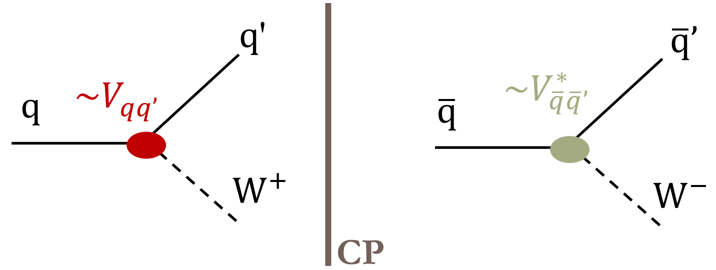
BSM CP VIOLATION SEARCHES AT LHCb

Francesca Dordei, INFN - Cagliari (IT)
On behalf of the LHCb Collaboration

CP2023 Workshop

Les Houches, 13th February 2023



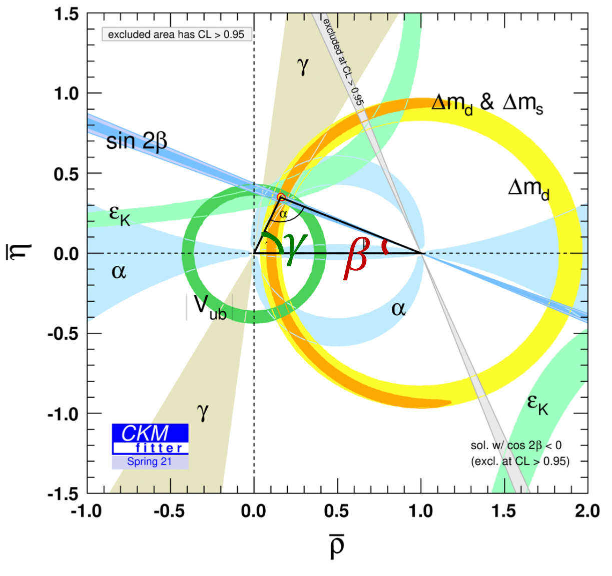
In the SM **quarks can change flavour**

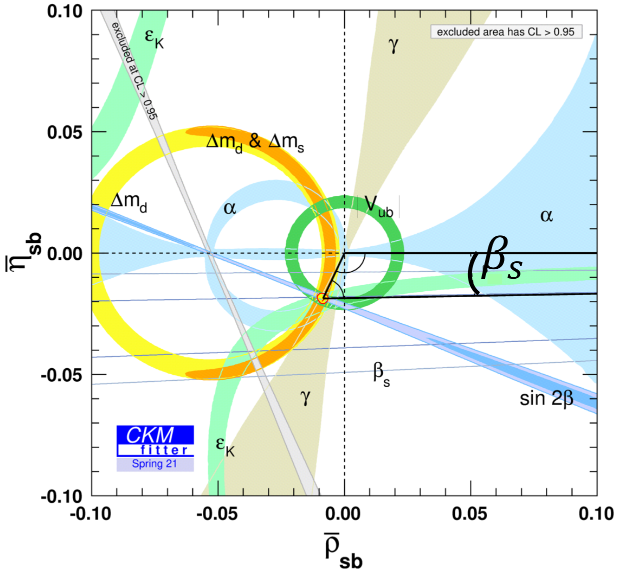
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

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

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





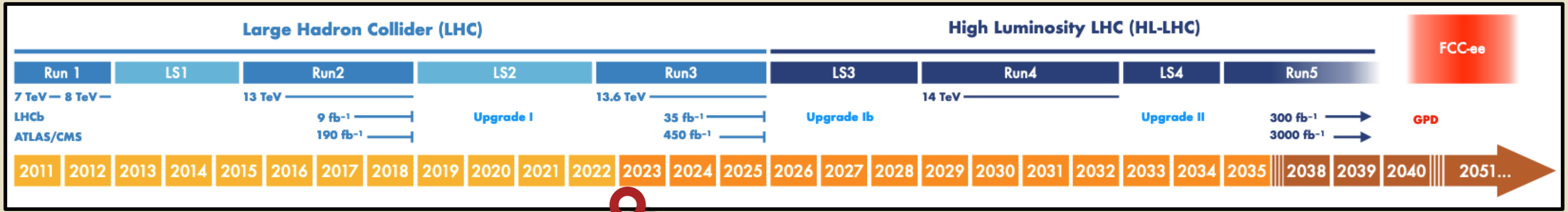
The CKM fit: still room for NP

- 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]
- Interesting **comparison of tree-level vs higher-order observables**. In the latter, unknown particles could contribute.
- Due to the CKM structure the **B system is favourable for CPV studies**. On the contrary, CPV in the Charm sector is predicted to be small since amplitudes are dominated by the first two generations.

The LHCb Collaboration

- About 1400 scientists, engineers and technicians
- 86 different universities and laboratories from 18 countries

The experimental scenario

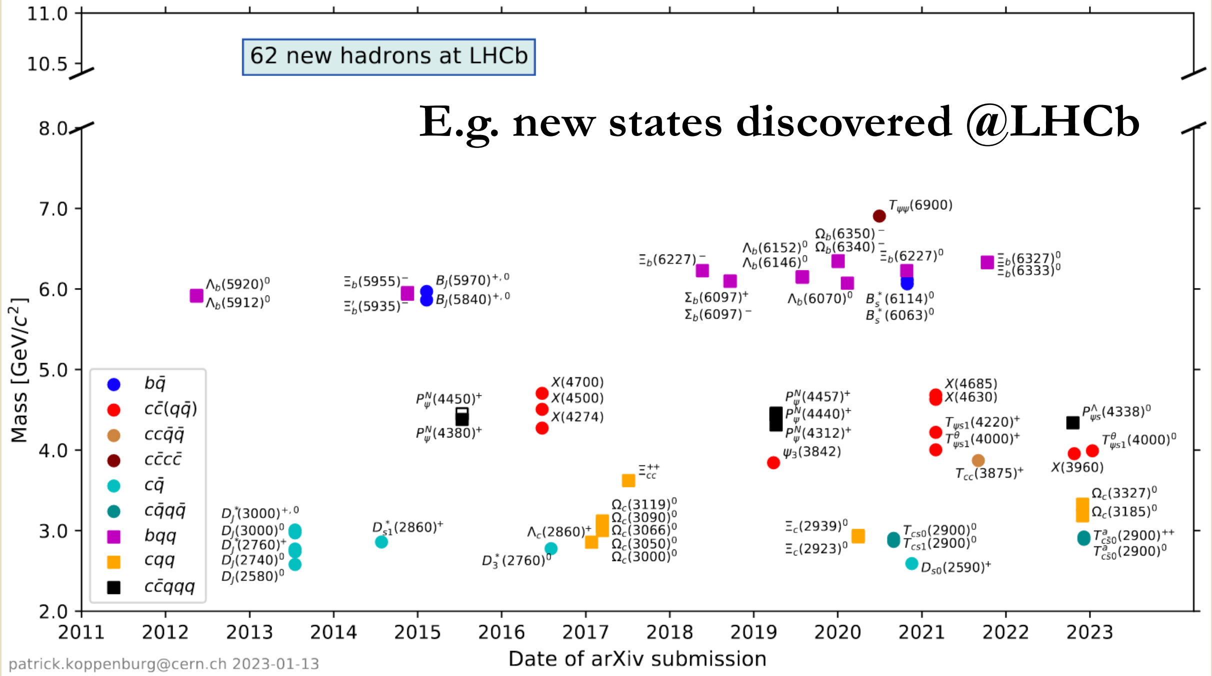


We are HERE

Run 1 + Run 2

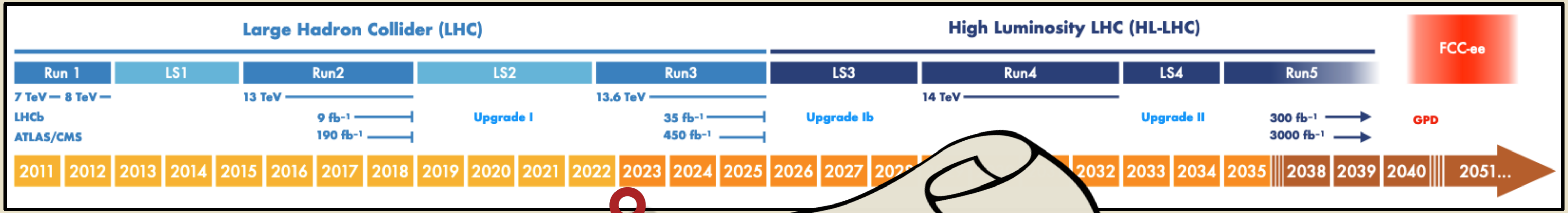
LBCb physics:

- **CP Violation + CKM**
- **Rare decays**
- **Charm** and Strange
- Spectroscopy
- Electroweak and QCD
- Dark sector
- Heavy ions
- Fixed target



Exemplifies the excellence in diversity!

The experimental scenario



Run 1 + Run 2

LBCb physics:

- **CP Violation + CKM**
- **Rare decays**
- **Charm** and Strange
- Spectroscopy
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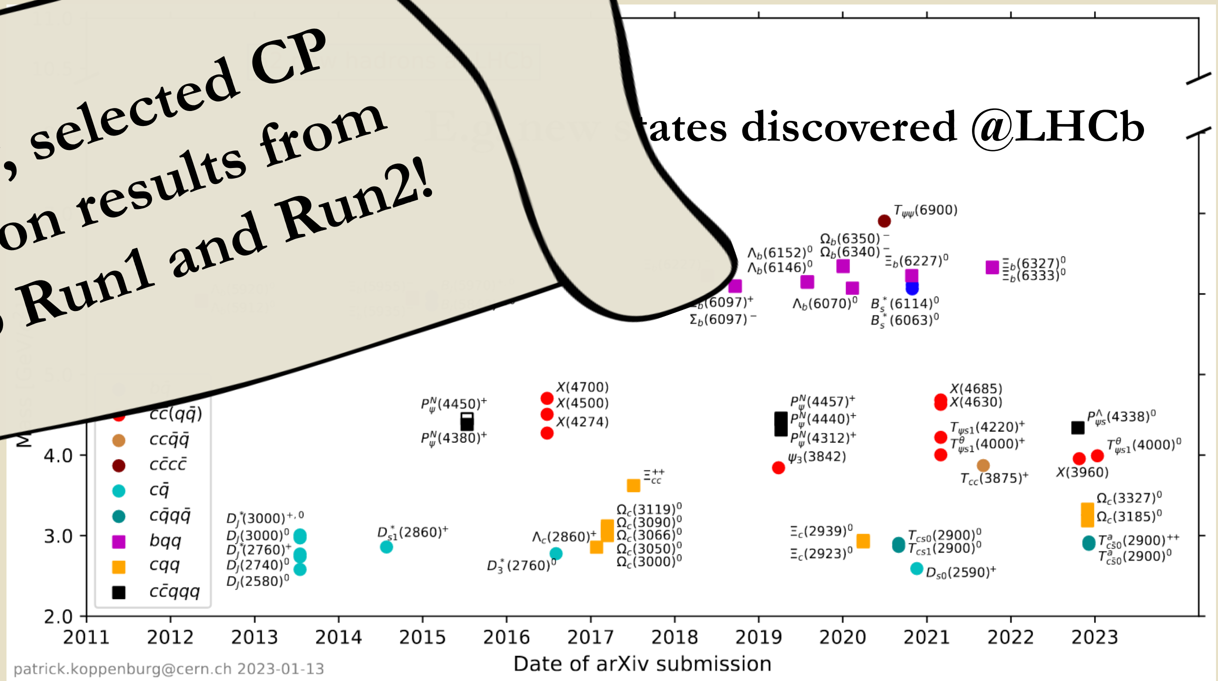
- Dark sector
- Heavy ions
- Fixed target

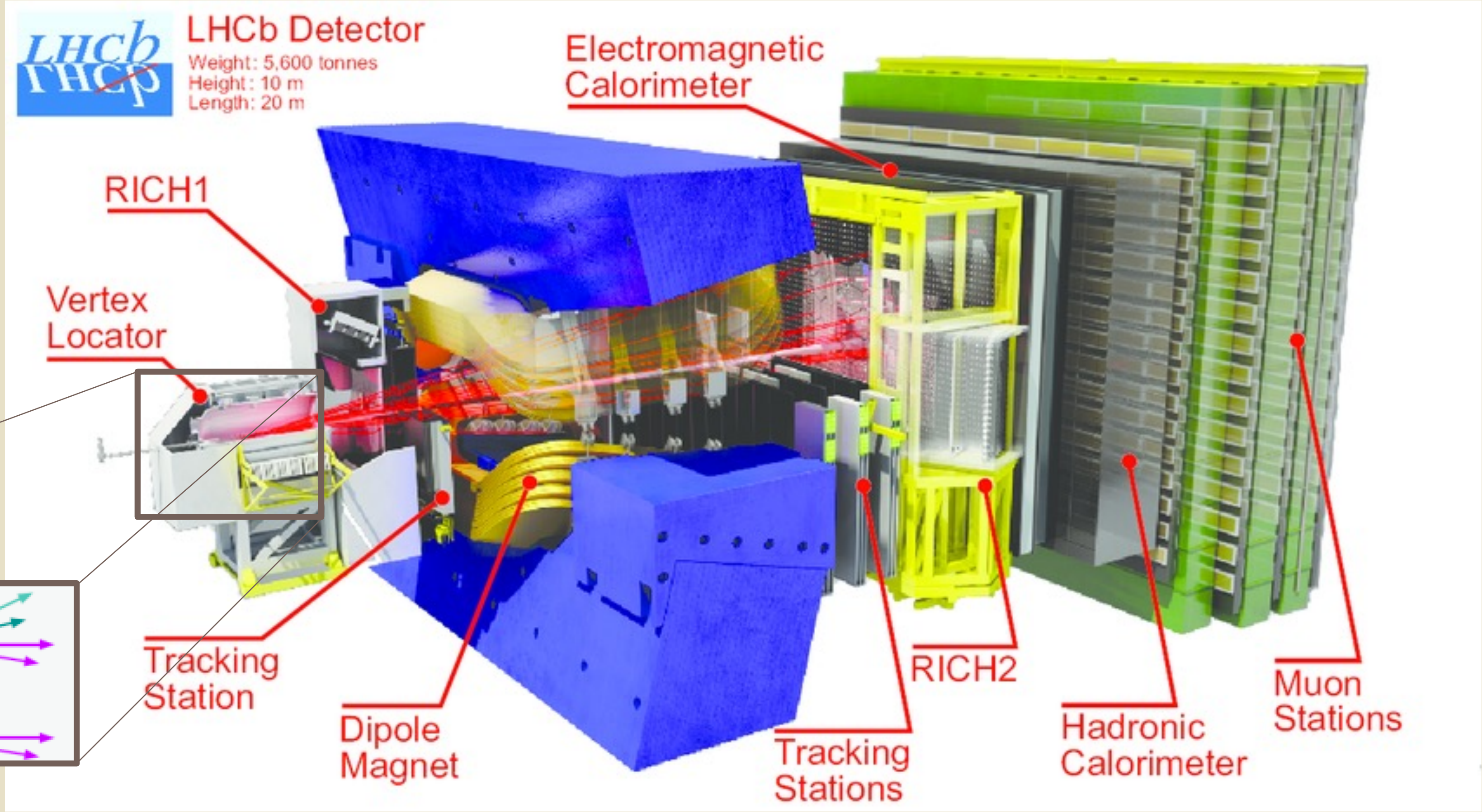
Today, selected CP violation results from LHCb Run1 and Run2!

