Recent CP violation results at the LHCb experiment

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2021/05/01

南开大学

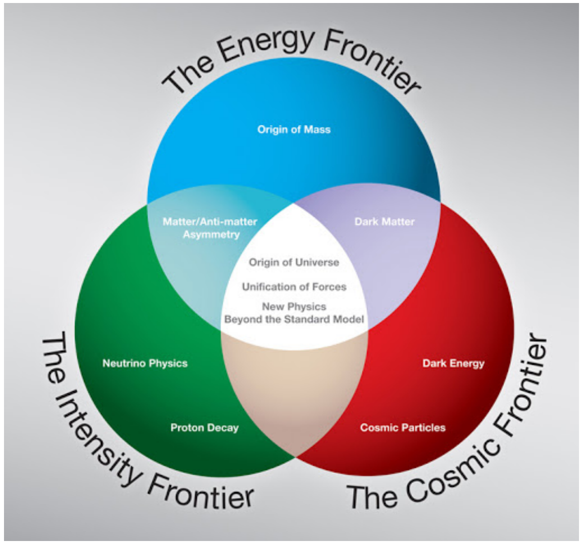
第三届重味物理和量子色动力学研讨会

Outline

- **Introduction**
- **Recent highlights on CKM angle γ measurements**
- **Recent highlights on charmless b decays**
- **A new tool for amplitude analysis**
- **Conclusion**

New Physics search

- All SM particles, including Higgs, have been found;
- However new mechanism needed for DM, matter-antimatter asymmetry, hierarchy problems etc.;
- Two ways to search for New Physics: direct search and indirect search through precision measurements;
- Examples in history: many beyond “current” model New Physics first found through indirect search

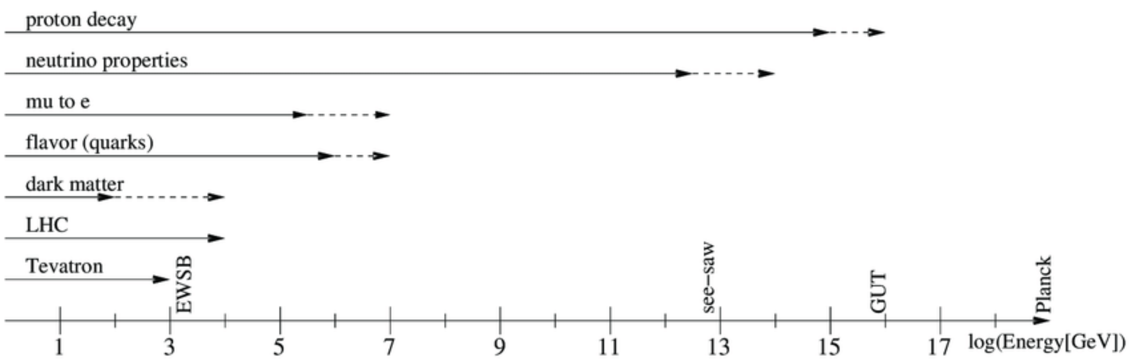


New Physics search at flavor sector

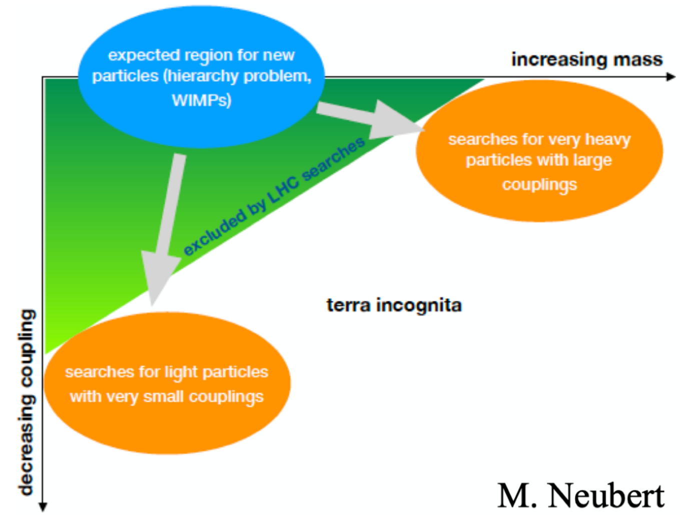
- Sensitive to New Physics scale much higher than direct search: 1-10^4 TeV

Couplings $\mathcal{O}(1)$ to avoid fine tuning

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}).$$



Experimental reach (with significant simplifying assumptions)

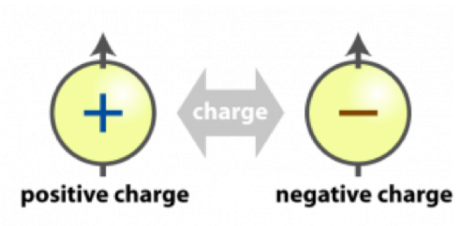


- Also “tasteful”, not only can tell there is New Physics, but also tell properties of New Physics based on flavor it couples to
- Statistics or precision is key for flavor program: New Physics scale, i.e. Dim = 6, proportional to $\sqrt[4]{\text{statistics}}$ or $1/\sqrt{\text{Uncertainty}}$,

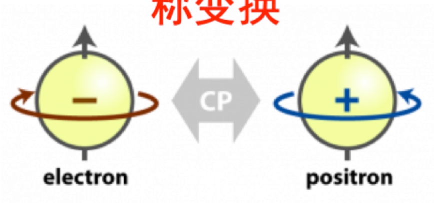
Fundamental questions

- If there are new CPV mechanism needed to explain the large matter-antimatter asymmetry observed in Universe; and what are they?

