CKM and CPV in charm and beauty decays at LHCb

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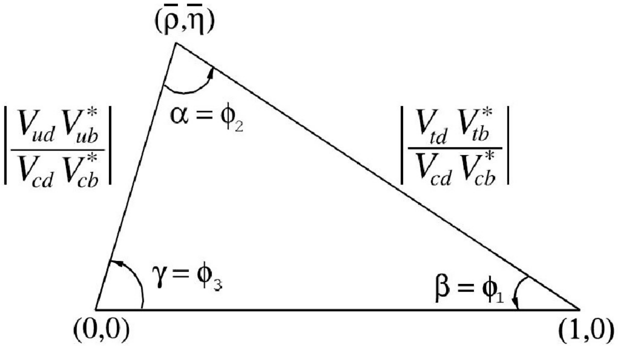
Outline

- Introduction to CKM and CPV
- The LHCb detector
- List of most relevant/recent LHCb measurements
  - Not exhaustive list
  - B^0 and B_s^0 mixing phases
  - The γ angle
  - CPV in charm
- Conclusions and outlook

The CKM matrix

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

3x3 complex unitary

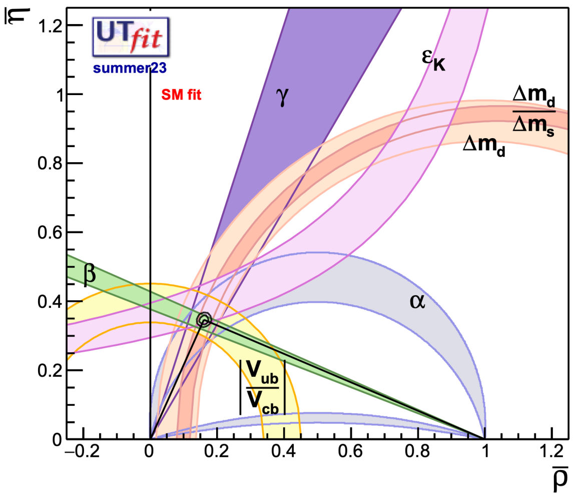


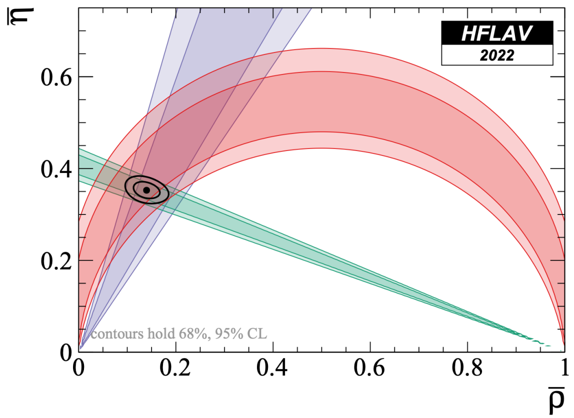
Unitary conditions

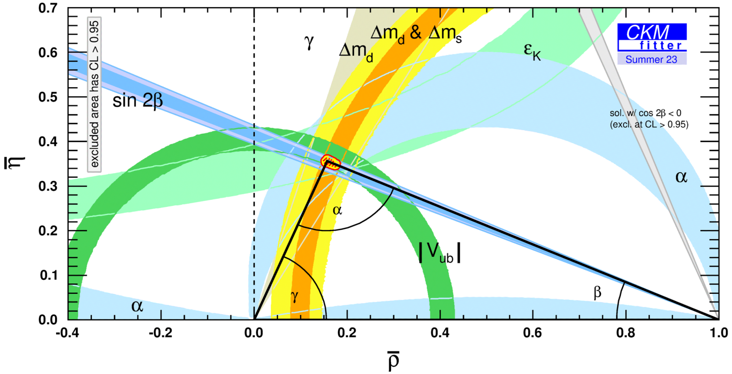
- The CKM matrix accommodates the mixing between mass and flavour eigenstates of quarks that arises from the electroweak symmetry breaking (Higgs mechanism)
- Encodes the strength of quark flavour-changing transitions
- Governs the breaking of CP symmetry in the SM

CKM metrology

- One of the most powerful tools to test the Standard Model
- The CKM matrix has only 4 parameters
  - The Unitary Triangle is highly overconstrained from many measurements
  - Unique consistency check

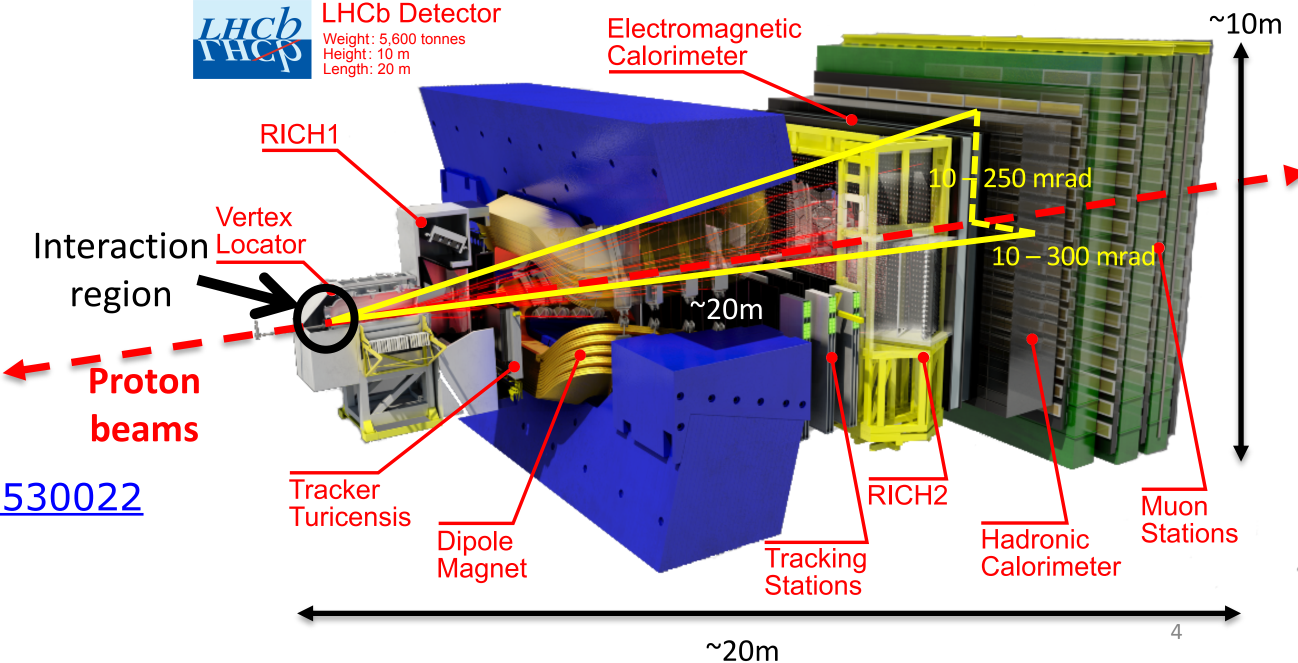






The LHCb detector

- LHCb is able to exploit the unique heavy-flavour factory that is the LHC
  - Very large cross section for $b\bar{b}$ and $c\bar{c}$ quark pairs
    - All kind of beauty hadrons are produced including beauty baryons and B_c^+
  - Excellent time resolution (σ_t ~ 45 fs), momentum resolution ($\delta p/p$ ~ 0.4-0.6%), PID performances (RICH, Muon, CALO)



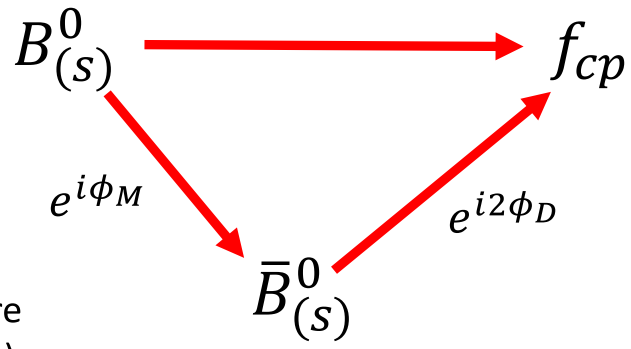
[JINST 3 S08005](#)
[Int. J. Mod. Phys. A 30 (2015)1530022](#)

Neutral B mixing phases

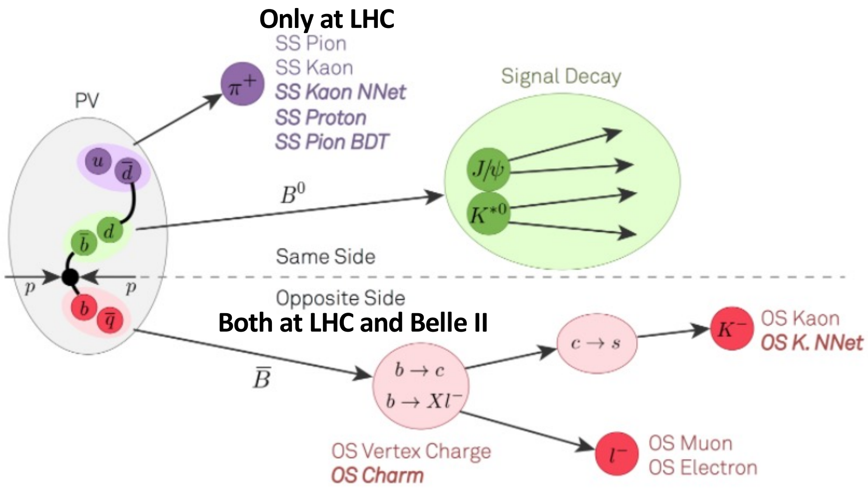
[PRL132(2024)021801, LHCb-PAPER-2023-041, PRL132(2024)051802, PRL131(2023)171802]

$B^0_{(s)}$ mixing phases

- Time-dependent CPV allows constraints to the UT apex to be derived from B^0 (sin2β) and B_s^0 (ϕ_s) mixing phases
  - **Measure CP phase in the interference between B-mixing and decay**
  - Golden modes are $\mathrm{B}^0 \to J/\psi K_S^0$ and $B_s^0 \to J/\psi h^+ h'^-$ since are dominated by tree-level $b \to c\bar{c}q$ transitions (No CPV in decay)



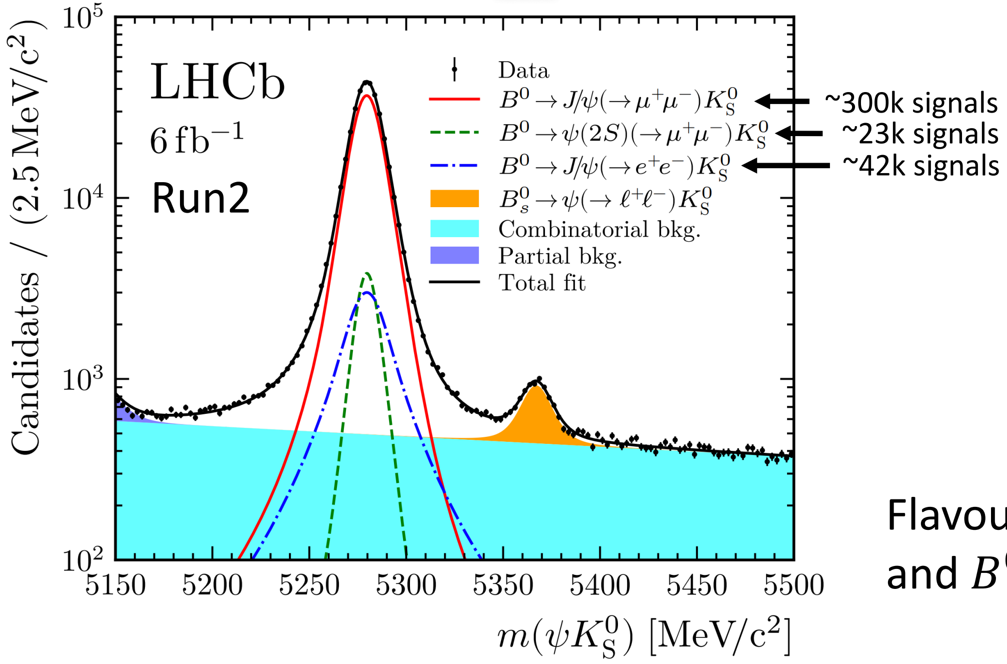
- Fundamental to identify the flavour of the B at the production → flavour tagging
  - $\sigma^2_{CP} \propto \varepsilon_{eff}^{-2}$ effective tagging power
  - $\boldsymbol{\varepsilon_{eff}^{LHCb} \approx 5-8\%,\ \varepsilon_{eff}^{BelleII} \approx 30\%}$
    Belle II profits from the much cleaner environment, but LHCb can exploit much larger samples

