CKM angle γ measurements in LHCb

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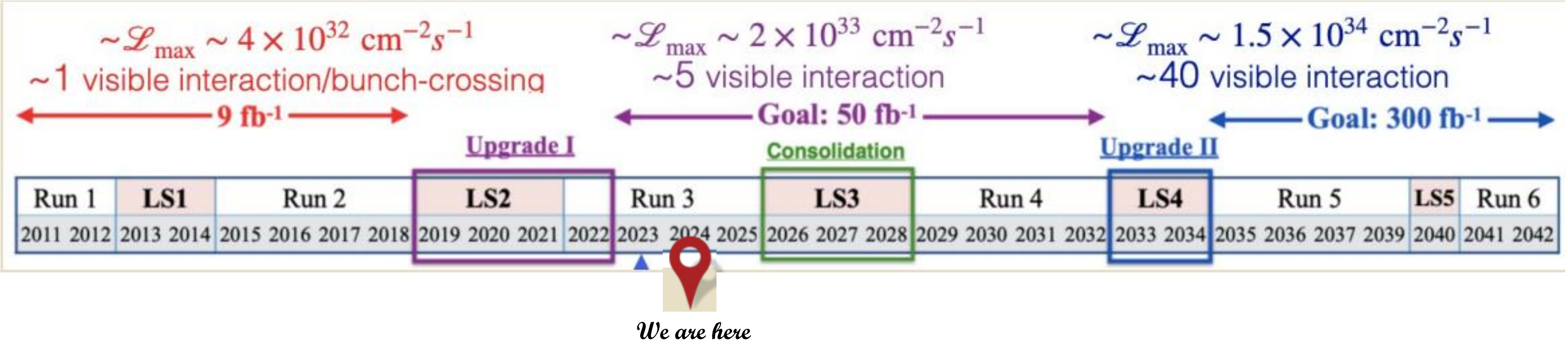
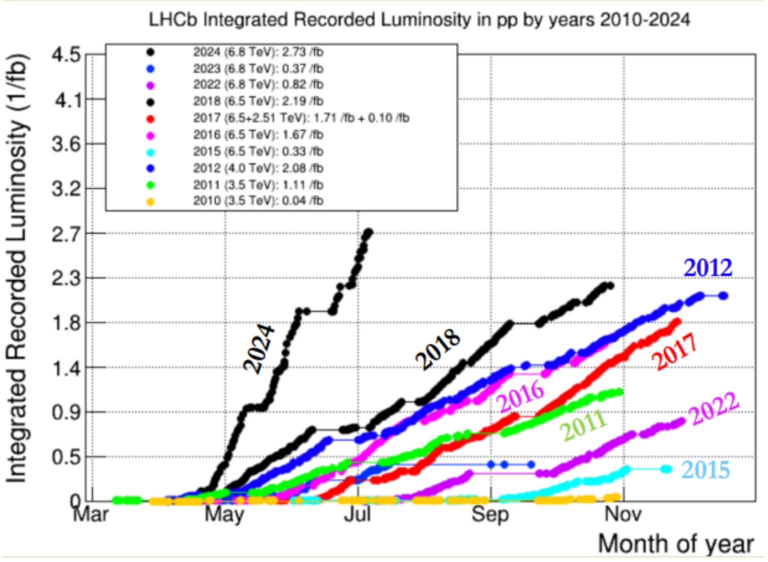
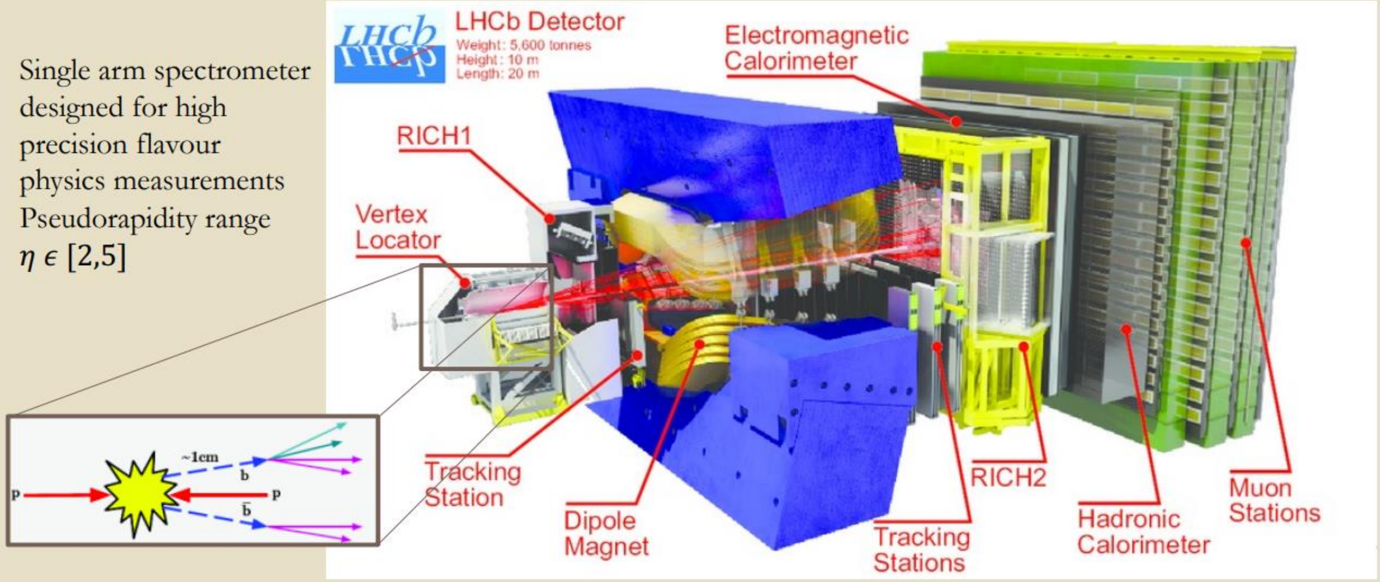
LHCb detector and dataset



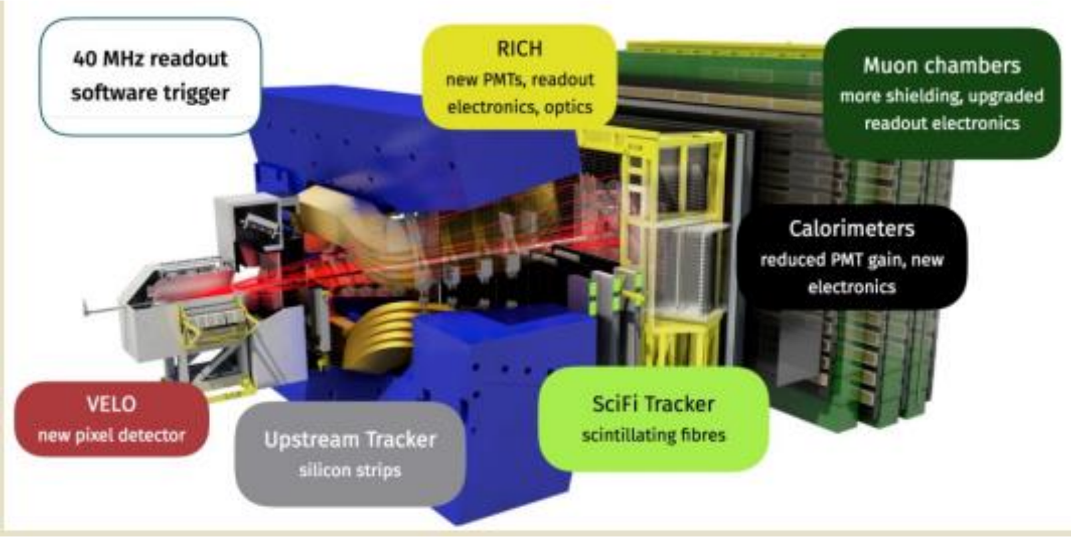


Run 1 & 2 (2011-2018)