C:物质—反物质变换



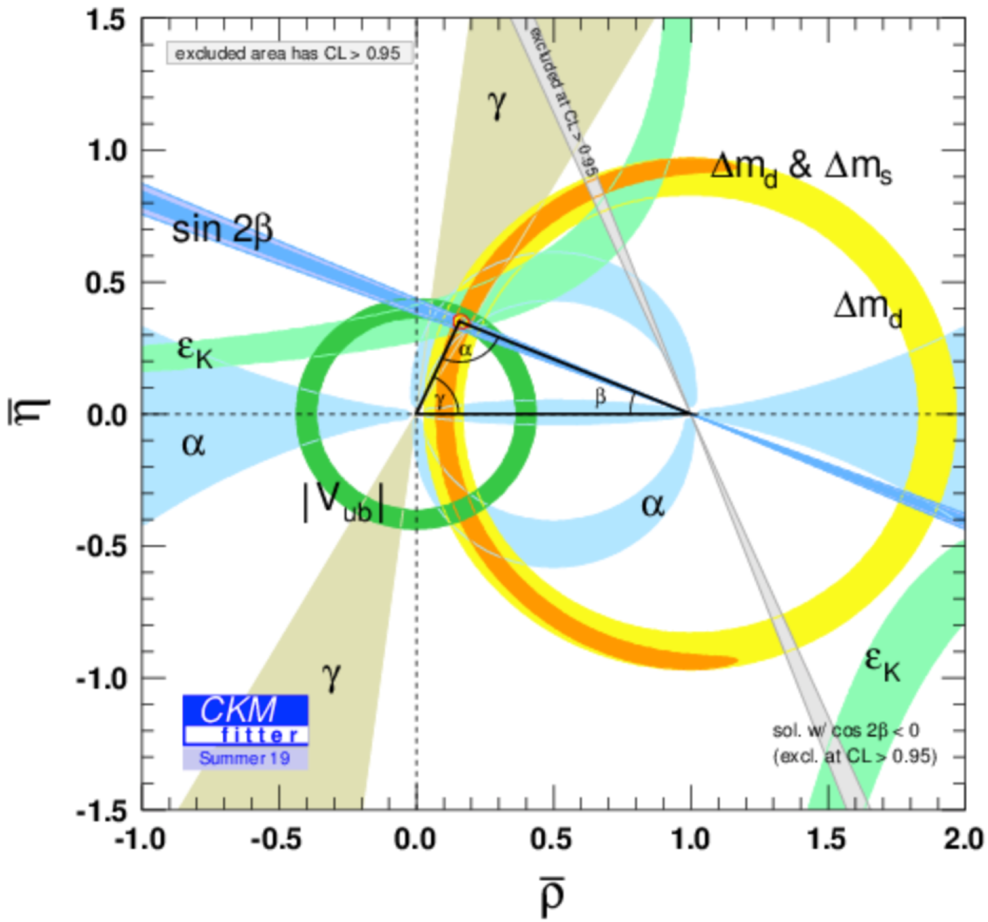
CP：电荷共轭和宇称变换



- If there are New Physics coupling to flavor sector? Their energy scale and properties?

CKM Physics

- SM CPV offered by CKM mechanism; however, orders of magnitude smaller than matter-antimatter asymmetry observed in Universe

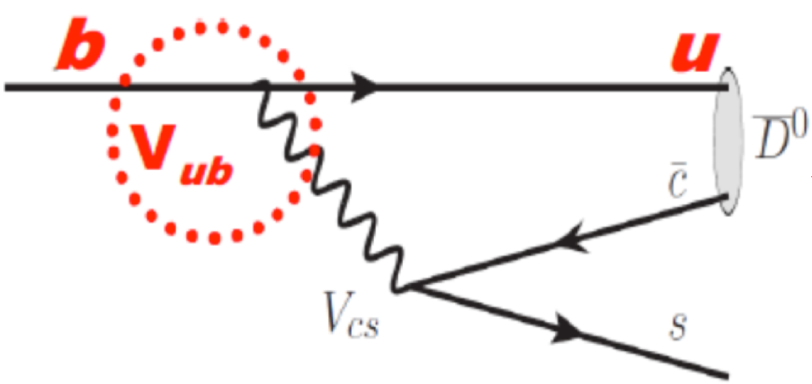


- CKM mechanism can explain what has been observed in current experiments, though still ~20% space for New Physics; More precision needed
- Strategy:
  - SM candle: tree level measurements such as γ, $|V_{ub}|$, $|V_{cb}|$ etc.
  - New Physics search: finding deviations in loop level processes w.r.t SM predictions

Key parameter: angle γ

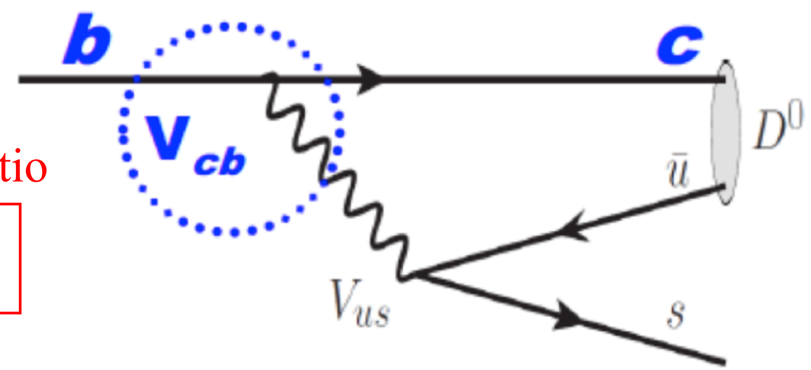
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

- Angle γ is the phase response for CPV in SM, directly related to the triangle of b quarks
- Measured through $b \to u$ and $b \to c$ interference with $B \to D^{(*)} K^{(*)}$ etc., theoretically clean



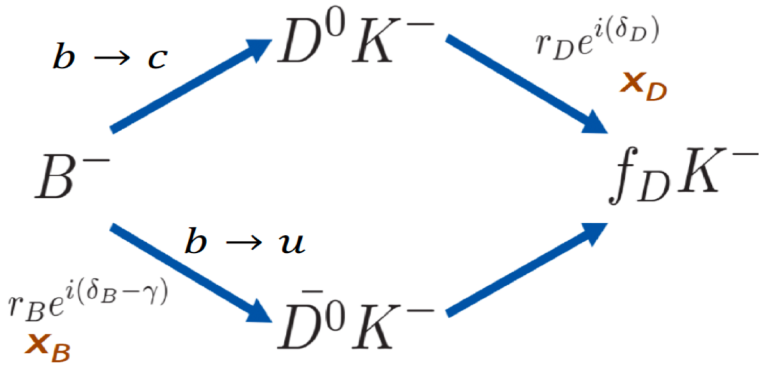
Amplitude ratio

$r_B e^{i\delta_B}$



- Indirect measurements give: $\gamma = \left(65.7^{+1.0}_{-2.5}\right)^\circ$ [CKMFitter19]
- Before LHCb, precision from B-factories around 14°

Probe γ in different methods



D^0 and $\overline{D^0}$ decay to same final states to interference

GLW: D = CP eigenstates, e.g. KK, ππ — PLB 253 (1991) 483; PLB 265 (1991) 172

ADS: D = quasi-flavour-specific states e.g. Kπ — PRL 78 (1997) 3257

GGSZ: D = self-conjugate multi(3)-body states e.g. $K_s\pi\pi$ — PRD 68 (2003) 054018

GLS: ADS variant with singly Cabbibo-suppressed decay $D \to K_s K\pi$ — PRD 67 (2003) 071301

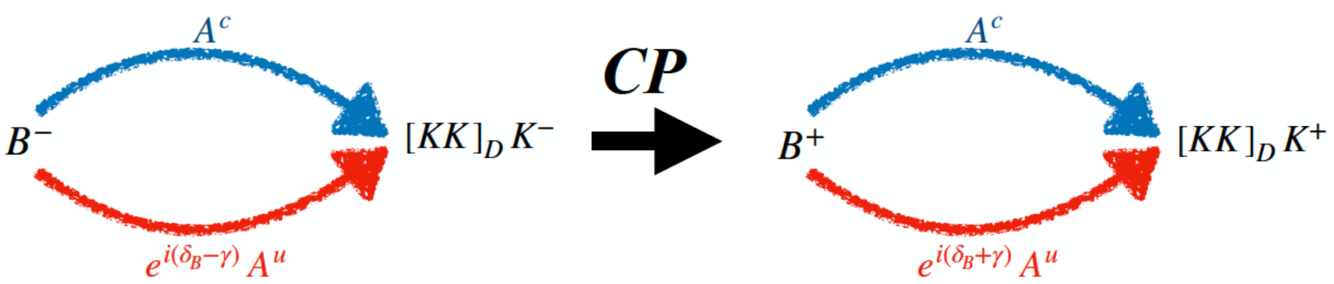
time-dependent $B_s \to D_s K$, $B^0 \to D\pi$ etc — Nucl. phys. B 672 (2003) 459