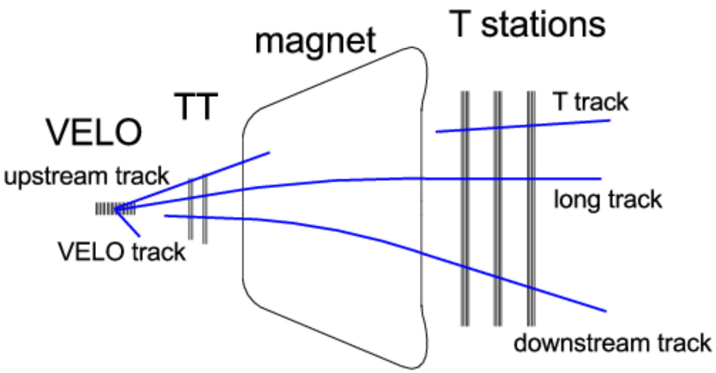


Measurement of sin2β with $B^0 \to \psi K_S^0$

[PRL132(2024021801)]

- Combined analysis of three modes and four $K_S^0 \to \pi^+\pi^-$ reconstruction (LL, DD, LD and UL)
  - LD and UL used for the first time in TD measurements
    ➔ ~13% of signal yields



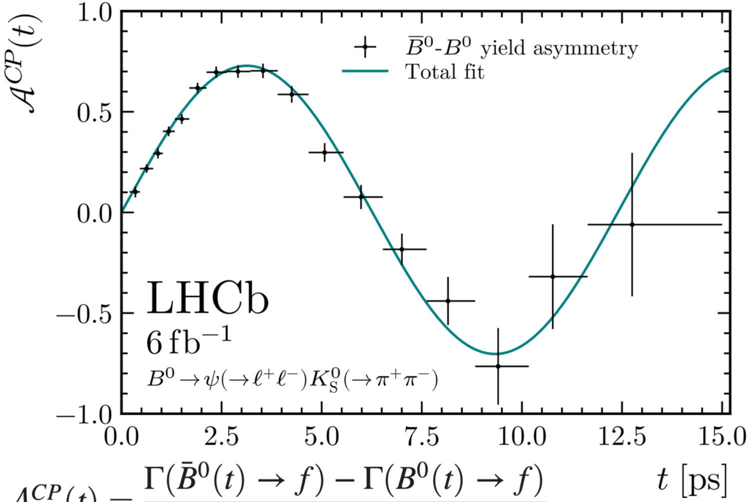


Channel	ε_{eff} [%]
$B^0 \to J/\psi(\to \mu^+\mu^-)K_S^0$	3.98
$B^0 \to J/\psi(\to e^+e^-)K_S^0$	5.96
$B^0 \to \psi(2S)(\to \mu^+\mu^-)K_S^0$	3.89

Flavour tagging calibrated with $B^+ \to \psi K^+$ and $B^0 \to \psi K^{*0}$

Measurement of sin2β with $B^0 \to \psi K_S^0$

[PRL132(2024021801)]



$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = \frac{S\sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

$$S_{\psi K_S^0} = 0.717 \pm 0.013(\mathrm{stat}) \pm 0.008(\mathrm{syst}) \sim \sin 2\beta$$

$$C_{\psi K_S^0} = 0.008 \pm 0.012(\mathrm{stat}) \pm 0.003(\mathrm{syst}) \sim 0$$

Better than previous WA

Systematic uncertainties

Source	$\sigma(S)$	$\sigma(C)$
Fitter validation	0.0004	0.0006
Decay-time bias model	0.0007	0.0013
FT $\Delta\epsilon_{\mathrm{tag}}$ portability	0.0014	0.0017
FT calibration portability	0.0053	0.0001
$\Delta\Gamma_d$ uncertainty	0.0055	0.0017

Projections on uncertainties

[arXiv:1808.08865, arXiv:1808.10567]

Observable	LHCb Run1	LHCb 25/fb	LHCb 300/fb	Belle II
$S_{\psi K_S^0}$	0.04	0.011	0.003	0.005

Higher yields of LHCb will compete with better FT in Belle II

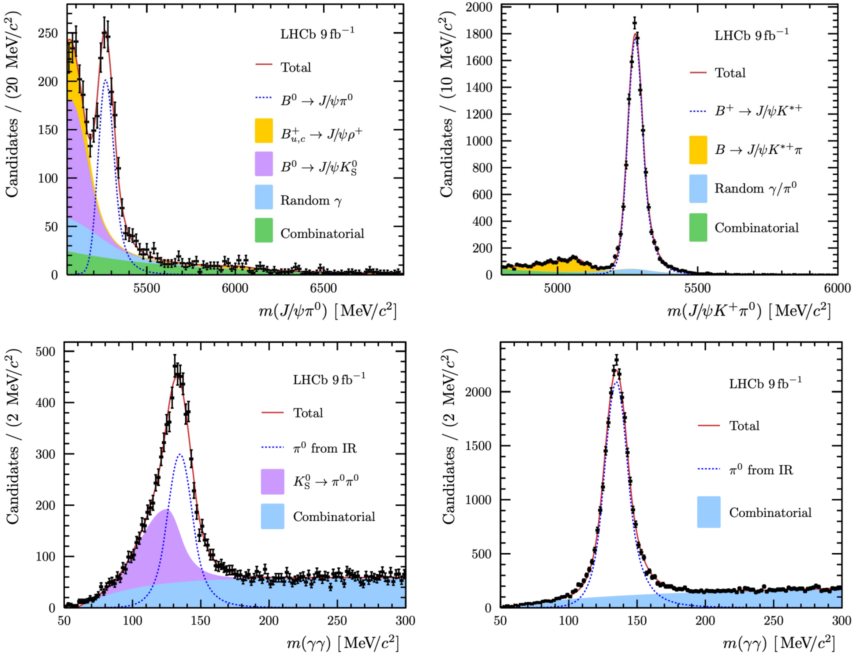
Measurement of BR of $B^0 \to J/\psi\pi^0$

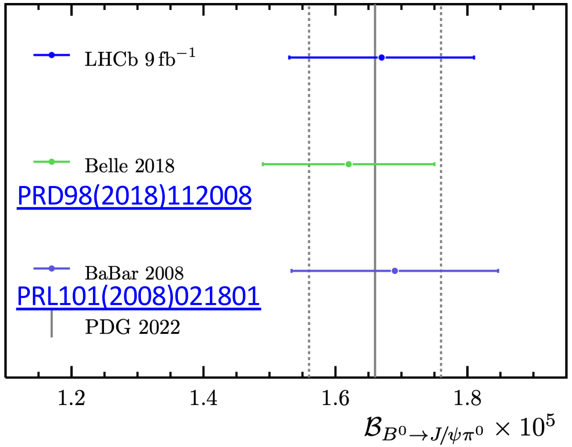
NEW

LHCb-PAPER-2023-041

- Important input to estimate the effect of penguin contamination (δ) in sin2β: $S_{\psi K^0_S} = \sin(2\beta + \delta)$
  - Requires TD CPV measurement
- Difficult measurement at LHCb
  - Presence of π^0 and small FlavourTagging power
  - Started with BR measurement relative to the $B^+ \to \psi K^{*+}(K^+\pi^0)$ mode

Only resolved π^0





LHCb compatible with B-factories with similar precision

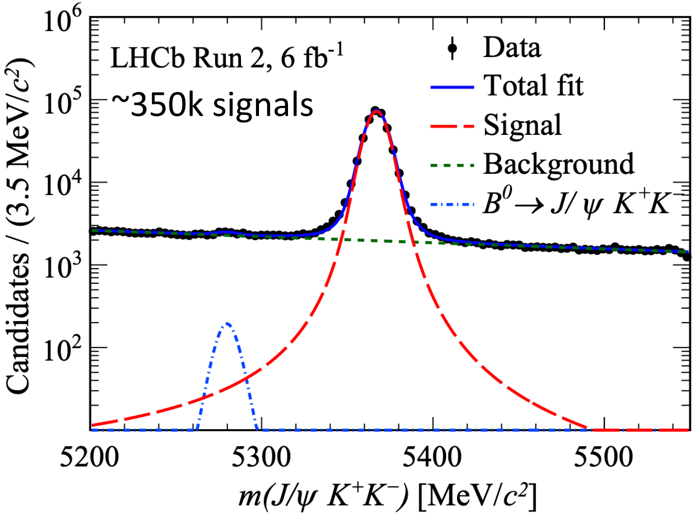
$$\frac{\mathcal{B}_{B^0\to J/\psi\pi^0}}{\mathcal{B}_{B^+\to J/\psi K^{*+}}} = (1.153 \pm 0.053 \pm 0.048) \times 10^{-2}$$

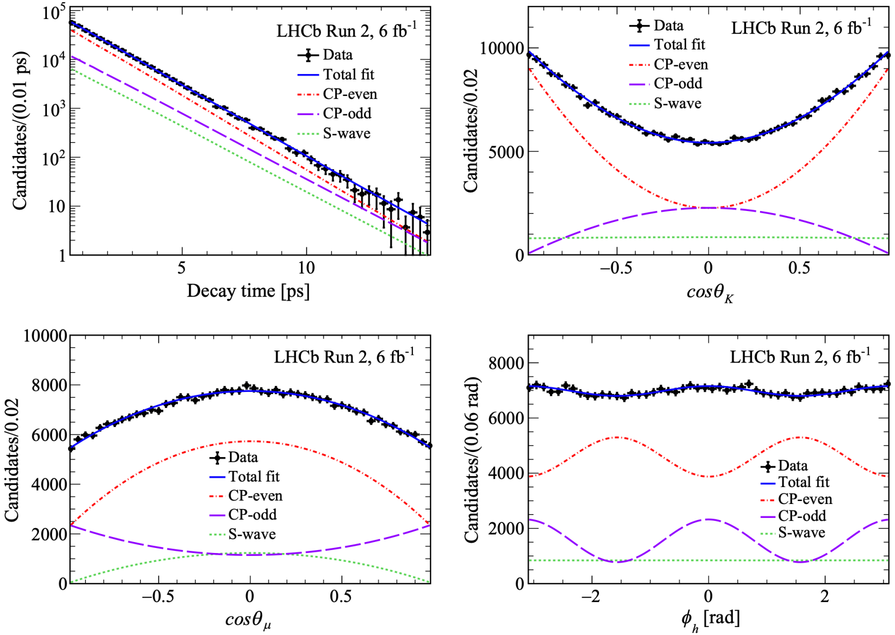
$$\mathcal{B}_{B^0\to J/\psi\pi^0} = (1.670 \pm 0.077 \pm 0.069 \pm 0.095) \times 10^{-5}$$