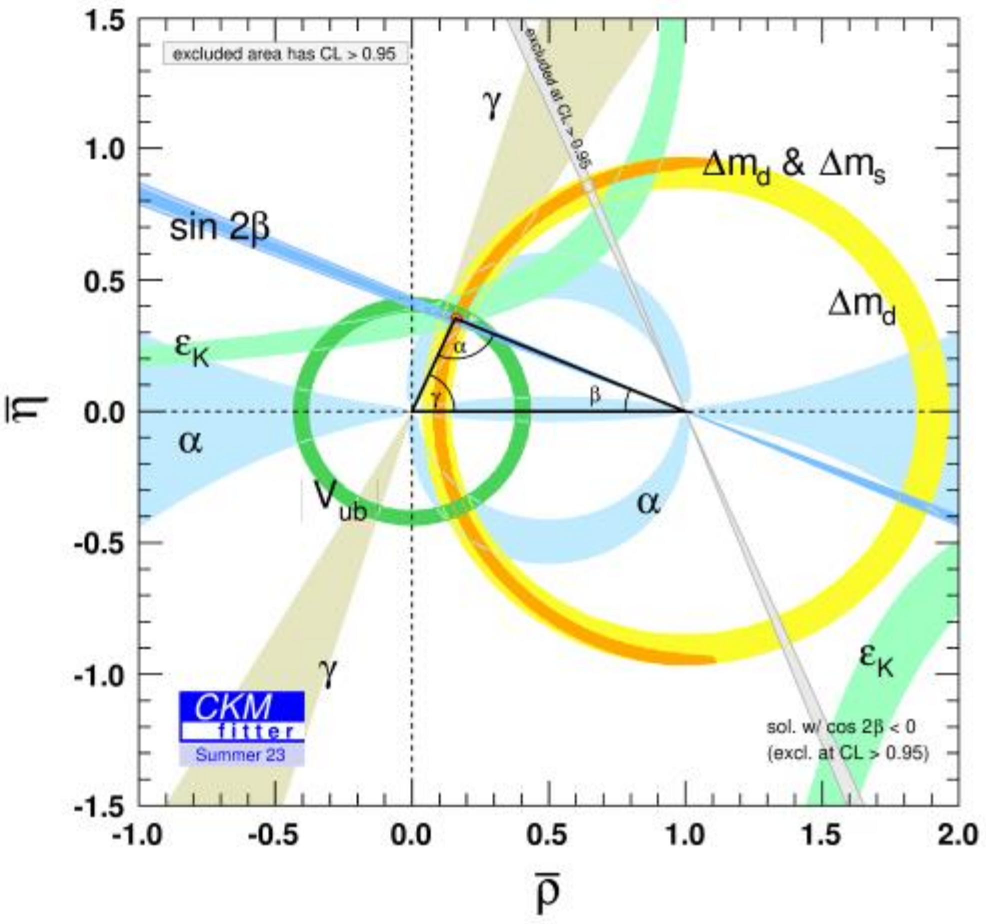
- Single arm spectrometer designed for high precision flavour physics measurements
- Pseudorapidity range $\eta \in [2,5]$



New detector for LS2 (now)

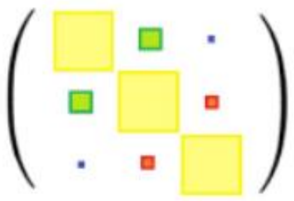


CKM angle



CKM matrix unitarity: key test of the SM

$$V_{\text{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} =$$

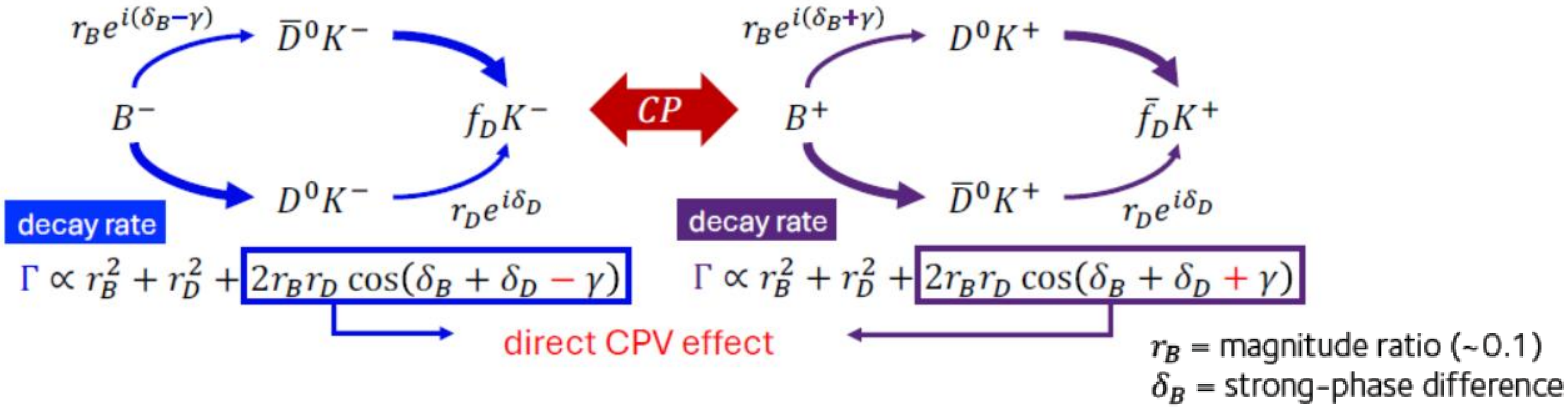


$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0,$$

- CKMfitter 2023 indirect world average $\gamma = (66.3^{+0.7}_{-1.9})^\circ$
- HFLAV 2024 direct world average $\gamma = (66.4^{+2.8}_{-3.0})^\circ$

How to measure γ: direct CPV

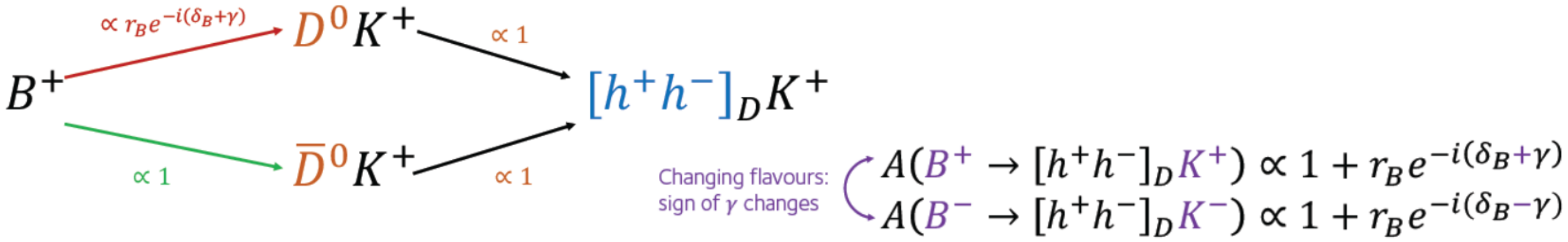
- Interference between favoured *b→c* and suppressed *b→u* decay amplitude
- Ideal decays: B→DK (clean background, large branching fraction)



- Different method according to *D* decay modes
  - GLW method: CP modes such as $D \to K^+K^-, \pi^+\pi^-$
  - ADS method: Flavor modes such as $D \to K\pi, K\pi\pi^0$
  - BPGGSZ method: $D \to K_s\pi\pi / K_sKK$ (golden mode)

GLW method [1,2]

- D CP-even final states such as D→K^+K^-,$\pi^+\pi^-$,$\pi^+\pi^-\pi^0$…



- Use the yields of B+ and B- to construct observables related to γ

$$A^f = \frac{N(B^- \to f_D K^-) - N(B^+ \to f_D K^+)}{N(B^- \to f_D K^-) - N(B^+ \to f_D K^+)} = \frac{2\kappa r_B sin\delta_B sin\gamma}{R^f}$$

$$R^f = \frac{N(B^- \to f_D K^-) - N(B^+ \to f_D K^+)}{N(B^- \to [K\pi]_D K^-) - N(B^+ \to [K\pi]_D K^+)} = 1 + r_B^2 + 2\kappa r_B cos\delta_B cos\gamma$$

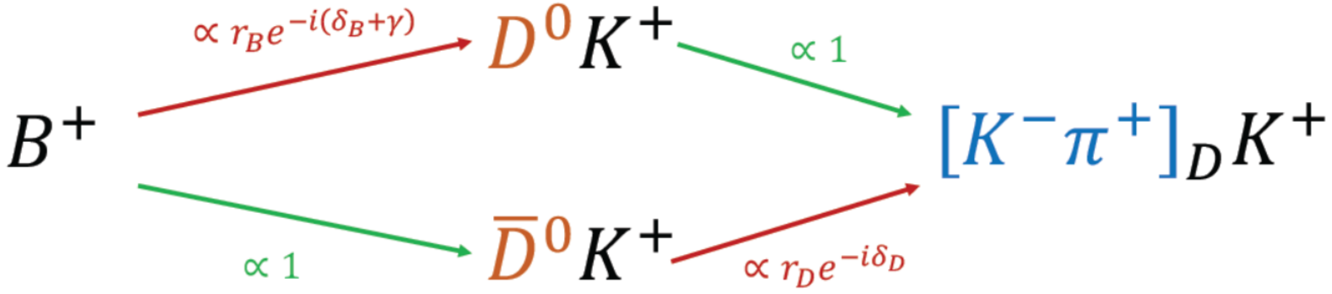
insert a factor of (κ=2F_+-1) before interference terms (F_+=CP even content), need charm input

Notice r_B/δ_B need input

[1] M. Gronau and D. Wyler, Phys. Lett. B265 (1991) 172
[2] M. Gronau and D. London, Phys. Lett. B253 (1991) 483

ADS method[1,2]

- Consider the Cabibbo-favored decay $D^0 \rightarrow K^- \pi^+$ and doubly-Cabibbo-suppressed decay $D^0 \rightarrow K^+ \pi^-$



