau\nu_\tau$	$\mathcal{B}(D \to \tau\nu_\tau) = (1.20 \pm 0.27)\cdot 10^{-3}$	
	$D \to \mu\nu_\mu$	$\mathcal{B}(D \to \mu\nu_\mu) = (3.77 \pm 0.17)\cdot 10^{-4}$	$f_{D_s}/f_D = 1.1782 \pm 0.0006 \pm 0.0033$
	$D \to \pi\ell\nu_\ell$	$\|V_{cd}\|_{\rm SL} f_+^{D\to\pi}(0) = 0.1426 \pm 0.0018$	$f_+^{D\to\pi}(0) = 0.624 \pm 0.004 \pm 0.006$
$\|V_{cs}\|$	$W \to c\bar{s}$	$\|V_{cs}\|_{\rm not\ lattice} = 0.967 \pm 0.011$	
	$D_s \to \tau\nu_\tau$	$\mathcal{B}(D_s \to \tau\nu_\tau) = (5.32 \pm 0.10)\cdot 10^{-2}$	
	$D_s \to \mu\nu_\mu$	$\mathcal{B}(D_s \to \mu\nu_\mu) = (5.43 \pm 0.16)\cdot 10^{-3}$	$f_{D_s} = 249.23 \pm 0.27 \pm 0.65$ MeV
	$D \to K\ell\nu_\ell$	$\|V_{cs}\|_{\rm SL} f_+^{D\to K}(0) = 0.7180 \pm 0.0033$	$f_+^{D\to K}(0) = 0.742 \pm 0.002 \pm 0.004$
$\|V_{ub}\|$	semileptonic B	$\|V_{ub}\|_{\rm SL} = (3.86 \pm 0.07 \pm 0.12)\cdot 10^{-3}$	form factors, shape functions
	$B \to \tau\nu_\tau$	$\mathcal{B}(B \to \tau\nu_\tau) = (1.09 \pm 0.24)\cdot 10^{-4}$	$f_{B_s}/f_B = 1.2118 \pm 0.0020 \pm 0.0058$
$\|V_{cb}\|$	semileptonic B	$\|V_{cb}\|_{\rm SL} = (41.22 \pm 0.24 \pm 0.37)\cdot 10^{-3}$	form factors, OPE matrix elements
$\|V_{ub}/V_{cb}\|$	semileptonic Λ_b	$\frac{\gamma(\Lambda_b\to p\mu^-\bar\nu_\mu)_{q^2>15}}{\gamma(\Lambda_b\to\Lambda_c\mu^-\bar\nu_\mu)_{q^2>7}} = (0.918 \pm 0.083)\cdot 10^{-2}$	$\frac{\zeta(\Lambda_b\to p\mu^-\bar\nu_\mu)_{q^2>15}}{\zeta(\Lambda_b\to\Lambda_c\mu^-\bar\nu_\mu)_{q^2>7}} = 1.471 \pm 0.096 \pm 0.290$
	semileptonic B_s	$\frac{\gamma(B_s\to K^+\mu^-\bar\nu_\mu)_{q^2>15}}{\gamma(B_s\to D_s^+\mu^-\bar\nu_\mu)_{q^2>7}} = (3.25 \pm 0.28)\cdot 10^{-3}$	$\frac{\zeta(B_s\to K^+\mu^-\bar\nu_\mu)_{q^2>7}}{\zeta(B_s\to D_s^+\mu^-\bar\nu_\mu)_{q^2>7}} = 0.363 \pm 0.001 \pm 0.065$
	inclusive	$\|V_{ub}/V_{cb}\|_{\rm incl} = 0.100 \pm 0.006 \pm 0.003$	
α	$B \to \pi\pi,\ \rho\pi,\ \rho\rho$	branching ratios, CP asymmetries	isospin symmetry
β	$B \to (c\bar{c})K$	$\sin(2\beta)_{[c\bar{c}]} = 0.708 \pm 0.011$	subleading penguins neglected
	$B^0 \to D^{(*)}h^0$	$\cos(2\beta) = 0.91 \pm 0.25$	
γ	$B \to D^{(*)}K^{(*)}$	$\gamma = (65.9^{+3.3}_{-3.5})^\circ$	GGSZ, GLW, ADS methods
ϕ_s	$B_s \to J/\psi(KK,\pi\pi)$	$(\phi_s)_{b\to c\bar{c}s} = -0.039 \pm 0.016$	
$V_{tq}^* V_{tb}$	Δm_d	$\Delta m_d = 0.5065 \pm 0.0019\ \rm ps^{-1}$	$\hat{B}_{B_s}/\hat{B}_{B_d} = 1.007 \pm 0.010 \pm 0.014$
	Δm_s	$\Delta m_s = 17.765 \pm 0.006\ \rm ps^{-1}$	$\hat{B}_{B_s} = 1.313 \pm 0.012 \pm 0.030$
	$B_s \to \mu\mu$	$\mathcal{B}(B_s \to \mu\mu) = (3.45 \pm 0.29)\cdot 10^{-9}[\times(1-0.063)]$	$f_{B_s} = 228.75 \pm 0.69 \pm 1.87$ MeV
$V_{td}^* V_{ts}$ and $V_{cd}^* V_{cs}$	ε_K	$\|\varepsilon_K\| = (2.228 \pm 0.011)\cdot 10^{-3}$	$\hat{B}_K = 0.7567 \pm 0.0020 \pm 0.0123$
			$\kappa_\varepsilon = 0.940 \pm 0.013 \pm 0.023$