B_s^0 mixing phase with $B_s^0 \to J/\psi K^+ K^-$

[PRL132(2024)051802]

- In the SM is very small and very precisely determined
  - $\phi_s = -0.0368^{+0.0006}_{-0.0009}$ CKMFitter, $\phi_s = -0.0368 \pm 0.0010$ UTFit
- **Unique to LHC experiments** thanks to the large Lorentz boost in p-p collisions → $\Delta t = \Delta L/\gamma\beta c$
- Golden mode is $B_s^0 \to J/\psi K^+ K^-$
  - Need angular analysis to disentangle CP-even and CP-odd contributions





- Flavour tagging calibrated with $B^+ \to J/\psi K^+$ and $B_s^0 \to D_s^- \pi^+$ → $\varepsilon_{eff} \approx 4\%$
- Decay-time resolution calibrated with prompt fake signals → $\sigma_t \approx 42$ps

B_s^0 mixing phase with $B_s^0 \to J/\psi K^+ K^-$

[PRL132(2024)051802]

Polarisation independent results

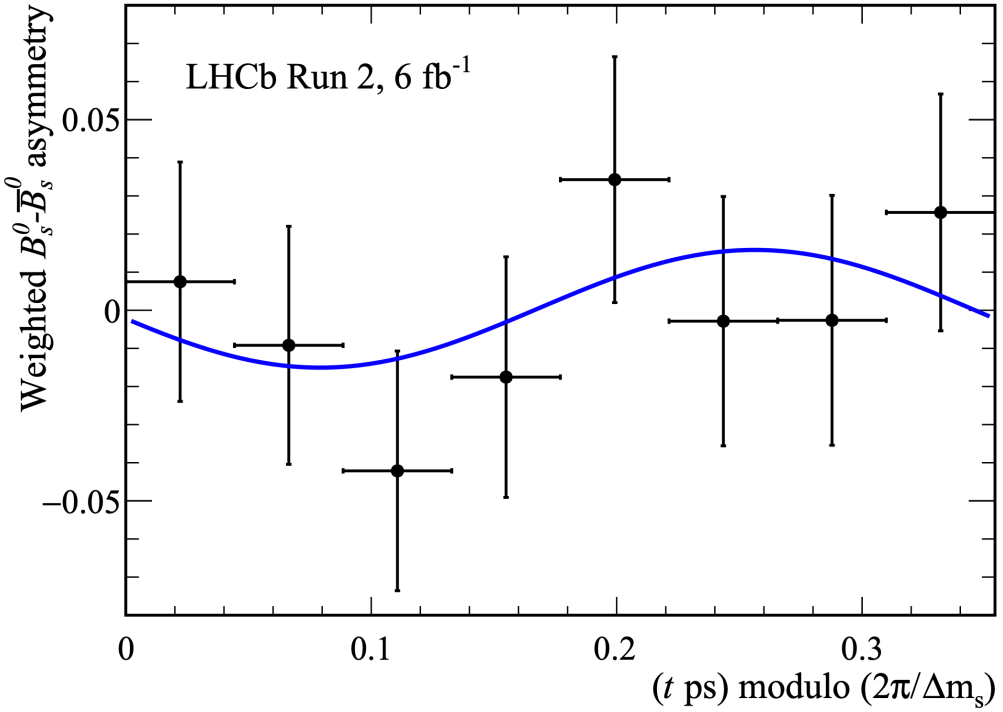
Parameter	Values	Stat.	Syst.
ϕ_s [rad]	-0.039	± 0.022	± 0.006
$\lvert\lambda\rvert$	1.001	± 0.011	± 0.005
$\Gamma_s - \Gamma_d [\mathrm{ps}^{-1}]$	-0.0056	$^{+0.0013}_{-0.0015}$	± 0.0014
$\Delta\Gamma_s [\mathrm{ps}^{-1}]$	0.0845	± 0.0044	± 0.0024
$\Delta m_s [\mathrm{ps}^{-1}]$	17.743	± 0.033	± 0.009
$\lvert A_\perp\rvert^2$	0.2463	± 0.0023	± 0.0024
$\lvert A_0\rvert^2$	0.5179	± 0.0017	± 0.0032
$\delta_\perp - \delta_0$ [rad]	2.903	$^{+0.075}_{-0.074}$	± 0.048
$\delta_\parallel - \delta_0$ [rad]	3.146	± 0.061	± 0.052

Combination with Run1

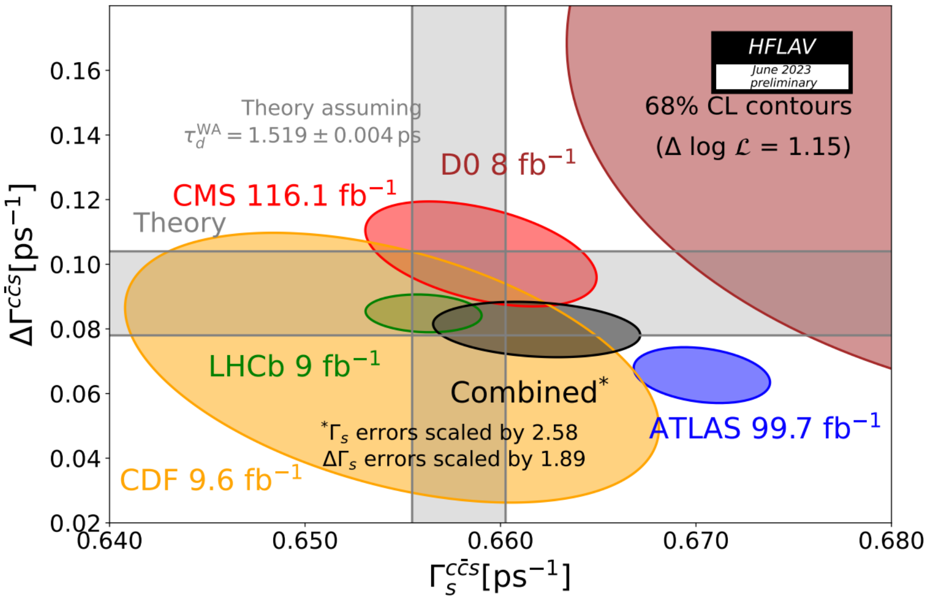
$$\phi_s = -0.044 \pm 0.020 \text{ rad}$$