- r_B/δ_B can be obtained directly, but external input r_D/δ_D

$$\Gamma(B^\pm \rightarrow f_D K^\pm) \propto r_B^2 + r_D^2 + 2R_f r_B r_D cos(\delta_B + \delta_D \pm \gamma)$$
$$\Gamma\left(B^\pm \rightarrow \bar{f}_D K^\pm\right) \propto 1 + r_B^2 r_D^2 + 2R_f r_B r_D cos(\delta_B - \delta_D \pm \gamma)$$

Need inputs from charm factory

$$R_{K3\pi} e^{-i\delta_{K3\pi}} = \frac{\int A_{K^-3\pi}(x) A_{K^+3\pi}(x) dx}{A_{K^-3\pi}(x) A_{K^+3\pi}(x)}$$

- For $K3\pi$ mode, coherence factor $R_{K3\pi}$ and $\delta_{K3\pi}$ averaged over phase space not good for whole space

[1] D. Atwood, I. Dunietz, and A. Soni, Phys. Rev. Lett. 78 (1997) 3257
[2] D. Atwood, I. Dunietz, and A. Soni , Phys. Rev. D63 (2001) 036005

Dalitz method[1]

- Golden mode: D→$K_s\pi\pi$/K_sKK (large statistic, large r_D)
  - Model-dependent method (not used now)
  - Model-independent binned method (BPGGSZ method[1])
- Binned Dalitz plane according to δ_D, measure $B^\pm$ yields in each bins
  - Sensitivity from **phase-space distribution**, not overall asymmetries → not impacted by production/detection asymmetries
  - LHCb latest $\boldsymbol{K_s hh}$ result: $\gamma = (68.7^{+5.2}_{-5.1})^o$(uncertainty~1° from BESIII input) *JHEP* ***02*** *(2021) 169*

$$r_B \exp[i(\delta_B \pm \gamma)] = x_\pm + i y_\pm$$

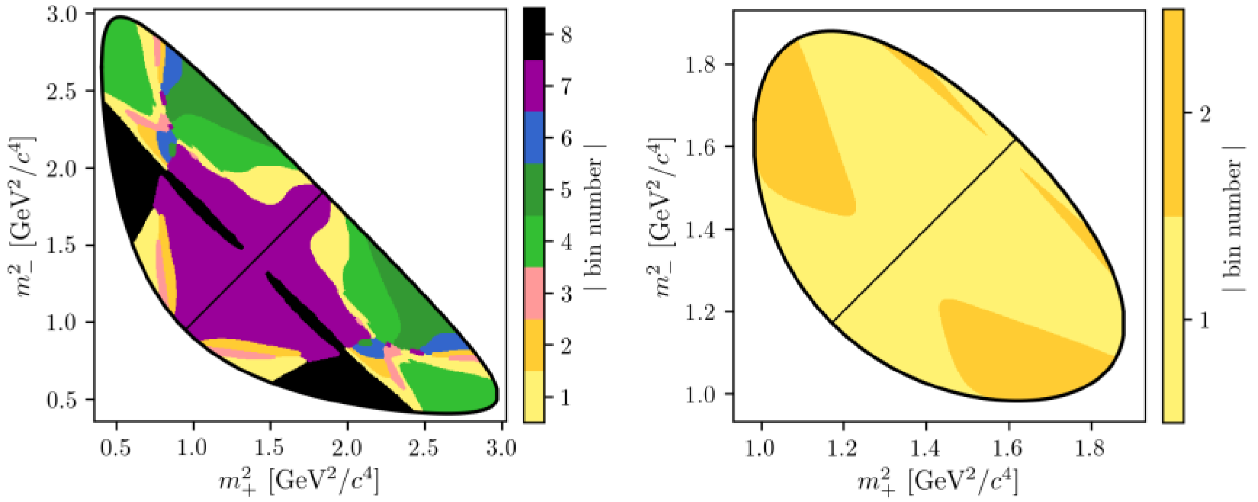
$$N^-_{\mp i} \propto F_{\pm i} + (x_-^2 + y_-^2) F_{\mp i} + 2\sqrt{F_i F_{-i}} (x_\pm c_{\pm i} \mp y_\pm s_{\pm i})$$

F_i : Fractional yield of flavour tagged D^0 into bin i

Measured in control channel: $\bar{B}^0 \to D^{*+}\mu^-\nu_\mu X$

c_i/s_i : Strong phase difference of $D^0 - \bar{D}^0$ decays

External input from BESIII and CLEO-c



[1] A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D 68 (2003) 054018

$B^0 \to DK^{*0}, D \to h^+h'^-(\pi^+\pi^-)$

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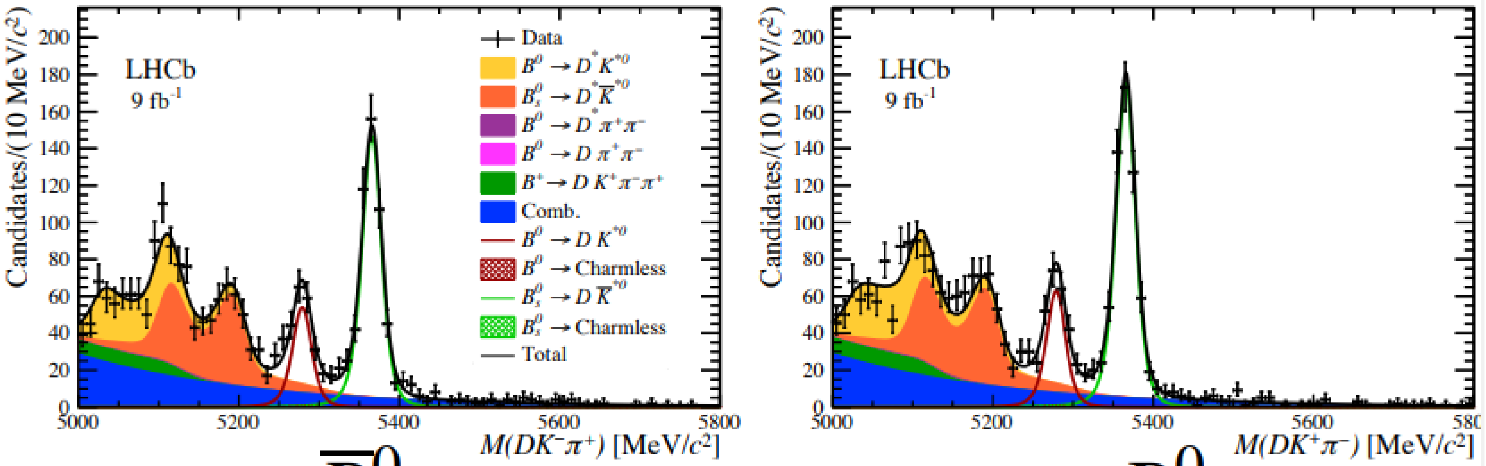
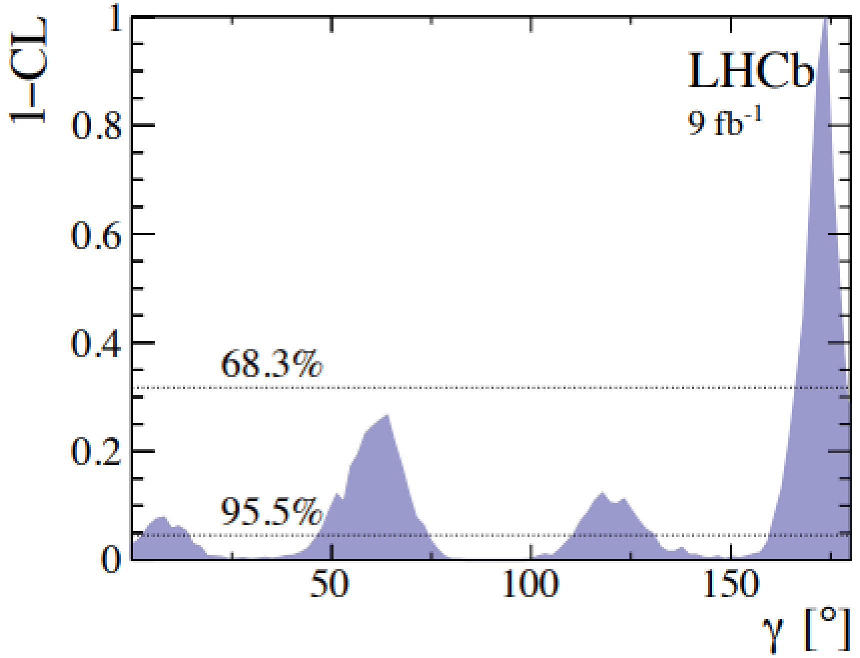
- ADS & GLW method
- "Self-tagging" mode, flavor of the B is determined by the charges of the K* daughters
- Simultaneous measurement
  - $D \to K^\pm\pi^\mp(\pi^+\pi^-)$
  - $D \to \pi^+\pi^-(\pi^+\pi^-)$
  - $D \to K^+K^-$
- Multiple solutions
  - Solution most compatible with existing measurements is

$$\gamma = (61.7 \pm 8.0)^\circ$$

  - Require further input, such as $D \to K_s hh$



$\overline{B}^0$ Invariant mass fit result for $D \to K^+K^-$ B^0



$B^0 \to DK^{*0}, D \to K_S^0 h^+ h^-$

Eur. Phys. J. C 84, 206 (2024)

