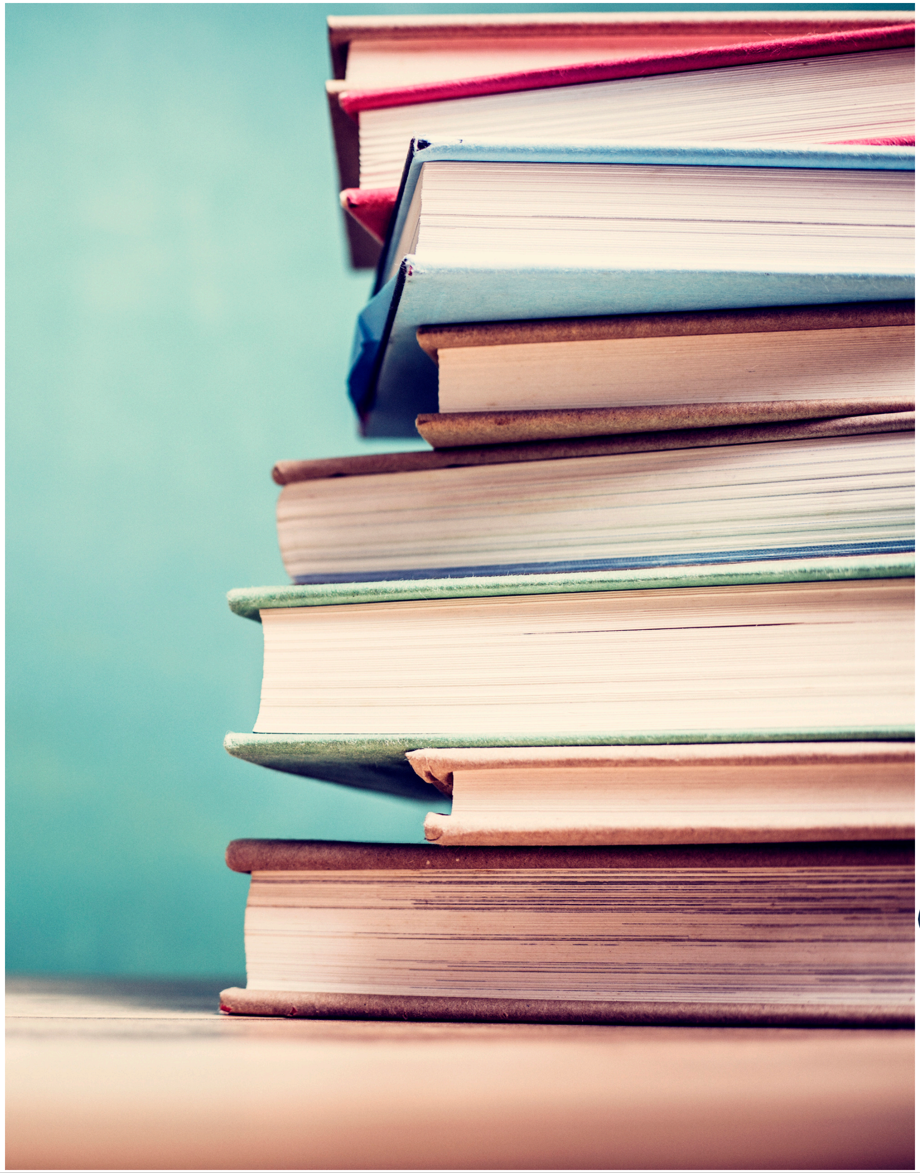
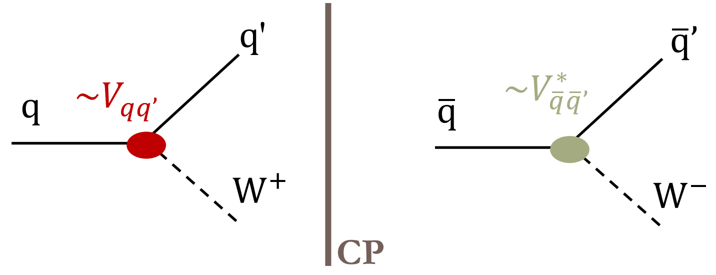


RECENT DEVELOPMENTS AND FUTURE PROSPECTS IN CP VIOLATION

Francesca Dordei (she/her), INFN - Cagliari (IT)
On behalf of the LHCb and Belle II Collaborations

PASCOS 2024

ICISE Quy Nhon, 9th July 2024



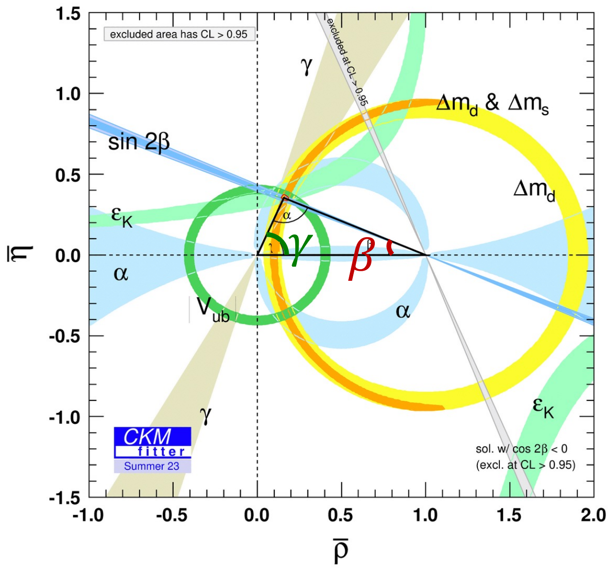
In the SM **quarks can change flavour**

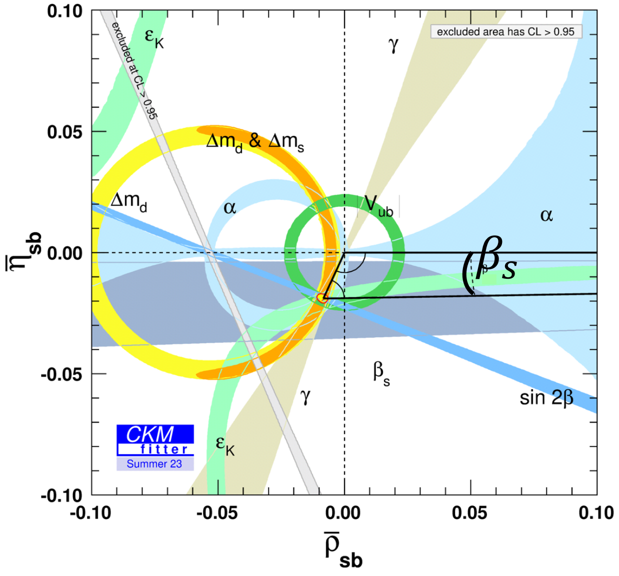
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity $V_{\mathrm{CKM}} \cdot V^{\dagger}_{\mathrm{CKM}} = \mathrm{I}$ imposes several conditions which give rise to **"unitarity" triangles**

E.g. Unitarity condition from 2nd and 3rd columns

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

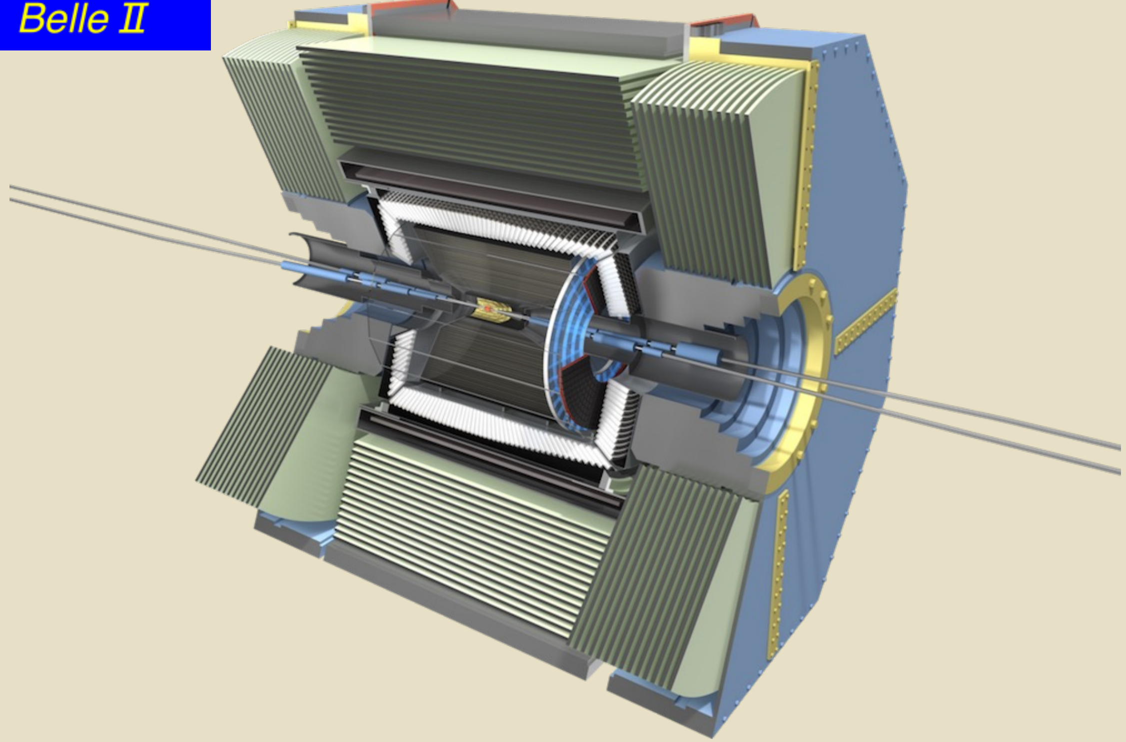


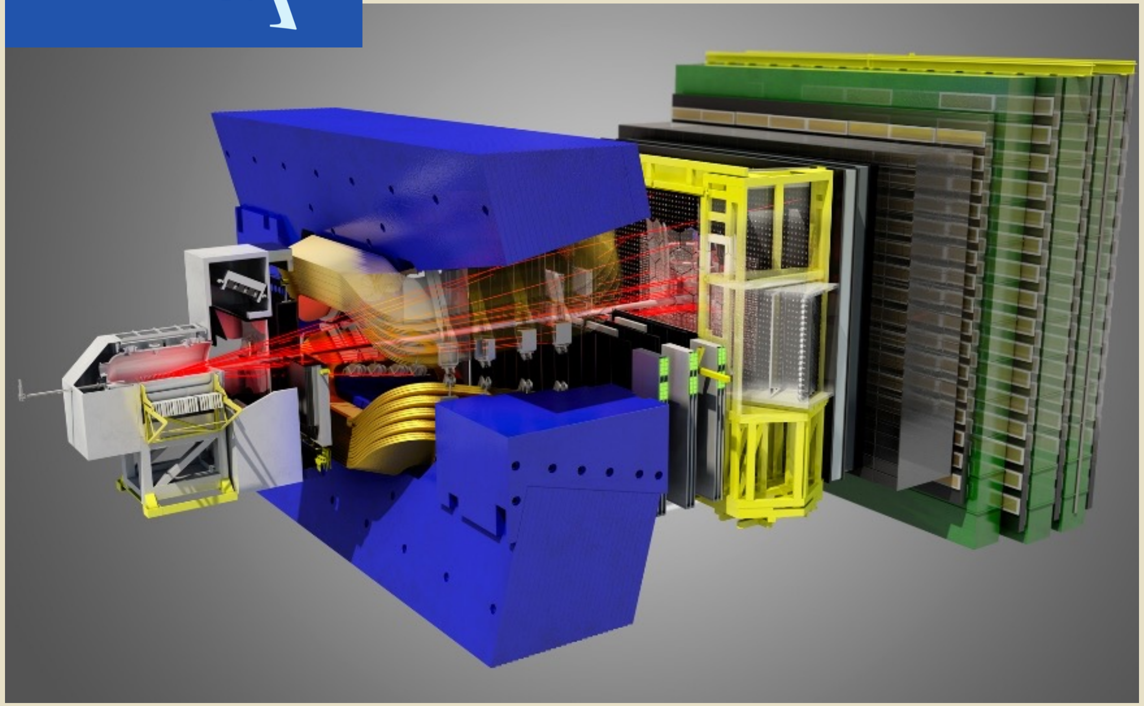


The CKM matrix

- The CKM matrix accommodates the **mixing between mass and flavour eigenstates** of quarks that arises from the EW symmetry breaking, **only measured source of CPV**!
- The SM works so remarkably well that we have to make **more and more precise measurements**
- **O(10-20%) NP contributions to most loop-level processes (FCNC) are still allowed**
    - See e.g. J. Charles at al arXiv:1309.2293 [hep-ph]
- Due to the CKM structure the **B system is favourable for CPV studies**. But important to investigate also the charm sector.