CKM global fit: theoretical inputs, dealing with hadronic effects

→ Need to deal with **hadronic effects** inherent to the quark sector

→ Determine $\mathcal{L}^{eff}_{SM\,(NP)} \sim \Sigma_i C_i(\mu) \times O_i(\mu)$, where $\mu \sim \mathcal{O}(\text{few})$ GeV: C_i collects *short*-distance physics; O_i collects *long*-distance physics

(semi-)leptonic decays	$\pi \to \ell\nu$, $K \to \pi\ell\nu$, etc.★ decay constants, form factors Ex.: f_π, $f_+^{K\to\pi}(0)$ $-p_\mu f_\pi = \langle 0 \vert (\bar{d}\gamma_\mu\gamma_5 u) \vert \pi(p)\rangle$, $f_+^{K\to\pi}(q^2)(p+p')_\mu + f_-^{K\to\pi}(q^2)(p-p')_\mu = \langle \pi(p') \vert (\bar{s}\gamma_\mu P_L u) \vert K(p)\rangle$
Meson-mixing	$B_{(s)}\overline{B}_{(s)}$, $K\overline{K}$: bag-parameters $\widehat{B}_{B_s}$, $\widehat{B}_{B_s}/\widehat{B}_{B_d}$, $\widehat{B}_K$ $\frac{2}{3} m_K^2 f_K^2 B_K = \langle \overline{K} \vert (\bar{s}\gamma^\mu P_L d)\,(\bar{s}\gamma_\mu P_L d) \vert K\rangle$

→ Lattice QCD: extractions of non-perturbative parameters; averages typically dominated by **systematic uncertainties**
(fermion action, $a \to 0$, $L \to \infty$, mass extrapolations...)

★ **etc. means: D→ Klν, B→ D$^{(*)}$lν / πlν**

Overall results of the *CKM*fitter 2023 update

The global fit remains excellent, **preliminary** results:

CKM'21: p-value $\sim$ 29% (1.1σ) $\to$ **CKM'23**: p-value $\sim$ 67% (0.4σ)

$A = 0.8215^{+0.0047}_{-0.0082}$ (0.8% unc.)

$\lambda = 0.22498^{+0.00023}_{-0.00021}$ (0.1% unc.)