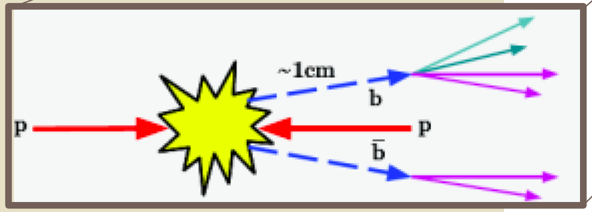


Exemplifies the excellence in diversity!

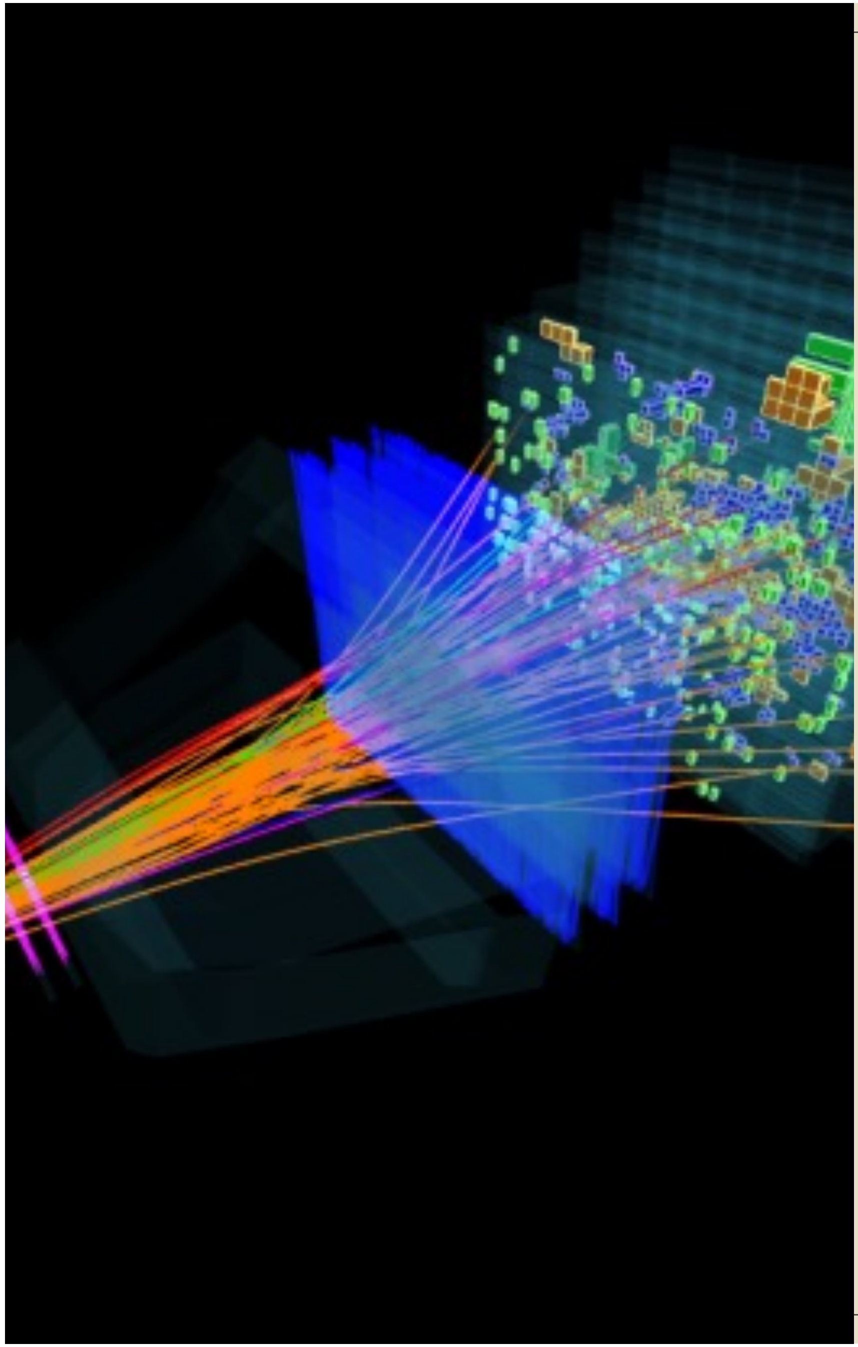
The LHCb detector in Run 1&2 (2011-2018)

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



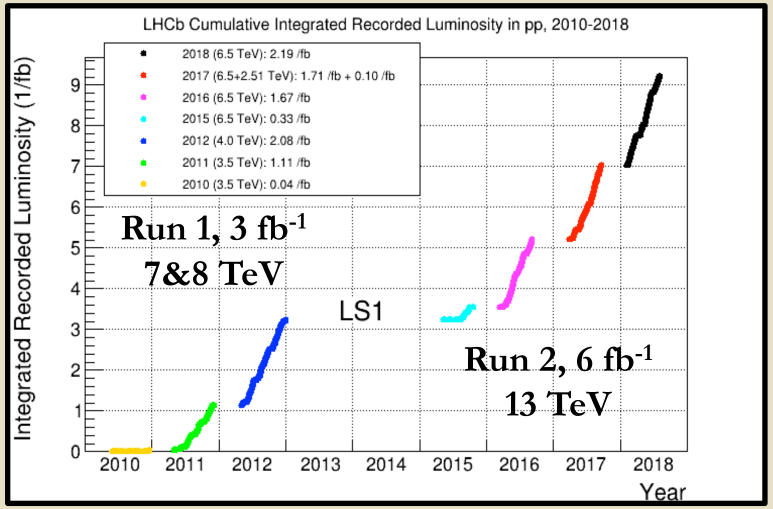


LHCb Detector Performance
Int. J. Mod. Phys. A30 (2015)1530022



Flavour physics @LHCb Run 1-2

- # of Primary Vertices ~ 2
- Decay time resolution: ~45 fs
- IP res: ~20 μm for high p_T
- Highly eff. Particle IDentification
- Excellent primary and secondary vertex reconstruction
  [INT.J.MOD.PHYS A30 (2015) 1530022]



Large number of beauty and charm hadrons within LHCb acceptance:

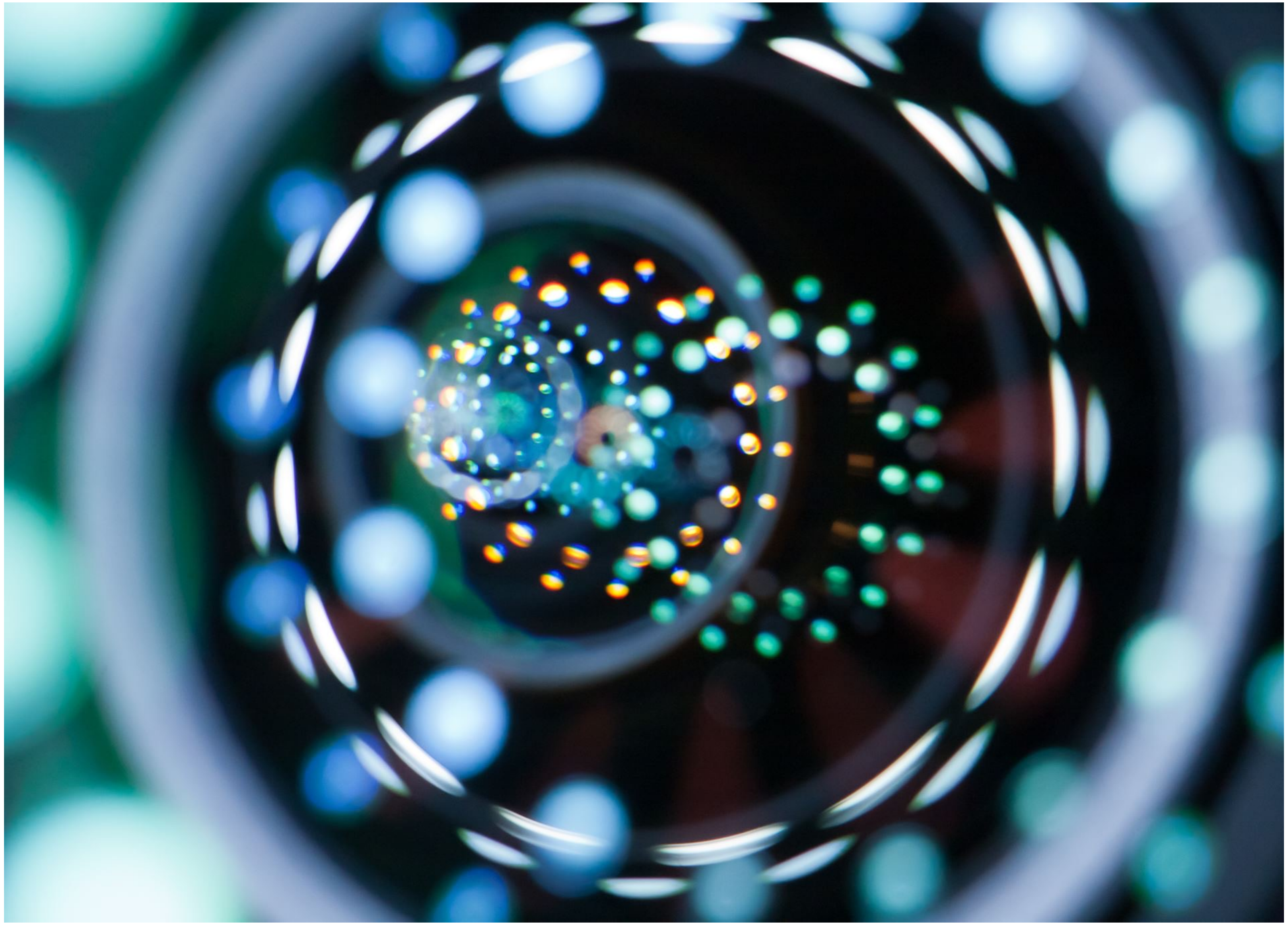
$\sigma_{b\bar{b}}$(7 TeV) = 72.0 ± 0.3 ± 6.8 μb

$\sigma_{b\bar{b}}$(13 TeV) = 144 ± 1 ± 21 μb

[PRL 119 (2017) 169901]

$\sigma_{c\bar{c}}$(7 TeV) = 2369 ± 3 ± 152 ± 118 μb

[JHEP 05 (2017) 074]



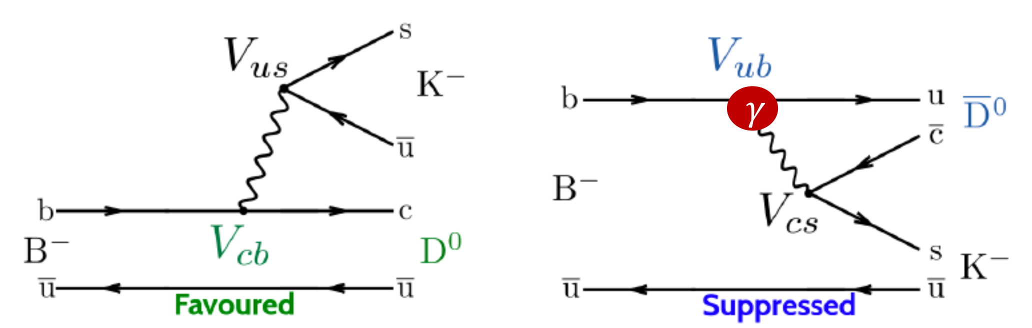
PHYSICS RESULTS

Status of γ

- $\gamma = -\arg(V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$
- TI measurements of γ from B decays mediated only by tree-level transitions provide a **standard candle for the SM** (assuming no new physics in tree-level decays [Phys. Rev. D 92, 033002 (2015)] $\Longrightarrow$ **Theoretically clean** $[\delta\gamma/\gamma] \lesssim \mathcal{O}(10^{-7})$ [JHEP 1401 (2014) 051]
- This can be compared with γ values from B decays involving loop-level transitions, such as $B^0_{d,s} \to hh'$ decays ($h = K, \pi$), to **get signs of NP**

→If the assumption is dropped, Upgrade 2 will allow to search for NP.

◦ Can be measured in the interference between $b \to c$ (favoured) and $b \to u$ (suppressed) transitions, e.g.:



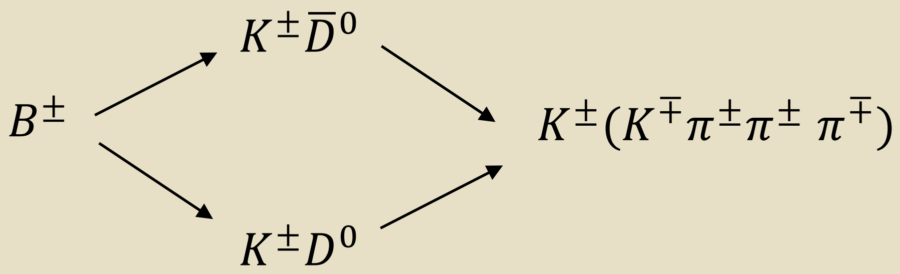
Ratio of magnitudes

$$\frac{A_{sup}}{A_{fav}} = r_B^{Dh} e^{i(\delta_B^{Dh} \pm \gamma)}$$

Strong phase difference, **ext. input from CLEO and BES III**

Small signal yields (BR 10^{-7}), small interference effects (10%). Combining a plethora of independent decay modes is the key to achieve the ultimate precision.