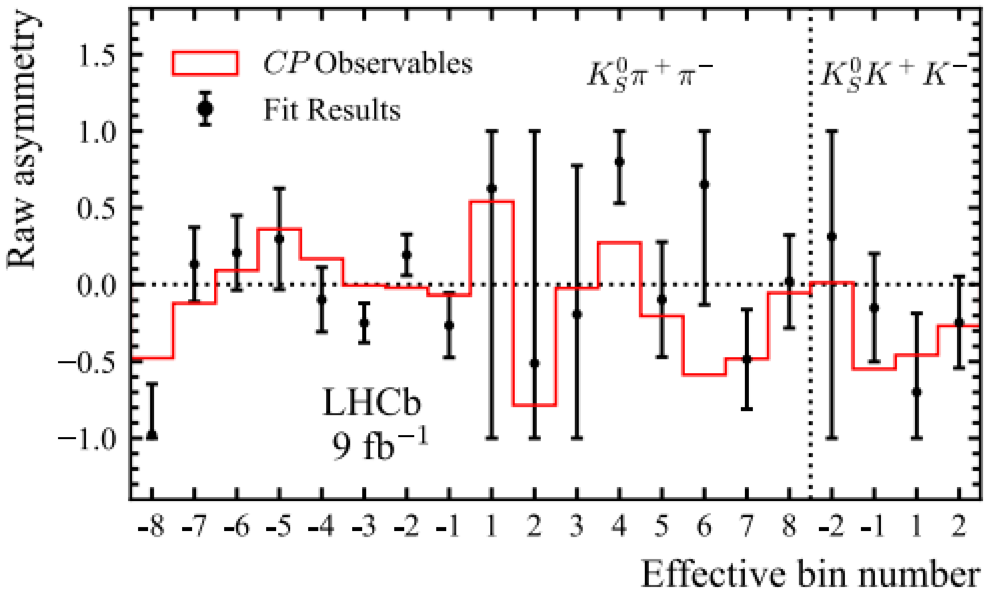
- BPGGSZ method: model independent

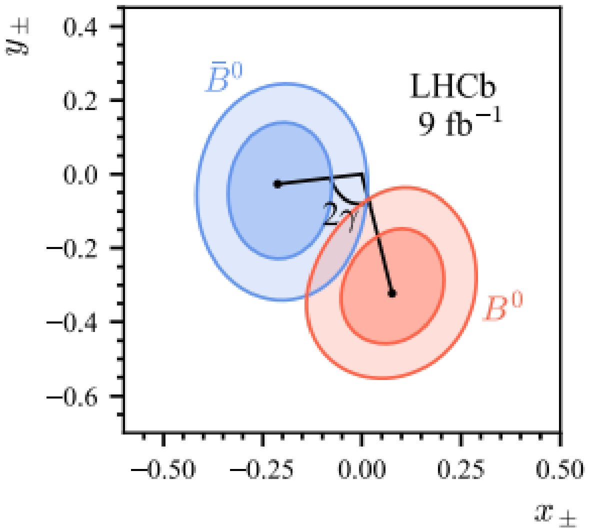
- Simultaneous fit to extract

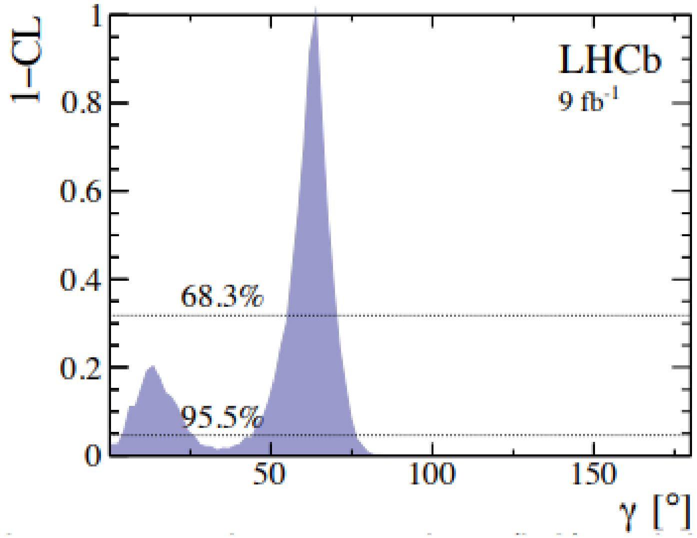
$$x_\pm = r_{B^0}^{DK^*}\cos(\Delta\delta_{B^0}^{DK^*} \pm \gamma)$$
$$y_\pm = r_{B^0}^{DK^*}\sin(\Delta\delta_{B^0}^{DK^*} \pm \gamma)$$

- Combination with $h^+h'^-(\pi^+\pi^-)$:

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



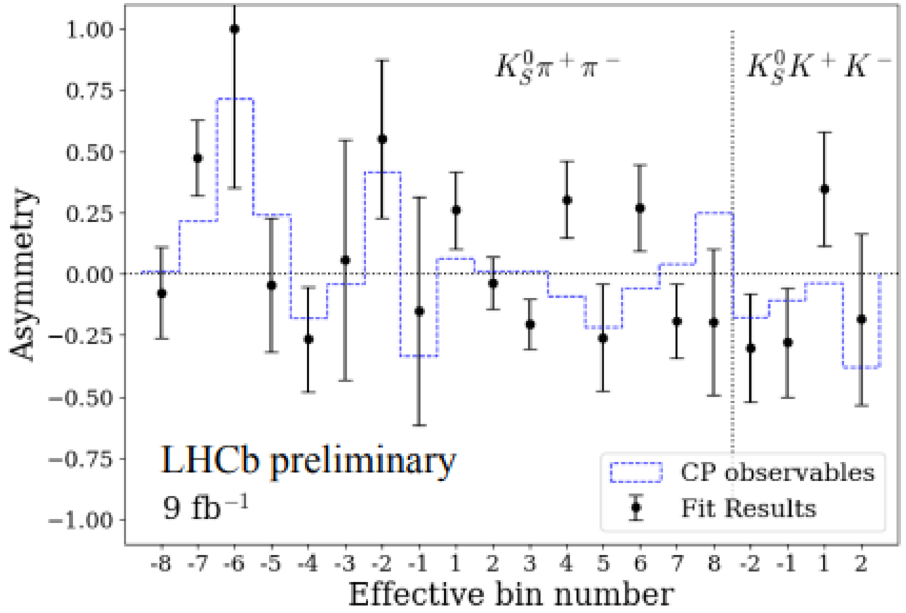




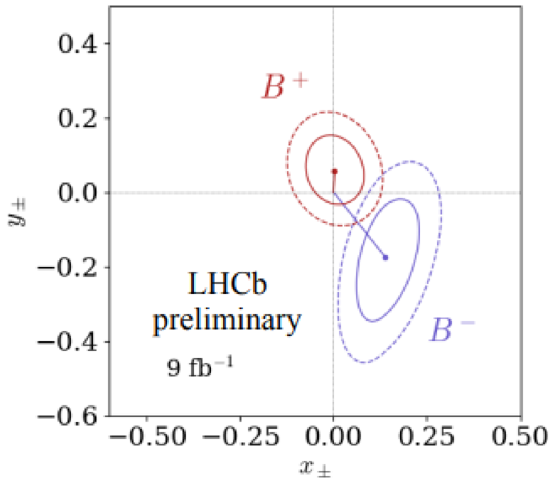
$B^{\pm} \to DK^{*\pm}$

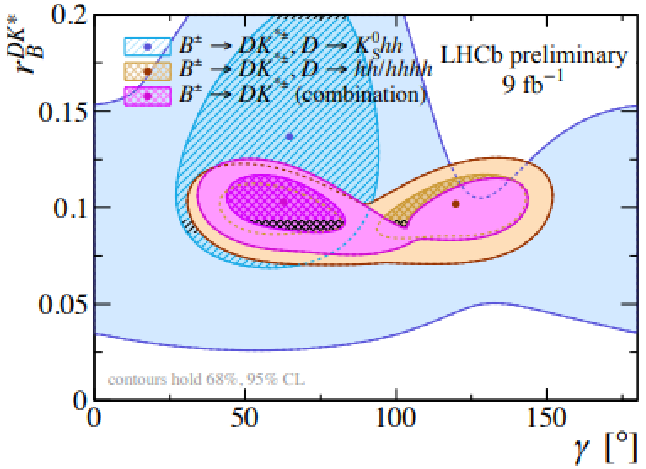
LHCb-PAPER-2024-023

- Simultaneous measurement
  - $D \to K^{\pm}\pi^{\mp}(\pi^{+}\pi^{-})$
  - $D \to \pi^{+}\pi^{-}(\pi^{+}\pi^{-})$
  - $D \to K^{+}K^{-}$
  - $D \to K_S^0 h^{+}h^{-}$