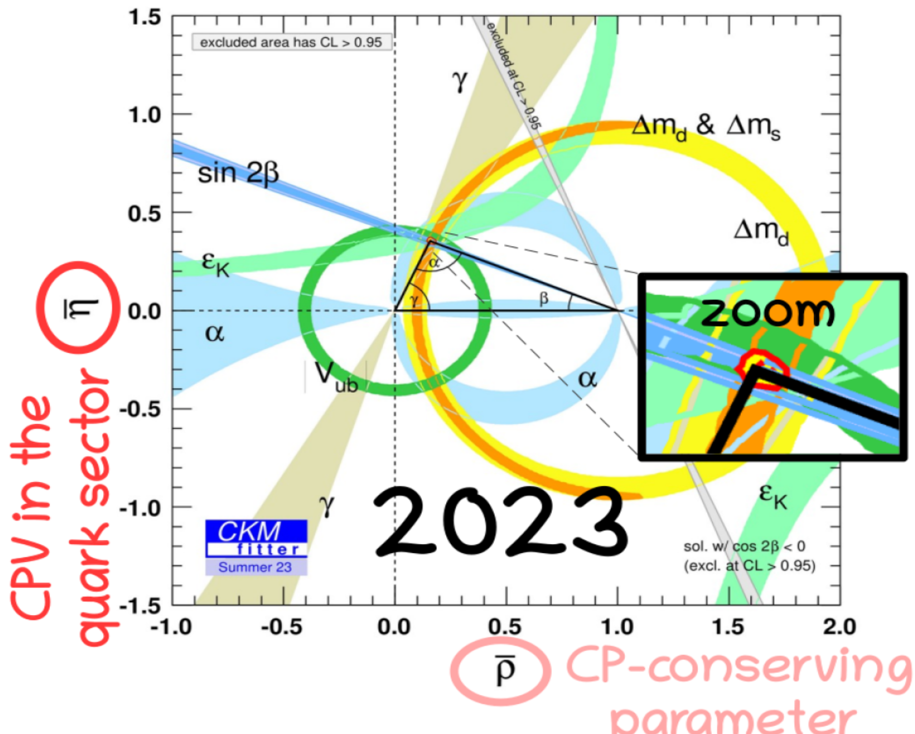
$\bar{\rho} = 0.1562^{+0.0112}_{-0.0040}$ (4.9% unc.)

$\bar{\eta} = 0.3551^{+0.0051}_{-0.0057}$ (1.5% unc.)

68% C.L. intervals

$\bar{\rho}, \bar{\eta}$: $\sim$ 20% more precise

B_d Unitary Triangle:



