Latest Results of flavor physics at LHCb

Wenbin Qian （钱文斌）
University of Chinese Academy of Sciences
(中国科学院大学)

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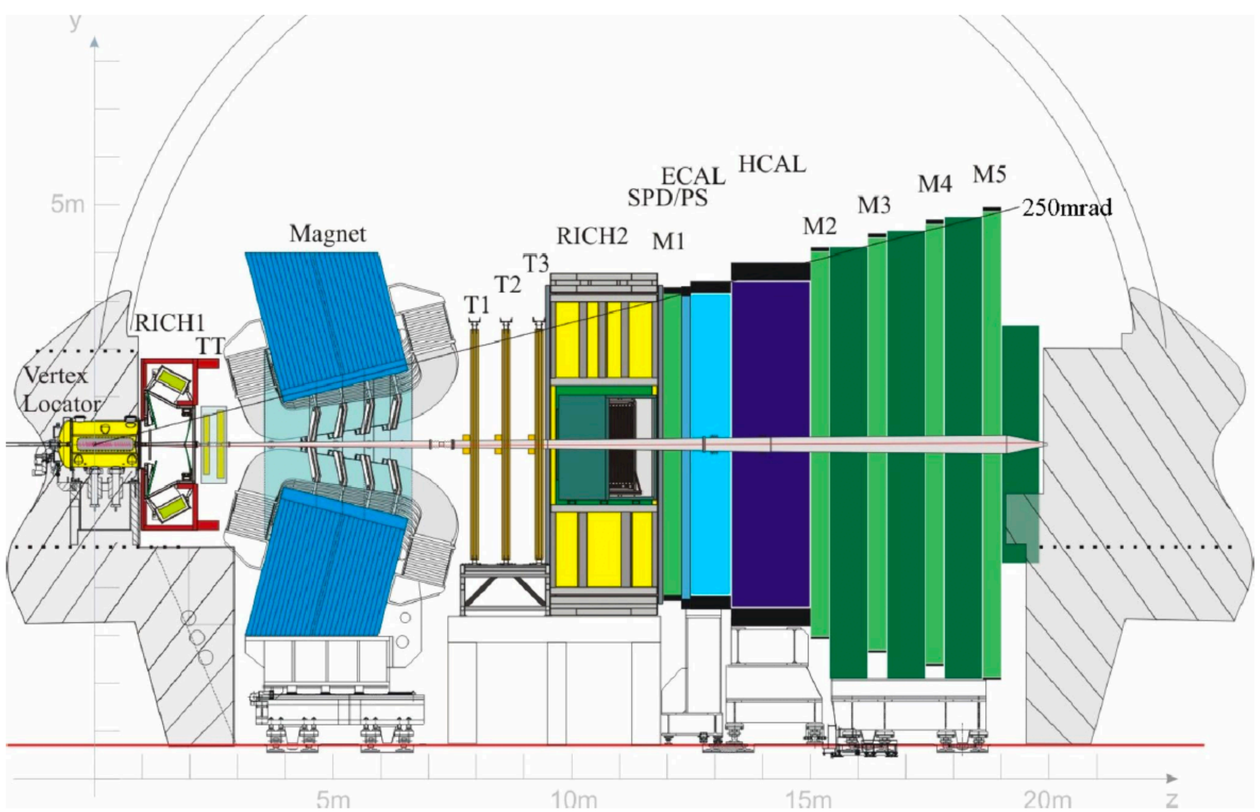
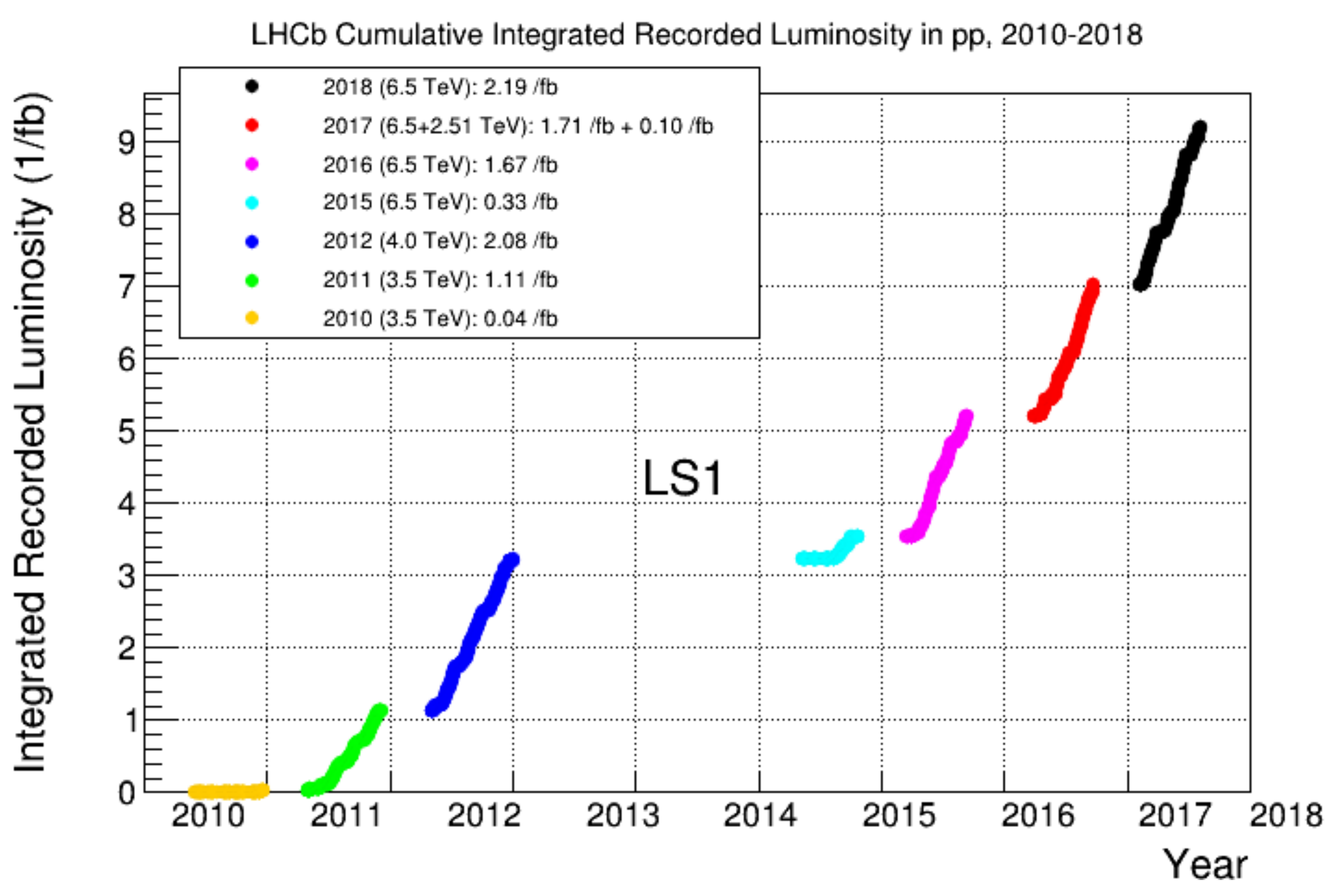
Outline

- ➢ **General introduction**
- ➢ **Recent highlights from spectroscopy studies**
- ➢ **CKM physics status and its potential for future studies**
- ➢ **Conclusion**

LHCb operation status

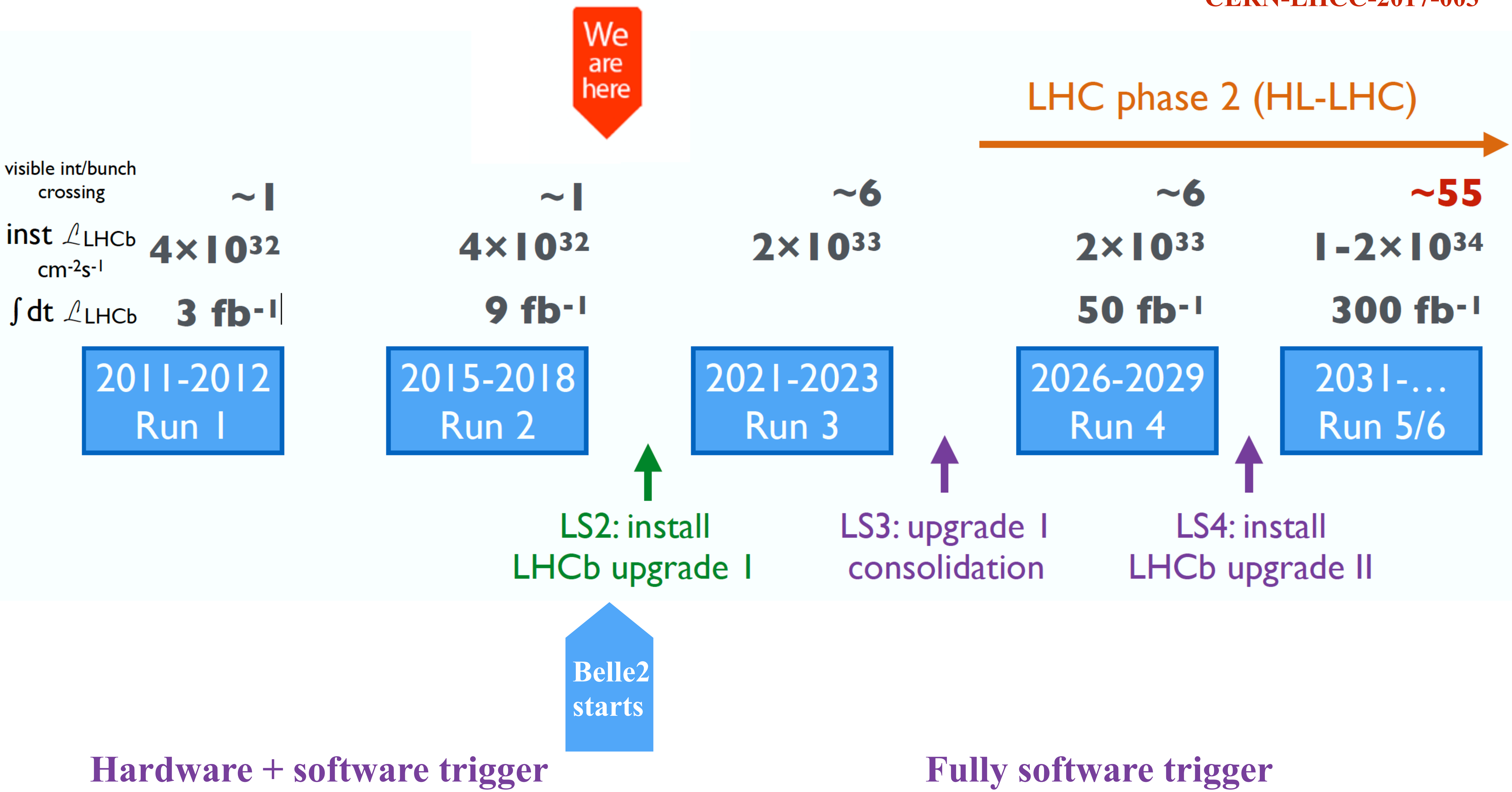
- ➢ **Wonderful performance with the LHCb detector**
- ➢ **Run 1 + Run 2 (4×Run 1), 9.1 fb^{-1} pp collision data collected**
- ➢ **Also collected p-Pb, Pb-Pb collision data for QGP studies**





LHCb upgrade plans

CERN-LHCC-2017-003



- ➢ **Upgrade I: several detector replaced; 40 MHz readout with fully software trigger**
- ➢ **Upgrade II: new ideas under study on tracking, calorimeter, timing info etc**

Flavor physics @ LHCb

➢ Understanding properties of quarks and leptons and interactions between different generations

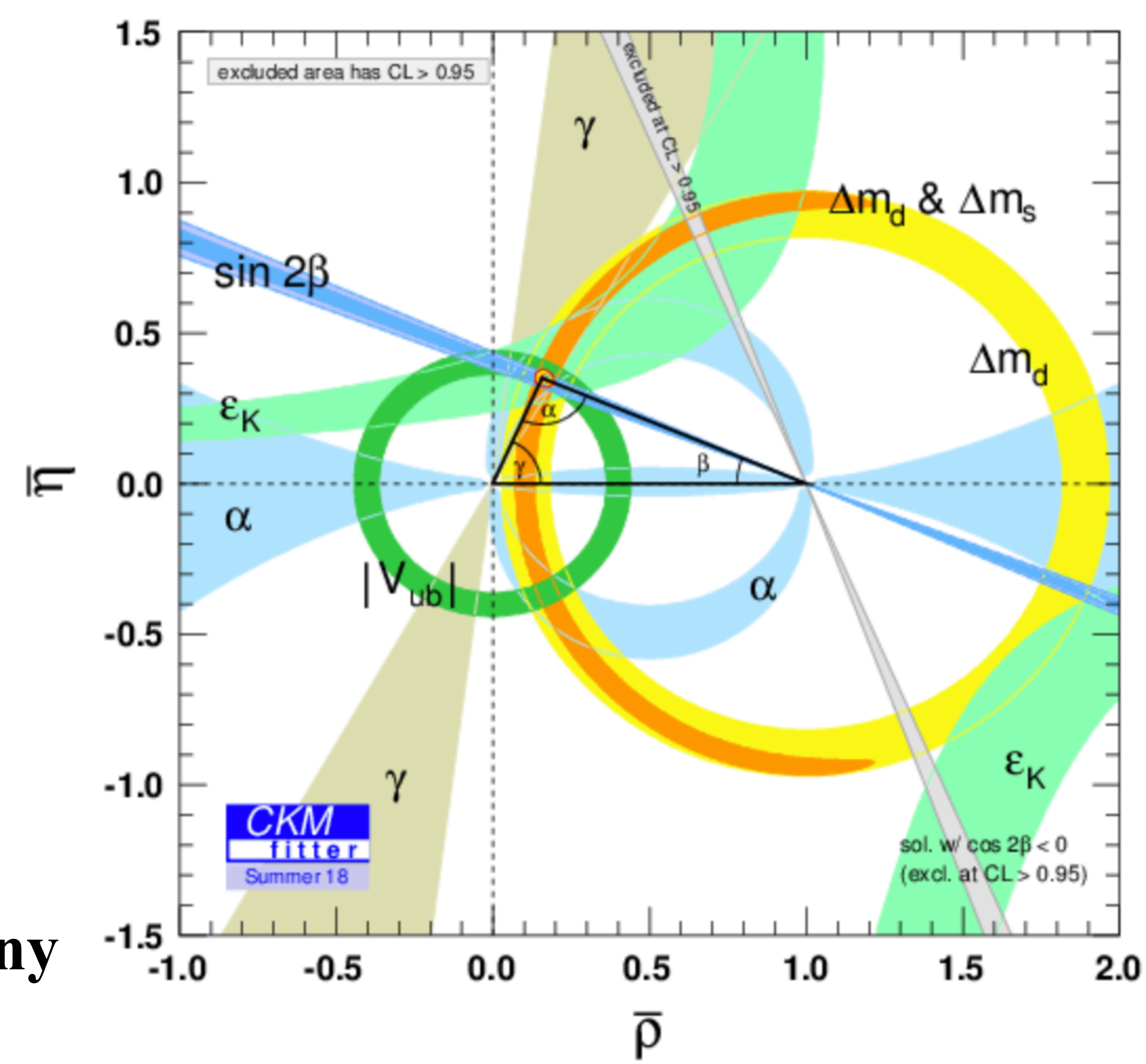
Spectroscopy, heavy quark production …

➢ Search for physics beyond SM through precision test

All SM particles, including Higgs, found; however new mechanism needed (DM, matter-antimatter asymmetry, hierarchy problem …)

No sign for BSM particles found through direct searches yet

Precise test of CKM mechanism, NP within FCNC, LFV and LNV searches , LFU test…

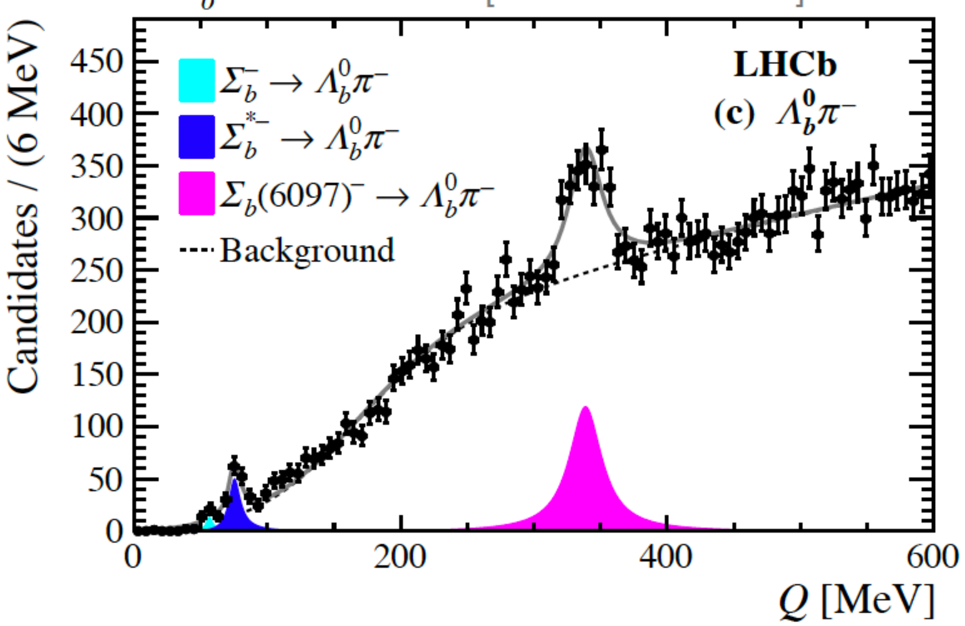


➢ LHCb China group is leading force in many important topics

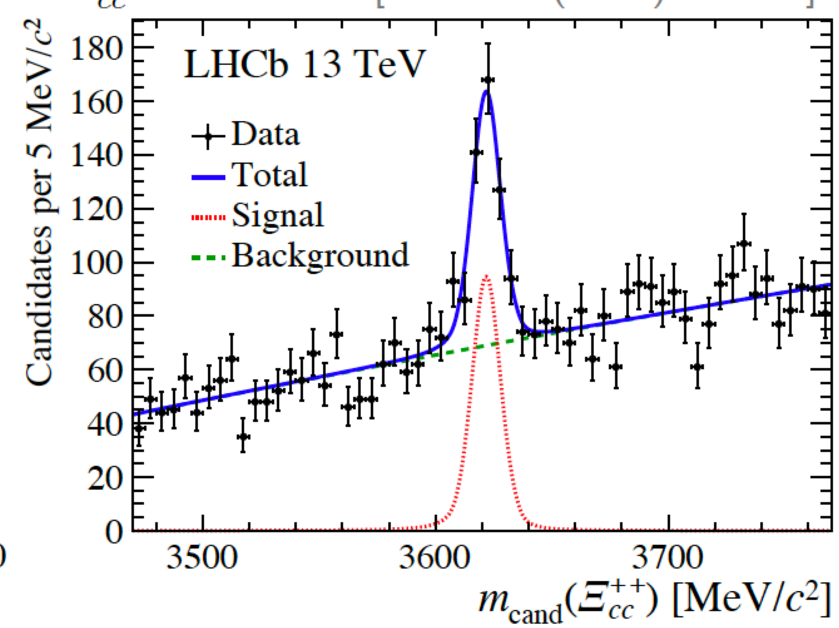
Spectroscopy @ LHCb

➢ **Many new particles discovered in LHCb, including Z(4430), pentaquark state, Ξ_{cc}^{++}, D_3(2760) …**

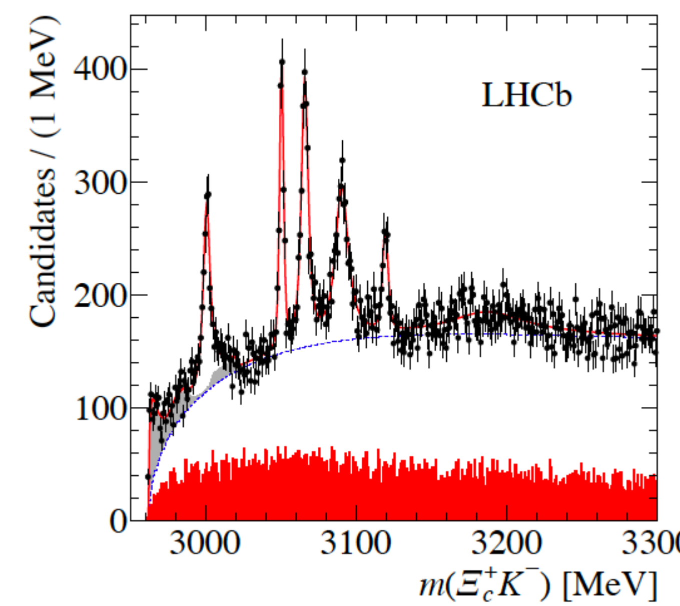
$\Lambda_b^0\pi^\pm$ resonances [arXiv:1809.07752]



Ξ_{cc}^{++} observation [PRL 119 (2017) 112001]

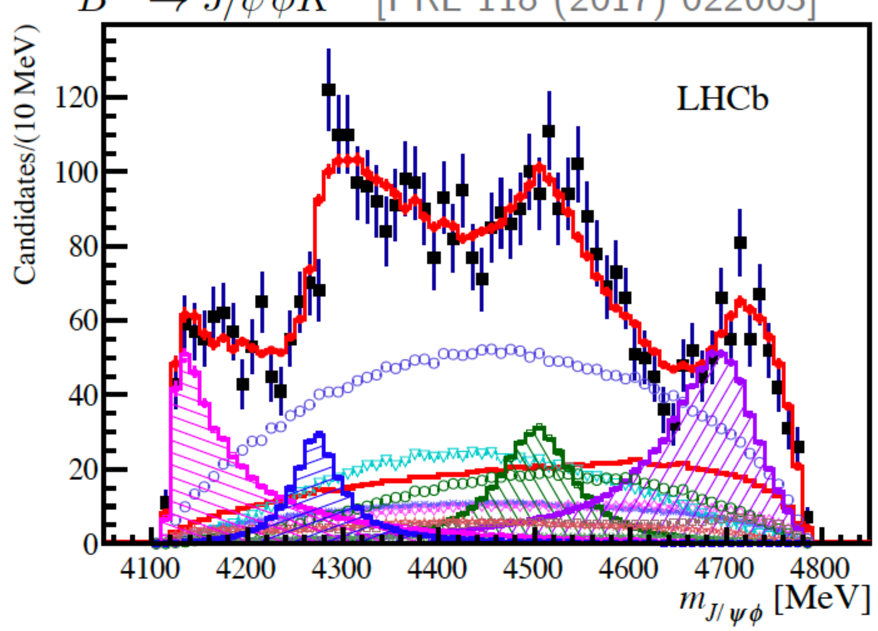


Ω_c states [PRL 118 (2017) 182001]

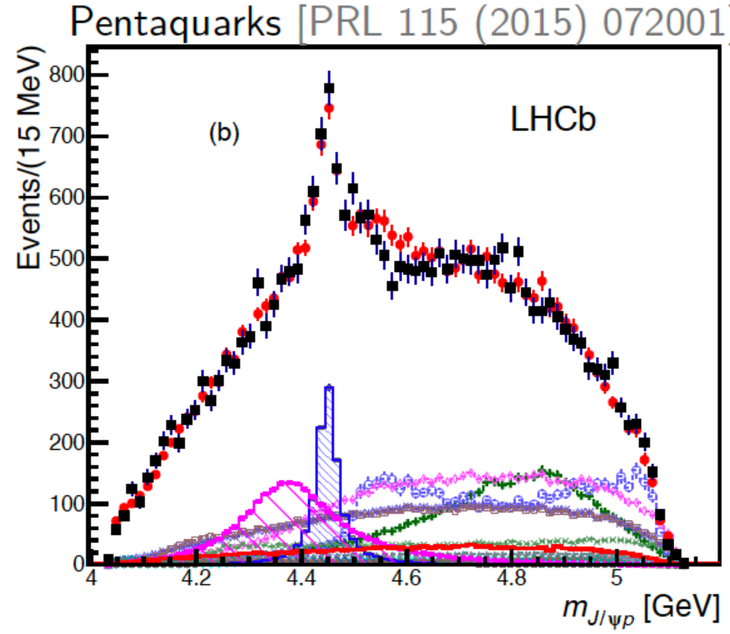


And many more!

