CKM measurements at LHCb

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on behalf of the LHCb collaboration

CIPANP 2022

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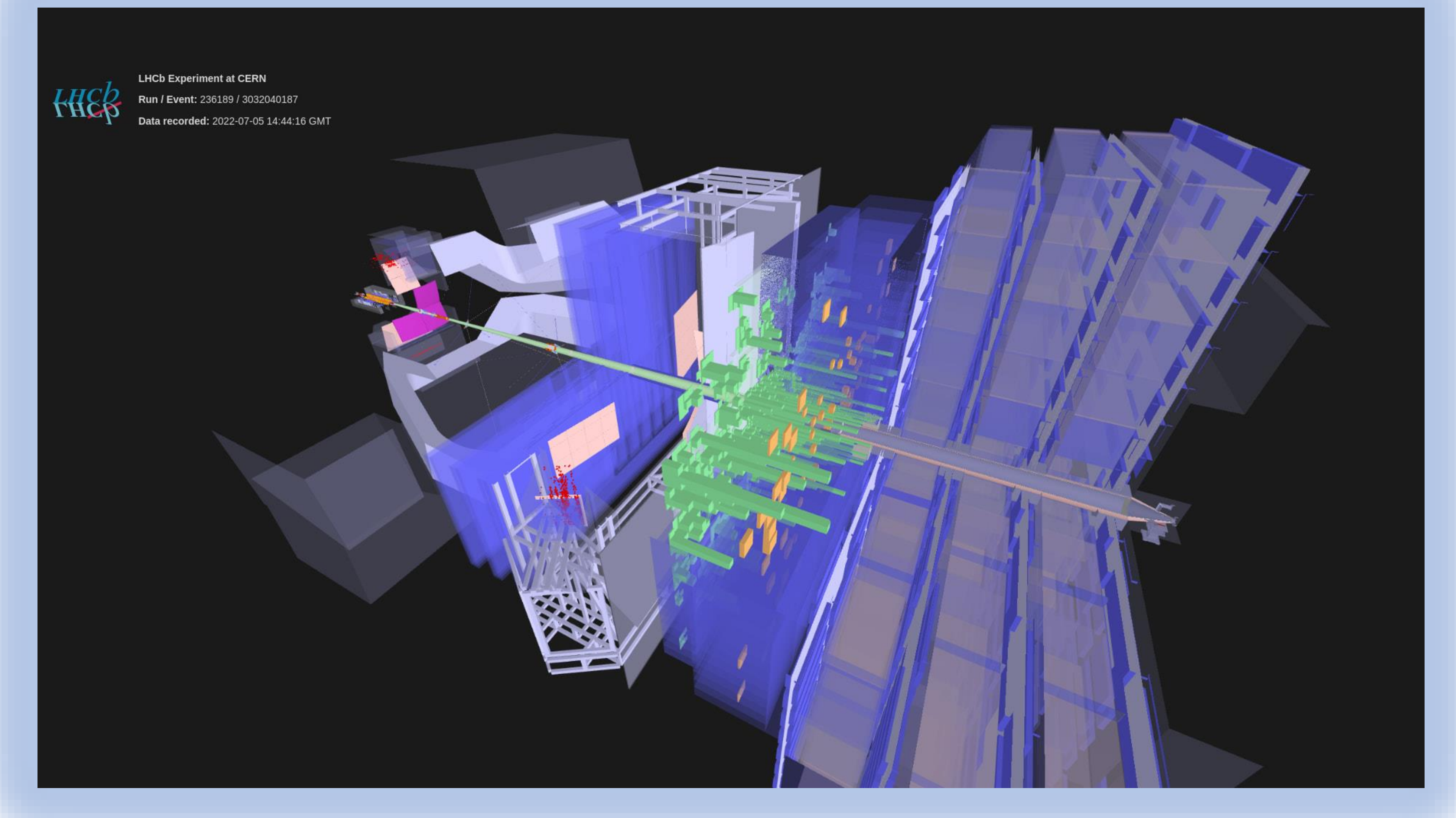

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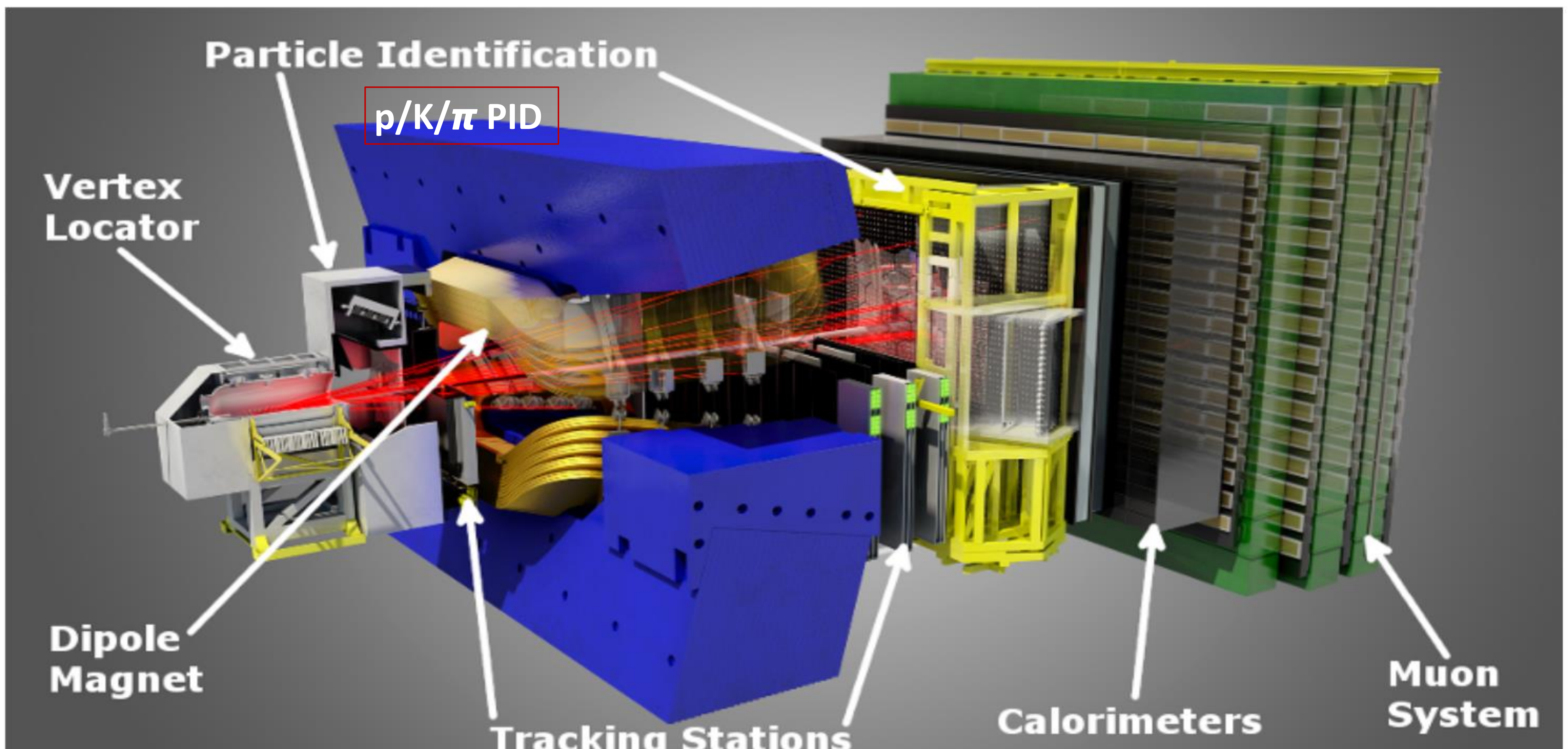
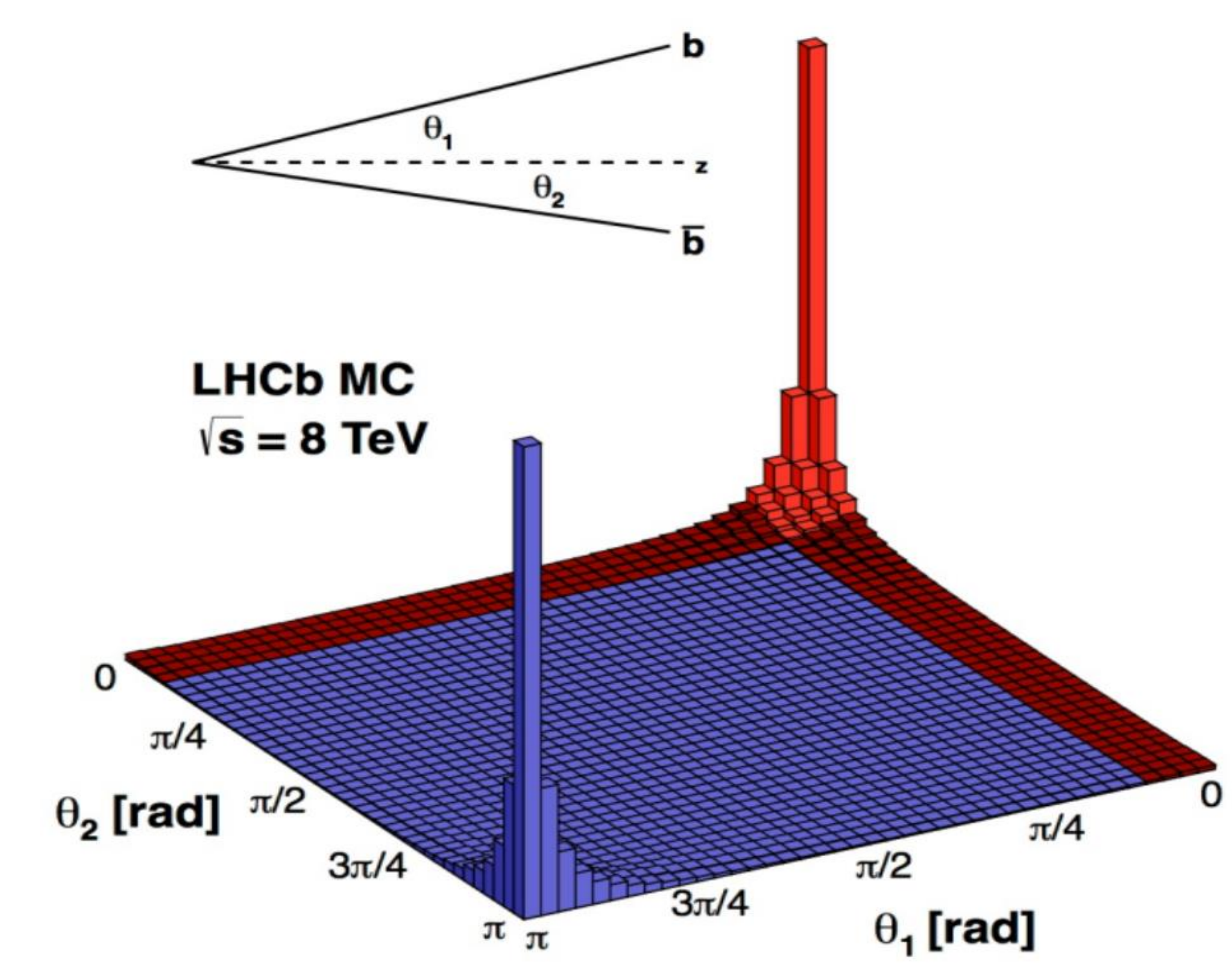
LHCb: Large Hadron Collider Beauty Experiment

- Precision measurements of particles containing b and c quarks mainly produced in the forward direction at LHC
- A single-arm forward spectrometer covering the pseudo-rapidity range $2 < \eta < 5$
- Precise vertexing, tracking, particle identification and reconstruction



- Run1
  - 1 fb^{-1} @ 7 TeV - (2011)
  - 2 fb^{-1} @ 8 TeV – (2012)
- Run2
  - 6 fb^{-1} @ 13 TeV – (2015 -2018)

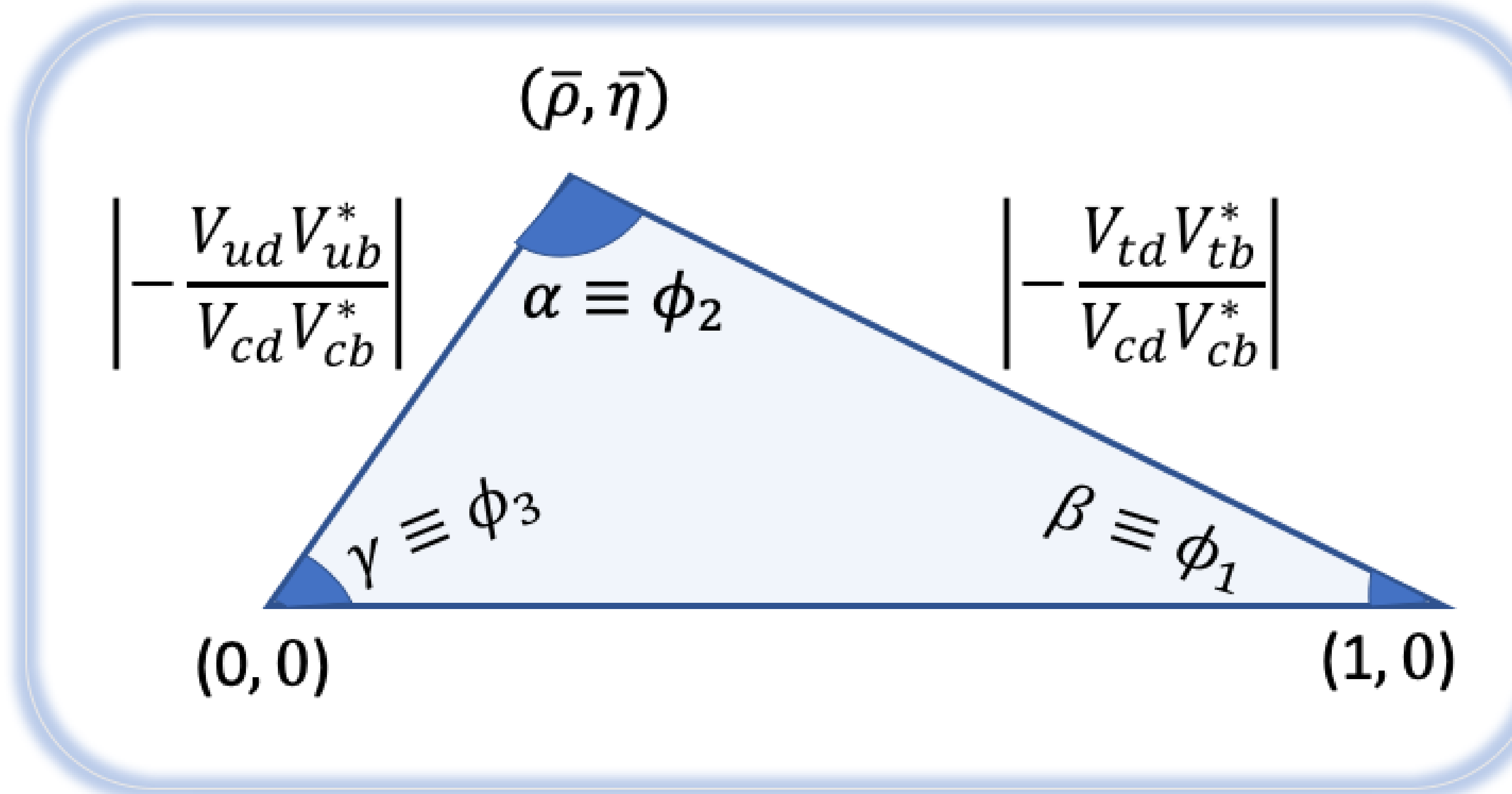


Physics motivation: CKM matrix and Unitarity Conditions

- The rates of the decay processes are parametrized in different ways by CKM matrix elements

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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



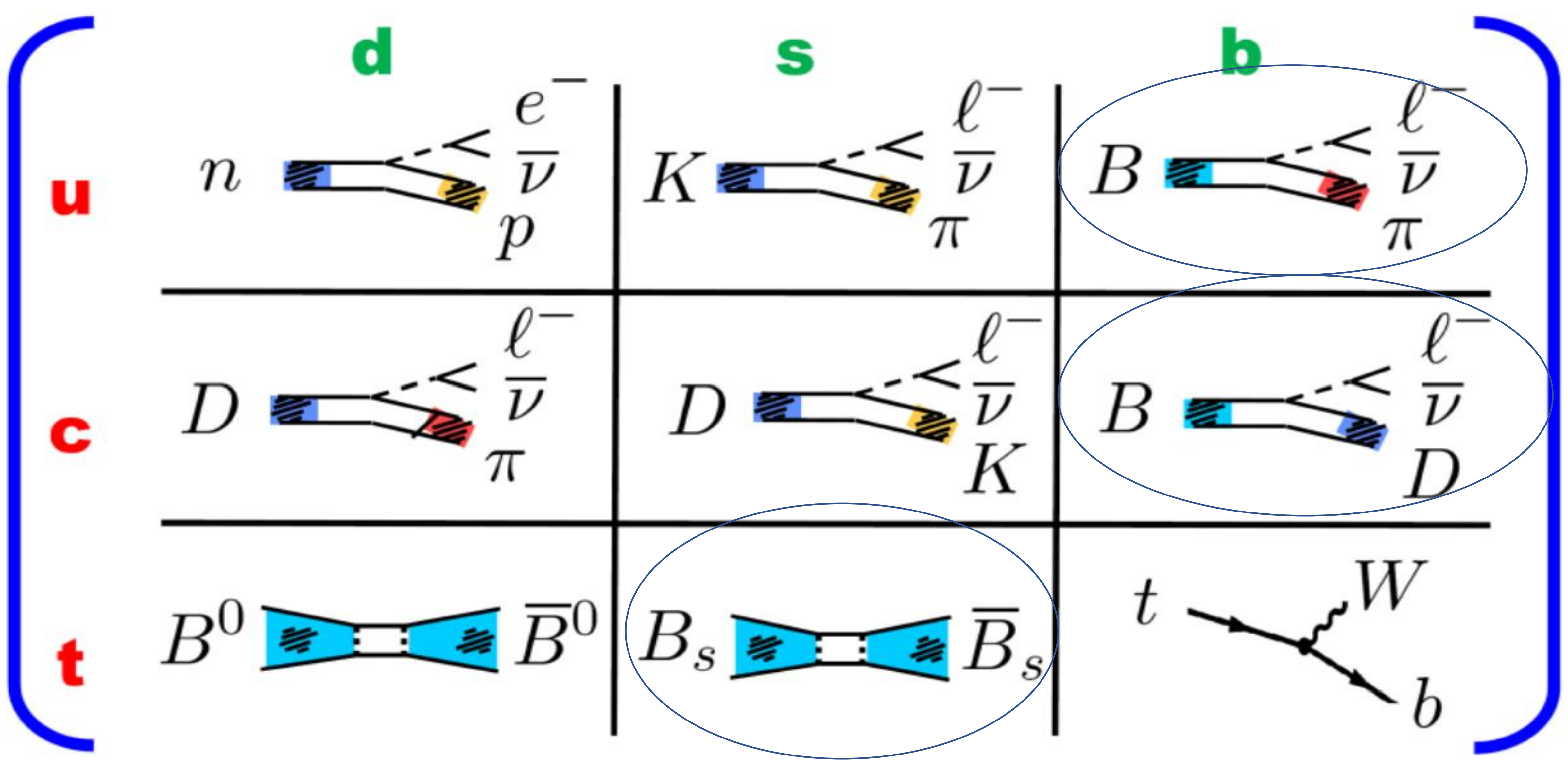
$$\mathbf{V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0}$$

- Overconstraint the CKM elements precisely is one of the key goal of the **Flavour Physics**

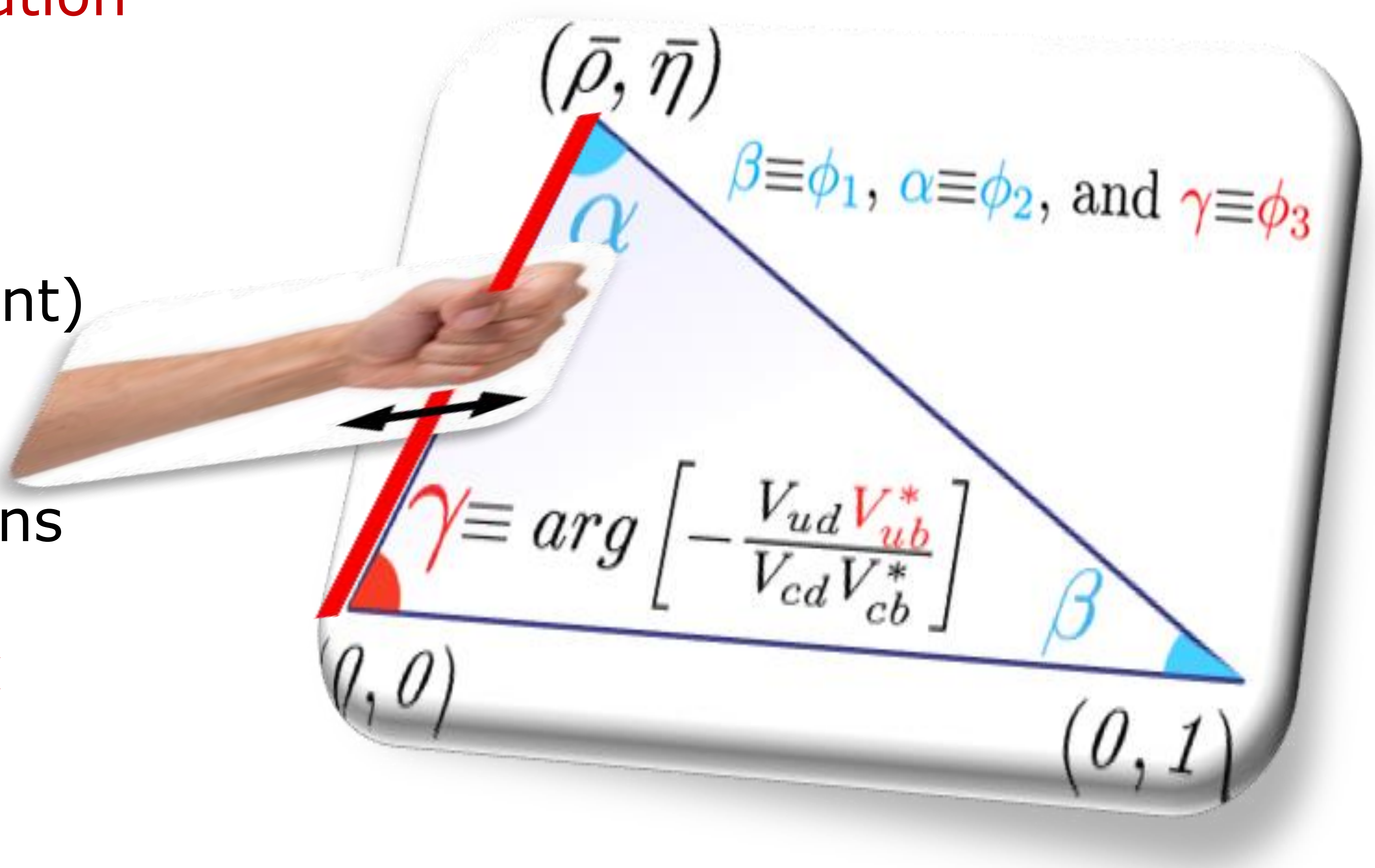
  - 4 parameters: $A,\ \lambda,\ \rho, \eta$
    - 3 angles
    - 1 complex phase

  - Parameters are obtained and tested wrt data (rich pheno and large mass range): Nucleons, K, D, $B_{(s)}$ and top quark physics