L. Vale Silva @ CKM2023

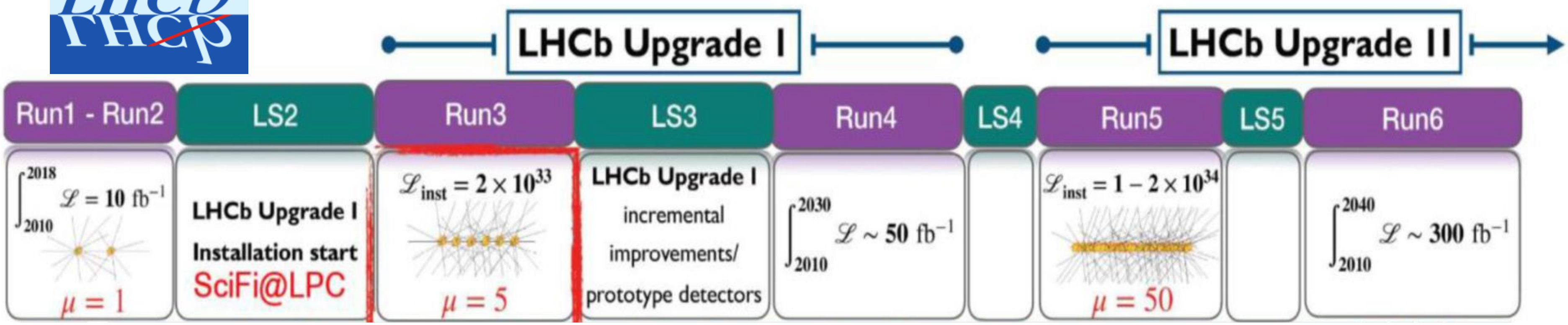
b : $|V_{xb}|$, α, β, γ, Δm_d, Δm_s

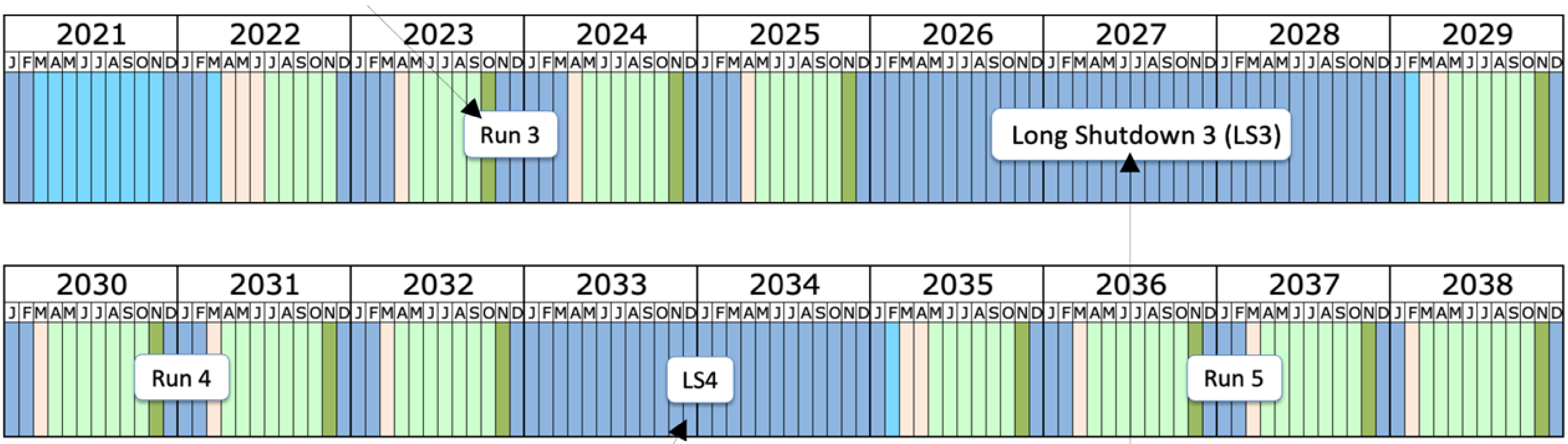
s : ε_K

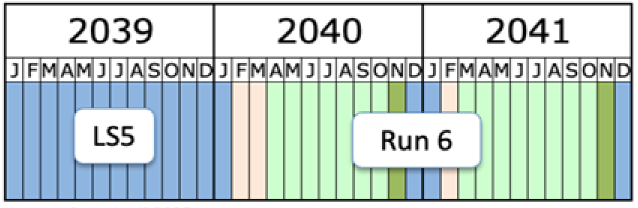
INTENSITY frontier

Supplemental material

LOOKING FORWARD to the bright FUTURE







LOOKING FORWARD to the bright FUTURE

[This plot to be updated with actual numbers from 2022 & 2023]

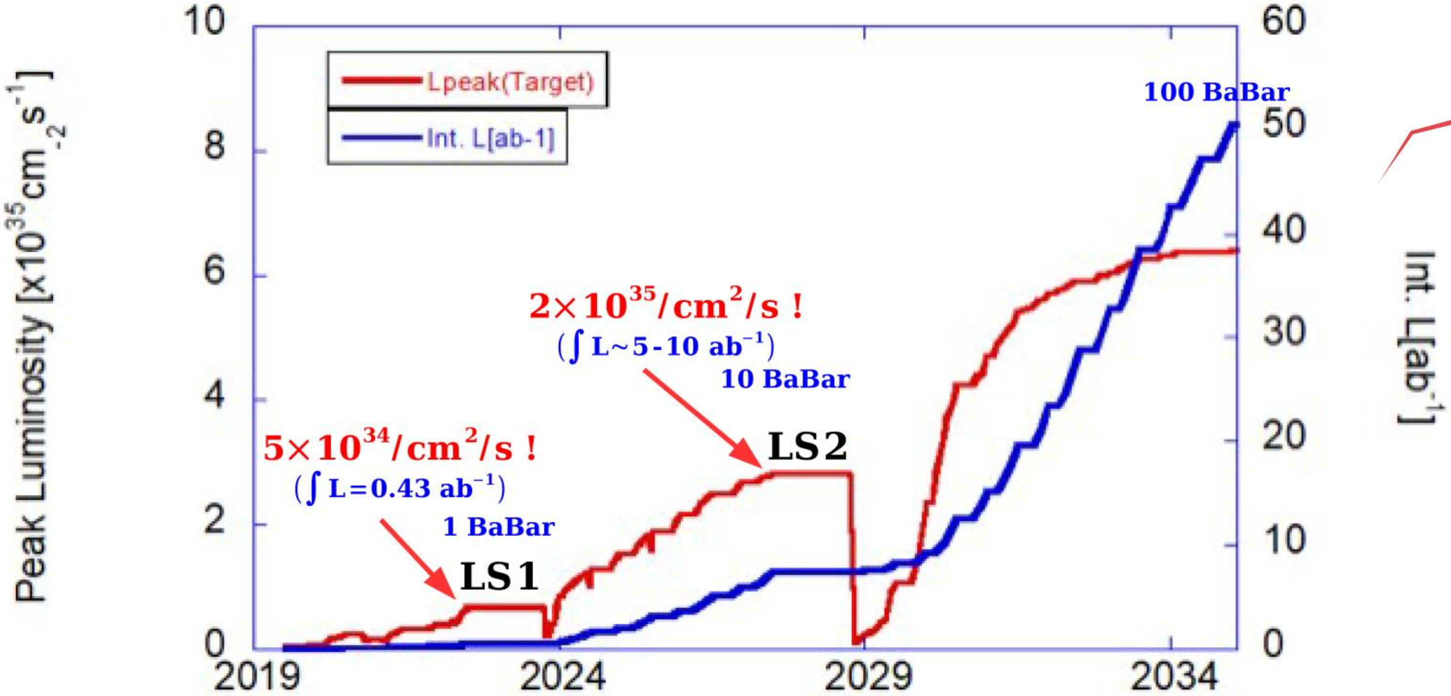
- Upgrade 1 designed to collect 50/fb, which we can collect by end of Run 4
- Opportunity to run for another 6 years