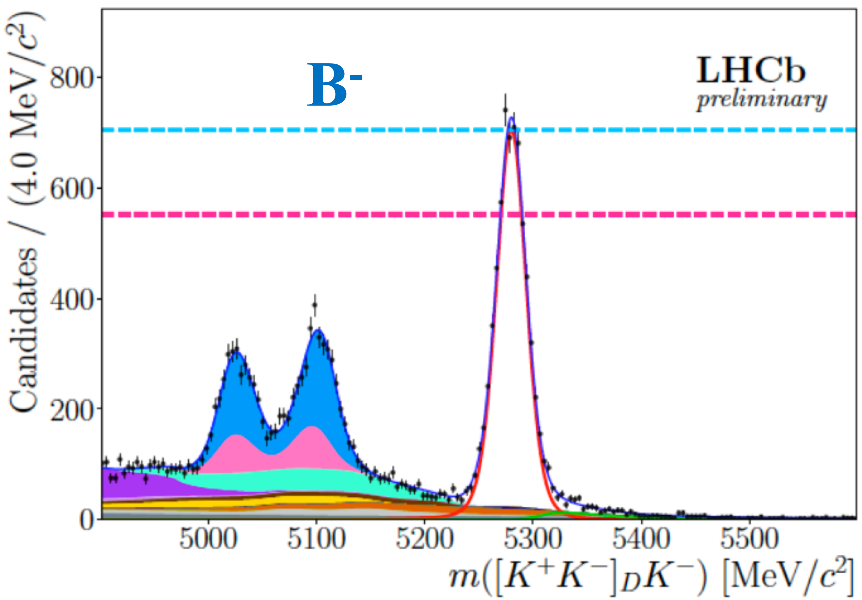
Dalitz (GW) method: $B^0 \to DK\pi$ — PRD 79 (2009) 051301

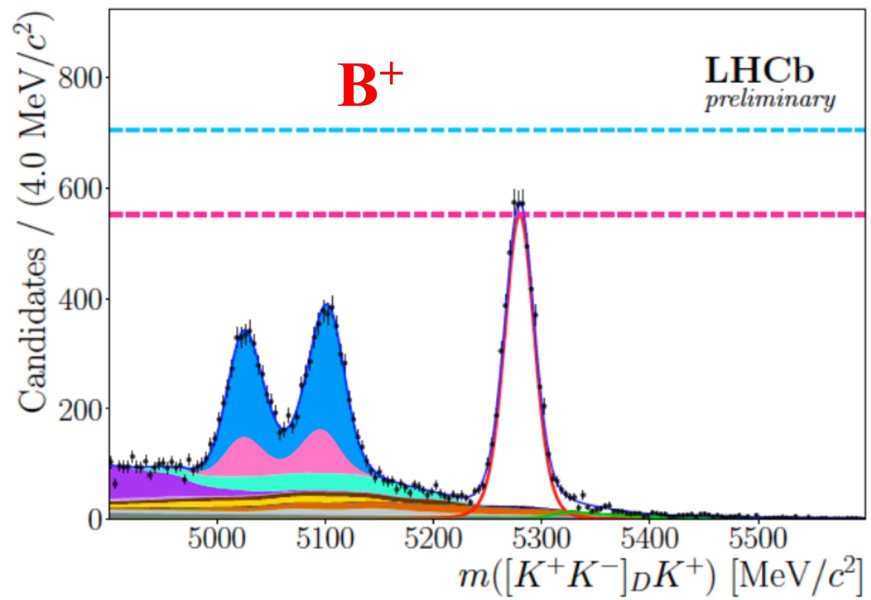
Sensitivities of γ from many channels, important to measure as many as possible

Two-body D decays

- GLW/ADS measurements now performed with full Run1+Run2 data, for $B \to DK, D\pi$ and partially reconstructed $B \to D^*K, D^*\pi$



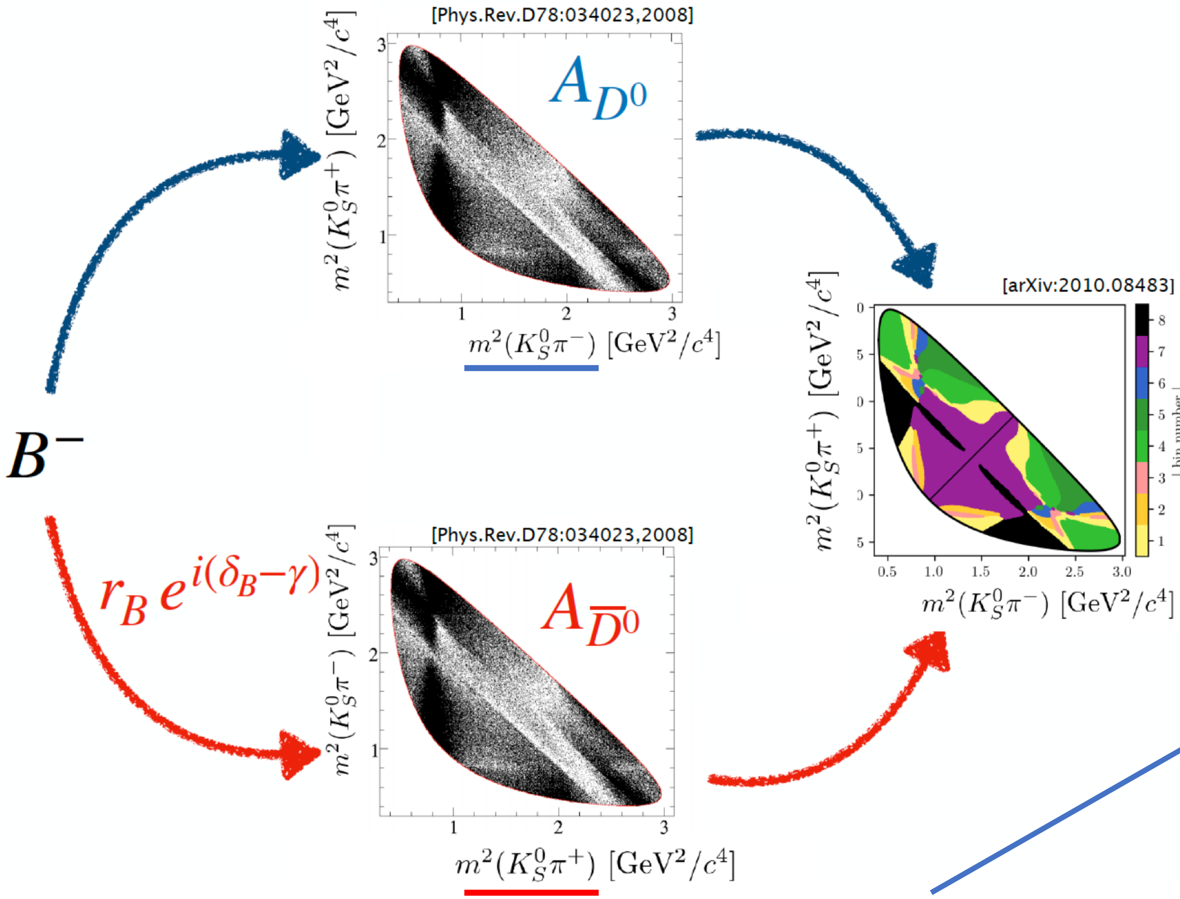




Three-body D decays

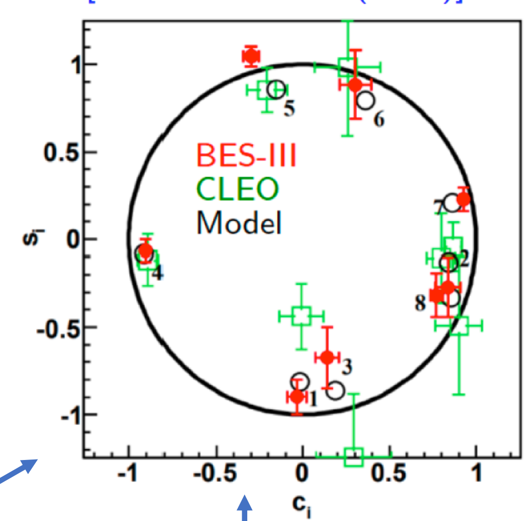
LHCb-PAPER-2020-019

- BPGGSZ (GLW/ADS over Dalitz plot) measurements now performed with full Run1+Run2 data, for $B \to DK, D \to Ks\pi\pi, KsKK$