$V_{CKM} =$



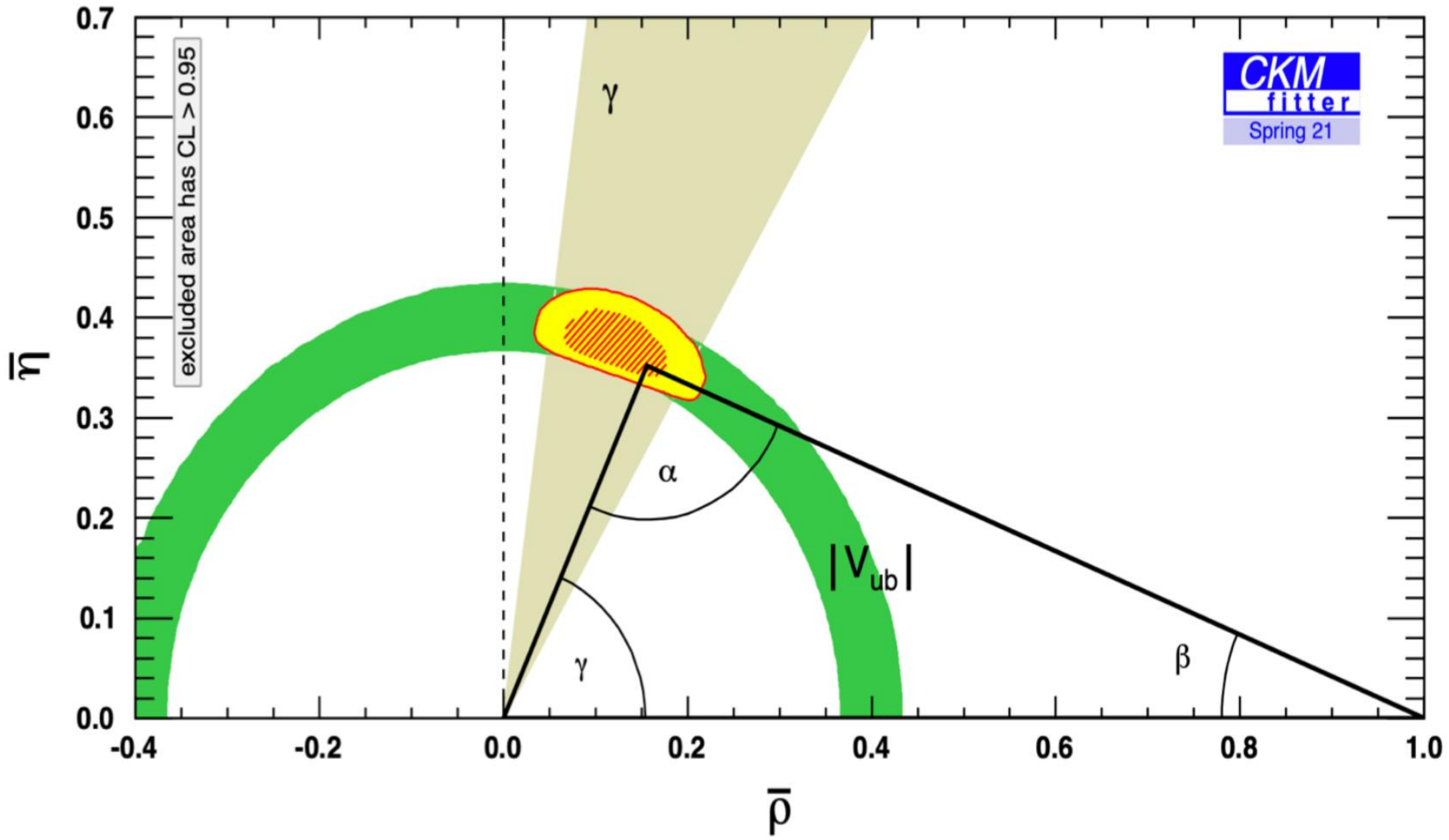
- In order to verify the unitarity of the CKM matrix
  - Complex phase $\gamma = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$ which is source of CP violation can be measured from the processes mediated
    - Only angle accessible at **Tree-level** (direct measurement)
      - theoretically clean
      - "**Standard Candle**" of the Standard Model
      - Interference between b→c and b→ u quark transitions
  - Precise measurements of the magnitudes of the CKM matrix elements : mixing, branching fractions
  - Sub-degree level of measurements to be compared with the CKMfitter global fit to challenge the Standard Model



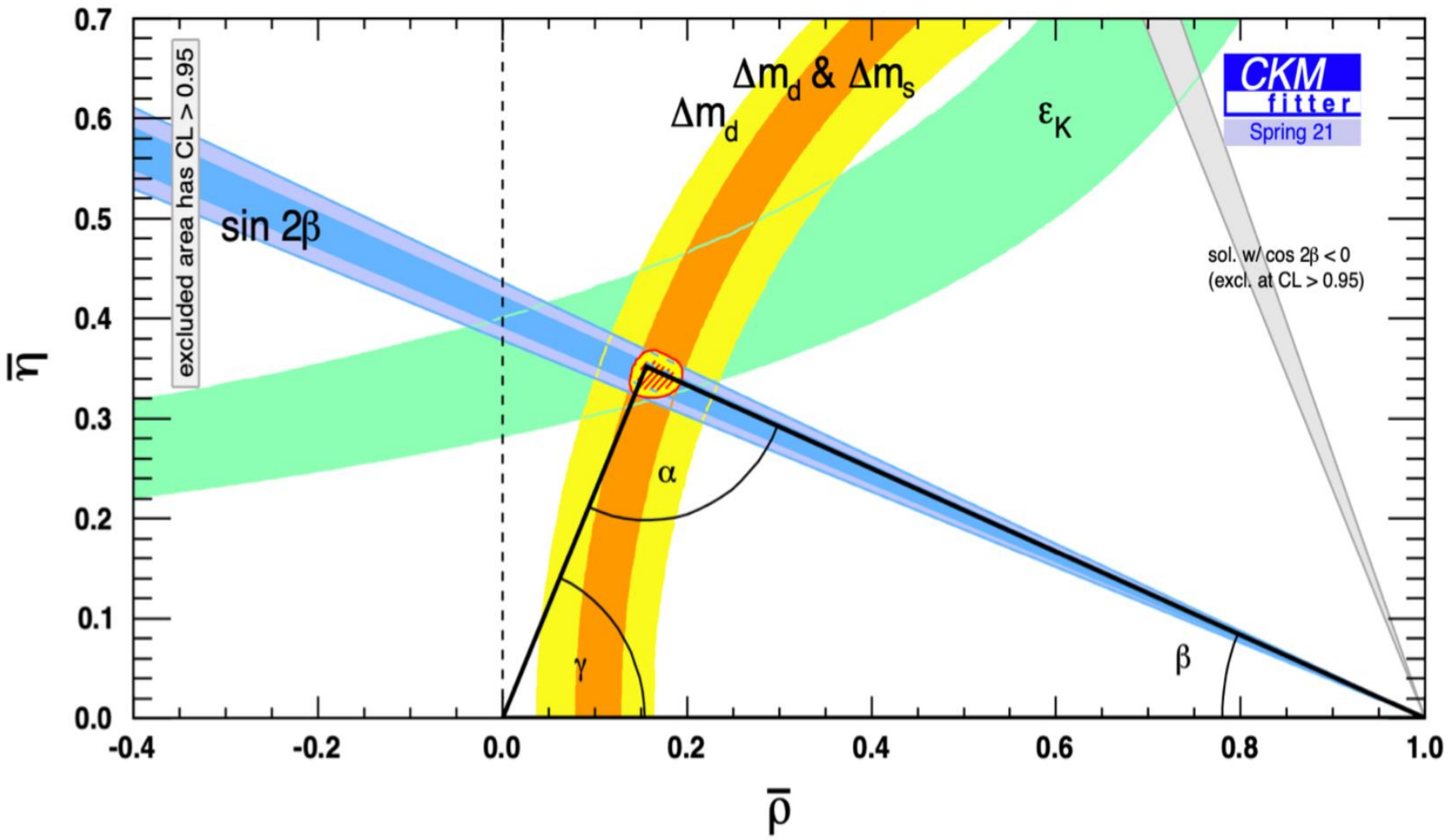
- **Loop-level** (indirect measurement) – sensitive to New Physics (NP)

Physics motivation : Unitarity triangle

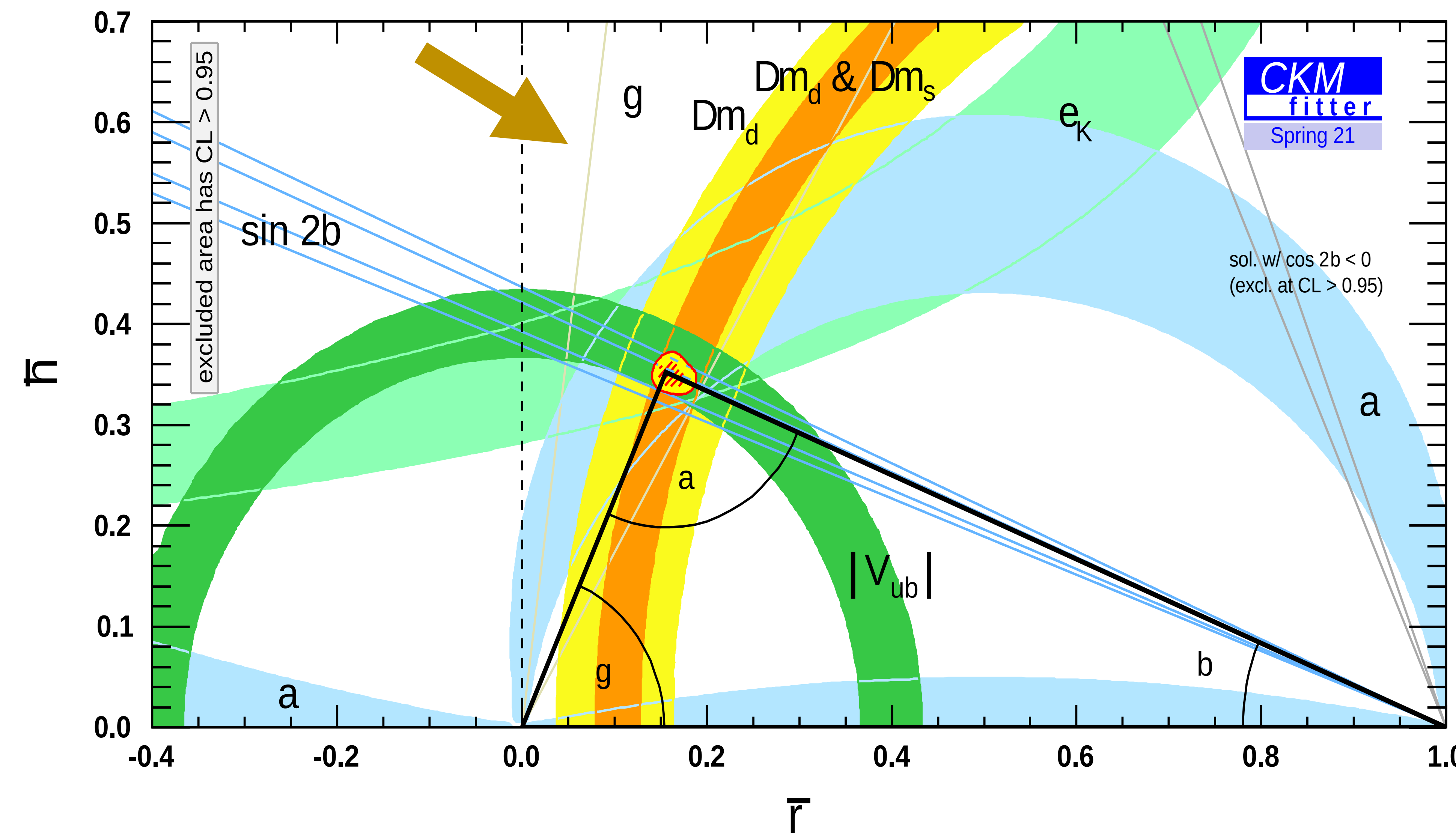
- Discrepancy between these will indicate "**New Physics**"
- Many different channels used to measure the angles and sides of the triangle



Direct measuments
(Pure SM like)



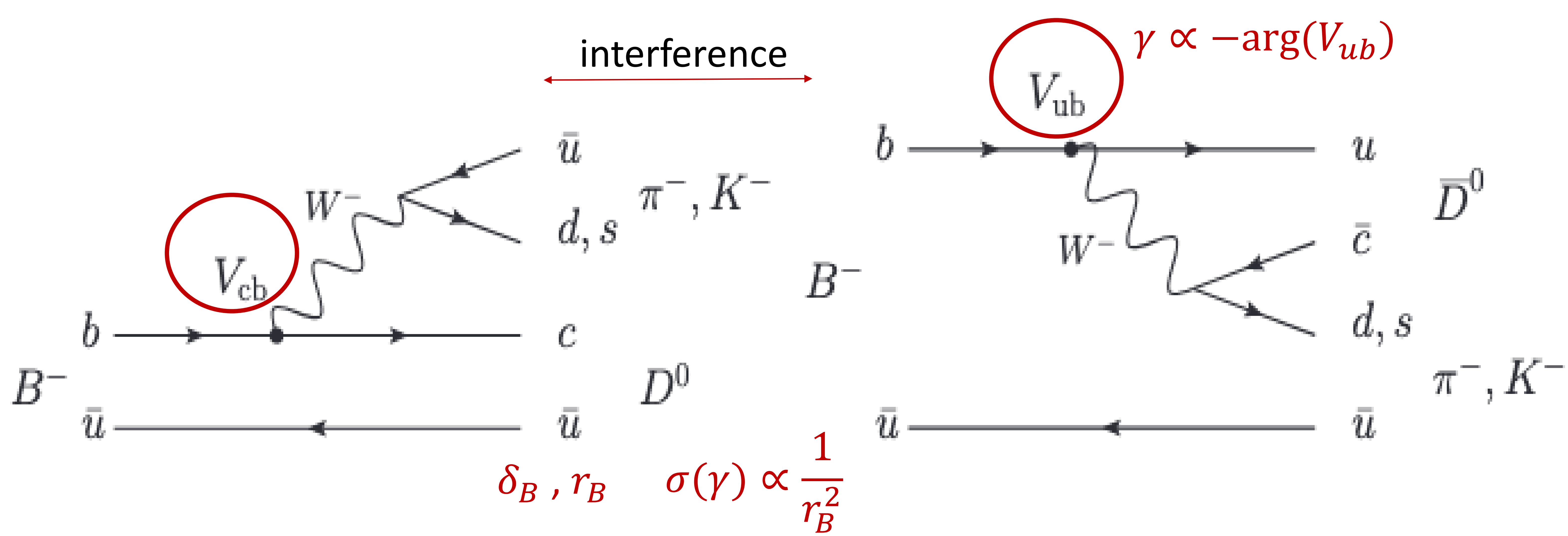
Indirect measurements
(Possible sensitivity to NP)



CKM angle γ in $B^{\pm} \to D\,K^{\pm}$ with $D \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$

NEW preliminary
LHCb-PAPER- 2022-017

- Sensitivity to γ determined by the interference between favoured b→c and suppressed b→u quark transitions in the tree level
- Analysis based on Run1+Run2 data sample corresponding to an integrated luminosity of $9fb^{-1}$

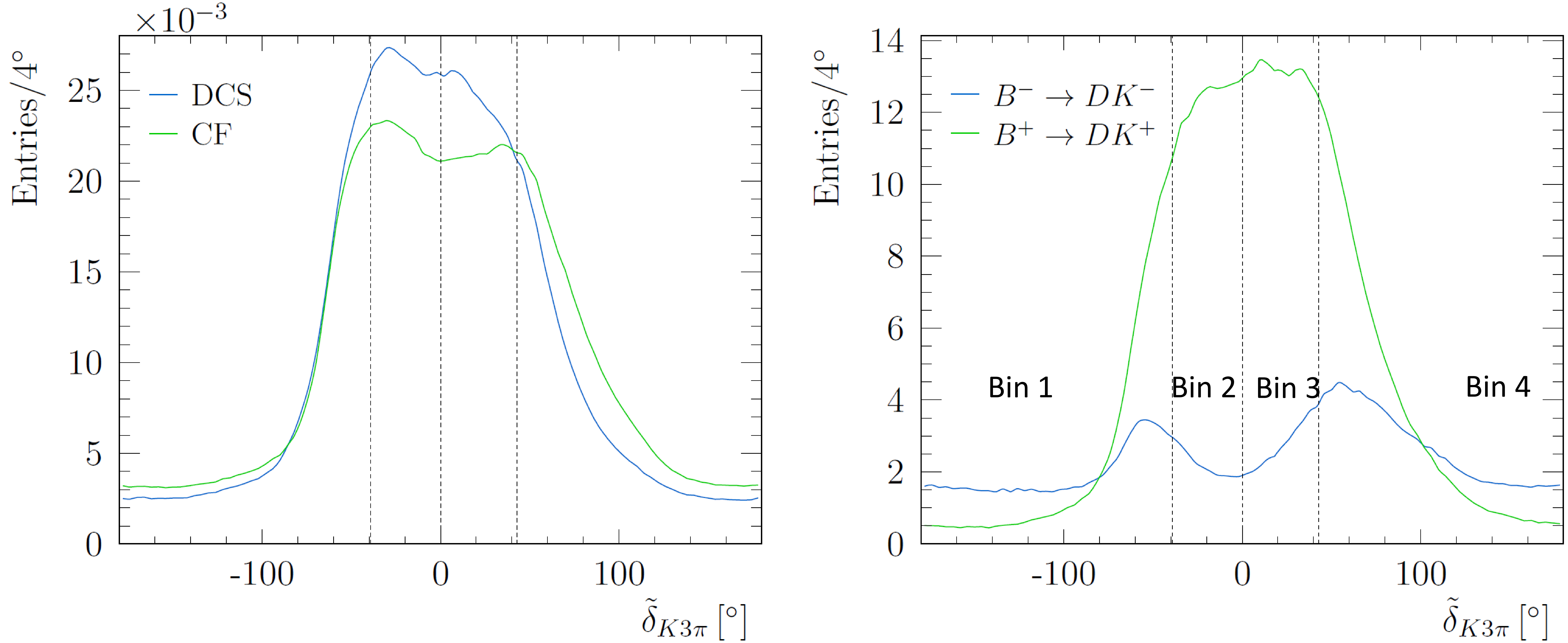


CKM angle γ in $B^{\pm} \to D K^{\pm}$ with $D \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$

NEW preliminary LHCb-PAPER- 2022-017

- This analysis based on the study " **Improved sensitivity to the phase γ through binning phase space in $B^- \to DK^-, D \to K^+\pi^-\pi^-\pi^+$"** by T. Evans, J. Libby, S. Malde and G. Wilkinson [Physics Letters B, 802 (2020)]

- A binning scheme is proposed in the phase space of $D^0 \to K^+\pi^-\pi^-\pi^+$ to maximise the sensitivity to CKM angle **γ** (The coherence factor R_D is larger in bins 2 and 3 and less diluted)



- **First use of this approach, based on a four bins choice**

CKM angle γ in $B^{\pm} \to D K^{\pm}$ with $D \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$

NEW preliminary LHCb-PAPER- 2022-017

- The measurement for $D \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$ decay mode in four bins of D-decay phase space

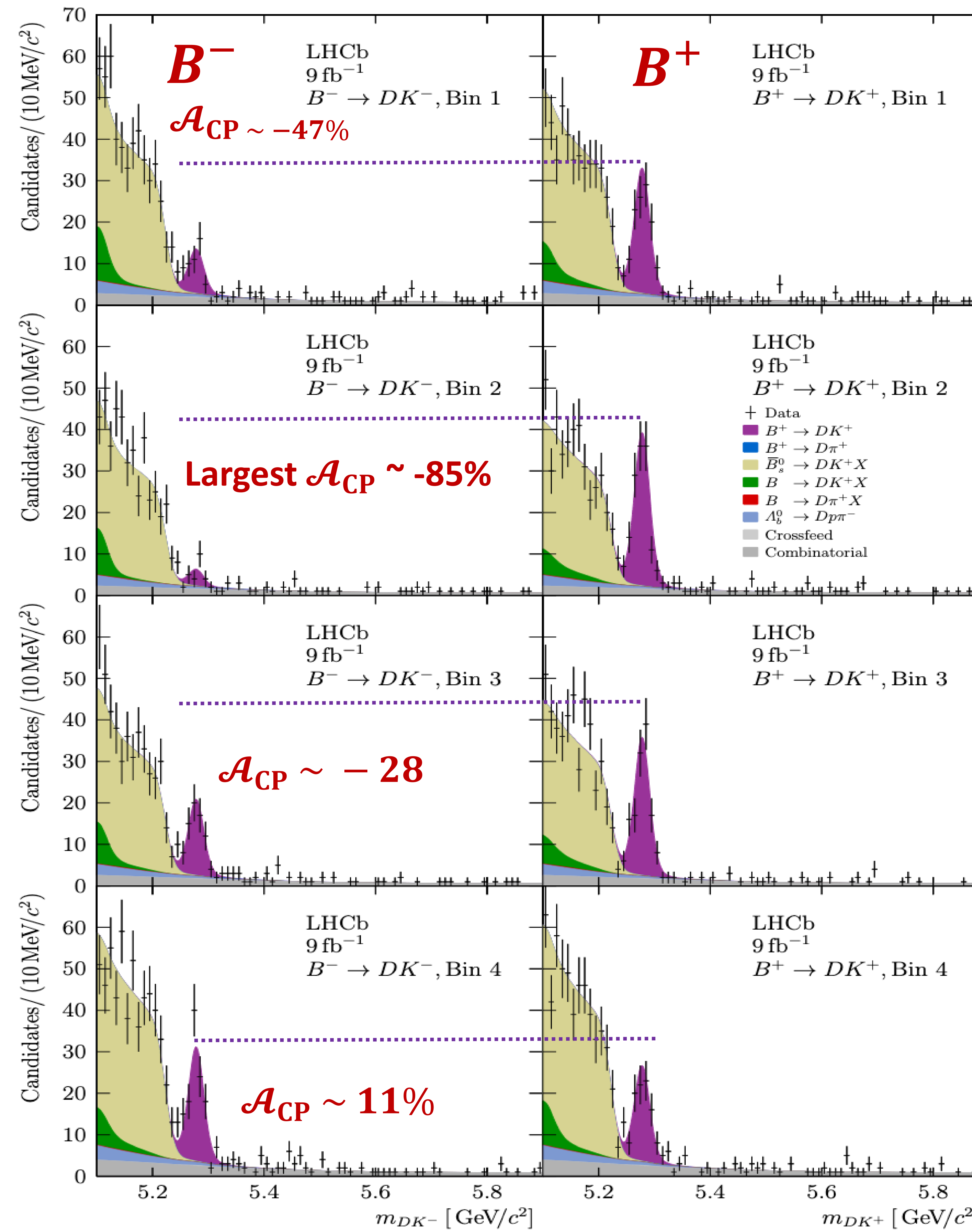
Bin	Limits ($\tilde{\delta}_{K3\pi}$)	$R^i_{K3\pi}$	$\delta^i_{K3\pi}$
1	$-180^\circ < \tilde{\delta}_{K3\pi} \leq -39^\circ$	$0.66\,^{+0.18}_{-0.21}$	$(117\,^{+14}_{-19})^\circ$
2	$-39^\circ < \tilde{\delta}_{K3\pi} \leq 0^\circ$	$0.85\,^{+0.14}_{-0.21}$	$(145\,^{+23}_{-14})^\circ$
3	$0^\circ < \tilde{\delta}_{K3\pi} \leq 43^\circ$	$0.78\,^{+0.12}_{-0.12}$	$(160\,^{+19}_{-20})^\circ$
4	$43^\circ < \tilde{\delta}_{K3\pi} \leq 180^\circ$	$0.25\,^{+0.16}_{-0.25}$	$(288\,^{+15}_{-29})^\circ$

➢ D decay hadronic parameters from CLEO-C, BESIII ([JHEP05 (2021) 164])

- One of the most precise measurement by a single charm D meson decay mode

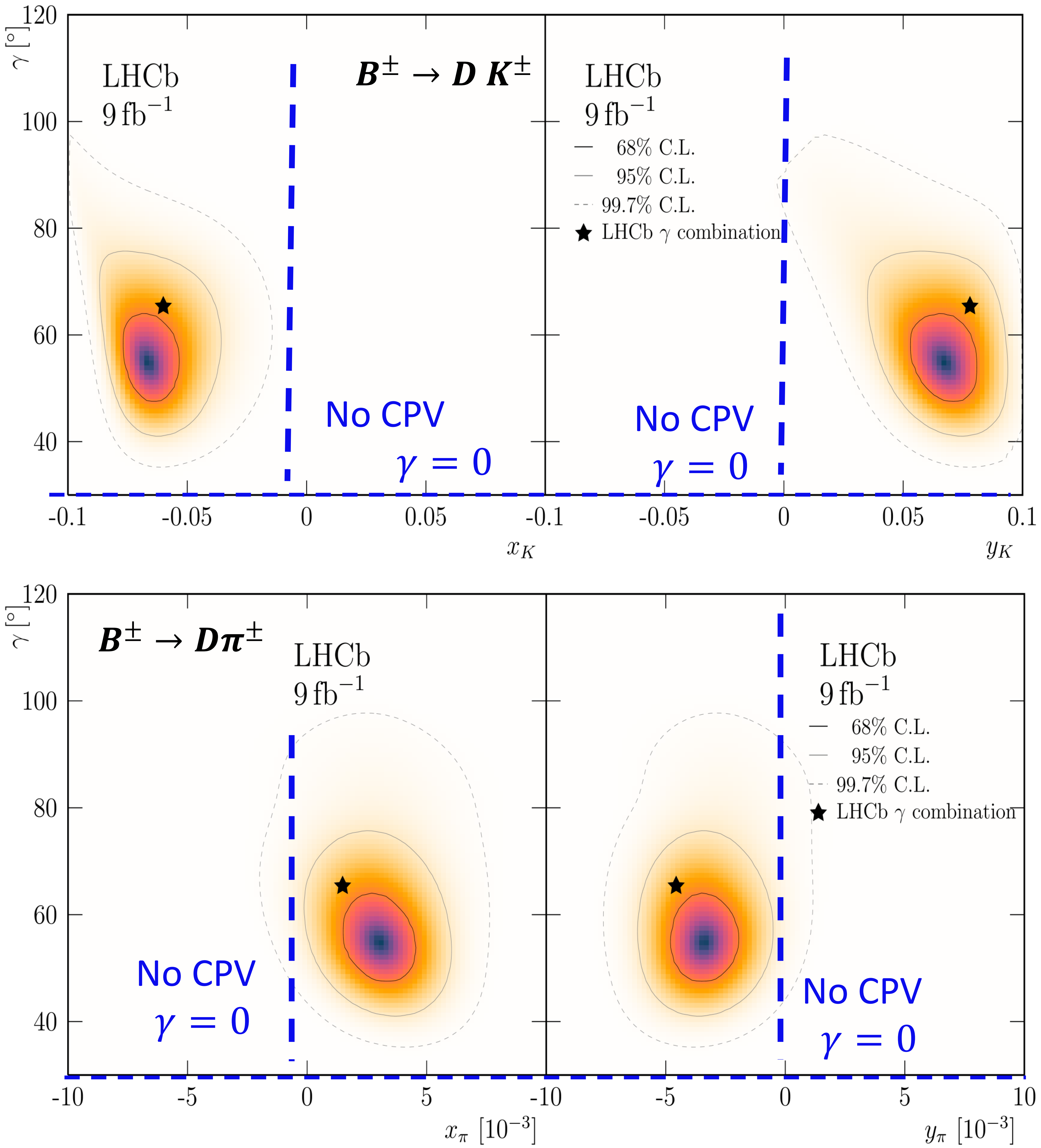
- Large difference between the invariant mass of charged B^+ and B^- hadrons designate CP asymmetry

Largest $\mathcal{A}_{CP}$ ~ 85% !