  [Assuming minimal commissioning time]
- Design Upgrade 2 detector to be able to accumulate maximum possible integrated luminosity
  - At least 300/fb by end of HL-LHC
  - Factor 6 increase in data → unprecedented sample and compelling physics programme

"The full physics potential of the LHC and the HL-LHC, including the study of flavour physics, ... should be exploited", European Strategy 2020

T. Gershon at the LHCb week Marseille Sept 23

Calendrier de Belle II



run 1 ($\rightarrow$ juin 2022): luminosite integre ~ 0.43 ab^{-1}, $4-5\times10^{34}$/cm^2/s
PXD complet (2 couches) a installe durant LS1 (2022-2023)
(+beampipe + TOP PMTs)
run 2 ($\rightarrow$ 2027): luminosite integre 5-10 ab^{-1}, 2×10^{35}/cm^2/s

2027: collider upgrade (QCS+RF) $\rightarrow$ installation upgraded detector

run 3 ($\rightarrow$ > 2030): 50 ab^{-1}

K. Trabelsi @ CS IN2P3 27/10/2022

LOOKING FORWARD to the bright FUTURE

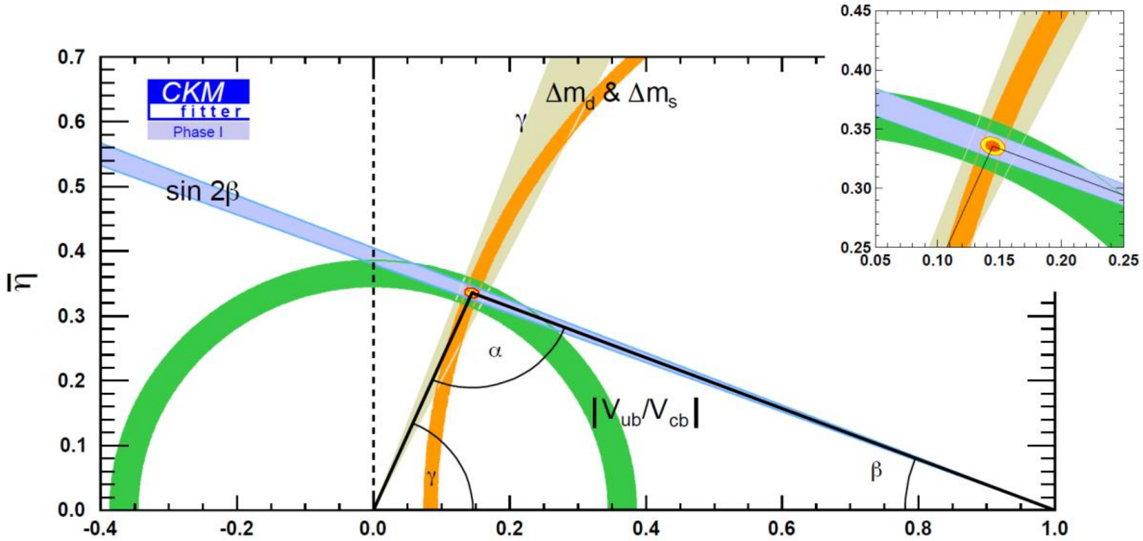
Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	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}	–