Direct measurement of γ



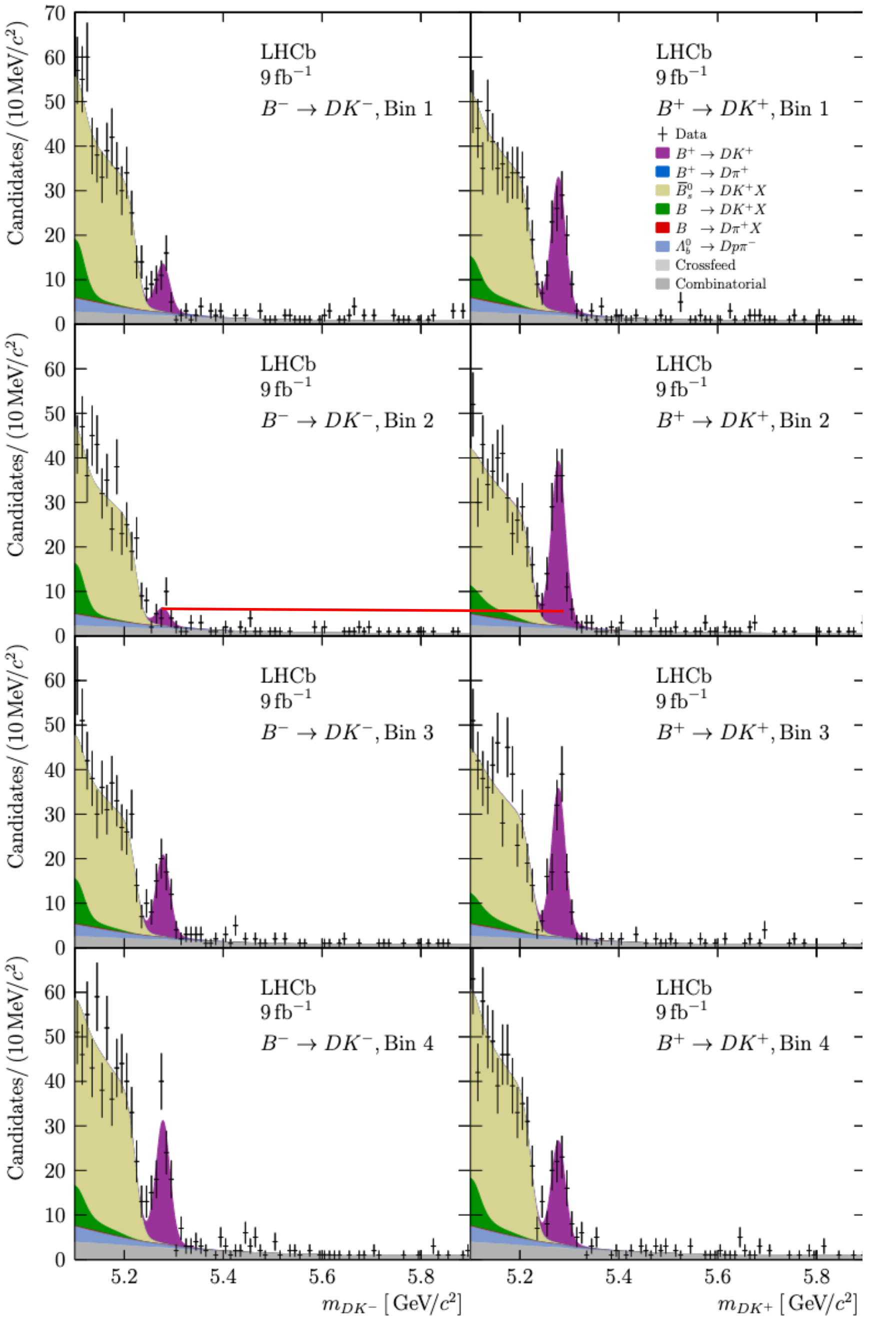
Largest CPV ever measured (~85%)!

- Recent LHCb measurement with the full dataset
- Model-independent determination **in 4 bins of the D decay phase space** with different strong phases
- **Second most precise measurement from a single D mode**

$$\gamma = (54.8^{+6.0}_{-5.8}(\text{stat.})^{+0.6}_{-0.6}(\text{syst.})^{+6.7}_{-4.3}(\text{ext.}))^{\circ}$$

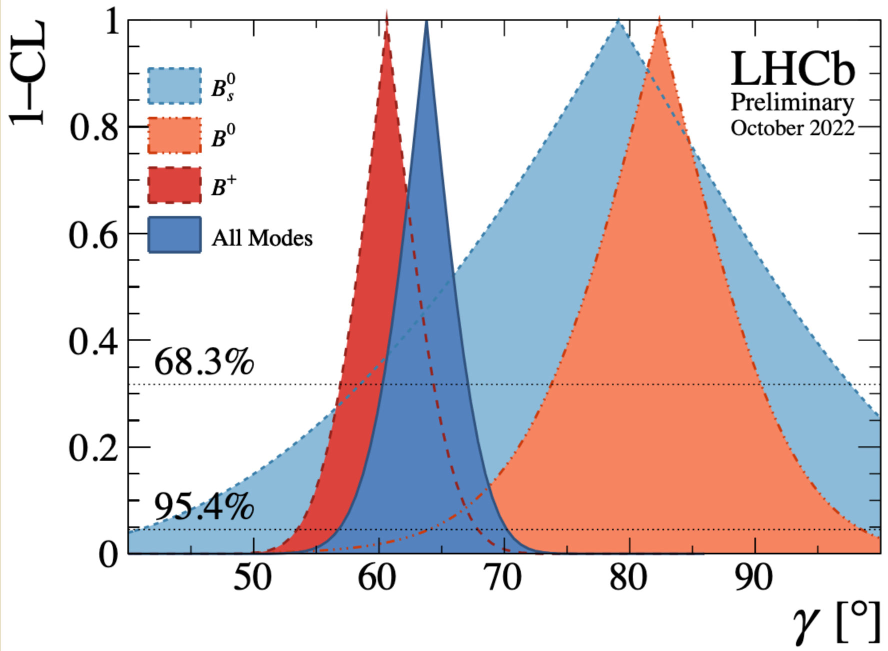
- Using inputs from BESIII/CLEO

[LHCb-PAPER-2022-017, arXiv:2209.03692]



State of the art of γ

- Strategy similar to previous combinations: frequentist treatment.
- This combination includes new and updated measurements.



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

- In agreement with previous and global averages $\gamma = (65.6^{+1.1}_{-2.7})^\circ$ [CKMFitter]
- Statistically limited, ample room for NP.

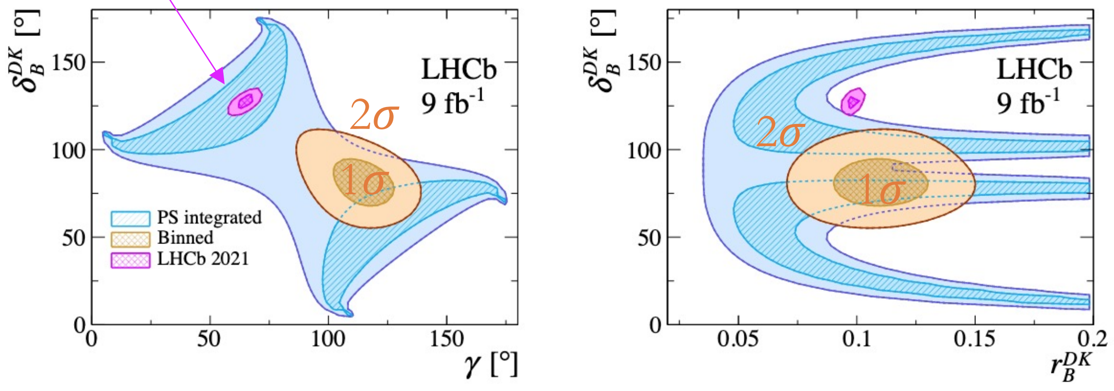
[LHCb-CONF-022-003]

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**

Using the binned analysis alone:

$$\begin{aligned}
\gamma &= (116^{+12}_{-14})^\circ, \\
\delta_B^{DK} &= (81^{+14}_{-13})^\circ, \\
r_B^{DK} &= 0.110^{+0.020}_{-0.020}, \\
\delta_B^{D\pi} &= (298^{+62}_{-118})^\circ, \\
r_B^{D\pi} &= 0.0041^{+0.0054}_{-0.0041},
\end{aligned}$$

Analysis of other decay modes at LHCb

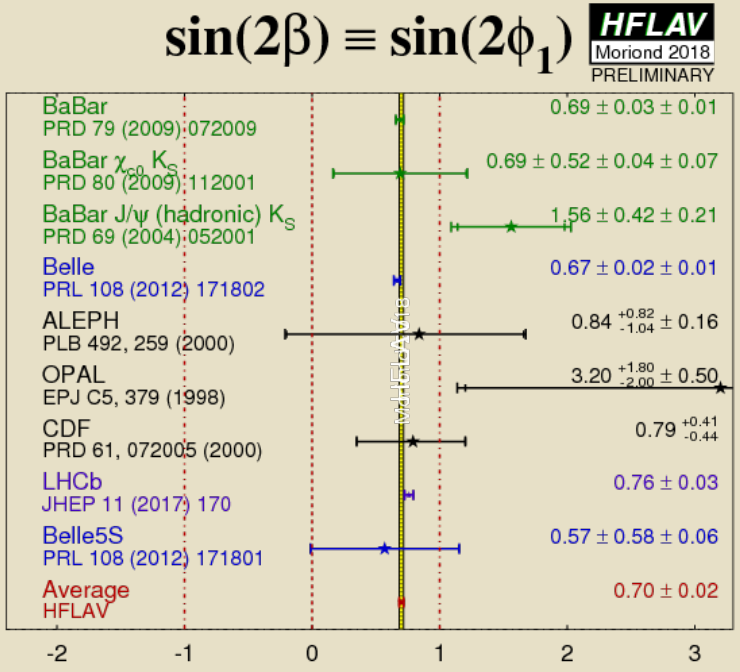


Latest measurement of γ

- First study of CP violation in the decay mode $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D\, h^{\pm}$, with $h = K, \pi$
- Self conjugated D decay mode, analysis performed **in bins of phase space**
- External charm-decay parameters taken from LHCb amplitude analysis
- Phase space integrated measurement also performed for $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$
- Full Run 2 exploited, precision of the four-body D-decay studies is limited by the sample size.

[Submitted the 24th of January: arXiv:2301.10328]

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



Golden channel $B^0 \to J/\psi K_s^0$, averages including all charmonium:

LHCb:

- $\boldsymbol{S = 0.760 \pm 0.034}$ [JHEP 11(2017) 170]. (RUN 1 ONLY)

Belle:

- $\boldsymbol{S = 0.667 \pm 0.026}$ [PRL 108(2012) 171802]

Babar:

- $\boldsymbol{S = 0.691 \pm 0.031}$ [PRD 79(2009) 072009]

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

[HFLAV 2018]

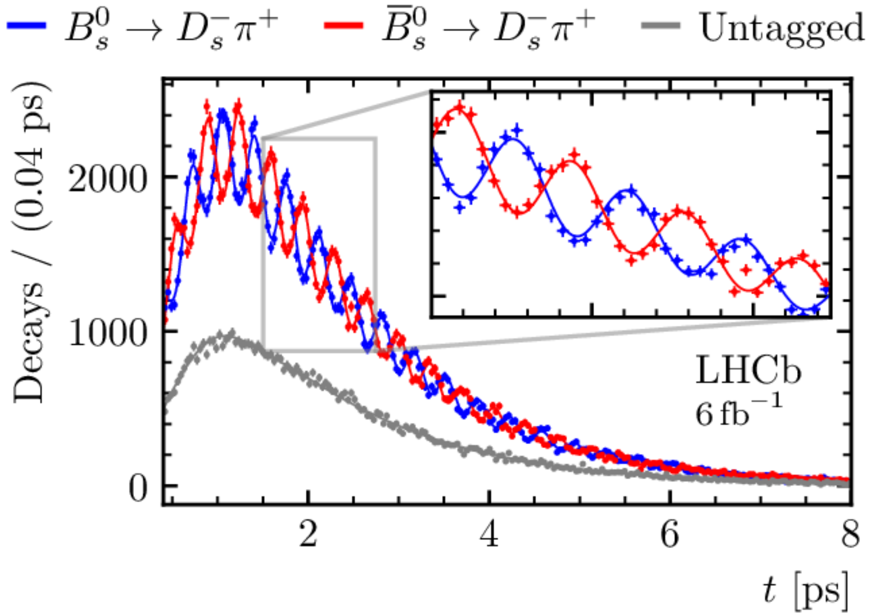
$$S^{SM} \equiv \sin(2\beta) = 0.731^{+0.029}_{-0.016}$$

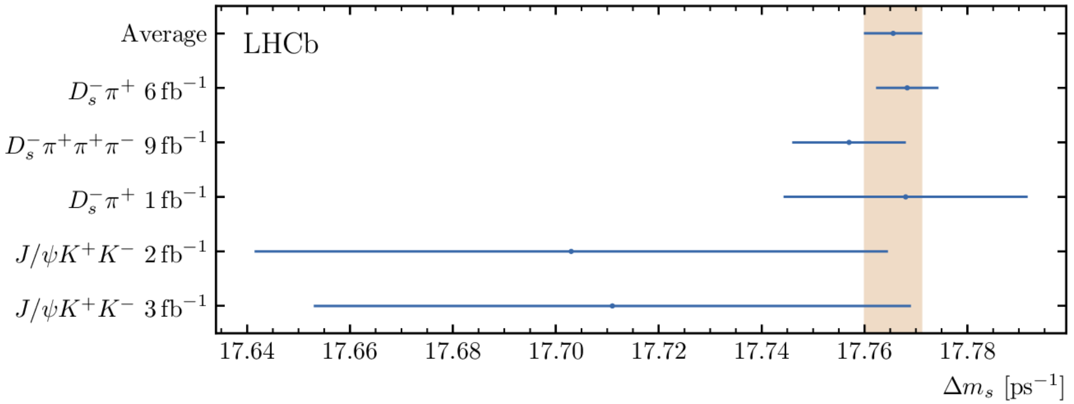
[CKMfitter]

- LHCb has a similar precision to the B-factories

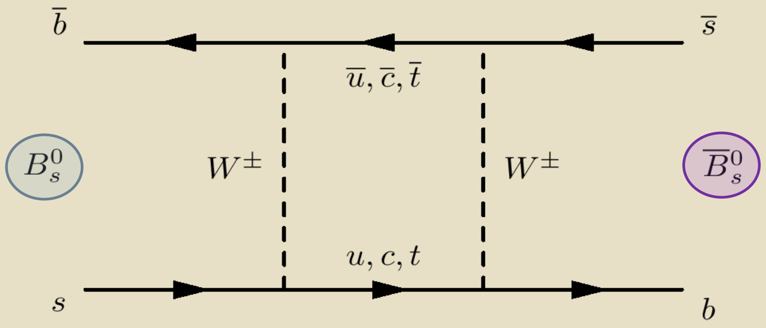
B_s^0 mixing

$$|B_L> = p\,|B_s^0> \; + q\,|\bar{B}_s^0>$$
$$|B_H> = p\,|B_s^0> - q\,|\bar{B}_s^0>$$





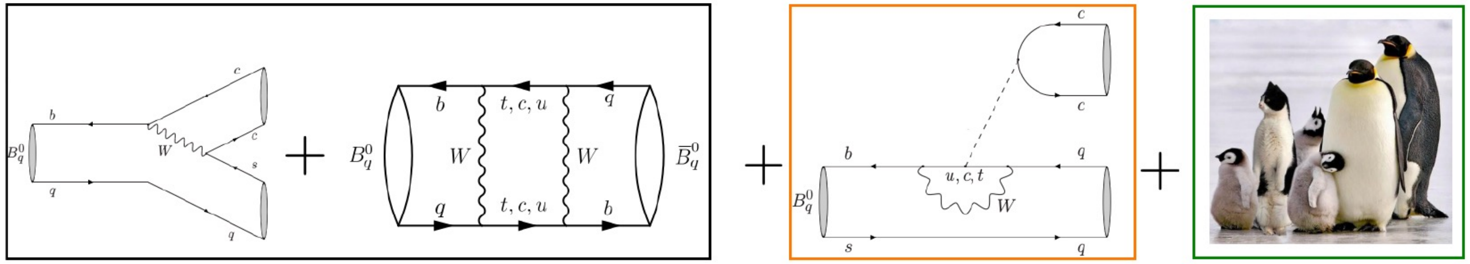
- Neutral B_s^0 mass(~CP) eigenstates characterised by **sizeable difference in decay width and mass**!
  $\Delta\Gamma_s/\Gamma_s = 0.124 \pm 0.008$, $\Delta m_s/\Gamma_s \approx 30$