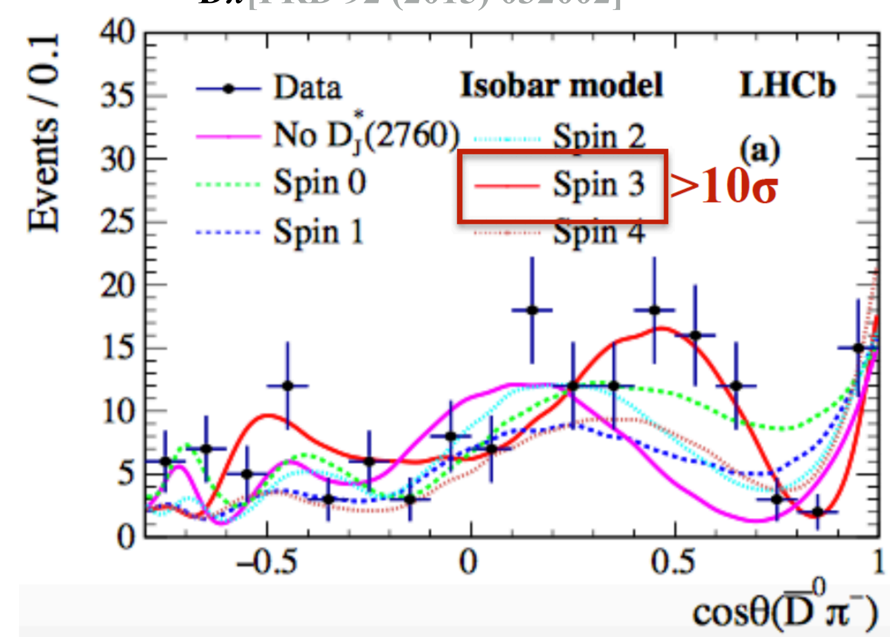
$B^+ \to J/\psi\phi K^+$ [PRL 118 (2017) 022003]



Pentaquarks [PRL 115 (2015) 072001]



$D\pi$ [PRD 92 (2015) 032002]

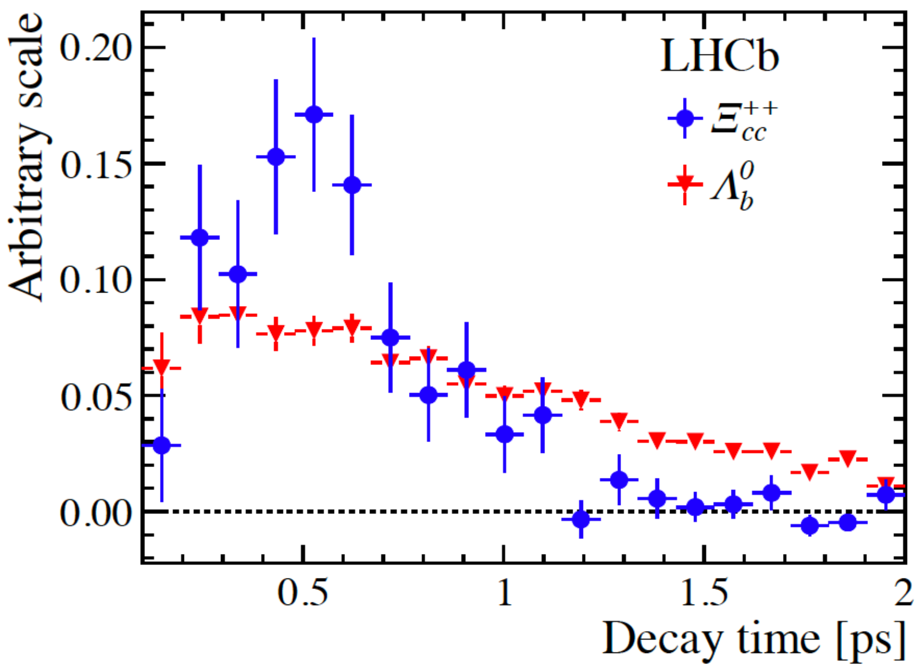


➢ **More "exciting/excited" particles are coming**

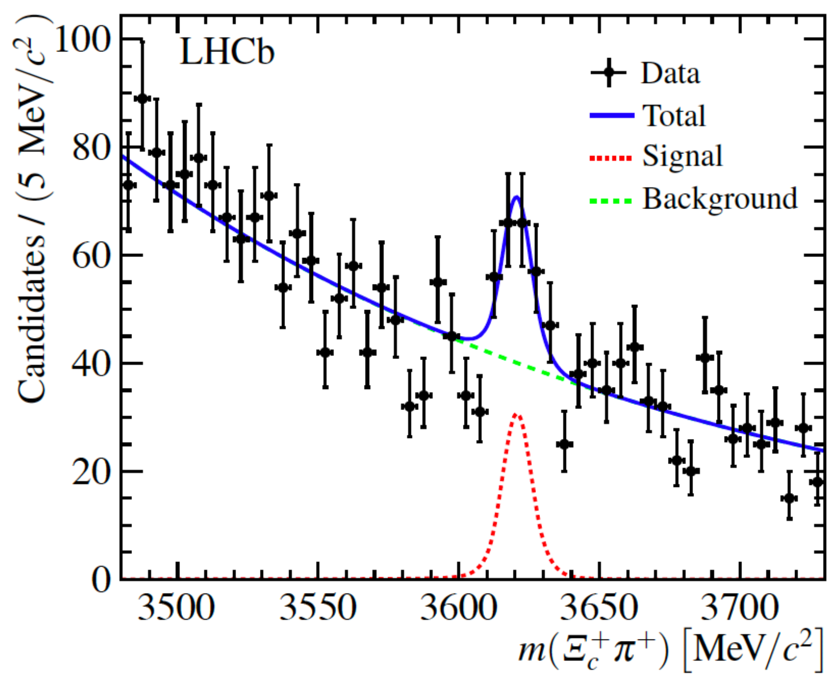
Understanding particles

➢ **Particles properties (spin-parity, lifetime, decay modes etc) important for understanding nature of particles**

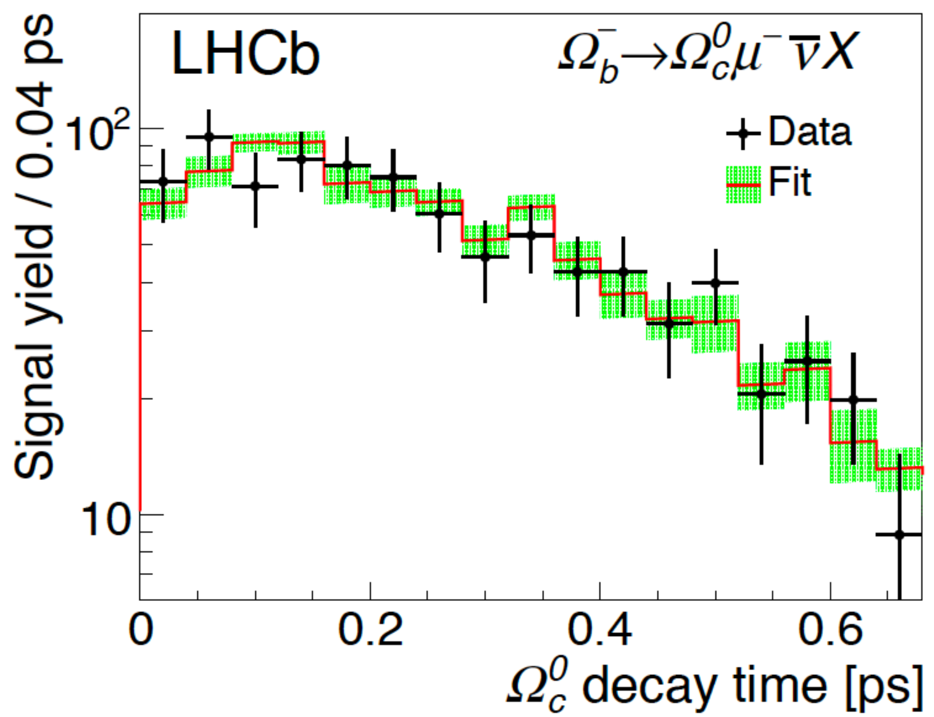
[PRL 121 (2018) 052002]



[PRL 121 (2018) 162002]



[PRL 121 (2018) 092003]



➢ **Sometimes surprise comes: Ω_c (from b-decays) lifetime four time more than previous value (69±12 fs)**

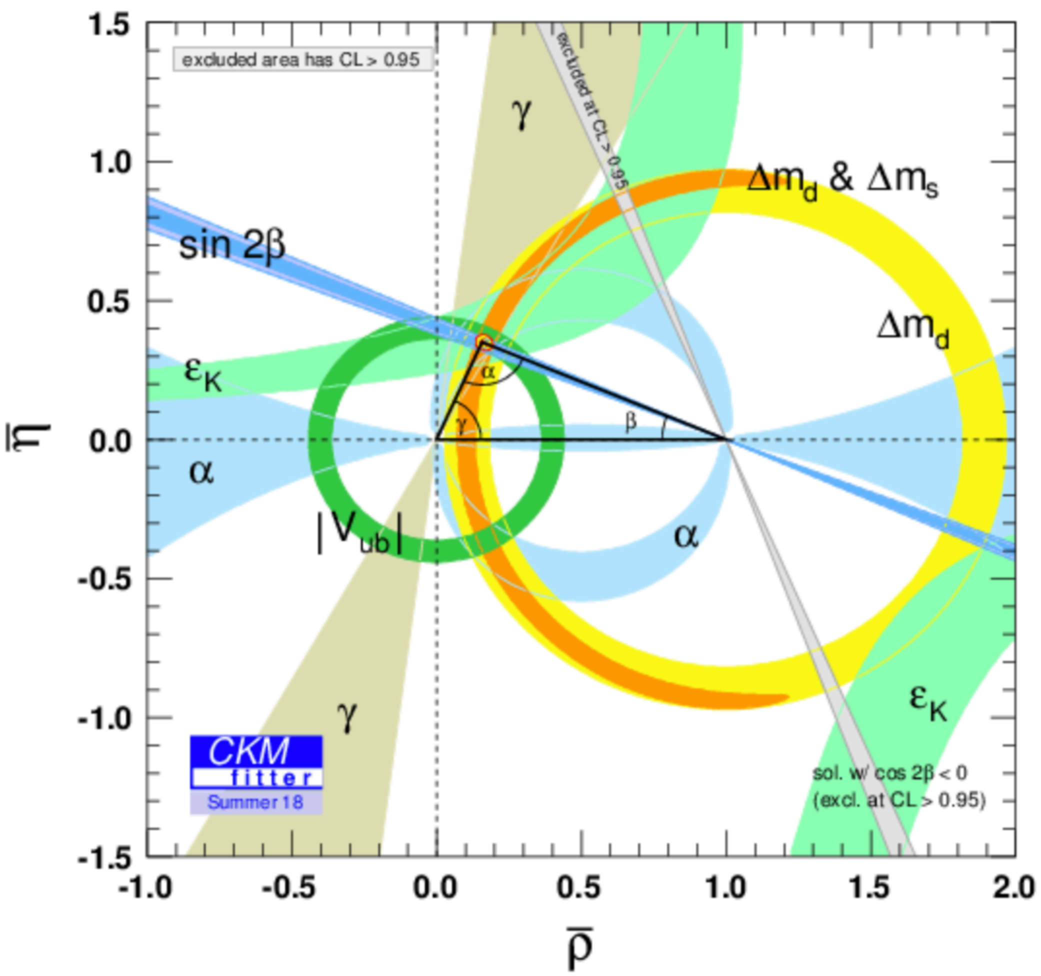
$$\tau(\Omega_c) = (268 \pm 24_{\text{stat.}} \pm 10_{\text{syst.}} \pm 2_{D\,\text{lifetime}})\ \text{fs}$$

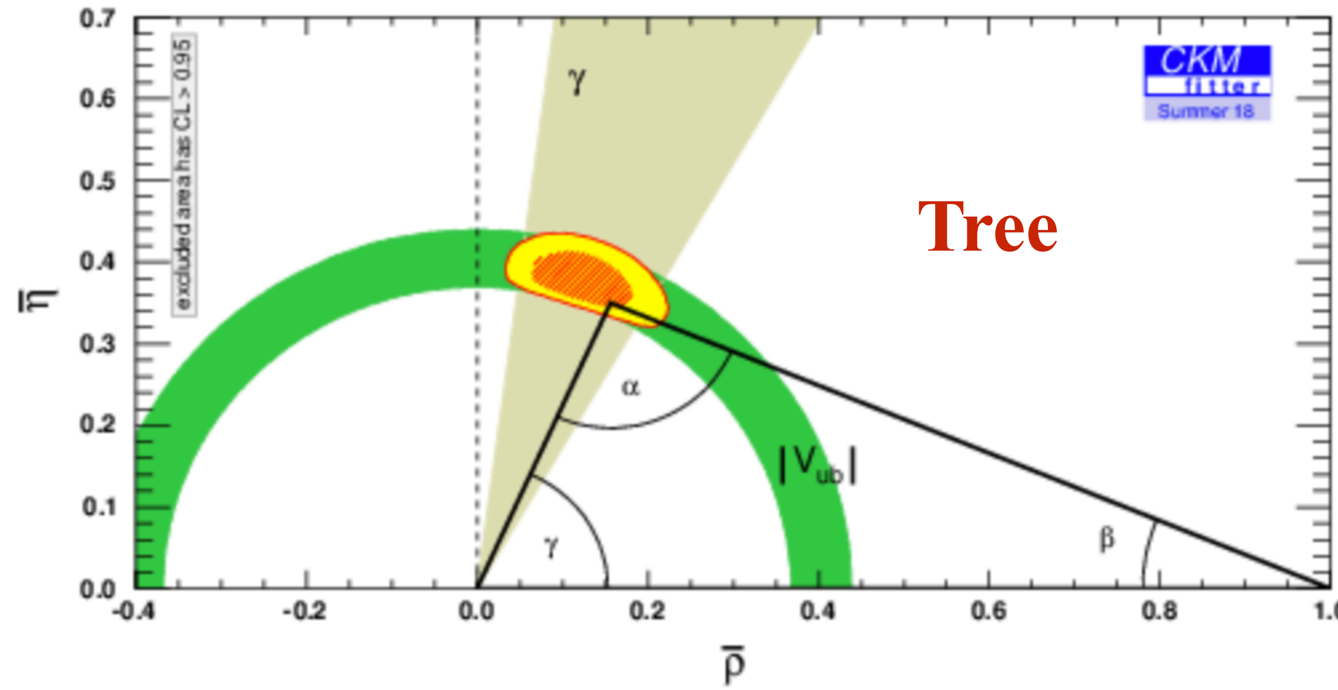
➢ **LHCb-China group is working to confirm/disprove using prompt produced Ω_c**

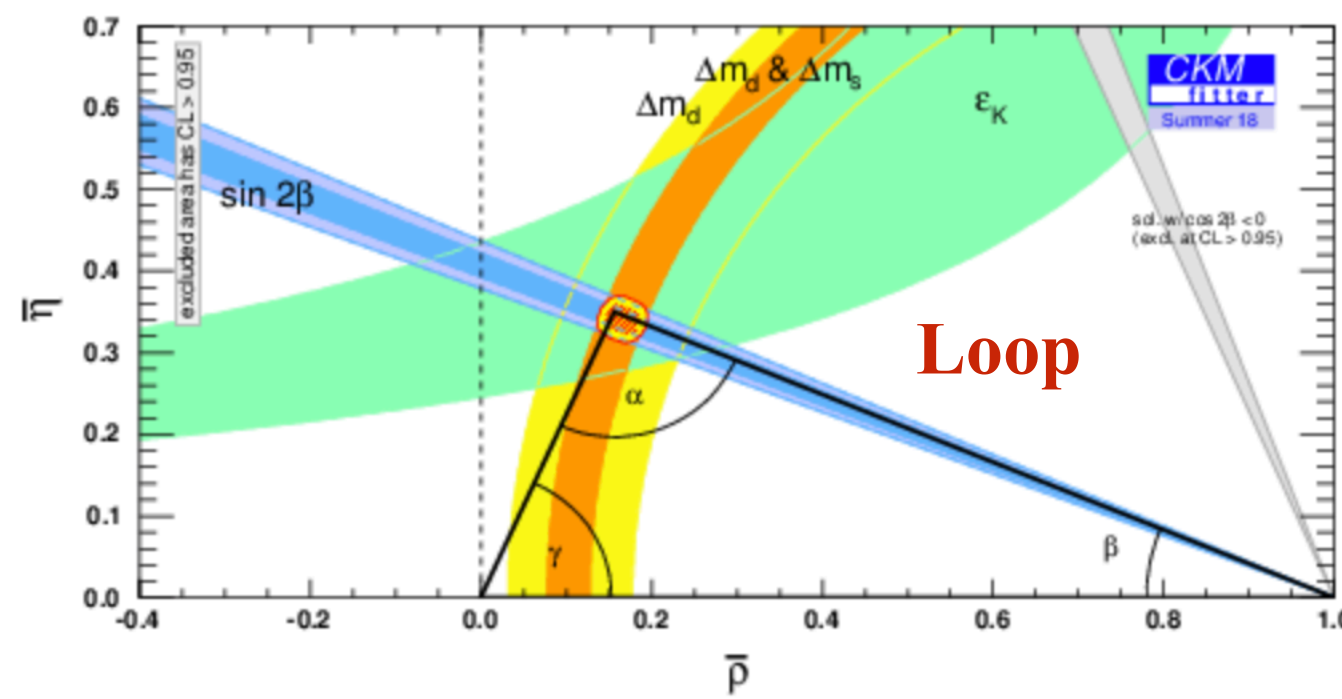
➢ **While continue excellence in QCD physics, efforts from LHCb-China group now also on CKM physics and rare decays, searching for New Physics**

Unitary triangle

➢ **The "famous" triangle (origin of CPV in SM) and related variables: γ, α, β, β_s, $|V_{ub}|$, $|V_{cb}|$, Δm_d, Δm_s etc.**



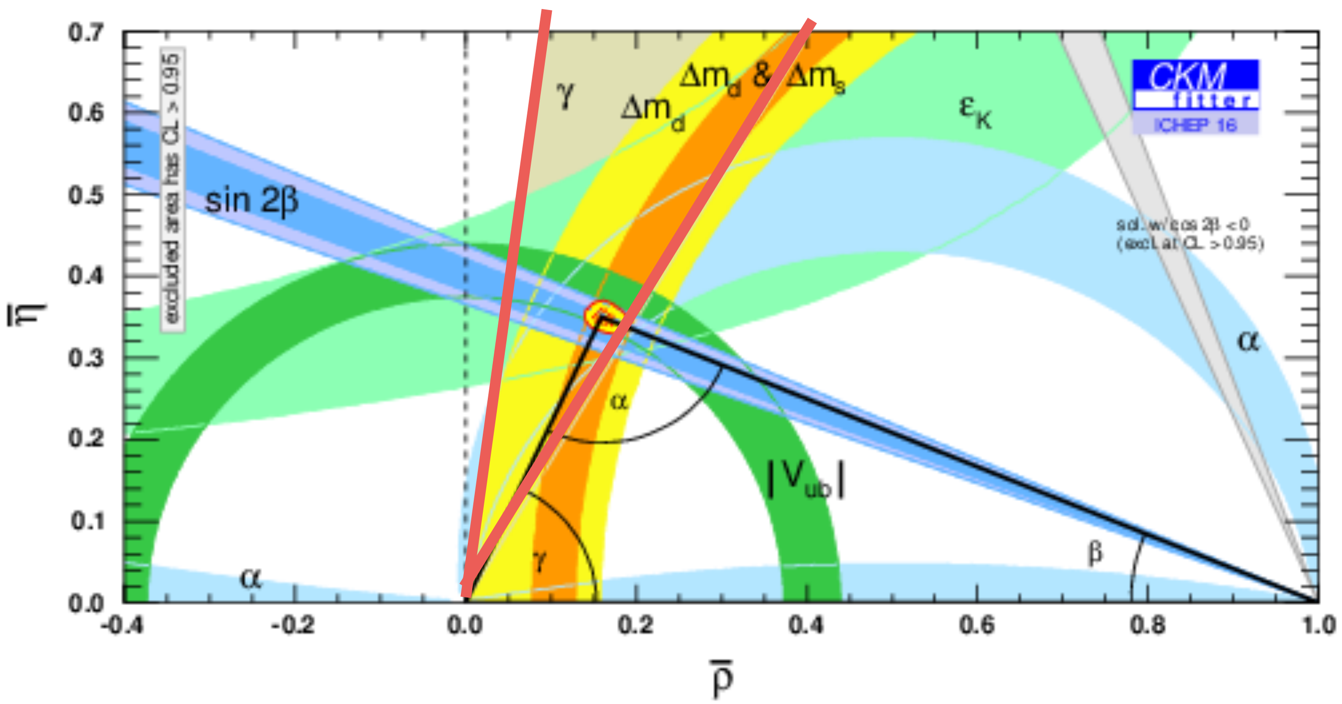




CKM angle γ

$$\gamma = \arg\left[-V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)\right]$$

➢ **Previous least well known CKM parameter**



Direct: $\gamma = (73.5^{+4.3}_{-5.0})^\circ$

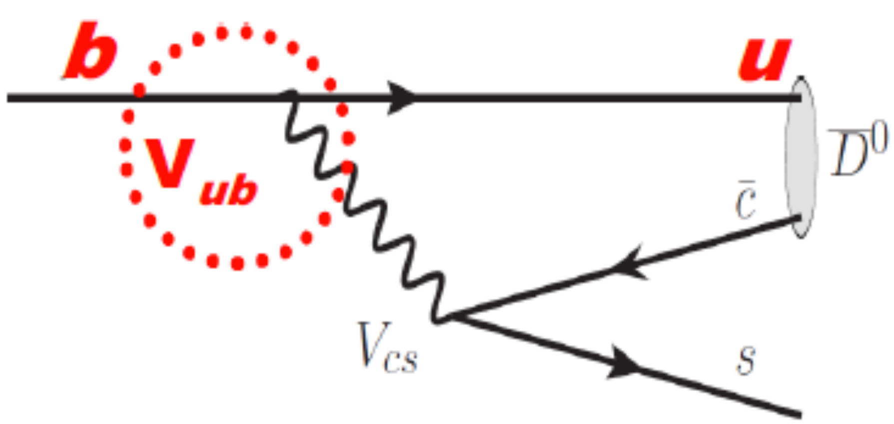
VS

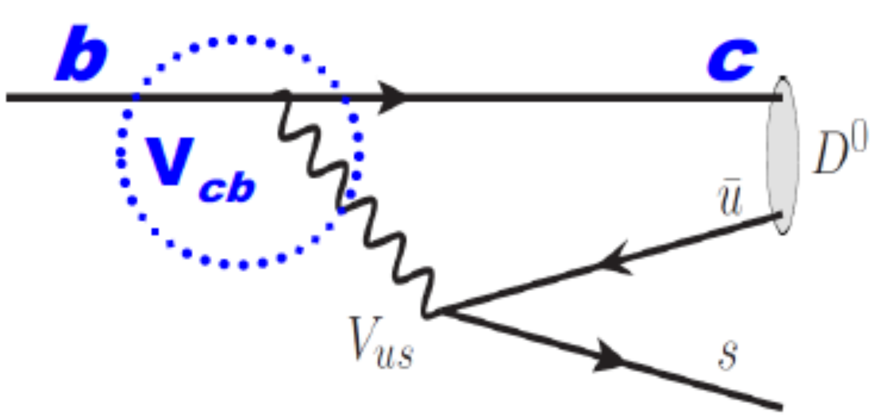
Indirect: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$

New Physics?