See Physics case for an LHCb Upgrade II + the Belle II Physics book

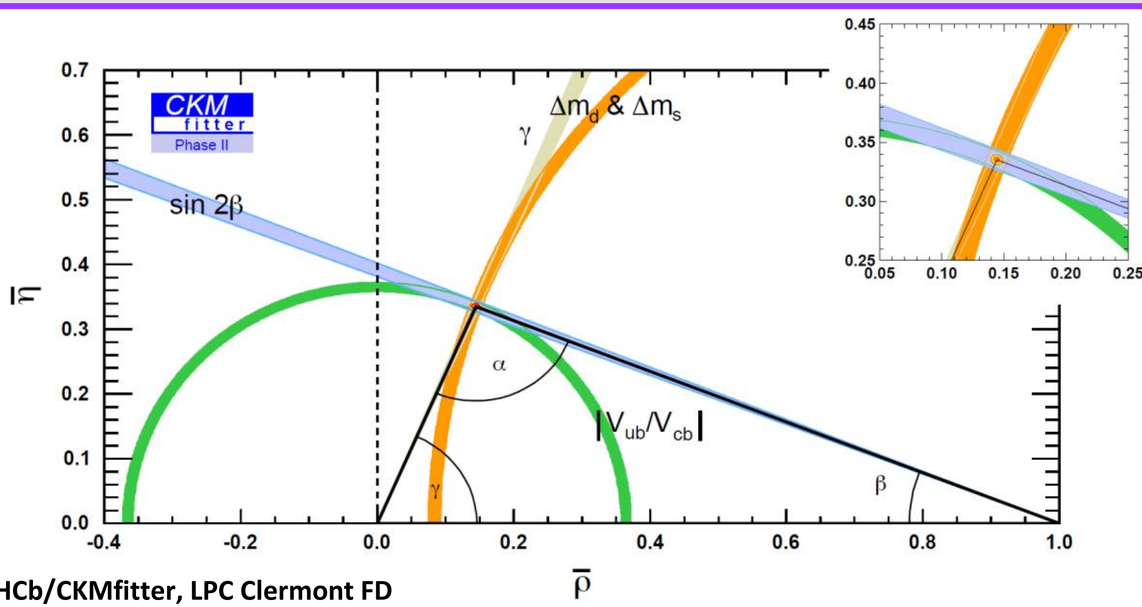
LOOKING FORWARD!

Phase I: LHCb at 23 fb^{-1}, CMS/ATLAS at 300 fb^{-1}, Belle II at 50 ab^{-1}.