The protagonists





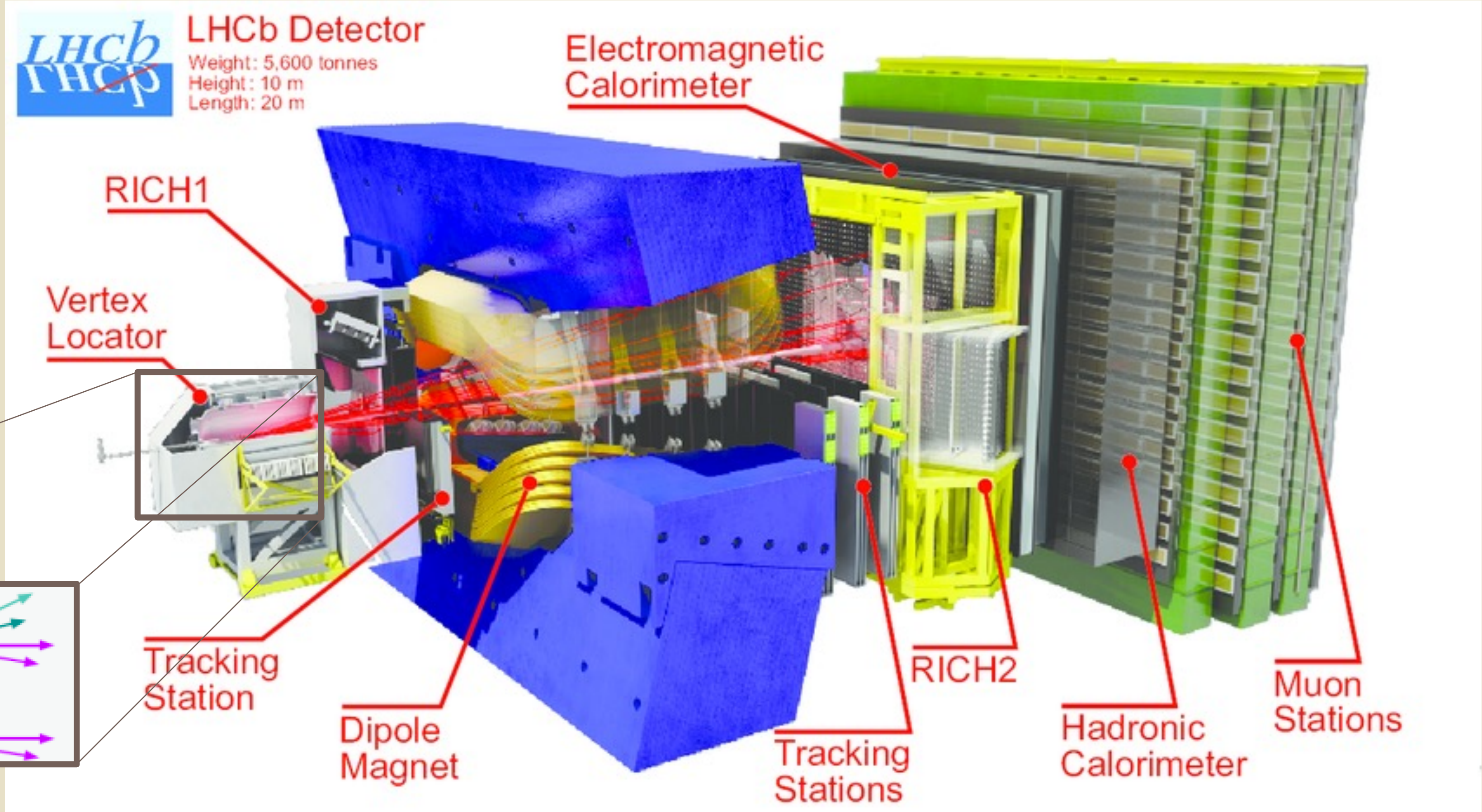
Today, selected results from LHCb and Belle II on CP violation!

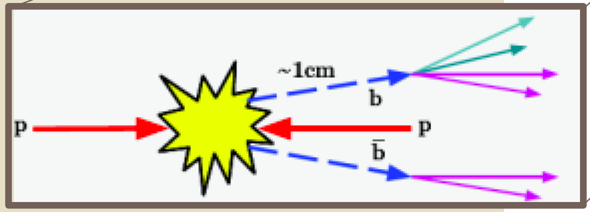
The LHCb Collaboration

- About 1400 scientists, engineers and technicians
- About 100 different universities and laboratories from more than 20 countries

The LHCb detector in Run 1 & 2 (2011-2018)

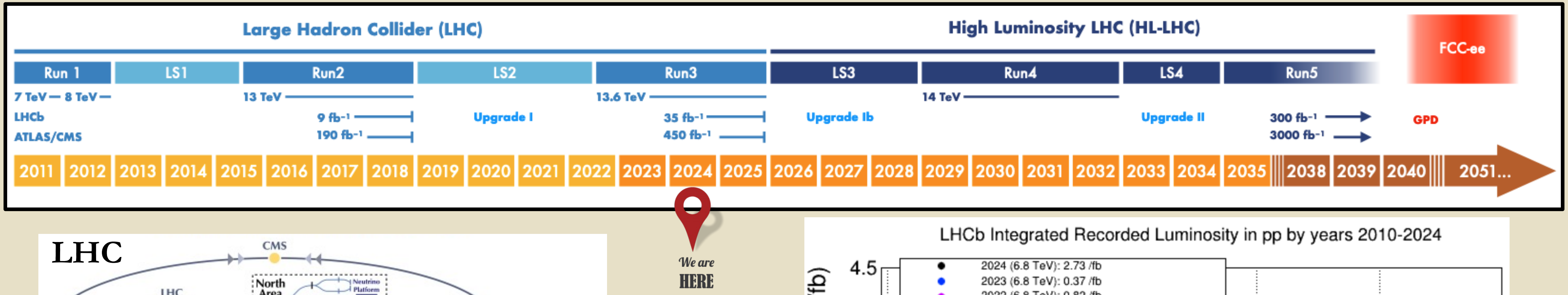
- Single arm spectrometer designed for high precision flavour physics measurements
- Pseudorapidity range $\eta \epsilon [2,5]$

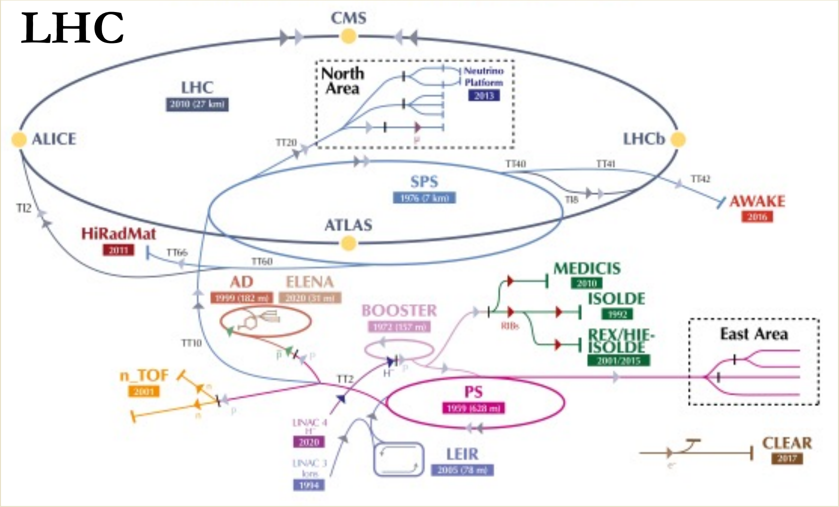


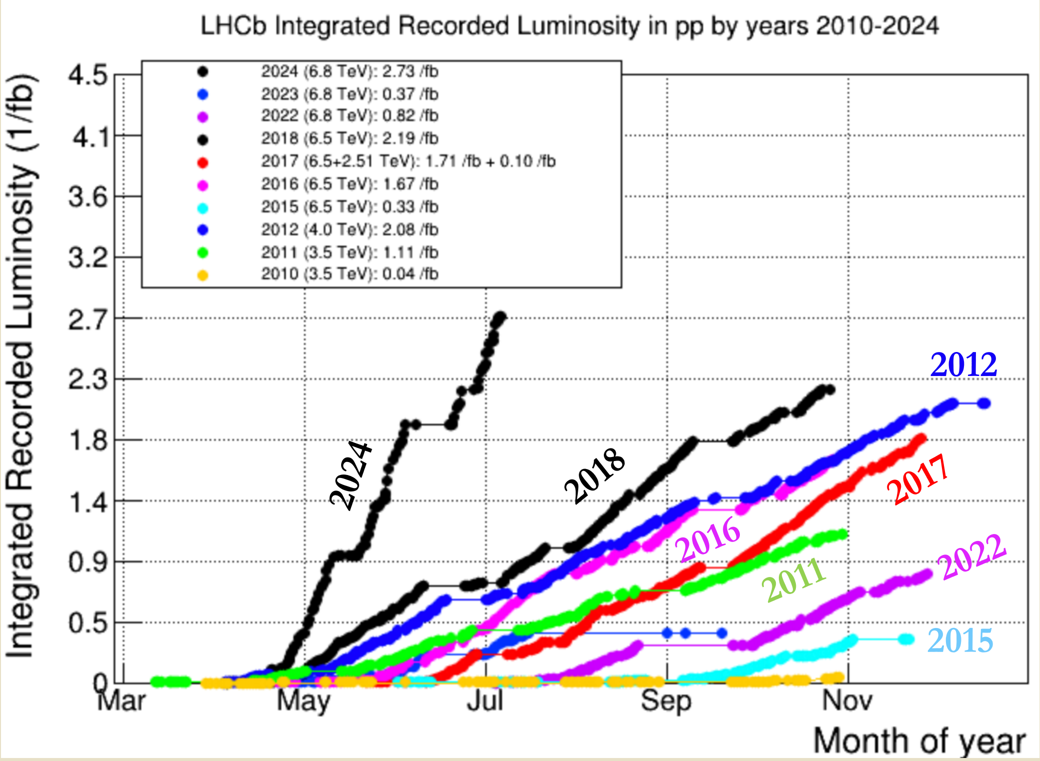


LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015)1530022

The LHCb experimental scenario



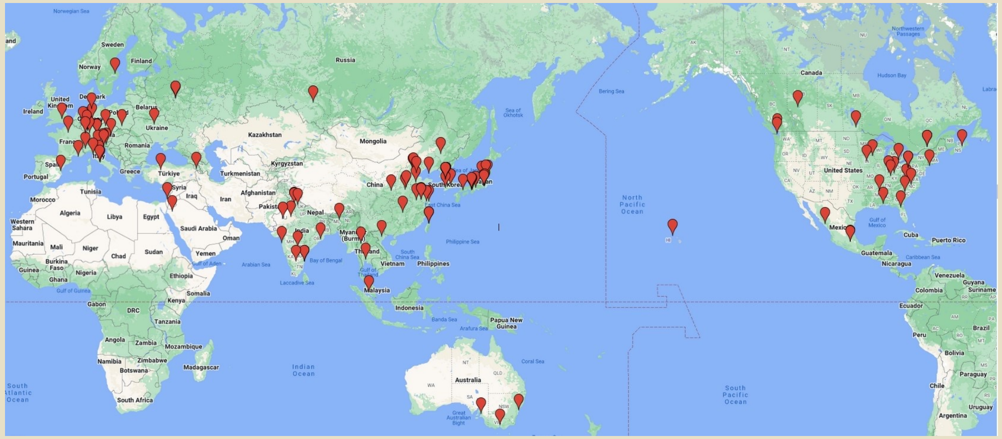




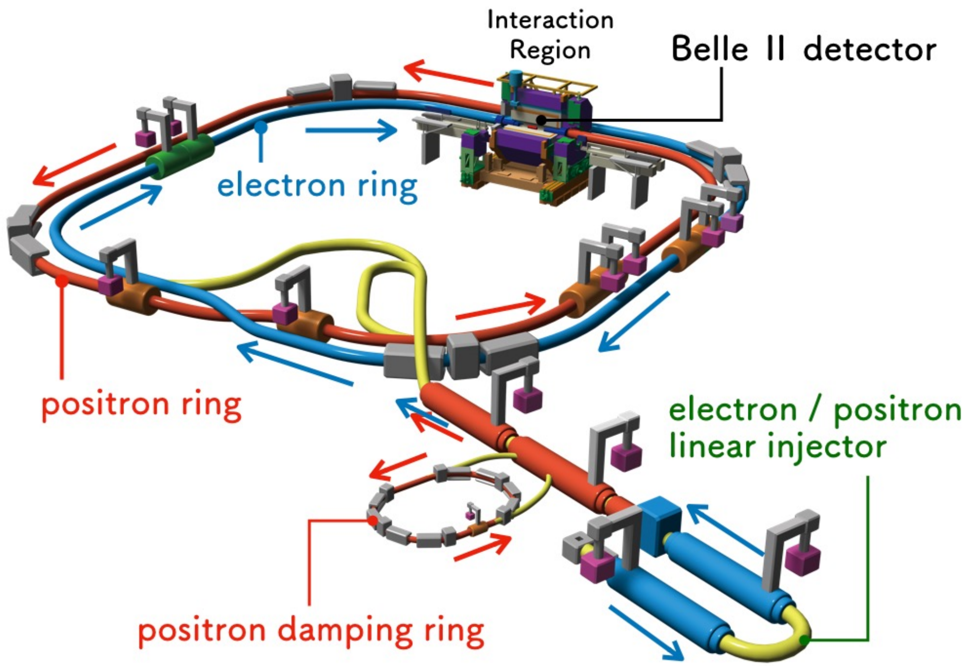
- ➢ Now: proton-proton collisions at $\sqrt{s}$ =13.6 TeV
- ➢ Luminosity in Run 3 already bigger than 2018
- ➢ Today, **results from Run 1 and Run 2,** ~9 fb^{-1}

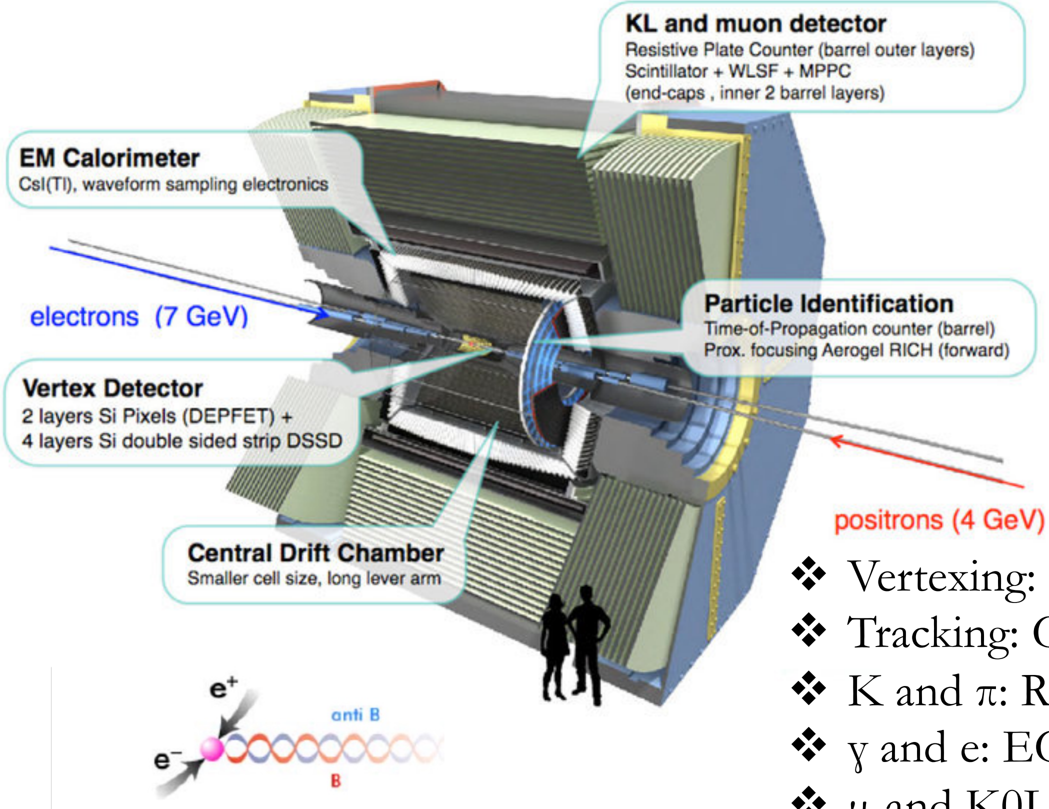
The Belle II Collaboration

- About 1200 scientists, engineers and technicians
- About 130 different universities and laboratories from about 30 countries