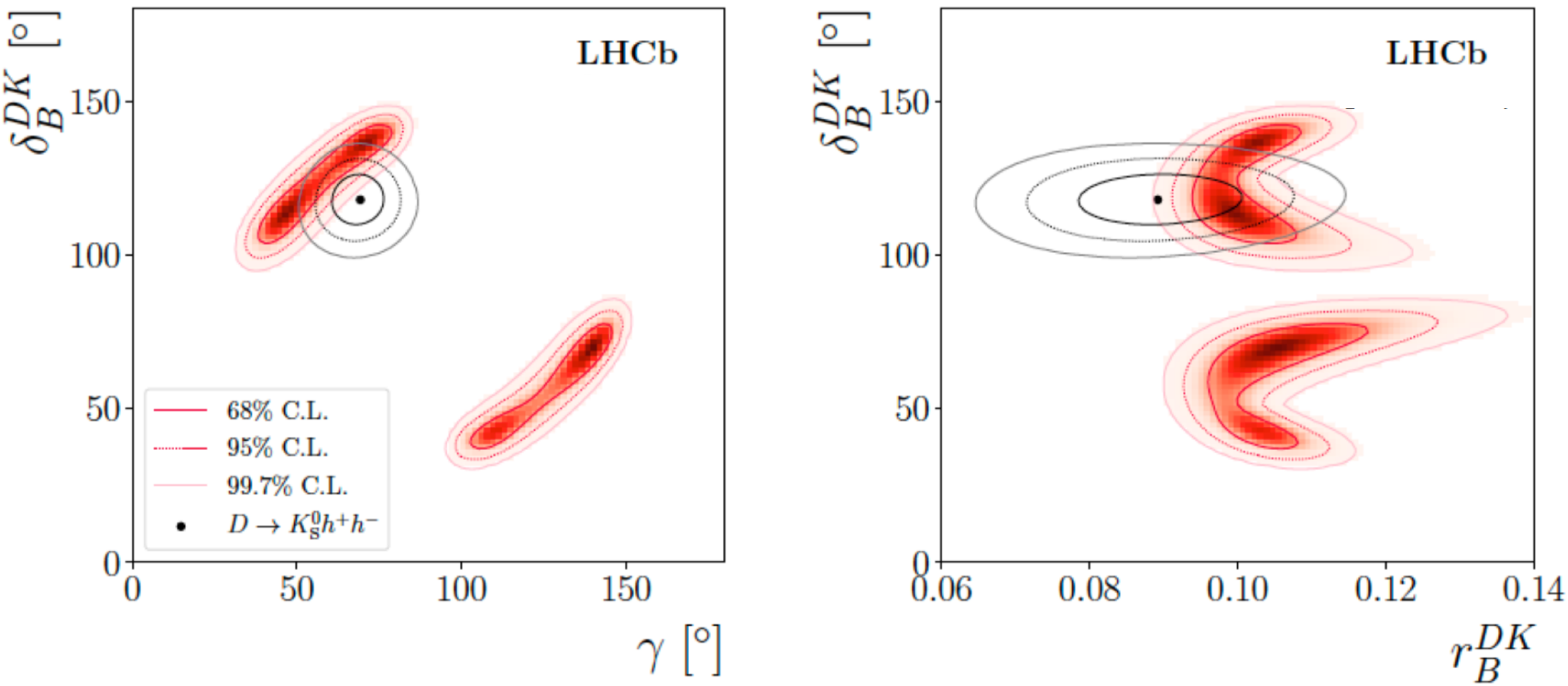
New charm input from BES-III (4 * CLEO-c stat)

[PRD101, 112002(2020)]



$$A_{B^\mp}(m^2_{K_s\pi^+}, m^2_{K_s\pi^-}) = A_{D^0}(m^2_{K_s\pi^+}, m^2_{K_s\pi^-}) + r_B\, e^{i(\delta_B \mp \gamma)} A_{D^0}(m^2_{K_s\pi^-}, m^2_{K_s\pi^+})$$

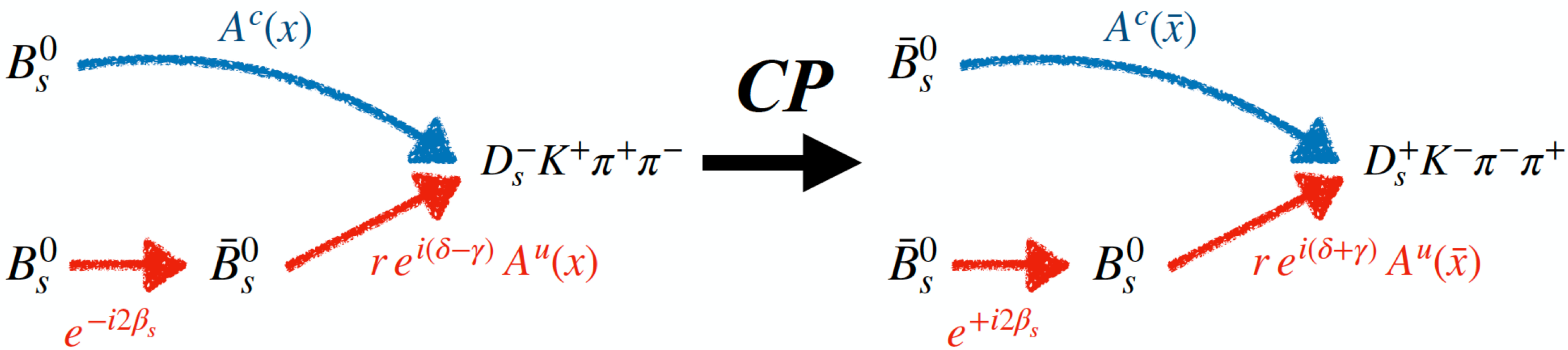
Combination between the two



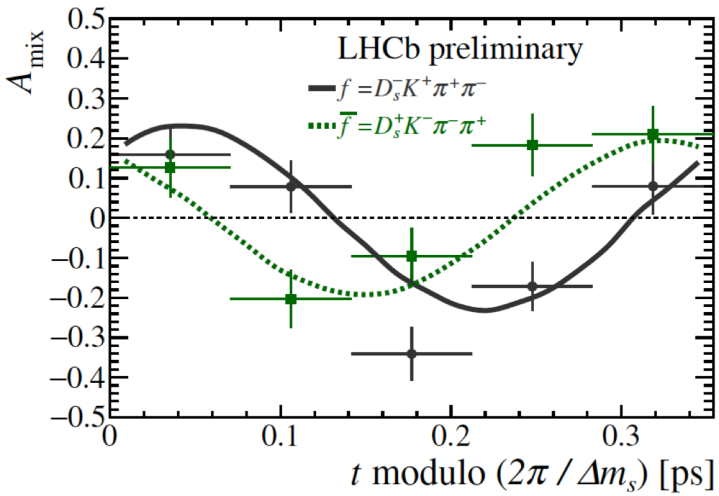
- Good agreement between the two modes (expected)
- Much better sensitivity when combined ➔ key feature for γ measurements
- Important to add more channels and compare between them