- First time for $B^{\pm} \to DK^{*\pm}$, $D \to K_S^0 h^{+}h^{-}$
- $\gamma = (63 \pm 13)°$
- First observation of the DCS $B^{\pm} \to DK^{*\pm}$, $D \to K^{\pm}\pi^{\mp}(\pi^{+}\pi^{-})$
- Low statistics





$B^\pm \to D^* h^\pm, D \to K_S^0 h^+ h^-$

❖ **Partial reconstructed** analysis

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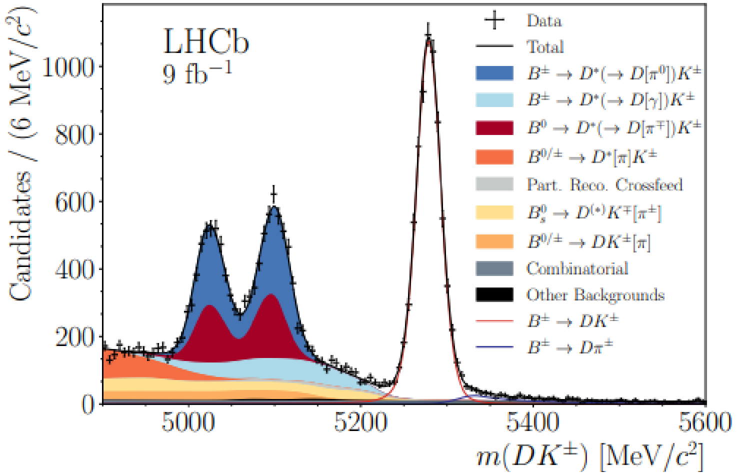

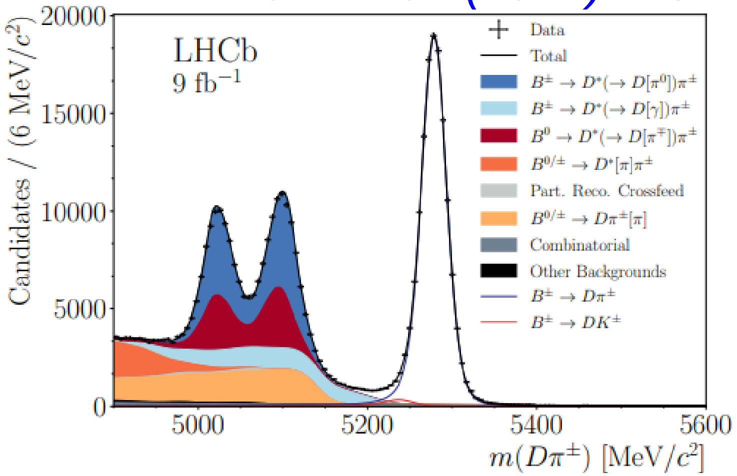

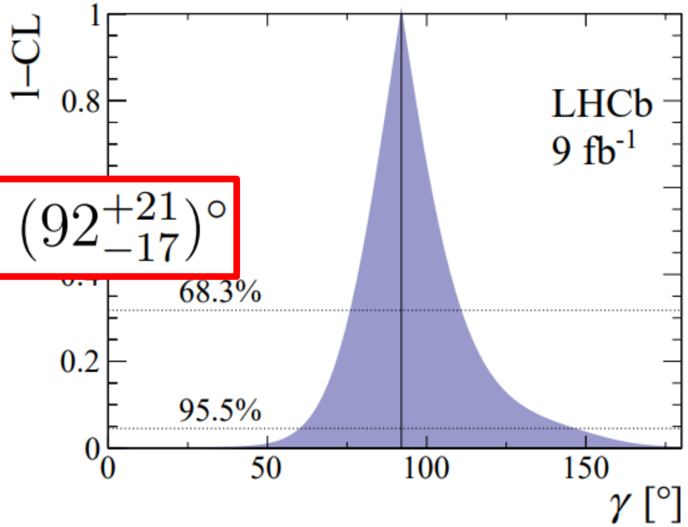

$\gamma = (92^{+21}_{-17})^\circ$

❖ **Full reconstructed** analysis

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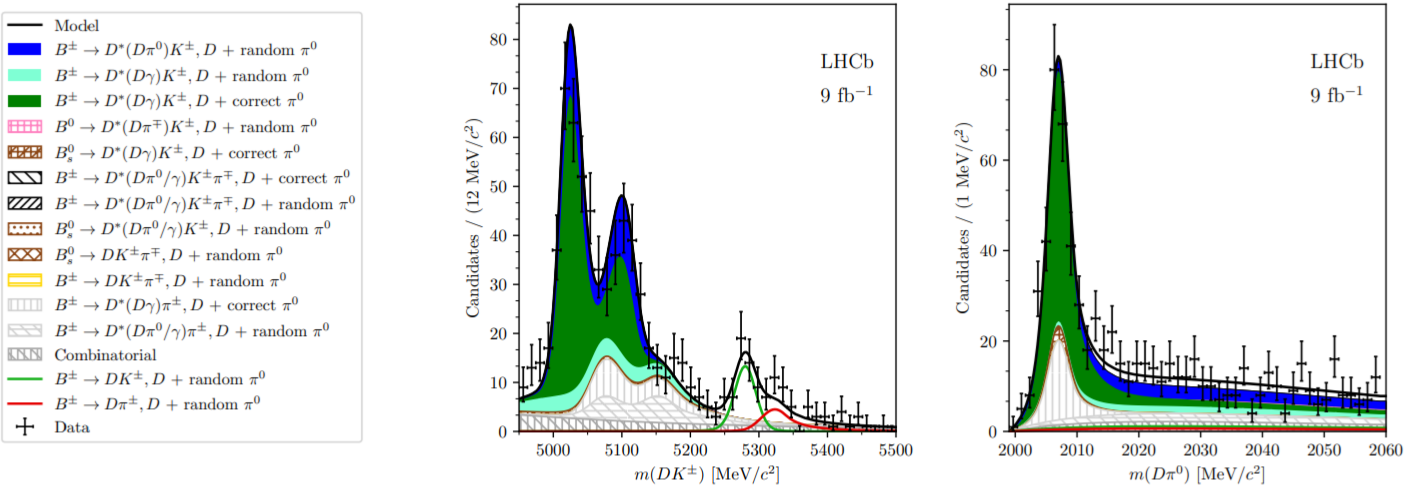
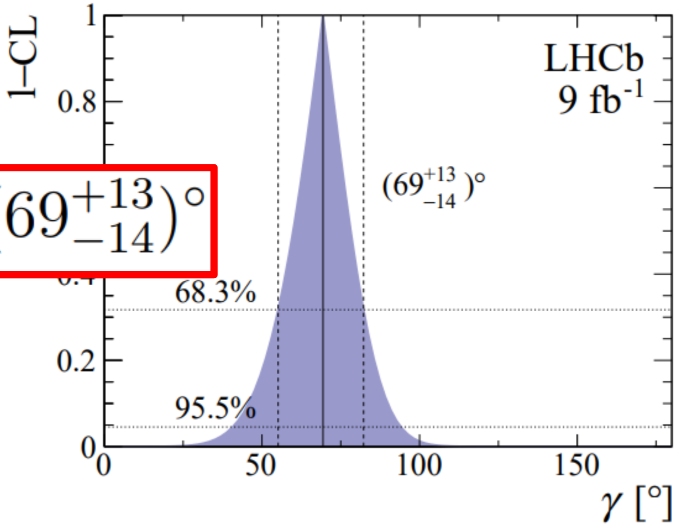