CKM angle γ in $B^\pm \to D K^\pm$ with $D \to K^\mp\pi^\pm\pi^\pm\pi^\mp$

NEW preliminary LHCb-PAPER- 2022-017



- $D \to K^\mp\pi^\pm\pi^\pm\pi^\mp$ decay provides a important contribution to the CKM angle γ combination: (best sensitivity from $D \to K_S^0\pi^+\pi^-$ [JHEP02 (2021) 169]
  - High branching fraction
  - Absence of neutral pions
- Confidence intervals for γ vs B-hadronic parameters in the cartesian parameterisation (x_K, y_K) and (x_π, y_π)
- B-hadronic parameters:

$$r_B^2 = x^2 + y^2$$

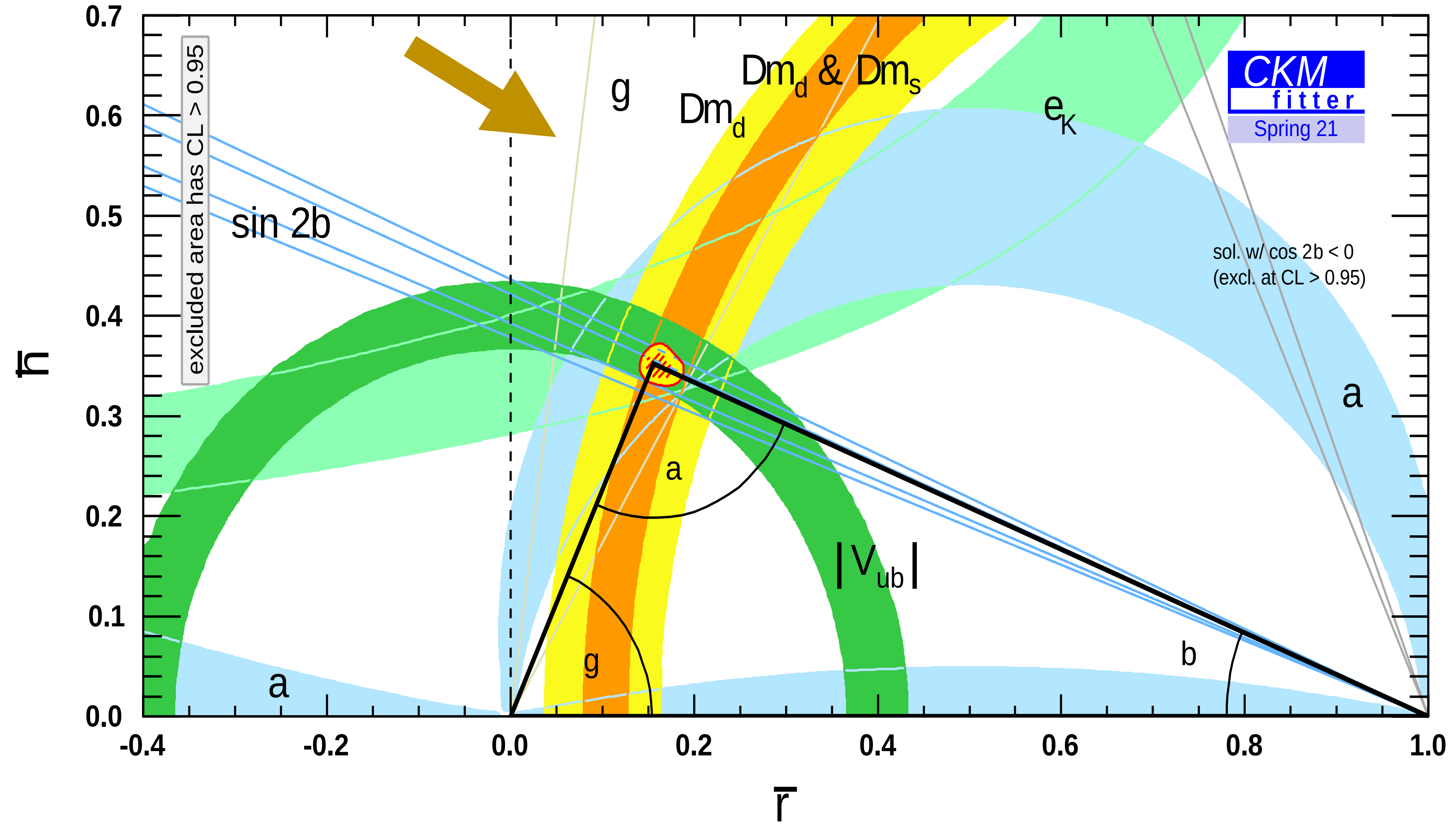
  - $r_B = (94.6^{+3.1+0.5+3.0}_{-3.1-0.5-2.3}) \times 10^{-3}$
  - $\delta_B = (134.6^{+6.0+0.7+8.6}_{-6.0-0.7-8.7})^\circ$
- The CKM angle γ is measured to be

$$\gamma = (54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.3})^\circ$$

➢ compatible with the measurements from [Eur. Phys. J. C (2021) 81: 226], [JHEP12 (2021) 141]

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

- This result will reduce the uncertainty on the CKM angle γ combination with measurements from B and D decays



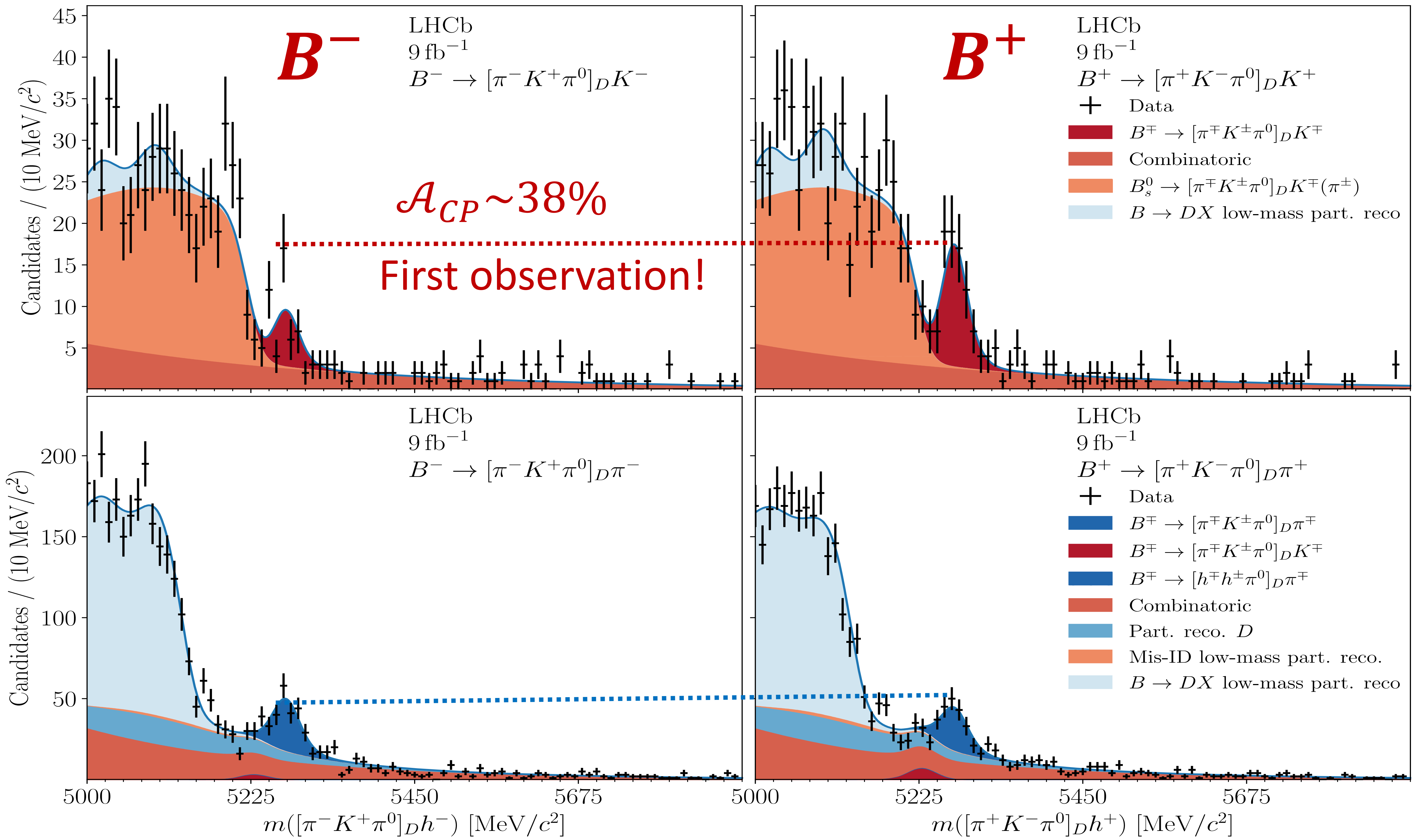
Constraints on the CKM $\boldsymbol{\gamma}$ from $B^{\pm} \to D(h^{\pm}h'^{\mp}\pi^{0})h^{\pm}$ decays

[LHCb-PAPER-2021-036]

- Analysis based on Run1+Run2 data sample corresponding to an integrated luminosity of $9fb^{-1}$
- h can be either kaon or pion

Constraints on the CKM γ from $B^{\pm} \to D(h^{\pm}h'^{\mp}\pi^{0})h^{\pm}$ decays

LHCb-PAPER-2021-036



- B candidates $B^{\mp} \to DK^{\mp}$ *and* $B^{\mp} \to D\pi^{\mp}$, where charm meson reconstructed in quasi-GLW and ADS method:

- $D \to \pi^+\pi^-\pi^0$
- $D \to K^+K^-\pi^0$
- $D \to K^+\pi^-\pi^0$
- $D \to \pi^+K^-\pi^0$ **(suppressed)**

Phys. Lett. B 740 (2015) 1

- R_D Coherence factor ~1

- Measurement of 11 CP violation observables with world best precision

- Signal yields from each decay modes used in the analysis:

Mode	Yield
$B^{\pm} \to [K^{\pm}K^{\mp}\pi^0]_D\pi^{\pm}$	4026 ± 77
$B^{\pm} \to [\pi^{\pm}\pi^{\mp}\pi^0]_D\pi^{\pm}$	14180 ± 140
$B^{\pm} \to [K^{\pm}\pi^{\mp}\pi^0]_D\pi^{\pm}$	140696 ± 589
$B^{\pm} \to [\pi^{\pm}K^{\mp}\pi^0]_D\pi^{\pm}$	293 ± 27
$B^{\pm} \to [K^{\pm}K^{\mp}\pi^0]_DK^{\pm}$	401 ± 29
$B^{\pm} \to [\pi^{\pm}\pi^{\mp}\pi^0]_DK^{\pm}$	1189 ± 51
$B^{\pm} \to [K^{\pm}\pi^{\mp}\pi^0]_DK^{\pm}$	12265 ± 158
$B^{\pm} \to [\pi^{\pm}K^{\mp}\pi^0]_DK^{\pm}$	155 ± 19

- First observation of $B^- \to [\pi^- K^+ \pi^0]K^-$ suppressed mode with a significance of **$7.8\,\sigma$** !

- **Evidence of a large CP asymmetry !**

$$A_{ADS(K)} = -0.38 \pm 0.12 \pm 0.02$$

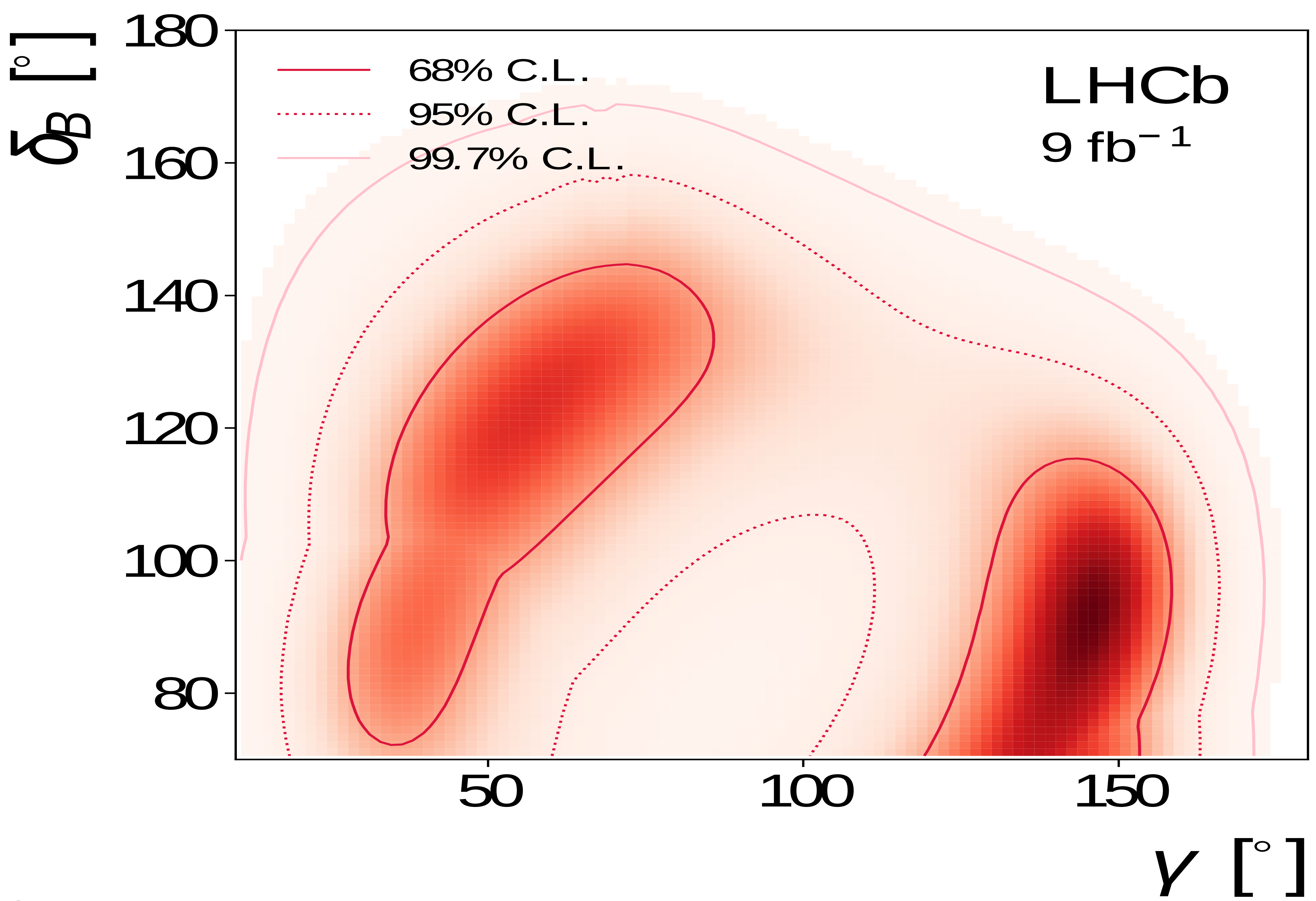
Constraints on the CKM γ from $B^{\pm} \to D(h^{\pm}h'^{\mp}\pi^{0})h^{\pm}$ decays

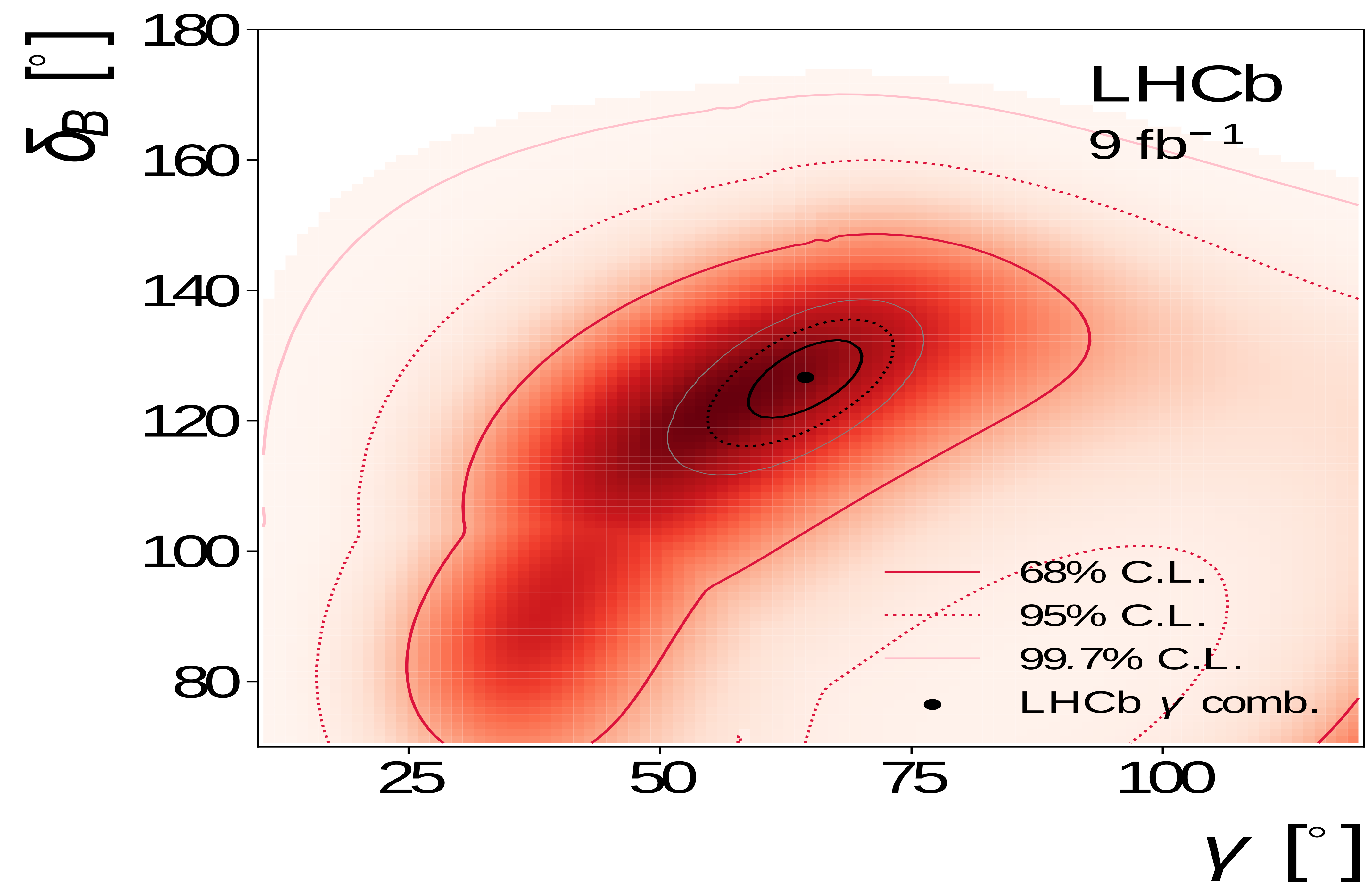
LHCb-PAPER-2021-036

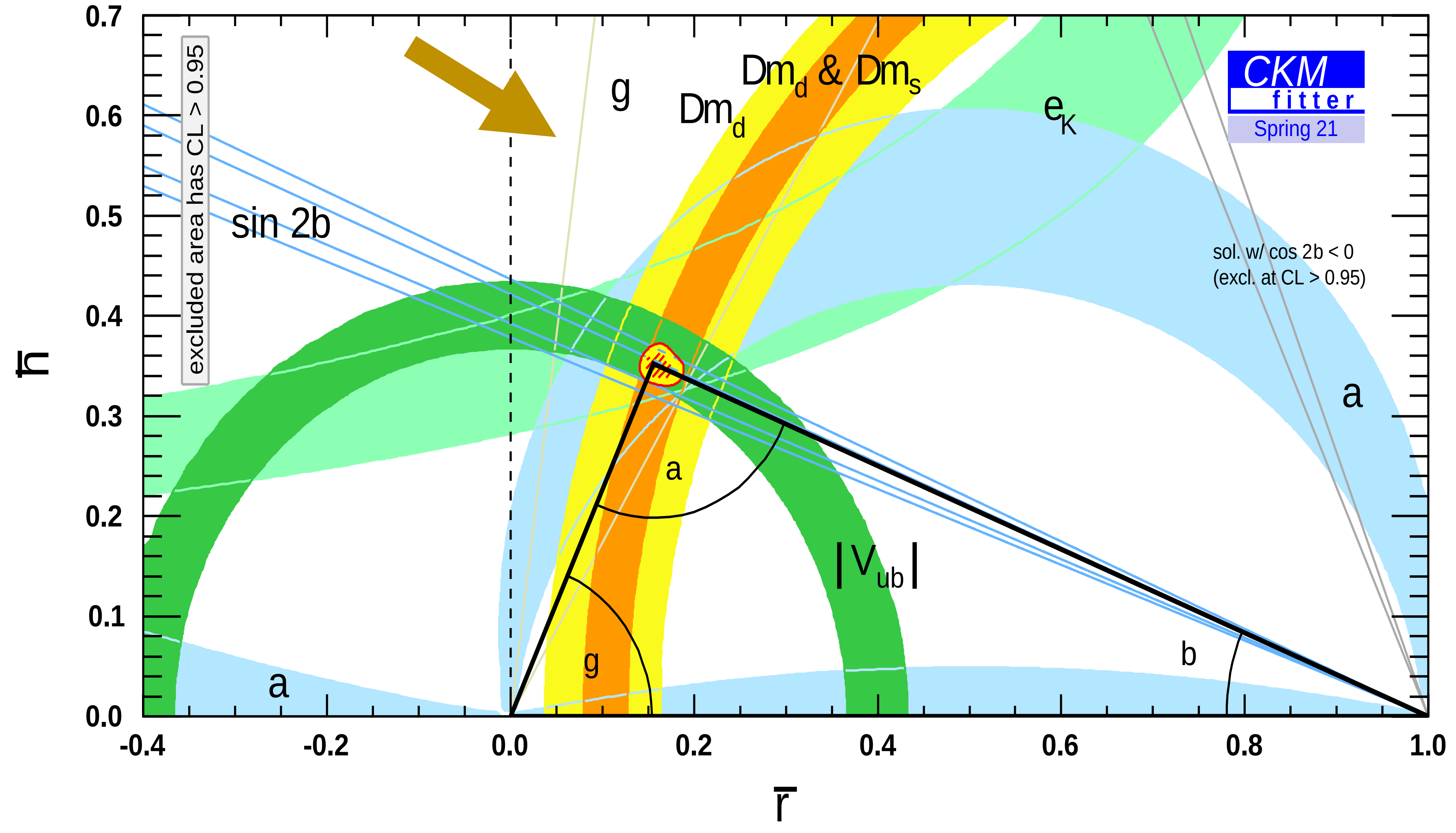
- Confidence regions of the strong phase vs the CKM angle γ
- Results interpreted in terms of:
  - $\gamma = (56^{+24}_{-19})^{\circ}$
  - $\delta_B = (122^{+19}_{-23})^{\circ}$
  - $r_B = (9.3^{+1.0}_{-0.9})^{\circ} \times 10^{-2}$

➢ Consistent with the LHCb γ combination! [JHEP12 (2021) 141]

$R^{KK\pi^0}$	=	1.021	±	0.079	±	0.005
$R^{\pi\pi\pi^0}$	=	0.902	±	0.041	±	0.004
$A_K^{K\pi\pi^0}$	=	−0.024	±	0.013	±	0.002
$A_K^{KK\pi^0}$	=	0.067	±	0.073	±	0.003
$A_K^{\pi\pi\pi^0}$	=	0.109	±	0.043	±	0.003
$A_\pi^{KK\pi^0}$	=	−0.001	±	0.019	±	0.002
$A_\pi^{\pi\pi\pi^0}$	=	0.001	±	0.010	±	0.002
R_K^+	=	0.0179	±	0.0024	±	0.0003
R_K^-	=	0.0085	±	0.0020	±	0.0004
R_π^+	=	0.00188	±	0.00027	±	0.00005
R_π^-	=	0.00227	±	0.00028	±	0.00004







Simultaneous determination of CKM angle γ and charm mixing parameters

JHEP12 (2021) 141

- Measurements are performed from beauty and charm sectors which are sensitive to γ and charm mixing parameters.