Super KEKB: asymmetric energy accelerator to provide e^+ (4GeV)-e^-(7GeV) collisions





- Vertexing: PXD+SVD
- Tracking: CDC
- K and π: RICH + TOP
- γ and e: ECL
- μ and K0L: KLM

Super KEKB and Belle II

- βγ ~ 0.284
- $\mathrm{BR}(\Upsilon(4S) \to B\bar{B}) > 96\%$
- Coherent B-meson pair production:
  - one B to determine flavour (tag side)
  - other B for CP measurement (CP side)

The Belle II experimental scenario

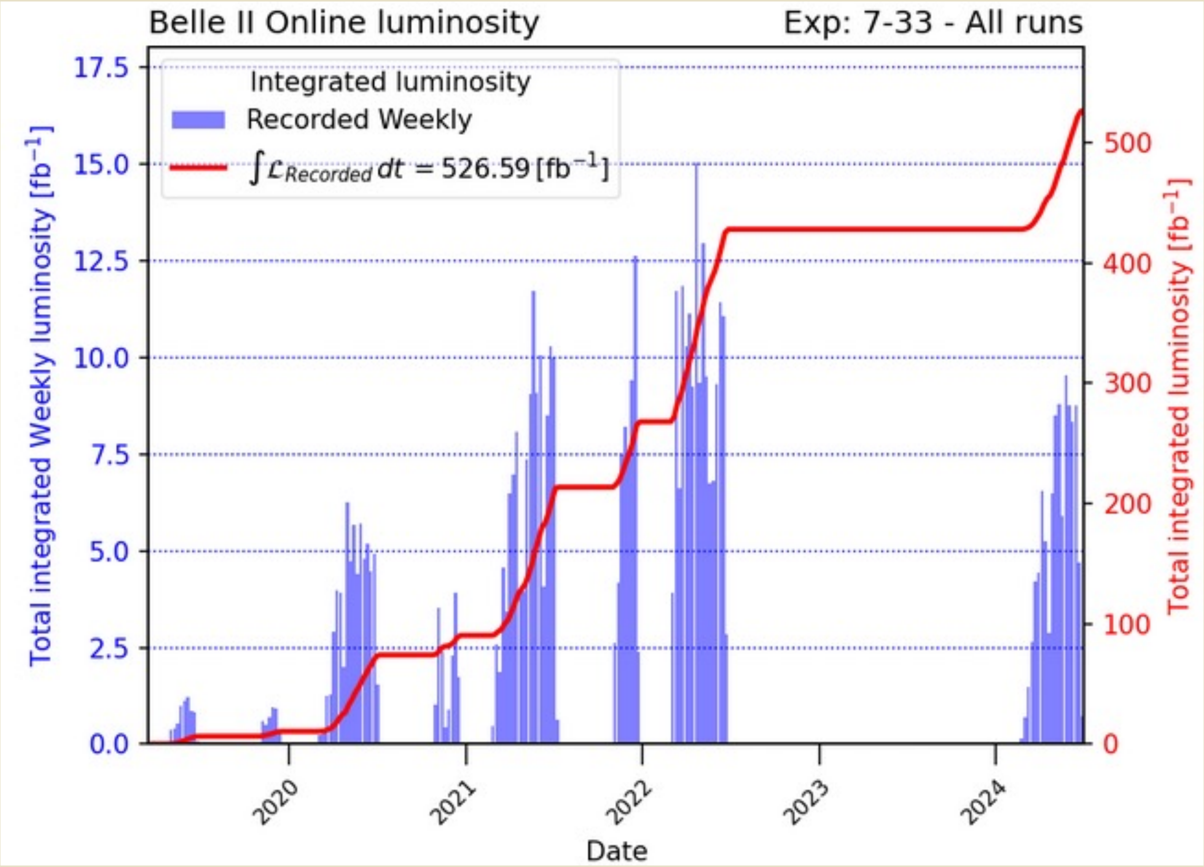
- **World record luminosity** $4.7\times10^{34}\ cm^{-2}s^{-1}$

- Run I: recorded 424 fb^{-1} of data ~ equivalent to BaBar and 1/2 of Belle data sample
- Run I: Data taken between 2019 - 2022
- **Run I data at $\Upsilon(4S)$ resonance: 362 fb^{-1}**

Today results on this sample!

- 42 fb^{-1} of off-resonance data [60 MeV below $\Upsilon(4S)$]
  - compared to ~90 fb^{-1} from Belle
- 19 fb^{-1} above the $\Upsilon(4S)$ resonance

- **Run II has started from early 2024**
- In total Run I + Run II recorded ~530 fb^{-1} of data

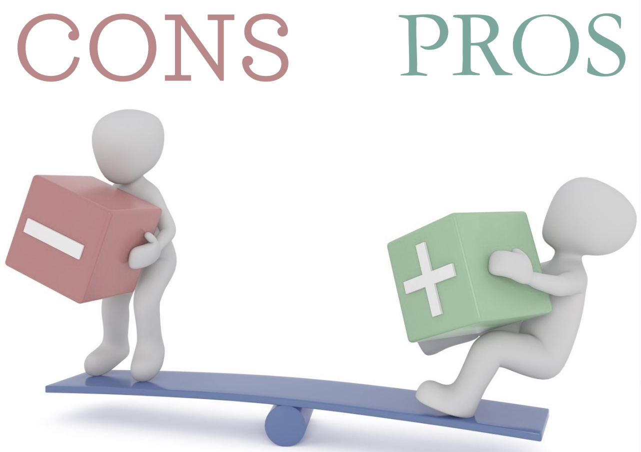


Hadron colliders VS B-factories

- **Production cross section $\sigma_{b\bar{b}}$ much larger** at hadron colliders → Typical $b\bar{b}$ rate of O(100kHz) vs O(10Hz)
- **Larger variety of hadron types produced**: B^+B^-(40%), $B^0\bar{B}^0$ (40%), $B_s^0\bar{B}_s^0$(10%), B_c(<0.1%), b-baryons(10%) plus large charm cross-section!

  ➡ Compared to mostly B^+B^- and $B^0\bar{B}^0$

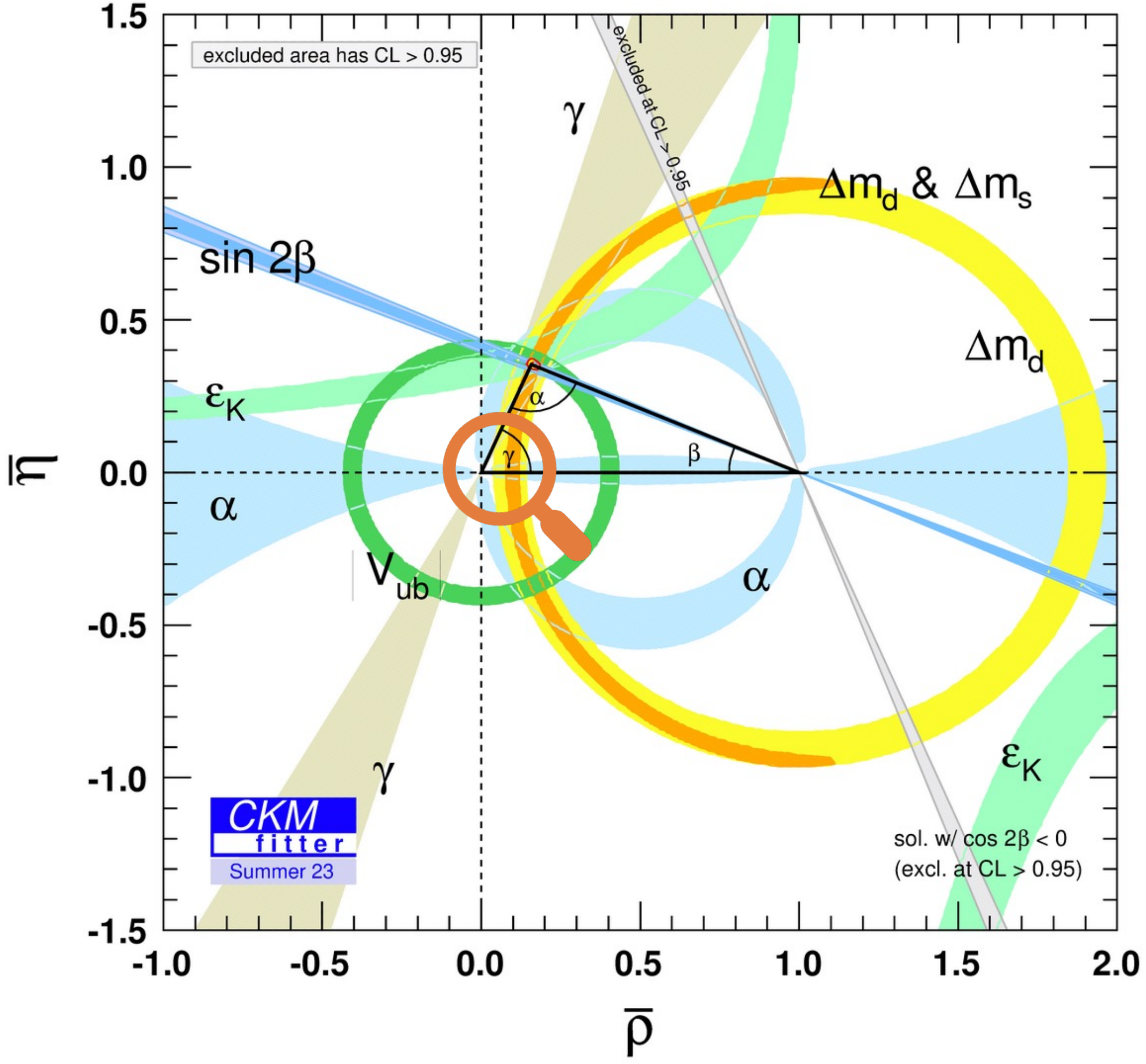
- **Larger b-hadron boost**: decay vertexes well separated



- **Purity of the event much better** at B-factories: $\sigma_{b\bar{b}}/\sigma_{inel}$ significantly smaller at hadron colliders!
- **Coherent production of $B\bar{B}$ pairs** and thus coherent mixing

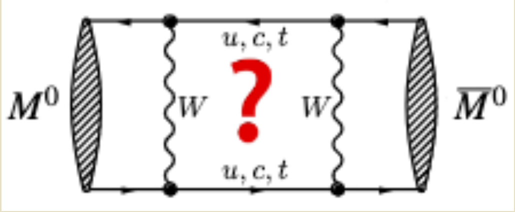
  ➡ These two features make **flavour tagging much more efficient**

- Known initial energy: **full reconstruction of the event** and access to modes with **neutrals in the final state**



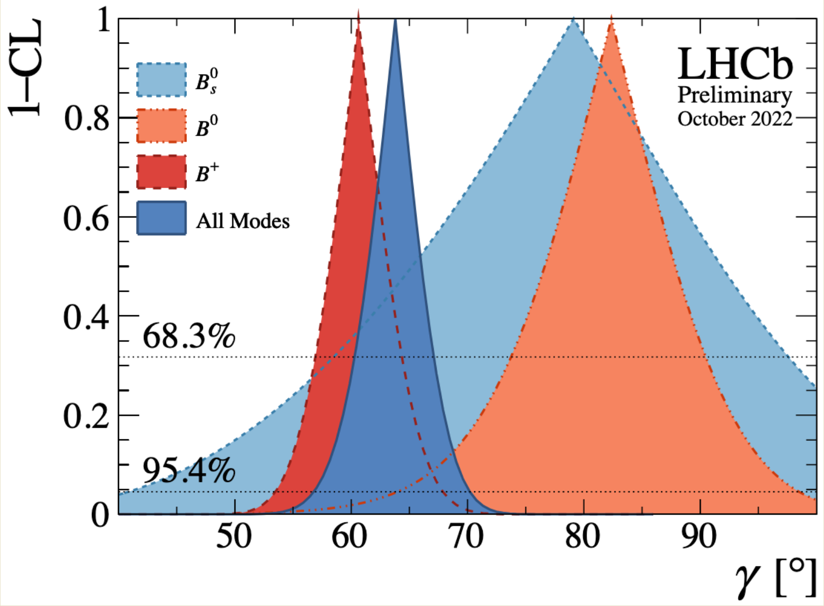
CKM ANGLES

- **Experimental checks of Unitarity Triangles are redundant**
- **Tree-level dominated processes** → SM benchmarks
- **Sizeable loop-level diagrams** → Eventual New Physics contributions



State of the art of γ

- Clean test of the SM: measurable with tree-level processes and theoretical uncertainty is $\sim 10^{-7}$ [JHEP01(2014)051]



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**
$B^\pm \to Dh^\pm$	$D \to K_S^0h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K_S^0K^\pm\pi^\mp$	[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**

LHCb combination
$\gamma = (63.8^{+3.5}_{-3.7})°$
[LHCb-CONF-2022-003]

- In agreement with previous and global averages $\gamma = (65.66^{+1.3}_{-1.2})°$ [CKMFitter]
- Statistically limited, still room for NP.