- To measure oscillation, need to know B_s^0 state at production (flavour tagging) and B_s^0 state at decay!
- Recent LHCb measurement of Δm_s uses $B_s^0 \to D_s^-\pi^+ / \bar{B}_s^0 \to D_s^+\pi^-$
- B_s^0 state at decay fixed by final state
- **Most precise measurement of Δm_s**
  $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032$ ps^{-1}

[Nature Physics 18 (2022) 1]

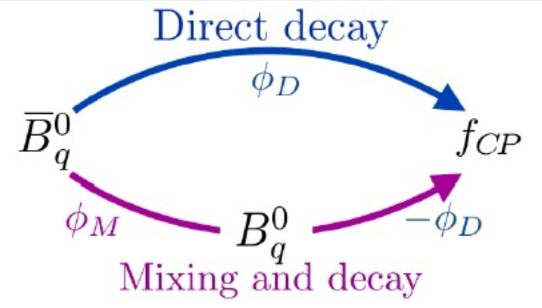
CP violation in B mixing and decay, φ_s

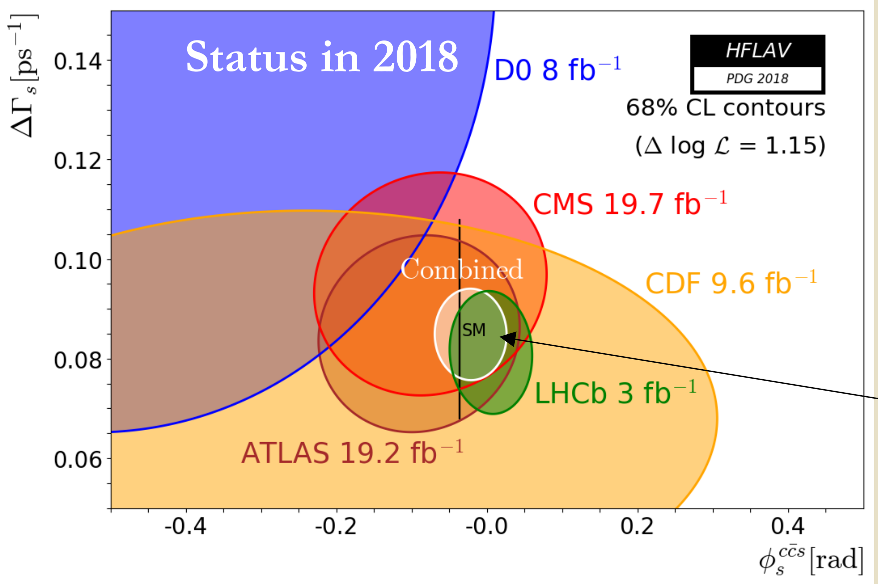


Dominant SM “tree” contribution

Higher order “penguin” contributions from non-perturbative hadronic effects

NP could be difficult to distinguish from penguins...





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

- Precisely predicted by the SM: $\boldsymbol{\varphi_s^{SM} = -36.86^{+0.93}_{-0.67}}$ **mrad** [CKMFitter]
- Golden channel exploited by LHCb, ATLAS, CMS: $B_s^0 \to J/\psi\phi$
- LHCb also measured many other channels

- World average (dominated by LHCb) consistent with predictions;
- Exp. uncertainty (31 mrad) almost a factor of 30 larger than uncert. of indirect determination when penguin pollution is ignored.

Overview of the φ_s results

Combination of all LHCb results
including '15+'16 $B_s^0 \to J/\psi KK$ and $B_s^0 \to J/\psi\pi\pi$

$$\varphi_s = -0.042 \pm 0.025 \text{ rad}$$
$$|\lambda| = 0.993 \pm 0.010$$
$$\Gamma_s = 0.6563 \pm 0.0021 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0813 \pm 0.0048 \text{ ps}^{-1}$$

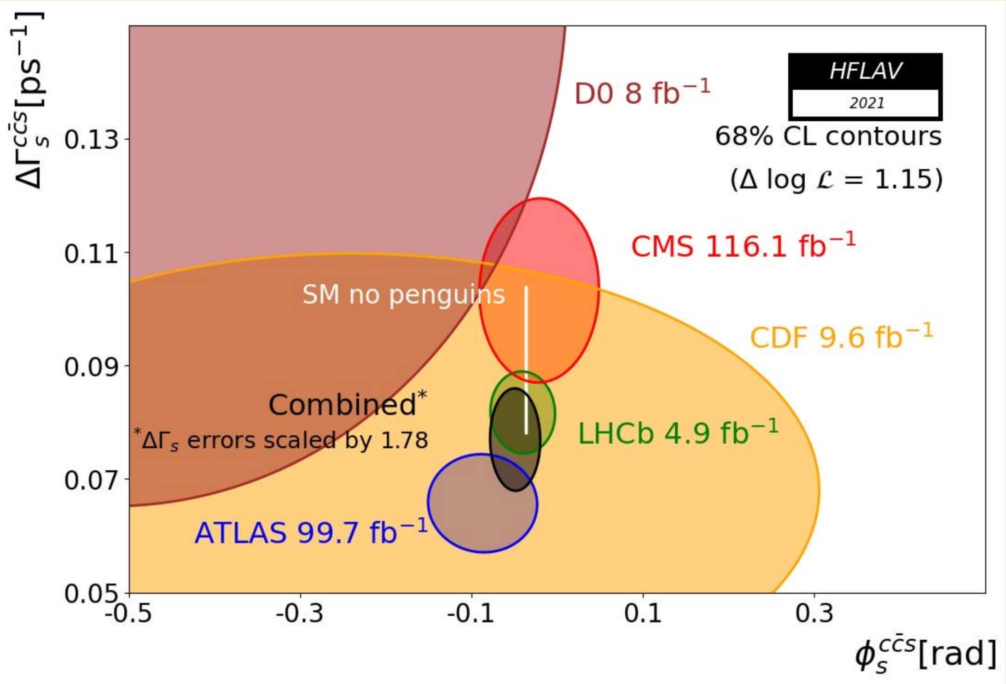
[Eur.Phys.J.C79(2019)706]

φ_s 0.1 σ away from SM
consistent with Standard Model

φ_s 1.6 σ away from 0
consistent with no CPV in interference

|λ| consistent with 1
consistent with no direct CPV

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



The HFLAV combination is:

$$\varphi_s = -0.049 \pm 0.019 \text{ rad}$$
$$\Delta\Gamma_s = 0.074 \pm 0.006 \text{ ps}^{-1}$$

[HFLAV]

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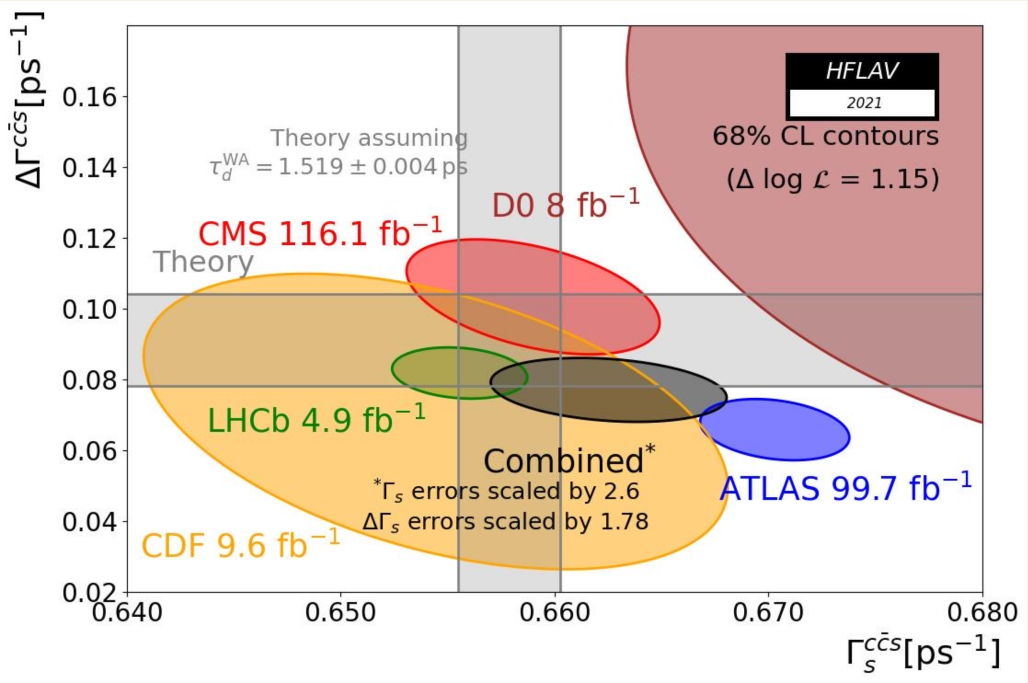

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[HFLAV]

CP violation in charm

- Searching for CP violation (CPV) in charm decays is a **stress test to the Standard Model**:
  - **Up-type quark**: complementary to studies in K and B systems
- **Small CP asymmetries expected** $\lesssim 0.1\%$ [Phys.Lett. B222 (1989) 501]
- CPV searched for since decades, **finally observed in 2019 with the ΔA_{CP} measurement** [Phys. Rev. Lett. 122, 211803]!

The raw asymmetry (A) in Cabibbo Suppressed $D^0 \to h^- h^+$ decays (h = K or π) includes both physics and detector effects:

$$A = A(D \to f) = \frac{N(D\to f) - N(\bar{D}\to\bar{f})}{N(D\to f) + N(\bar{D}\to\bar{f})} = \mathbf{A_{CP}} + A_D + A_P$$

Detection asym. from π^+soft or μ^+

Production asym. from D^{*+} or B decays

To eliminate these contributions:

$$\boldsymbol{\Delta A_{CP}} = A(K^+K^-) - A(\pi^+\pi^-) = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

- Experimentally robust as production and detection asymmetries cancel to first order
- $\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}}$

CP Violation observed @ 5.3σ!

- Additional measurements are needed to have a better understanding!

[LHCb-PAPER-2022-024, arXiv:2209.03179]

Time integrated CP asymmetry in $D^0 \to K^+K^-$

- Measuring time integrated asymmetries of single channels is much harder, the raw asymmetry must be corrected for using calibration samples to extract the physical asymmetry

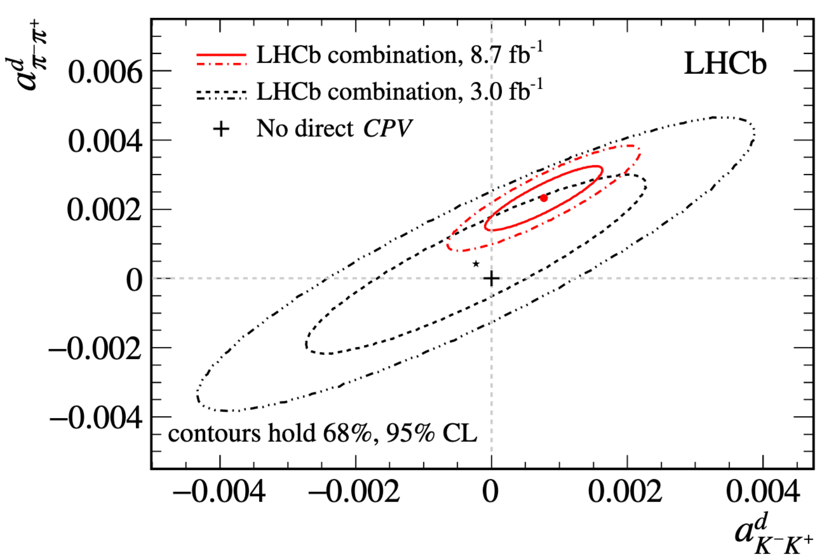
$$A = A(D \to f) = \frac{N(D\to f) - N(\bar{D}\to \bar{f})}{N(D\to f) + N(\bar{D}\to \bar{f})} = \mathbf{A_{CP}} + A_D + A_P$$

Detection asymmetry due to the detector

Production asymmetry in pp collisions

- Measurement from LHCb using the full Run2 dataset

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

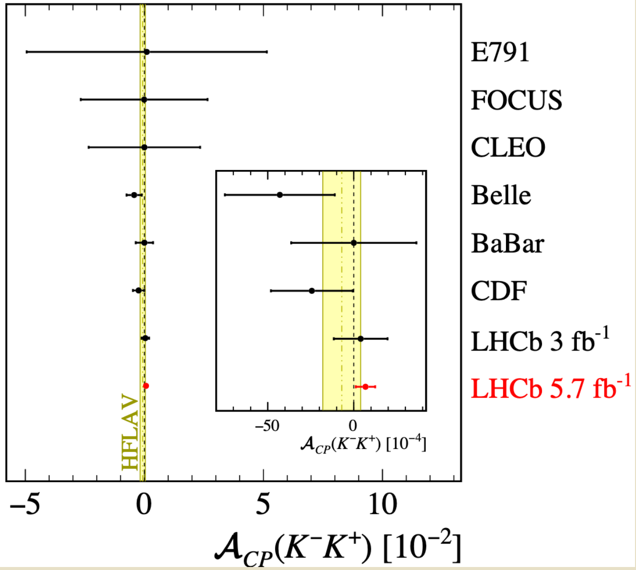


In combination with ΔA_{CP}:

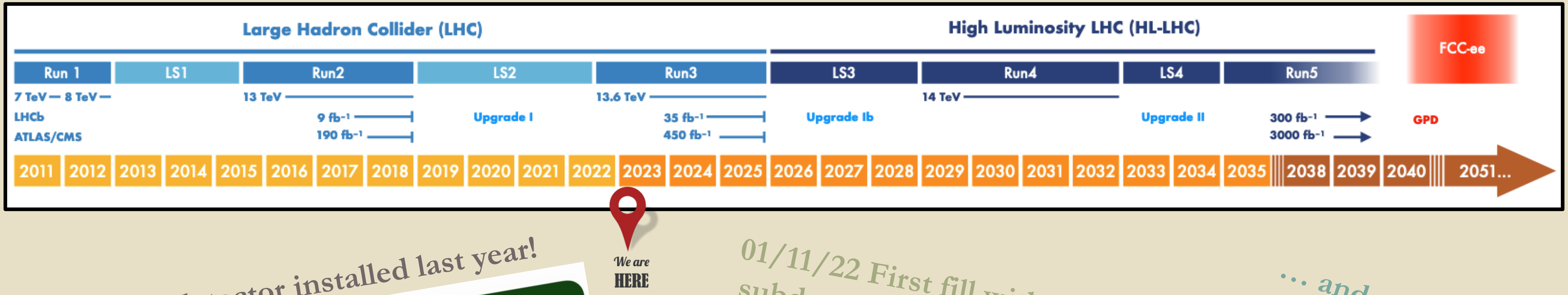
$$a^d_{K^+K^-} = (7.7 \pm 5.7)\times 10^{-4} \quad 1.4\sigma$$

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

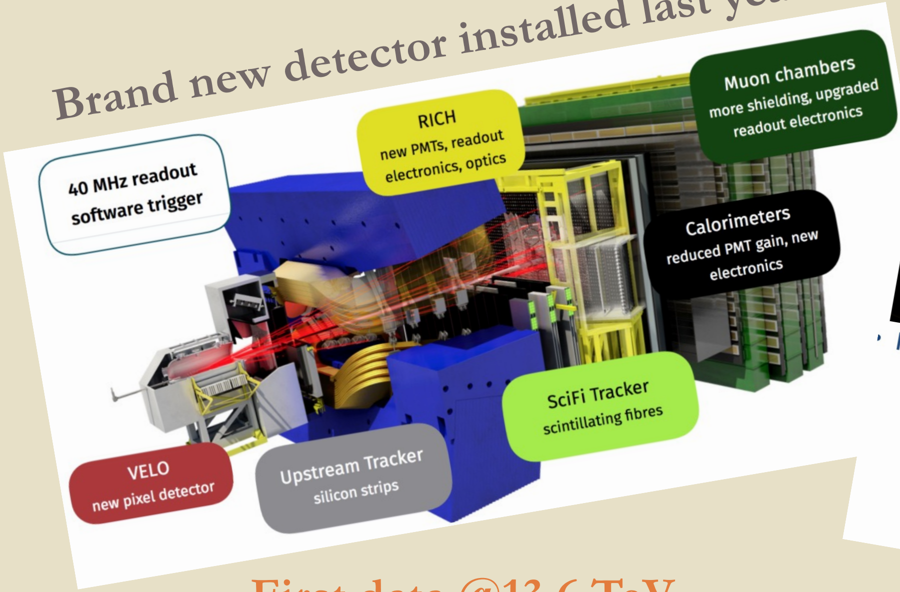
CP violation in the decay amplitude



The experimental scenario, this is not the end!