Combination of CKM γ and charm mixing parameters

JHEP12 (2021) 141

Inputs from beauty sector

Updated & New

B decay	D decay	Dataset
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-$	Run 1&2
$B^{\pm} \to Dh^{\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^0$	Run 1
$B^{\pm} \to Dh^{\pm}$	$D \to K_s^0 h^+h^-$	Run 1&2
$B^{\pm} \to Dh^{\pm}$	$D \to K_s^0 K^{\pm}\pi^{\mp}$	Run 1&2
$B^{\pm} \to D^*h^{\pm}$	$D \to h^+h^-$	Run 1&2
$B^{\pm} \to DK^{*\pm}$	$D \to h^+h^-$	Run 1&2 (2015-2016)
$B^{\pm} \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1&2 (2015-2016)
$B^{\pm} \to Dh^{\pm}\pi^+\pi^-$	$D \to h^+h^-$	Run 1
$B^0 \to DK^{*0}$	$D \to h^+h^-$	Run 1&2 (2015-2016)
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1&2 (2015-2016)
$B^0 \to DK^{*0}$	$D \to K_s^0\pi^+\pi^-$	Run 1
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	Run 1
$B_s^0 \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	Run 1
$B_s^0 \to D_s^{\mp}K^{\pm}\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	Run 1&2

- Combination of measurements sensitive to CKM angle γ performed
- 151 observables to determine 52 free parameters with all frequentist treatment

Inputs from charm sector

New

D decay	Observable(s)	Dataset
$D^0 \to h^+h^-$	ΔA_{CP}	Run 1&2
$D^0 \to h^+h^-$	y_{CP}	Run 1
$D^0 \to h^+h^-$	ΔY	Run 1&2
$D^0 \to K^+\pi^-$ (Single Tag)	$R^{\pm}, (x'^{\pm}), y'^{\pm}$	Run 1
$D^0 \to K^+\pi^-$ (Double Tag)	$R^{\pm}, (x'^{\pm}), y'^{\pm}$	Run 1&2 (2015-2016)
$D^0 \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	$(x^2+y^2)/4$	Run 1
$D^0 \to K_s^0\pi^+\pi^-$	x, y	Run 1
$D^0 \to K_s^0\pi^+\pi^-$	$x_{CP}, y_{CP}, \Delta x, \Delta y$	Run 1&2

Combination of CKM γ and charm mixing parameters

JHEP12 (2021) 141

- Most precise determination of γ from a single experiment, Belle-II experiment is coming on stage
- Different B modes agree at 2σ level
- Combination of Unitarity Triangle angle γ measurements of the LHCb with excellent agreement with the global fit results:
- **New average:** $\gamma = (65.4^{+3.8}_{-4.2})^\circ$ (direct measurement)
- $B_s^0 \to D_s^{\mp} K^{\pm}(\pi\pi)$ analysis used Run 1 & Run 2 [LHCb-CONF-2020-003]
    - constraint on $\gamma \sim 20^\circ$ level of precision and the most probable value seems to be high wrt the B^+ and B^0 measurements
- Coherence with

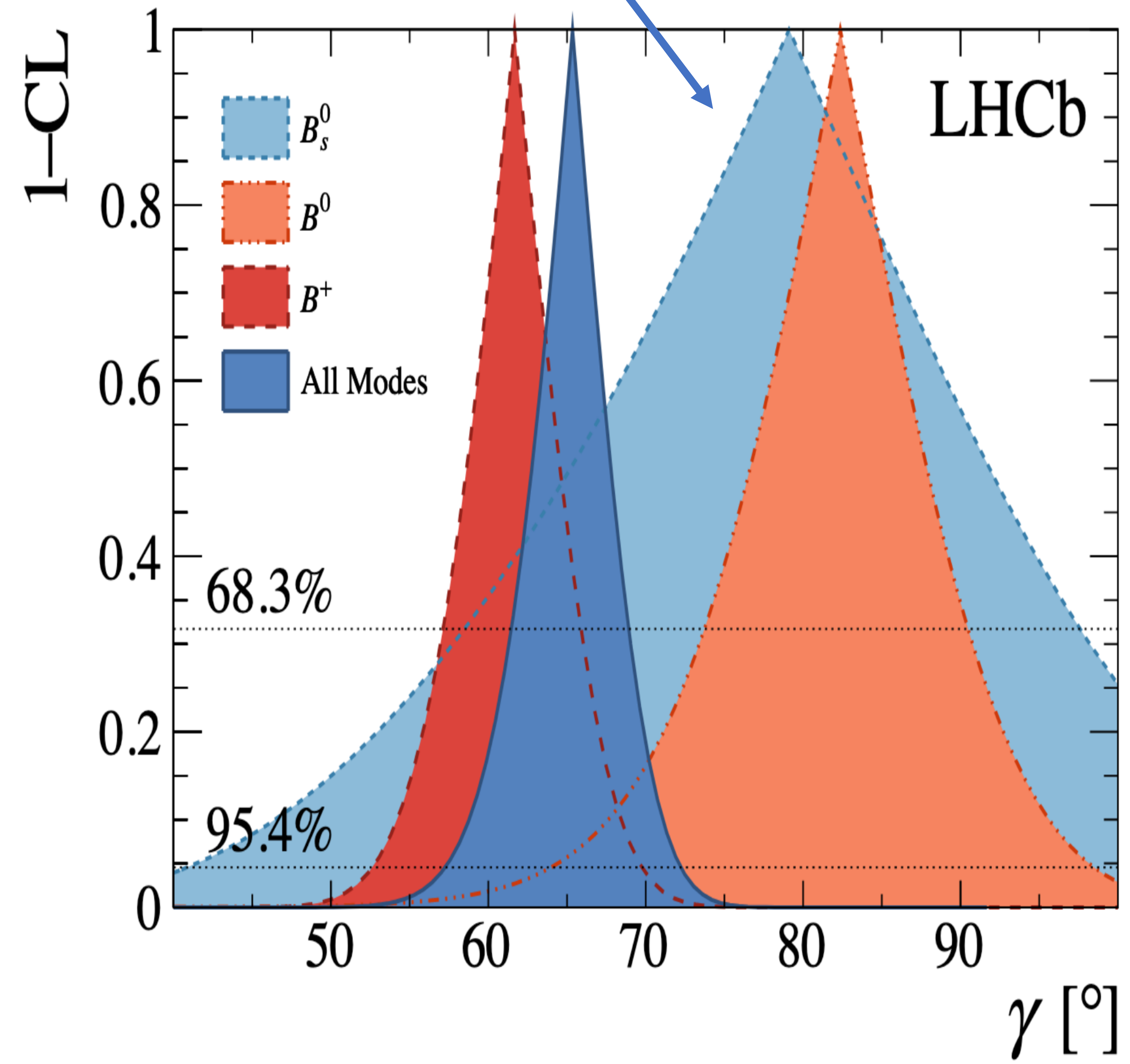
$\gamma = (65.6^{+0.9}_{-2.7})^\circ$ (CKM fitter, frequentist)

$\gamma = (65.8 \pm 2.2)^\circ$ (UT fit, Bayesian)

- Compatible with previous LHCb combination:

$\gamma = (74^{+5.0}_{-5.8})^\circ$ [LHCb-CONF-2018-002]

Time-dependent and tagging analysis $B_s^0 \to D_s^{\mp} K^{\pm}(\pi\pi)$



 JHEP12 (2021) 141

- Most precise charm mixing parameters determined by combining for the first time

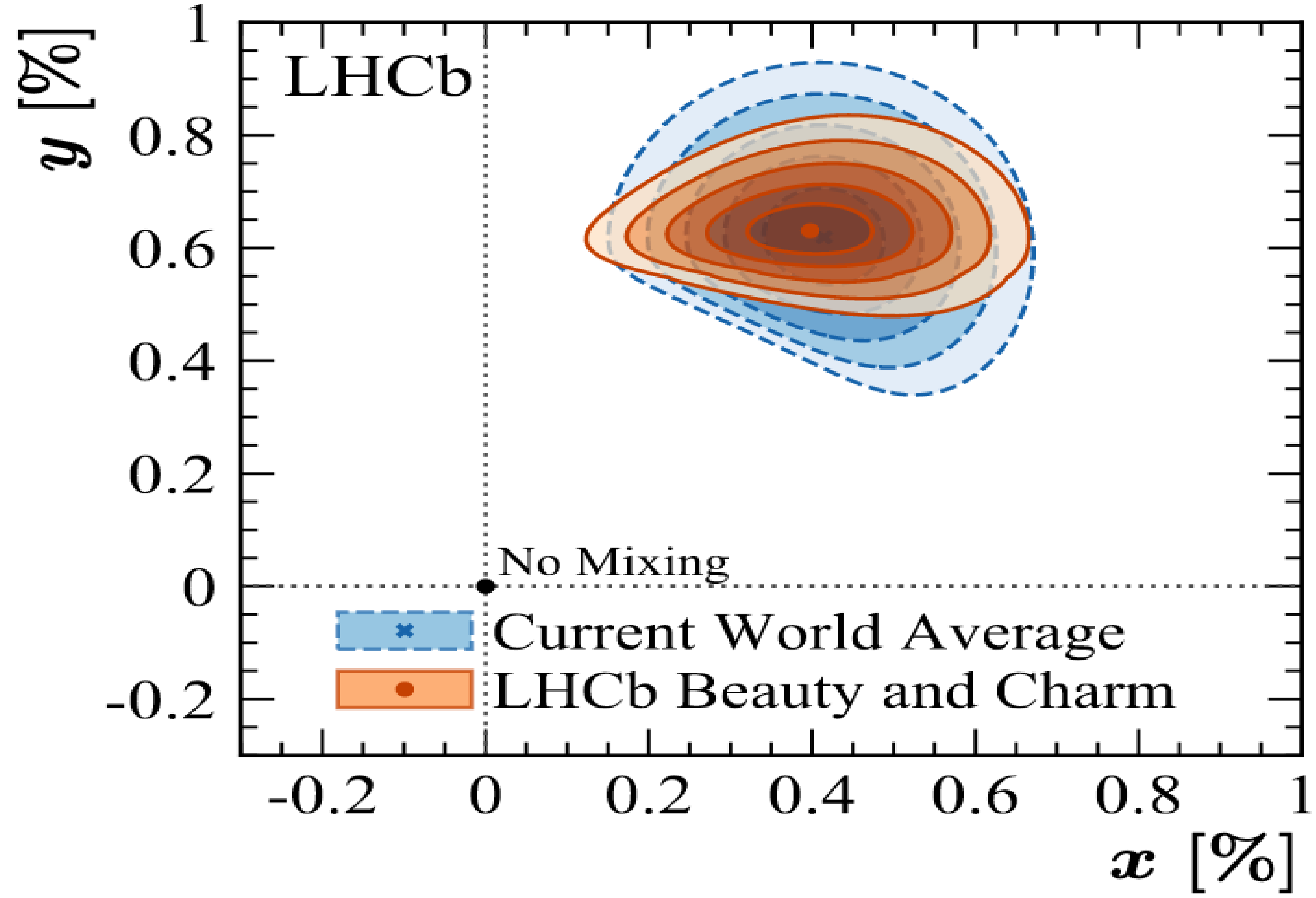
- $x \equiv \frac{\Delta M}{\Gamma} = (0.400^{+0.052}_{-0.053})\%$ $y \equiv \frac{\Delta\Gamma}{2\Gamma} = (0.630^{+0.033}_{-0.030})\%$

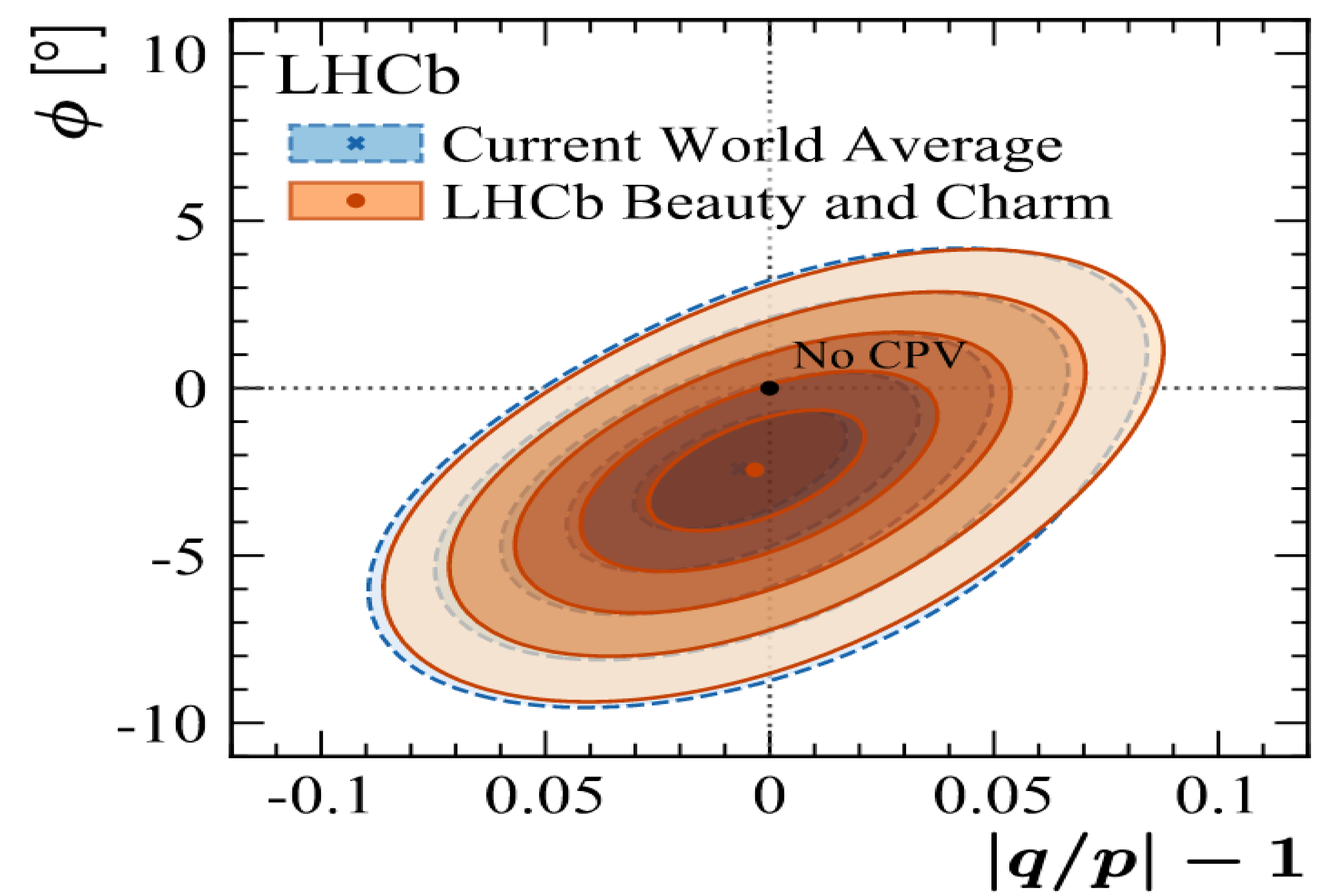
- $\left|\frac{q}{p}\right| = 0.997 \pm 0.016$ $\phi = (-2.4 \pm 1.2)^{\circ}$

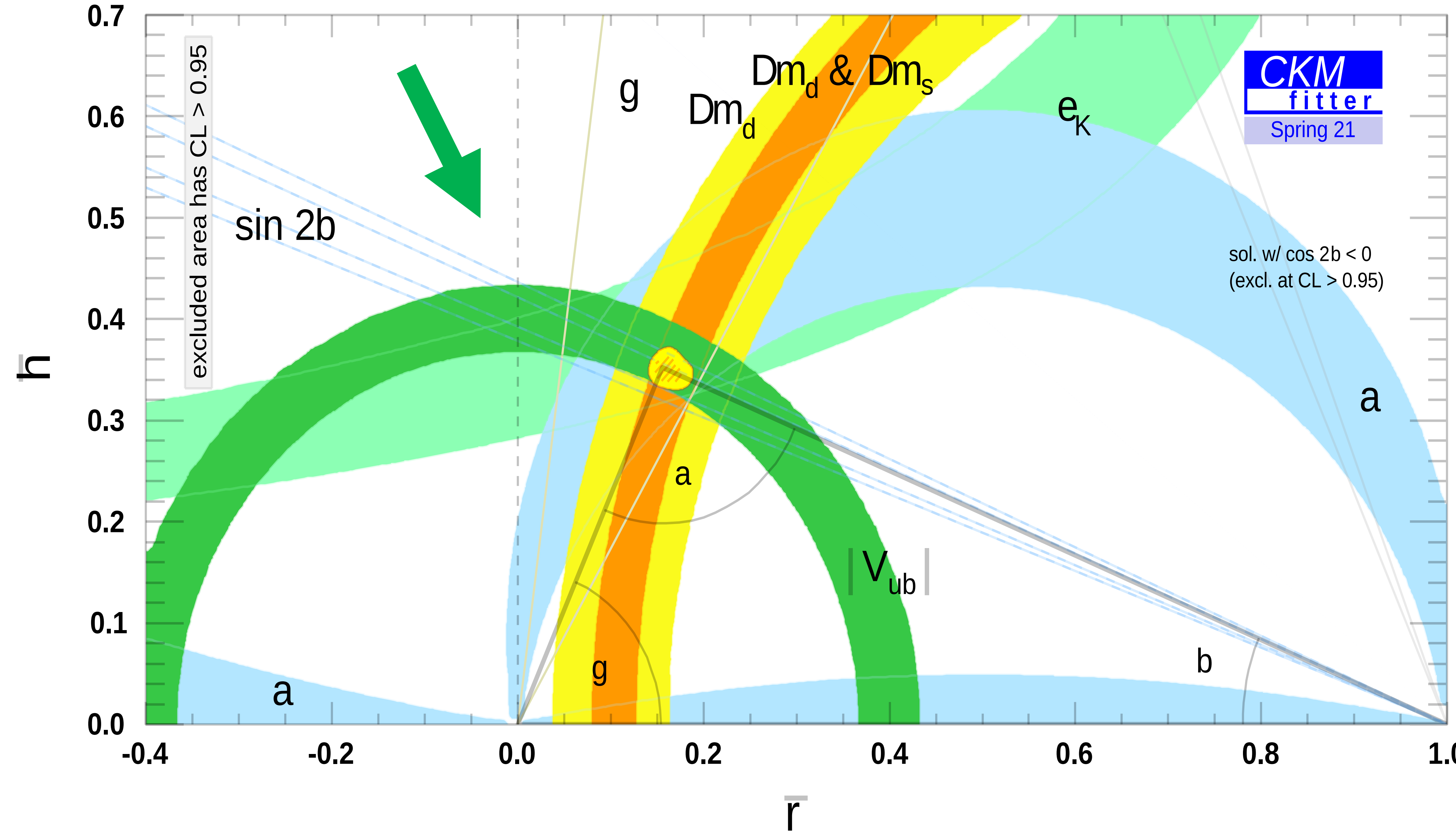
- Precision improved by a factor of 2 in y!