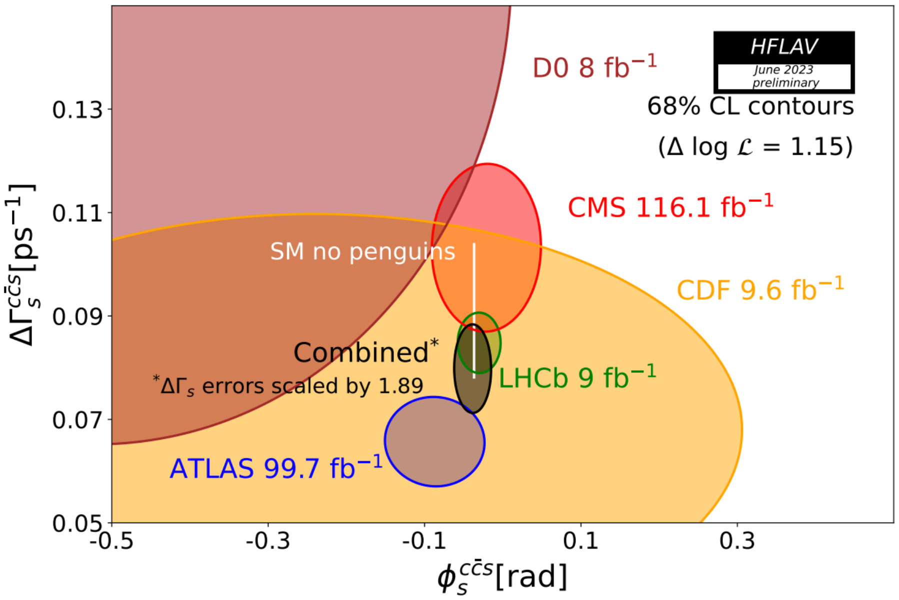
$$\lambda = 0.990 \pm 0.010$$

Polarisation-dependent results are consistent with each other

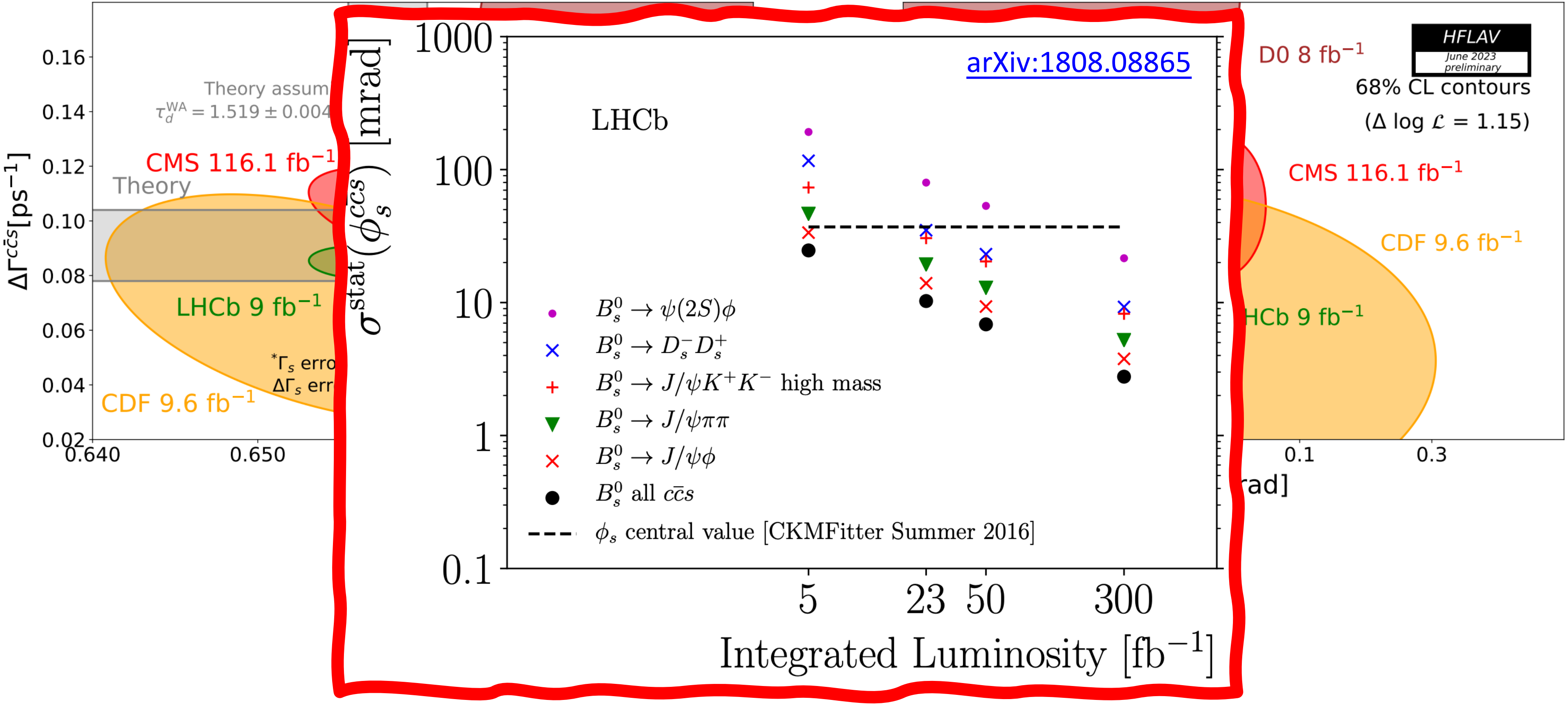


B_s^0 mixing phase





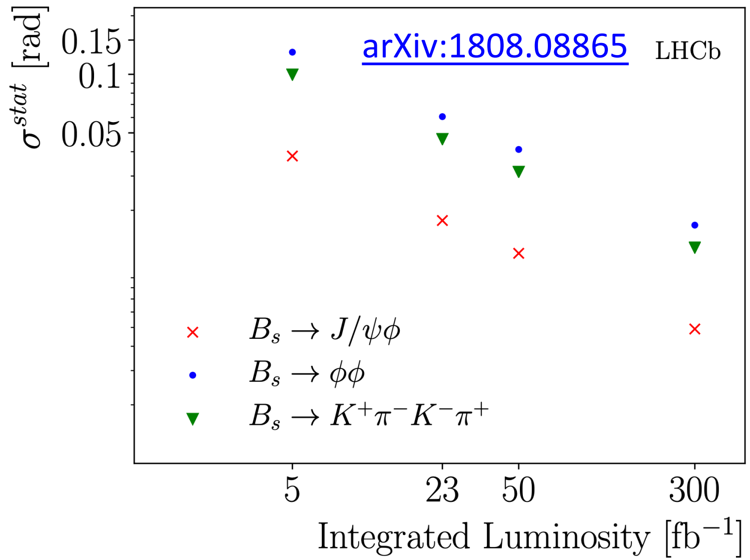
B_s^0 mixing phase



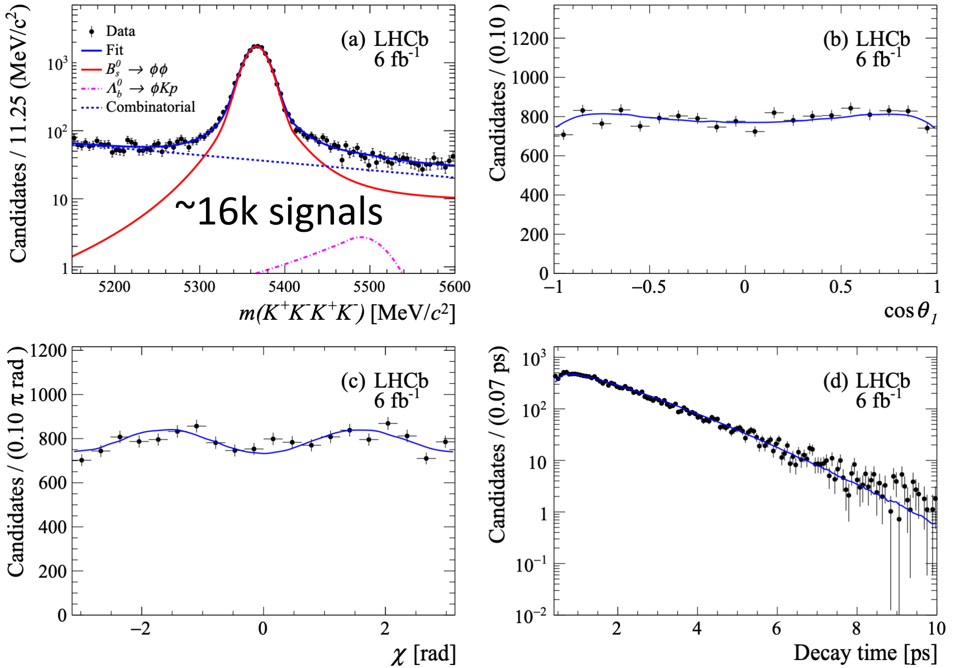
$B^0_{(s)}$ mixing phase with penguins

[PRL131(2023)171802]

- $B^0_s \to \phi(K^+K^-)\phi(K^+K^-)$ is a **pure penguin decay** → $\phi_s^{s\bar{s}s} \approx 0$
  - Very nice opportunity to compare SM quantities with quantities potentially affected by NP



Due to smaller statistics uncertainties will remain larger than for ϕ_s



Polarisation independent

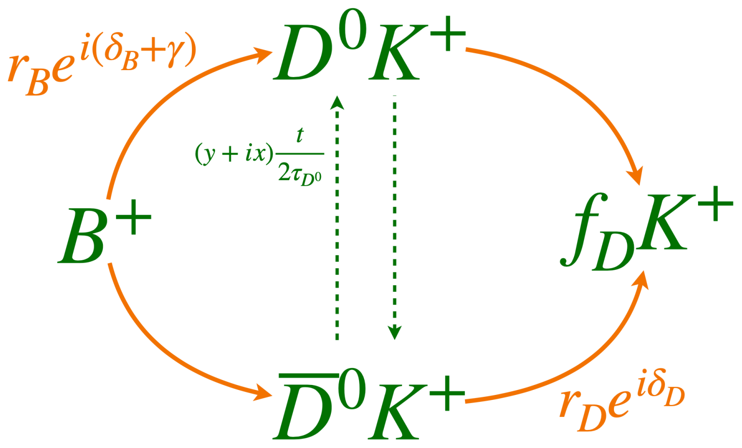
$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad},$$
$$|\lambda| = 1.004 \pm 0.030 \pm 0.009,$$

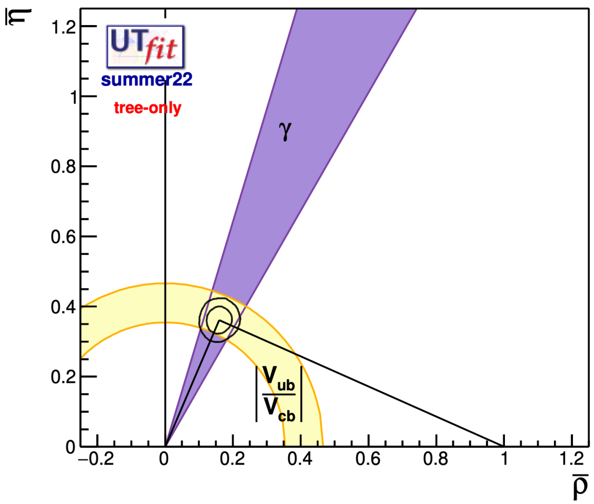
no evidence of polarisation dependence

The γ angle

[LHCb-CONF-2023-004, arXiv:2309.05514, arXiv:2401.17934, arXiv:2311.10434, arXiv:2310.04277]

The γ angle





- Very clean quantity to test the SM
  - Theoretical uncertainty on the interpretation of γ measurements is ~10^{-7} [Zupan & Brod 1308.5663]
- Current experimental uncertainty is < 4°
  - **Thanks to the combination of many modes each with different sensitivities to γ**
  - Given the current precision also **CPV and mixing effects in charm decays** must be taken into account
  - Knowledge of **hadronic D decay parameters** fundamental to improve sensitivity to γ

Time-dependent CPV with $B_s^0 \to D_s^{\mp} K^{\pm}$

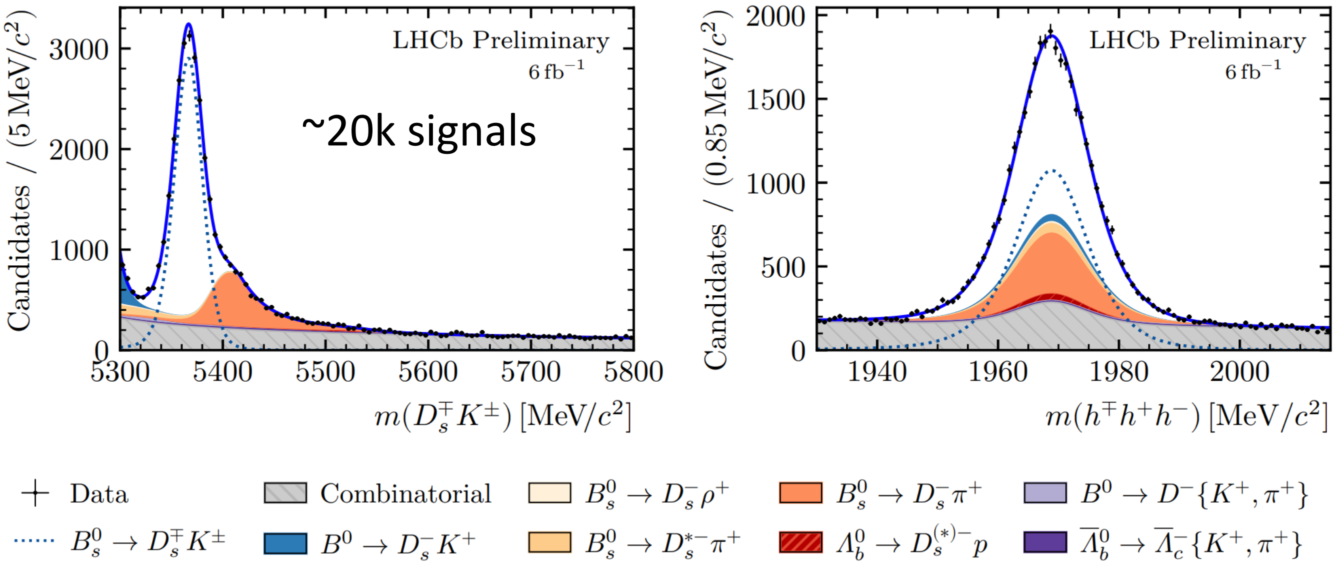
[LHCb-CONF-2023-004]

- Time-dependent CPV of this mode is sensitive to γ
  - Four decay rates, 5 CPV observables
    ➔ including also ϕ_s from external input the system is over constrained
- Five decay modes to reconstruct $D_s^{\mp}$
- Flavour tagging calibrated with $B_s^0 \to D_s^- \pi^+$ (also used for Δm_s measurement)

$$C_f = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2} ,$$

$$A_f^{\Delta\Gamma} = \frac{-2 r_{D_sK} \cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2} , \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2 r_{D_sK} \cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}$$

$$S_f = \frac{2 r_{D_sK} \sin(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2} , \quad S_{\bar{f}} = \frac{-2 r_{D_sK} \sin(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2} .$$