New story from B_s decays

LHCb-PAPER-2020-030



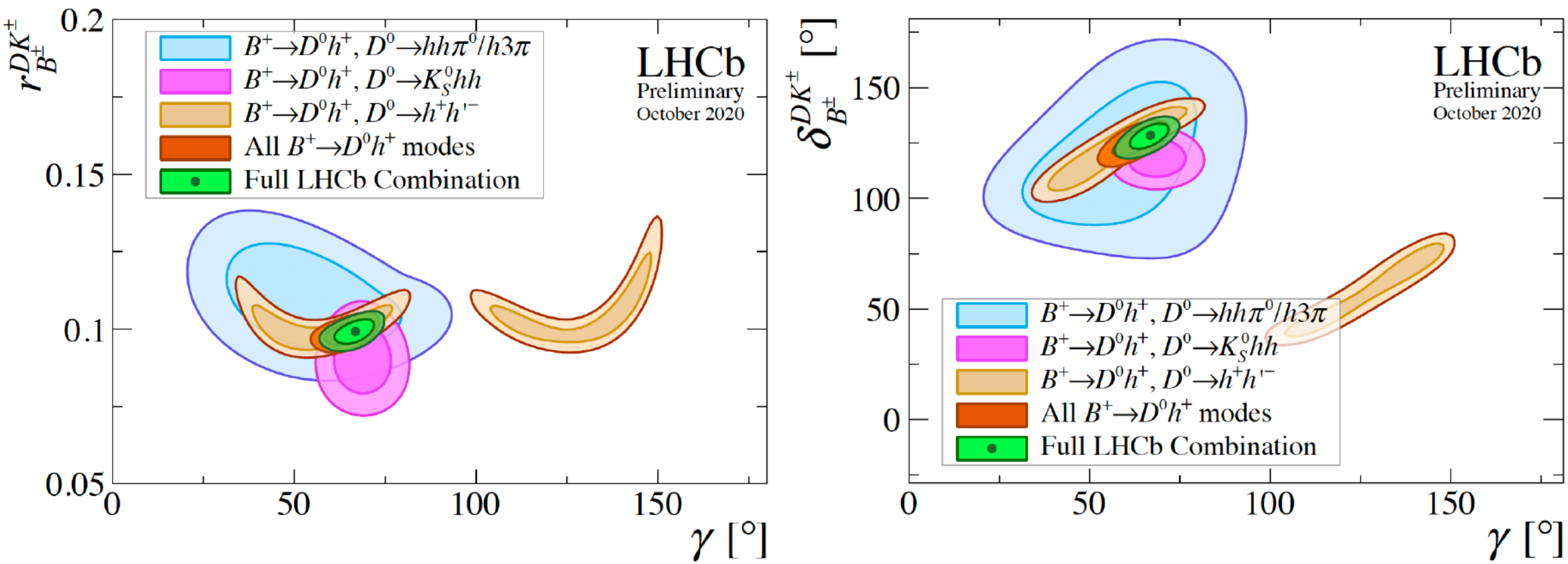
- $b \to u$ and $b \to c$ interference can also came with B_s mixing



		stat	sys	model
r	$0.56 \pm$	$0.05 \pm$	$0.04 \pm$	0.07
κ	$0.72 \pm$	$0.04 \pm$	$0.06 \pm$	0.04
δ [°]	$-14 \pm$	$10 \pm$	$4 \pm$	5
$\gamma - 2\beta_s$ [°]	$42 \pm$	$10 \pm$	$4 \pm$	5

New γ combination

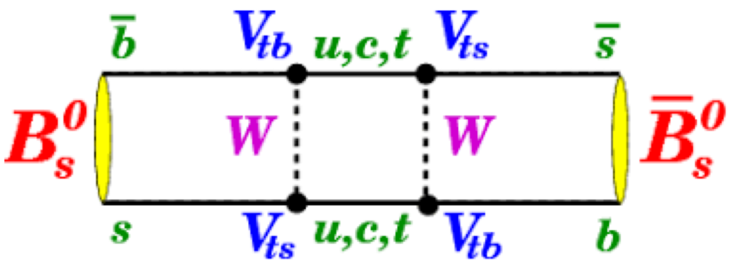
LHCb-CONF-2020-003



- Now precision mainly from B^+ decays, large potential from other b hadrons
- New average on γ from LHCb: $\gamma = (67 \pm 4)°$, compared to 14° in B-factories
- Also now much closer to indirect determination: $\gamma = (65.7^{+1.0}_{-2.5})°$

Mixing parameters

LHCb-PAPER-2021-005



$$i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix} = \begin{pmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M - i\frac{\Gamma}{2}\end{pmatrix}\begin{pmatrix}|B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle\end{pmatrix}$$

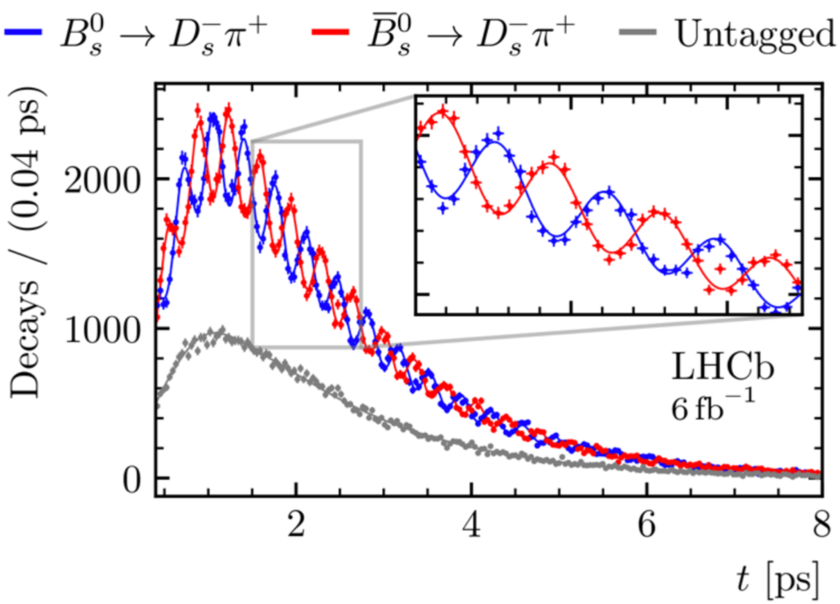
Mass eigenstates
Heavy & Light

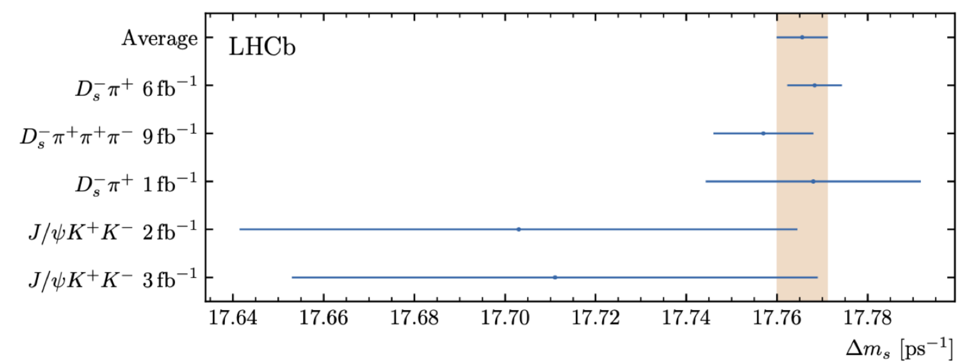
$$|B_H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$$
$$|B_L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$$