- See the talk Fred Blanc@ICHEP22 Bologna (recent improvements on charm mixing)

- World average: $x \equiv \frac{\Delta M}{\Gamma} = (0.409^{+0.048}_{-0.049})\%$ $y \equiv \frac{\Delta\Gamma}{2\Gamma} = (0.615^{+0.056}_{-0.055})\%$







First Observation of the decay $B_s^0 \rightarrow K^- \mu^+ \upsilon_\mu$ and a measurement of $|V_{ub}|/|V_{cb}|$

PRL 126, 081804 (2021)

- Analysis uses 2012 data sample corresponding to an integrated luminosity of 2 fb^{-1} @8 TeV

First Observation of the decay $B_s^0 \to K^- \mu^+ \upsilon_\mu$ and a measurement of $|V_{ub}|/|V_{cb}|$

[PRL 126, 081804 (2021)]

- $|V_{ub}|/|V_{cb}|$ is measured through the relation of the ratio of BF of $B_s^0 \to K^- \mu^+ \upsilon_\mu$ signal and $B_s^0 \to D_s^- \mu^+ \upsilon_\mu$ normalization channels

$$R_{BF} \equiv \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \upsilon_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \upsilon_\mu)} = \frac{N(B_s^0 \to K^- \mu^+ \upsilon_\mu)}{N(B_s^0 \to D_s^- \mu^+ \upsilon_\mu)} \frac{\epsilon(D_s^-)}{\epsilon(K^-)} \times \mathcal{B}(D_s^- \to K^- K^+ \pi^-) = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{FF_K}{FF_{D_s}}$$

experiment PDG Theory input

- Binned maximum-likelihood fit m_{corr} of the B_s^0 to obtain the signal and normalization yield

- m_{corr} defined as : $m_{corr} = \sqrt{m^2_{(X\mu)} + \frac{p_\perp^2}{c^2}} + p_\perp/c$

FF:form factor
ϵ: efficiency
LCSR: light cone sum rule
LQCD: lattice Quantum Chromodynamics

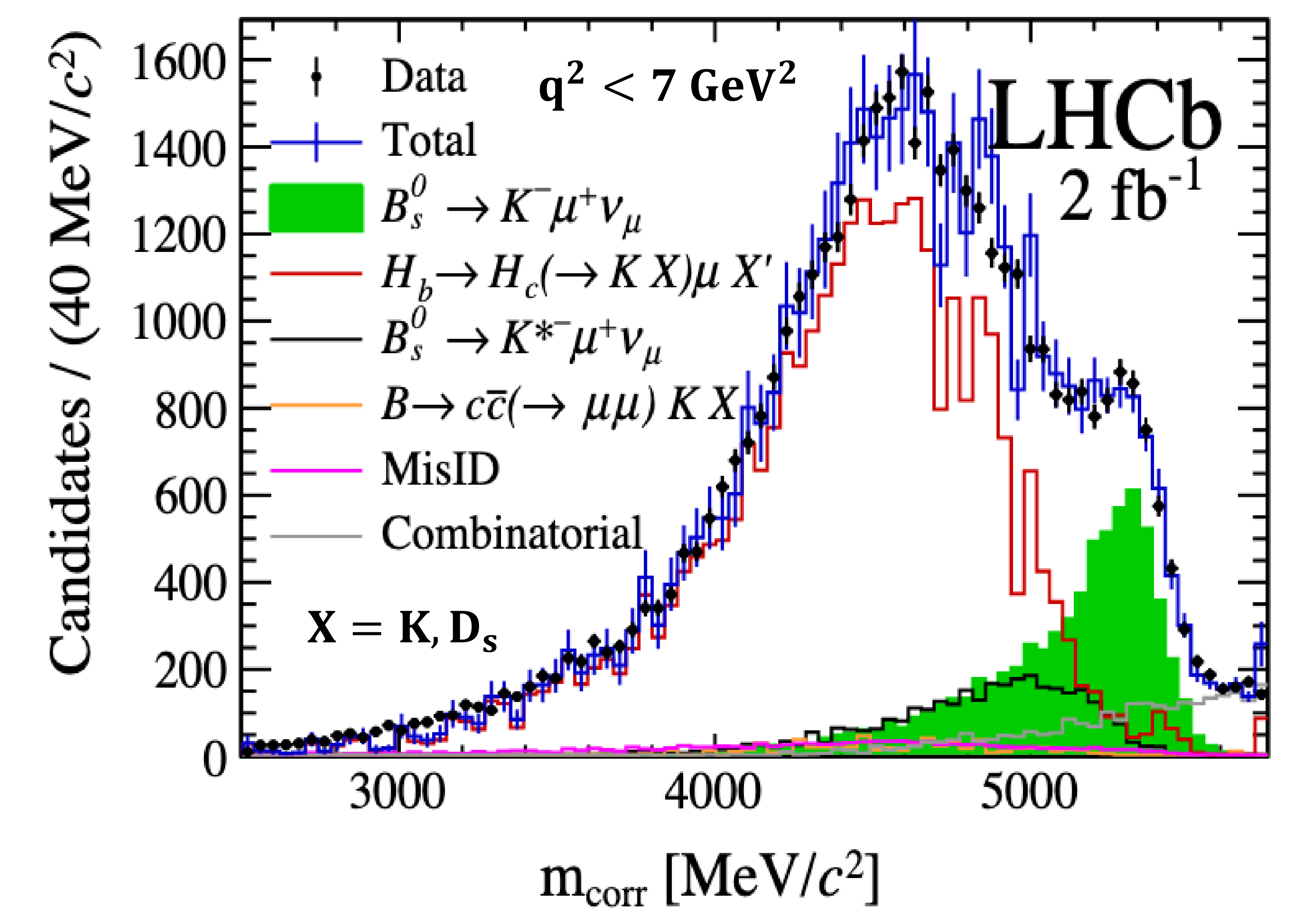
- Signal in two regions of q^2 :

> 7 [PRD 100, 034501 (2019)](LQCD)
< 7 [JHEP 08,112 (2017)] (LCSR)

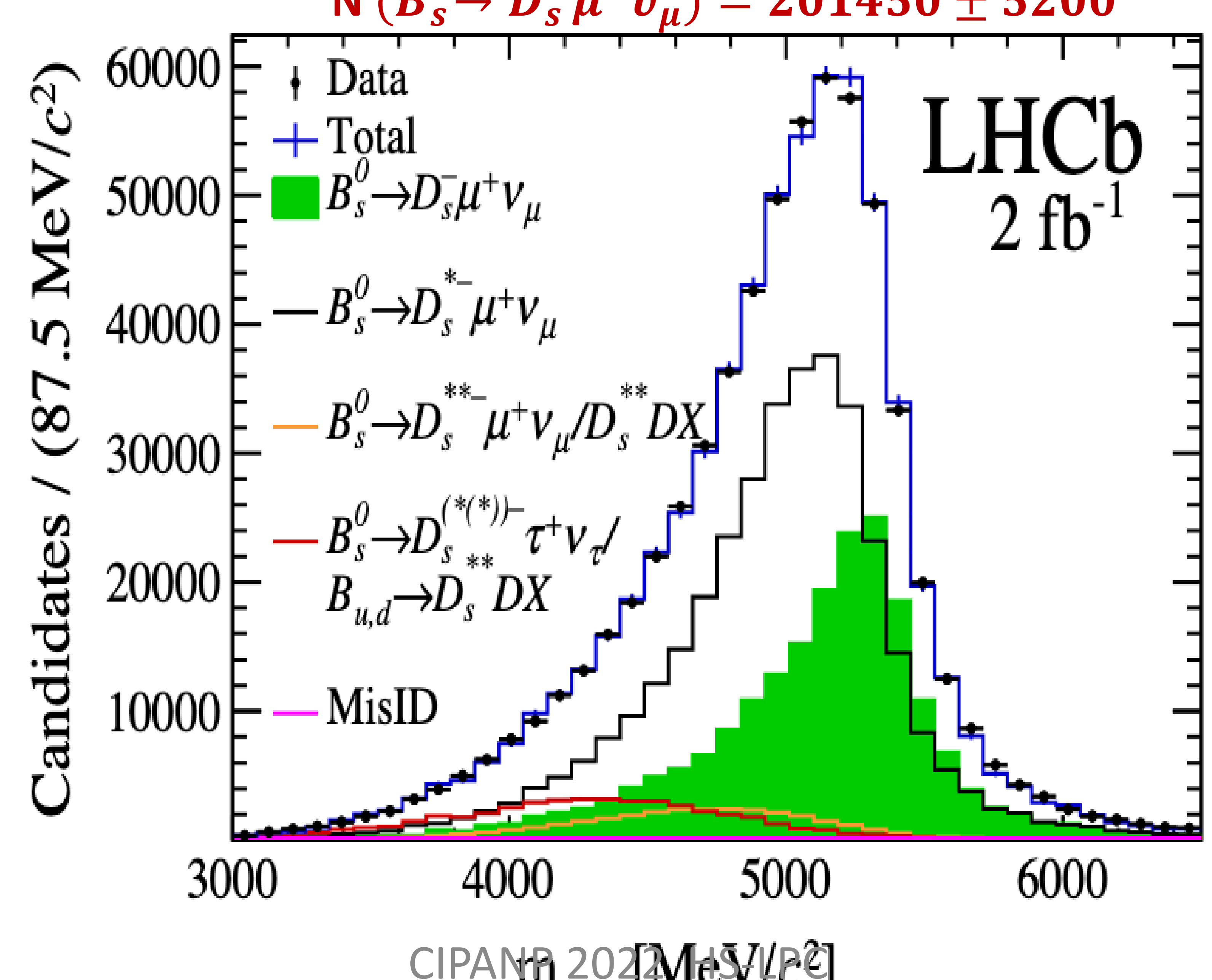
- V_{cb} by normalization channel $B_s^0 \to D_s^- \mu^+ \upsilon_\mu$ modelled by LQCD [Phys Rev D. 101 074513]

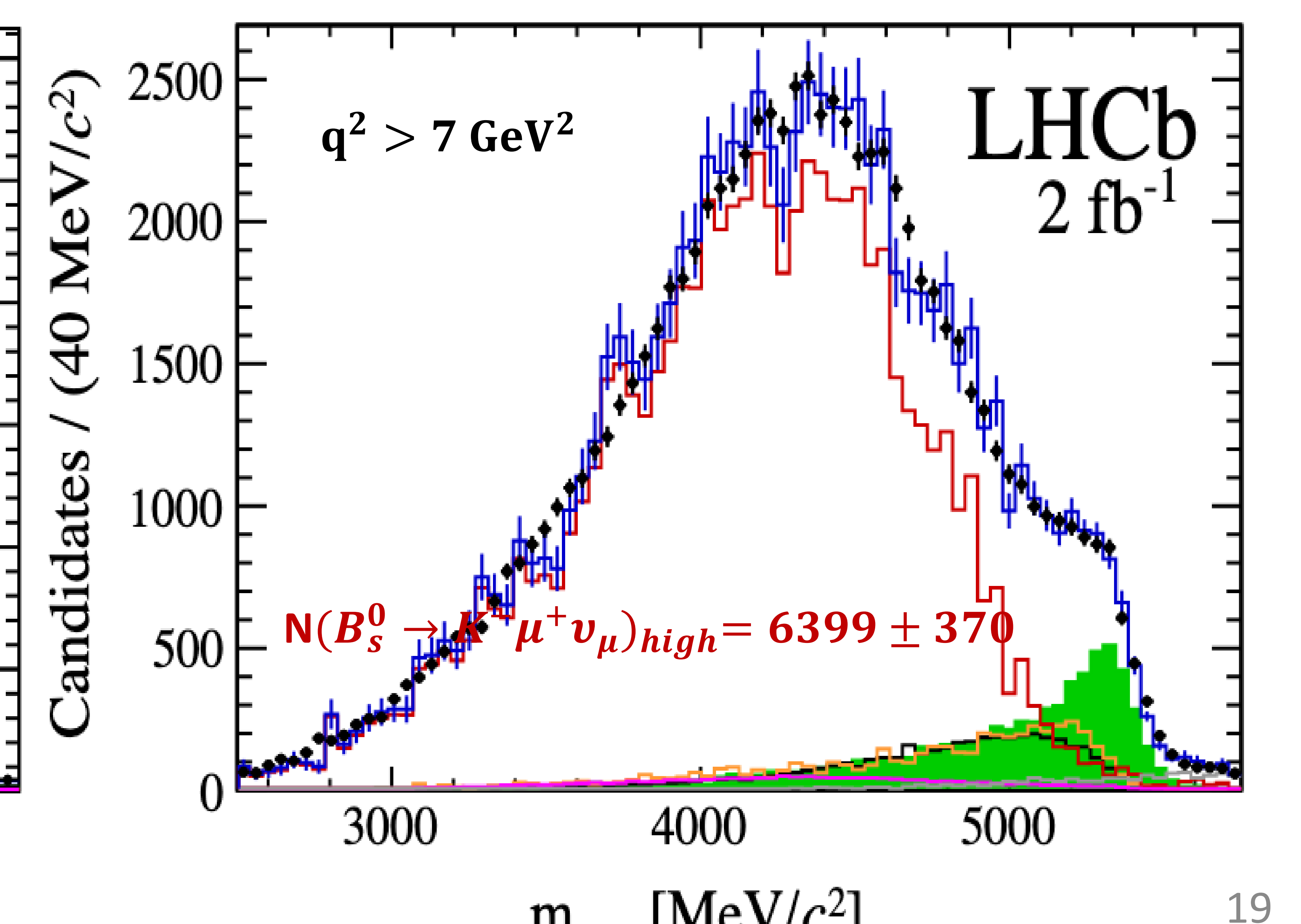
- q^2 is reconstructed up to twofold ambiguity using vertex and Λ_b^0 const [JHEP 02, 021 (2017)]

$N(B_s^0 \to K^- \mu^+ \upsilon_\mu)_{low} = 6922 \pm 285$



$N(B_s^0 \to D_s^- \mu^+ \upsilon_\mu) = 201450 \pm 5200$





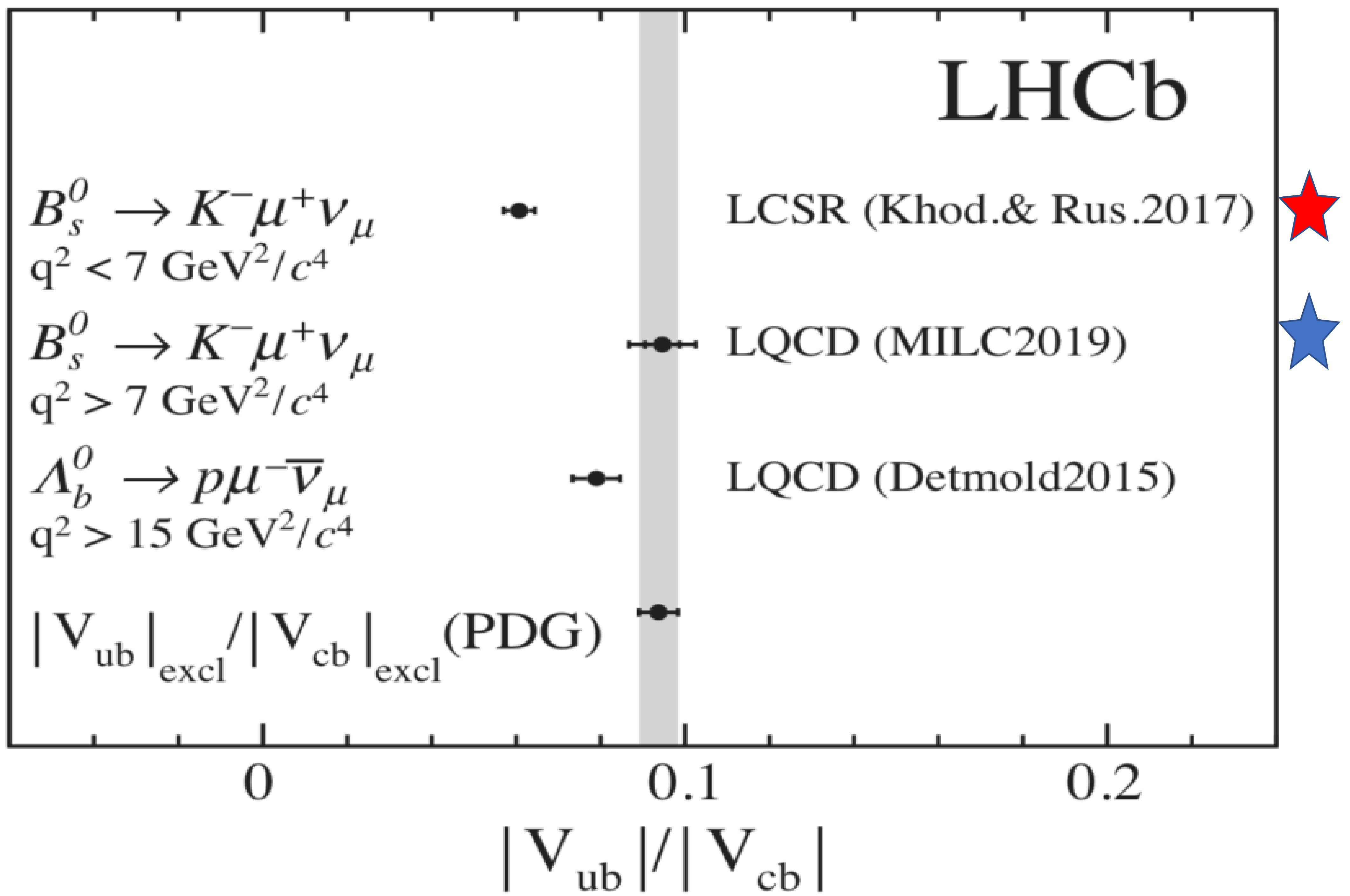
First Observation of the decay $B_s^0 \to K^- \mu^+ \upsilon_\mu$ and a measurement of $|V_{ub}|/|V_{cb}|$

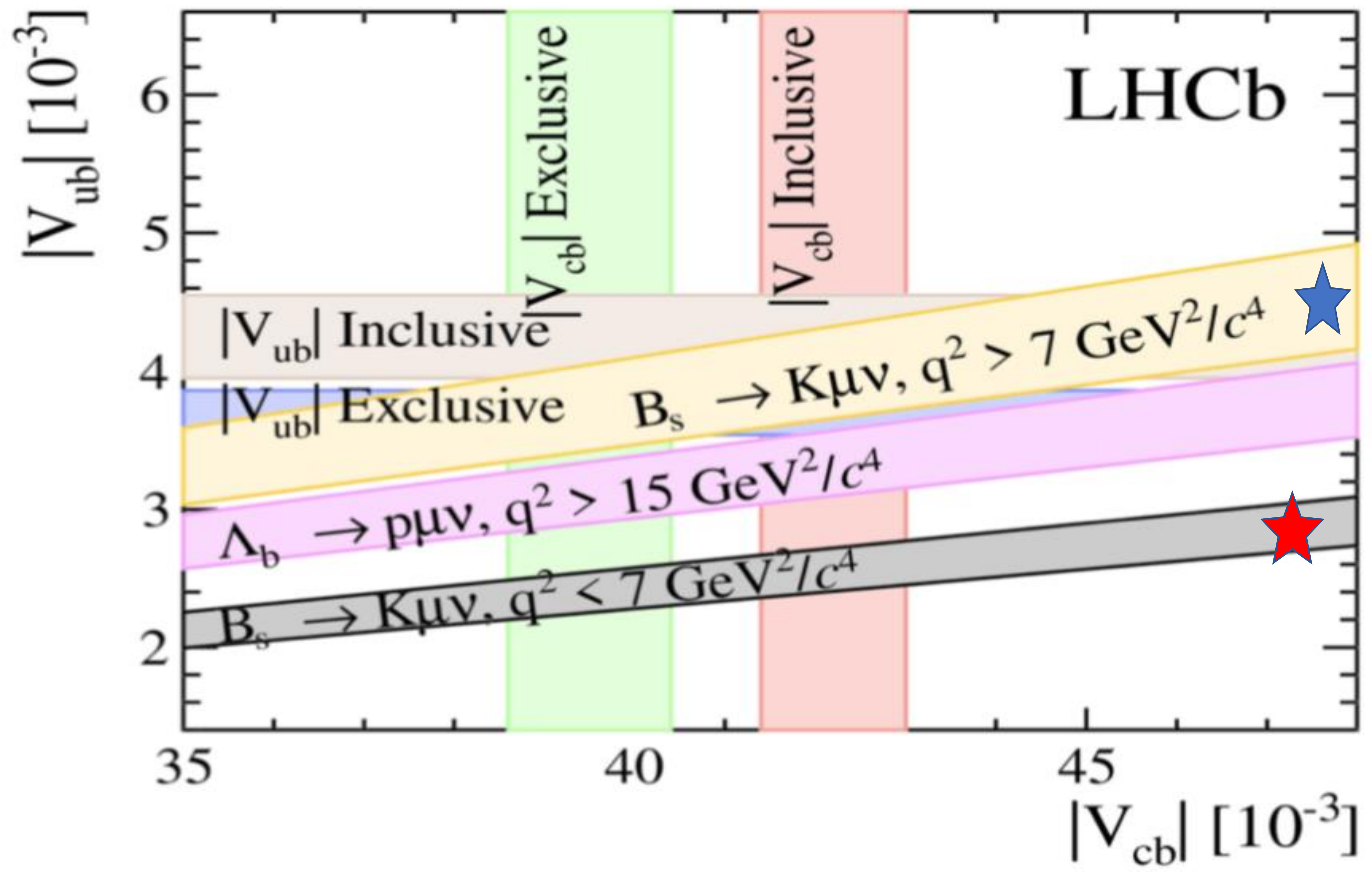
PRL 126, 081804 (2021)

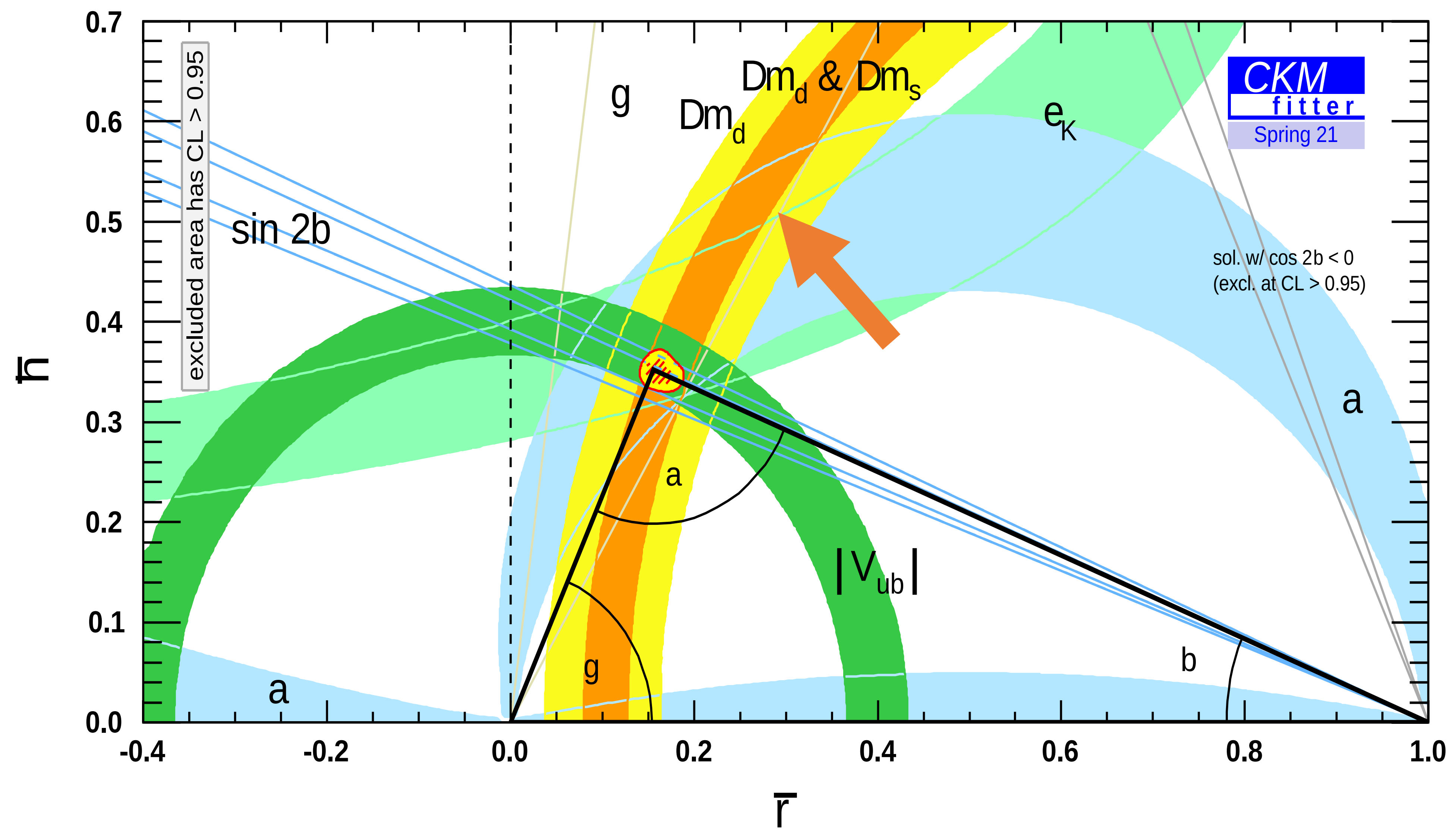
- First observation of suppressed semileptonic $B_s^0 \to K^- \mu^+ \upsilon_\mu$ decay and the ratio branching fraction measured:
  - $\mathcal{B}(B_s^0 \to K^- \mu^+ \upsilon_\mu) = [1.06 \pm 0.05(stat) \pm 0.08(syst)] \times 10^{-4}$
- The ratio $|\mathbf{V_{ub}}|/|\mathbf{V_{cb}}|$ is obtained in two q^2 reqions :
  - $|V_{ub}|/|V_{cb}|(low) = 0.0607 \pm 0.0015(stat) \pm 0.0013(syst) \pm 0.0008(D_s) \pm 0.0030(FF)$
  - $|V_{ub}|/|V_{cb}|(high) = 0.0946 \pm 0.0030(stat)^{+0.0024}_{-0.0025}(syst) \pm 0.0013(D_s) \pm 0.0068(FF)$

$$R_{BF} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \frac{FF_K}{FF_{D_s}}$$

- Discrepancy between the $|\mathbf{V_{ub}}|/|\mathbf{V_{cb}}|$ values is related to the difference in theoretical calculations of the FF