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    ➔ including also ϕ_s from external input the system is over constrained
- Five decay modes to reconstruct $D_s^{\mp}$
- Flavour tagging calibrated with $B_s^0 \to D_s^- \pi^+$
  (also used for Δm_s measurement) ➔ $\varepsilon_{eff} \approx 6\%$

$$C_f = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2},$$

$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}$$

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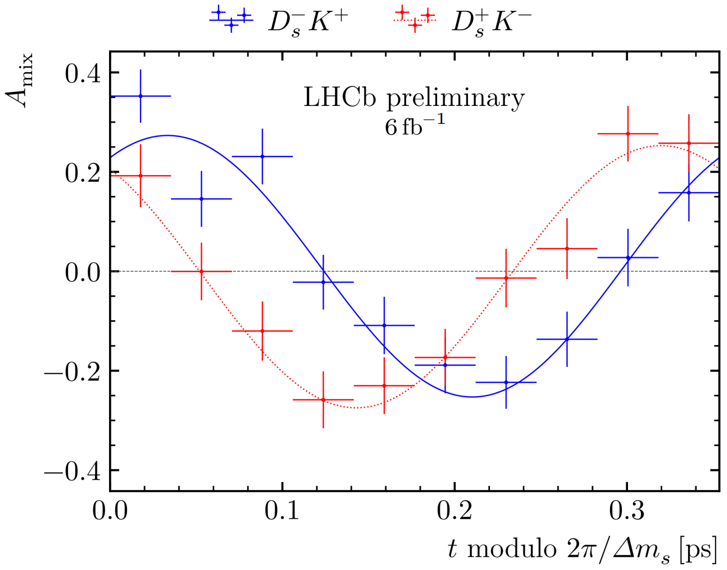
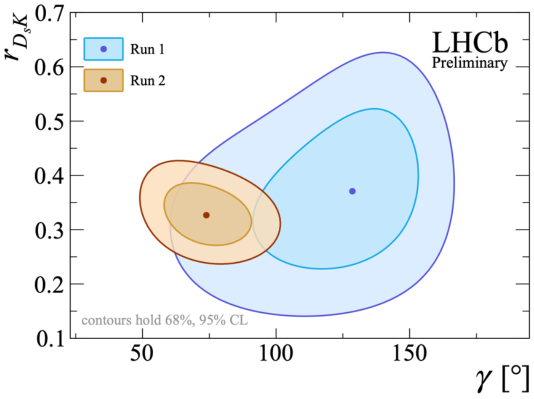
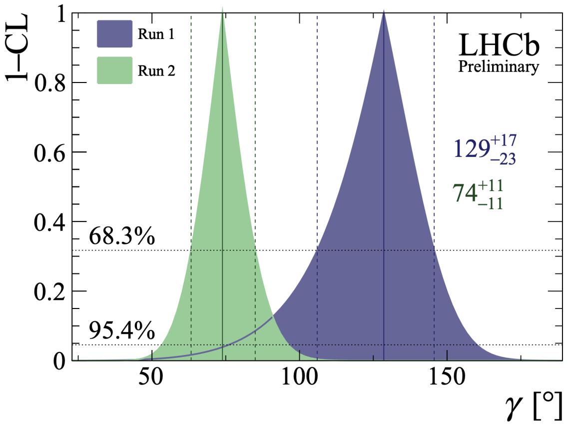




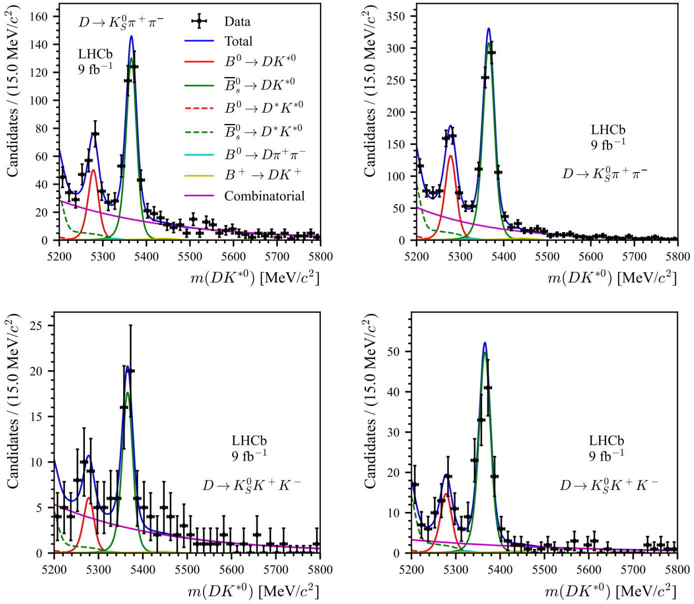


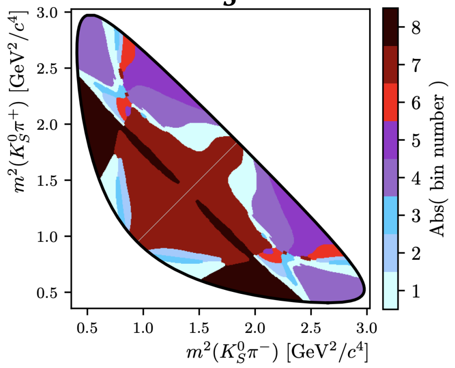
Very good agreement with LHCb average of γ
Previous tension with B^+ determination is solved

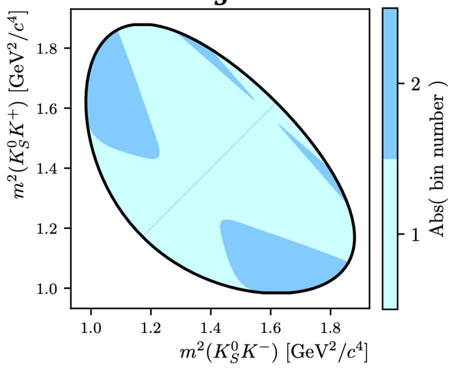
γ with $B^0 \to D^0(\to K_S^0 h^+ h^-) K^{*0}$ decays

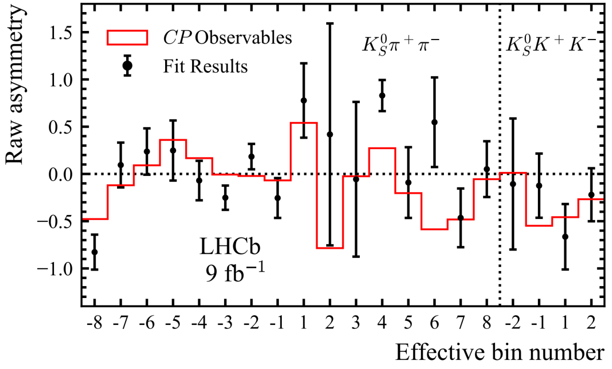
[arXiv:2309.05514]

- Measure CP asymmetries in bins of $D^0 \to K_S^0 h^+ h^-$ phase space
  - Binning schemes optimised to maximise sensitivity on γ
  - Most recent determinations of charm hadronic parameters from BESIII and CLEO-c [PRD101(2020)112002, PRD102(2020)052008, PRL124(2020)241802, PRD82(2010)112006]









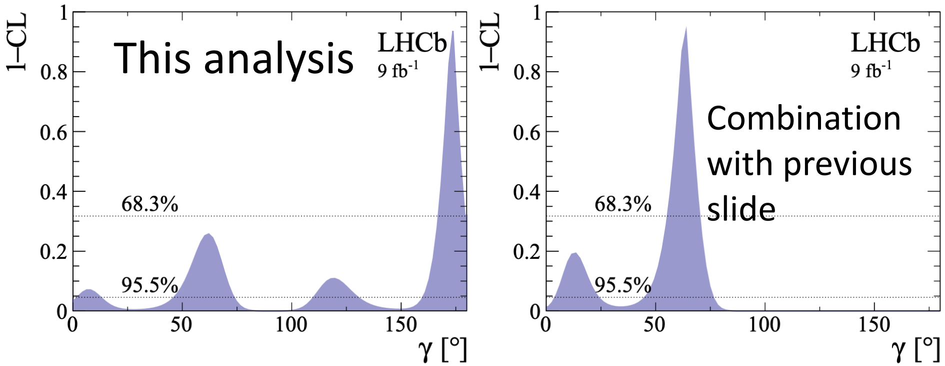
$$\gamma = (49^{+23}_{-18})^\circ,$$
$$r_{B^0} = 0.271^{+0.068}_{-0.066},$$
$$\delta_{B^0} = (236^{+19}_{-21})^\circ.$$

Results are compatible between each other and with LHCb average

γ with $B^0_{(s)} \to D^0 K^{*0}$ decays

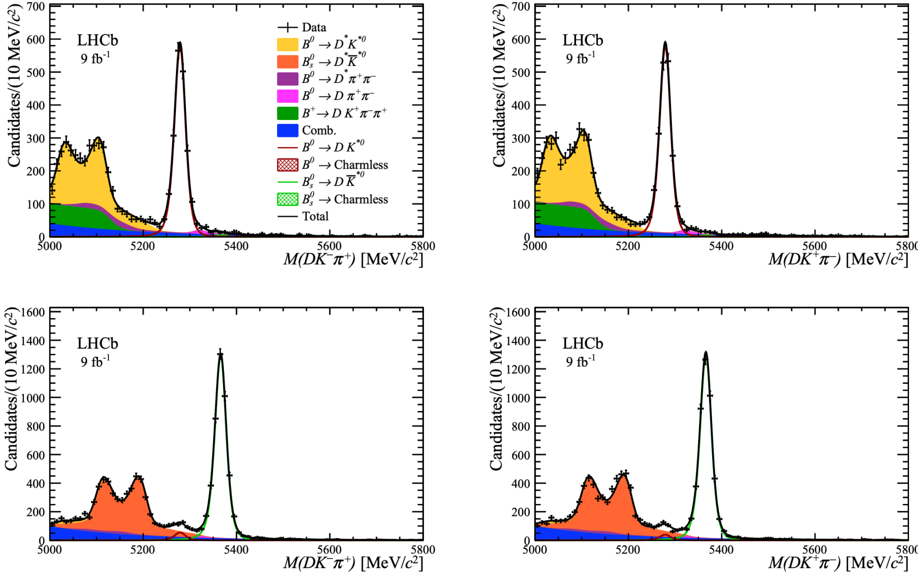
[arXiv:2401.17934]

- Combine measurements using 2- and 4-body decays of the D^0 meson
  - $K^{\mp}\pi^{\pm}$, $K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}$, $\pi^{+}\pi^{-}$, $\pi^{+}\pi^{-}\pi^{+}\pi^{-}$, $K^{+}K^{-}$
  - Binned phase space for $K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}$ to optimise sensitivity on γ using latest BESIII and CLEO-c results [JHEP05(2021)164,PRD106(2022)092004,PLB747(2015)9]



$$\gamma = (63.3 \pm 7.2)^{\circ}$$
$$r_{B^0}^{DK^*} = 0.233 \pm 0.016$$
$$\delta_{B^0}^{DK^*} = (191.8 \pm 6.0)^{\circ}$$

NEW

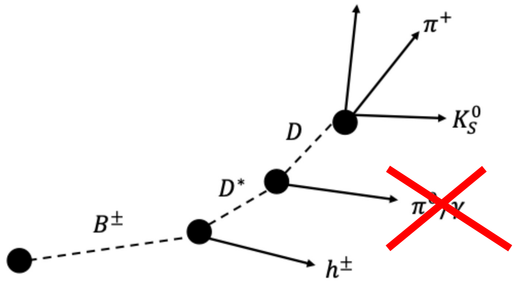


With these results the tension between B⁺ and B⁰ determination of γ goes away

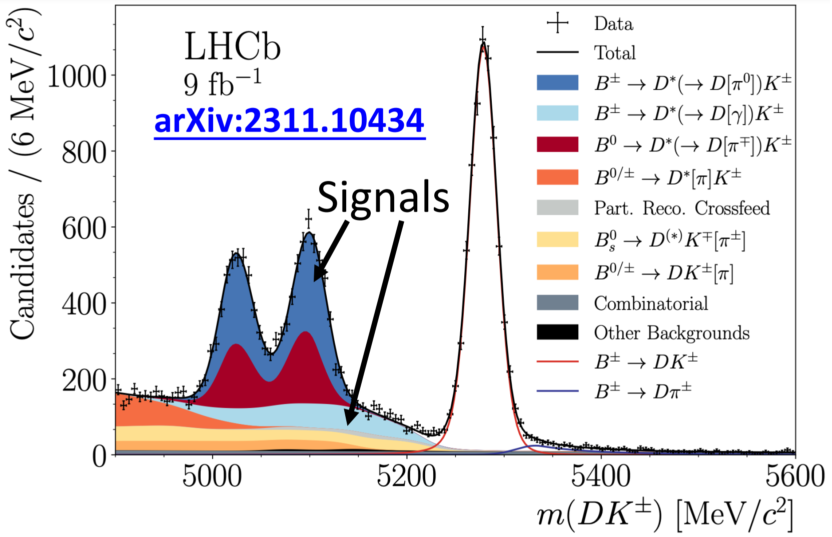
γ with $B^+ \to D^{*0}(\to D^0\ \gamma\ /\pi^0)h^+$ decays