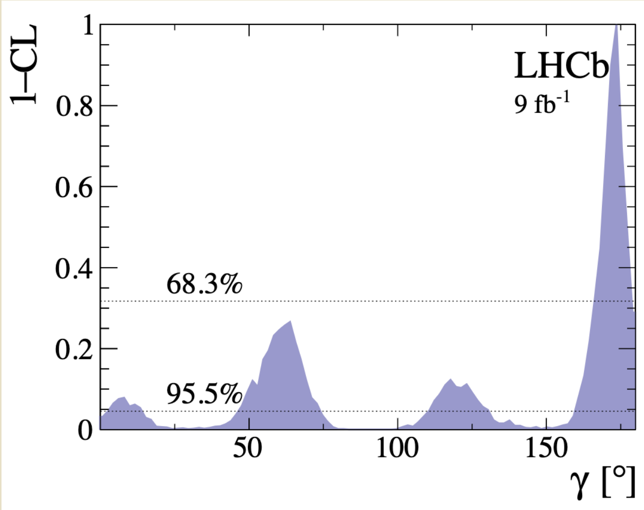
Frequentist approach, 173 observables, 52 parameters

Some γ analyses not included in combination

CPV in $B^0 \rightarrow DK^*(892)^0$

- 2 and 4-bodies D decays ($\pi^+\pi^-$, K^+K^-, $K^\mp\pi^\pm$, $4\pi^\pm$, $K^\pm\pi^\mp\pi^+\pi^-$)
- Simultaneous fit to D final states in $B^0/\bar{B}^0$ invariant mass to extract CPV observables

[arXiv:2401.17934]



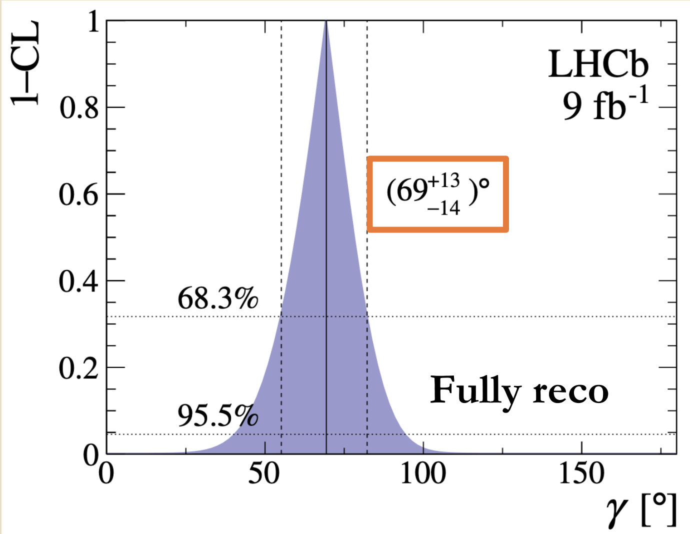
A combination with $B^0 \rightarrow D(K_S^0 hh)K^{*0}$ gives

$$\gamma = (63.2^{+6.9}_{-8.1})^\circ$$

CPV in $B^\pm \rightarrow D^* h^\pm$

- $D^* \rightarrow D\pi^0/\gamma$ and $D \rightarrow K_S^0\pi^+\pi^-$ / $K_S^0 K^+K^-$
- Strong phase inputs from BESIII and CLEO
- **Two approaches:** fully and partially reconstructed final states

[arXiv:2311.1043 and arXiv:2310.04277]



Using partially reco final states:

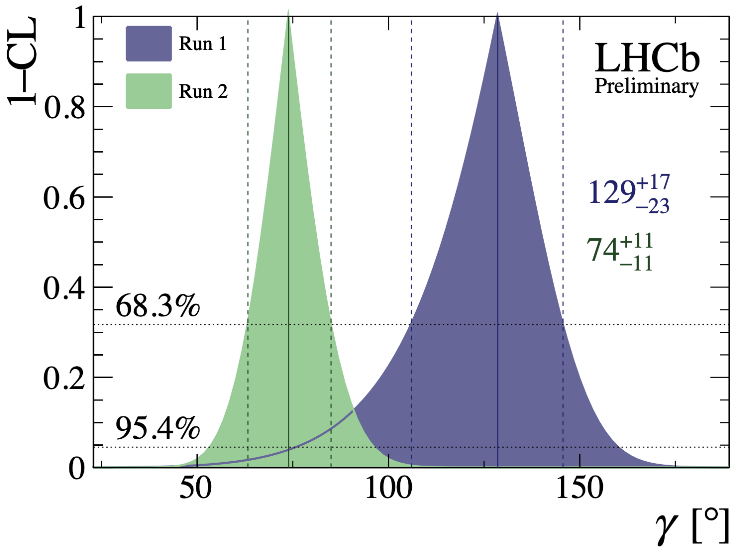
$$\gamma = (92^{+21}_{-17})^\circ$$

Negligible correlation within two approaches.

CPV in $B_s^0 \rightarrow D_s^\mp K^\pm$

- $D_s \rightarrow K^+K^-\pi^-$, $K^-\pi^+\pi^-$, $\pi^-\pi^+\pi^-$
- Need input on the B_s^0 mixing phase $-2\beta_s$

[LHCb CONF 2023-004]



Run II result:

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

Some γ analyses not included in combination

CPV in $B^0 \to DK^*(892)^0$

- 2 and 4-bodies D decays ($\pi^+\pi^-$, K^+K^-, $K^\mp\pi^\pm$, $4\pi^\pm$, $K^\pm\pi^\mp\,\pi^+\pi^-$)
- Simultaneous fit to D final states in $B^0/\bar{B}^0$ invariant mass to extract CPV observables

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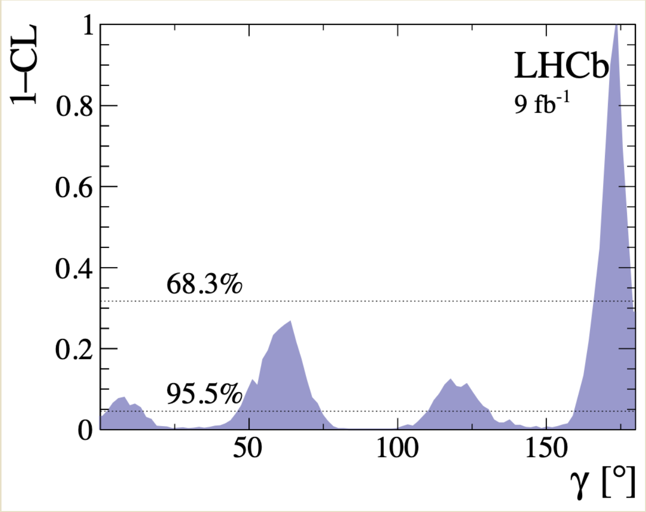

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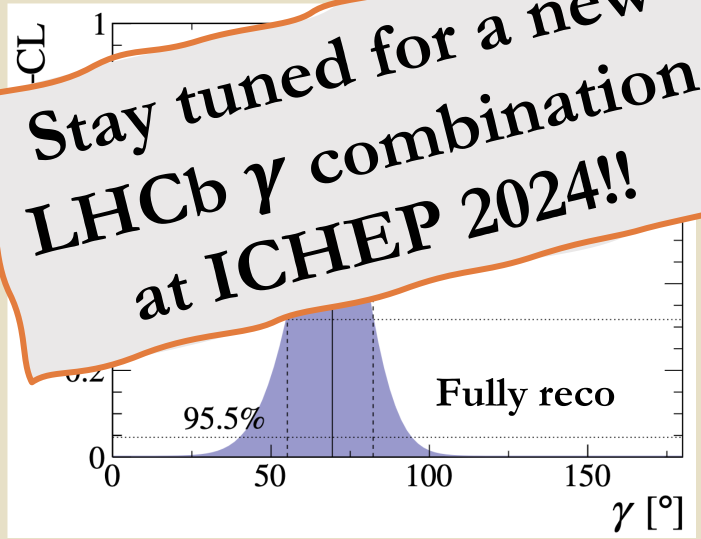
CPV in $B^\pm \to D^* h^\pm$

- $D^* \to D\pi^0/\gamma$ and $D \to K_S^0\pi^+\pi^-$ / $K_S^0K^+K^-$
- Strong phase inputs from BESIII and CLEO
- **Two approaches:** fully and partially reconstructed final states

[arXiv:2311.1043 and arXiv:...4277]



Stay tuned for a new LHCb γ combination at ICHEP 2024!!

Using partially reco final states:

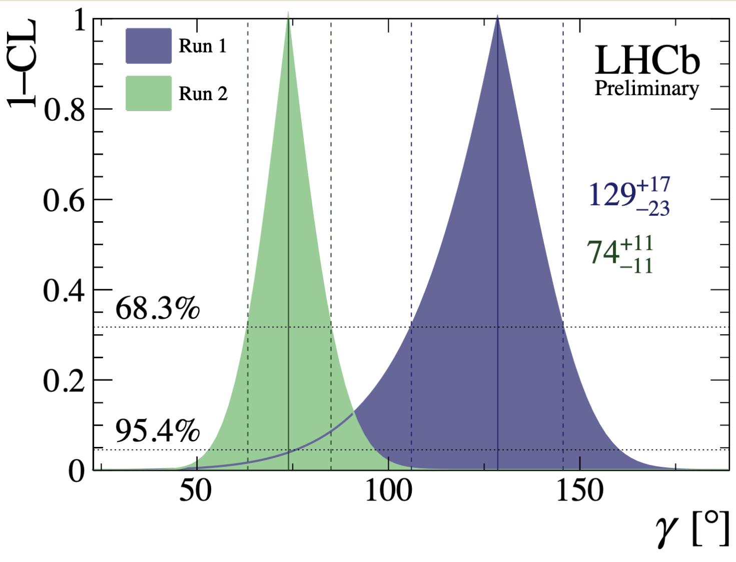
$$\gamma = (92^{+21}_{-17})^\circ$$

Negligible correlation within two approaches.

CPV in $B_s^0 \to D_s^\mp K^\pm$

- $D_s \to K^+K^-\pi^-$, $K^-\pi^+\pi^-$, $\pi^-\pi^+\pi^-$
- Need input on the B_s^0 mixing phase $-2\beta_s$

[LHCb CONF 2023-004]

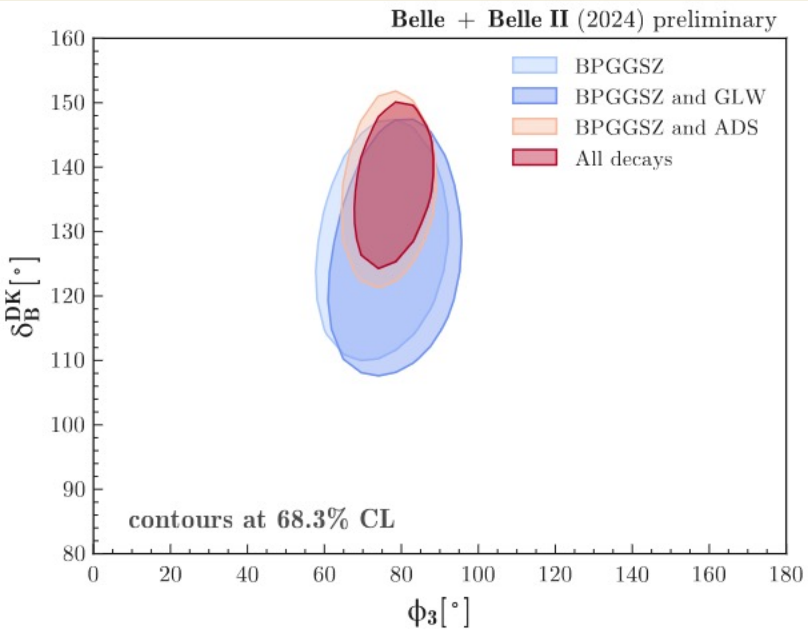


Run II result:

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

State of the art of γ

- Clean test of the SM: measurable with tree-level processes and theoretical uncertainty is $\sim 10^{-7}$ [JHEP01(2014)051]



Belle II combination
$\gamma = (78.6 \pm 7.3)^\circ$
[arXiv:2404.12817]

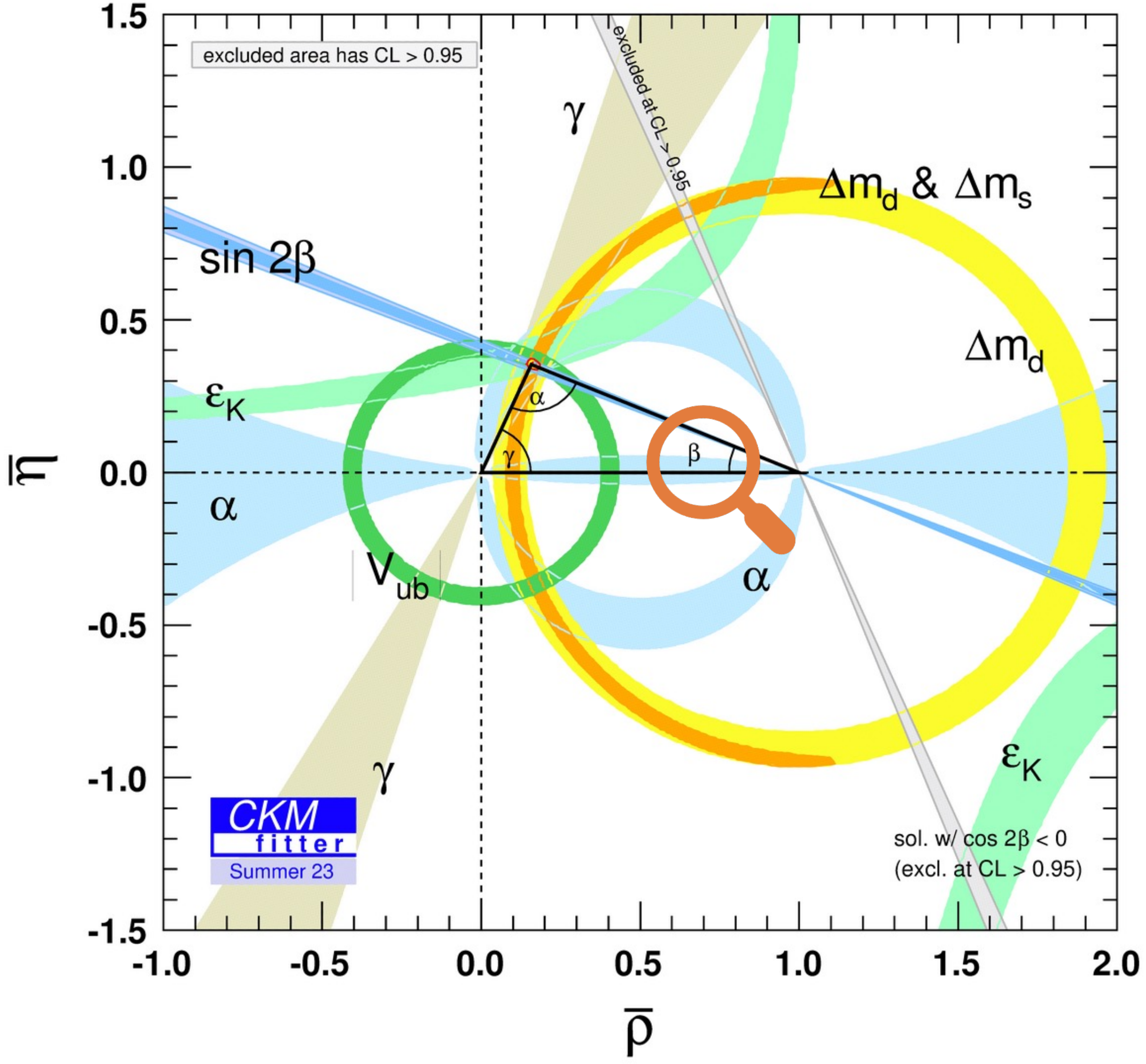
- Slightly above LHCb result and global averages $\gamma = (65.66^{+1.3}_{-1.2})^\circ$ [CKMFitter]
- Few ab^{-1} needed for a meaningful comparison.