➢ **γ at tree level: clean theory prediction δγ/γ ~ 10^{-7}**

JHEP 1401 (2014) 051





➢ **Sensitive channels with small BFs: need to combine many channels**

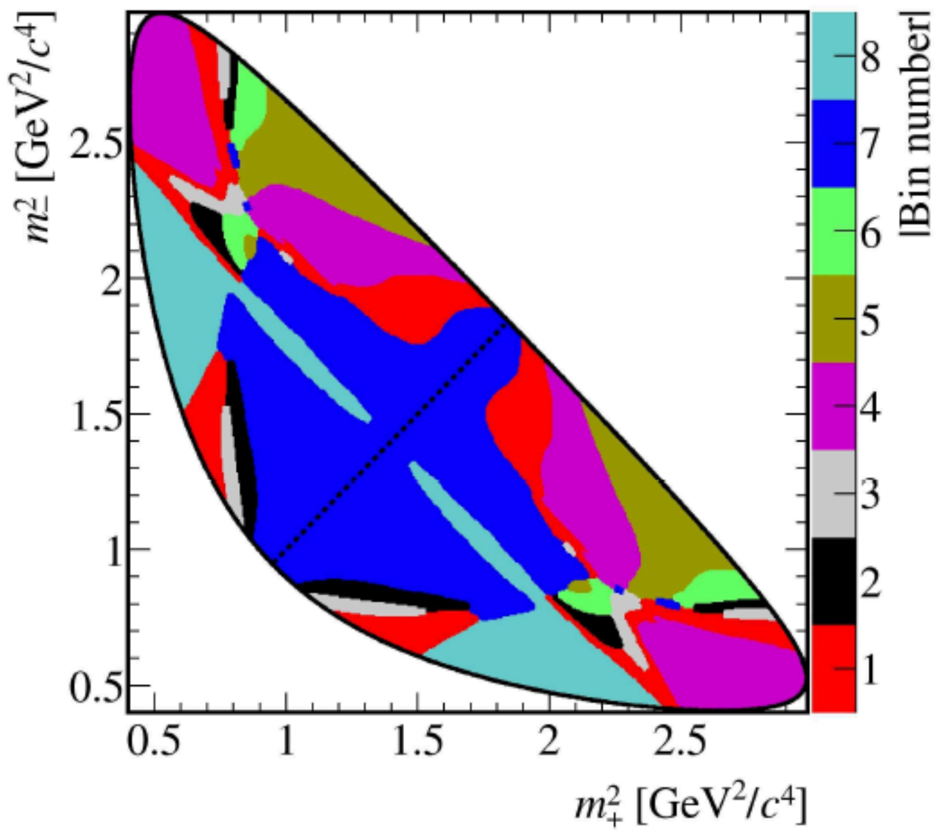
$B_s \to D_s K$, $B^+ \to DK^+$ with D to hh, Kshh, $D_s \to hhh$ etc, h = $K^\pm$, $\pi^\pm$

arXiv:1806.01202

New MI GGSZ analysis with Run 2 data

- **Measure γ with $B^{\pm}\to DK^{\pm}$, where D decays to $K_S\pi\pi$ and K_SKK, using 2 fb^{-1} Run 2 data**
- **Sensitivity to γ for each point in D Dalitz plot: MI divide Dalitz plot into bins and sensitivity to γ in each Dalitz bin**
- **Strong phase information of D decays from CLEO-c measurements (C_i, S_i)**
- **$|\text{Amplitude}|^2$ information from semileptonic control channel where D has definite flavor (F_i)**
- **Information of B decays:**

$$x_{\pm} = r_B \cos\left(\delta_B \pm \gamma\right)$$
$$y_{\pm} = r_B \sin\left(\delta_B \pm \gamma\right)$$



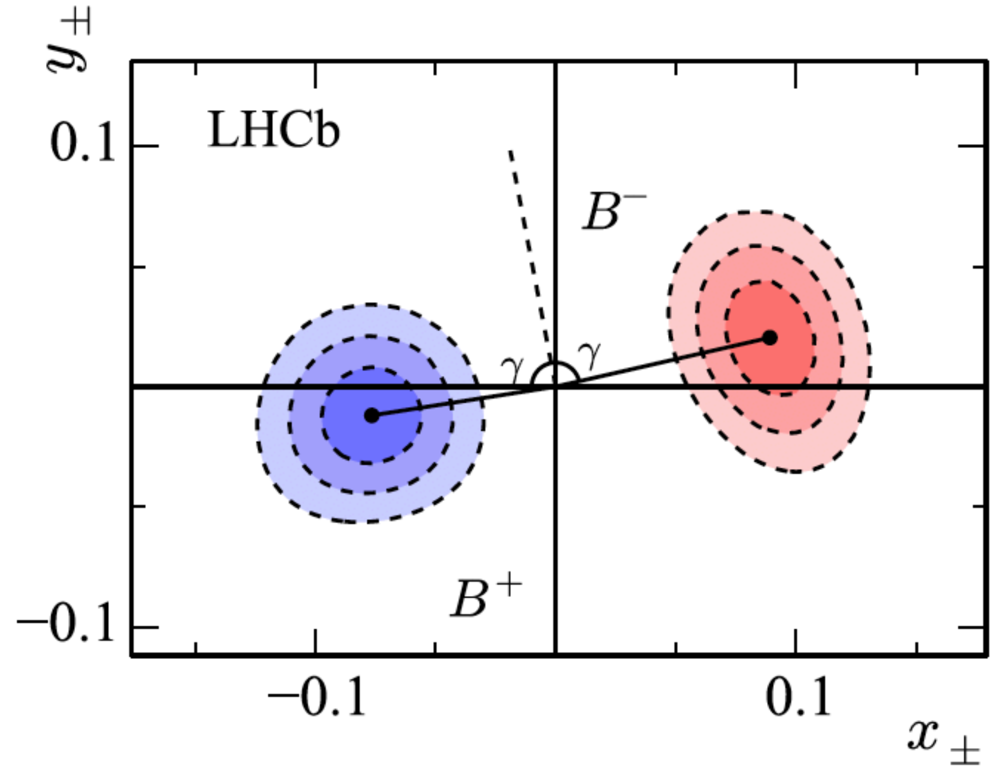
- **Number of events in each bin:**

$$N_{\pm i}^{+} = h_{B^+}\left(F_{\mp i} + \left(x_+^2 + y_+^2\right)F_{\pm i} + 2\sqrt{F_i F_{-i}}\left(x_+ c_{\pm i} + y_+ s_{\pm i}\right)\right)$$
$$N_{\pm i}^{-} = h_{B^-}\left(F_{\pm i} + \left(x_-^2 + y_-^2\right)F_{\mp i} + 2\sqrt{F_i F_{-i}}\left(x_- c_{\pm i} + y_- s_{\pm i}\right)\right)$$

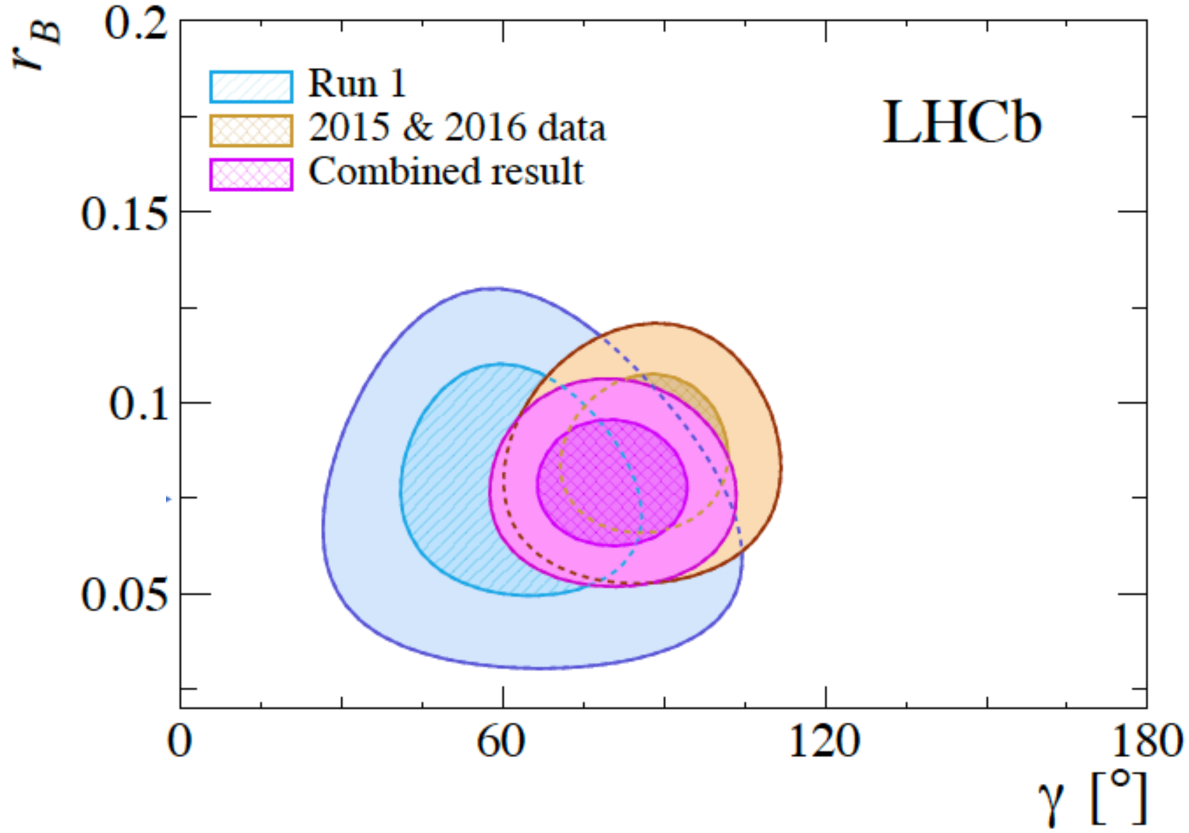
Results of GGSZ analysis with Run 2 data

- Using 2 fb^{-1} Run 2 data collected at 13 TeV

$$x_- = (\ \ 9.0 \pm 1.7 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_- = (\ \ 2.1 \pm 2.2 \pm 0.5 \pm 1.1) \times 10^{-2}$$
$$x_+ = (-7.7 \pm 1.9 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_+ = (-1.0 \pm 1.9 \pm 0.4 \pm 0.9) \times 10^{-2}$$



- Extract information of γ and r_B



- Combination of Run 1 and Run 2

$$\gamma = 80^\circ\,{}^{+10^\circ}_{-9^\circ}\,\left({}^{+19^\circ}_{-18^\circ}\right),$$
$$r_B = 0.080\,{}^{+0.011}_{-0.011}\,\left({}^{+0.022}_{-0.023}\right),$$
$$\delta_B = 110^\circ\,{}^{+10^\circ}_{-10^\circ}\,\left({}^{+19^\circ}_{-20^\circ}\right).$$

- New method proposed in EPJC 78 (2018) 121 for future improvement

New TD measurements related to γ

JHEP 03 (2018) 059

- TD results of $B_s \to D_s^{\mp} K^{\pm}$ with 3 fb^{-1} Run 1 data published early this year;

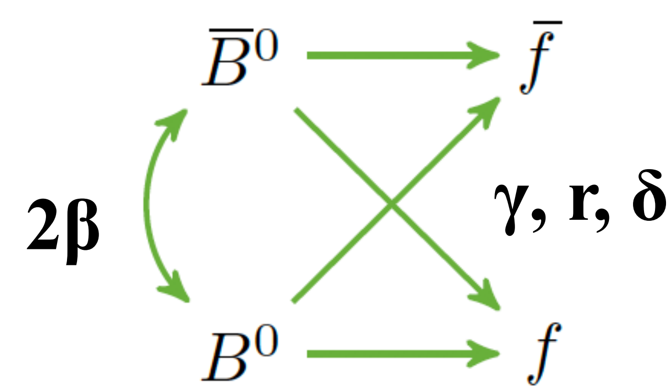
JHEP 06 (2018) 084

- New TD results on $B^0 \to D^{\mp}\pi^{\pm}$ with 3 fb^{-1} Run 1 data

$B_s^0 \to D_s^{\mp} K^{\pm}$	$B^0 \to D^{\mp}\pi^{\pm}$
$\Gamma_{B^0\to f} \propto \lambda^3$	$\Gamma_{B^0\to f} \propto \lambda^2$
$\Gamma_{\bar{B}^0\to f} \propto \lambda^3$	$\Gamma_{\bar{B}^0\to f} \propto \lambda^4$

$$r = \left|\frac{\bar{A}_f}{A_f}\right|$$

Small r, but very large statistics



- **The main formula:**

$$A_f(t) = \frac{\Gamma_{B^0\to f}(t) - \Gamma_{\bar{B}^0\to f}(t)}{\Gamma_{B^0\to f}(t) + \Gamma_{\bar{B}^0\to f}(t)} = \frac{C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta\Gamma/2\, t) + A_f^{\Delta\Gamma} \sinh(\Delta\Gamma/2\, t)}$$

- C_f, S_f and $A_f^{\Delta\Gamma}$: functions of γ, r, δ, β_s, and $\beta_{(s)}$, $\Delta m_{(s)}$, Γ, $\Delta\Gamma_s$, r(Dπ) from external inputs

JHEP 03 (2018) 059

JHEP 06 (2018) 084

Results from TD analyses

$B^0 \to D^{\mp}\pi^{\pm}$

$$S_f = 0.058 \pm 0.020(\text{stat}) \pm 0.011(\text{syst})$$
$$S_{\bar{f}} = 0.038 \pm 0.020(\text{stat}) \pm 0.007(\text{syst})$$

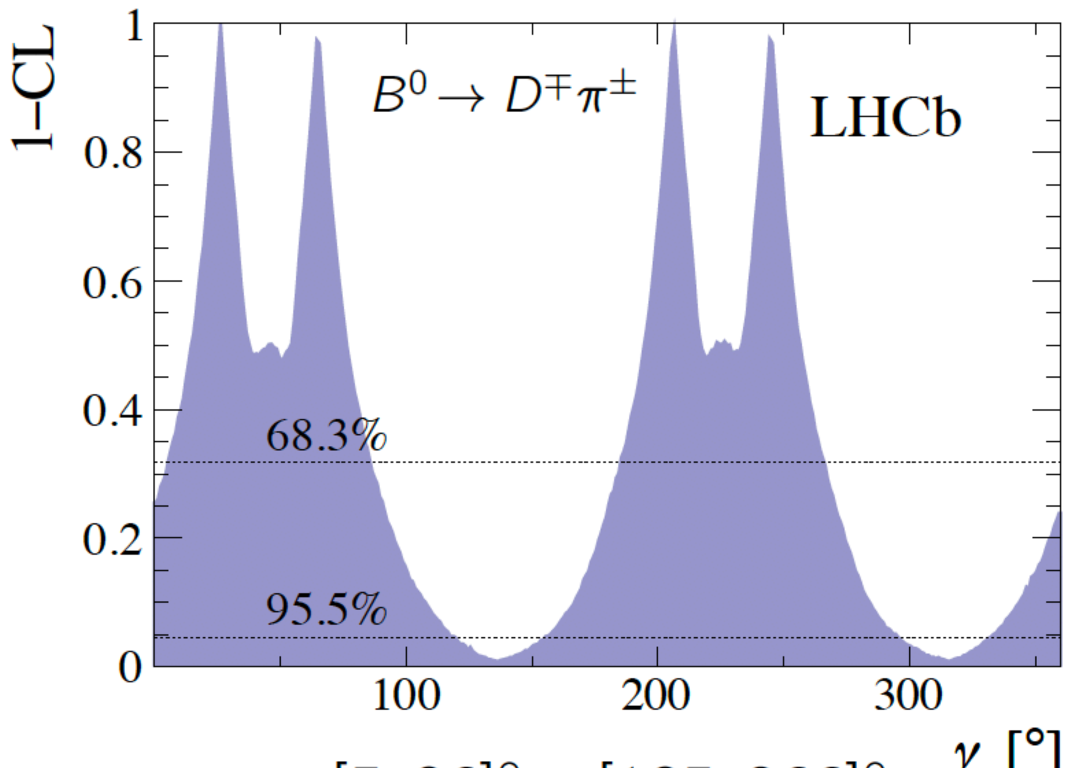
consistent with Belle and Babar, but more precise

2.7σ CPV

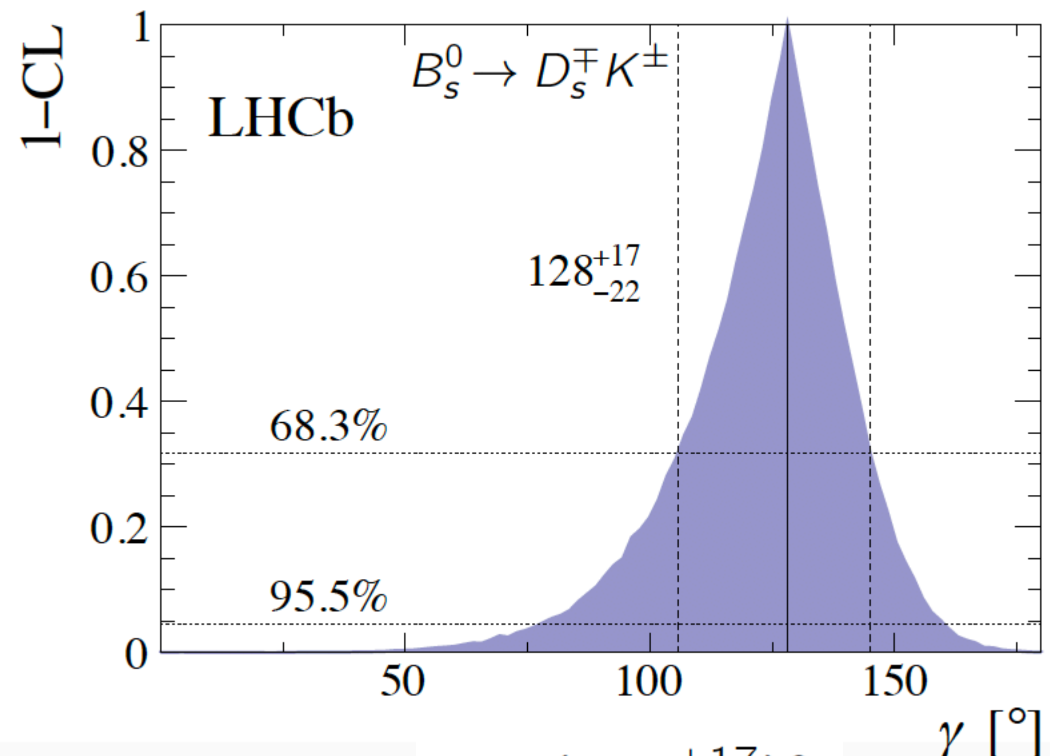
$B_s \to D_s^{\mp}K^{\pm}$

C_f	$0.730 \pm 0.142 \pm 0.045$
$A_f^{\Delta\Gamma}$	$0.387 \pm 0.277 \pm 0.153$
$A_{\bar{f}}^{\Delta\Gamma}$	$0.308 \pm 0.275 \pm 0.152$
S_f	$-0.519 \pm 0.202 \pm 0.070$
$S_{\bar{f}}$	$-0.489 \pm 0.196 \pm 0.068$