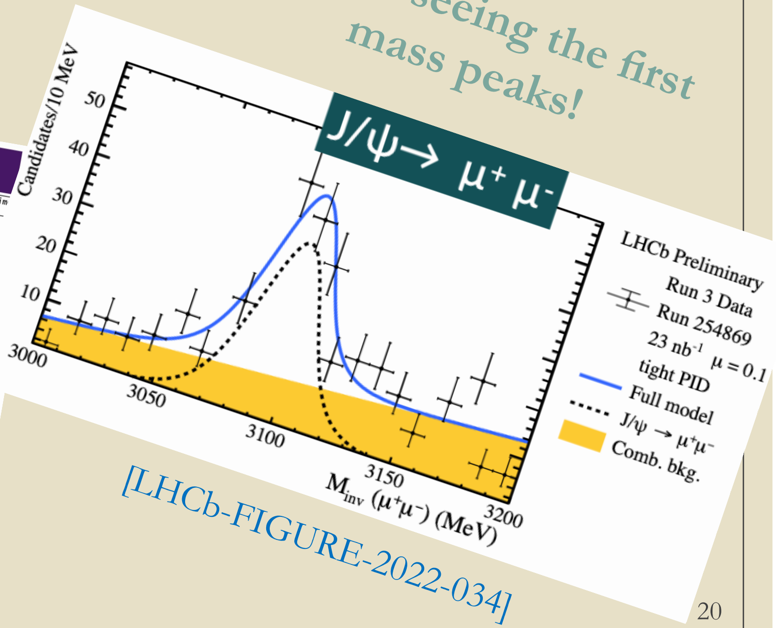
Brand new detector installed last year!



First data @13.6 TeV registered the 5th of July 2022!

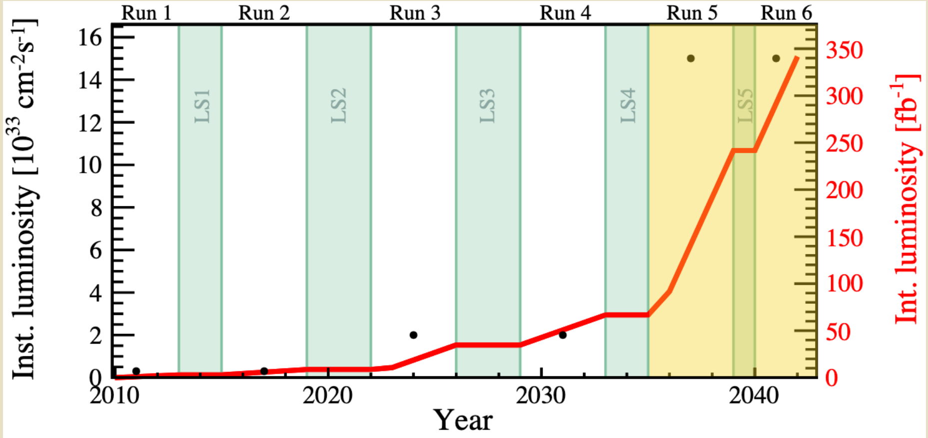
01/11/22 First fill with all subdetectors included…

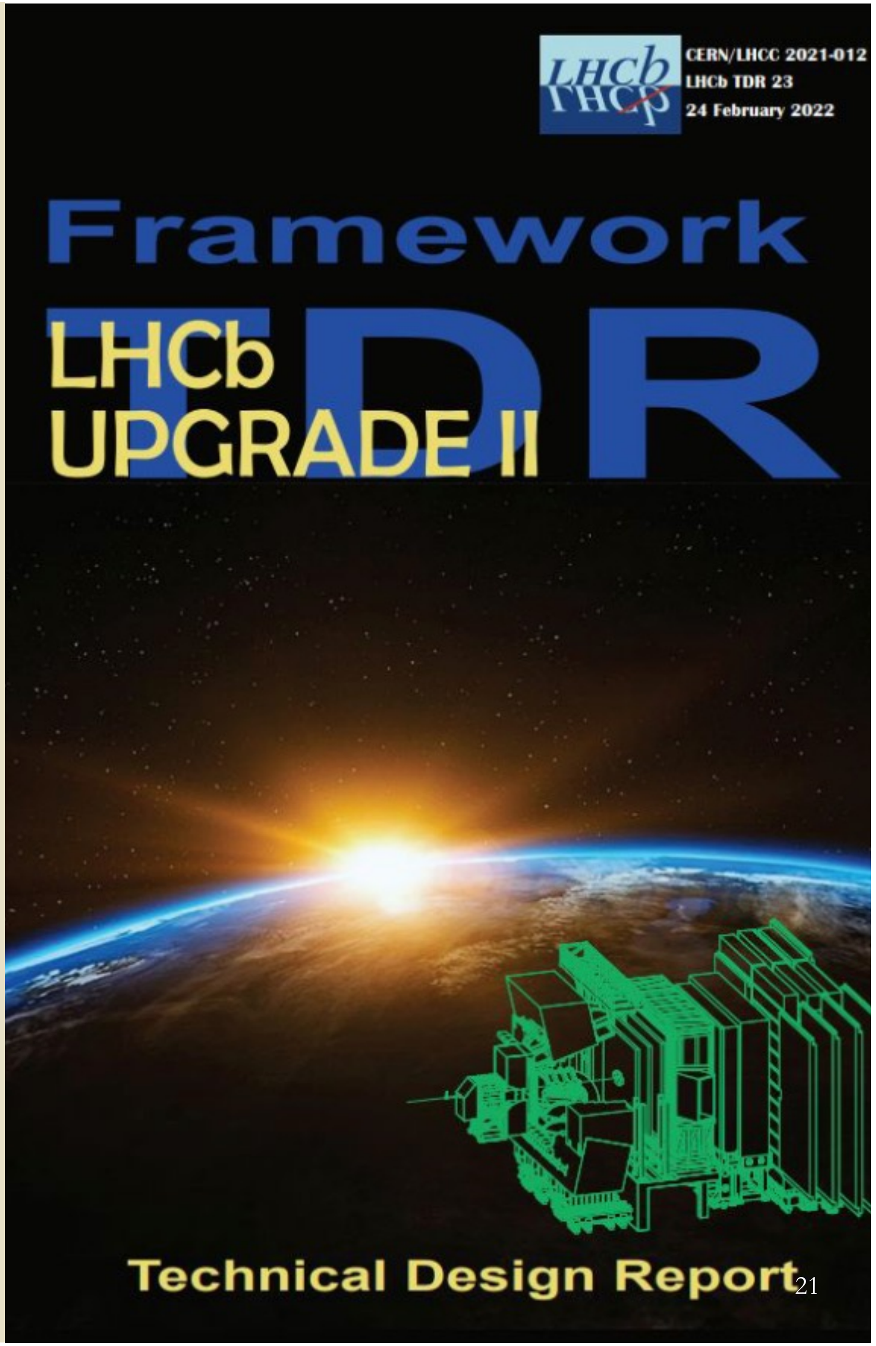
… and seeing the first mass peaks!



[LHCb-FIGURE-2022-034]

Looking further into the future





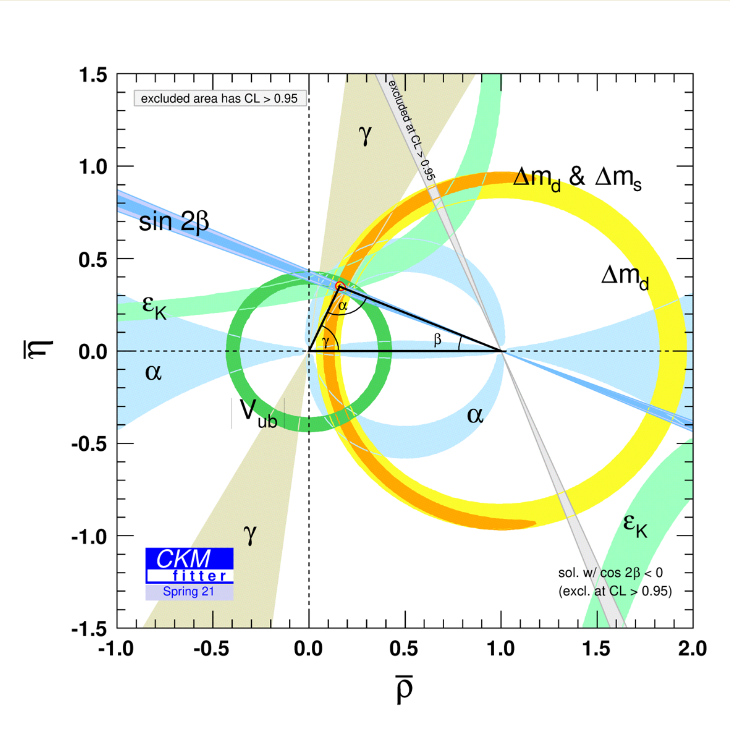
LHCb in Run 5&6?

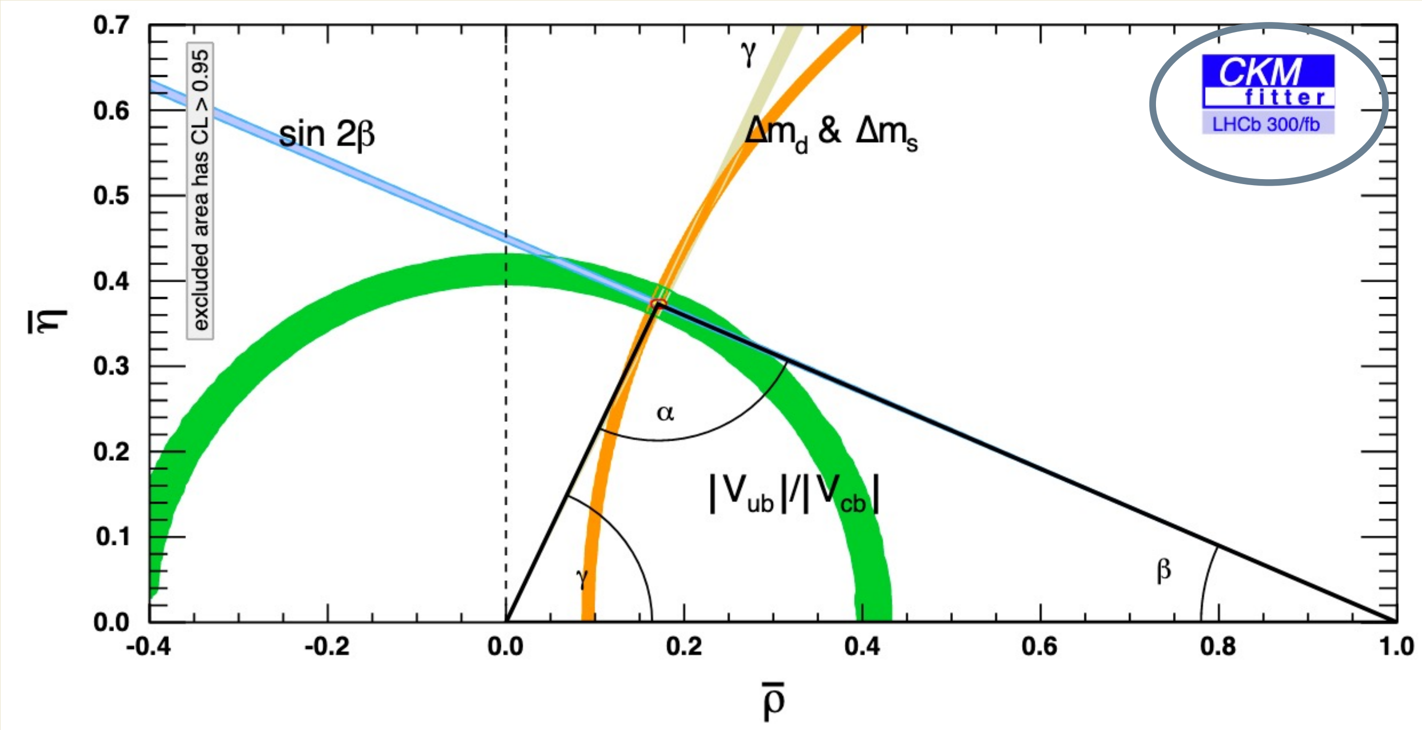
Target: ~300 fb^{-1}

- 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!