With $|p|^2 + |q|^2 = 1$

Phase $\phi_s^{SM} - arg(-\frac{M_{12}}{\Gamma_{12}}) \approx 0.004\ rad$

- Mass eigenstates different from flavor eigenstates





$$17.7656 \pm 0.0057\,\text{ps}^{-1}$$

- Textbook measurements, most precise to date; call for better precision on lattice parameters

Textbook story continues

LHCb-PAPER-2020-029

2001
Beauty particles: Time-dependent *CP* violation in B^0 meson decays
BaBar and Belle collaborations

2004
Beauty particles: Time-integrated *CP* violation in B^0 meson decays
BaBar and Belle collaborations

2013
Beauty-strange particles: Time-integrated *CP* violation in B_s^0 meson decays
LHCb collaboration

2020
Beauty-strange particles: Time-dependent *CP* violation in B_s^0 meson decays
LHCb collaboration

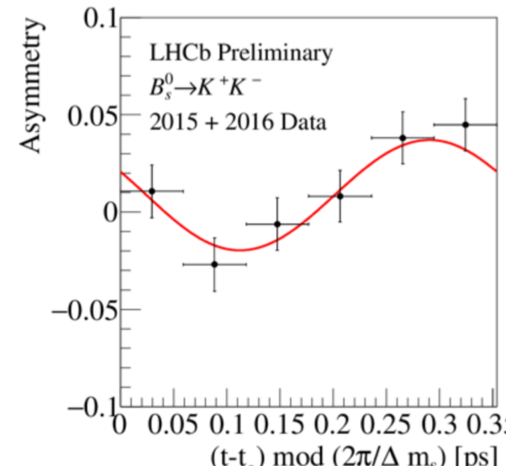
TODAY

1964
Strange particles: *CP* violation in K meson decays
J. W. Cronin, V. L. Fitch *et al.*

1999, 2001
Strange particles: *CP* violation in decay
KTeV and NA48 collaborations

2012
Beauty particles: *CP* violation in B^+ meson decays
LHCb collaboration

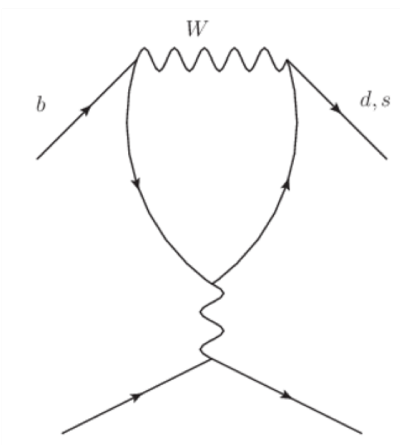
2019
Charm particles: *CP* violation in D^0 meson decays
LHCb collaboration



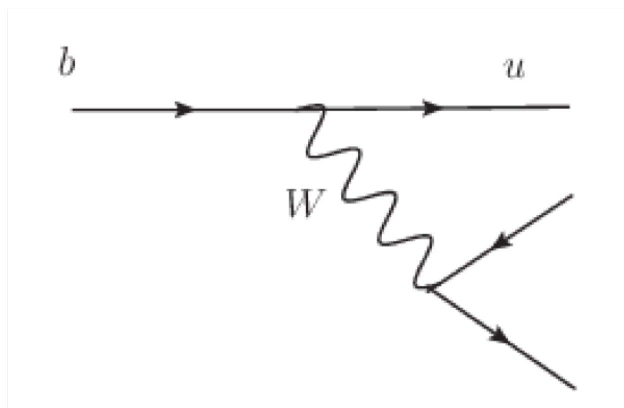
A first discovery of time-dependent CP violation in B_s^0 decays

Looking for new physics in penguins

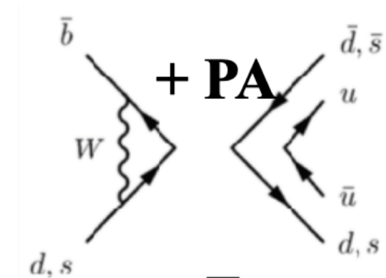
- Not only from global fit, but also from new physics sensitive channels
- New sources of CP violation easy to enter in penguins: smoking gun for NP search
- Competitive contributions from tree and penguin diagrams: large CPV

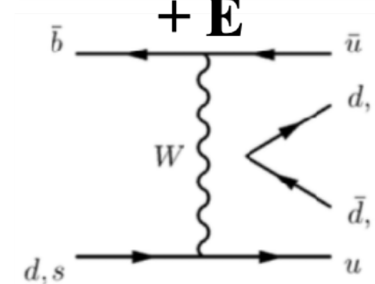


$|V_{td}|e^{i\beta}$ or $-|V_{ts}|e^{-i\beta_s}$



$|V_{ub}|e^{-i\gamma}$



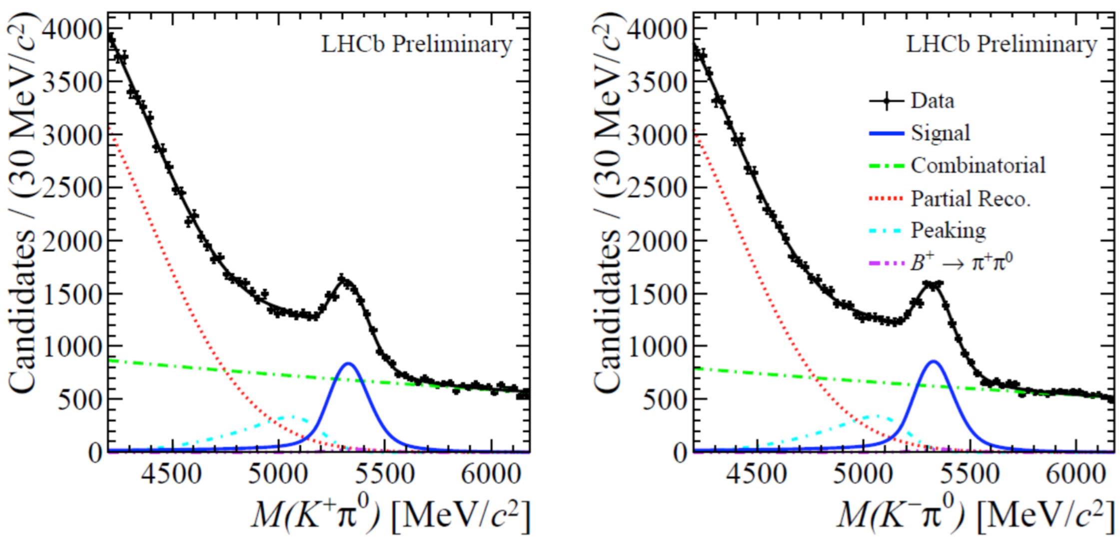


+ New Physics

$K\pi$ puzzle

- CPV from interference between suppressed tree-level process and QCD/EW penguin is sensitive for New Physics, $K\pi$ puzzle as an example [LHCb-PAPER-2020-040]
- Simple version of $K\pi$ puzzle: Isospin violated as $A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-) = 0.122 \pm 0.022$ (HFLAV); More complicated version involves full analysis of $K\pi$ system and tension also found inside.