- **Interpretation of the results**



$\gamma \in [5, 86]^\circ \cup [185, 266]^\circ$

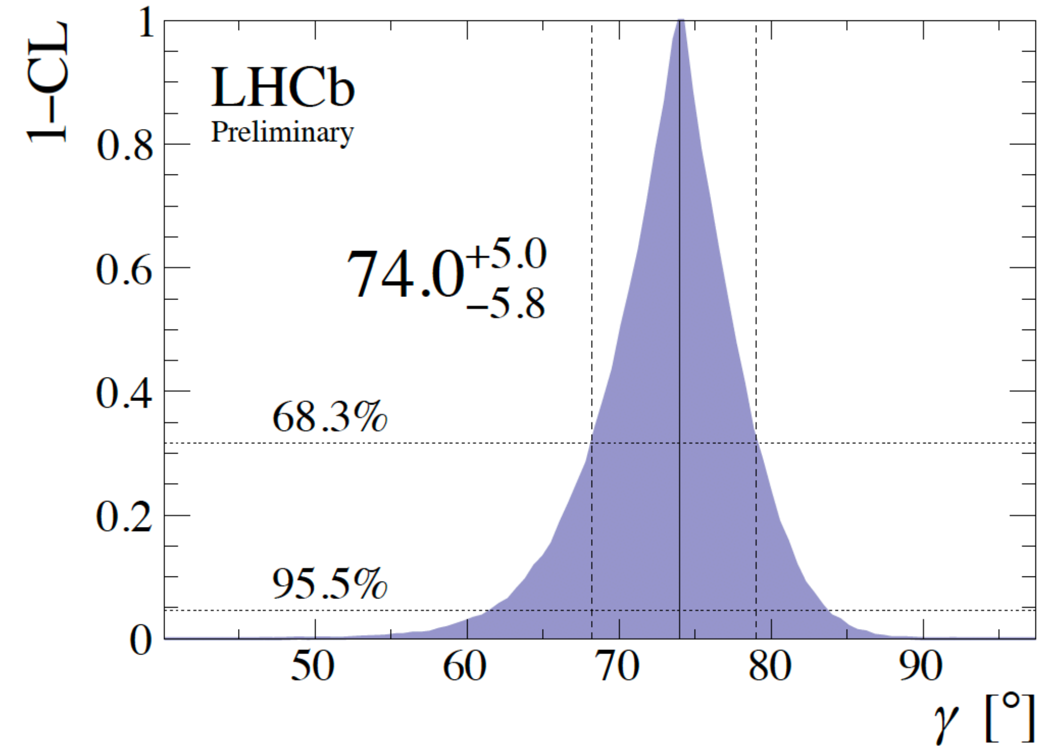


$\gamma = (128^{+17}_{-22})^\circ$

γ combination

➢ **Adding all the measurements, we have**

B decay	D decay	Method	Ref.	Dataset[†]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1



World average: $\gamma = \left(73.5^{+4.2}_{-5.1}\right)^{\circ}$

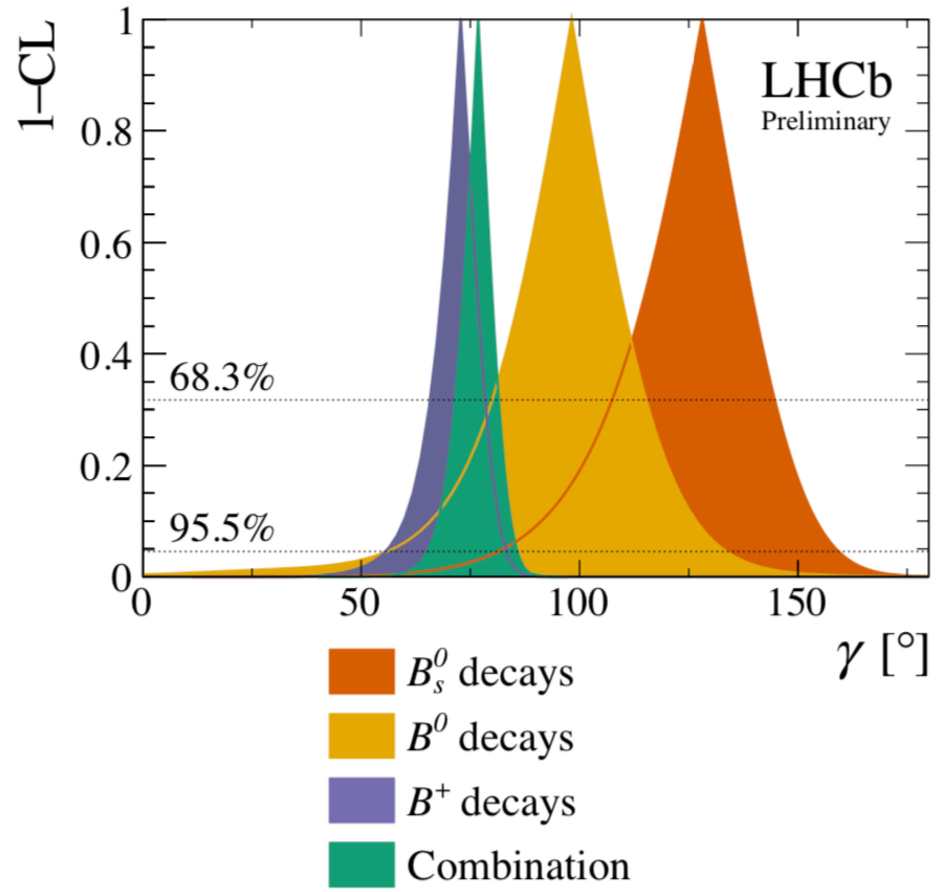
HFLAV winter 2018

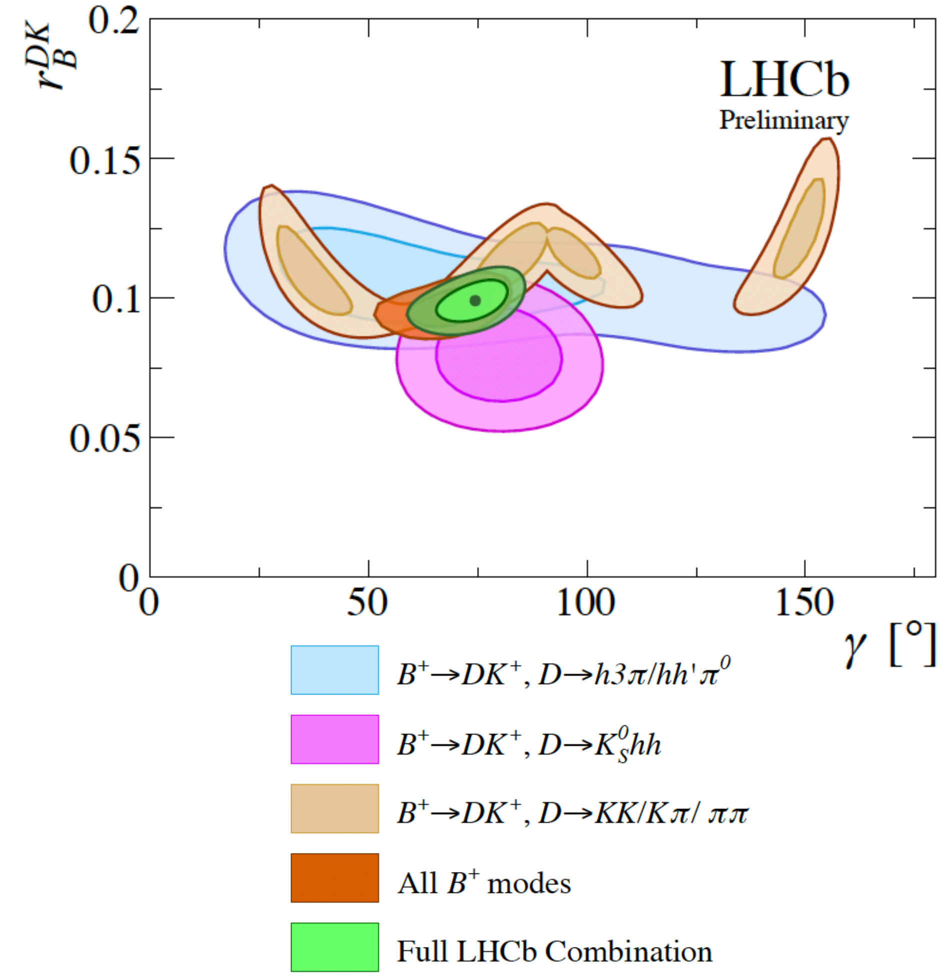
➢ **Inputs from BESIII important, combining efforts will help**

γ combination

- ➢ **Comparing different processes**

LHCb-CONF-2018-002





- ➢ **Some tension exists, interesting to follow-up**
- ➢ **Future sensitivities (scaled according to statistical uncertainties)**

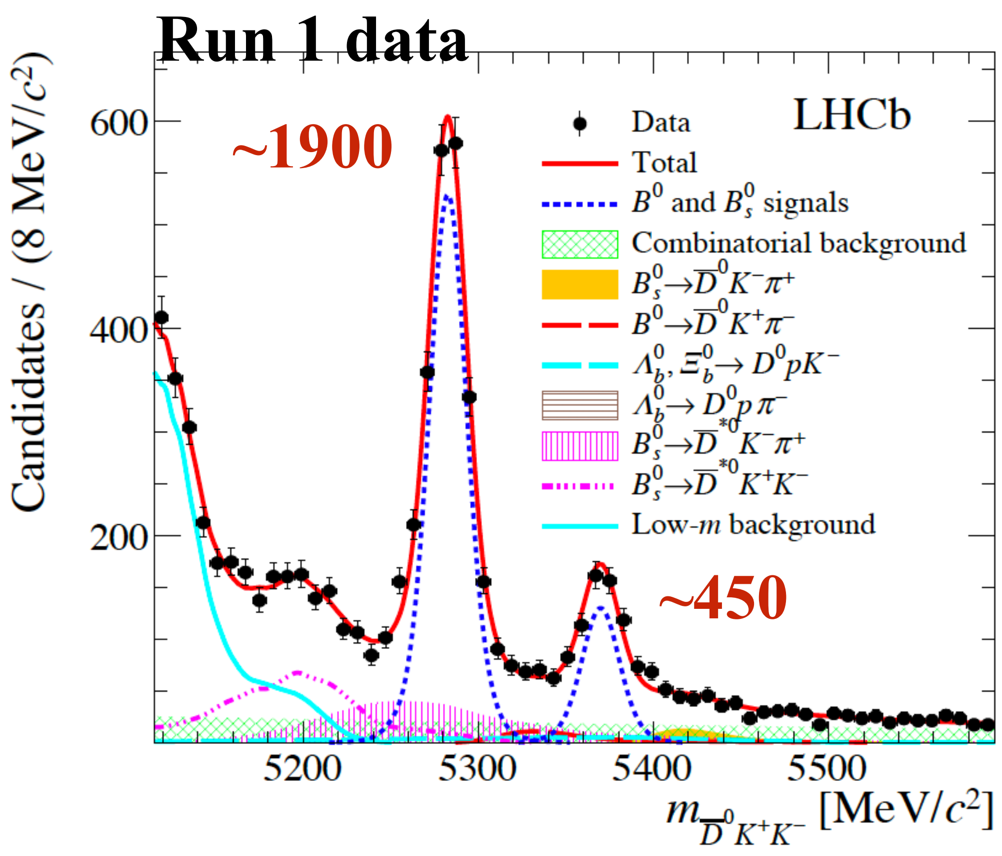
Run 1	Run 2	Upgrade 1	Upgrade 2
5.5°	2.8°	0.71°	0.28°

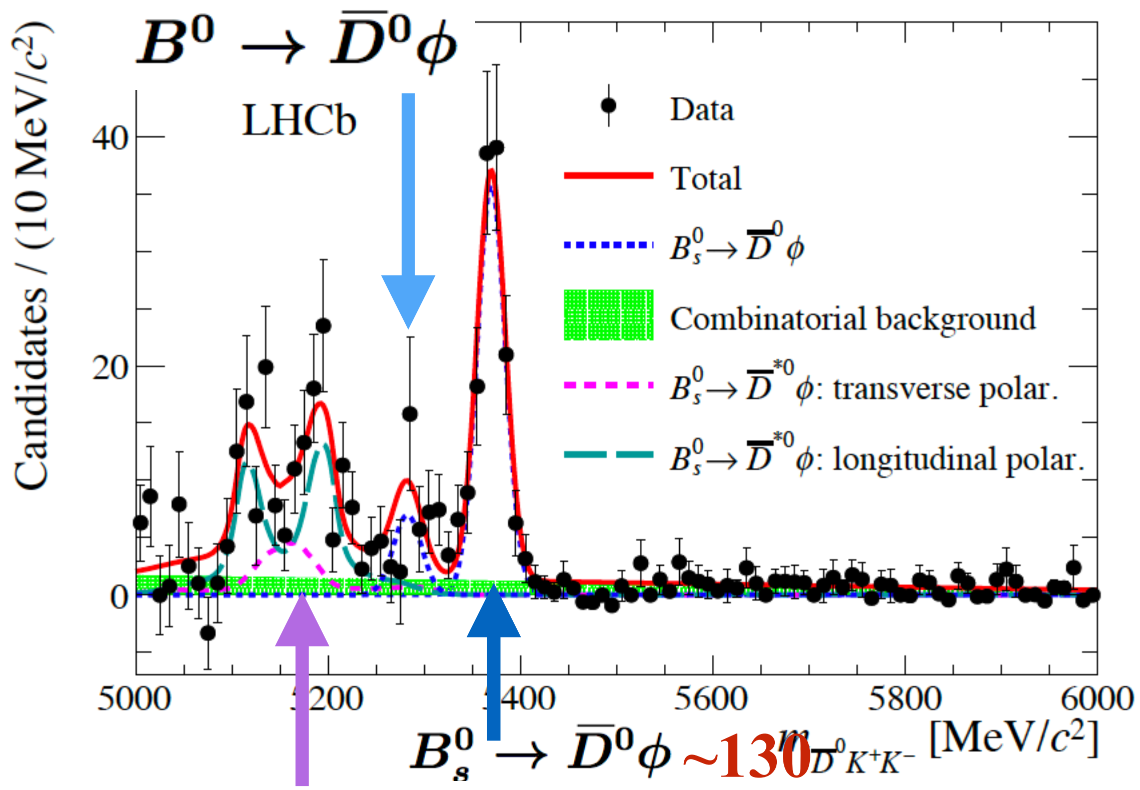
- ➢ **LHCb is continuing to investigate its potential in γ measurements**

Phys. Rev. D 98 (2018) 072006
Phys. Rev. D 98 (2018) 071103(R)

Extra channels for γ

- $B^0 \to \overline{D}^0 KK$ and $B_s \to \overline{D}^0 KK$ decays
  - Time-Dependent Dalitz analyses to access CKM angle γ and $\beta_{(s)}$
  - Not only probe $\sin 2\beta_{(s)}$, but also $\cos 2\beta_{(s)}$
  - Dalitz structures interesting for charm spectroscopy studies
- $B_s \to D^{(*)}\phi$ decays: special cases where final states are in CP eigenstates





- Comparable sensitivity on γ w.r.t. that of the golden GGSZ mode expected for $B_s \to D^{(*)}\phi$ decays and we are currently working on its measurements

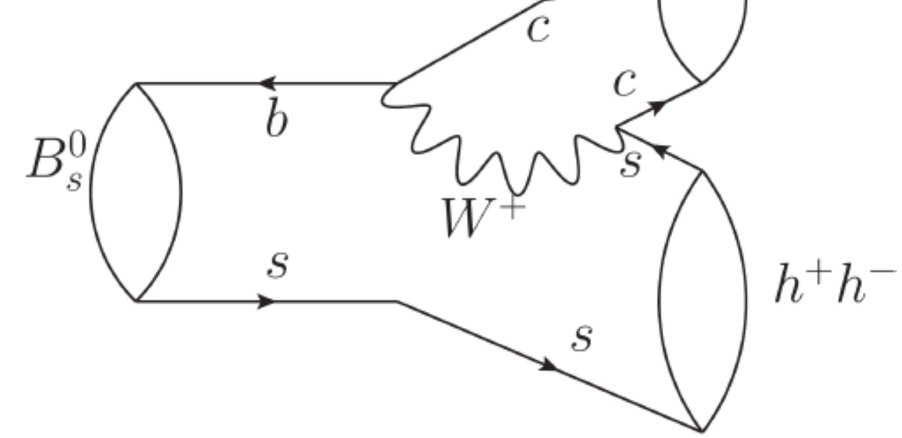
ϕ_s measurements

➢ **The golden channels for b→c$\bar{c}$s process: B_s→J/ψKK, J/ψ$\pi\pi$**

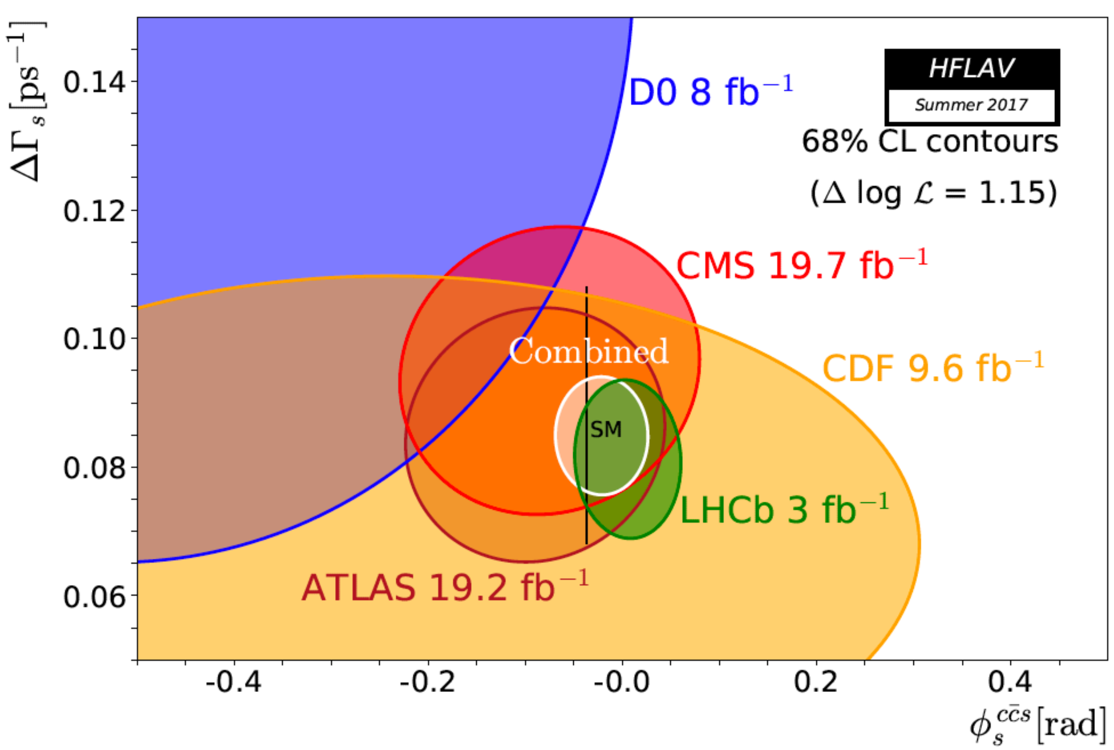
Final LHCb Run I results:

$J/\psi K^+K^-$ in ϕ region	$-58 \pm 49 \pm 6$ mrad	[PRL 114 (2015) 041801]
$J/\psi K^+K^-$ in high mass K^+K^- region	$119 \pm 107 \pm 34$ mrad	[JHEP 08 (2017) 037]
$J/\psi \pi^+\pi^-$	$70 \pm 68 \pm 8$ mrad	[PLB 713 (2012) 378]
Overall	1 ± 37 mrad	

$$\phi_s^{c\bar{c}s} = -2\beta_s$$



➢ **LHCb dominates combination; currently consistent with SM**



HFLAV combination

$$\phi_s^{c\bar{c}s} = -0.021 \pm 0.031 \text{ rad}$$
$$\Delta\Gamma_s = 0.085 \pm 0.006 \text{ ps}^{-1}$$
$$\Gamma_s = 0.6640 \pm 0.0020 \text{ ps}^{-1}$$

Penguin effects under control

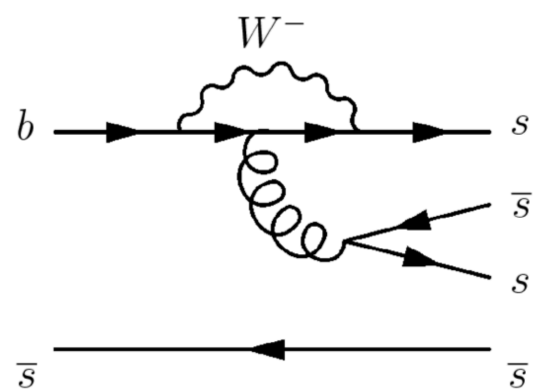
$$\Delta\phi_s \sim 0.001 \pm 0.020 \text{ rad}$$

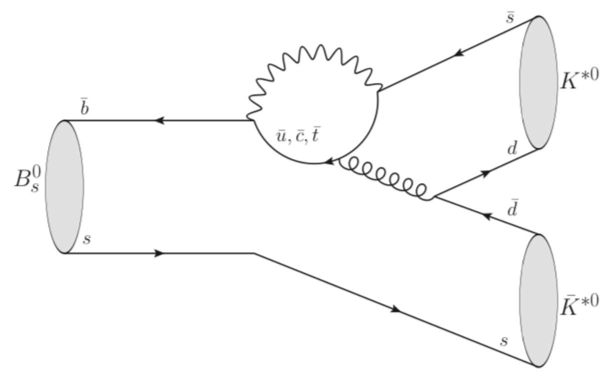
$\phi_s^{c\bar{c}s} \overset{\text{SM}}{=} -0.0370 \pm 0.0006$ rad **[CKMFitter, PRD 84 (2011) 033005]**

$\Delta\Gamma_s \overset{\text{SM}}{=} 0.088 \pm 0.020$ ps^{-1} **[M. Artuso et al, arXiv:1511.09466]**

ϕ_s measurements and prospects

➢ Similar (much harder) analyses performed for Bs→ϕϕ and Bs→Kπ Kπ for $\phi_s^{s\bar{s}s}$ and $\phi_s^{d\bar{d}s}$





$\phi_s^{s\bar{s}s} \sim 0$

$\phi_s^{s\bar{s}s}$ = -0.17±0.15±0.03 rad

$\phi_s^{d\bar{d}s} \sim 0$

$\phi_s^{s\bar{d}d} = -0.10 \pm 0.13 \pm 0.14$ rad,

➢ LHCb prospects for ϕ_s in different processes

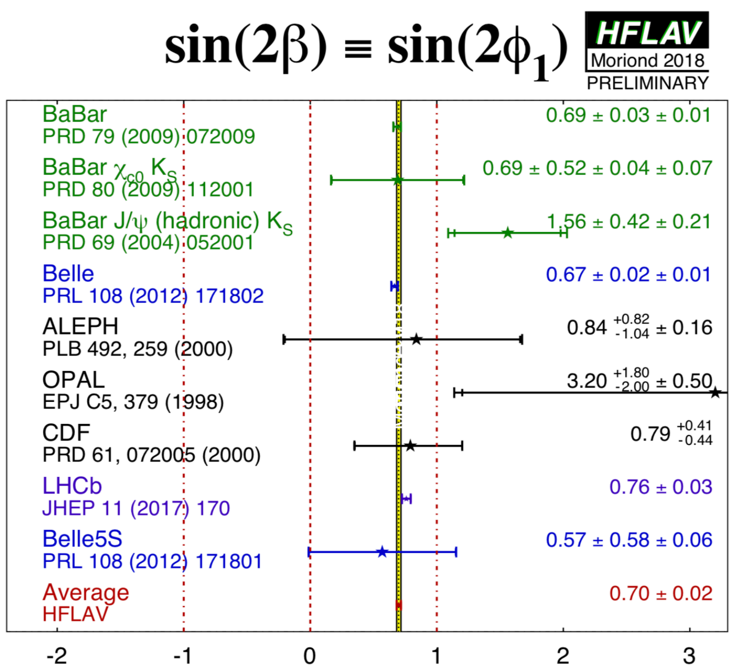
	Run 1	Run 2	Upgrade I	Upgrade II
$\phi_s^{c\bar{c}s}$	37 mrad	15 mrad	4 mrad	2 mrad
$\phi_s^{d\bar{d}s}$	180 mrad	90 mrad	22 mrad	10 mrad
$\phi_s^{s\bar{s}s}$	150 mrad	75 mrad	19 mrad	8 mrad