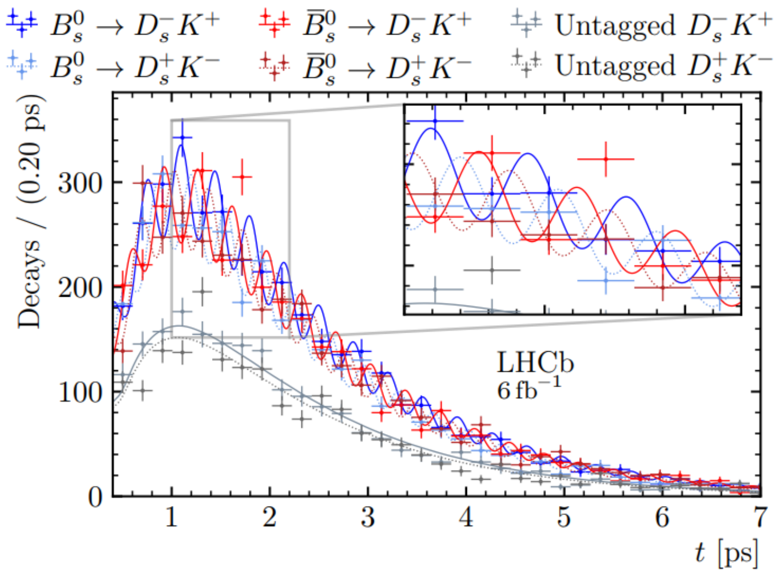
$\gamma = (69^{+13}_{-14})^\circ$

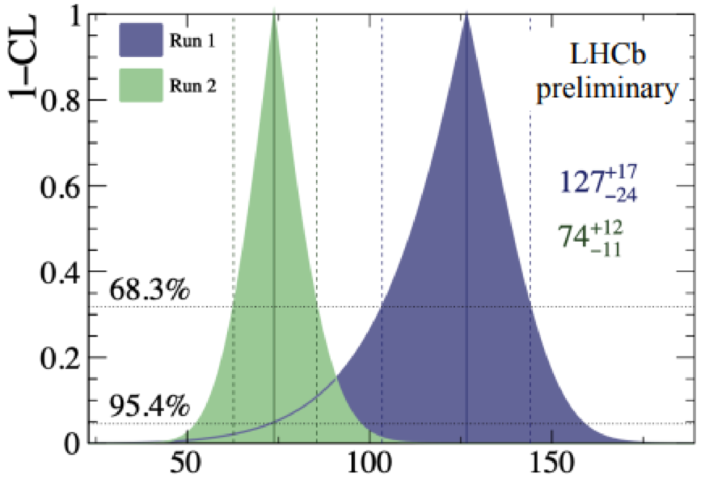
- r_B parameters propagates the difference in precision
- Low correlation between 2 method due to different selection criteria, combination is ongoing

How to measure γ: CPV in mixing and decay

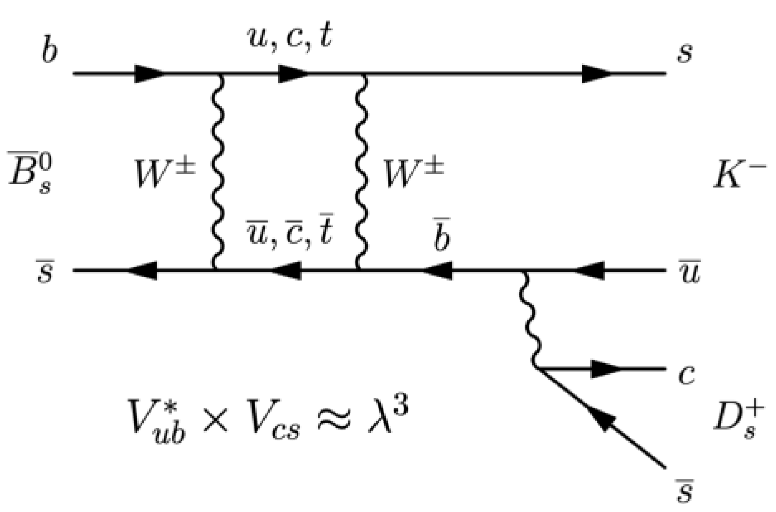
LHCb-PAPER-2024-020

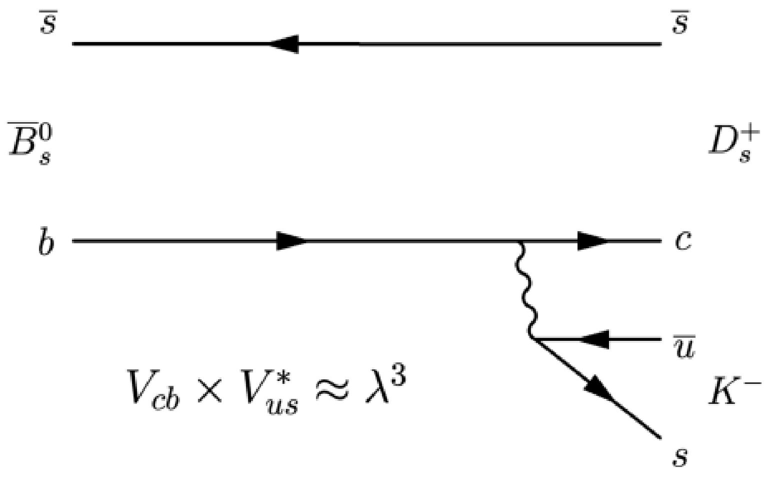
- Time dependent measurement
- Golden decays: $B_S \to D_S K$
  - larger interference: $r_B^{D_sK} \sim 0.4$ ($r_B^{DK^+} \sim 0.1$)
  - Use flavor tagging to determine the initial flavor
  - Interference between mixing and decay amplitudes gives sensitivity to **$\gamma+(-)2\beta_{(s)}$**





$$\gamma = (81^{+12}_{-11})^\circ$$



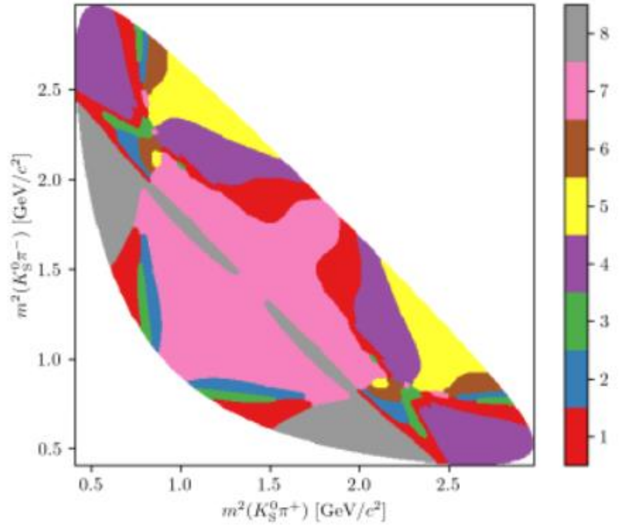


Unbinned model-independent method

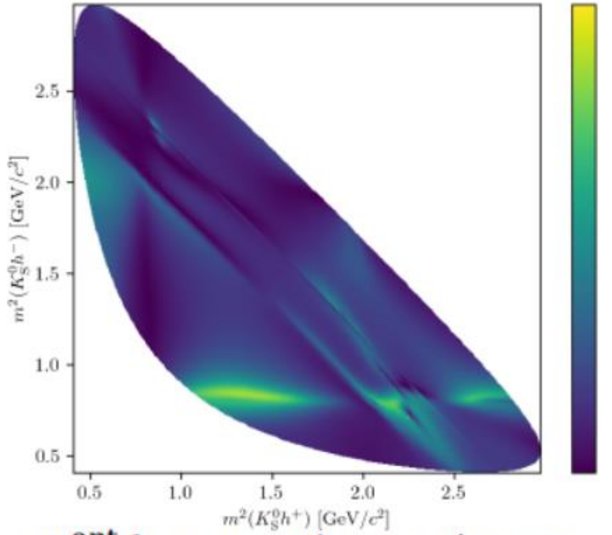
- Basic idea: Bins → Events (*Eur. Phys. J. C, 2018, 78(2)*)
  - Make most use of amplitude info in phase space

- Binned approach: average over phase space regions
  - ignore variance inside each bin
  - stastical sensitivity diluted due to binning

- Fourier expansion the amplitude by strong phase
  - parameters definition similar to BPGGSZ method
  - events with lower uncertainty of $\gamma \Rightarrow$ higher weight assigned
  - dependence on others (amplitude, signal purity): optimal weight w^{opt} to minimize γ uncertainty