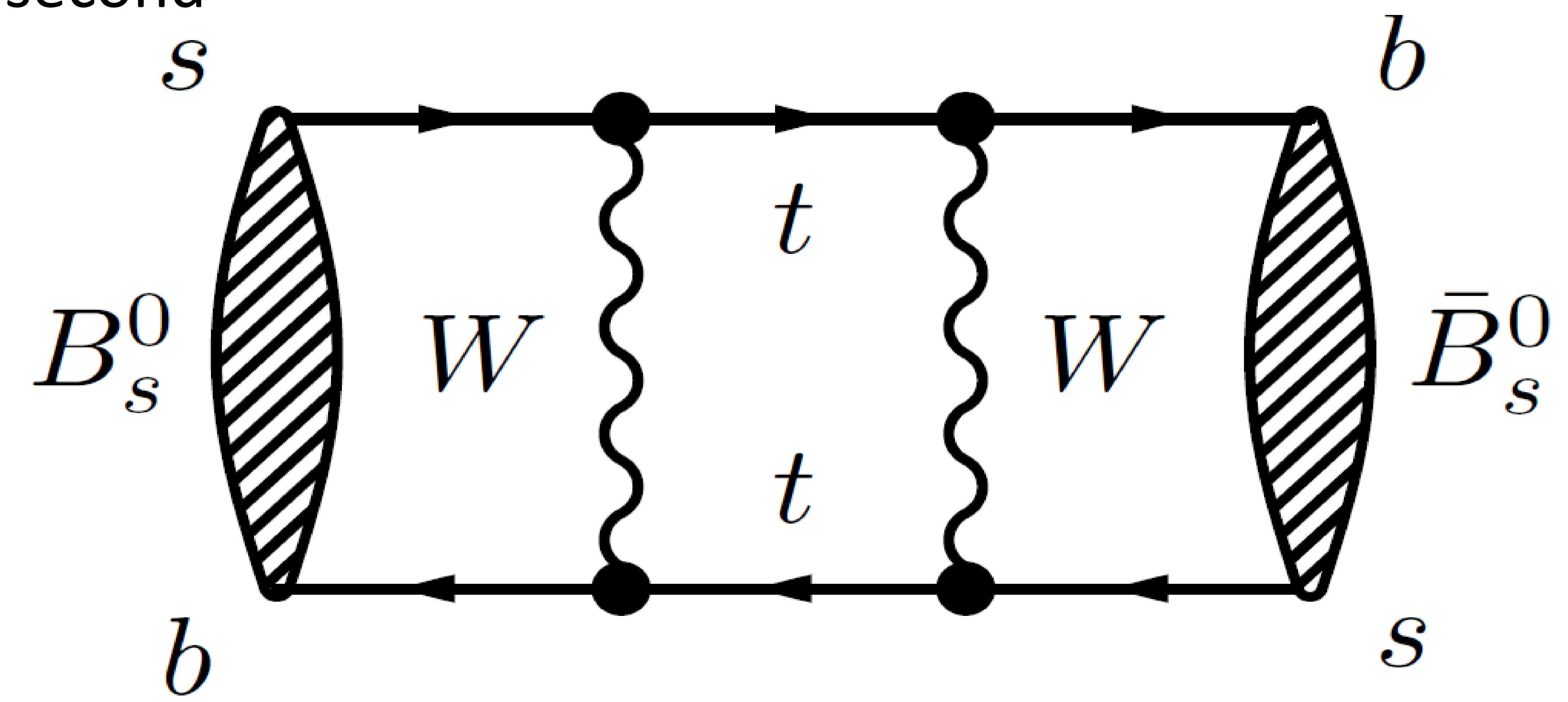




Precise determination of the $B_s^0 - \bar{B}_s^o$ oscillation frequency Δm_s

Nature Physics 18, (2022) 1-5

- This analysis uses the full Run 2 data sample corresponding to an integrated luminosity of 6 fb^{-1}
- B_s^0 mesons can oscillate to its anti-particle $\bar{B}_s^o$ ~ 3×10^{12} per second



Precise determination of the $B_s^0 - \bar{B}_s^0$ oscillation frequency

Nature Physics 18, (2022) 1-5

➢ Time-dependent analysis of $B_s^0 \rightarrow D_s^- \pi^+$

- Most precise result of the $\boldsymbol{\Delta m_s = m_H - m_L}$ (heavy (H) and light (L) mass eigenstates) oscillation frequency :

$$\Delta m_s = 17.7683 \pm 0.0051(\text{stat}) \pm 0.0032(\text{syst})\text{ps}^{-1}$$

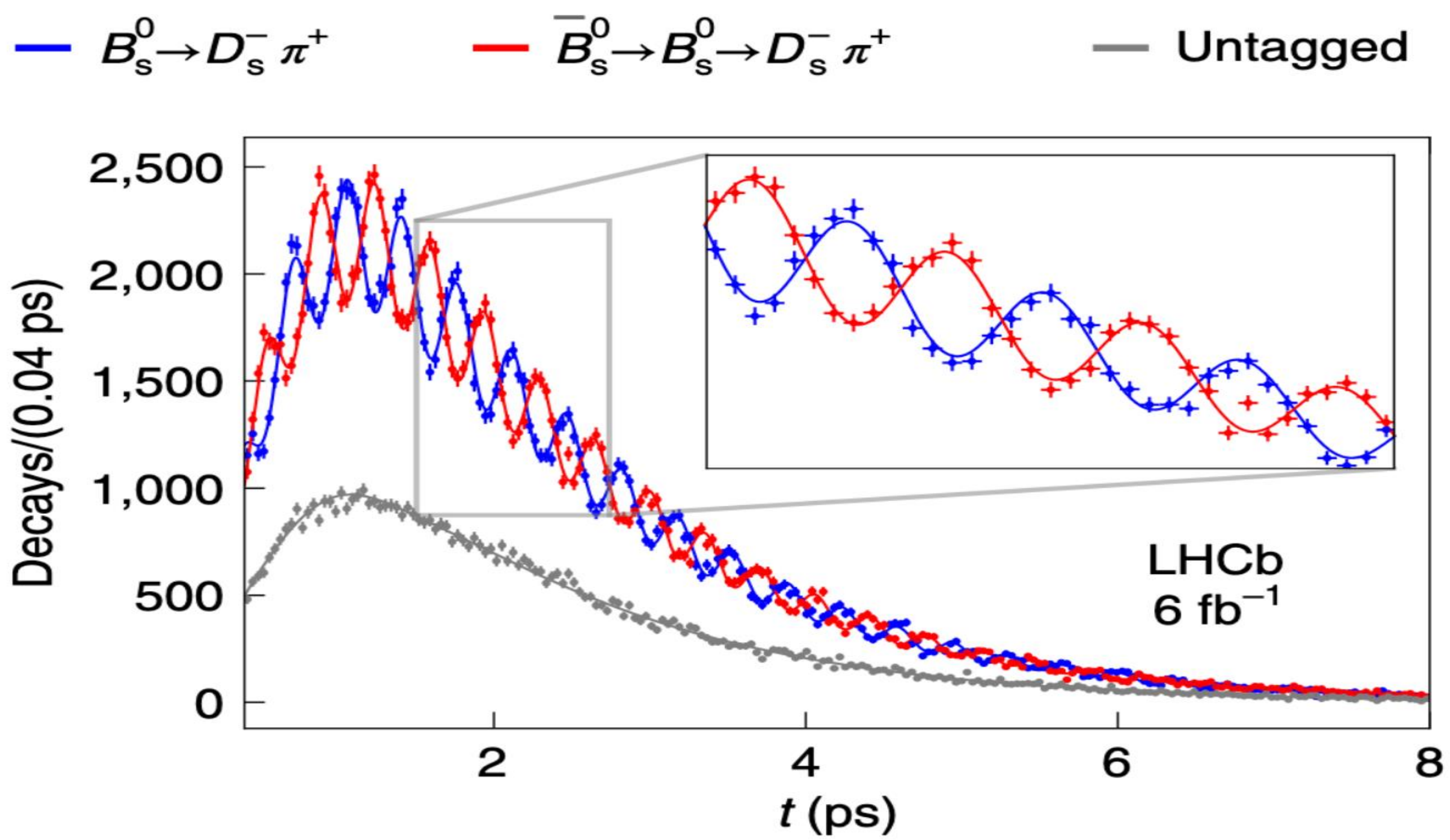
➢ Current Δm_s precision improved by a factor of 2!

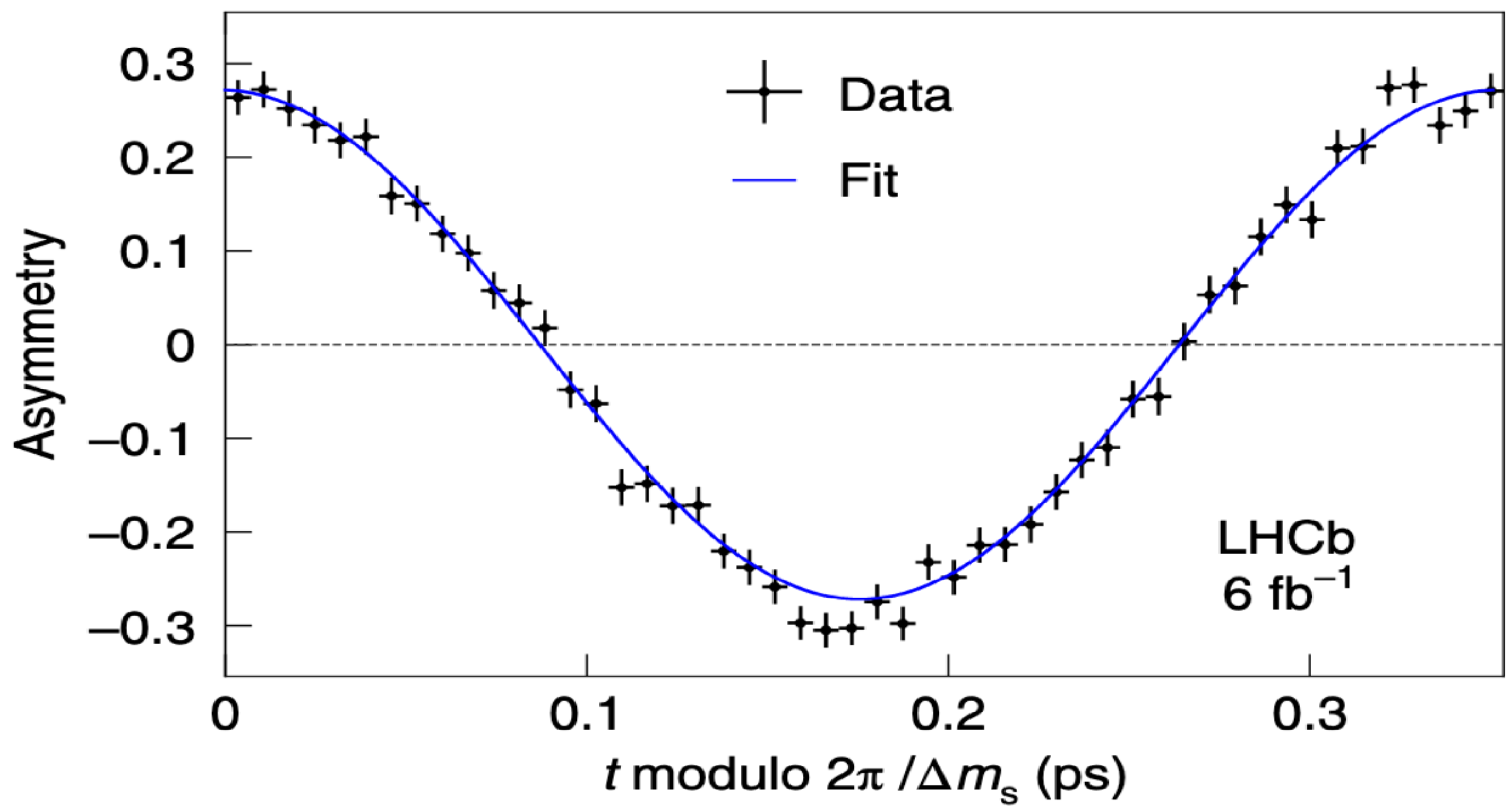
- Fit to the $B_s^0 \rightarrow D_s^- \pi^+$ decay time distribution :

$$P(t) \approx e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cos(\Delta m_s t)\right]$$

- The asymmetry distribution between the tagged-unmixed and tagged-mixed samples is defined as:

$$A(t) = \frac{N(B_s^0 \rightarrow D_s^- \pi^+, t) - N(\bar{B}_s^0 \rightarrow D_s^- \pi^+, t)}{N(B_s^0 \rightarrow D_s^- \pi^+, t) + N(\bar{B}_s^0 \rightarrow D_s^- \pi^+, t)}$$





Precise determination of the $B_s^0 - \bar{B}_s^o$ oscillation frequency

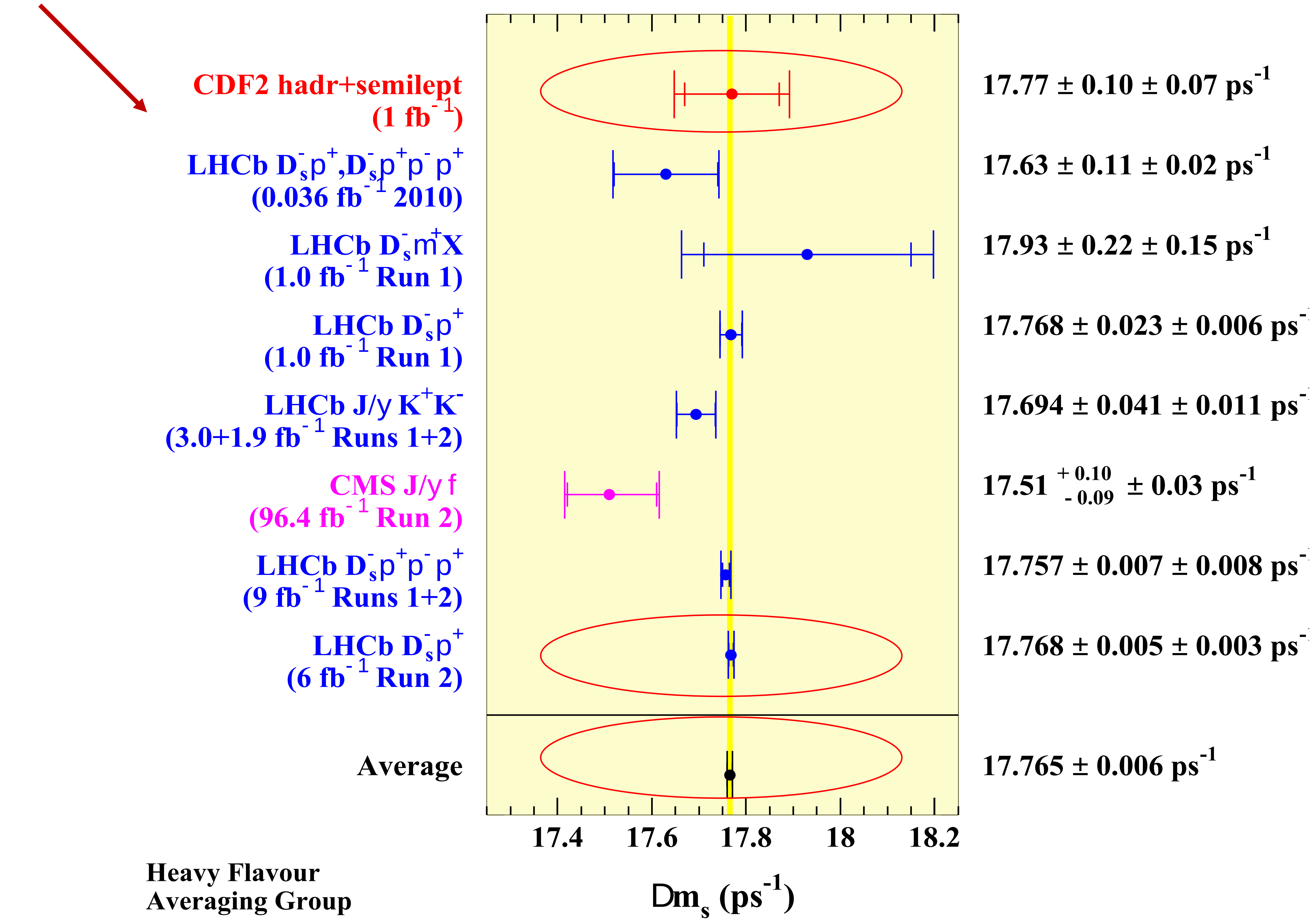
Nature Physics 18, (2022) 1-5

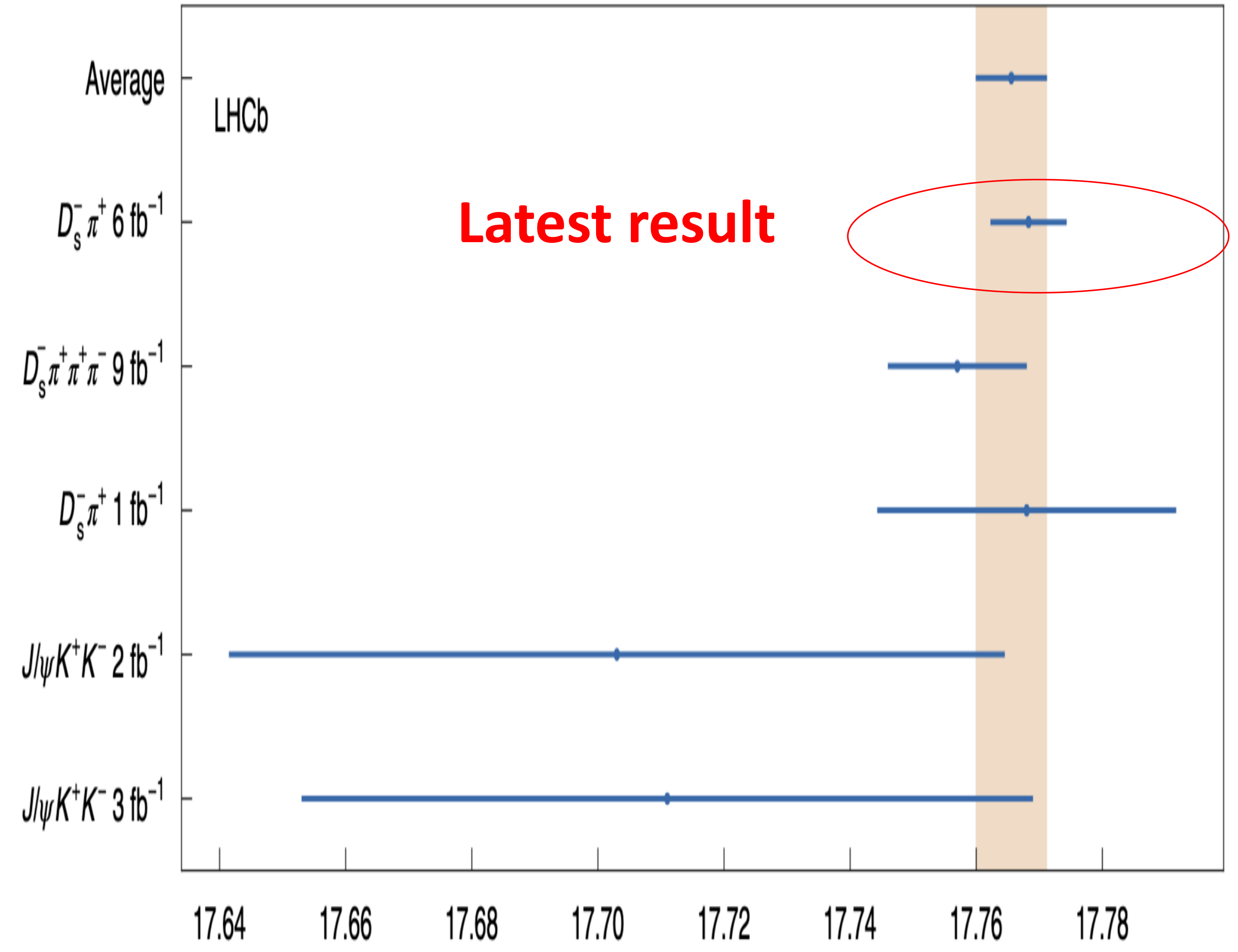
➢ Δm_s

- Precise oscillation frequency measurement by LHCb $\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032 ps^{-1}$
- Combined result from all LHCb measurements using Run 1 & Run 2 data: $\Delta m_s = 17.7656 \pm 0.0057 ps^{-1}$
- The result is compatible with SM prediction: $\Delta m_s = 18.4^{+0.7}_{-1.2} ps^{-1}$

[JHEP 12 (2019) 009]

➢ History of Δm_s



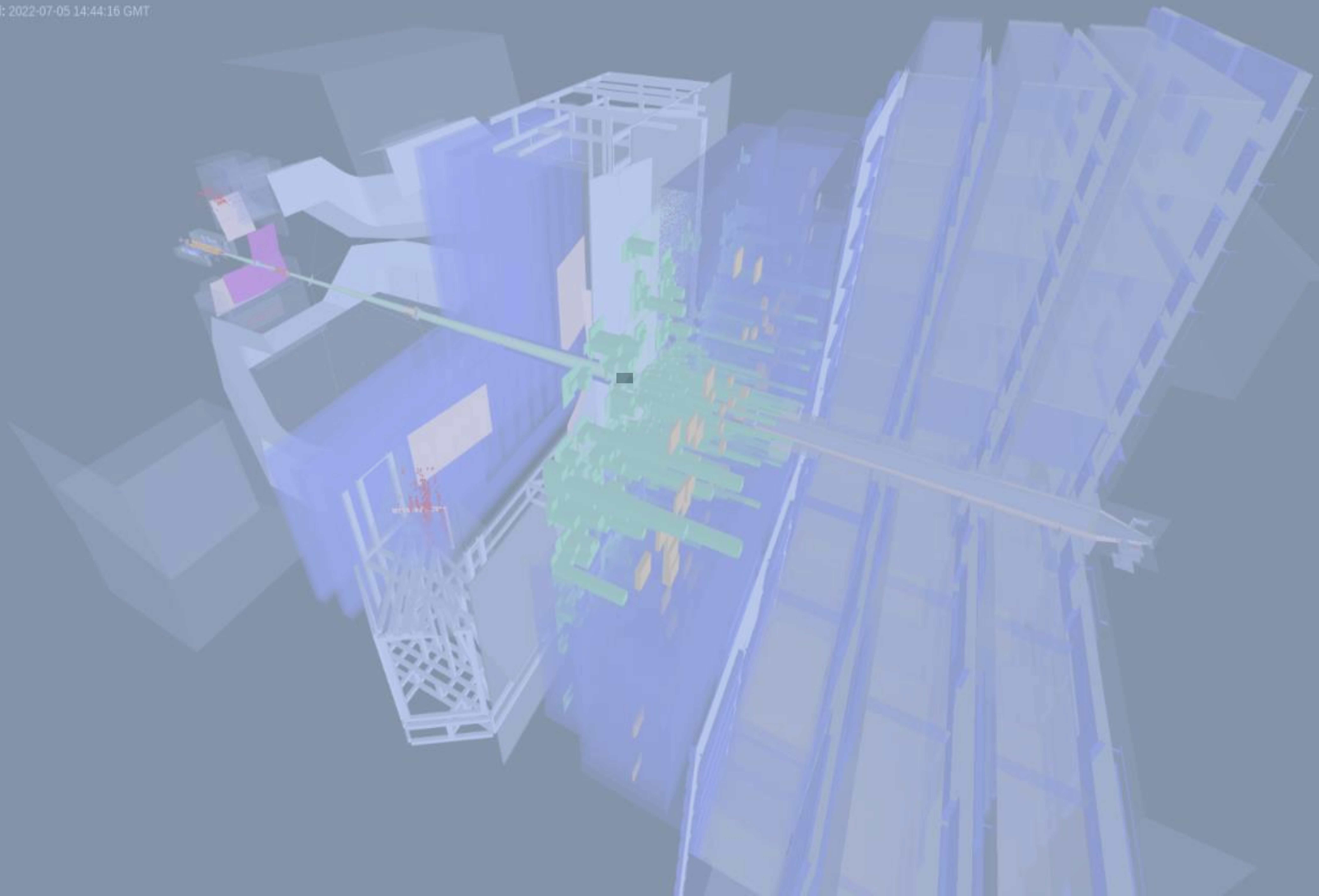


Conclusions

- LHCb shows great success at flavor physics program with Run 1 and Run 2
- Largest CP violation observed ~ 85% by a single charm decay mode $B^{\pm} \to D\, K^{\pm}$, $D \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$
- First observation of $B^{\pm} \to [\pi^{\pm}K^{\mp}\pi^{0}]K^{\pm}$ with a significance of $7.8\,\sigma$
- $\boldsymbol{\gamma}$ combination with a best sensitivity to date by a single experiment
- First observation of the $B_s^0 \to K^-\mu^+\upsilon_\mu$ decay and measure $|\mathrm{V_{ub}}|/|\mathrm{V_{cb}}|$ in two q^2 regions
- Most precise determination of $B_s^0 - \bar{B}_s^o$ oscillation frequency Δm_s in of $B_s^0 \to D_s^-\pi^+$ with full Run 2 data
- With Run 3 and Run 4, LHCb expect to collect 50 fb^{-1} data
- LHCb aims more precise measurements with increased data samples and higher collision energy

Stay Tuned !