Several methods used

- GLW $B^\pm \to D^0_{CP} K^\pm$ [arXiv:2308.05048]
  - Use CP eigenstate of D meson
- ADS [PRL 78 (1997) 3257]
  - Enhancement of CP violation by using doubly-Cabibbo suppressed decays.
- BPGGSZ $D^0 \to K_s h^+ h^-$ [JHEP 2022(2022)63]
  - Different amplitude and strong phase in different region of Dalitz plot.
- GLS $D^0 \to K_s K \pi$ [JHEP 09(2023)146]
  - D-decay strong phase from CLEO-c & BESIII

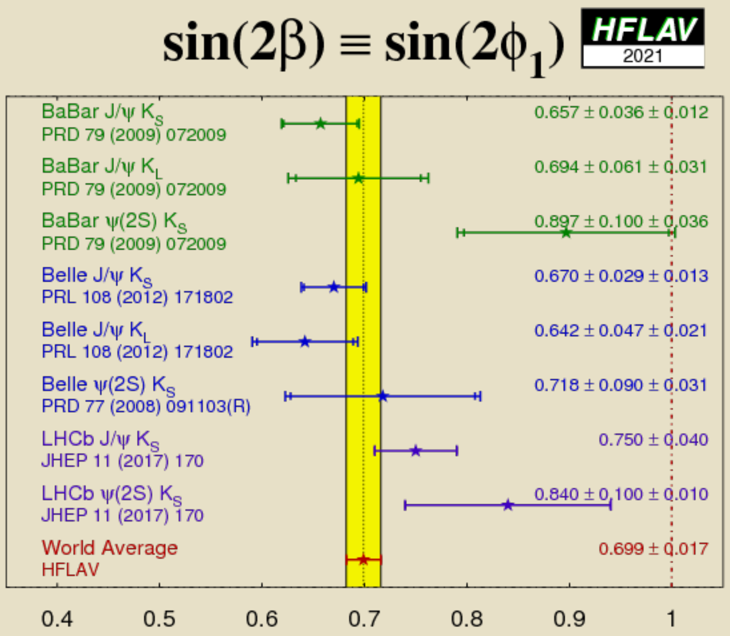
Likelihood with 60 input observables

- including 15 auxiliary inputs (D-decay)
- 16 free parameters


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
V_ub
α
γ
ε_K
CKM fitter
Summer 23
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

CKM ANGLES

$\sin(2\beta)$



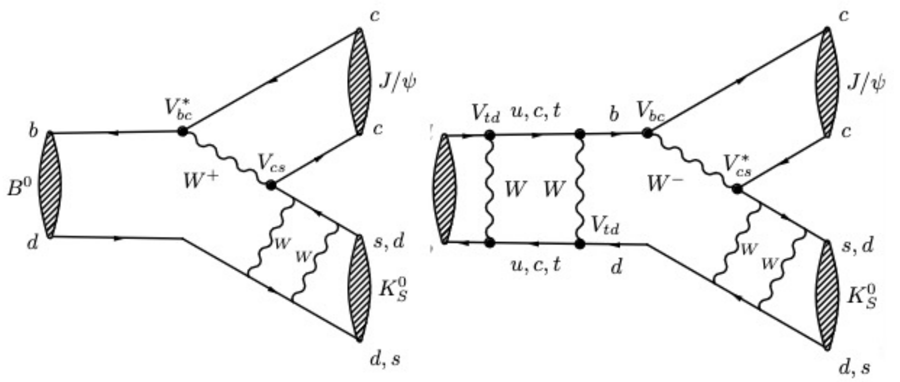
$$S \equiv -\eta_{CP}\sin(2\beta) = 0.699 \pm 0.017$$

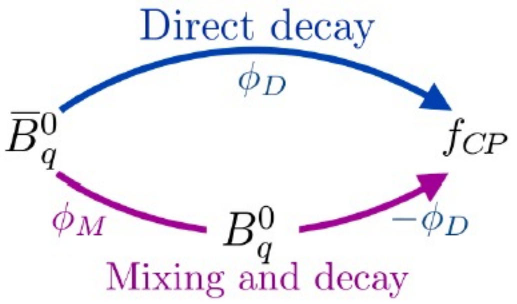
Pure CP-even $\eta_{CP} = +1$ [HFLAV 2021]

$$S^{SM} \equiv \sin(2\beta) = 0.731^{+0.029}_{-0.016}$$

[CKMfitter]

- Golden channel $\boldsymbol{B^0 \to J/\psi K^0_s}$





No CPV in mixing $|q/p| = 1$

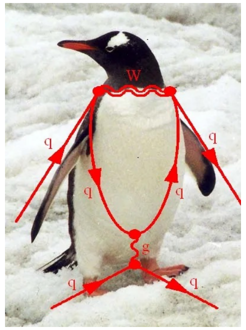
CPV in the decay $|B\rangle \to |f\rangle \neq |\bar{B}\rangle \to |\bar{f}\rangle$

$$A_{CP,f}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{S_f \sin(\Delta m_{d(s)}t) - C_f \cos(\Delta m_{d(s)}t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2}t\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_{d(s)}}{2}t\right)}$$

CPV in the interference of mixing and decay

$\Delta\Gamma_d = 0$ in this analysis

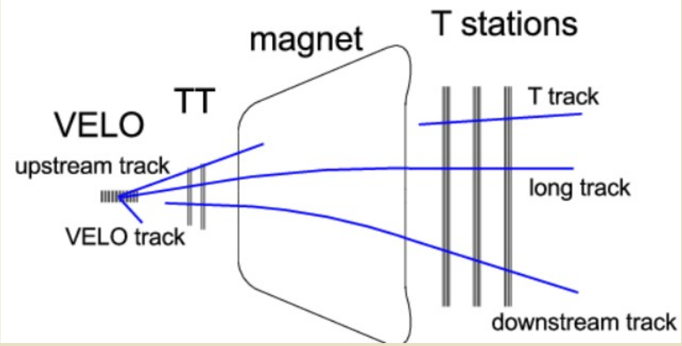
- Ruled by B^0 mixing and tree-level $b \to c\bar{c}s$ transitions
  - Penguin contributions are measured to be negligible



State of the art of $\sin(2\beta)$ in LHCb

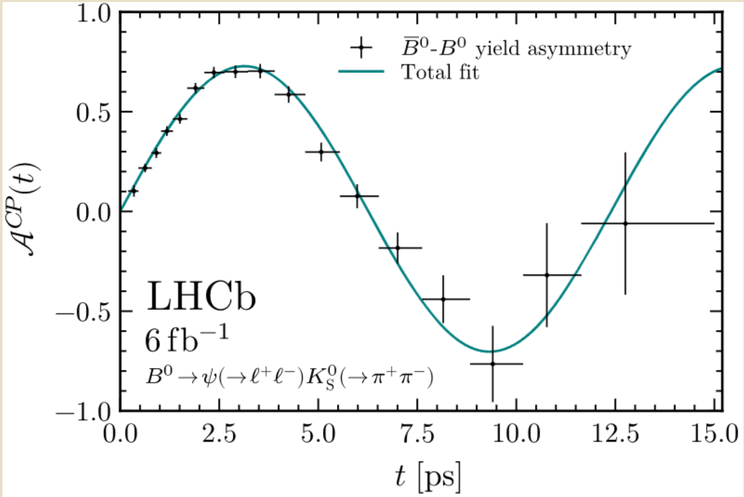
- **LHCb measurement using all Run 2 data + combination with Run 1**
- Analysed **all charmonium**: $J/\psi \to \mu\mu, ee$ and $\psi(2S) \to \mu\mu$
- Four $K_S^0 \to \pi^+\pi^-$ reconstruction categories: LL, DD, **LD, UL**
- Flavour tagging calibrated with $B^+ \to \psi K^+$ and $B^0 \to \psi K^{*0}$

used for the first time in TD measurements (~13% of signal yields)



Channel	# of events	$\varepsilon_{tag}[\%]$
$B^0 \to J/\psi(\to \mu\mu)K_S^0$	$\sim 300k$	4.661 ± 0.013
$B^0 \to J/\psi(\to ee)K_S^0$	$\sim 40k$	6.462 ± 0.032
$B^0 \to \psi(2S)(\to \mu\mu)K_S^0$	$\sim 20k$	4.59 ± 0.04

[PRL 132, 021801 (2024)]



- **Run 2 simultaneous fit** to all channels
  - $\boldsymbol{S = 0.717 \pm 0.013 \pm 0.008}$
  - $\mathbf{C = 0.008 \pm 012 \ \pm 0.003}$

More precise than WA!!

- All ψ modes are consistent. **Final LHCb Run 1 and Run 2 result**
  - $\boldsymbol{S = 0.724 \pm 0.014}$ (stat + sys) $\sim \sin(2\beta)$
  - $\mathbf{C = 0.004 \pm 0.012}$ (stat + sys) ~ 0

In agreement with predictions by CKMFitter and UTFit groups.

[PRD 91, 073007 (2015)] [JHEP 10, 081 (2006)]

State of the art of $\sin(2\phi_1/\beta)$ in Belle II

- **Belle II Run I analysis of $B^0 \to J/\psi K_s^0$ decays**
- Updated results using a **new algorithm that exploits a graph-neural-network, GFlaT**, used to determine the flavour of the B meson
- **Performance evaluated on data** using self-tagging $B^0 \to D^{(*)-}\pi^+$ decays (+18% relative wrt category based FT)

$\varepsilon_{tag}(\text{CB}) = (31.7 \pm 0.5 \pm 0.4)$ %
$\varepsilon_{tag}(\text{GFlaT}) = $ **$(37.4 \pm 0.4 \pm 0.3)$ %**

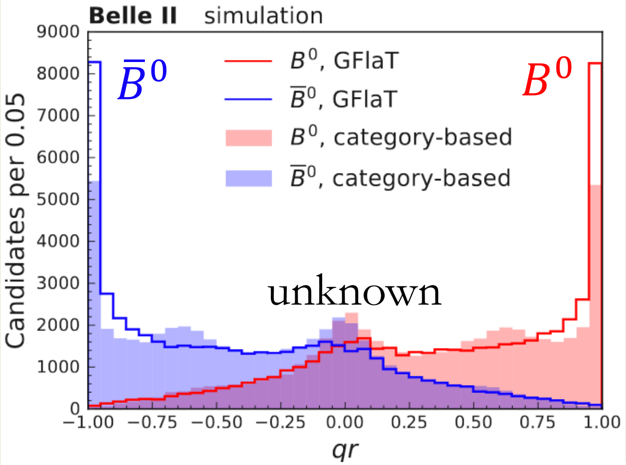
Uses information from all charged final-state particles (25 variables per track) and the relation between them.

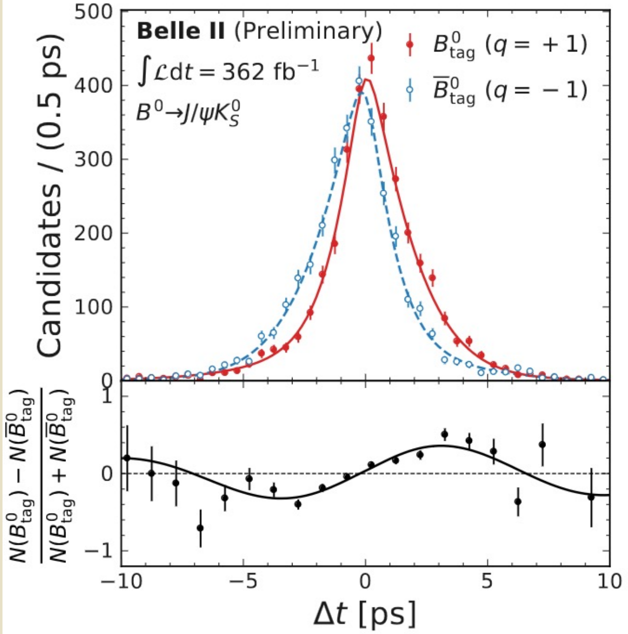
- Uses: J/ψ → $\mu\mu$ and J/ψ → ee
- Fit $\Delta E \equiv E - E_{beam}$ distribution to subtract background
- Fit background-subtracted Δt distribution to extract CPV parameters

Final Belle II Run I result:

- $S = 0.724 \pm 0.035 \pm 0.014$ ~ $\sin(2\beta)$
- $C = -0.035 \pm 0.026 \pm 0.013$ ~0

Statistical uncertainties 8% smaller than with category-based Flavour Taggers.