➢ LHCb-China group heavily involved in B_s→J/ψKK, J/ψππ and Bs→ϕϕ modes

Nature Phys. 11 (2015) 743-747

Other CKM parameters

➢ For sin2β, with Run 1 data, LHCb has **similar precision as B-factories**



➢ Future expectations:

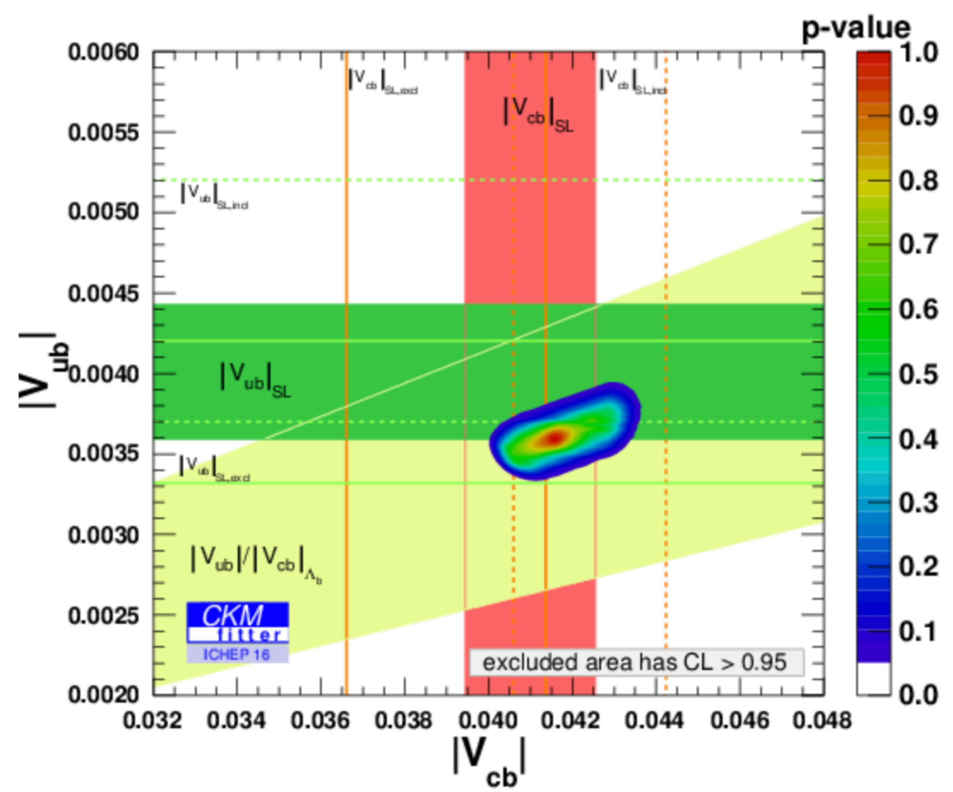
Run 1	Run 2	Upgrade I	Upgrade II
0.034	0.017	0.004	0.002

➢ For **$|V_{ub}|/|V_{cb}|$** and CKM angle **α**, future sensitivities **driven by Belle II**, but LHCb can still make important contributions

➢ LHCb has proved the ability to do $|V_{ub}|/|V_{cb}|$ measurement at hadron collider

➢ **New methods** also suggested to use LHCb data to solve ambiguities on α measurements

arXiv:1808.09391

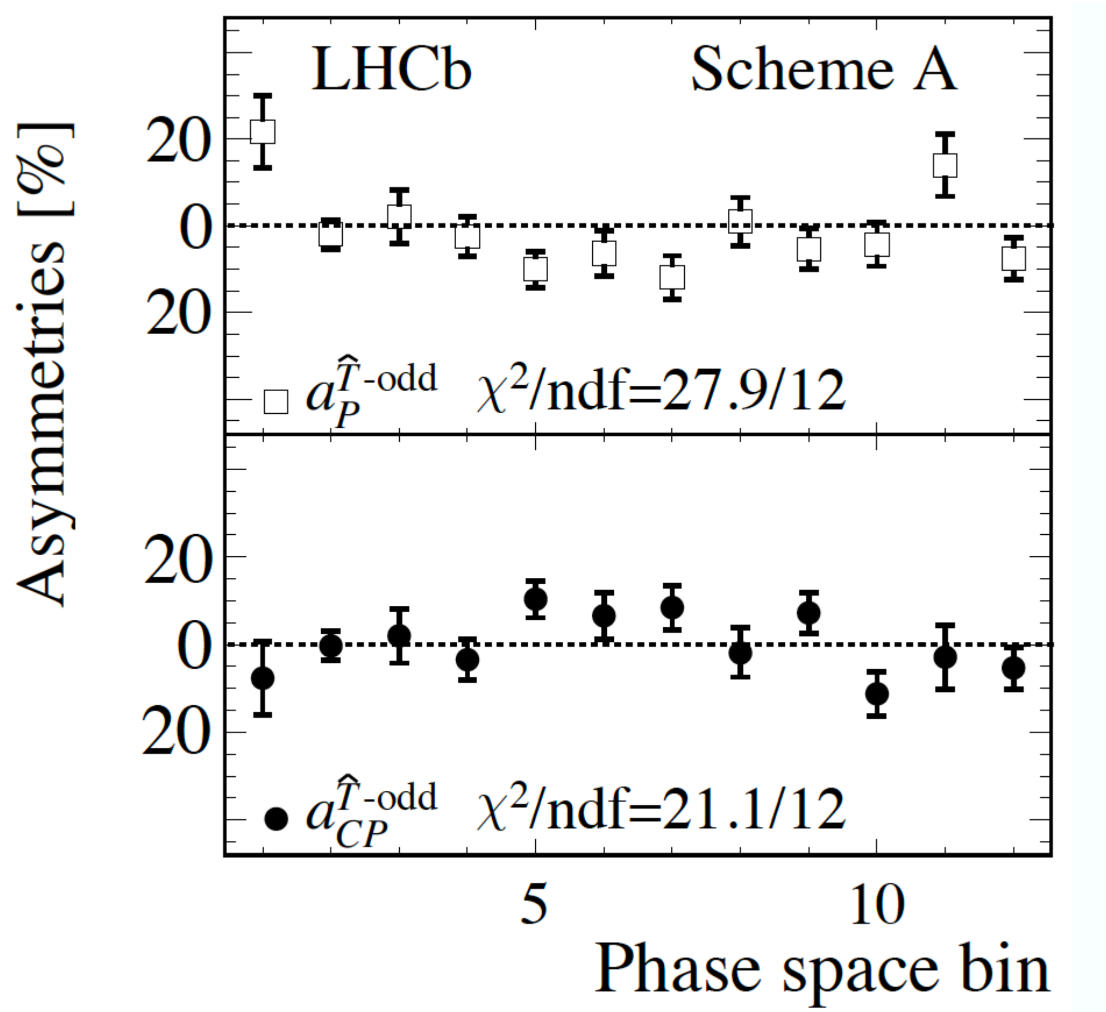


➢ Sensitivities on Δm_d and Δm_s are dominated by LHCb, but interpreting **limited by Lattice**

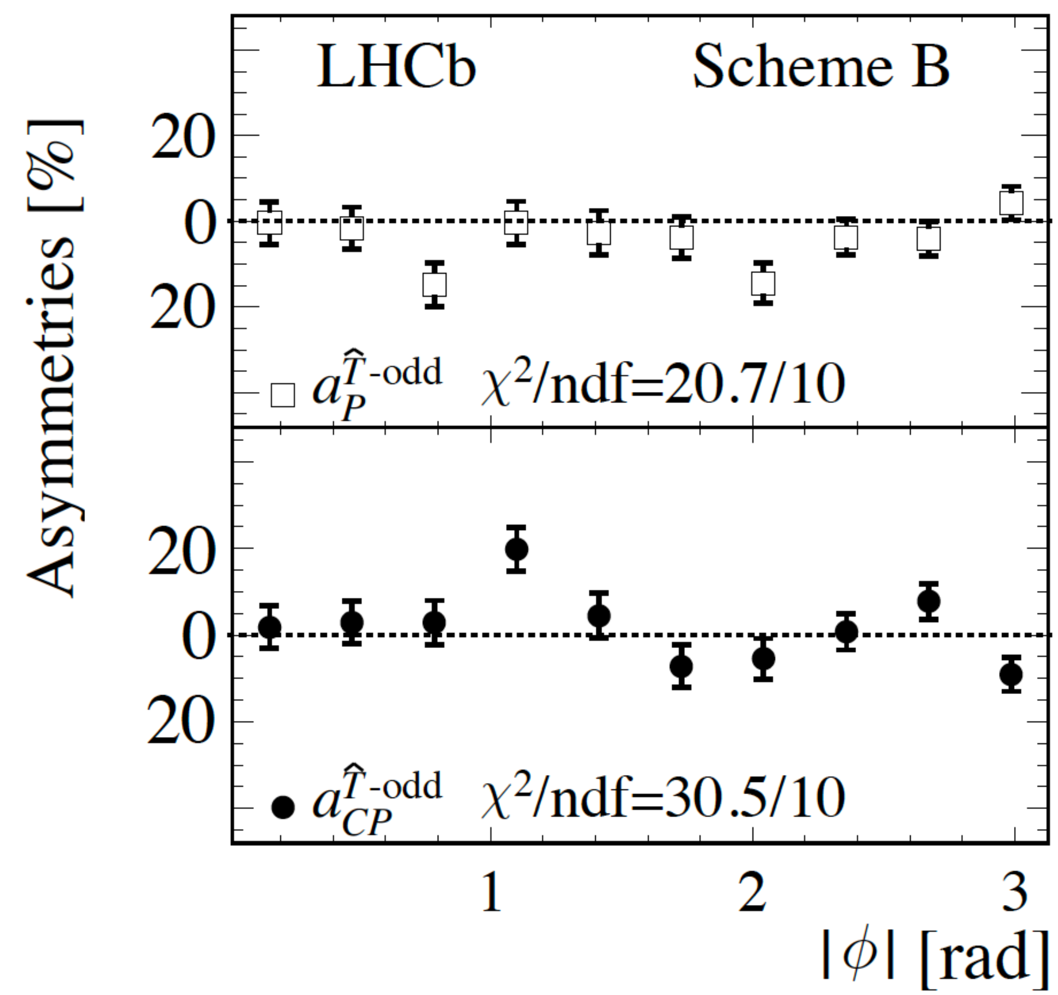
Nature Physics 13 (2017) 391

CPV in unexplored sectors

- ➢ **CPV found in many places, but not yet in D decays and baryon decays**
- ➢ **In baryon decays, first evidence for CPV with 3.3σ using triple products in $L_b \to p3\pi$ where non-zero values indicates violation of T-symmetries**



Binning based on resonant structures, e.g. ρ(770), N*, Δ++



Binning based on ϕ angle

- ➢ **LHCb-China group actively involving in searches for CPV in the two fields through other decay modes**

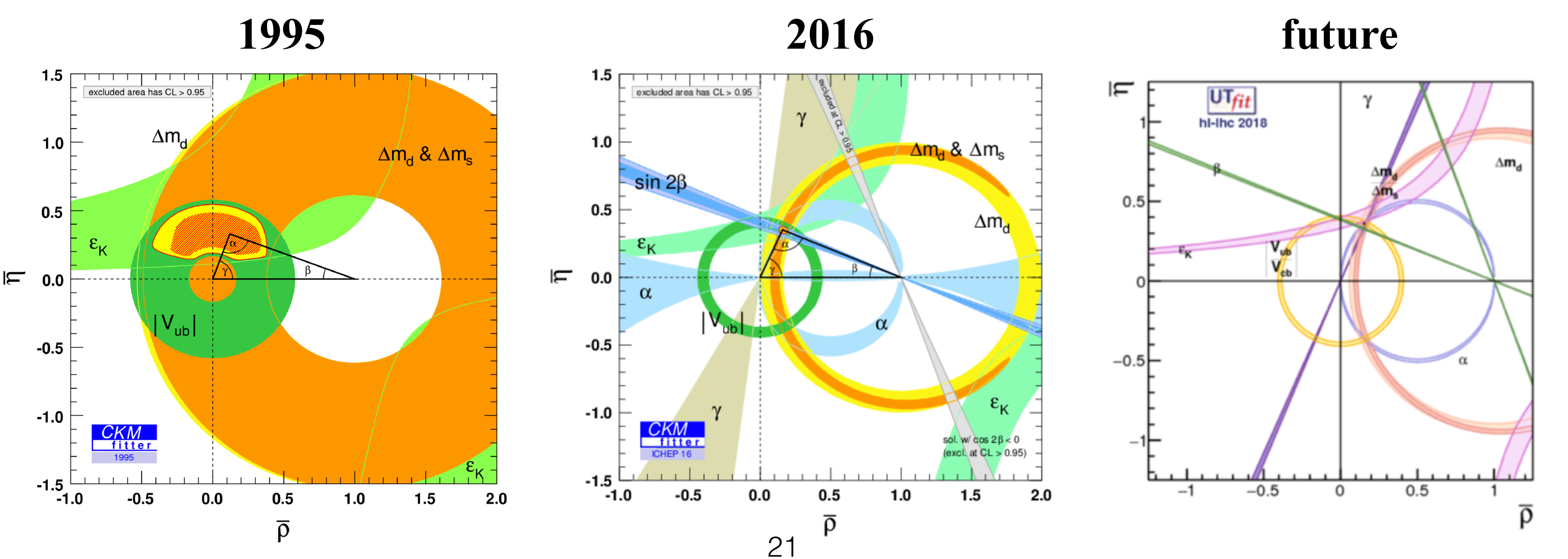
Conclusion

➢ LHCb has a **wide range of physics programs** and has already made many important contributions to answer fundamental questions

➢ Many particles have been discovered in LHCb and more will come

➢ While continuing to understand QCD, efforts from LHCb China group will also be on CKM physics

➢ **Unitarity test** shows results which are consistent with SM now, but **20% new physics** still allowed



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➢ LHCb has a **wide range of physics programs** and has already made many important contributions to answer fundamental questions

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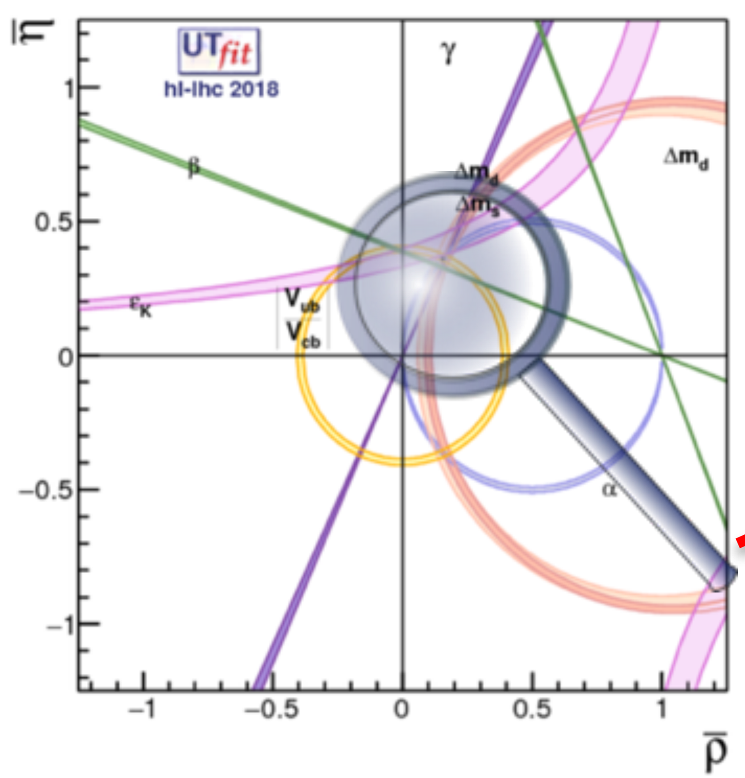
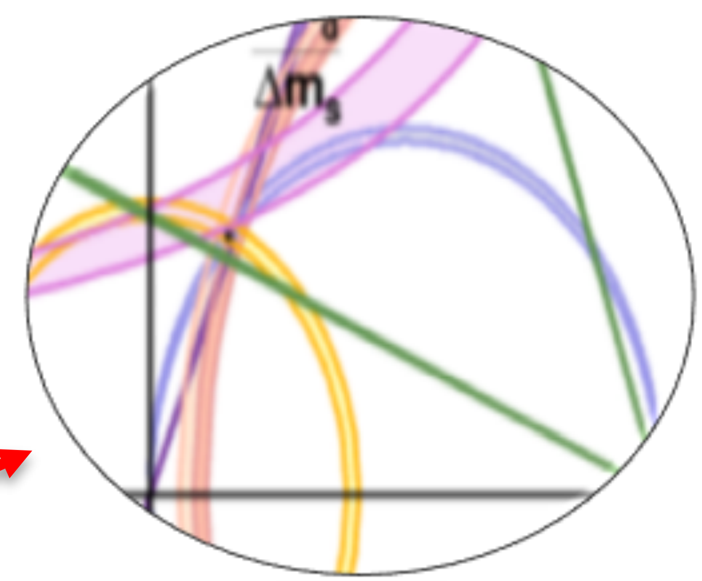




A lesson from discovery of CPV:
New physics normally hide in next decimal point

CPV and CKM matrix

➢ In SM, CPV offered through a single weak phase in the CKM matrix

$$V_{\rm CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

$s_{12} = \lambda$ **~ 0.23 (13°)** $s_{23} = A\lambda^2$ **~ 0.042 (2.4°)**

$s_{13}e^{i\delta} = V_{ub}^* = A\lambda^3(\rho + i\eta)$ **~ 0.0037 (0.2°) × exp(i 65.4°)**

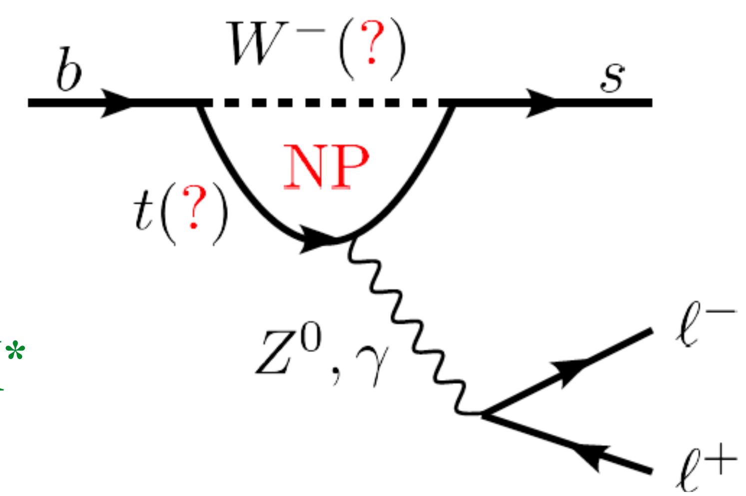
➢ **Successful model which explains all the current experiment measurements except matter-antimatter asymmetry observed in the Universe**

➢ **Unitarity test of CKM triangle offers a nice platform to combine all the efforts from different measurements**

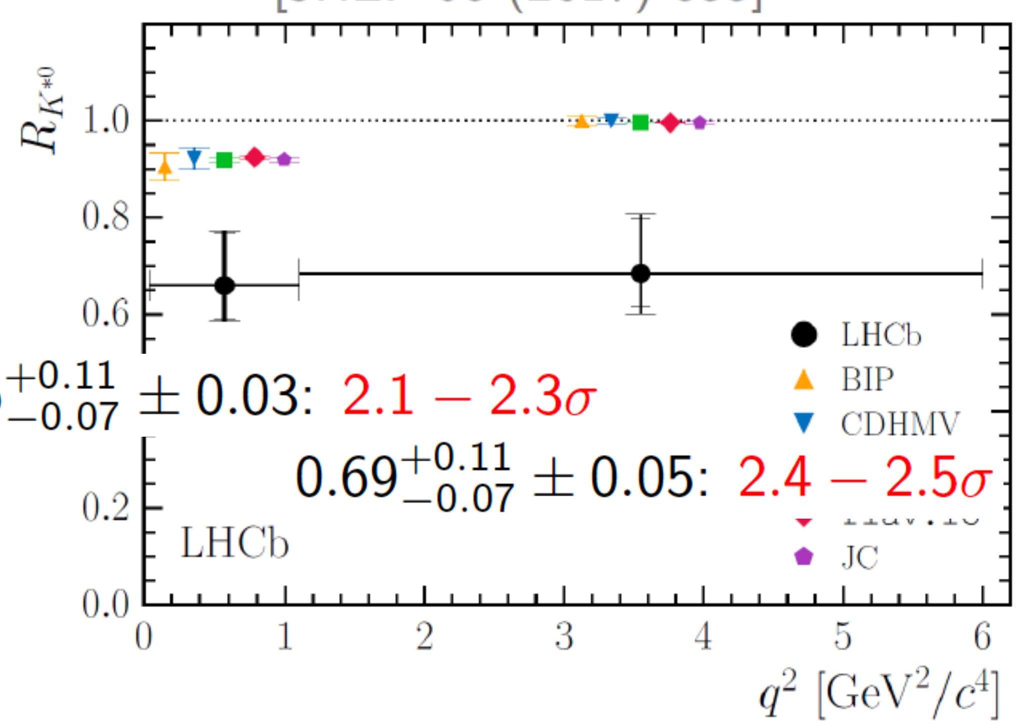
R(K) and R(K*)

➢ **Another LFU tests of μ and e are also of great interests**

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^-\mu^+)}{\mathcal{B}(B \to K^{(*)}e^-e^+)}$$