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{B(K^0\pi^+)}{B(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2B(K^+\pi^0)}{B(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2B(K^0\pi^0)}{B(K^+\pi^-)}$$



- Very difficult measurements in hadron colliders

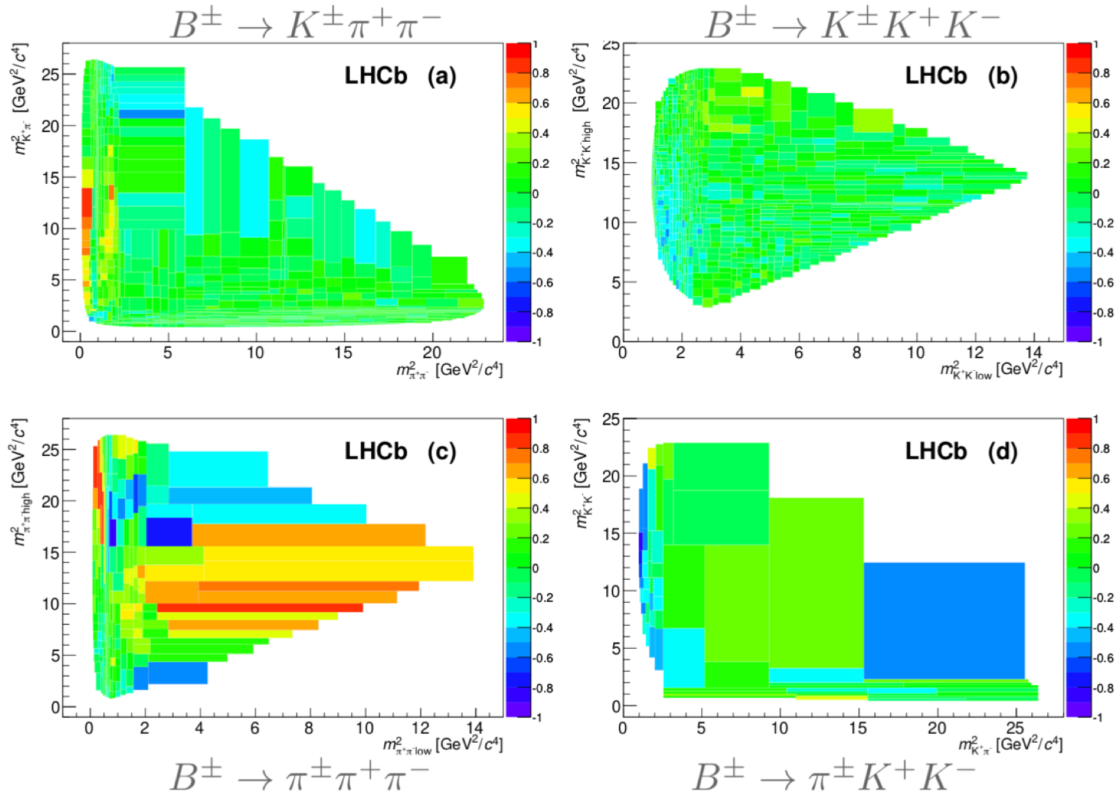
  $\mathbf{A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015(stat.) \pm 0.006(syst.) \pm 0.003(ext.)}$

- Strengthen the $K\pi$ puzzling and motivate further investigation in $B^0 \to K^0\pi^0$

CPV in three-body charmless B decays

PRL 112 (2014) 011081
PRL 111 (2013) 101801
PRD 90 (2014) 112004

- Interesting CPV pattern seen on Dalitz plot of $B^+ \to h^+h^-h'^+, h^{(\prime)} = K, \pi$
- Dalitz plot analysis needed to shed more light on understanding nature of these CPV



- Now, amplitude analyses of $B^+ \to \pi^+\pi^-\pi^+$ and $B^+ \to K^+K^-\pi^+$, with much larger statistics than previous B-factory analyses, has been performed

Dalitz plot analyses with CP violation

- Amplitude with CPV is modelled as

$$A(\Phi_3) = \sum_i A_i(\Phi_3) = \sum_i c_i F_i(\Phi_3)$$

Strong dynamics

$$\bar{A}(\bar{\Phi}_3) = \sum_i \bar{c}_i F_i(\Phi_3)$$

Strong + weak

- CPV then described as

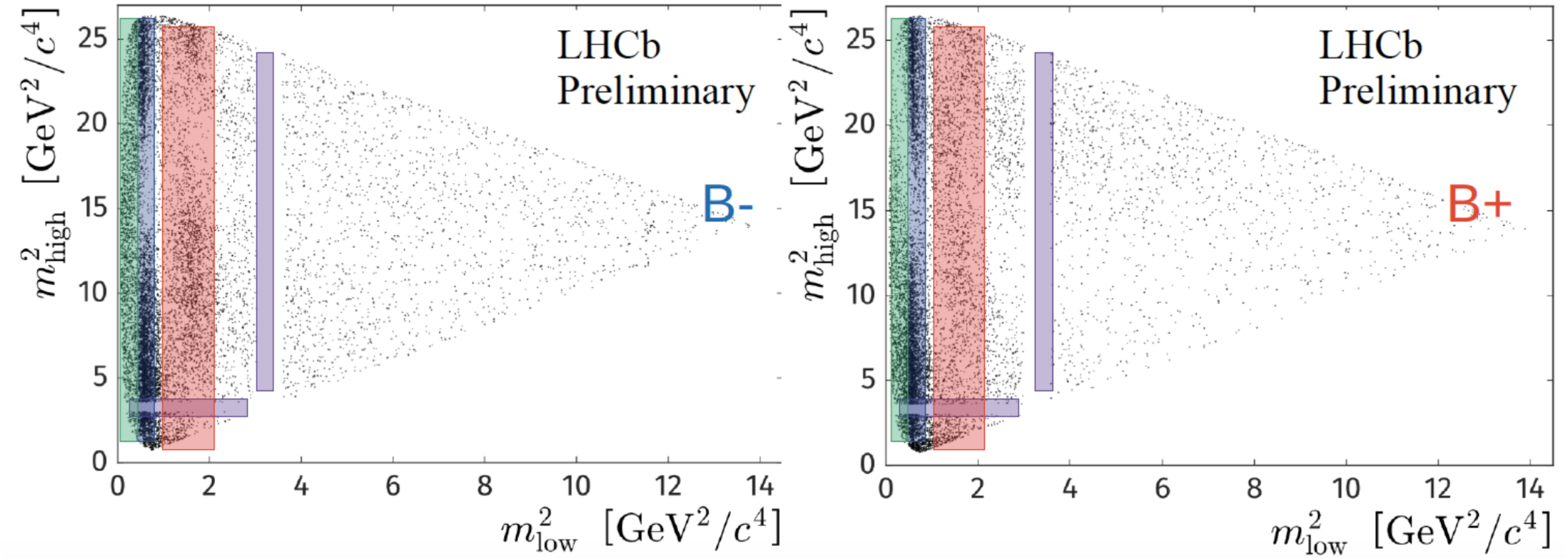
$$c_i = (x_i + \Delta x_i) + i(y_i + \Delta y_i)$$
$$\bar{c}_i = (x_i - \Delta x_i) + i(y_i - \Delta y_i)$$

- Observables:

$$\mathcal{F}_i \equiv \frac{\int d\Phi_3 |A_i(\Phi_3)|^2 + \int d\Phi_3 |\bar{A}_i(\Phi_3)|^2}{\int d\Phi_3 |A(\Phi_3)|^2 + \int d\Phi_3 |\bar{A}(\Phi_3)|^2} \qquad \mathcal{A}^i_{CP} \equiv \frac{\int d\Phi_3 |\bar{A}_i(\Phi_3)|^2 - \int d\Phi_3 |A_i(\Phi_3)|^2}{\int d\Phi_3 |\bar{A}_i(\Phi_3)|^2 + \int d\Phi_3 |A_i(\Phi_3)|^2}$$