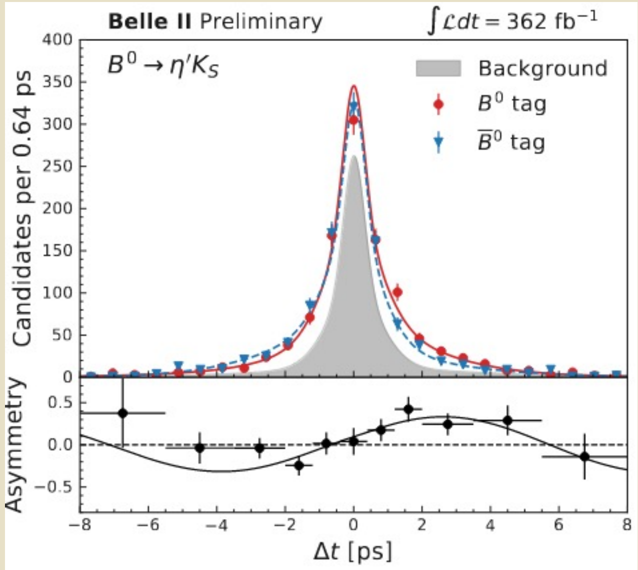
[ArXiv:2402.17260] Accepted by PRD

Time-dependent CPV in charmless B decays

Run I $B \to \eta' K_S^0$

- $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$
- $\eta' \to \rho(\to \pi^+\pi^-)\gamma$
- High BF, theoretically clean
  - 829 ± 35 signal events

[ArXiv:2402. 03713]

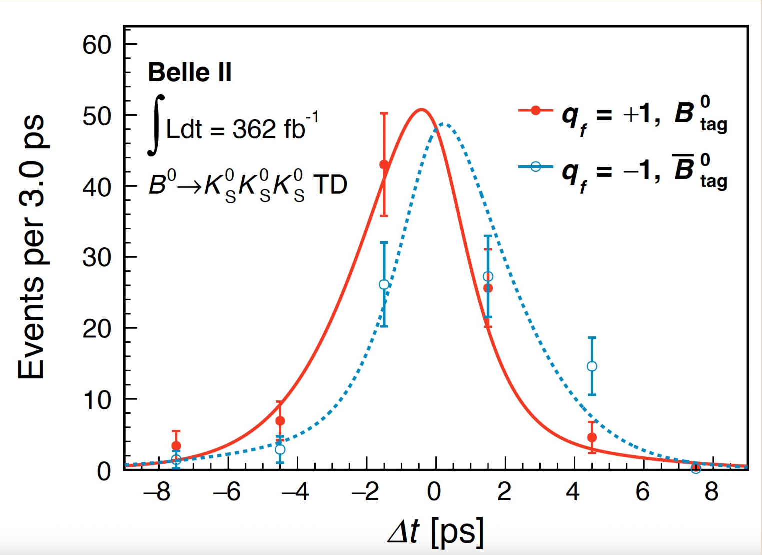


$S = +0.67 \pm 0.10 \pm 0.04$
$C = -0.19 \pm 0.08 \pm 0.03$

Run I $B \to K_S^0 K_S^0 K_S^0$

- Challenge: no prompt tracks from B vertex
- Use $K_S^0 \to \pi^+\pi^-$ extrapolated to interaction point
  - 158^{+14}_{-13} signal events

[ArXiv:2403.02590]

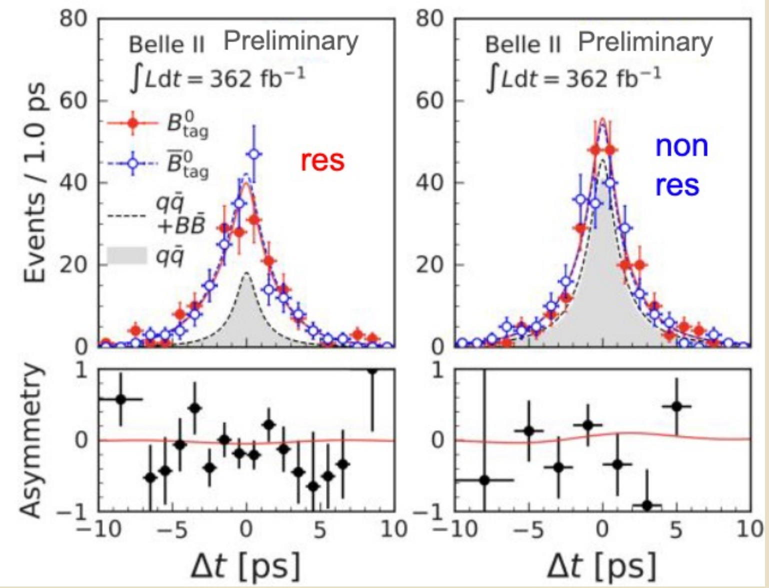


$-1 < S < -0.72$
$-0.29 < C < 0.14$

Run I $B \to K_S^0 \pi^0 \gamma$

- Vertex from $K_S^0 \to \pi^+\pi^-$ and IP constraint
- Expected to have small/none mixing ind. CPV

[See S. Lacaprara FPCP 2024]

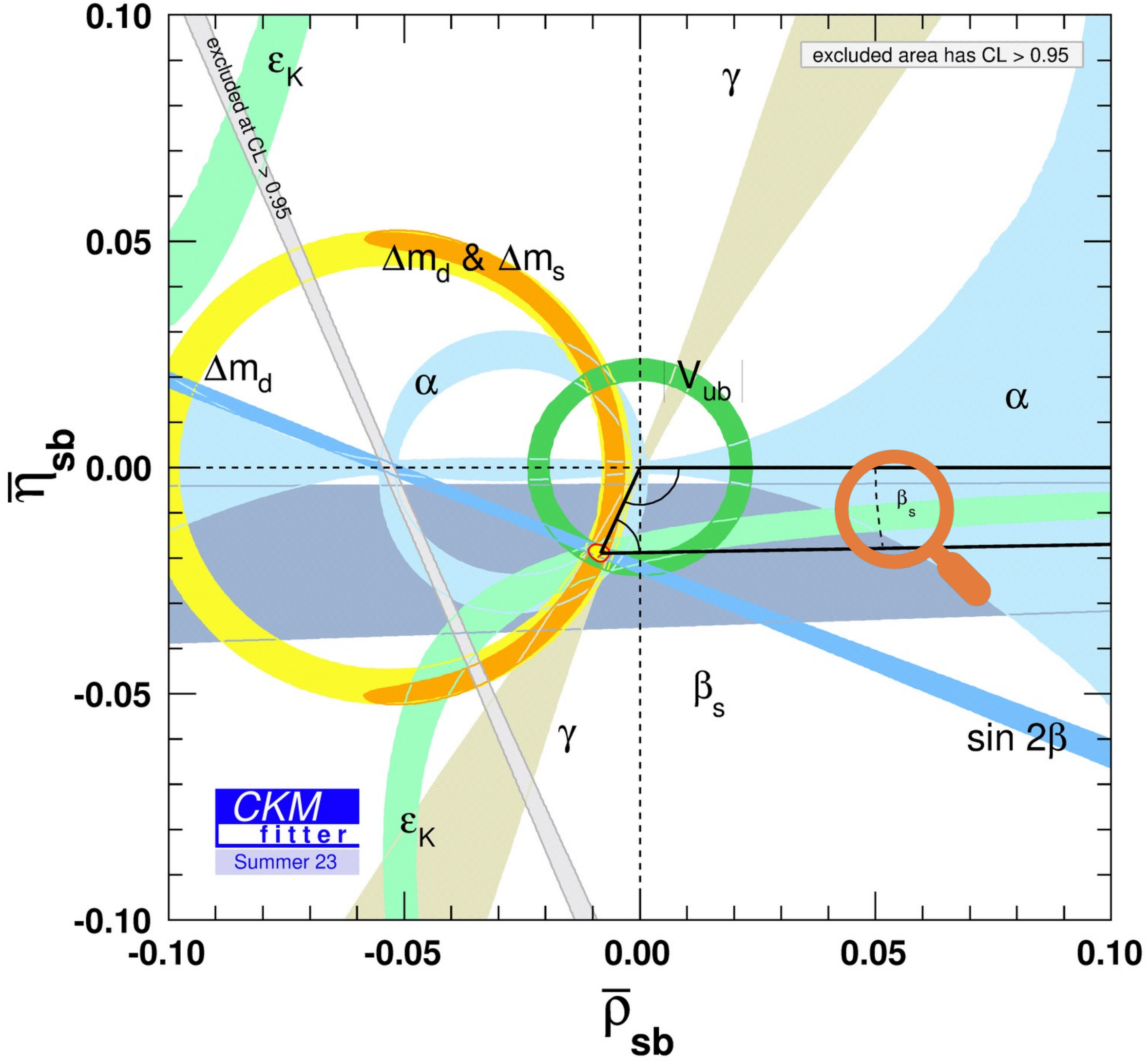


$S = 0.00^{+0.27}_{-0.26}\ ^{+0.03}_{-0.04}$
$C = 0.10 \pm 0.13 \pm 0.03$

Resonant $K^{*0}(\to K_S^0\pi^0)\gamma$

$S = 0.04^{+0.45}_{-0.44} \pm 0.10$
$C = -0.06 \pm 0.25 \pm 0.07$

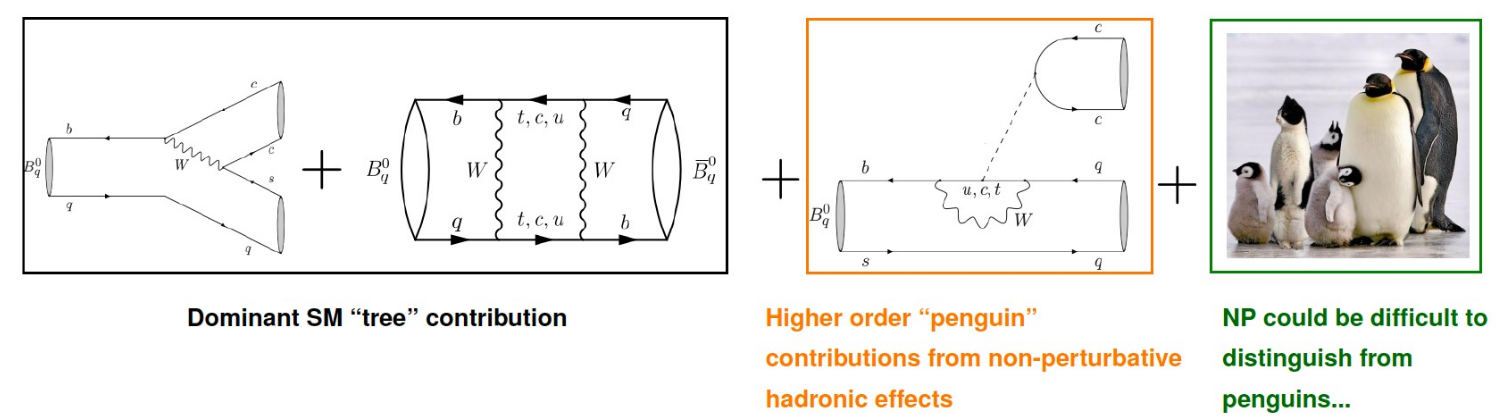
Non Resonant $K_S^0\pi^0\gamma$

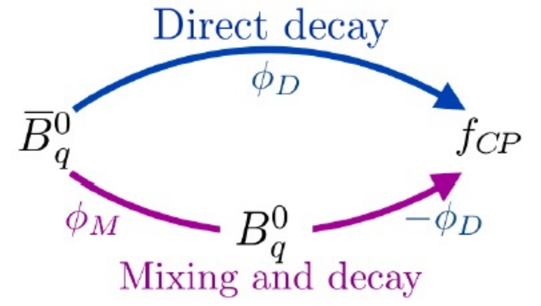


0.10
0.05
0.00
-0.05
-0.10
-0.10
-0.05
0.00
0.05
0.10
$\bar{\eta}_{sb}$
$\bar{\rho}_{sb}$
excluded area has CL > 0.95
excluded at CL > 0.95
ε_K
γ
Δm_d & Δm_s
Δm_d
α
V_{ub}
α
β_s
β_s
γ
sin 2β
ε_K
CKM fitter
Summer 23

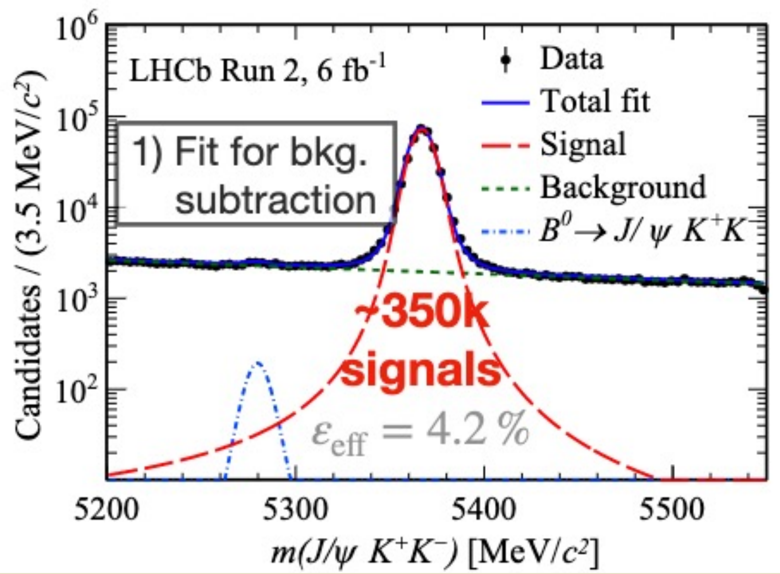
CKM ANGLES

CP violation in B mixing and decay, φ_s





[PRL 132 (2024) 051802, 2308.01468]



CP-violating phase arising from interference between mixing and decay.