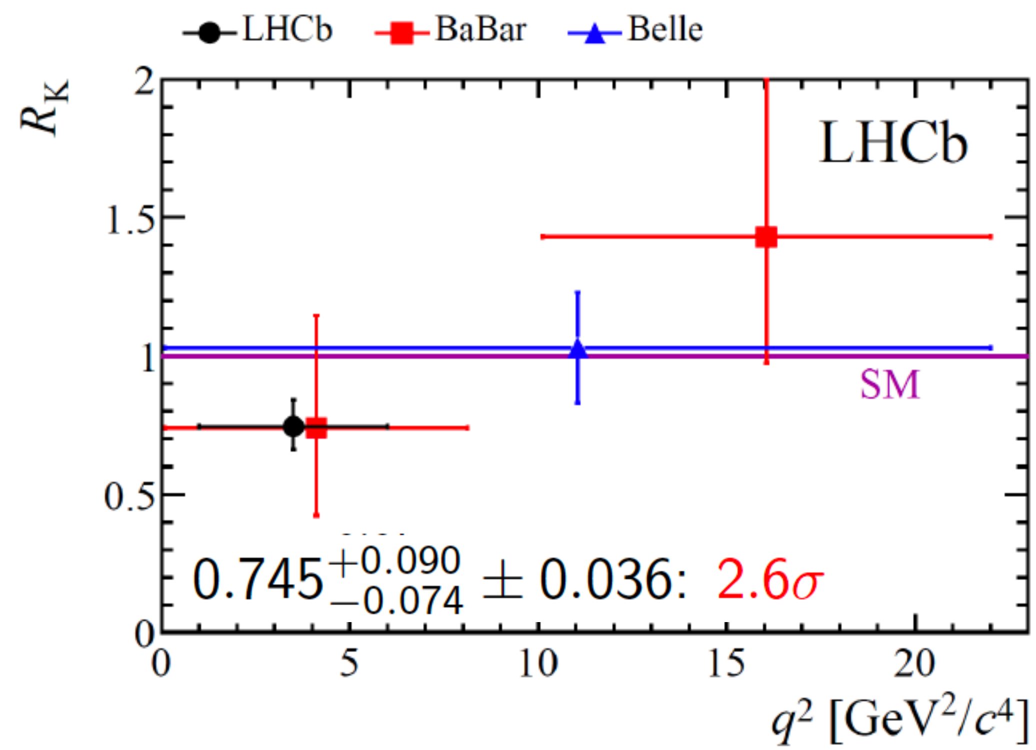


SM: 1.000 ± 0.001 for K and 0.991± 0.002 for K*



$0.66^{+0.11}_{-0.07} \pm 0.03$: $2.1 - 2.3\sigma$

$0.69^{+0.11}_{-0.07} \pm 0.05$: $2.4 - 2.5\sigma$



$0.745^{+0.090}_{-0.074} \pm 0.036$: 2.6σ

- BIP [EPJC 76 (2016) 440]
- CDHMV [JHEP 04 (2017) 016]
- EOS [PRD 95 (2017) 035029]
- flav.io [EPJC 77 (2017) 377]
- JC [PRD 93 (2016) 014028]

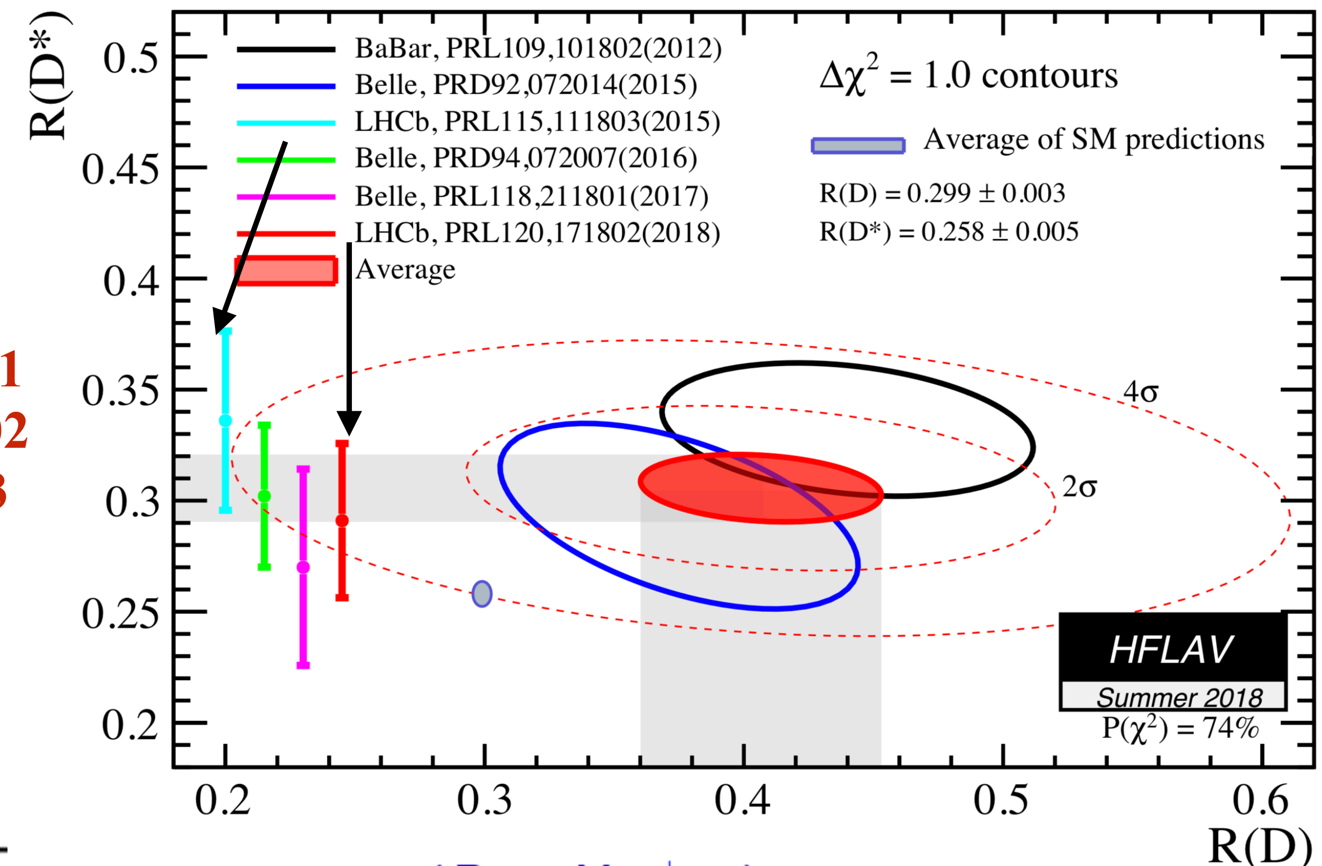
- LHCb [PRL 113 (2014) 151601]
- Belle [PRL 103 (2009) 171801]
- BaBar [PRD 86 (2012) 032012]

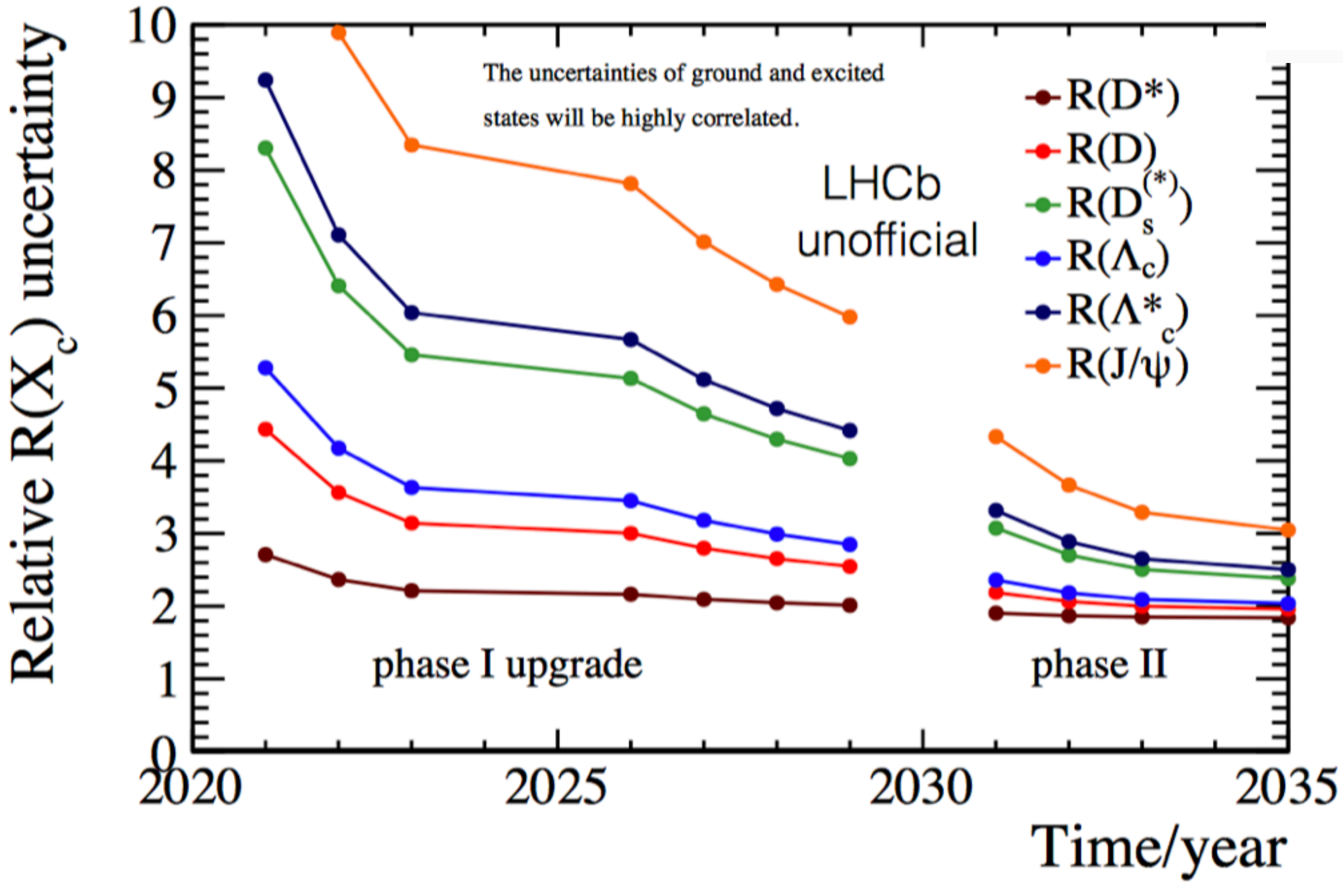
R(D), R(D*) and R(J/ψ)

➢ **Lepton flavor universality test becomes a hot topic after many deviations seen from B-factories and LHCb measurements**

PRL 115 (2015) 112001
PRL 120 (2018) 171802
PRD 97 (2018) 072013

➢ **LHCb has performed $R(D^*)$ in muonic channel in 2015 and now also in hadronic channel**





$$R(X_c) = \frac{\mathcal{B}(B \to X_c \tau^+ \nu_\tau)}{\mathcal{B}(B \to X_c \mu^+ \nu_\mu)}, \quad X_c = D^* \text{ or } J/\psi$$

➢ **Besides measurements in B_c system have also been measured**

PRL 120 (2018) 121801

➢ **Assumes that all the systematic uncertainties scale w.r.t. statistic except those can't or reply on external inputs**

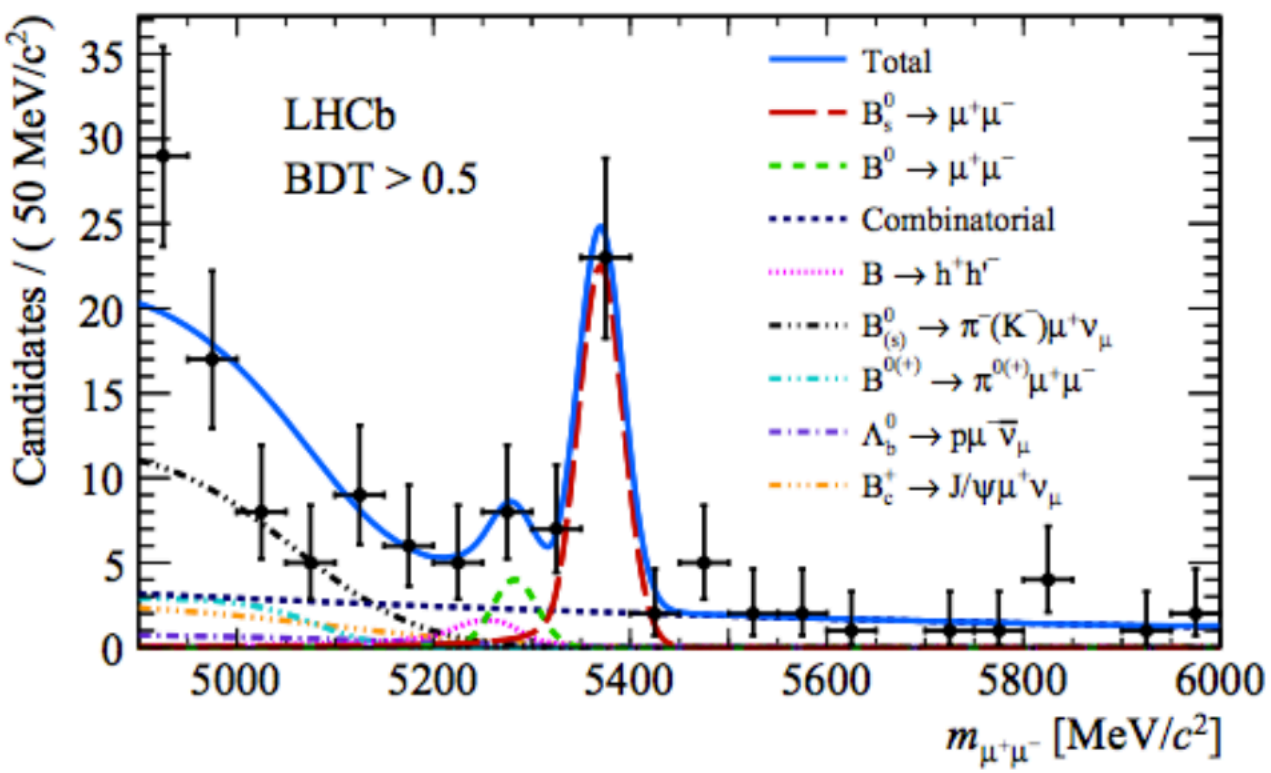
Summary of prospects

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x\sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

$B_{(s)} \to \mu\mu$

- Highly suppressed FCNC mode, sensitive to new physics



$$BF_{SM}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

$$BF_{SM}(B_s^0 \to \mu^+\mu^-) = (3.60 \pm 0.18) \times 10^{-9}$$

Bobeth et al. [PRL 112(2014)101801]

Altmannshofer et al. [arXiv:1702.05498]

- First single experiment observation by LHCb (4.4 fb^{-1})

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+0.7}_{-0.6}) \times 10^{-9} \ (S = 7.8\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at 95\% CL}$$

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

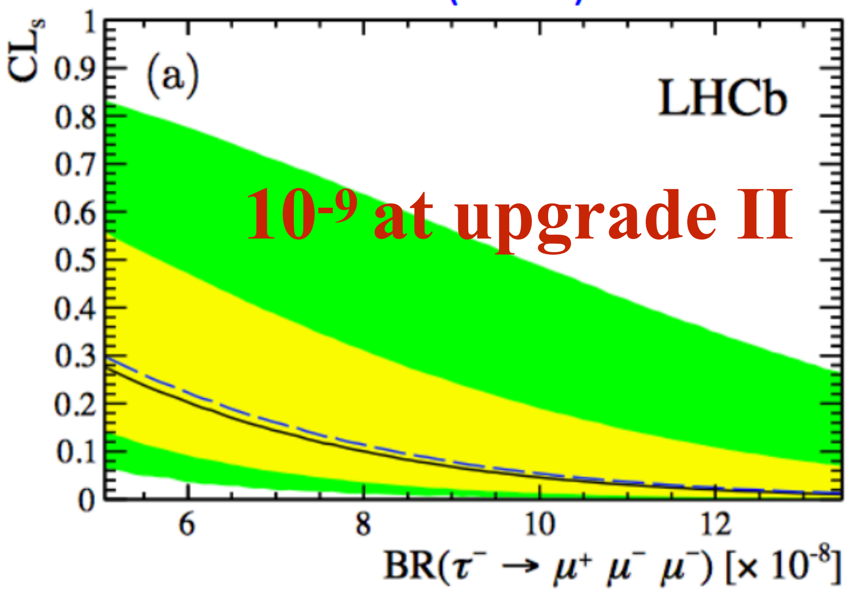
- Yet consistent with SM

- In upgrade II, we may expect 10% precision on the ratio between two modes and 0.03 ps on effective lifetime
- CPV will also be interesting

Other rare decays

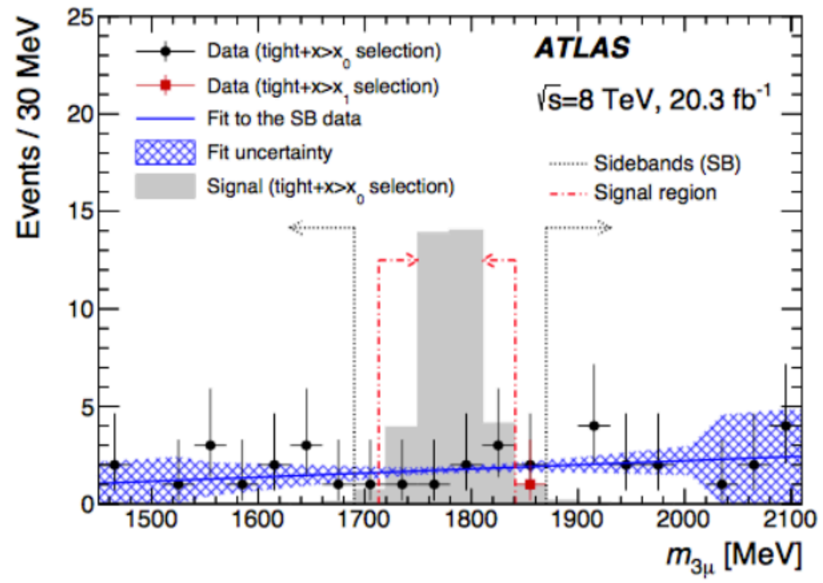
- ➢ **Statistics is the name of the game;**
- ➢ **Sensitivity scaled according to 1/√N**

JHEP 02 (2015) 121



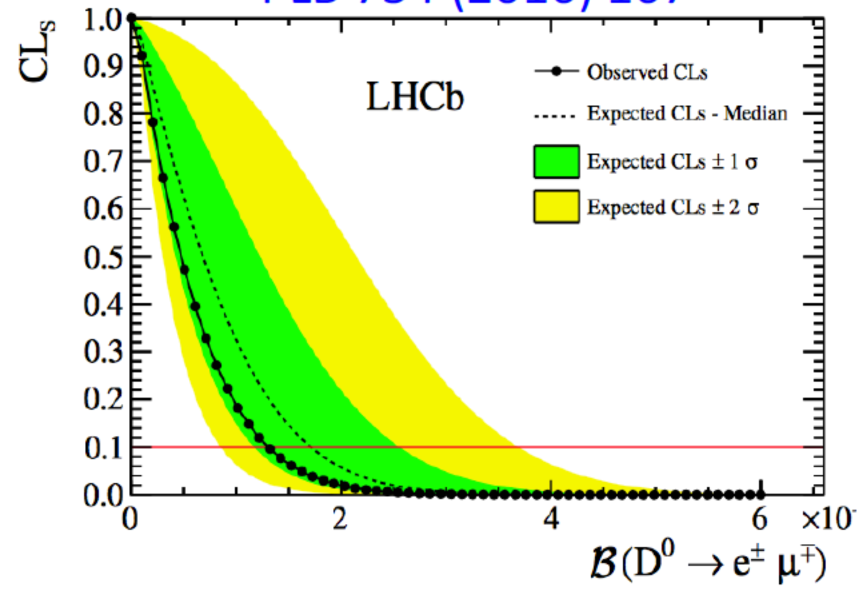
$\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-) < 4.6\ (5.6) \times 10^{-8}$

EPJC 76 (2016) 232



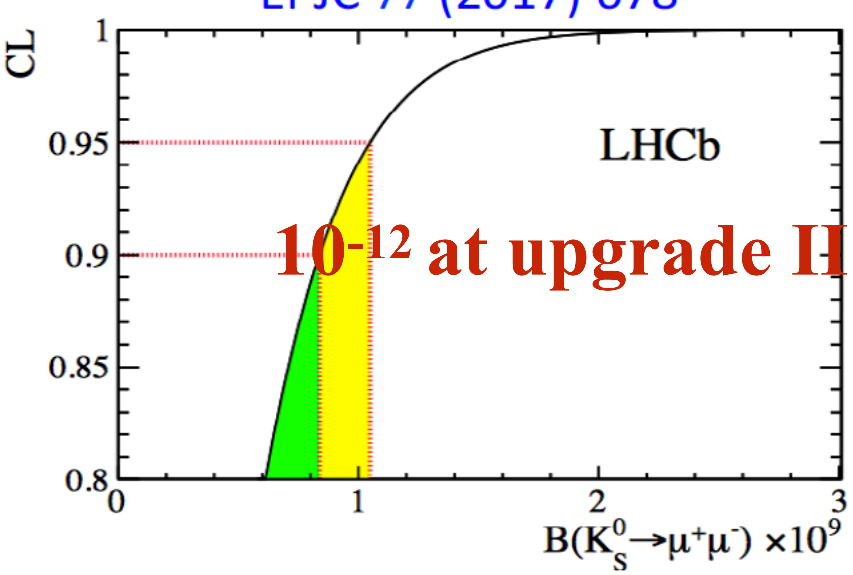
$\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-) < 3.76 \times 10^{-7}$

PLB 754 (2016) 167



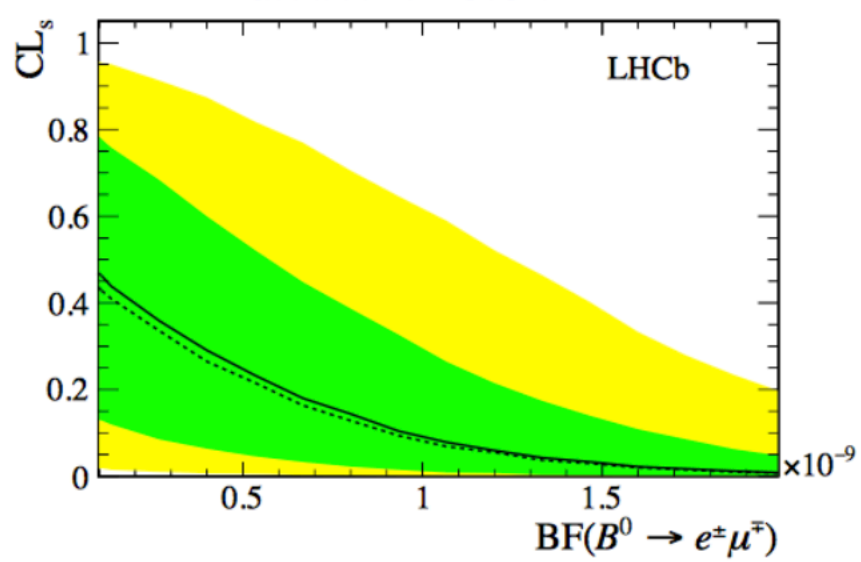
$\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.3(1.6) \times 10^{-8}$