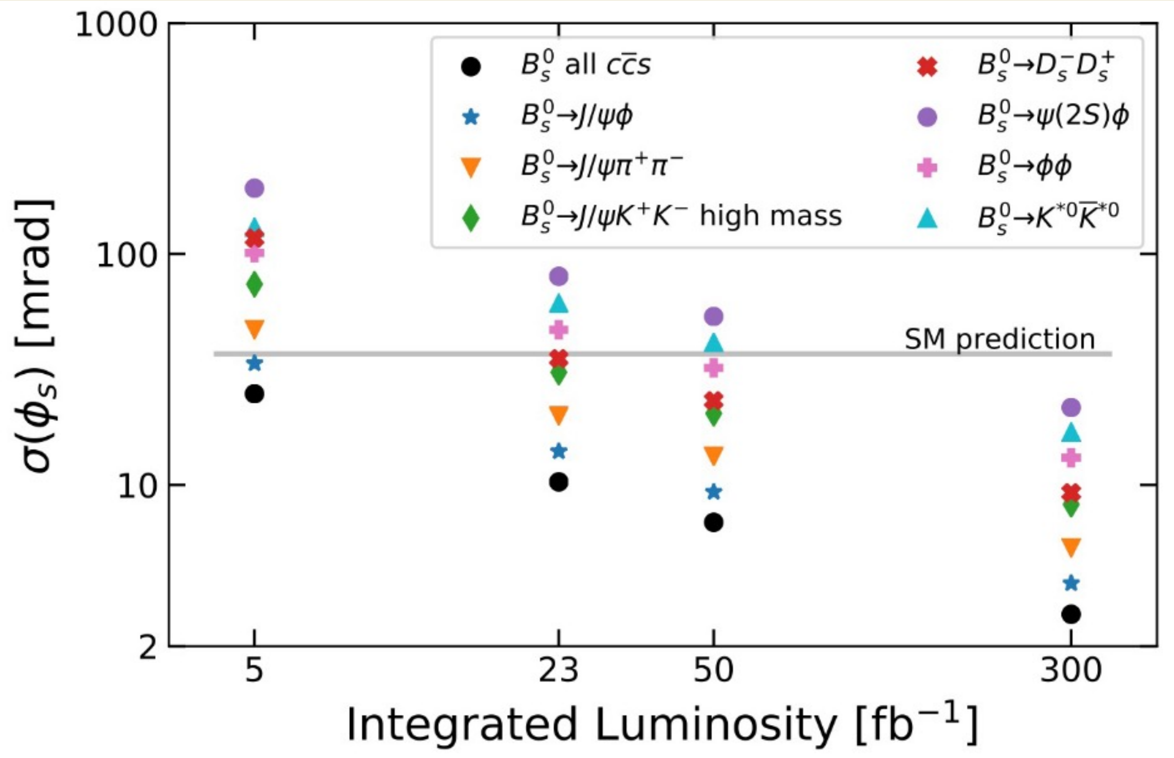
What could be achieved in Upgrade II?





[arXiv:1808.08865]

Prospects for the future II



[LHCB-PUB-2018-009]

CP-violation from the interference between mixing and decay in the B_s^0 system

300/fb: $\sigma^{STAT}(\varphi_s) \sim$ 4 mrad from $B_s^0 \to J/\psi KK$ only

- **φ_s expected to be statistically limited**
- **Upgrade II sensitivity below SM prediction in multiple channels**

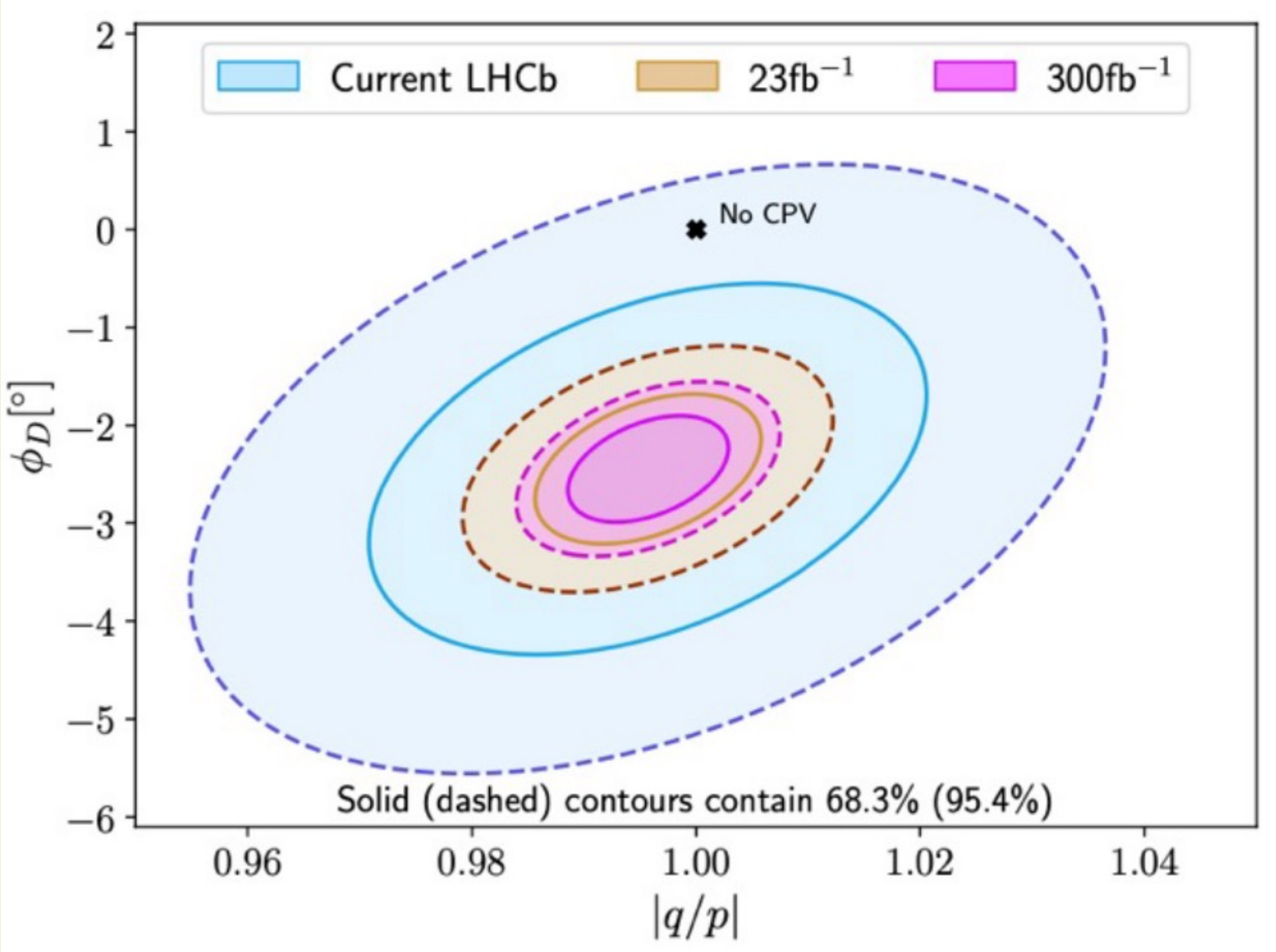
Impact of Upgrade I and II very important for φ_s!

Prospects for the future III

CP violation in charm

With more data, LHCb has the potential to map the structure of CP violation in the charm system.
Merely scratching the surface now!

LHCb Upgrade II is the only planned facility with a realistic possibility to observe particle anti-particle difference in charm mixing
(at >5σ if present central values are assumed)



[LHCB-PUB-2018-009]

Conclusions and remarks

- 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.

- CPV discovery in charm opens a new tool to investigate the SM

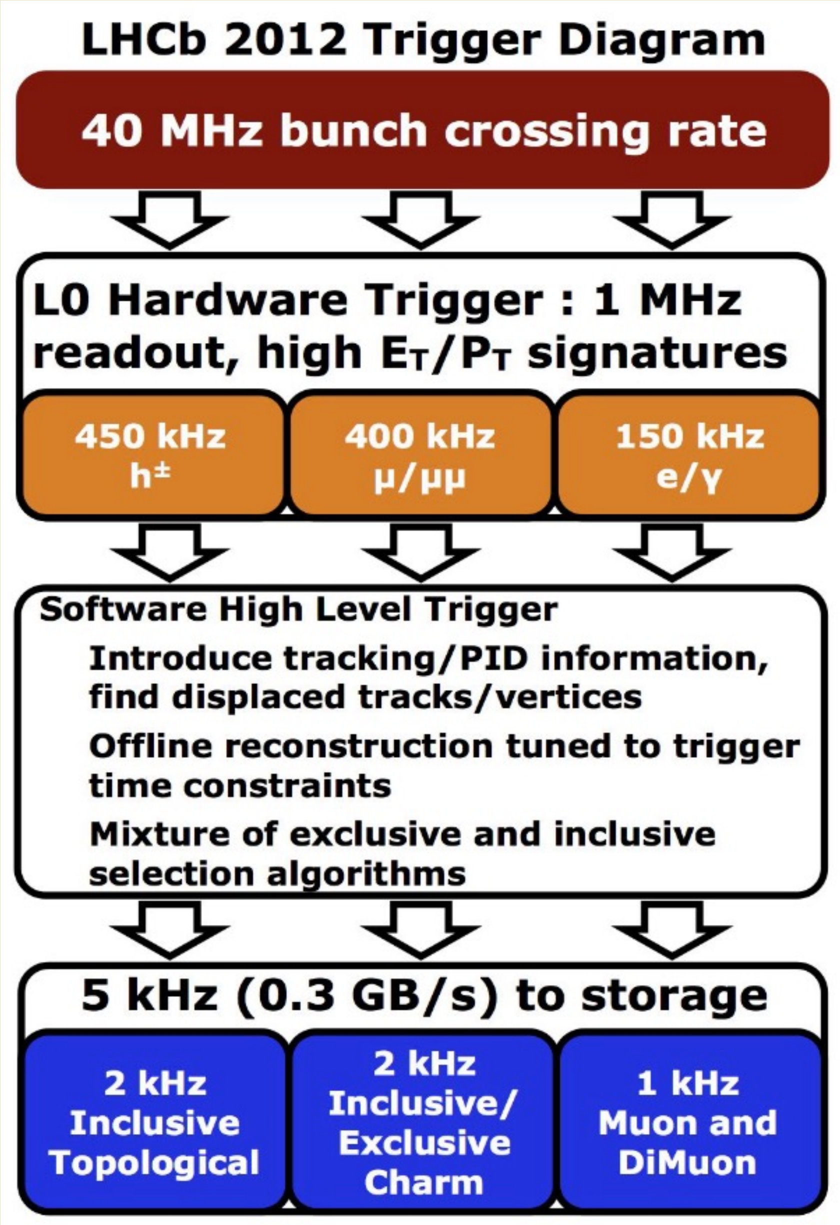
- All results in this sector in **good agreement with SM**, need to go to even **higher precision**: now focused on Run3 to get the new detector in shape to acquire an even larger dataset!

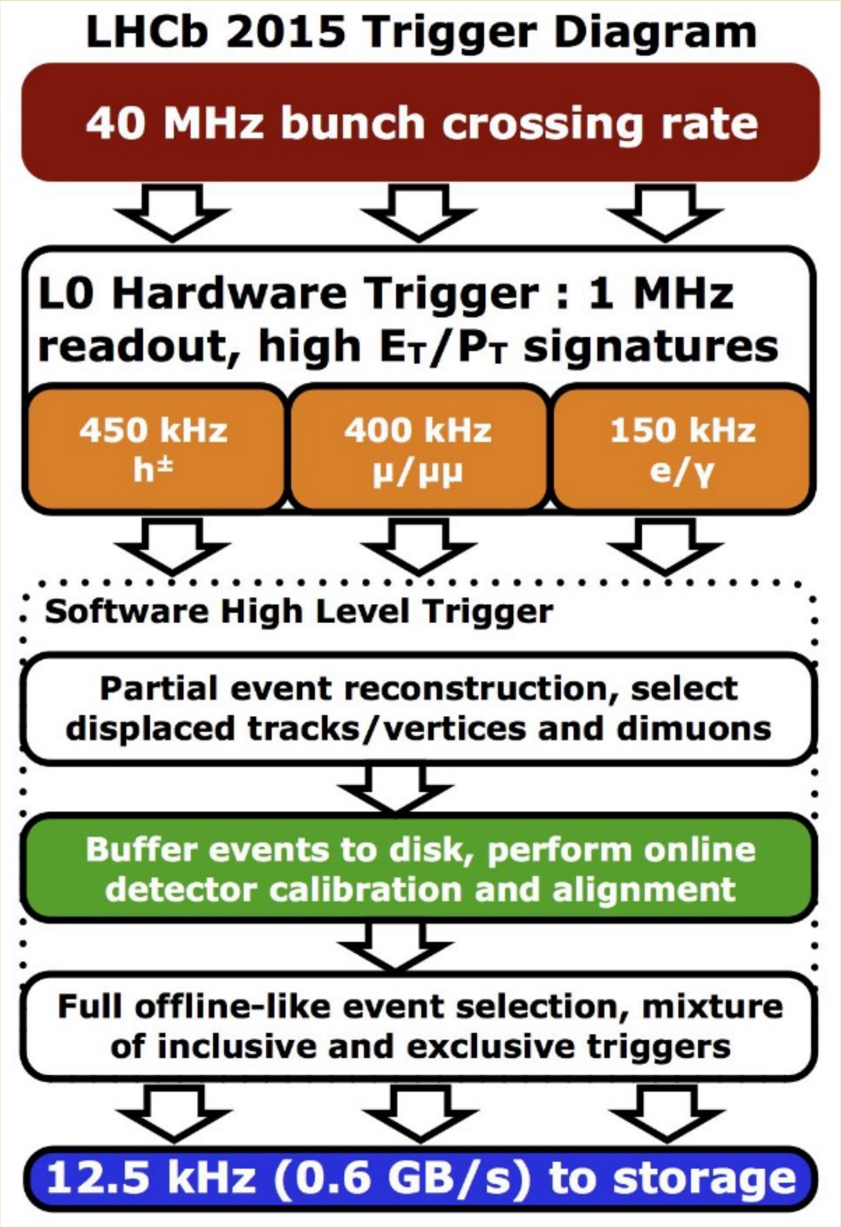
- **Excellent prospects for precision measurements in the Upgrade II** phase of LHCb.

"And if someone dares to yawn during your presentation, this pointer easily transforms from a laser to a taser!"