- Precisely predicted by the SM: $\boldsymbol{\varphi_s^{SM} = -2\beta_s = -36.8^{+0.9}_{-0.6}}$ **mrad**

[CKMFitter]

- **Golden channel** exploited by LHCb, ATLAS, CMS: $B_s^0 \to J/\psi\phi$
- LHCb also measured many other channels

- Full Run 2 analysis of $B_s^0 \to J/\psi KK$ with KK pair in the vicinity of ϕ;
- Angular analysis is needed to disentangle CP-even and CP-odd contributions, FT calibrated with $B^+ \to J/\psi K^+$ and $B_s^0 \to D_s^- \pi^+$, ε^{eff}=4%

Run 2 φ_s result from LHCb

Using full Run 2 $B_s^0 \to J/\psi KK$

$$\varphi_s = -0.039 \pm 0.022 \pm 0.006 \text{ rad}$$
$$|\lambda| = 1.001 \pm 0.011 \pm 0.005$$
$$\Gamma_s - \Gamma_d = 0.0056^{+0.0013}_{-0.0015} \pm 0.0014 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024 \text{ ps}^{-1}$$

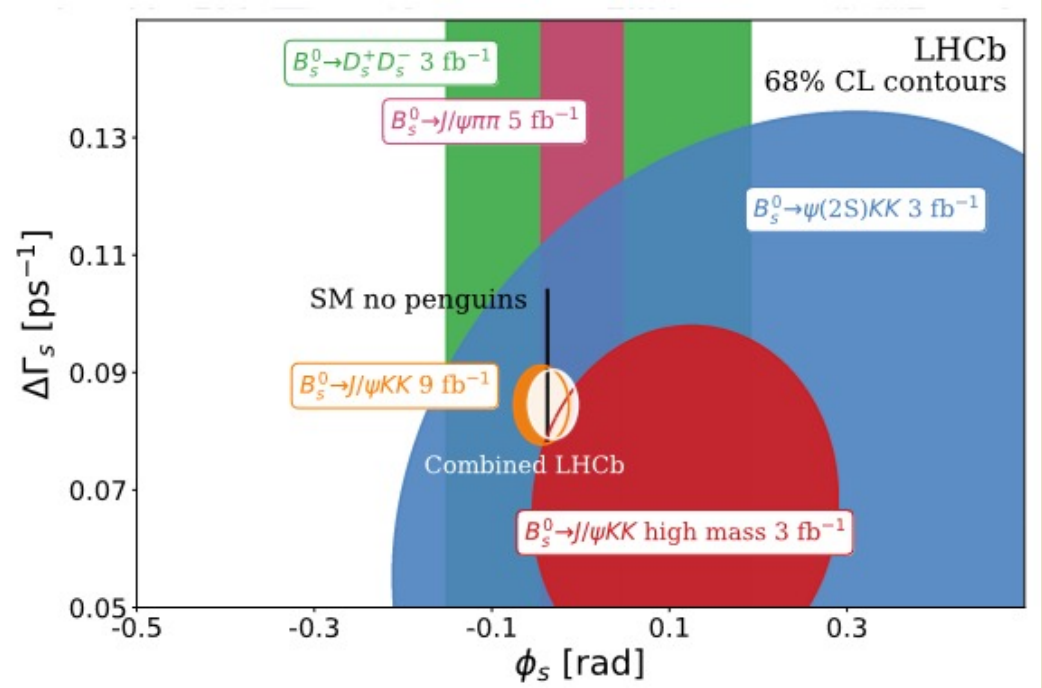
[PRL 132 (2024) 051802, 2308.01468]

φ_s consistent with Standard Model

φ_s 1.7 σ away from 0
consistent with **no CPV in interference**

|λ|, which measures CPV in decay, ~ 1
consistent with no direct CPV

$\Gamma_s - \Gamma_d$ consistent with HQE prediction
[JHEP12 (2017) 068]



Run 1 + Run 2

$$\varphi_s = -0.044 \pm 0.020 \text{ rad}$$
$$|\lambda| = 0.990 \pm 0.010 \text{ rad}$$

Run 2 φ_s result from LHCb

Using full Run 2 B_s^0

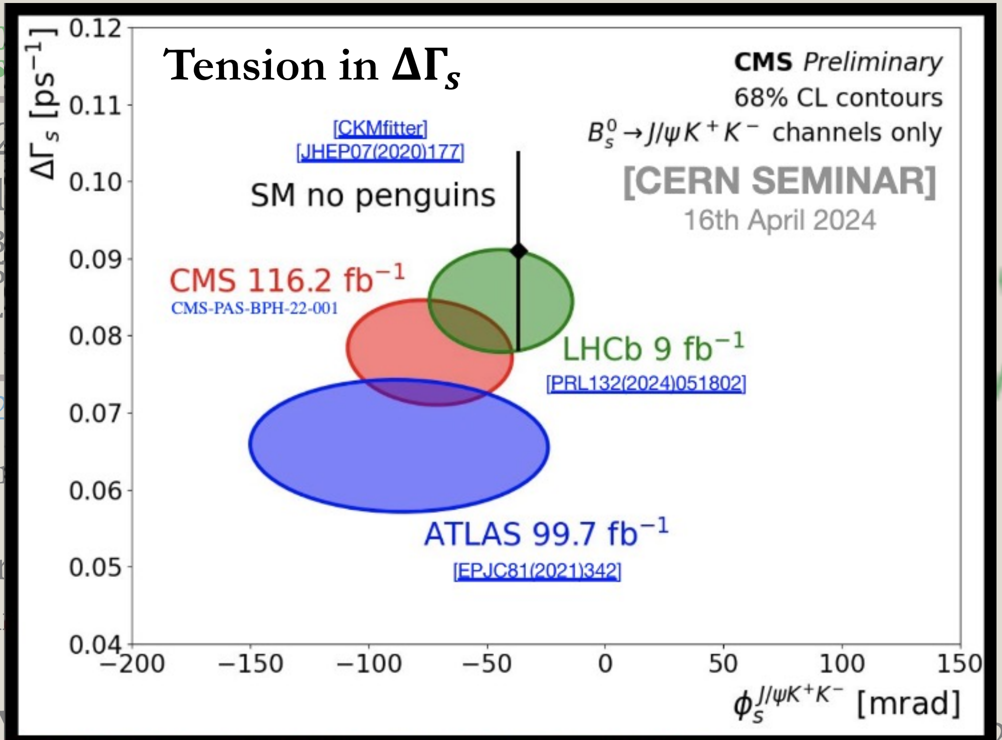
$\varphi_s = -0.039 \pm 0.022$
$|\lambda| = 1.001 \pm 0.01$
$\Gamma_s - \Gamma_d = 0.0056^{+0.0013}_{-0.0015}$
$\Delta\Gamma_s = 0.0845 \pm 0.0044$

[PRL 132

$\boldsymbol{\varphi_s}$ **consistent with Sta**

$\boldsymbol{\varphi_s}$ **1.7 σ away f**
consistent with **no CPV i**

|λ| consistent
consistent with no direct CPV



Run 2 $B_s^0 \to J/\psi KK$

Run 1 + Run 2

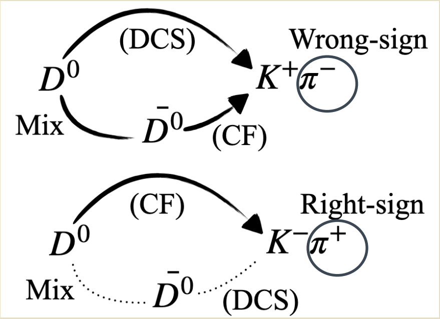
$\varphi_s = -0.044 \pm 0.020$ rad
$|\lambda| = 0.990 \pm 0.010$ rad

$\boldsymbol{\Gamma_s - \Gamma_d}$ **consistent with HQE prediction**

[JHEP12 (2017) 068]

Mixing and CPV in charm: $D^0 \to K^+\pi^-$

- Charm is the only up-type quark that mixes and allows precise CPV measurements.
- Tagging D^0's from $D^{*\pm} \to D^0\pi^\pm$ via the π charge.
- To measure the CPV fit time-dependent WS/RS ratios



$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\bar{D}^0(t) \to K^+\pi^-)} \qquad R^-_{K\pi}(t) \equiv \frac{\Gamma(\bar{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$

Since oscillating parameters $x_{12}, y_{12} \ll 1$

$$R^\pm_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\frac{t}{\tau_{D^0}} + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

CP-violating parameters

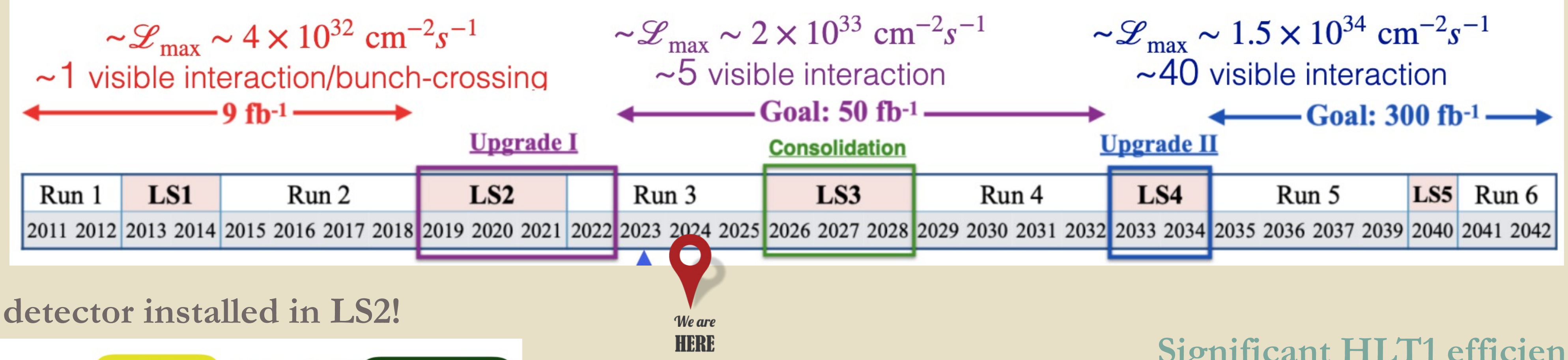
mixing parameters

	This result Run 1 + 2
$R_{K\pi}$	$(342.7 \pm 1.9)\times10^{-5}$
$c_{K\pi}$	$(52.8 \pm 3.3)\times10^{-4}$
$c'_{K\pi}$	$(12.0 \pm 3.5)\times10^{-6}$
$A_{K\pi}$	$(-6.6 \pm 5.7)\times10^{-3}$
$\Delta c_{K\pi}$	$(2.0 \pm 3.4)\times10^{-4}$
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6)\times10^{-6}$

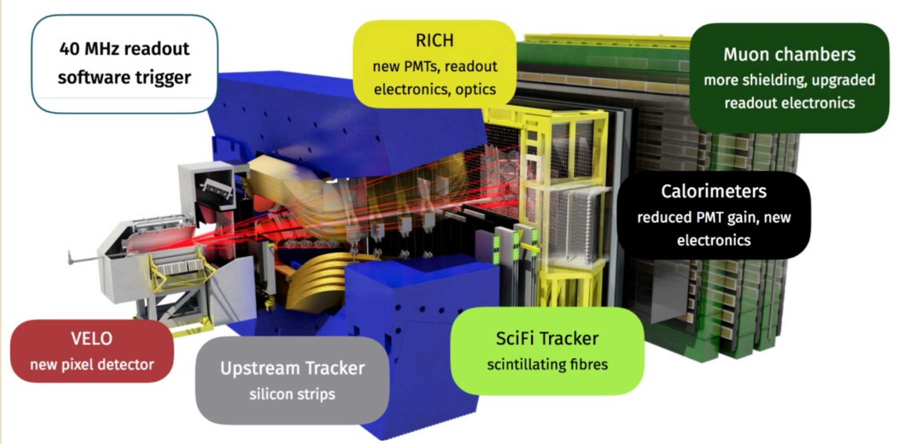
- Mixing observables: first evidence for a significant quadratic term
- CPV observables: no evidence of CPV neither in decay, mixing nor interference
- 40% improvement in precision wrt the previous best result

CERN Seminar 26/03/2024

The experimental scenario, this is not the end!

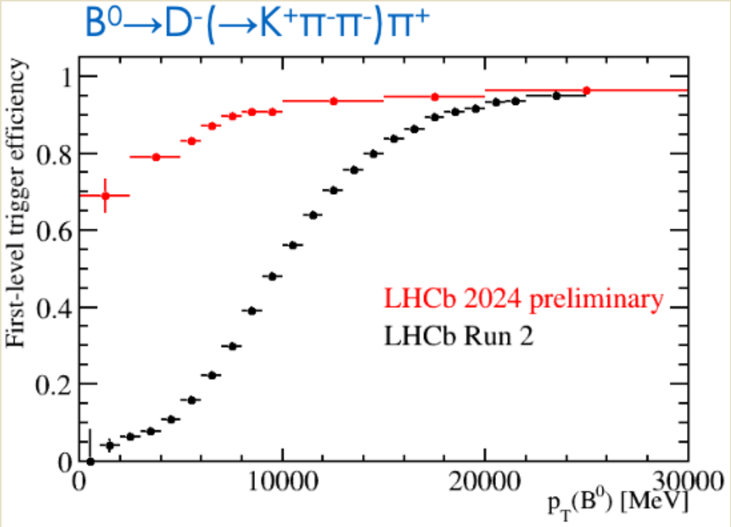


Brand new detector installed in LS2!