[arXiv:2311.10434, arXiv:2310.04277]

- Both full and partial (no γ or π^0) reconstruction of D^{*0}
  - Negligible correlation between the two samples
- Reconstruct D^0 in the $K_S^0 h^+ h^-$ final state
  - Same binned method as in slide 19



Partial reconstruction



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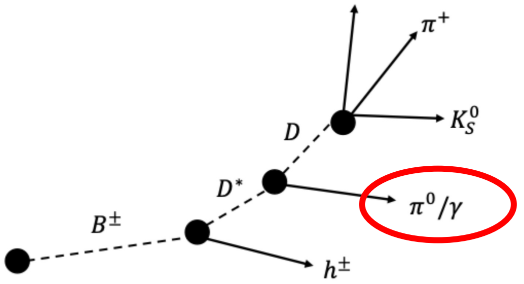
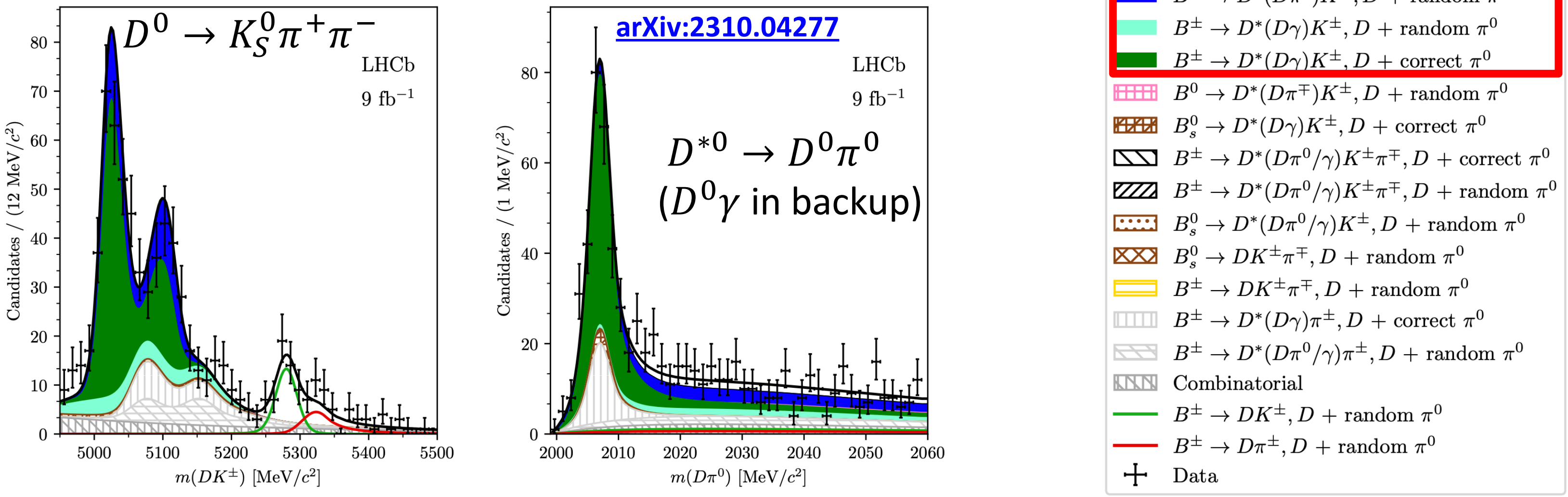


Full reconstruction - 2D fit to disentangle contributions



Components sensitive to γ

γ with $B^+ \to D^{*0}(\to D^0\,\gamma\,/\pi^0)h^+$ decays

[arXiv:2311.10434, arXiv:2310.04277]

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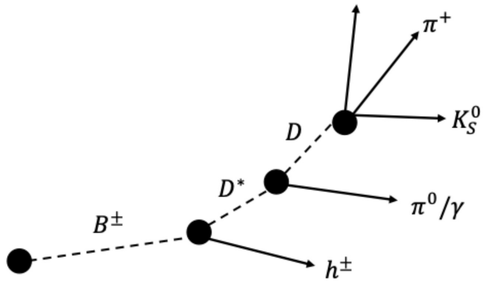


Partial reconstruction

arXiv:2311.10434

$$\gamma = (92^{+21}_{-17})^\circ,$$
$$r_B^{D^*K} = 0.080^{+0.022}_{-0.023},$$
$$\delta_B^{D^*K} = (310^{+15}_{-20})^\circ,$$
$$r_B^{D^*\pi} = 0.009^{+0.005}_{-0.007},$$
$$\delta_B^{D^*\pi} = (304^{+37}_{-38})^\circ.$$

Full reconstruction

arXiv:2310.04277

$$\gamma = (69^{+13}_{-14})^\circ,$$
$$r_B^{D^*K} = 0.15 \pm 0.03,$$
$$r_B^{D^*\pi} = 0.01 \pm 0.01,$$
$$\delta_B^{D^*K} = (311 \pm 14)^\circ,$$
$$\delta_B^{D^*\pi} = (37 \pm 37)^\circ.$$

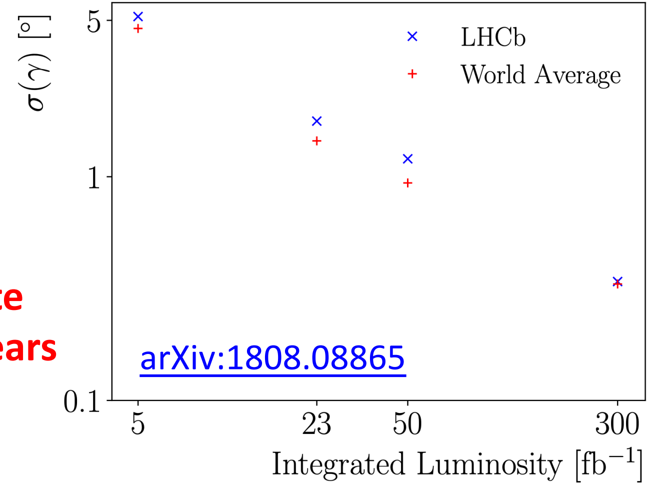
Results are compatible between each other and with LHCb average

γ combination and prospects

- Latest LHCb combination includes many measurements
  - Frequentist approach with 173 observables and 52 parameters
  - **Results shown before not yet included**
  - **Their inclusion will solve the previous tension between B^+ and B^0**

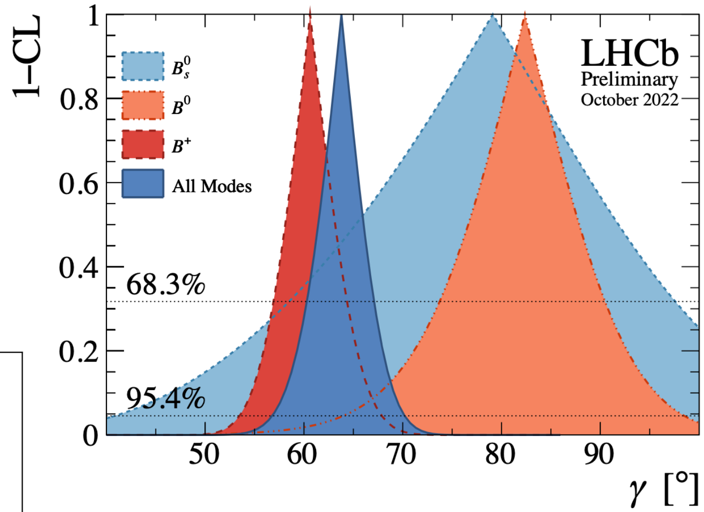
	γ (°)
LHCb	**$63.8^{+3.5}_{-3.7}$ °**
CKMfitter	$65.6^{+1.1}_{-2.7}$ °
UTFit	$65.8^{+2.2}_{-2.2}$ °

LHCb and Belle II will compete on a similar level in the next years



arXiv:1808.08865

LHCb-CONF-2022-003



Precise determination from BESIII of charm hadronic parameters will be fundamental to reach the ultimate precision

arXiv:2103.05988, PRD101(2020) 112002

CPV in charm

[arXiv:2310.19397, JHEP09(2023)129]

CPV in the charm sector

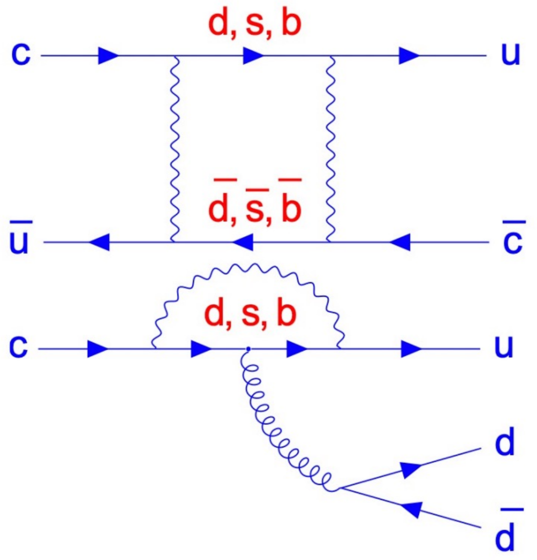
- **Unique laboratory to study CPV in up-type quark decays**
- CPV in charm is highly suppressed in the SM
  - Beauty loop suppressed by smallness of CKM elements:

$$CPV \propto \mathrm{Im}\left(\frac{V_{cb}V_{bu}^{*}}{V_{cs}V_{su}^{*}}\right) \approx -6\times10^{-4}$$

  - Strange-down loops suppressed by GIM mechanism

$$\frac{(m_s^2-m_d^2)}{m_W^2} \sim 0 \text{ in the u-spin limit}$$

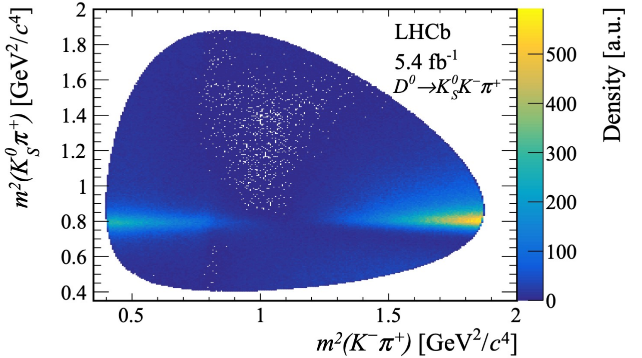
- **Theory predictions complicated by QCD effects that are large and difficult to compute**
- Huge charm data sample from LHCb lead to **first observation of CPV in $D^0 \to h^+h^-$ decays in 2019** [PRL122(2019)211803]
  - Great improvement in efficiency in Run2 thanks to software trigger
  - New measurements in more channels needed to unravel the mystery