BACKUP

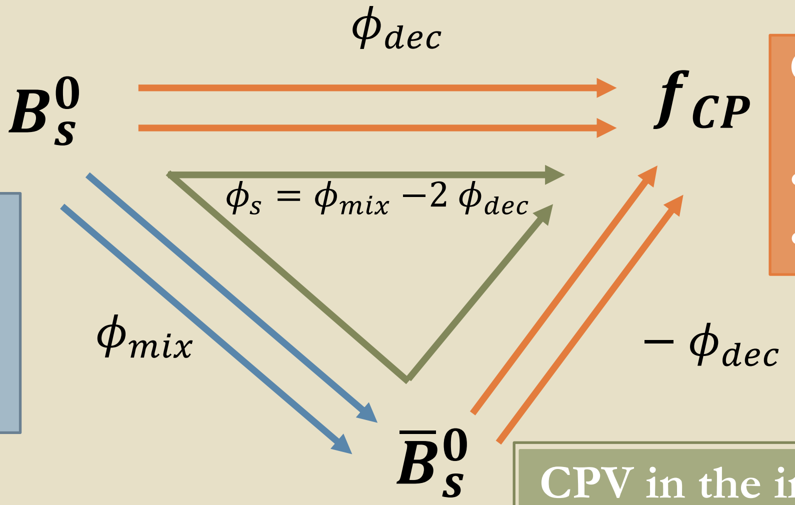
LHCb Trigger System





Different kinds of CP violation

- Must have **two interfering amplitudes** with different strong (δ) and weak (φ) phases
- For a B_s^0 decay to a **CP eigenstate *f***, CP-violating effects depend on $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$



CPV in mixing

- $P(B_s^0 \to \bar{B}_s^0) \neq P(\bar{B}_s^0 \to B_s^0)$
- $|q/p| \neq 1$

CPV in decay

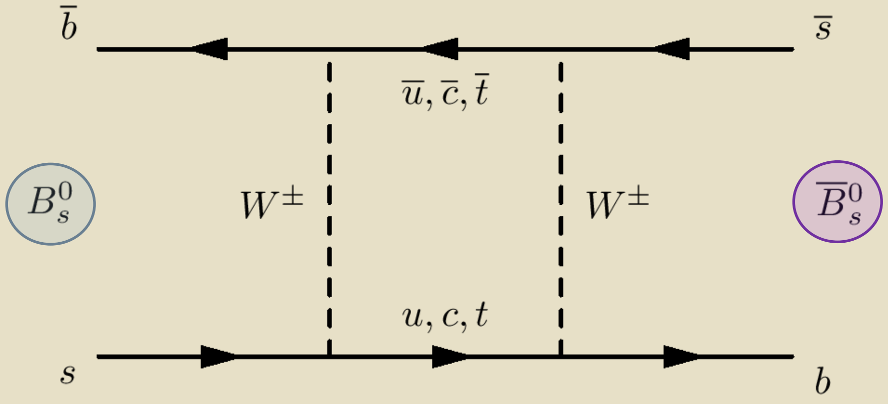
- $P(B_s^0 \to f) \neq P(\bar{B}_s^0 \to f)$
- $|\bar{A}_f / A_f| \neq 1$

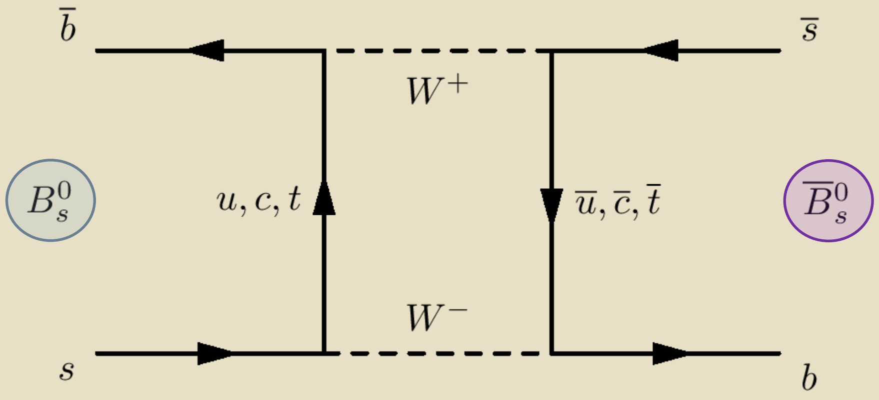
CPV in the interference between decay and mixing

- $P(B_s^0 \to f) \neq P(B_s^0 \to \bar{B}_s^0 \to f)$
- $\arg(\lambda_f) \neq 0$

B flavour mixing

- Neutral B_s^0 mesons can **oscillate** between their particle and anti-particle states





The physical mass eigenstates (L,H) are admixtures of the weak eigenstates:

$$|B_L> = p\,|B_s^0> \; + q\,|\bar{B}_s^0>$$
$$|B_H> = p\,|B_s^0> - q\,|\bar{B}_s^0>$$

- with **mass difference** $\Delta m = m_H - m_L$ and **decay-width difference** $\Delta\Gamma = \Gamma_L - \Gamma_H$
- flavor at production (t=0) could be different from flavour at decay time t

Flavour tagging in the future

Almost everything will be new in Run3 (similar situation as in 2010)

- **Upgrade challenge**: increase in track multiplicity and pile-up (~6 for Upgrade-I and ~55 for Upgrade-II) that have negative effect on ω and ε_{tag}.
- FT performance directly linked to the ability to associate PV $\Leftrightarrow$ track. To improve/maintain tagging performance need:
  - **Hardware**: timing information (upgrade-II workshops)
  - **Software**: deep neural networks to learn correlations between all tracks and the signal B meson (inclusive taggers), need to reduce significantly persisted info.

Control of penguin pollution

- U-spin or SU(3) flavour symmetry to constrain size of penguin with b→cc̄d (related by s-d spectator exchange)
- Penguin pollution and/or CP violation **could be different for each polarisation state**, f ∈ (0, ⊥, ∥, S)

→ no sign yet of dependence in $B_s^0 \to J/\psi$ KK (also in Run 2) so penguins are small

- **SU(3)$_F$: $B_s^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi \rho^0$ are b→cc̄d transitions.**

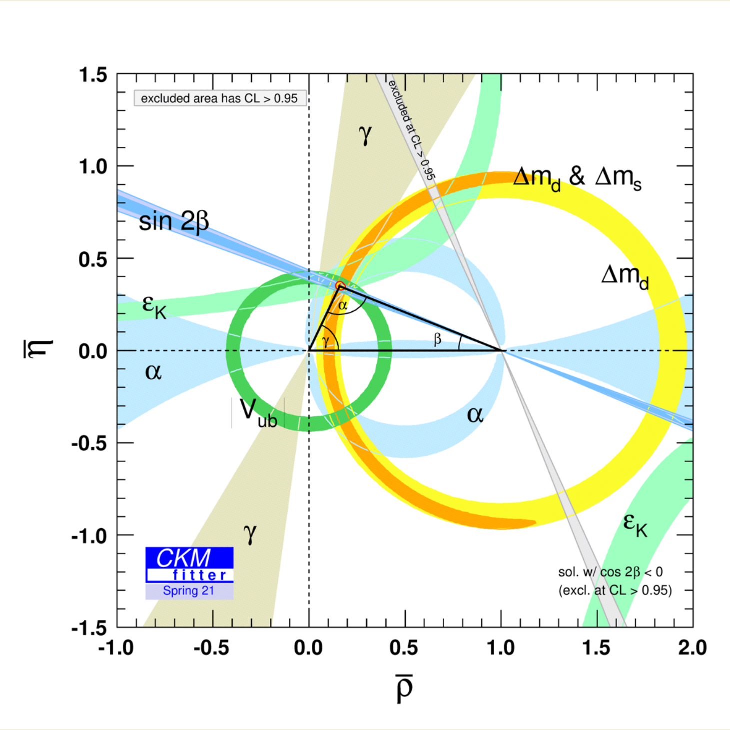
$$\Delta\phi_{s,0}^{J/\psi\,\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})\;{}^{+0.004}_{-0.009}\,(\text{syst})\text{ rad}$$
$$\Delta\phi_{s,\parallel}^{J/\psi\,\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\text{ rad}$$
$$\Delta\phi_{s,\perp}^{J/\psi\,\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\text{ rad}$$

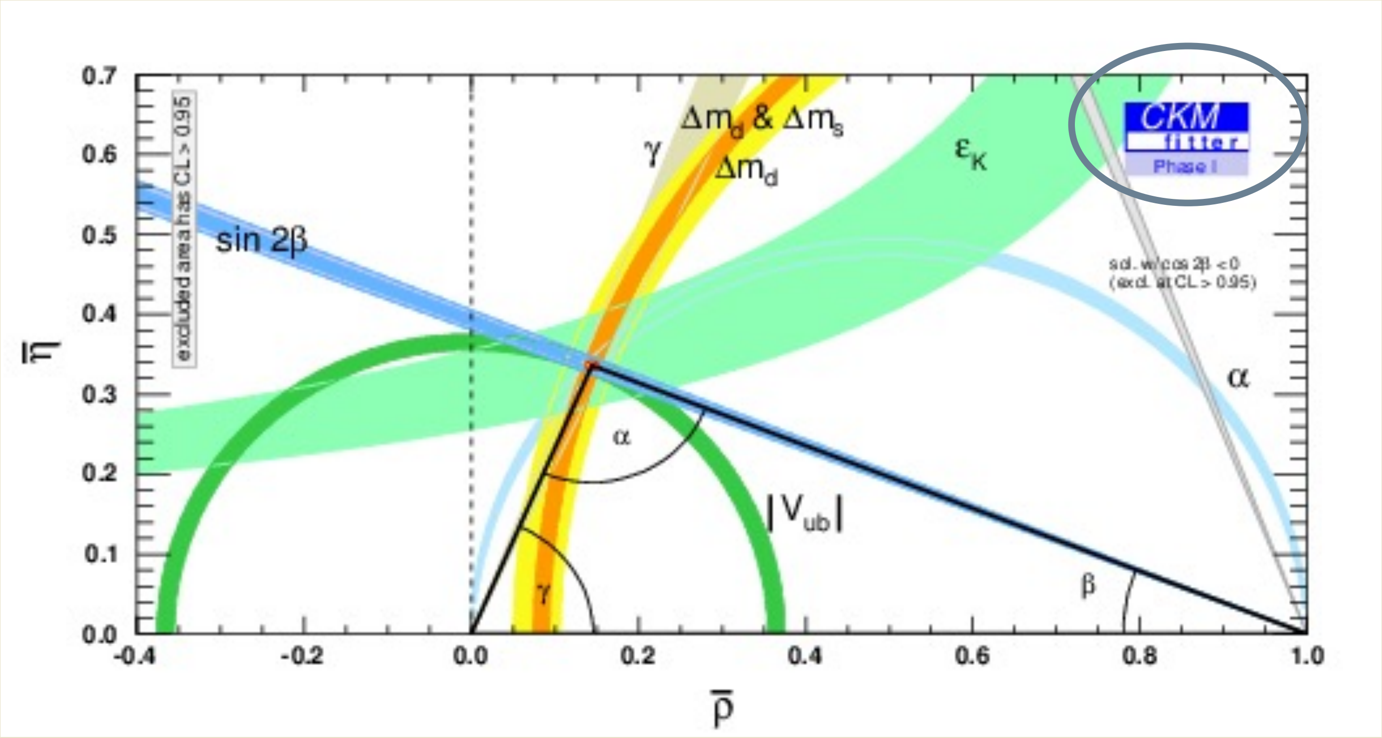
[JHEP 11 (2015) 082]

Precision of ~10 mrad
To be compared with the current precision of HFLAV of **21 mrad**

Fundamental to update these analyses, expected sensitivity **at 300/fb is 1.5 mrad** (statistically limited)
+ adding $B_s^0 \to J/\psi\omega$ and $B^0 \to J/\psi\varphi$ (E + PA diagrams only)

What could be achieved with Run3+4?



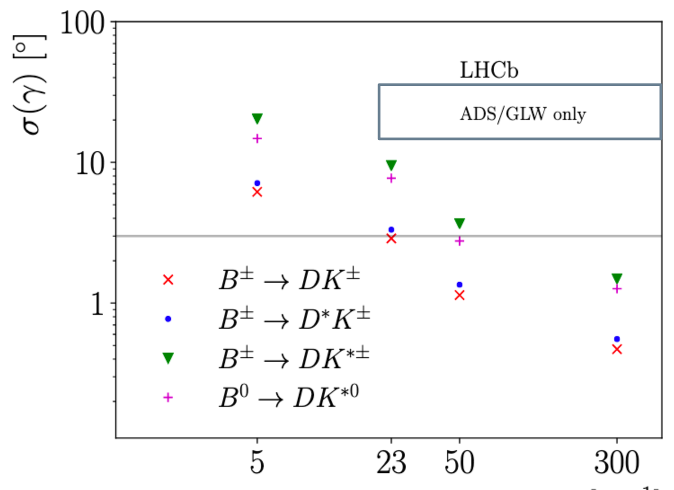


[arXiv:1808.08865]

Prospects for γ

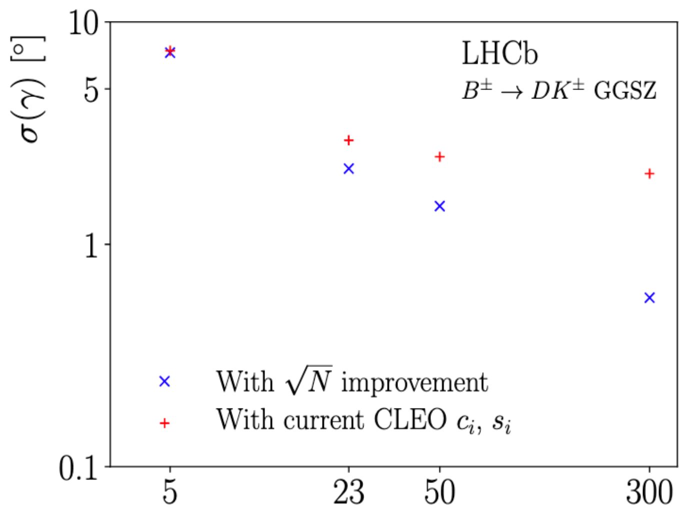
- 4° with Run 2 data (~ 9 fb^{-1})
- 1.5° by the end of Run 3 (~ 22 fb^{-1})
- < 1° by the end of Run 4 (~ 50 fb^{-1})
- ~0.4° in Phase 2 upgrade (~ 300 fb^{-1})

[arXiv:1709.10308v5][CERN-LHCC-2017-003]



[arXiv:1808.08865]

- D reconstructed in a 2 charged-track final state
- All ADS/GLW asymm. currently statistically limited
- Dominant syst., due to knowledge of background contributions, expected to scale with statistics



[arXiv:1808.08865]

- D is reco in a 3-body self-conjugated final state
- Powerful input to the overall determination of γ
- Need good description of strong phase difference δ_D
  - Current inputs taken from CLEO-c (current syst ~ 2°)
  - Future BESIII and LHCb charm inputs are vital

Interest triggered by a measurement from D0 yielding an anomalous like-sign dimuon asymmetry [Phys. Rev. D 89, 012002 (2014)]

- Consider a **flavour-specific** final state f:

$$B^0_{(s)} \to f \quad \text{or} \quad \overline{B}^0_{(s)} \to B^0_{(s)} \to f$$

$$\overline{B}^0_{(s)} \to \overline{f} \quad \text{or} \quad B^0_{(s)} \to \overline{B}^0_{(s)} \to \overline{f}$$

- $a_{sl} \equiv \frac{\Gamma(\overline{B}^0_{(s)}(t)\to f) - \Gamma(B^0_{(s)}(t)\to \overline{f})}{\Gamma(\overline{B}^0_{(s)}(t)\to f) + \Gamma(B^0_{(s)}(t)\to \overline{f})} \cong \frac{\Delta\Gamma}{\Delta M} \tan \phi_M$

LHCb measured both $a_{sl}^{d,s}$ using Run I

- $a_{sl}^{s} = (0.39 \pm 0.26(\text{stat}) \pm 0.20(\text{syst}))\%$
  [Phys. Rev. Lett. 117, 061803 (2016)]
- $a_{sl}^{d} = (-0.02 \pm 0.19(\text{stat}) \pm 0.30(\text{syst}))\%$
  [Phys. Rev. Lett. 114, 041601 (2015)]

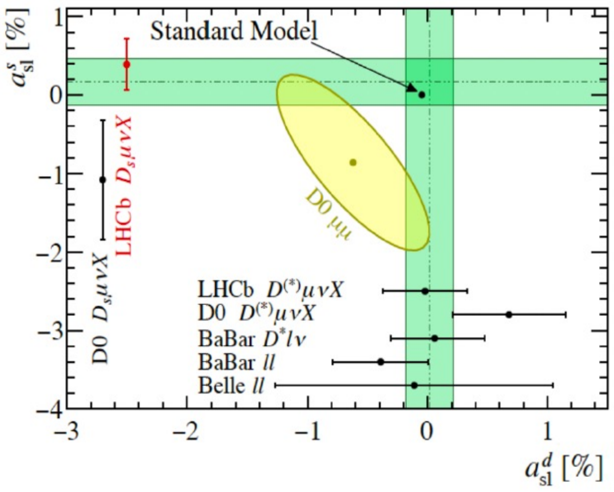
ATLAS measured same- and opposite-sign charge asymmetries based on the μ charge from a top and the charge of the soft μ from a b-hadron in $t\bar{t}$ events [JHEP 02 (2017) 071]

- Four *CP* asymmetries (one mixing and three direct) compatible with SM (uncertainty $\sim$ 1%).