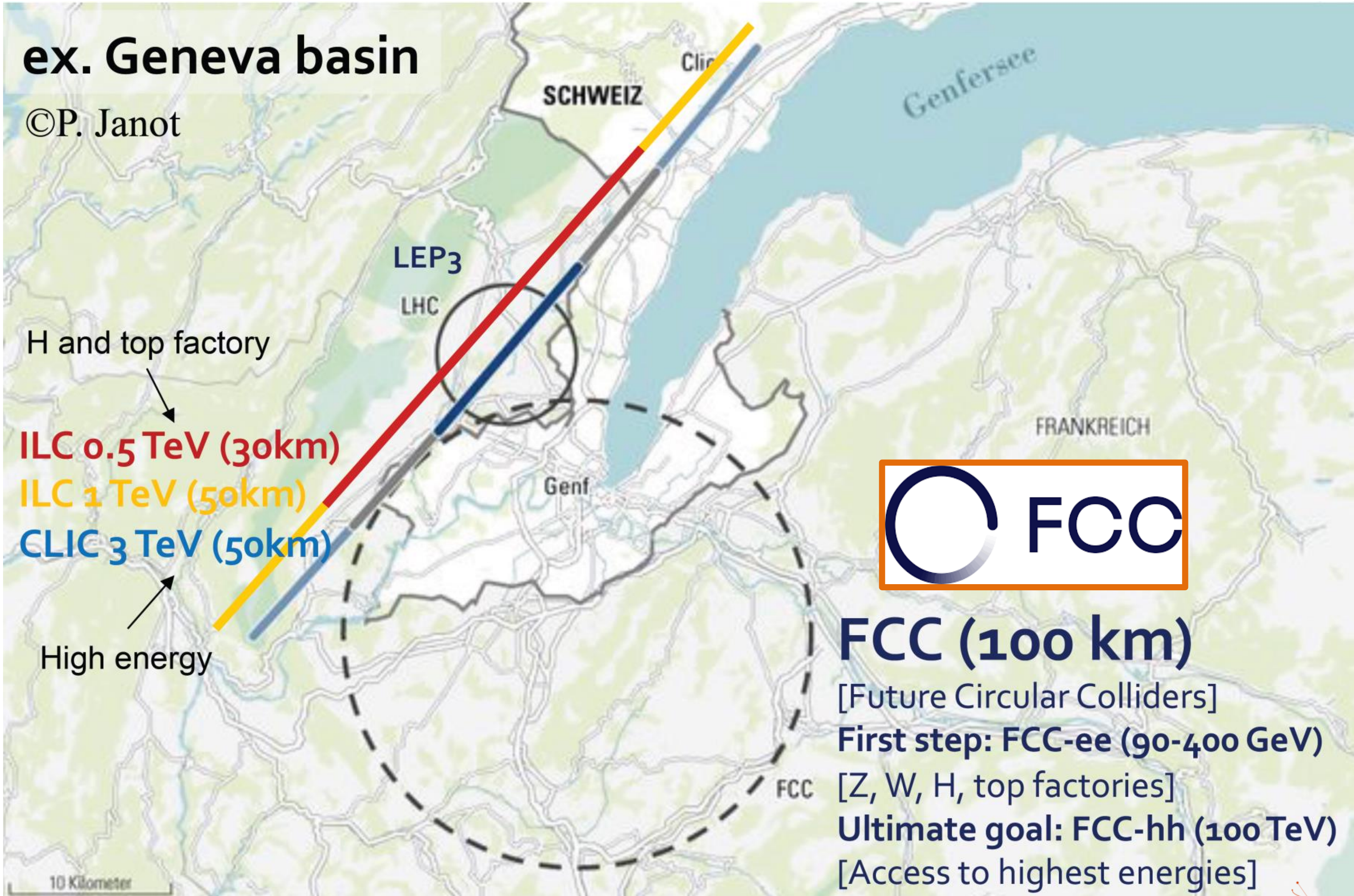
~in about 10 years

Phase II: LHCb at 300 fb^{-1}, CMS/ATLAS at 3000 fb^{-1}, and Belle II at 50 ab^{-1}.



~20 years

LOOKING FORWARD after 2040 !



Annecy ↓

https://fcc-cdr.web.cern.ch/

After 2040: FCC a GigaZ factory !

Eur. Phys. J. Plus (2021) 136:837
https://doi.org/10.1140/epjp/s13360-021-01814-0

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Heavy-quark opportunities and challenges at FCC-ee

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Abstract The abundant production of beauty and charm hadrons in the 5×10^{12} Z^0 decays expected at FCC-ee offers outstanding opportunities in flavour physics that in general exceed those available at Belle II and are complementary to the heavy-flavour programme of the LHC. A wide range of measurements will be possible in heavy-flavour spectroscopy, rare decays of heavy-flavoured particles and *CP*-violation studies, which will benefit from the low-background experimental environment, the high Lorentz boost and the availability of the full spectrum of hadron species. This essay first surveys the important questions in heavy-flavour physics and assesses the likely theoretical and experimental landscape at the turn-on of FCC-ee. From this certain, measurements are identified where the impact of FCC-ee will be particularly important. A full exploitation of the heavy-flavour potential of FCC-ee places specific constraints and challenges on detector design, which in some cases are in tension with those imposed by the other physics goals of the facility. These requirements and conflicts are discussed.

between 1989 and 1995, 18×10^6 Z bosons were collected at LEP@CERN, FCC aims for 5×10^{12} !

So LEP every few minutes of FCC operation!

At Z pole *qqbar* pairs:
- **15% are $b\bar{b}$ → 750×10^9**
- **12% are $c\bar{c}$ → 600×10^9**

Almost all triggerable and can be reconstructed (high eff'cy) in e^+e^- @Z (91.2GeV/c²) clean collisions !

A place for ultra-high heavy flavour precision and rares decays

It's every goodness & advantages from LHCb and from Belle II (very few drawbacks)!