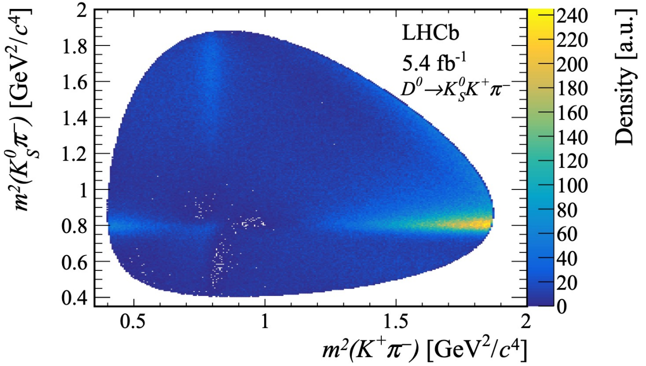


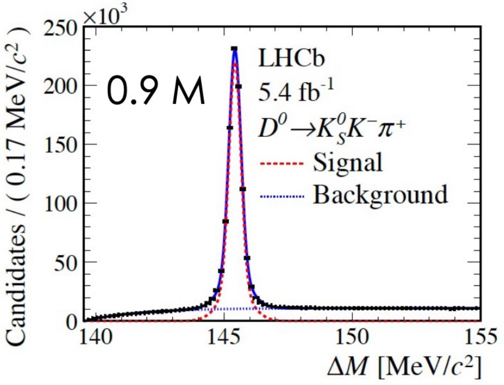
Search for CPV in $D^0 \to K_S^0 K^{\pm}\pi^{\mp}$

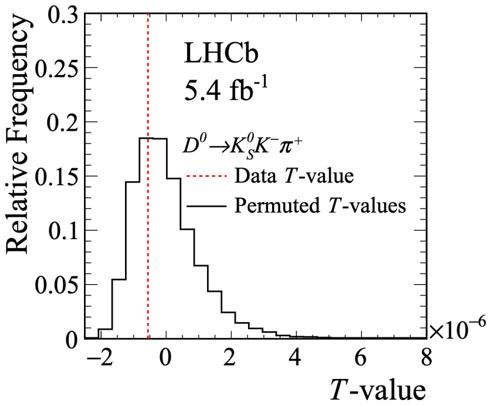
[arXiv:2310.19397]

- Rich resonant structure in the Dalitz plane
- Model independent search
  - Energy test: Search for differences in the D^0 and $\overline{D}^0$ Dalitz plot via the distances between decays in the phase-space distributions.
  - Sensitive to ~2% CP asymmetries and 2° of phase difference







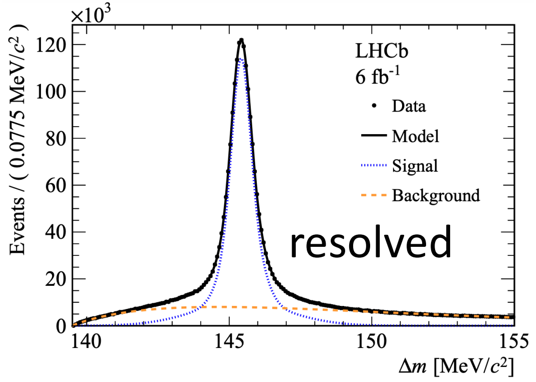


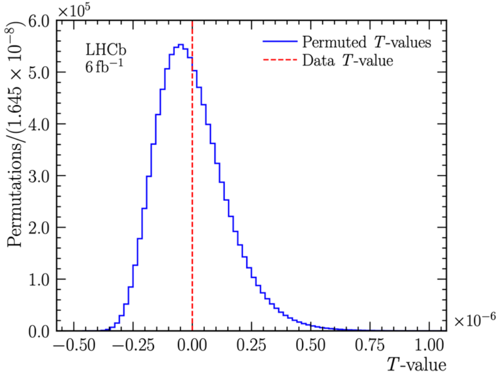
No significant difference between D^0 and $\overline{D}^0$ is observed (p-value > 60%)

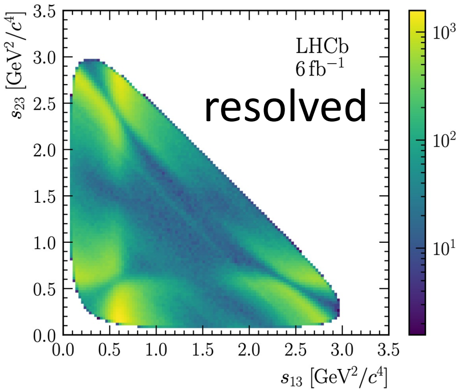
Search for CPV in $D^0 \to \pi^+\pi^-\pi^0$

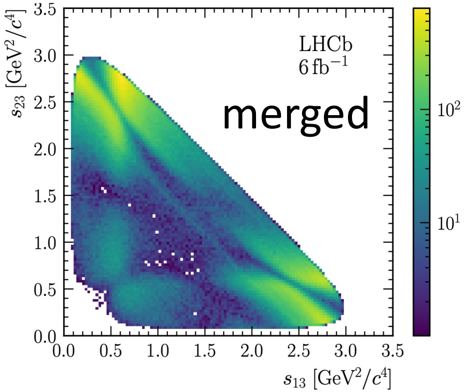
[JHEP09(2023)129]

- Same method as in the previous slide
- Two different reconstruction of $\pi^0 \to \gamma\gamma$
  - The two photons make a merged cluster in the ECAL
  - The two photons make separated (resolved) clusters in the ECAL
- Sensitivity limit are at 0.5% for asymmetries and 0.5° for phase differences





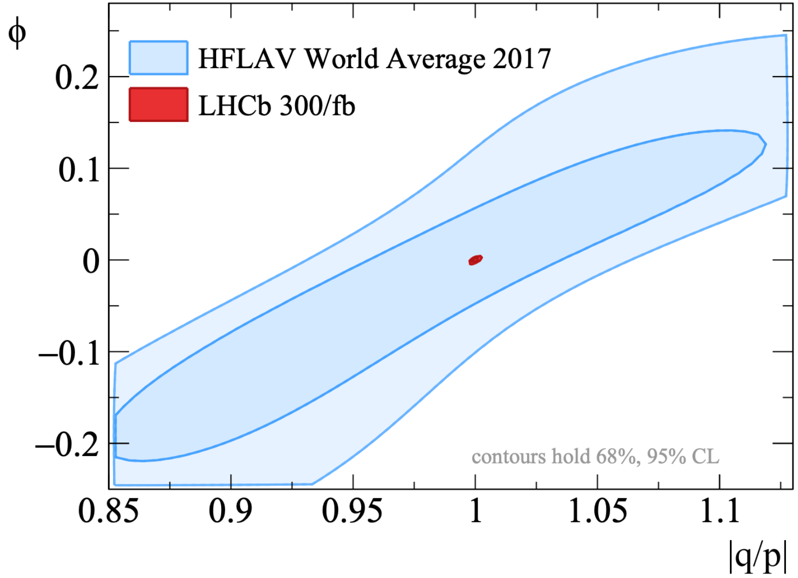




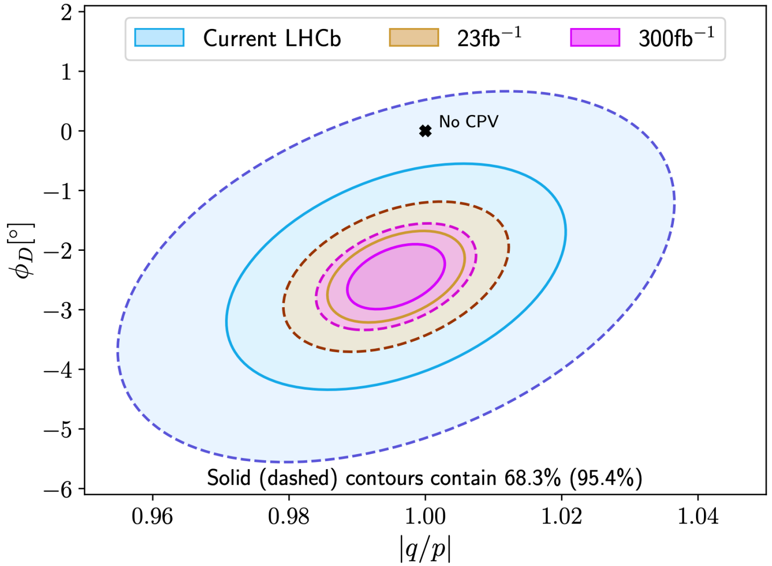
No significant difference between D^0 and $\overline{D}^0$ is observer (p-value = 0.62 for CP-conservation)

Outlook on charm CPV

arXiv:1808.08865



LHCb-TDR-023



LHCb (and its upgrades) will be the biggest charm factory ever
It is essential to exploit it,
but that will require extreme control of experimental and theoretical systematics

Conclusions

- A lot of results are still being produced with LHCb Run1+Run2 sample
  - World leading measurements of mixing phases of neutral B mesons
  - New measurements of $B \to Dh$ decays continuously improving the constraints on the γ angle and on the UT apex
  - LHCb is still exploiting its enormous charm data sample to chase new evidences of CP violation in this sector
- No evidence of discrepancies is observed with respect to SM expectations
  - Shrinking the precision on many CPV observables will be fundamental to test the CKM paradigm to its ultimate precision
  - LHCb Upgrade I is going to start to collect data with the potential to more than double its sample in the next two years
  - Complementarity and cross-check with Belle II will be fundamental as well

BACKUP

A story full of successes

1950's Discovery of parity violation

1960's CP violation in K decays

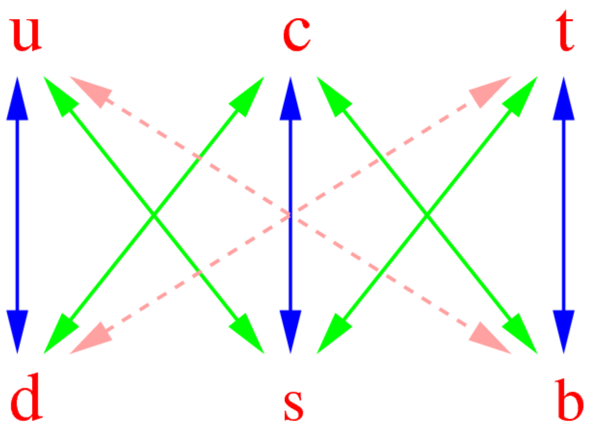
1980's Inference on top quark mass from B mixing

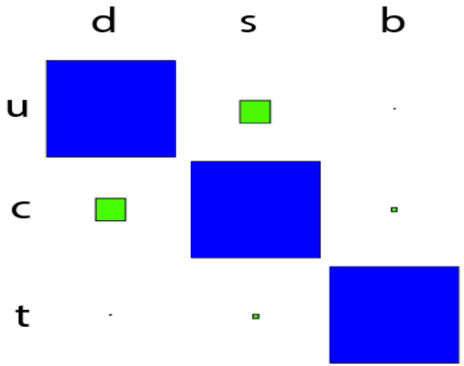
2000's CP violation in B decays

2020's CP violation in D decays

Cartoon presented by N. Cabibbo at the Berkeley conference in 1966

The CKM matrix

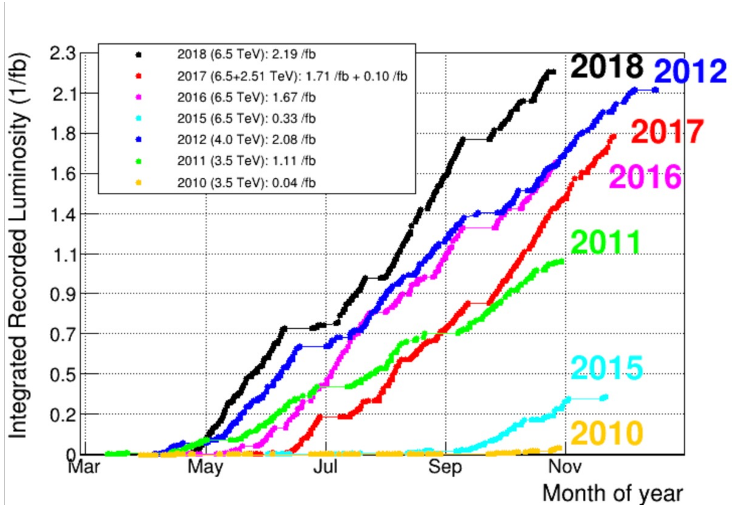




- The CKM matrix accommodates the mixing between mass and flavour eigenstates of quarks that arises from the electroweak symmetry breaking (Higgs mechanism)
- Encodes the strength of quark flavour-changing transitions
- Governs the breaking of CP symmetry in the SM