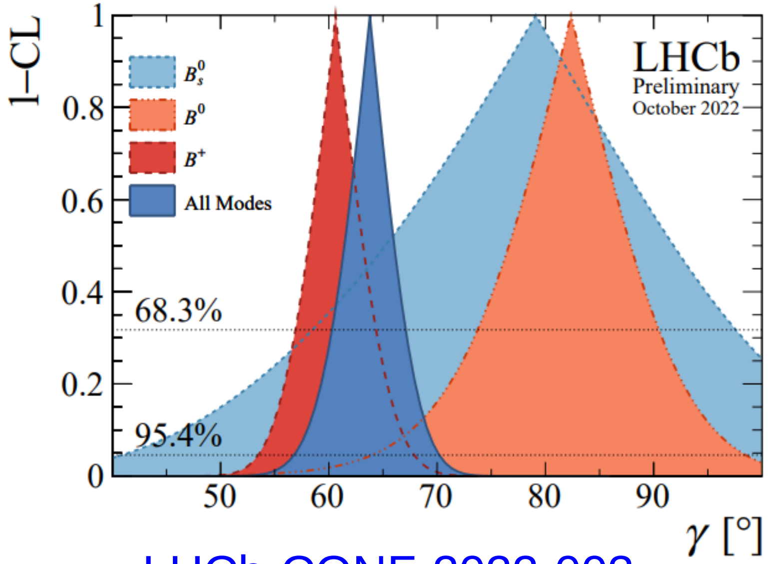
optimal binning scheme



w^{opt} from pseudo-experiments

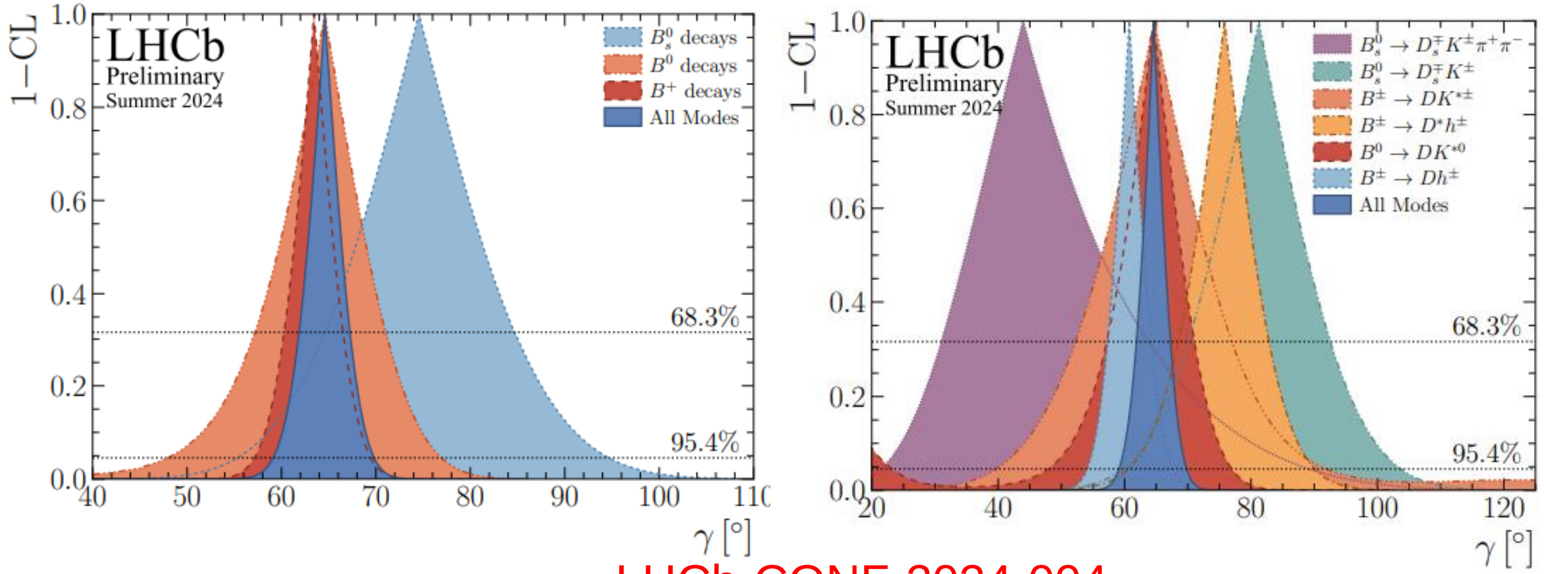
LHCb&BESIII joint analysis is in WG review

LHCb γ combination



LHCb-CONF-2022-003

$\gamma = (63.8^{+3.5}_{-3.7})^o$



LHCb-CONF-2024-004

$\boldsymbol{\gamma = (64.6 \pm 2.8)^o}$

Species	Value [°]	68.3% CL Uncertainty [°]	95.4% CL Uncertainty [°]
B^+	60.6	$^{+4.0}_{-3.8}$	$^{+7.8}_{-7.5}$
B^0	82.0	$^{+8.1}_{-8.8}$	$^{+17}_{-18}$
B_s^0	79	$^{+21}_{-24}$	$^{+51}_{-47}$
All	63.8	$^{+3.5}_{-3.7}$	$^{+6.9}_{-7.5}$

Species	Value [°]	68.3% CL Uncertainty [°]	95.4% CL Uncertainty [°]
B^+	63.4	$^{+3.2}_{-3.3}$	$^{+6.4}_{-6.5}$
B^0	64.6	$^{+6.5}_{-7.5}$	$^{+12}_{-17}$
B_s^0	75	$^{+10}_{-11}$	± 20
All	64.6	± 2.8	$^{+5.5}_{-5.7}$

- Combination of all LHCb public results → **<3° precision**
- previous tension between charged and neutral *B* resolved
- Still large uncertainty for B_s mode

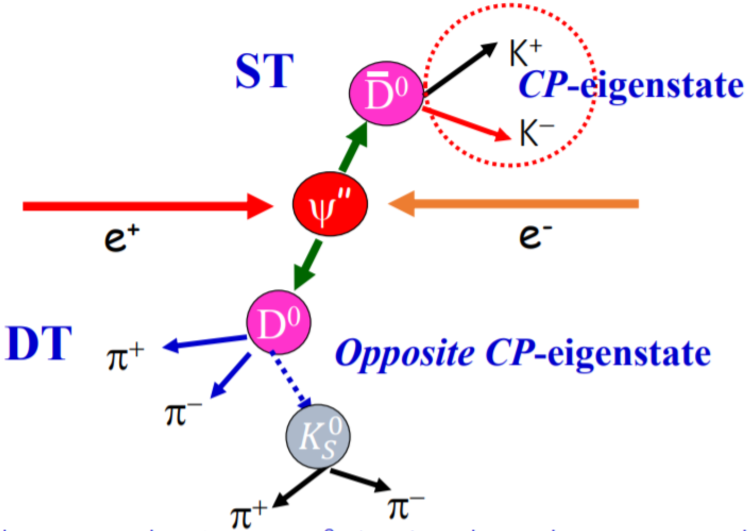
- $\psi(3770)$ is a spin -1 states, therefore the amplitude of $\psi(3770) \rightarrow D\bar{D}$:

$$(|D^0\rangle|\overline{D^0}\rangle - |\overline{D^0}\rangle|D^0\rangle)/\sqrt{2}$$ [anti-symmetric wave function]

The amplitude for two D mesons to decay to states *F* and *G* is [D. Atwood and A. Soni, PRD68, 033003 (2003)]:

$$\Gamma(F|G) = \Gamma_0\,[A_F^2\bar{A}_G^2 + \bar{A}_F^2A_G^2 - 2R_FR_GA_F\bar{A}_FA_G\bar{A}_G\cos[\delta_D^F - \delta_D^G]]$$

The coherence factor κ_F and the strong phase difference δ_D can be extracted



The DT mode K^+K^- *vs.* $K_S^0\pi^+\pi^-$ is selected as an example.

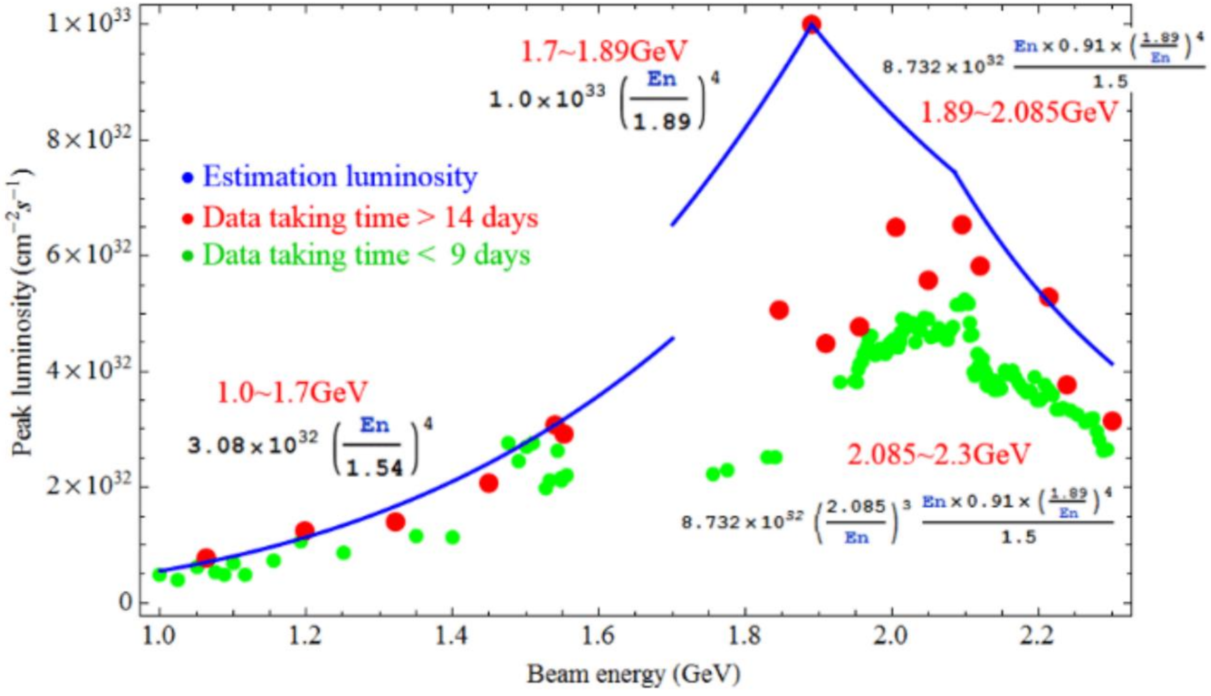
- ✓ Single tag (ST) samples: decay products of only one D meson are reconstructed
- ✓ Double tag (DT) samples: decay products of both D mesons are reconstructed
- ✓ Some typical reconstructed D decay modes