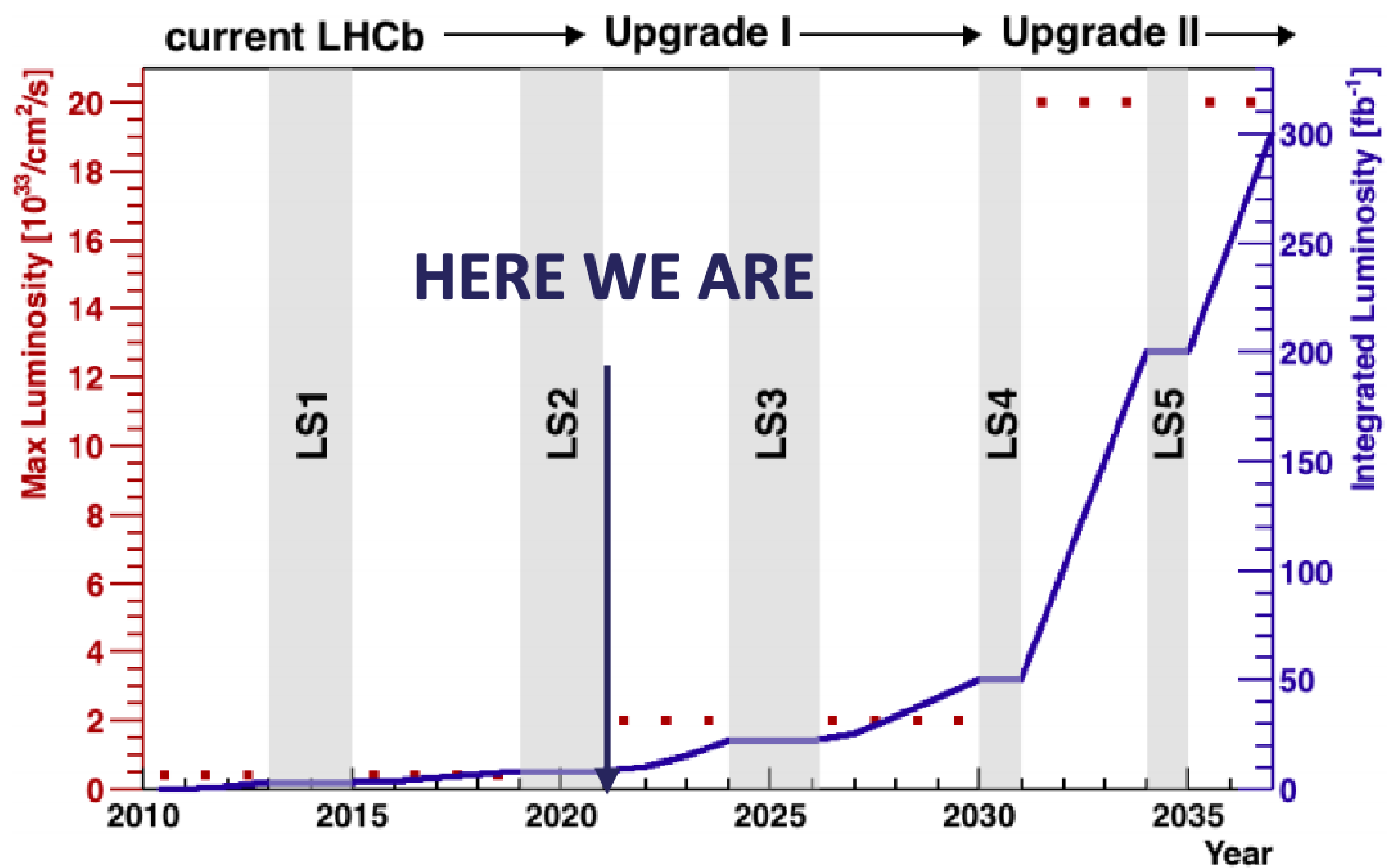
Thank you for your attention!



BACKUP SLIDES

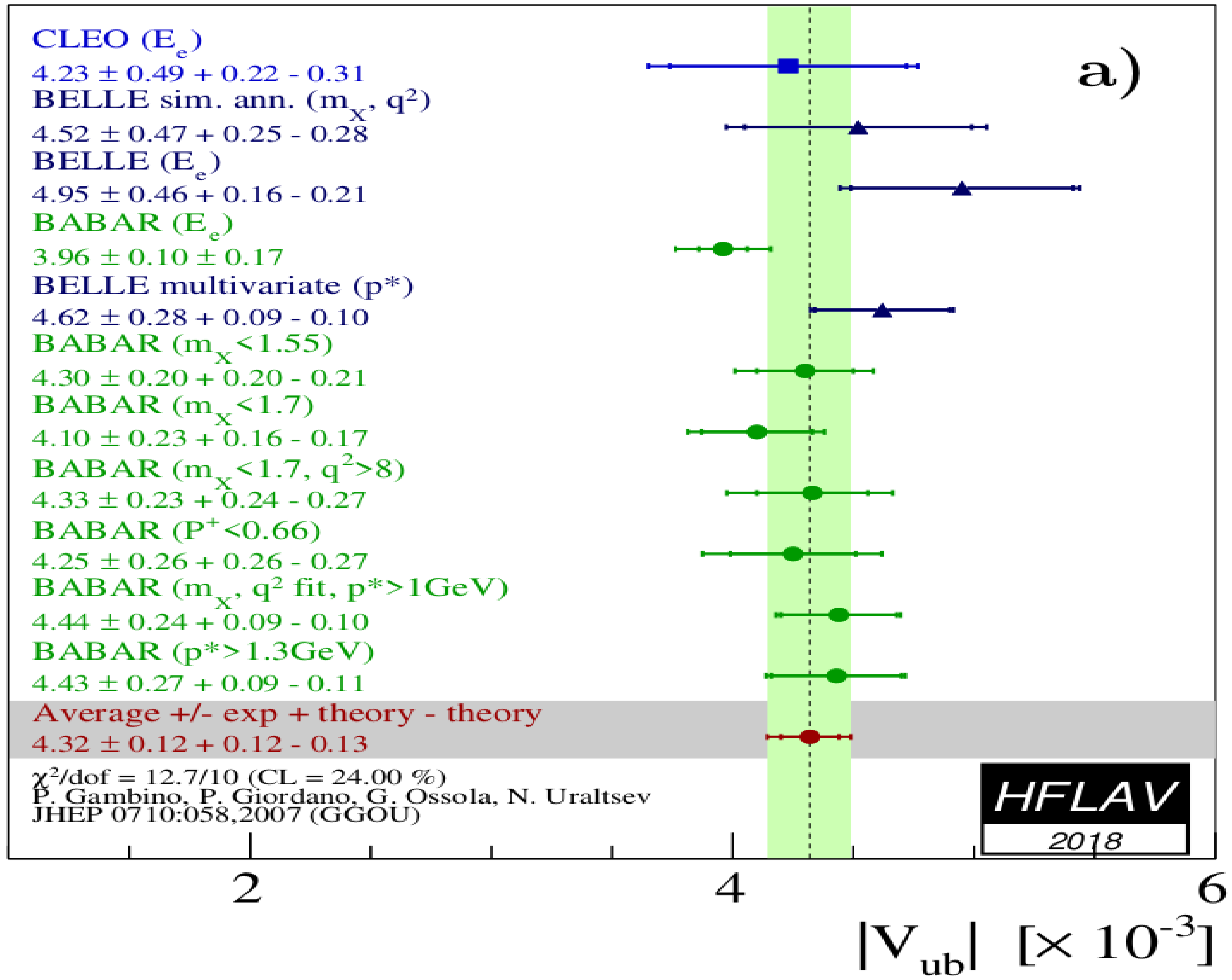
LHCb: Large Hadron Collider Beauty Experiment

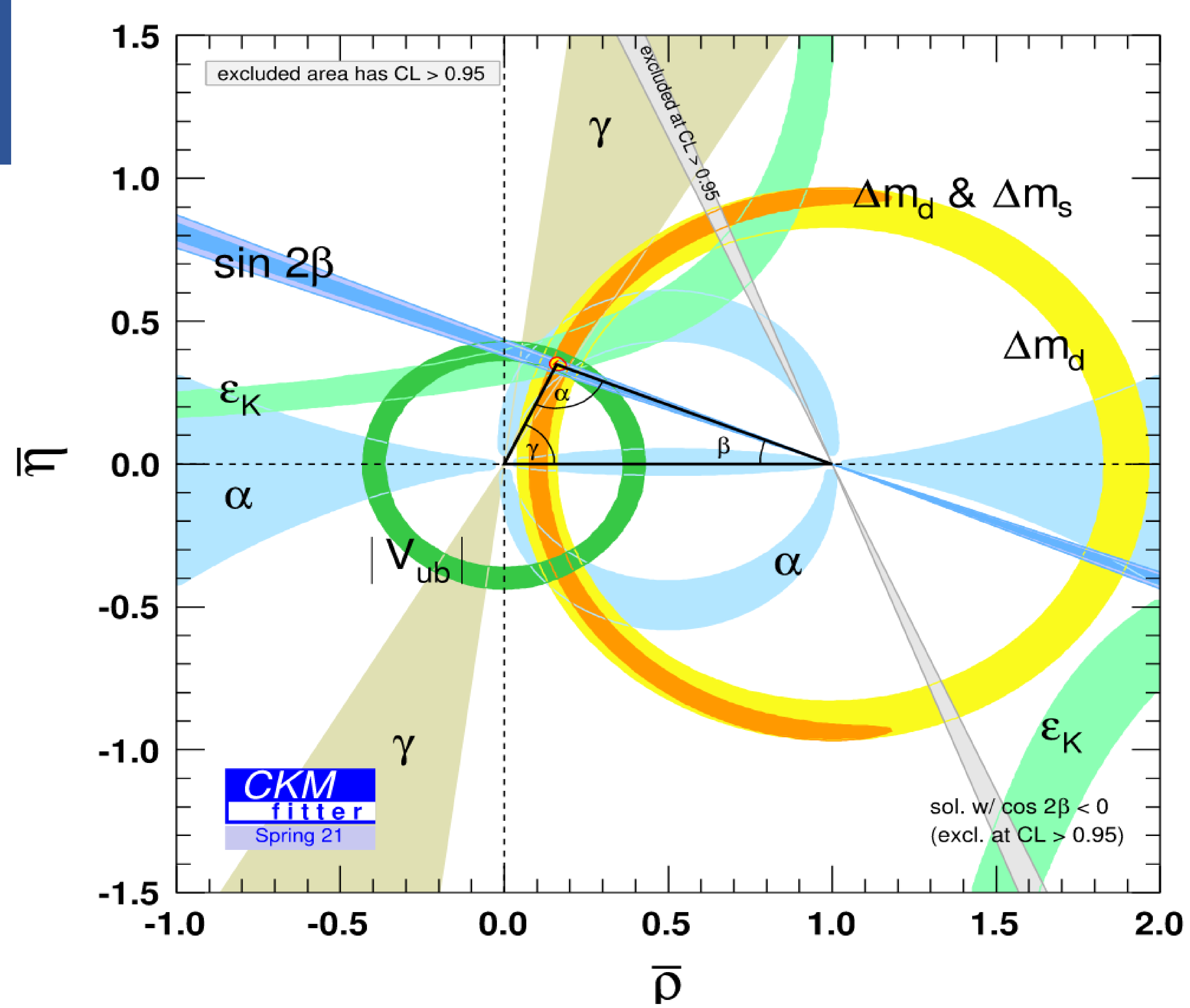
- Identification: $\varepsilon(h \to h)\sim 90\%, miss\ \varepsilon(h \to h)\sim 5\%, \varepsilon_{\mu}\sim 97\%$
- IP resolution: $\sigma_{IP} = 20\mu m$
- Momentum resolution: $\frac{\Delta p}{p} = 0.5 - 0.8\%$
- Mass resolution: $\sigma(m_{B\to hh}) \approx 22MeV$
- Time resolution: 45-55 fs



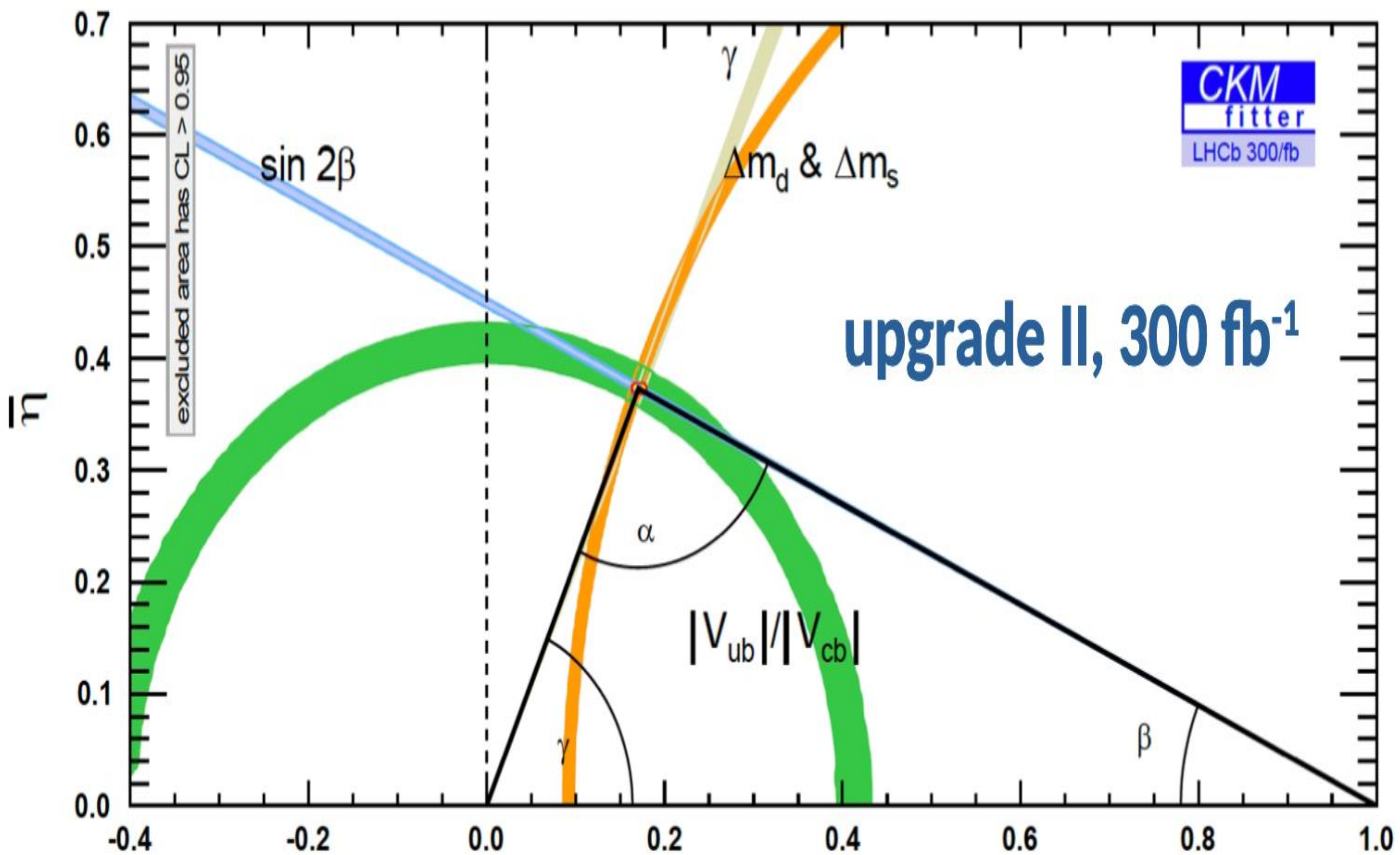
By W. Krupa @BEACH 2022

Physics motivation : measurement of CKM Unitarity

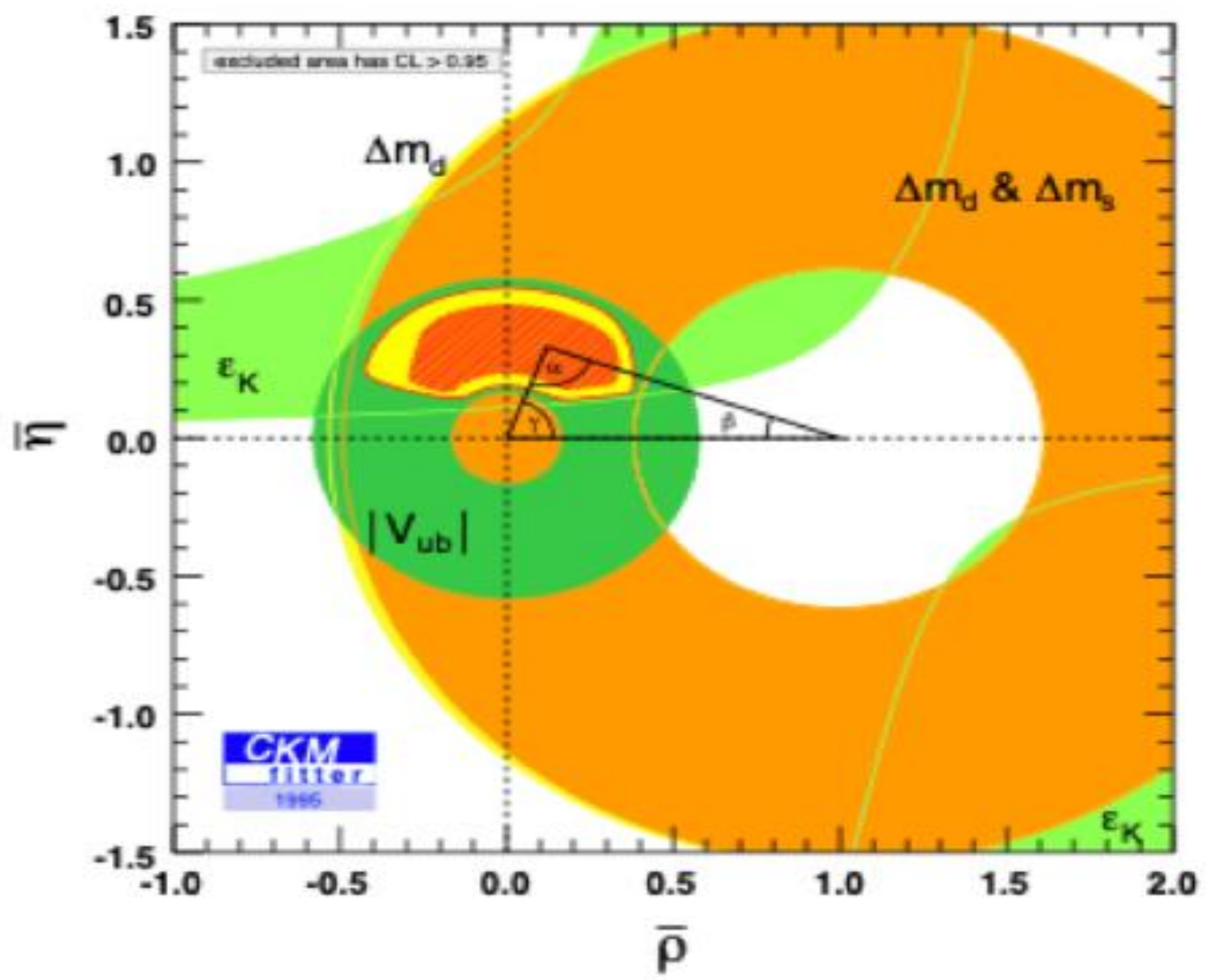




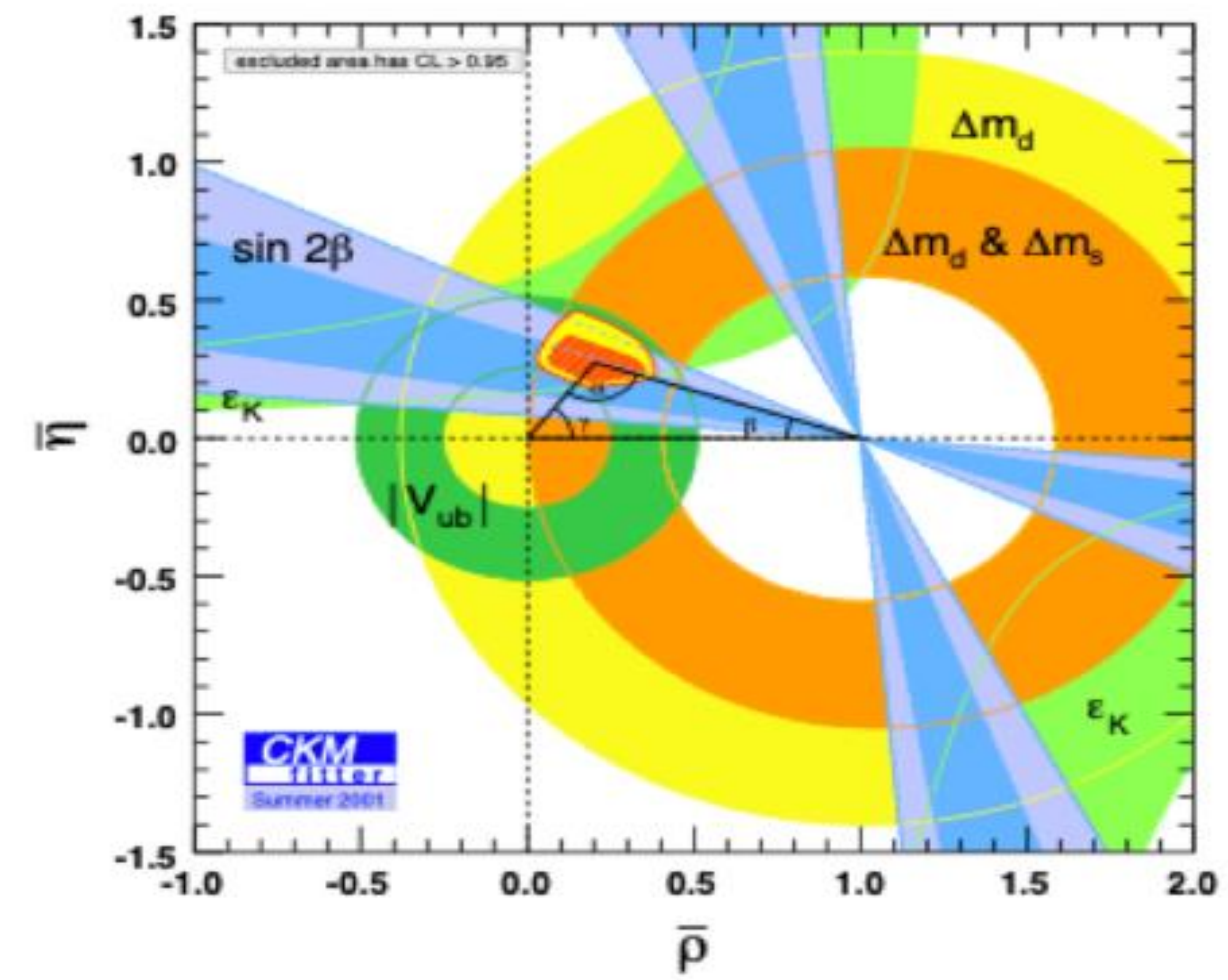
	HFLAV [1]	**CKMfitter** [2]	**UTfit** [3]
α [°]	$85.2^{+4.8}_{-4.3}$	$91.9^{+1.6}_{-1.2}$	90.1 ± 2.2
β [°]	22.2 ± 0.7	$23.41^{+1.53}_{-0.68}$	23.8 ± 1.3
γ [°]	$66.2^{+3.4}_{-3.6}$	$65.5^{+1.1}_{-2.7}$	65.8 ± 2.2
ϕ_s [rad]	−0.050 ± 0.019	$-0.03682^{+0.00060}_{-0.00086}$	−0.0370 ± 0.0010