$\not{CP}$ in mixing is very small in the SM

$a_{sl}^{d}(B^0)^{SM}$	$= (-4.1 \pm 0.6) \cdot 10^{-4}$
$a_{sl}^{s}(B_s^0)^{SM}$	$= (+1.9 \pm 0.3) \cdot 10^{-5}$

[Lenz & Nierste, arXiv:1102.4274 [hep-ph]]



CP violation in B mixing

The Bd width difference

deviation in the value of $\Delta\Gamma_d$ from the SM prediction has recently been proposed as a pc
xplanation for the anomalous like-sign dimuon charge asymmetry measured by the D0 co
rXiv:1409.6963 (2014)] [Phys. Rev. D 89, 012002 (2014)].

$$\left|\frac{\Delta\Gamma_d}{\Gamma_d}\right|^{\mathrm{SM}} = (0.42 \pm 0.08)\%$$

[arXiv:1409.6963 (2014)]

DELPHI	$\lvert\Delta\Gamma_d\rvert/\Gamma_d < 18\%$ at 95% CL	[Z. Phys. C76, 579 (1997)]
BaBar	$-6.8\% < \mathrm{sign}(Re_{\lambda_{CP}})\Delta\Gamma_d/\Gamma_d < 8.4\%$	[Phys.Rev.D 70:012007 (2004)]
Belle	$\mathrm{sign}(Re_{\lambda_{CP}})\Delta\Gamma_d/\Gamma_d = (1.7 \pm 1.8 \pm 1.1)\%$	[Phys. Rev. D 85, 071105(R) (2
LHCb	$\Delta\Gamma_d/\Gamma_d = (-4.4 \pm 2.5 \pm 1.1)\%$	[JHEP04 (2014) 114]
ATLAS	$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1 \pm 0.9)\%$	[JHEP06 (2016) 081]

oth LHCb and ATLAS measure it comparing the decay time distributions of $B^0 \to J/\psi K_S$
$^0 \to J/\psi K^{*0}$ decays [J. Phys. G 42 (2015) 119501]:

- ATLAS measurement (full Run I) is the most precise measurement from a single exp date;
- LHCb measurement still on a limited data sample (2011 only) $\Rightarrow$ factor 7 in statistics available from 2012 and Run II;

Some thoughts on γ in Upgrade 2

- Since the bulk of the sensitivity to γ comes from the difference in rates of the $B - \bar{B}$ processes, a **precise control of asymmetries in charged-particle identification and detection is crucial**
  → these systematic uncertainties are considered to scale with integrated luminosity

- Upgrade of the calorimeter will greatly expand LHCb's capabilities for modes with neutrals in the final state.

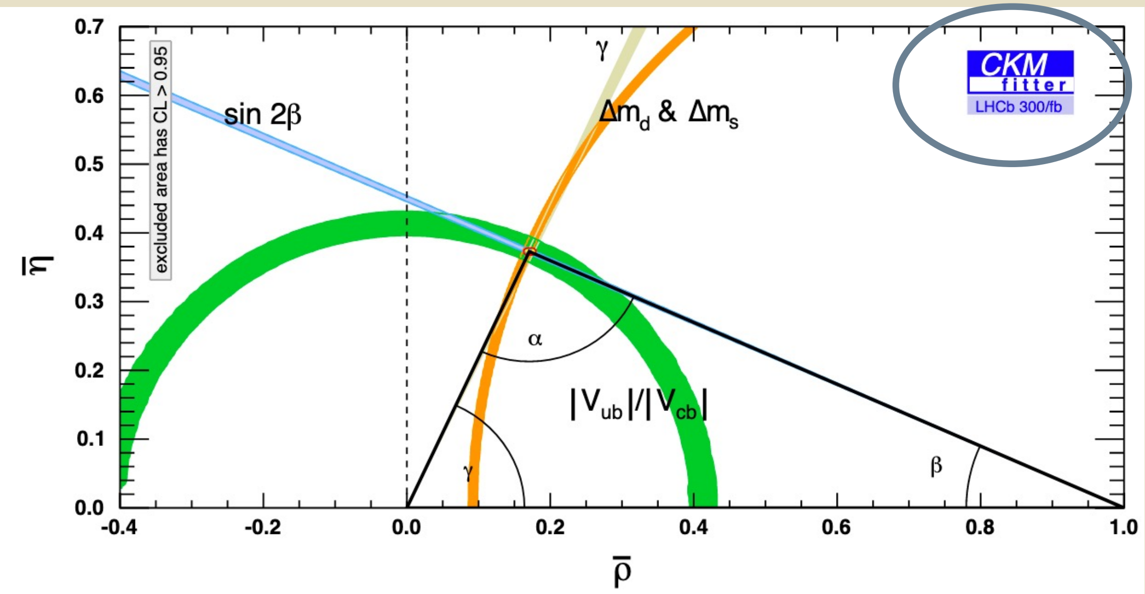
- Upgrade 2 will also make it interesting to measure γ using baryonic decays
  → **TORCH** system particularly helpful in allowing for low-momentum separation of protons and kaons

- Addition of **magnet-side stations** may lead to important signal-yield improvements, particularly for high-multiplicity final states.

- Constrain $\beta_{(s)}$ without penguin contaminations → $\sim 2^{\circ}$ sensitivity on $\gamma - 2\beta_s$ from $B_s^0 \to D_s K$

Prospects for $\sin(2\beta)$

- @50/fb: $\sigma_{stat} = 0.006$ with $B^0 \to J/\psi K_s^0$
- @300/fb: $\sigma_{stat} = 0.003$ with $B^0 \to J/\psi K_s^0$



[arXiv:1808.08865]

Systematics:

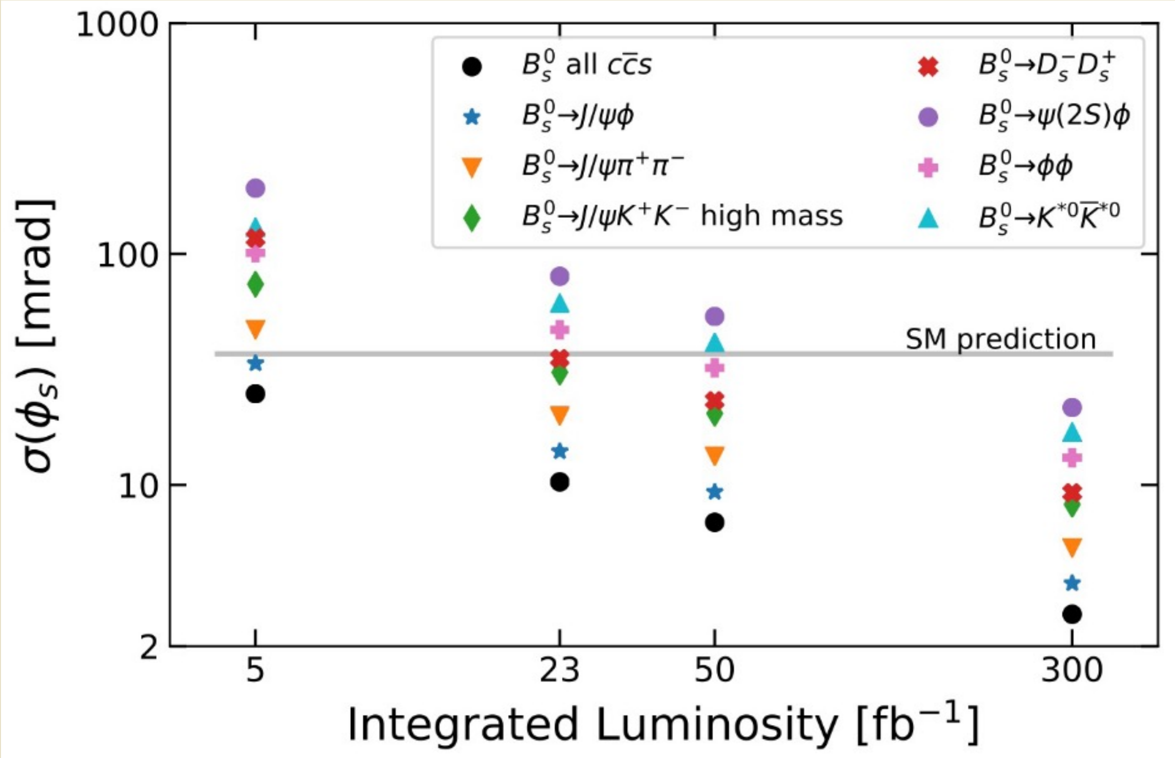
- Mostly depends on size of control samples → scale with statistics
- Important to understand how to take into account $K^0 - \overline{K}^0$ CP violation and nuclear cross-section asymmetry.

Leading sources of systematic uncertainty are different between Belle II and LHCb

Penguins controlled using $B^0 \to J/\psi \pi^0$ and $B_s^0 \to J/\psi K_s^0$

- $B_s^0 \to J/\psi K_s^0$ studied by LHCb [Phys. Rev. Lett. 115 (2015) 031601]
- Belle II expects a good precision for $B^0 \to J/\psi \pi^0$
- Improving ECAL will allow also LHCb to contribute
- Upgrade II will also allow to study other SU(3) related modes

Prospects for the future



[LHCB-PUB-2018-009]

- Include gain in trigger for $B_s^0 \to D_s^- D_s^+$ after Upgrade 1
- Same performances as in Run I
  - Assumed tagging power 4%
- Additional modes planned: $J/\psi \to ee$, $\eta' \to \rho^0\gamma$ or , $\eta' \to \eta\pi\pi$ or $\gamma\gamma$ as cross cheks

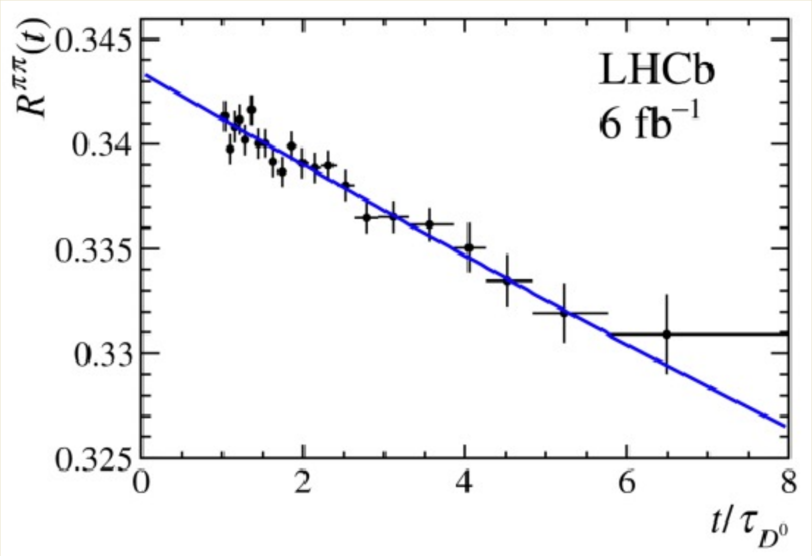
300/fb: $\sigma^{STAT}(\varphi_s)$ ~ 4 mrad from $B_s^0 \to J/\psi KK$ only

- **φ_s expected to be statistically limited**

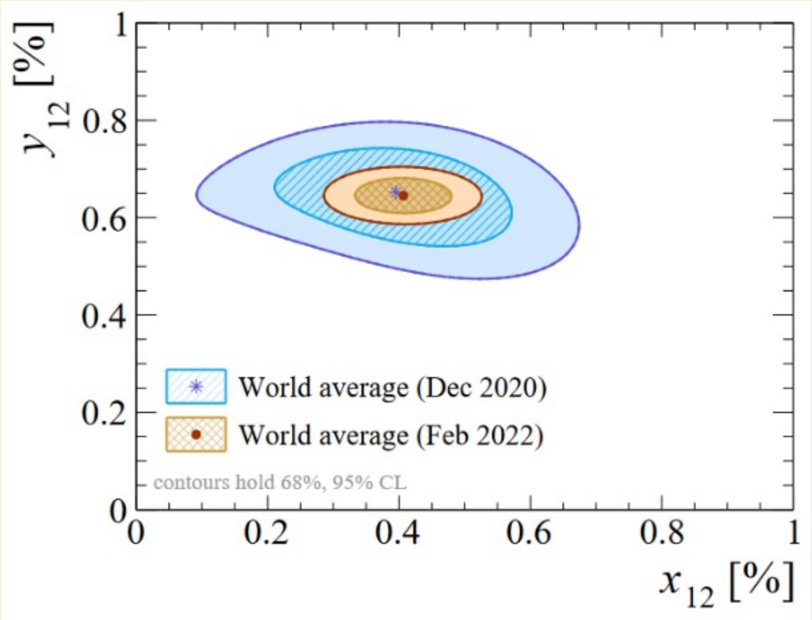
Impact of Upgrade I and II very important for φ_s!

Charm mixing

- Until very recently (2020), no observation yet of charm mixing (extremely difficult).
- New measurement: **precise determination of lifetime difference**
- Study two-body D^0-meson decays
- Decay $D^0 \to K^-\pi^+$ is a **CP-mixed state**: $\tau(D^0 \to K^-\pi^+) \approx 1/\Gamma$
- Decay $D^0 \to h^-h^+ (h \in \pi, K)$ is a **CP-even state**: $\tau(D^0 \to h^-h^+) < \tau(D^0 \to K^-\pi^+)$
- From difference in lifetimes determine $\boldsymbol{y} = (\mathbf{6.96} \pm \mathbf{0.26} \pm \mathbf{0.13}) \times \mathbf{10^{-3}}$
- The new world average becomes: $\boldsymbol{y} = (6.46^{+0.24}_{-0.25}) \times \mathbf{10^{-3}}$, improving the previous result by more than a factor of two.



[PRD 105 (2022) 092013]



[PRD 105 (2022) 092013]