Tag group	
Flavor	$K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^-\pi^+, K^+e^-\bar{\nu}_e$
CP-even	$K^+K^-, \pi^+\pi^-, K_S^0\pi^0\pi^0, K_L^0\pi^0, \pi^+\pi^-\pi^0$
CP-odd	$K_S^0\pi^0, K_S^0\eta, K_S^0\omega, K_S^0\eta', K_L^0\pi^0\pi^0$
Mixed-CP	$K_S^0\pi^+\pi^-$

Key datasets for charm physics:

- 2010-2011: $2.9\,\text{fb}^{-1}$ at $\psi(3770)$
- 2013-2019: $7.3\,\text{fb}^{-1}$ of $D_s\bar{D}_s^*$
- 2020: $4.5\,\text{fb}^{-1}$ of $\Lambda_c^+\bar{\Lambda}_c^-$
- 2021-2022: $5.0\,\text{fb}^{-1}$ at $\psi(3770)$
- 2022-: $\sim 8\,\text{fb}^{-1}$ at $\psi(3770)$

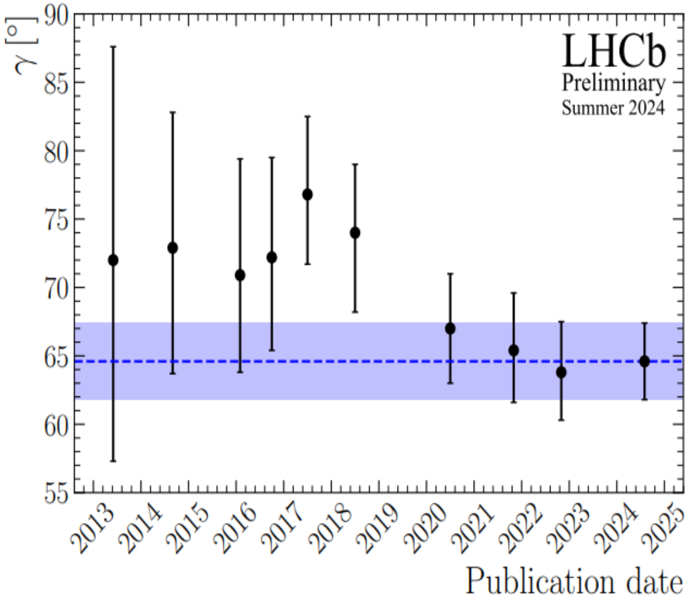
20 fb^{-1} $\psi(3770)$ data is ready

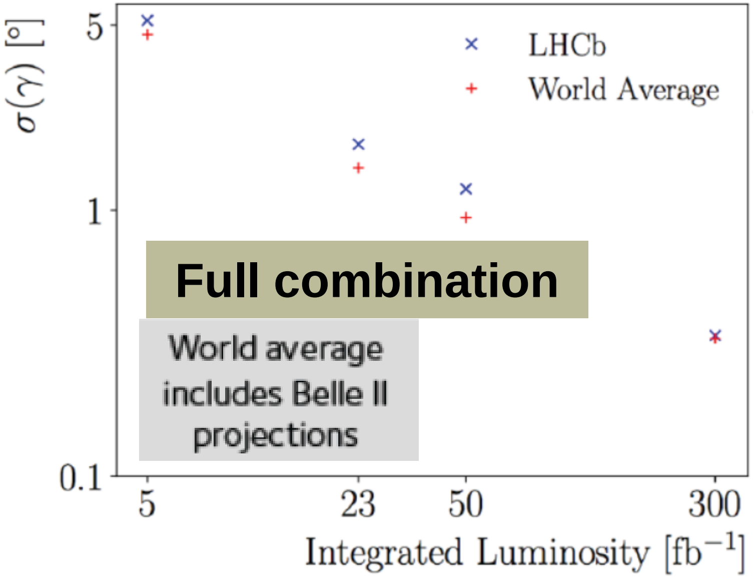


BEPCII peak luminosity.

Threshold produced $\psi(3770) \to D\bar{D}$ provide a unique access to strong parameters information for γ measurement at LHCb/BelleII

Future prospects for γ @ LHCb

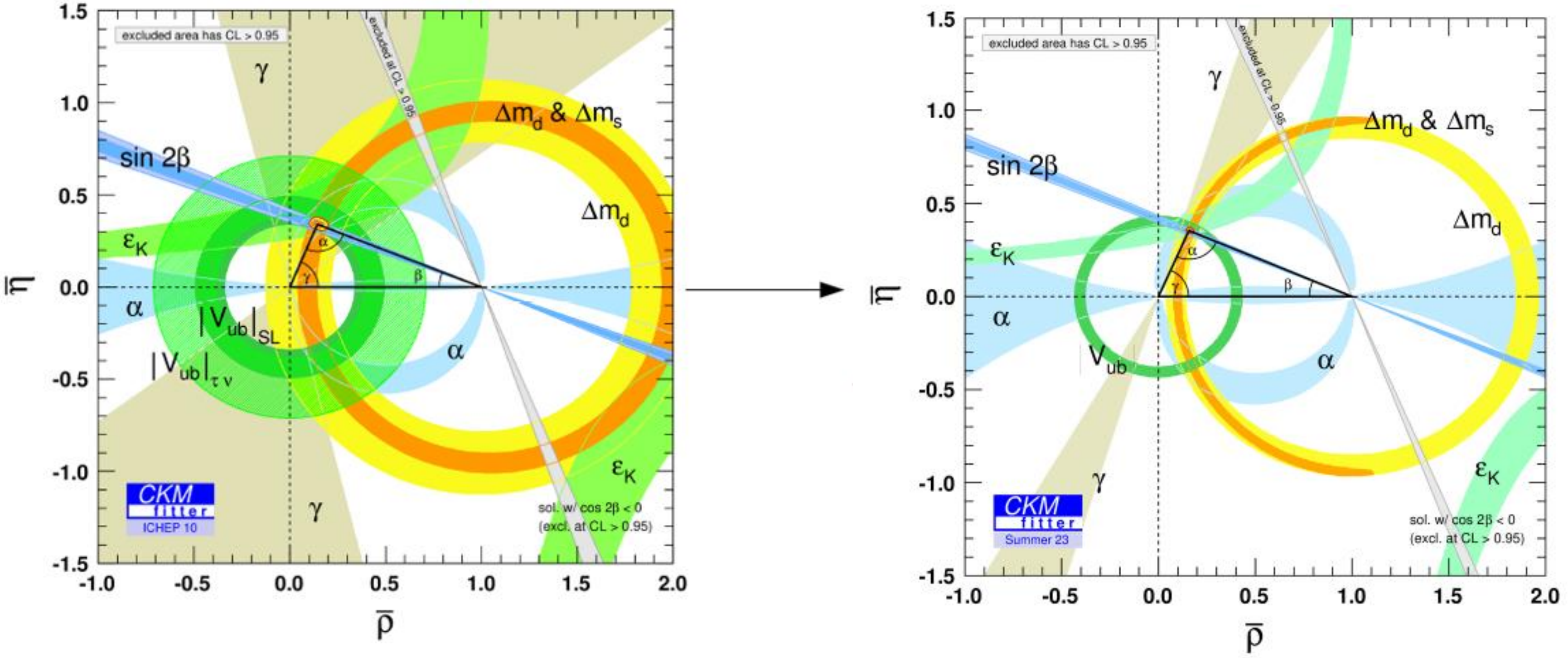




- Status now :
  - Error for γ is about 3°
  - BESIII contribute about 1°
- Around 2030
  - Less than 1° will be achieved
  - BESIII 20fb^{-1} data → improve the error to 0.4°
- (>)2035
  - LHCb upgradeII → sensitivity <0.4°
  - Need more charm factory data (STCF)

dataset	Int. Lum.	year	sensitivity
LHCb Run1 (7,8TeV)	3 fb^{-1}	2012	8°
LHCb Run2 (13TeV)	6 fb^{-1}	2018	4°
BelleII Run	50 ab^{-1}	202?	1-2°
LHCb upgrade (14TeV)	50 fb^{-1}	2030	<1°
LHCb upgradeII (14TeV)	200 fb^{-1}	(>)2035	<0.4°

- CKM angle γ measurement is one of the major goal for LHCb



- γ no longer the least precisely known of the weak phases, now **<3º precision**
- BESIII 20/fb data is ready, STCF for future
- Run3 data will be soon added, more modes studied
- More data in future, better knowledge!

Thank you!