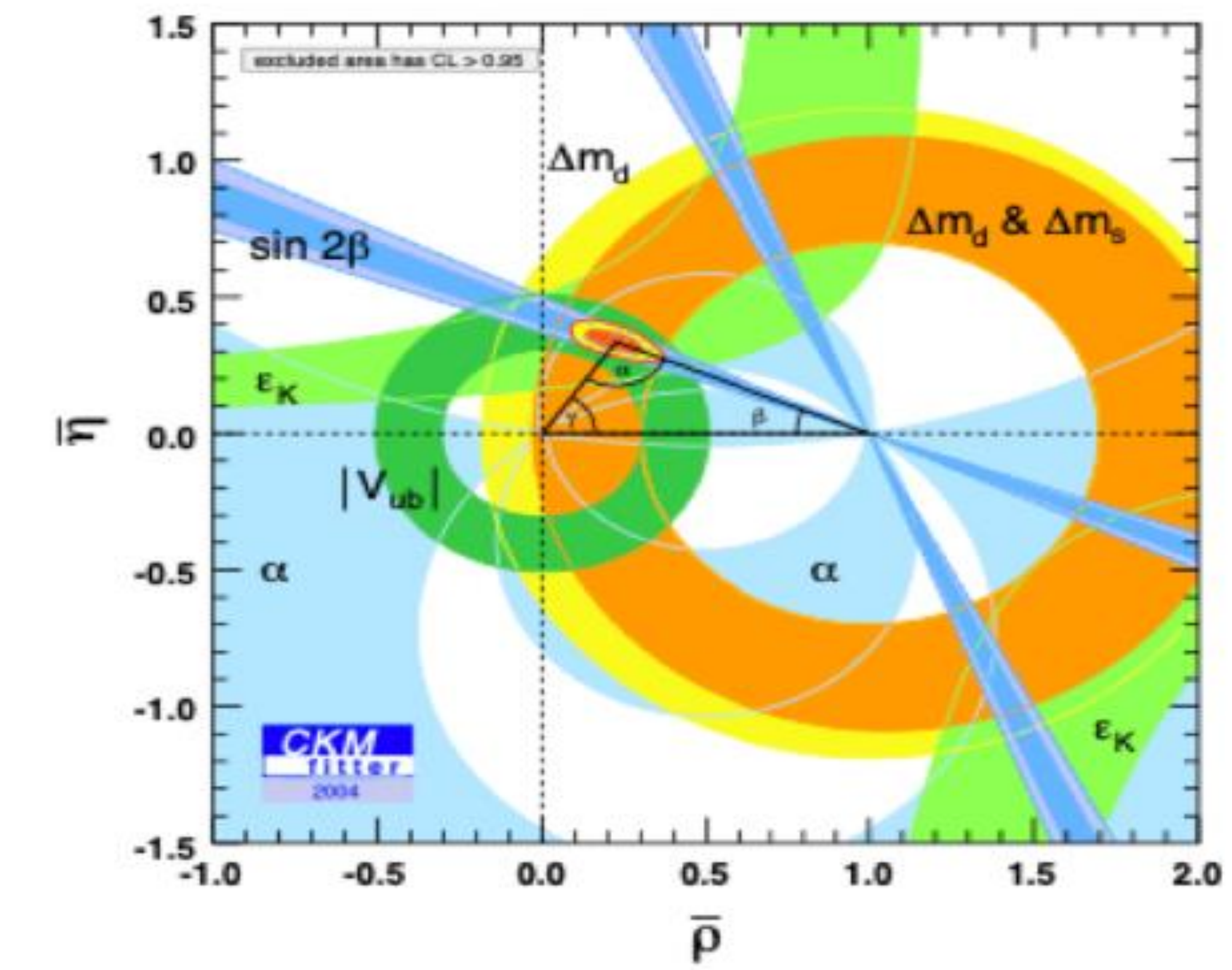
CKM status over the years



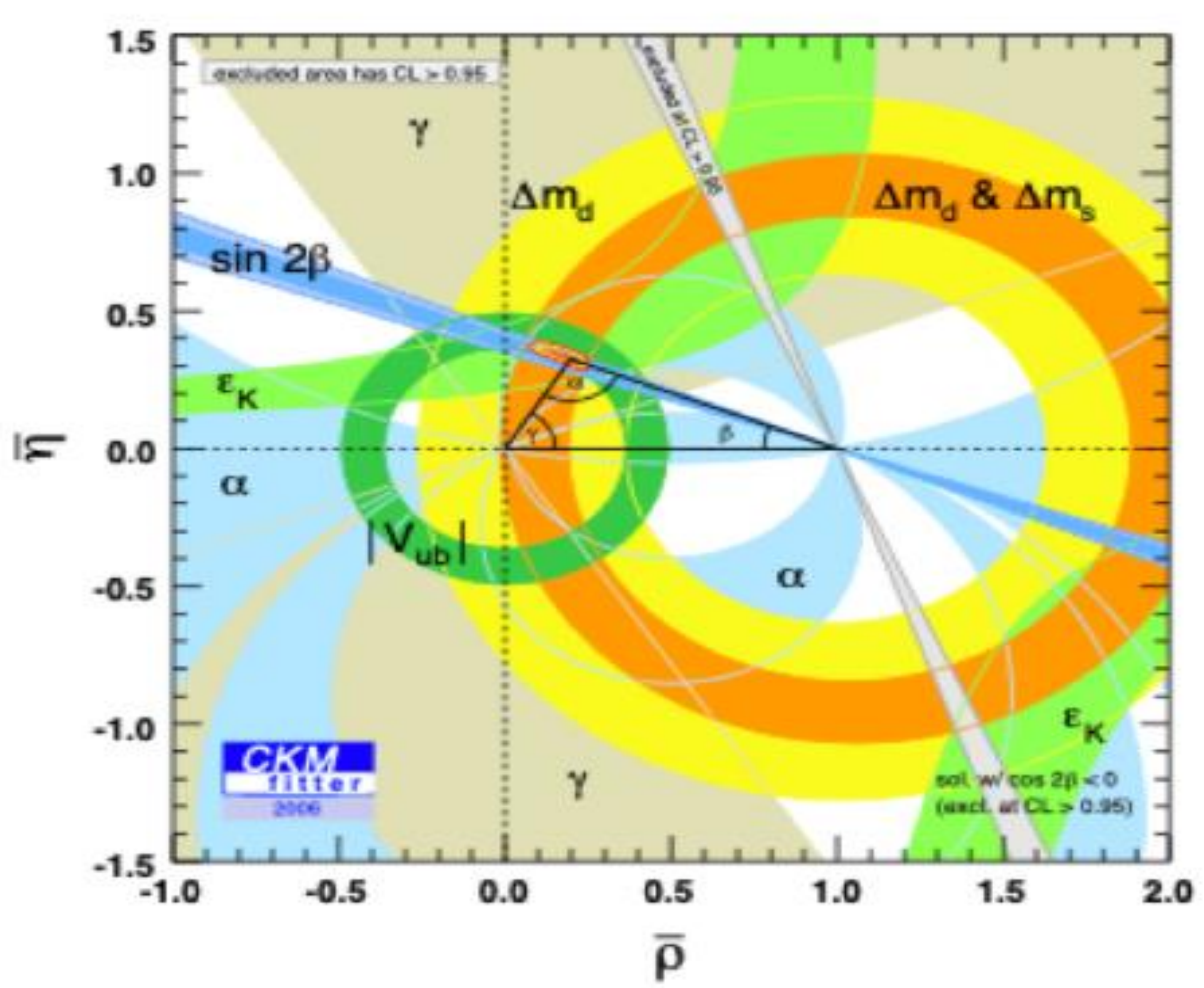
1995



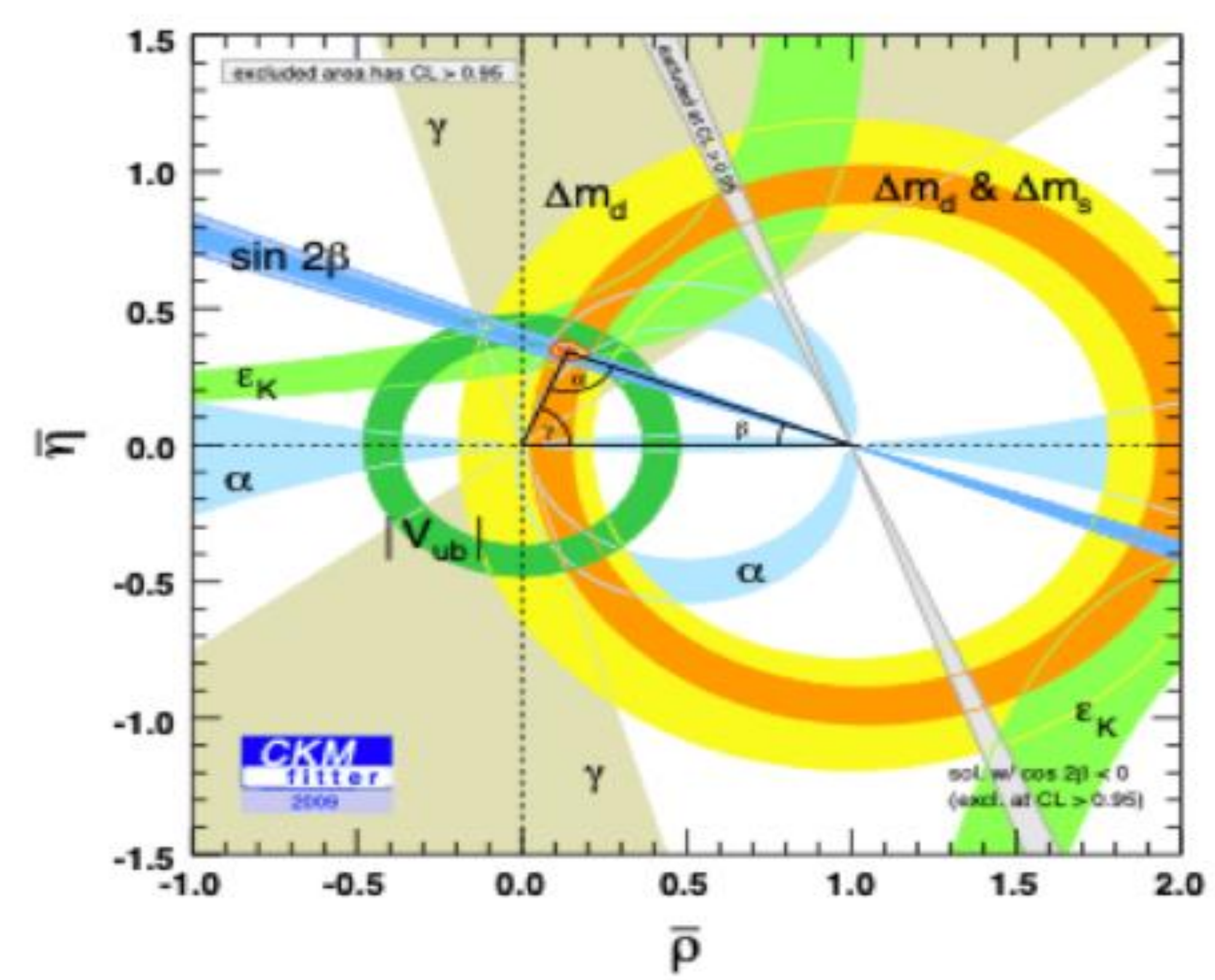
2001



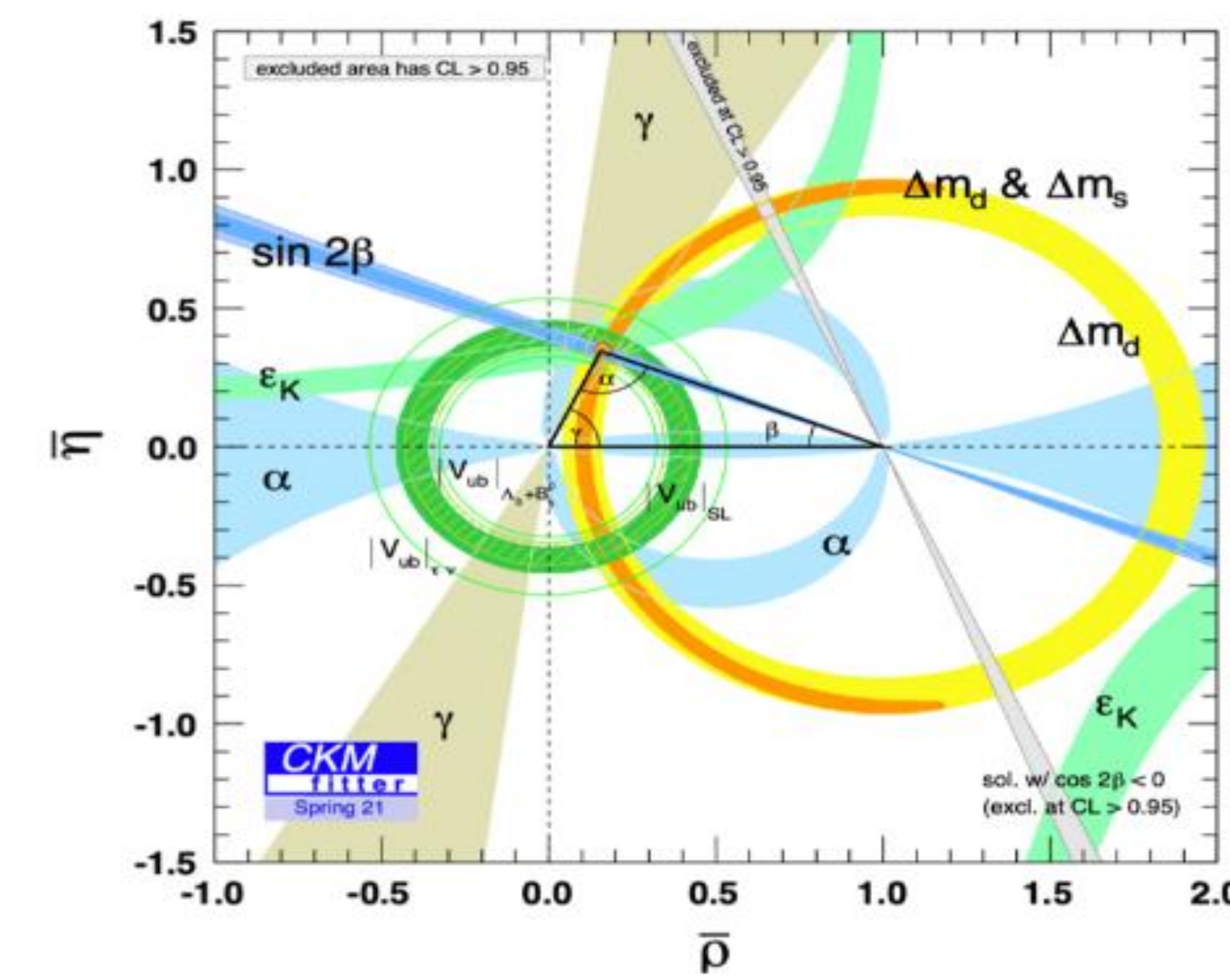
2004



2006



2009



2021

Combination of CKM γ and charm mixing parameters

JHEP12 (2021) 141

- Confidence intervals and best-fit values for γ when splitting the combination inputs by initial B meson species

Species	Value [°]	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
B^+	61.7	$^{+4.4}_{-4.8}$	[56.9, 66.1]	$^{+8.6}_{-9.5}$	[52.2, 70.3]
B^0	82.0	$^{+8.1}_{-8.8}$	[73.2, 90.1]	$^{+17}_{-18}$	[64, 99]
B^0_s	79	$^{+21}_{-24}$	[55, 100]	$^{+51}_{-47}$	[32, 130]

- Confidence intervals and best-fit values for γ when splitting the combination inputs by time-dependent and time-integrated methods

Method	Value [°]	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
Time-dependent	79	$^{+21}_{-24}$	[55, 100]	$^{+51}_{-47}$	[32, 130]
Time-integrated	64.9	$^{+3.9}_{-4.5}$	[60.4, 68.8]	$^{+7.8}_{-9.6}$	[55.3, 72.7]

Combination of CKM γ and charm mixing parameters

JHEP12 (2021) 141

Decay	Parameters	Source	Ref.	Status since Ref. [17]
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb	[24]	As before
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[45]	As before
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[11]	**Updated**
$B_s^0 \to D_s^\mp K^\pm(\pi\pi)$	ϕ_s	HFLAV	[11]	**Updated**
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}^+$, $F_{K\pi\pi^0}^+$	CLEO-c	[46]	As before
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{4\pi}^+$	CLEO-c	[46]	As before
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[47–49]	**Updated**
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII	[41, 47–49]	**Updated**
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$, $\delta_D^{K_S^0K\pi}$, $\kappa_D^{K_S^0K\pi}$	CLEO	[50]	As before
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$	LHCb	[51]	As before

NEW * in preparation LHCb-PAPER- 2022-017

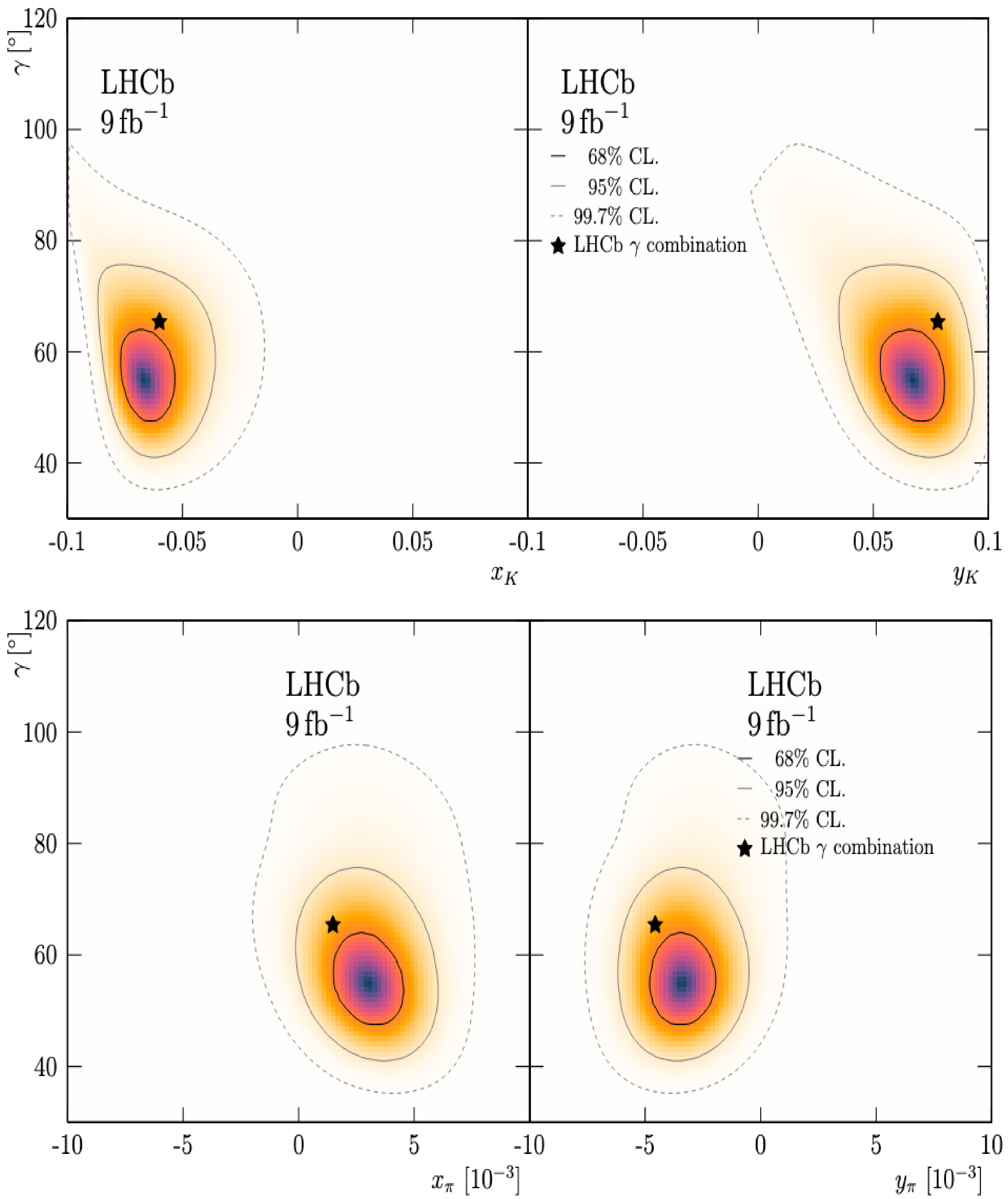


Table 3: Correlation matrix of γ with the B-hadronic parameters, expressed in the Cartesian form.

	γ	x_{DK}	y_{DK}	$x_{D\pi}$	$y_{D\pi}$
γ	1	−0.286	−0.305	−0.196	0.047
x_{DK}		1	0.911	−0.118	−0.211
y_{DK}			1	−0.076	−0.173
$x_{D\pi}$				1	0.357
$y_{D\pi}$					1

- Hadronic parameters in the cartesian form

$$x_{DK} = \left(-66.4 \,^{+\,7.6}_{-\,7.2} \,^{+\,0.9}_{-\,0.9} \,^{+\,10.0}_{-\,7.3}\right) \times 10^{-3},$$
$$y_{DK} = \left(\ 67.4 \,^{+\,7.1}_{-\,7.5} \,^{+\,0.8}_{-\,1.0} \,^{+\,11.1}_{-\,12.1}\right) \times 10^{-3},$$
$$x_{D\pi} = \left(\ 3.0 \,^{+\,1.2}_{-\,1.2} \,^{+\,0.1}_{-\,0.1} \,^{+\,0.9}_{-\,0.9}\right) \times 10^{-3},$$
$$y_{D\pi} = \left(-\ 3.4 \,^{+\,1.1}_{-\,1.1} \,^{+\,0.3}_{-\,0.3} \,^{+\,0.8}_{-\,0.8}\right) \times 10^{-3}.$$

@ICHEP by Tim Evans

Constraints on the CKM γ from $B^{\pm} \to D(h^{\pm}h'^{\mp}\pi^0)h^{\pm}$ decays

LHCb-PAPER-2021-036

- 11 observables are reported

$R^{KK\pi^0}$	$=$	1.021	$\pm$	0.079	$\pm$	0.005
$R^{\pi\pi\pi^0}$	$=$	0.902	$\pm$	0.041	$\pm$	0.004
$A_K^{K\pi\pi^0}$	$=$	-0.024	$\pm$	0.013	$\pm$	0.002
$A_K^{KK\pi^0}$	$=$	0.067	$\pm$	0.073	$\pm$	0.003
$A_K^{\pi\pi\pi^0}$	$=$	0.109	$\pm$	0.043	$\pm$	0.003
$A_\pi^{KK\pi^0}$	$=$	-0.001	$\pm$	0.019	$\pm$	0.002
$A_\pi^{\pi\pi\pi^0}$	$=$	0.001	$\pm$	0.010	$\pm$	0.002
R_K^+	$=$	0.0179	$\pm$	0.0024	$\pm$	0.0003
R_K^-	$=$	0.0085	$\pm$	0.0020	$\pm$	0.0004
R_π^+	$=$	0.00188	$\pm$	0.00027	$\pm$	0.00005
R_π^-	$=$	0.00227	$\pm$	0.00028	$\pm$	0.00004

- B candidates $B^{\mp} \to DK^{\mp}$ *and* $B^{\mp} \to D\pi^{\mp}$, where charm meson reconstructed in quasi-GLW and ADS method:

- $D \to \pi^+\pi^-\pi^0$
- $D \to K^+K^-\pi^0$
- $D \to K^+\pi^-\pi^0$
- $\boldsymbol{D \to \pi^+K^-\pi^0}$ **(suppressed)**

→First determination of the CP content of $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$

Analysis by M. Nayaka, J. Libbya,∗, S. Maldeb, C. Thomasb, G. Wilkinsonb,c, R. A. Briered, P. Naike, T. Gershonf, G. Bonvicinig

First Observation of the decay $B_s^0 \to K^- \mu^+ \upsilon_\mu$ and a measurement of $|V_{ub}|/|V_{cb}|$

PRL 126, 081804 (2021)

- Systematic uncertainties are summarized in the table

TABLE I. Relative systematic uncertainties on the ratio $\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)/\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)$, in percent.

Uncertainty	All q^2	Low q^2	High q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle identification	1.0	1.0	1.0
$\sigma(m_{\text{corr}})$	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration	$\cdots$	2.0	2.0
Efficiency	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$

Precise determination of the $B_s^0 - \bar{B}_s^0$ oscillation frequency

Nature 18, (2022) 1-5

Systematic uncertainties

Description	Systematic uncertainty [ps^{-1}]
Reconstruction effects:	
momentum scale uncertainty	0.0007
detector length scale	0.0018
detector misalignment	0.0020
Invariant mass fit model:	
background parametrisation	0.0002
$B_s^0 \to D_s^{*-}\pi^+$ and $B^0 \to D_s^-\pi^+$ contributions	0.0005
Decay-time fit model:	
decay-time resolution model	0.0011
neglecting correlation among observables	0.0011
Cross-checks:	
kinematic correlations	0.0003
Total systematic uncertainty	0.0032