- Tracking system completely replaced
- RICH: new photo-detectors + new optics
- New luminometer (PLUME), refurbished Beam Conditions Monitor (BCM)
- **Readout at 40MHz**: full software trigger

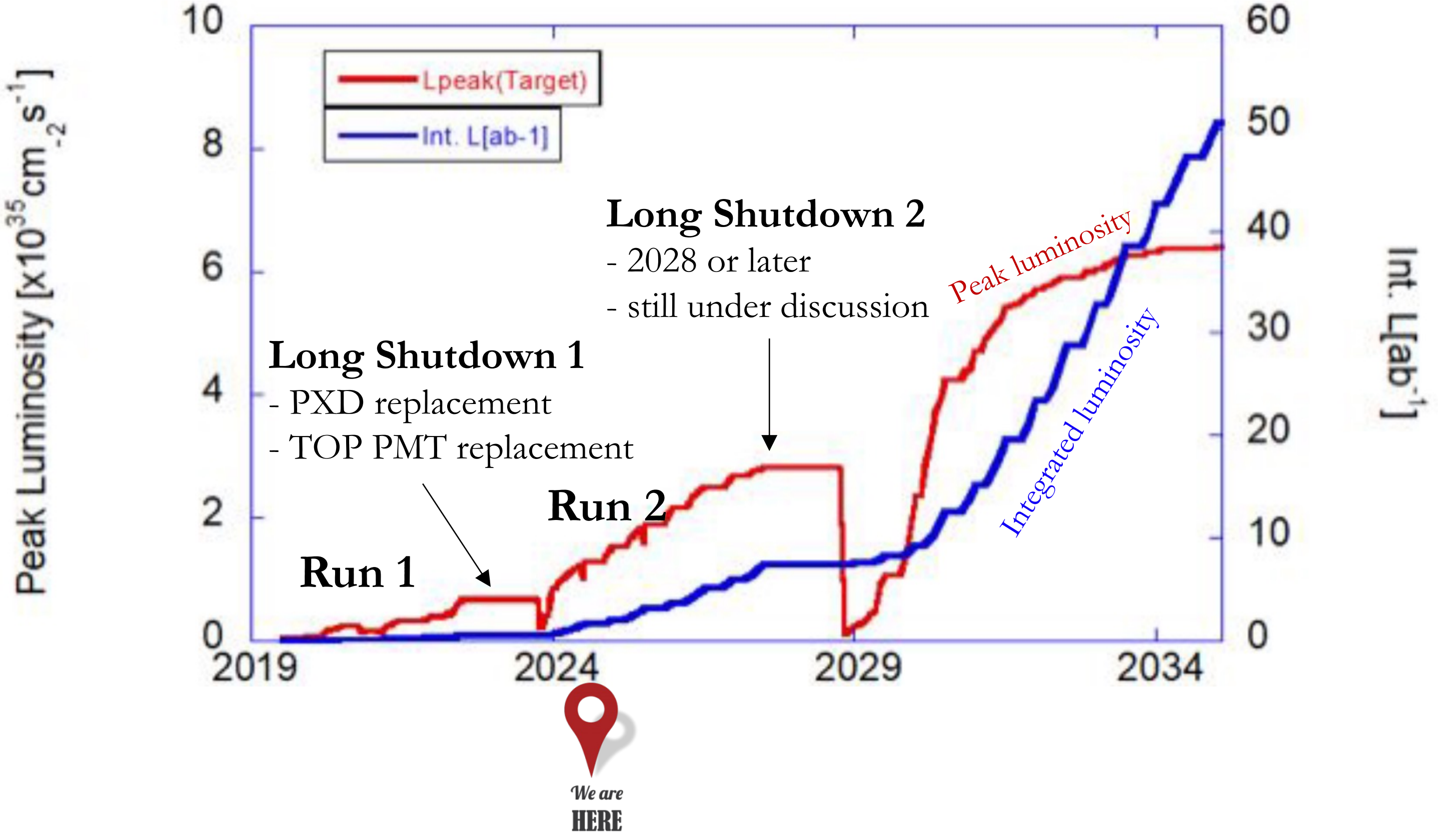
Significant HLT1 efficiency improvement wrt Run 2!



[LHCb-FIGURE-2024-006]

- **First data @13.6 TeV** the 5th of July 22!
- **5x instantaneous lumi** $2\times10^{33}\text{cm}^{-2}\text{s}^{-1}$
- Average **# of visible pp collisions μ=5.5**

2024 is the first opportunity to run at nominal conditions!



[PTEP (2019) 123C01]

THE EXPERIMENTAL SCENARIO, THIS IS NOT THE END!

Belle II goal:

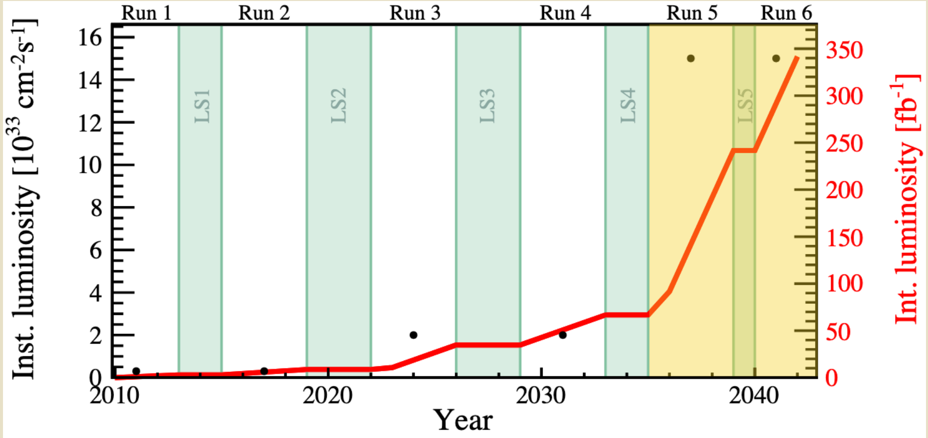
- $L=6x10^{35}$ cm^{-2} s^{-1}
- L_{int}~50 ab $^{-1}$

- **Run II data taking just started in January 2024!**

- **Waiting to enter 10^{35} cm^{-2} s^{-1} luminosity era.**

Looking further into the future

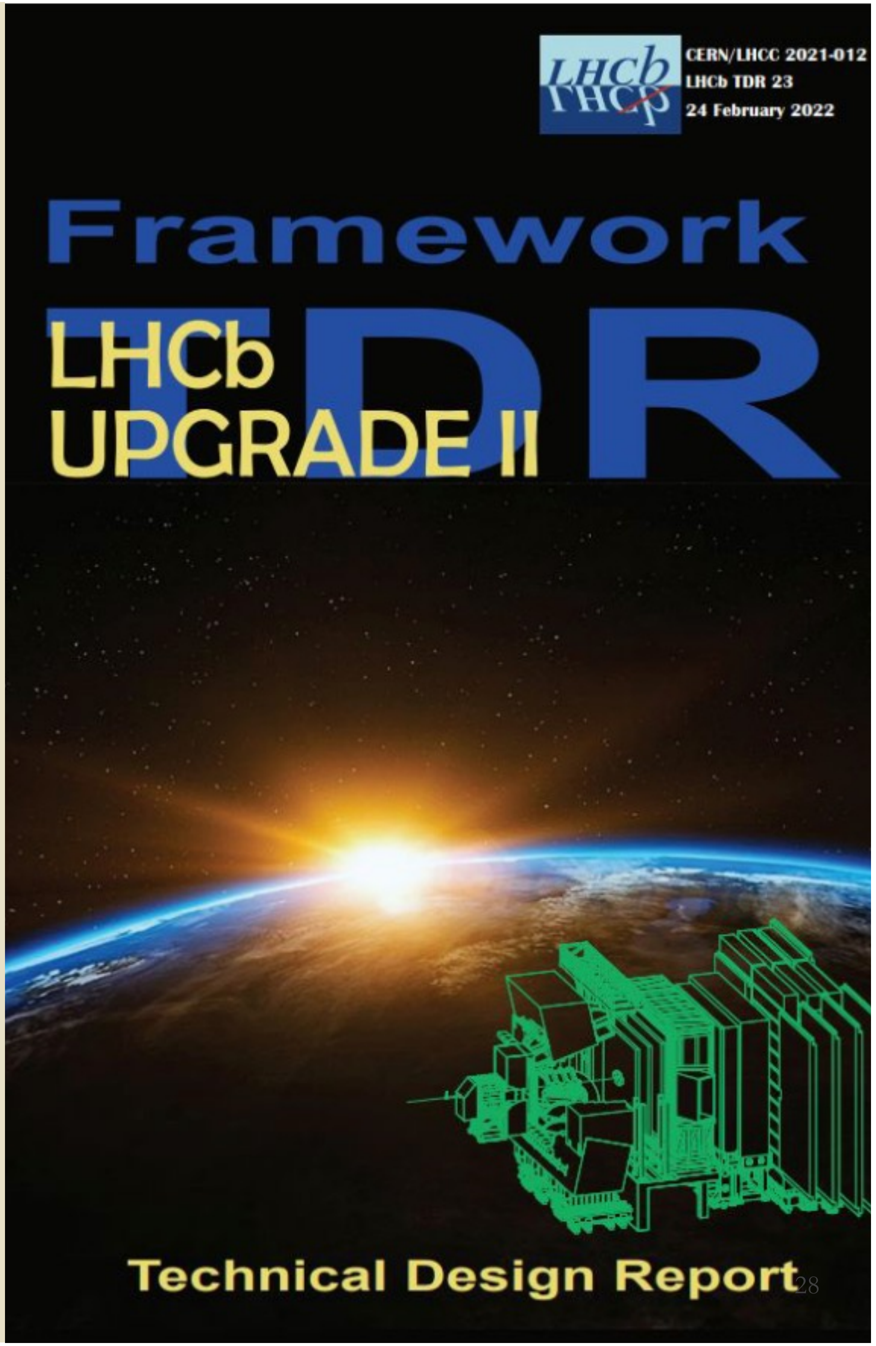
LHCb in Run 5&6?



Target: ~300 fb^{-1}

- Pile-up: ~40
- 200 Tb/second data produced
- To keep the same performance in more difficult conditions, **timing will be required** in some sub-detectors
- A lot of R&D on new technologies
- Sub-detector TDRs expected after Run 3

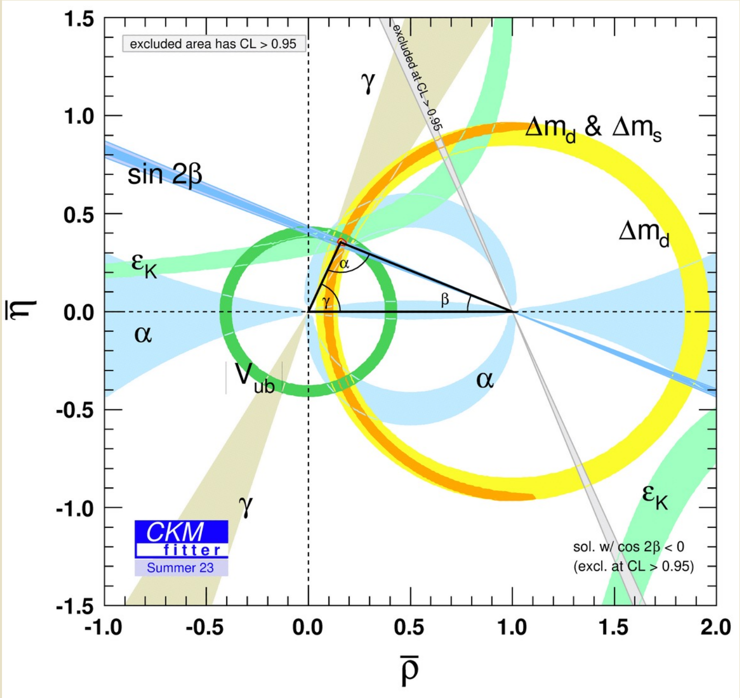
The HL-LHC provides an opportunity for the ultimate heavy-flavour experiment at the LHC!

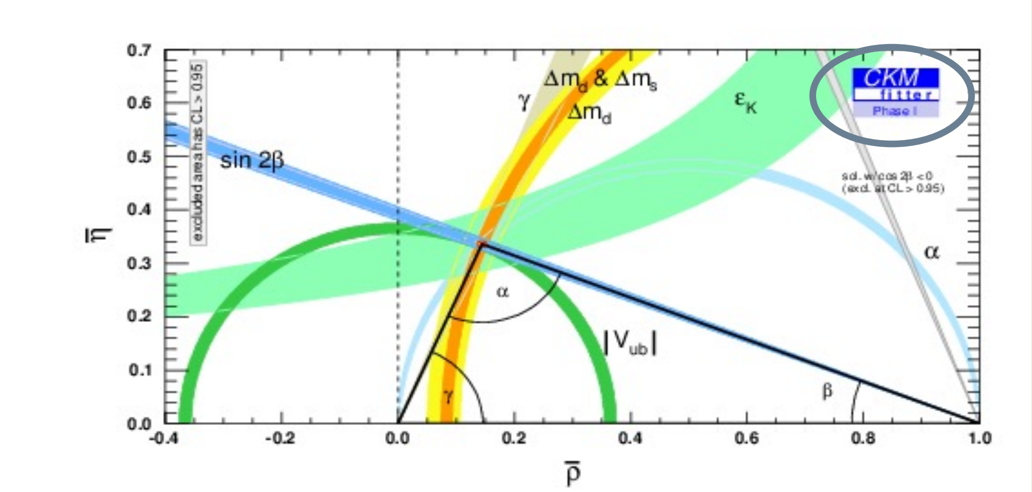


[arXiv:1808.08865]

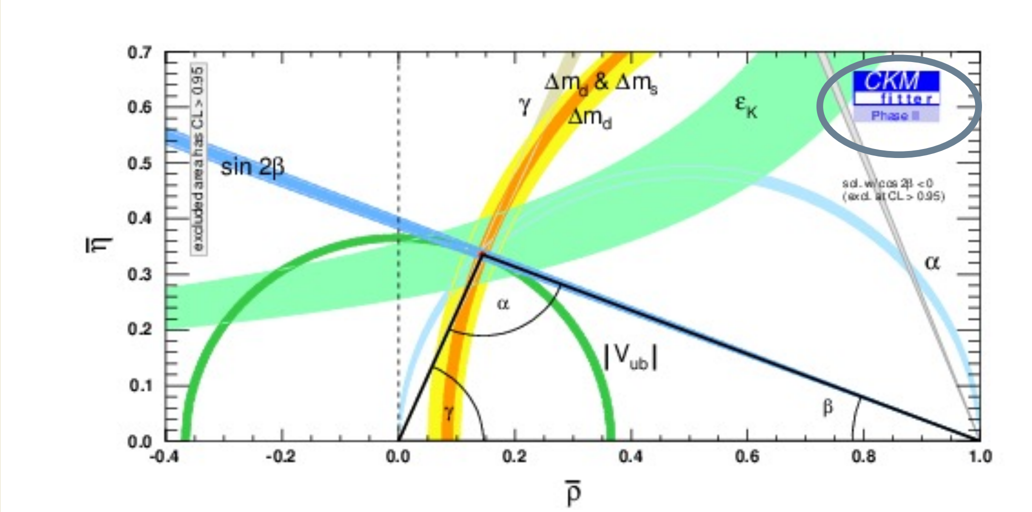
What could be achieved in the future?

NOW





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



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

Conclusions and remarks

- LHCb provides a unique laboratory to study CPV in the up-type quarks

  ➡ See also arXiv:2405.06556 Search for TD-CPV in $D^0 \to \pi^+\pi^-\pi^0$

- Interest in precision flavour measurements is stronger than ever

  ➡ If no direct evidence of NP pops out of the LHC, flavour physics can play a key role.

- Most of the results in the CKM sector in **good agreement with SM**, need to go to even **higher precision**: Run3 of LHCb and Run II of Belle II will permit to acquire a much larger dataset!

- Most of the measurements still limited by statistics.

- **Excellent prospects for precision measurements in the Upgrade II** phase of LHCb.