EPJC 77 (2017) 678



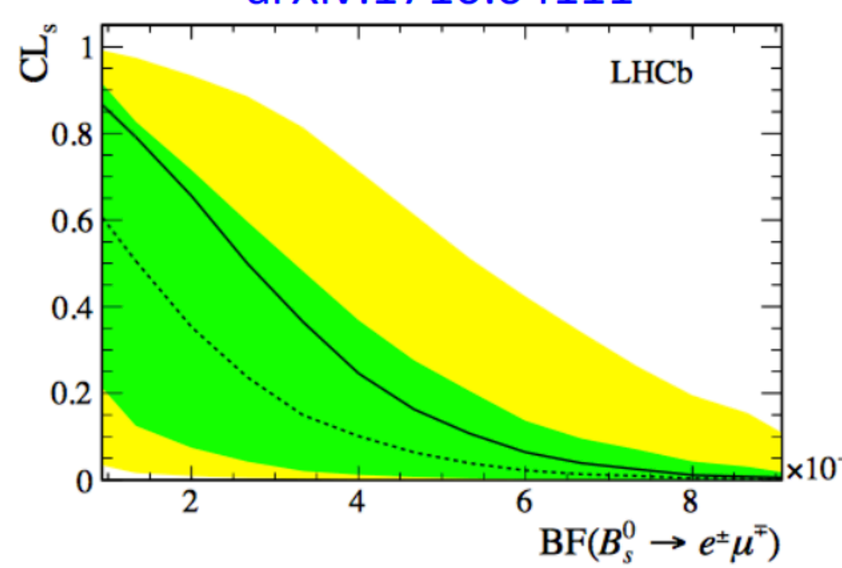
$\mathcal{B}(K^0_S \to \mu^+ \mu^-) < 0.8\ (1.0) \times 10^{-9}$

arXiv:1710.04111



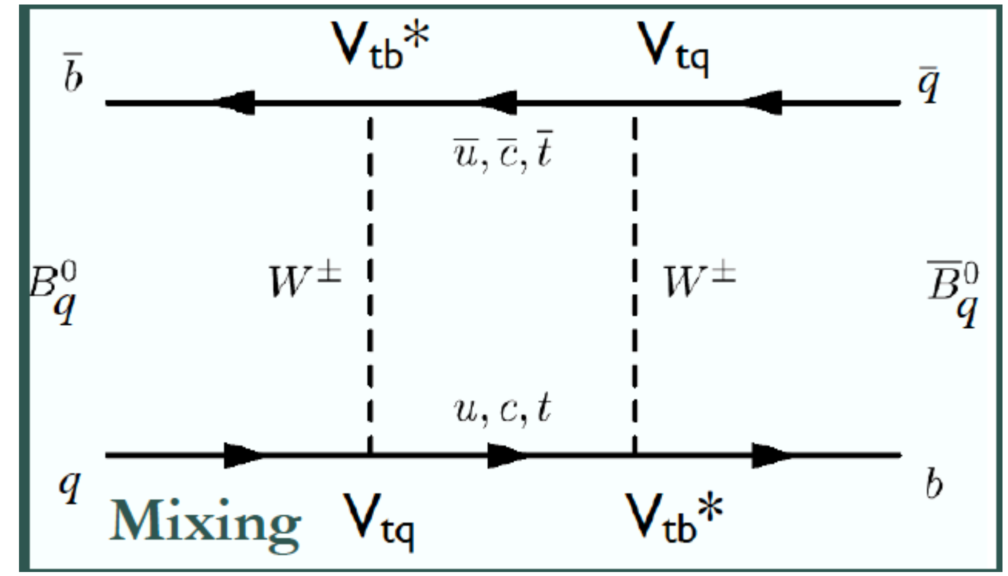
$\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 1.0\ (1.3) \times 10^{-9}$

arXiv:1710.04111



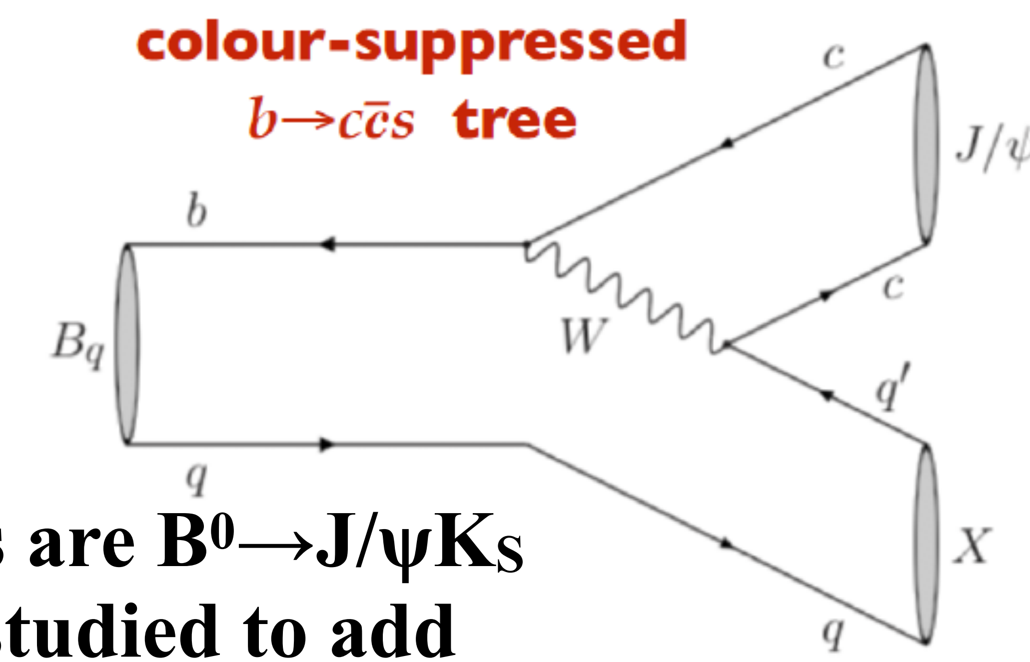
$\mathcal{B}(B^0_s \to e^\pm \mu^\mp) < 5.4\ (6.3) \times 10^{-9}$

β, βs



- β is the phase of V_{td}^* and β_s is the phase of V_{ts}^* and thus is accessed through loop diagrams, i.e. through mixing

- The processes are $b \rightarrow c\bar{c}s$ tree level dominated decay where penguin pollution is small (still need to know for precise measurements)



- Predictions from CKMfitter group gives:

$$2\beta^{\rm SM} = (47.48^{+2.26}_{-1.96})^{\circ}$$
$$2\beta_s^{\rm SM} = (2.122 \pm 0.037)^{\circ}$$

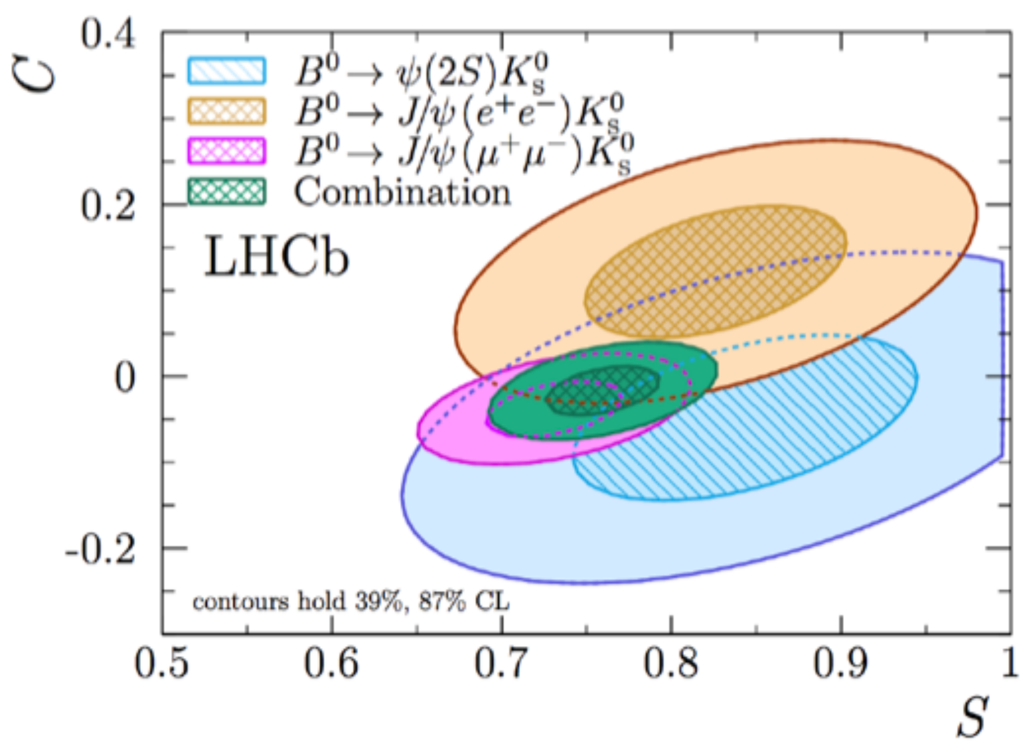
- Golden channels for the two measurements are $B^0 \rightarrow J/\psi K_S$ and $B_S \rightarrow J/\psi\phi$, while other channels are also studied to add further sensitivities to the two angles

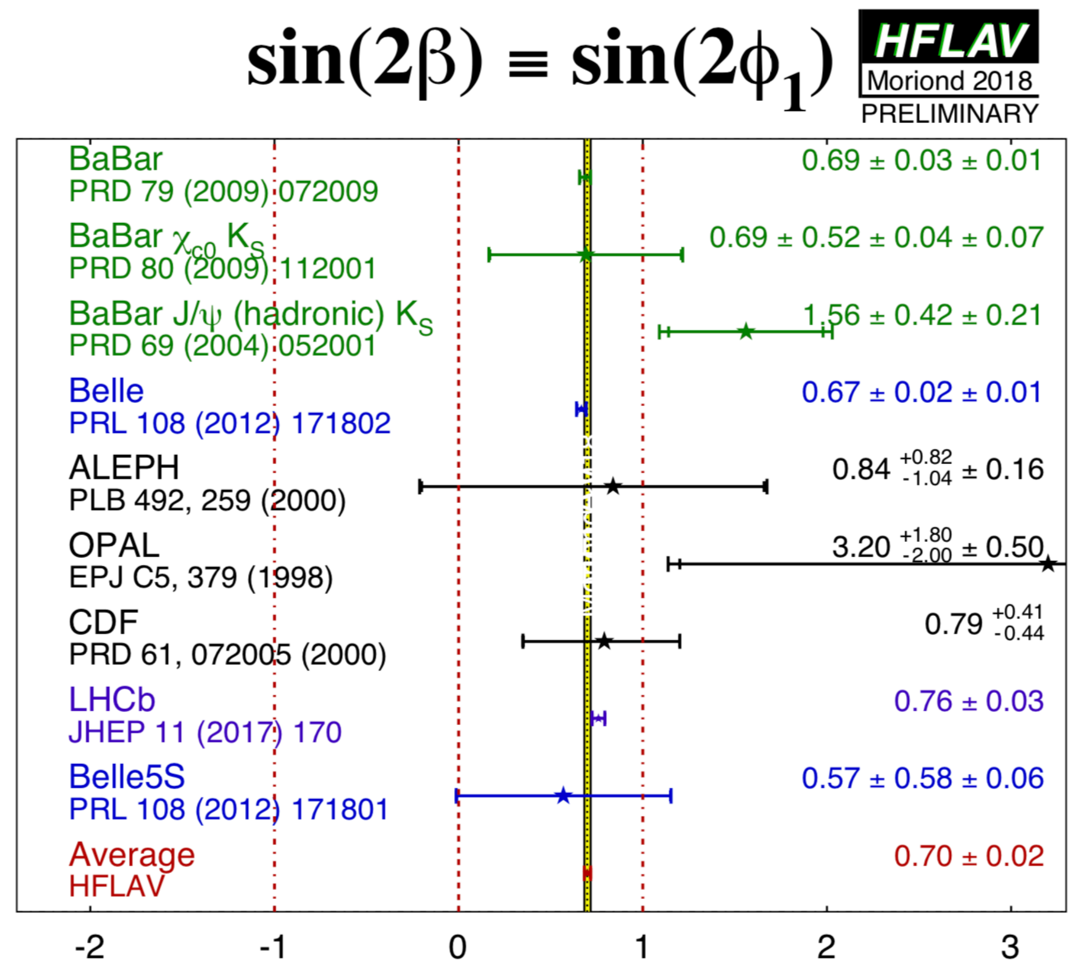
- Channels where penguin contributions are important are also studied for comparison to search for new physics, i.e. $B_S \rightarrow \phi\phi$, $B_S \rightarrow K^* \overline{K}^*$

sin2β

- ➢ **With Run 1 data, LHCb has a similar precision as B-factories**

$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$
$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$





- ➢ **Additional modes to golden channel ($B^0 \to J/\psi K_S$) add 15% more sensitivities**

- ➢ **Future expectations:**

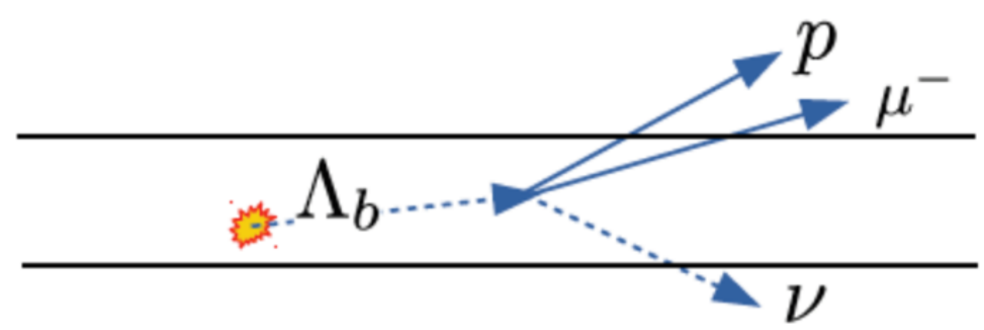
Run 1	Run 2	Upgrade I	Upgrade II
0.034	0.017	0.004	0.002

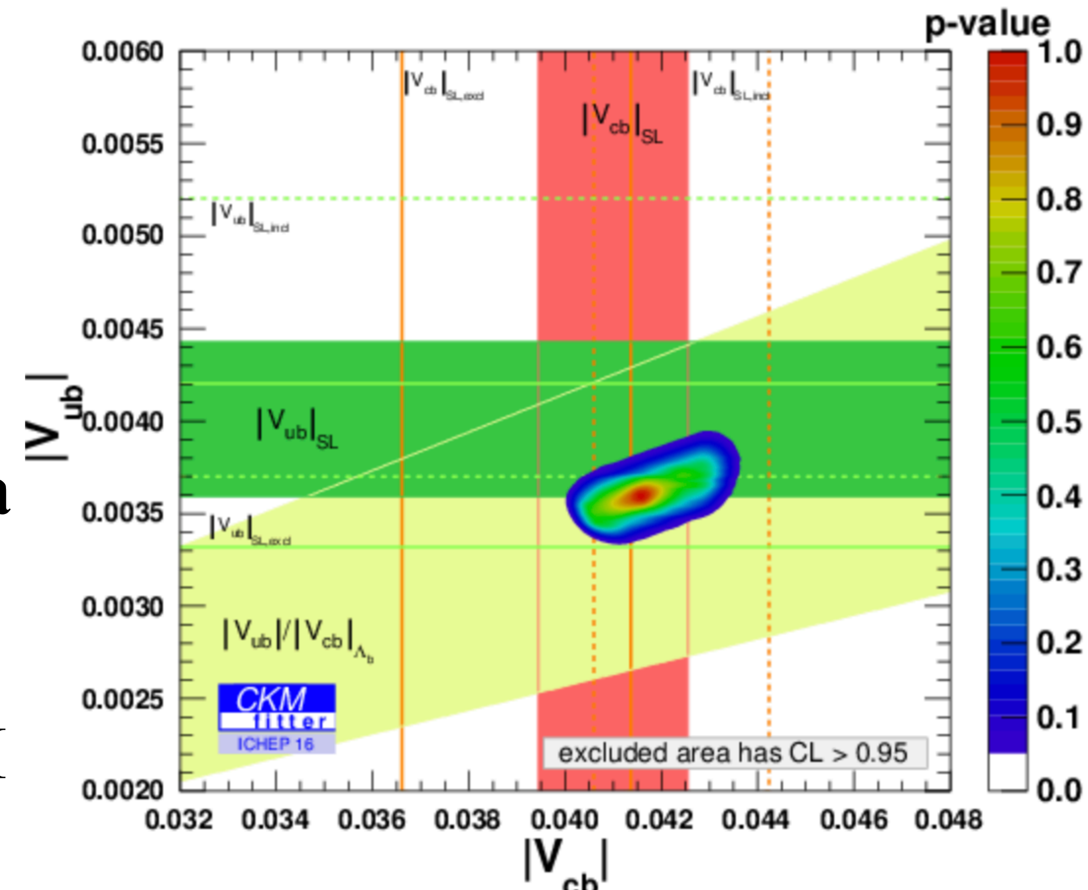
- ➢ **Upgrade statistics also gives sensitivity to the non-zero $\Delta\Gamma_d$ predicted in SM**

$|V_{ub}/V_{cb}|$ and α

Nature Phys. 11 (2015) 743-747

➢ **LHCb has proved the ability to do $|V_{ub}|/|V_{cb}|$ measurement at hadron collider**





➢ **Similar measurements can also be done via SL decays of Bs, Bc**

➢ **Future sensitivity will be driven by Belle II**

➢ **LHCb has limited access to CKM angle α, extracted using $B \to \pi\pi$, $\rho\pi$, $\rho\rho$; though LHCb has good sensitivity to $B^0 \to \pi^+\pi^-$, $B^0 \to \rho^0\rho^0$; sensitivity driven by inputs from B-factories**

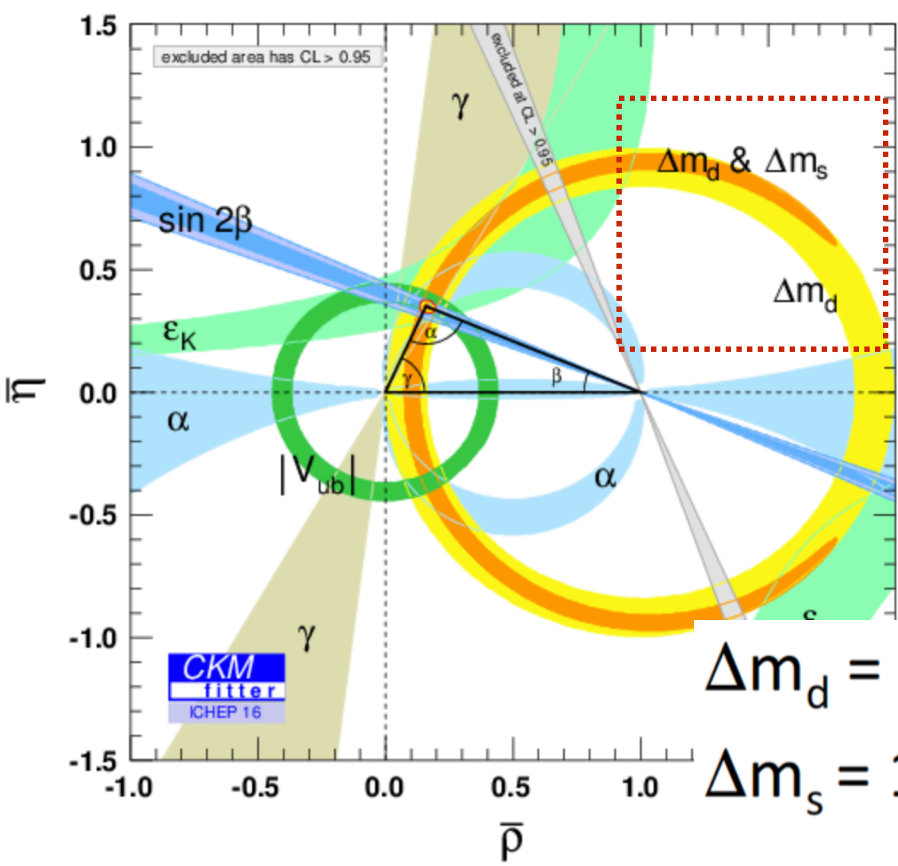
LHCb-PAPER-2018-025

➢ **A recent TD measurements on $B^0 \to \pi^+\pi^-$ and $B_S \to K^+K^-$ with 3 fb^{-1} data**

➢ **Hopefully we can do more with better calorimeter in upgrade**

Δm_d and Δm_s

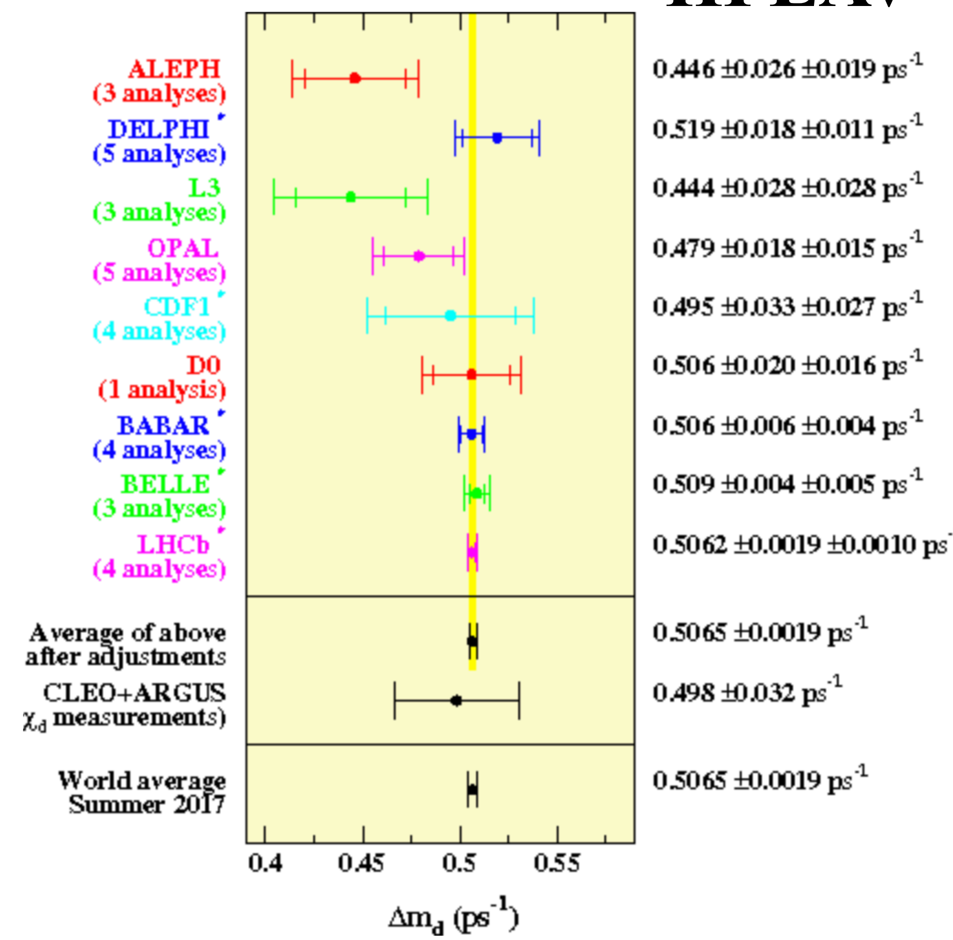
➢ **Combinations of oscillation frequency Δm_d and Δm_s are dominated by LHCb and may continue to be dominated by LHCb**