LHCb dataset

- Collected samples
  - p-p collisions for an integrated luminosity of 3.2 fb^{-1} in Run1 + 5.9 fb^{-1} in Run2 ➔ today's results
  - Pb-Pb, p-Pb and fixed target collisions (p-Gas)
- LHCb Upgrade I started in 2022:
  - 2022/23 have been mostly commissioning due to VELO accident with vacuum and LHC issue in Summer 2023
  - Current plan is to collect 7+7 fb^{-1} in 2024-25
    - More than doubling the statistics of Run1+Run2



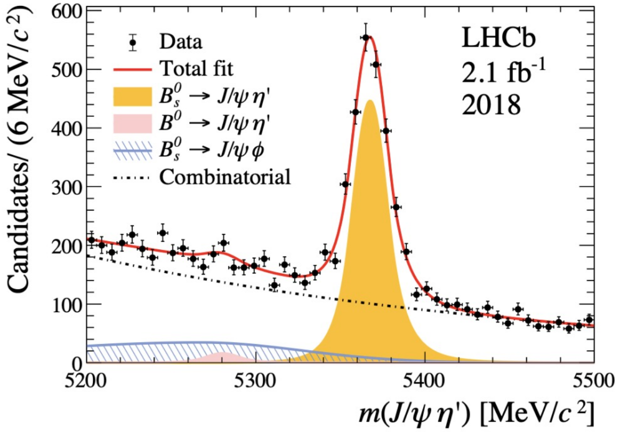
Measurement of $\Delta\Gamma_s$

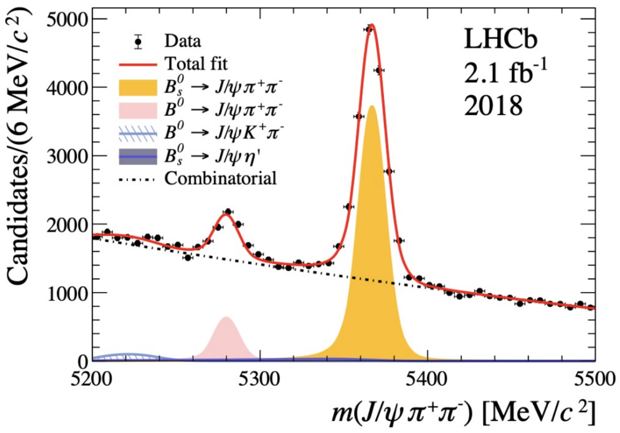
[arXiv:2310.12649]

- Measure the relative yields of $B_s^0 \to J/\psi\eta'(\to \rho^0\gamma)$ (CP-even) and $B_s^0 \to J/\psi f_0(980)(\to \pi^+\pi^-)$ (CP-odd) in bins of decay time
  - Extended unbinned simultaneous maximum-likelihood fit to 8 decay-time bins
  - Yield ratio in each bin is corrected for decay-time efficiency effects

$$R_i = \frac{N_\mathrm{L}}{N_\mathrm{H}} \propto \frac{\left[e^{-\Gamma_s t(1+y)}\right]_{t_1}^{t_2}}{\left[e^{-\Gamma_s t(1-y)}\right]_{t_1}^{t_2}} \cdot \frac{(1-y)}{(1+y)}$$

$$y = \Delta\Gamma_s / 2\Gamma_s$$





Measurement of $\Delta\Gamma_s$

[arXiv:2310.12649]

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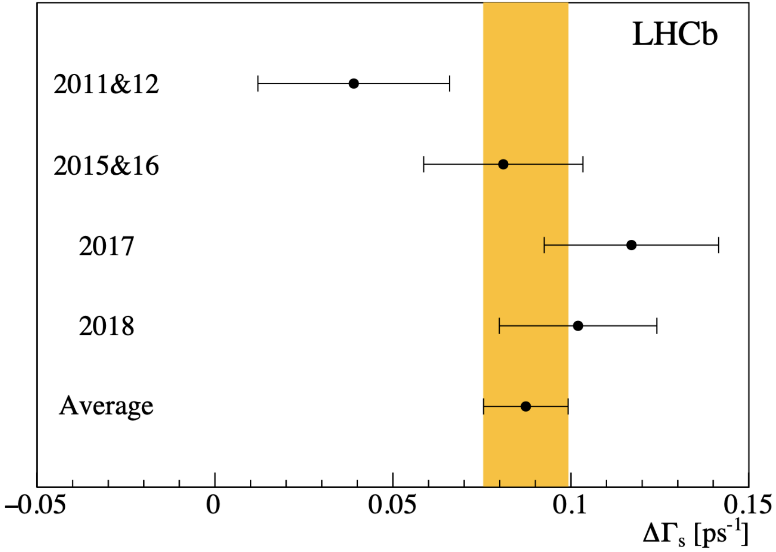
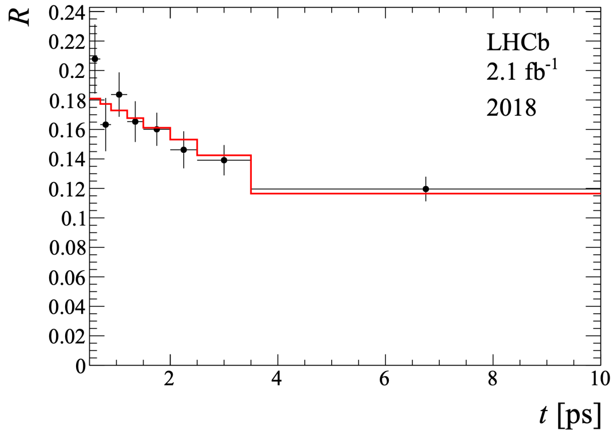


$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009 ps^{-1}$

HFLAV: $\Delta\Gamma_s = 0.080 \pm 0.006 ps^{-1}$

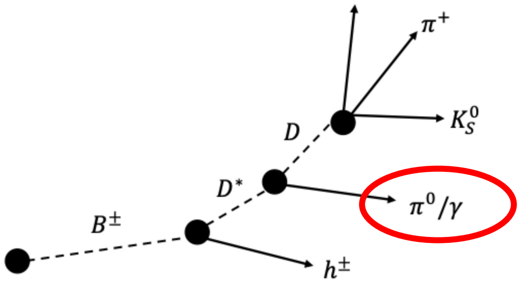


Source	Value $[\mathrm{ns}^{-1}]$
Simulation sample size	4.6
Acceptance model	3.0
Bin centre method	0.3
CP violation	0.1
Γ_s	0.1
$J/\psi\eta'$ background model	6.9
$J/\psi\pi^+\pi^-$ background model	0.8
Total	8.9

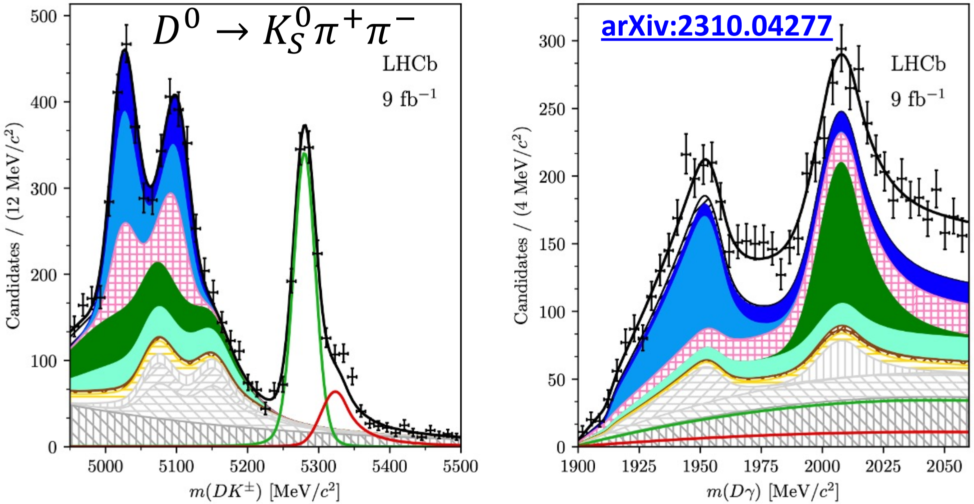
γ with $B^+ \to D^{*0}(\to D^0\ \gamma\ /\pi^0)h^+$ decays

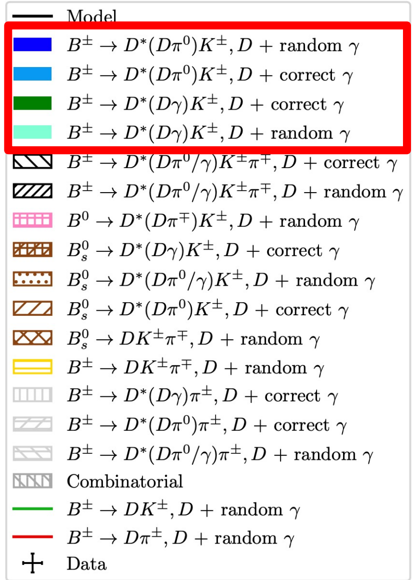
[arXiv:2311.10434, arXiv:2310.04277]

- Both full and partial (no γ or π^0) reconstruction of D^{*0}
  - Negligible correlation between the two samples
- Reconstruct D^0 in the $K_S^0 h^+ h^-$ final state
  - Same binned method as in slide 19



Full reconstruction - 2D fit to disentangle contributions





Components sensitive to γ

Search for CP violation in $D^0 \to \pi^- \pi^+ \pi^0$ decays with the energy test

[PLB 740 (2015) 158–167]

- Model independent Dalitz Plot analysis to look for CPV
  - method is unbinned and is based on test statistic $T = \Sigma_i (T_i + \bar{T}_i)$

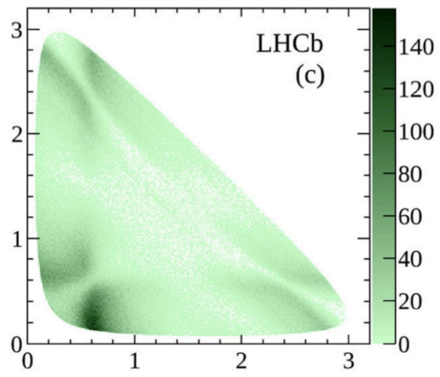
“Energy Test” [PRD 84 (2011) 054015]

$$T_i = \frac{1}{2n(n-1)} \sum_{j \neq i}^{n} \psi_{ij} - \frac{1}{2n\bar{n}} \sum_{j}^{\bar{n}} \psi_{ij},$$ → contribute of a single D^0

$$\bar{T}_i = \frac{1}{2\bar{n}(\bar{n}-1)} \sum_{j \neq i}^{\bar{n}} \psi_{ij} - \frac{1}{2n\bar{n}} \sum_{j}^{n} \psi_{ij}.$$ → contribute of a single $\bar{D}^0$

Ψ_{ij}: gaussian metric decreasing with ij-distance in the DP

T = 0 → no-CPV
T > 0 → CPV



Examples from simulation

introducing 2% direct CPV in ρ^+ resonance

introducing 1° CPV phase in ρ^+ resonance