$\Delta m_d = 0.5065 \pm 0.0019\ \mathrm{ps}^{-1}$

$\Delta m_s = 17.757 \pm 0.021\ \mathrm{ps}^{-1}$

HFLAV



➢ **However, interpreting are limited by Lattice inputs**

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2\ \eta_c S(x_t)\ A^2\lambda^6\ [(1-\bar{\rho})^2+\bar{\eta}^2]\ m_{B_d} f_{B_d}^2 \hat{B}_{B_d}$$

~7%

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left(\frac{\lambda}{1-\frac{\lambda^2}{2}}\right)^2 [(1-\bar{\rho})^2+\bar{\eta}^2]$$

~4%

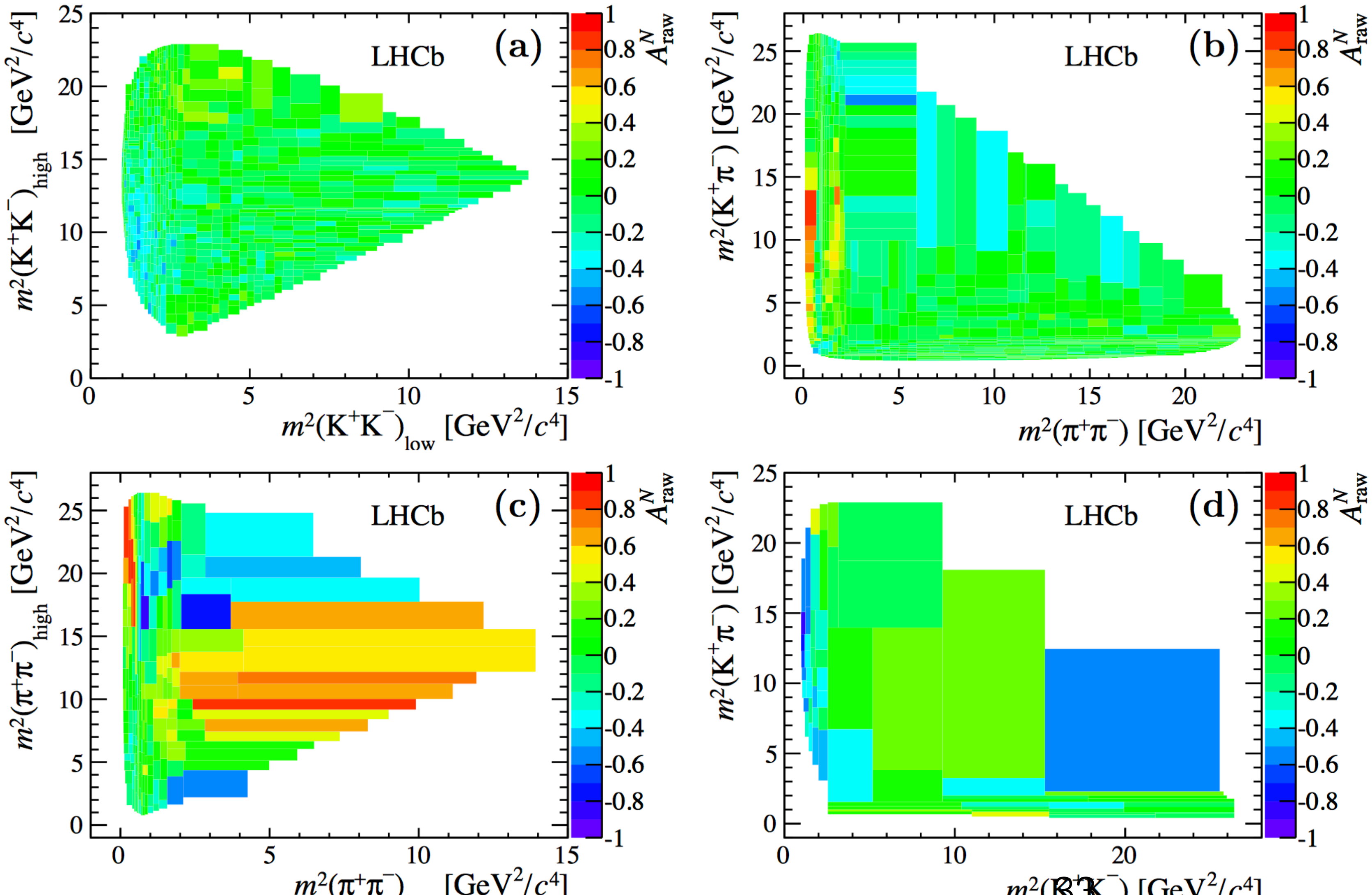
Efforts from Lattice community needed to further reduce uncertainty by a factor of 10 more

Three-body Charmless b decays

- Two-body charmless b decays have been used to extract CKM angles through complicated analyses while three-body charmless b decays contains more information over Dalitz plot and may have better sensitivities

- From experimental side, efforts have been made to give more information on the pattern through Dalitz plot analyses

PRD 90, 112004 (2014)



- Clearly also need theoretical efforts to give methods to extract angles precisely

- Some efforts have been made, but clearly not enough, for example, a very recent paper to predict CPV in B→f2(1270)π

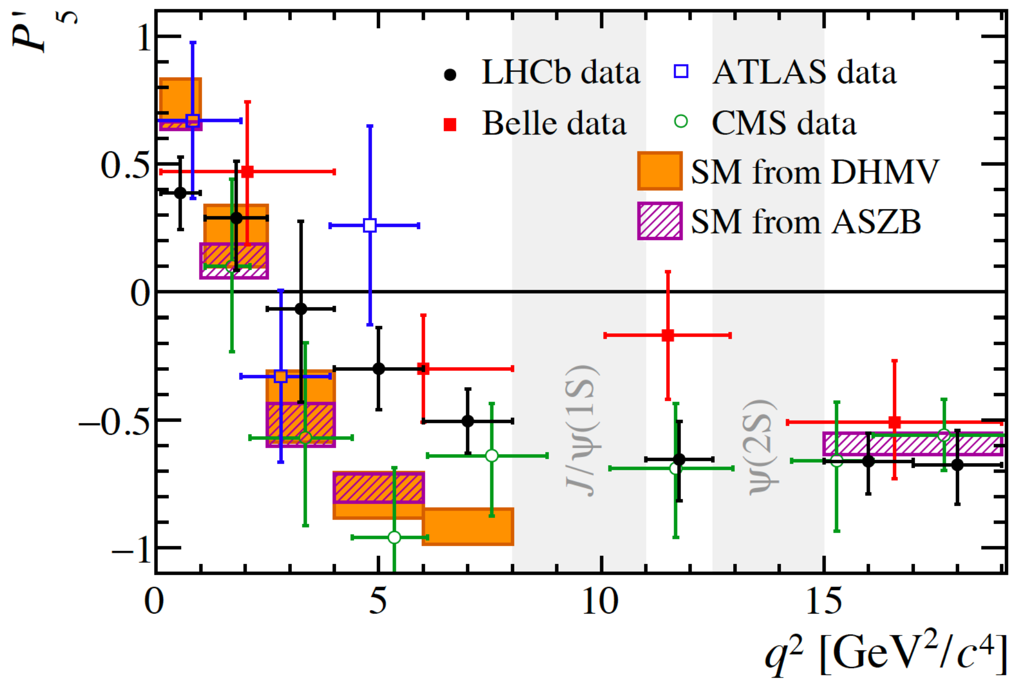
arXiv:1807.02641

Rare decays and Anomalies

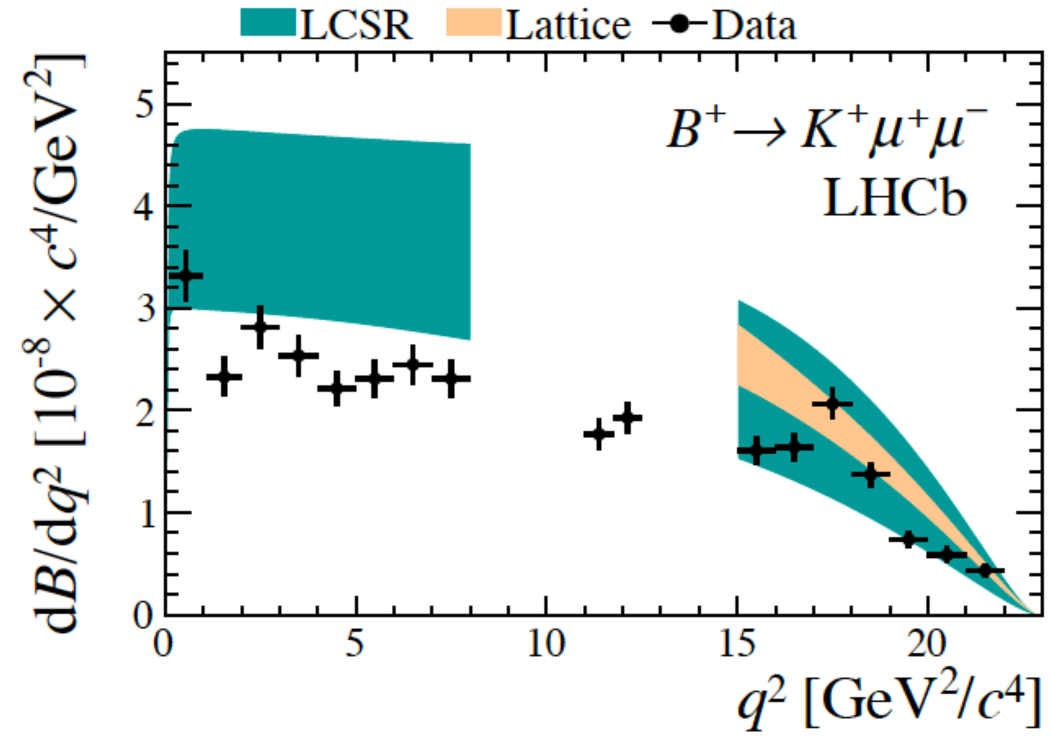
Anomalies

➢ **Anomalies seen in many b-decay processes (b→sll, b→clν)**

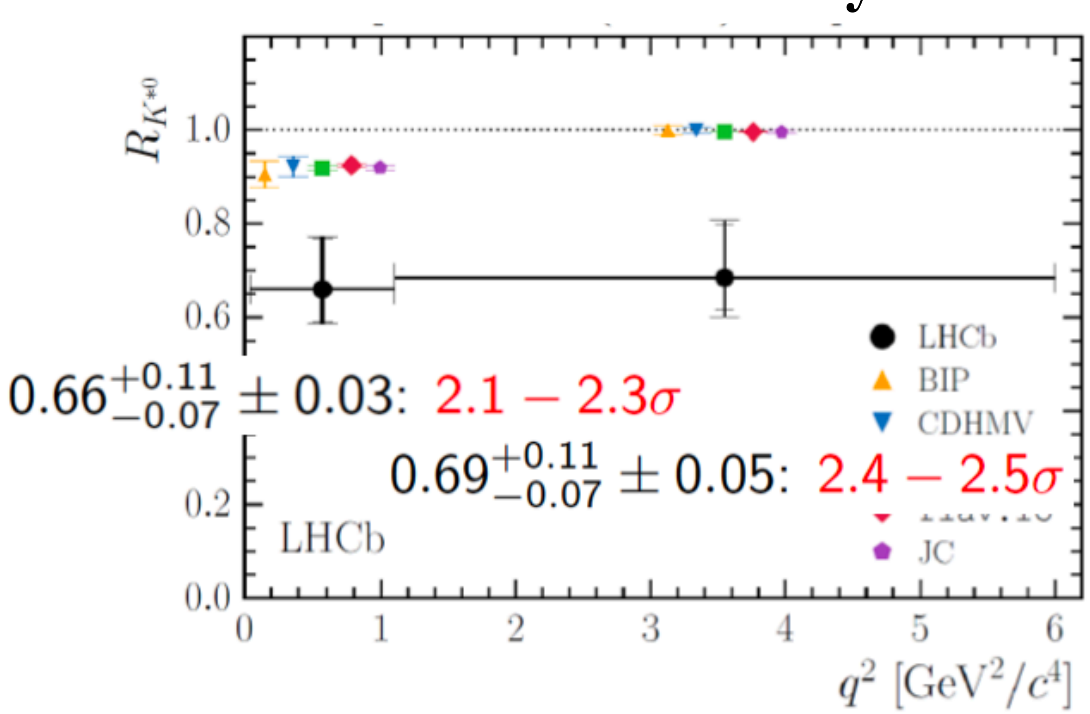
Angular observables of $B^0 \to K^* \mu\mu$



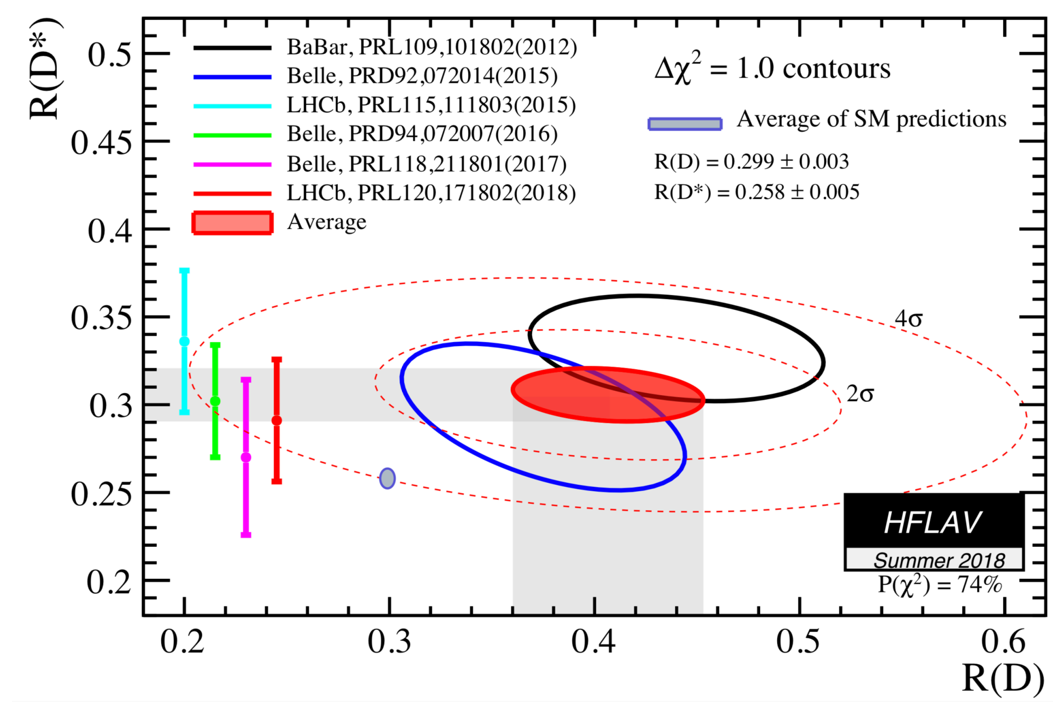
BF of many b→sll processes



LFU in b→sll decays



LFU in b→clν decays



JHEP 09 (2018) 146

New results in the sector

- Angular moments in $\Lambda_b \to \Lambda \mu\mu$ with Run 1+2 data (5 fb^{-1})

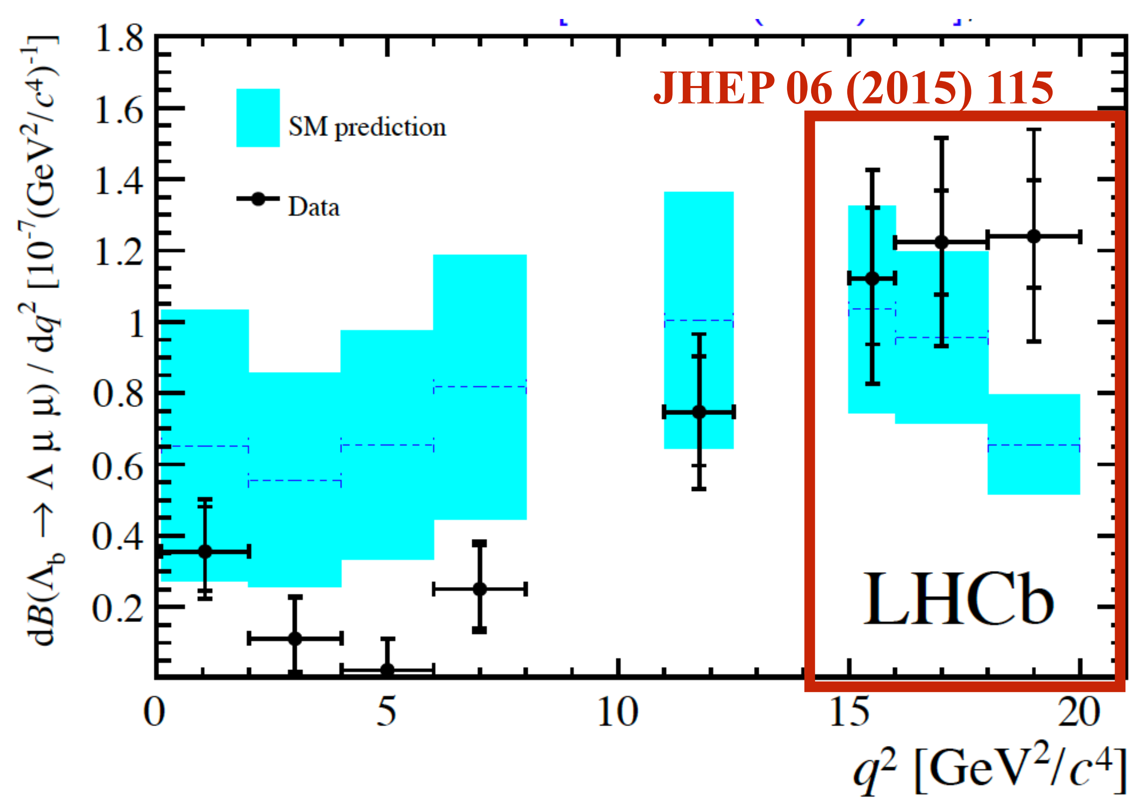
Looking in the region of low hadronic recoil

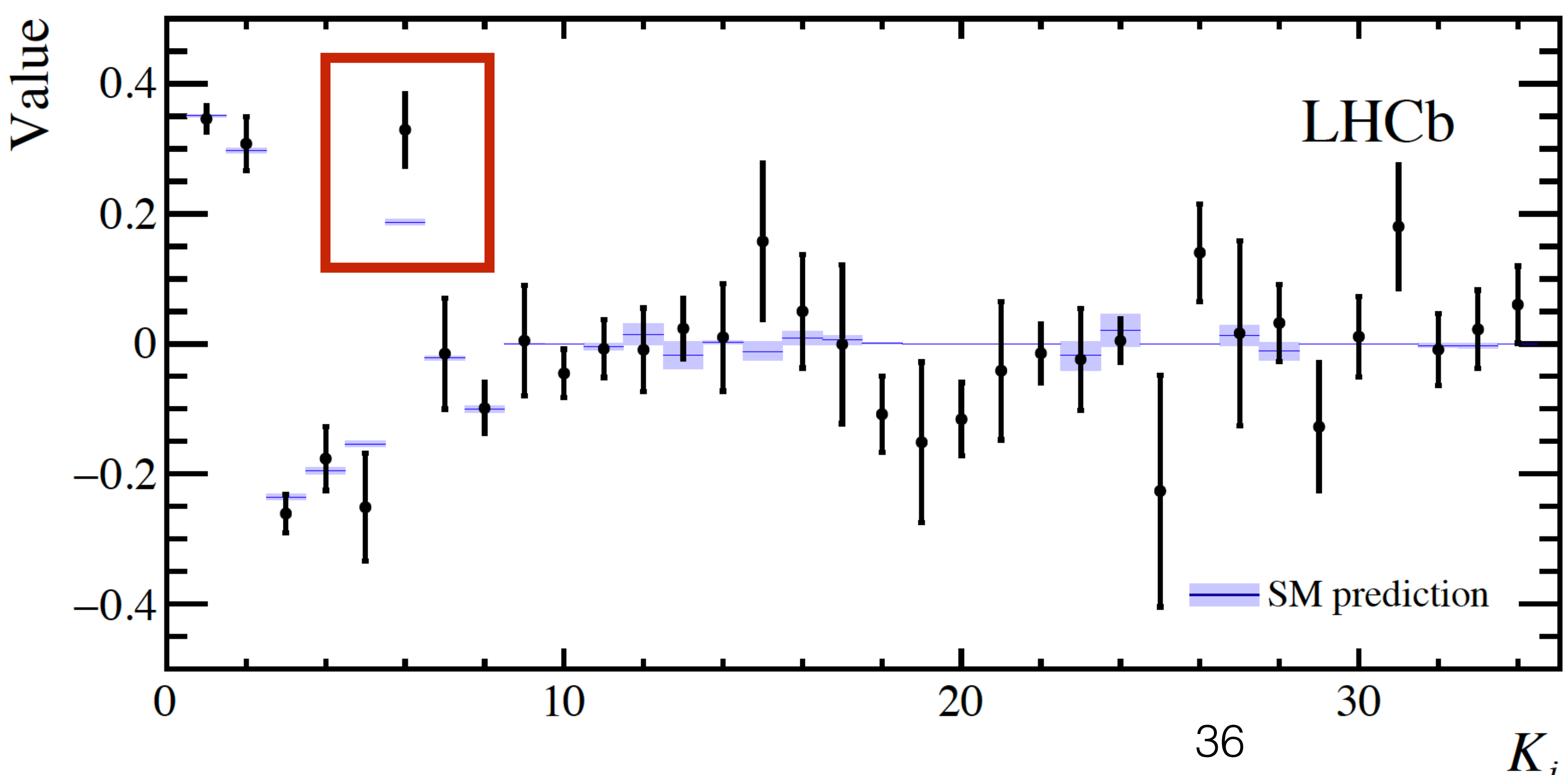
Around 300 (Run 1) + 300 (Run 2) events

Full angular analysis with 34 terms

$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2} \sum_i^{34} K_i f_i(\vec{\Omega}) \ ,$$

Consistent with SM





Can be combined to FB asymmetry:

$$A^{\ell}_{FB} = \tfrac{3}{2} K_3 = -0.39 \pm 0.04 \pm 0.01 \ ,$$
$$A^{h}_{FB} = K_4 + \tfrac{1}{2} K_5 = -0.30 \pm 0.05 \pm 0.02 \ ,$$
$$A^{\ell h}_{FB} = \tfrac{3}{4} K_6 = +0.25 \pm 0.04 \pm 0.01 \ ,$$

Small deviation for A^{lh}_{FB}