Dalitz plot analysis with $B^+ \to \pi^+\pi^-\pi^+$

- Dalitz plot analysis with 20594 ±1569 events (3 fb^{-1} data)



- Resonant contributions:

  $\rho - \omega, f_0(500), f_0(980)$,region: S-P wave interference

  $f_2(1270)$ region: D-S, P wave interference

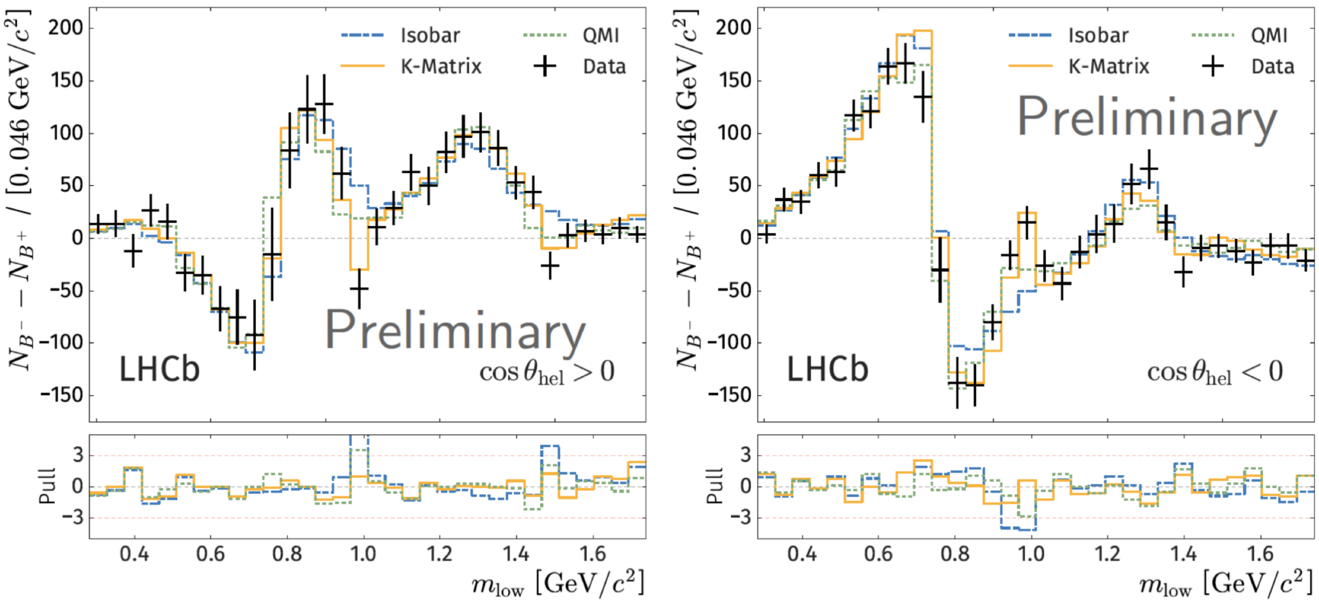
  High mass: $KK - \pi\pi$ rescattering

- Three different methods to describe S-wave: Isobar model, K-Matrix approach, quasi model independent approach

New CP violation patterns

LHCb-PAPER-2019-017
LHCb-PAPER-2019-018

- CP violation around $\rho(770)$ pole well described by the three S-wave models



- Over 25σ significance for CPV due to S-P interference, first observation
- CP violation sign flips around $\rho(770)$ pole and over helicity angle

Sign of CP violation

- CPV comes from inference of two processes:

$$A = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)} \qquad \bar{A} = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

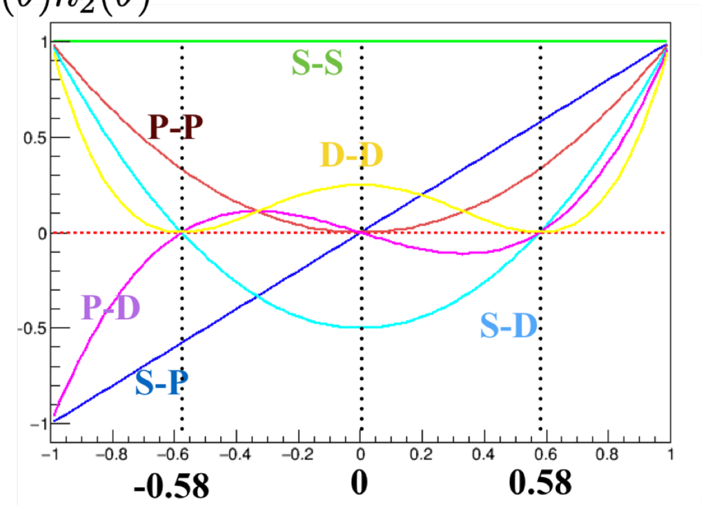
$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)$$

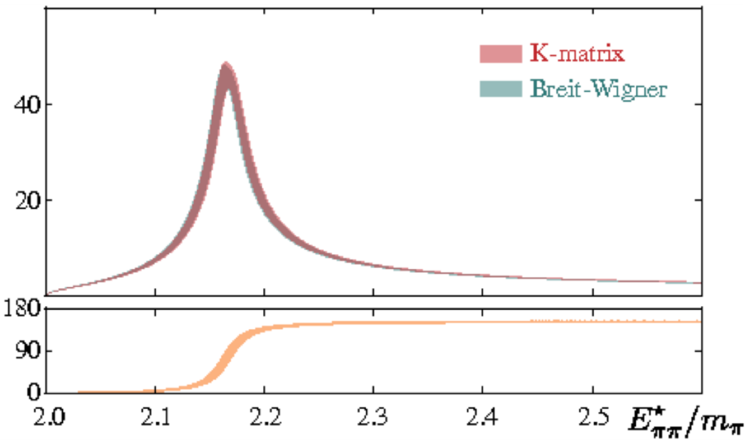
- Weak phases change sign under CP operation while strong phases don't

$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} = \frac{2a_1a_2h_1(\theta)h_2(\theta)\sin(\delta_1-\delta_2)\sin(\phi_1-\phi_2)}{a_1^2h_1^2(\theta) + a_2^2h_2^2(\theta) + 2a_1a_2h_1(\theta)h_2(\theta)\cos(\delta_1-\delta_2)\cos(\phi_1-\phi_2)}$$

θ : helicity angle **$h(\theta)$: angular distribution of resonance**

$h_1(\theta)h_2(\theta)$





A general and user-friendly partial wave analysis framework

Hao Cai[1], Chen Chen[5], Yi Jiang[2], Pei-Rong Li[3], Yin-Rui Liu[2], Xiao-Rui Lyu[2], Rong-Gang Ping[4], Wenbin Qian[2], Mengzhen Wang[5], Zi-Yi Wang[2], Liming Zhang[5],Yang-Heng Zheng[2]

[1]WHU, [2]UCAS, [3]LZU, [4]IHEP, [5]THU

- **Several independent fitters developed previously for dedicated analyses: e.g. Z(4430)$^+$ and pentaquark search, $B^0 \to \overline{D^0}\pi^+\pi^-$ analysis etc.**
- **Joint efforts + experience on previous analyses + very good students**

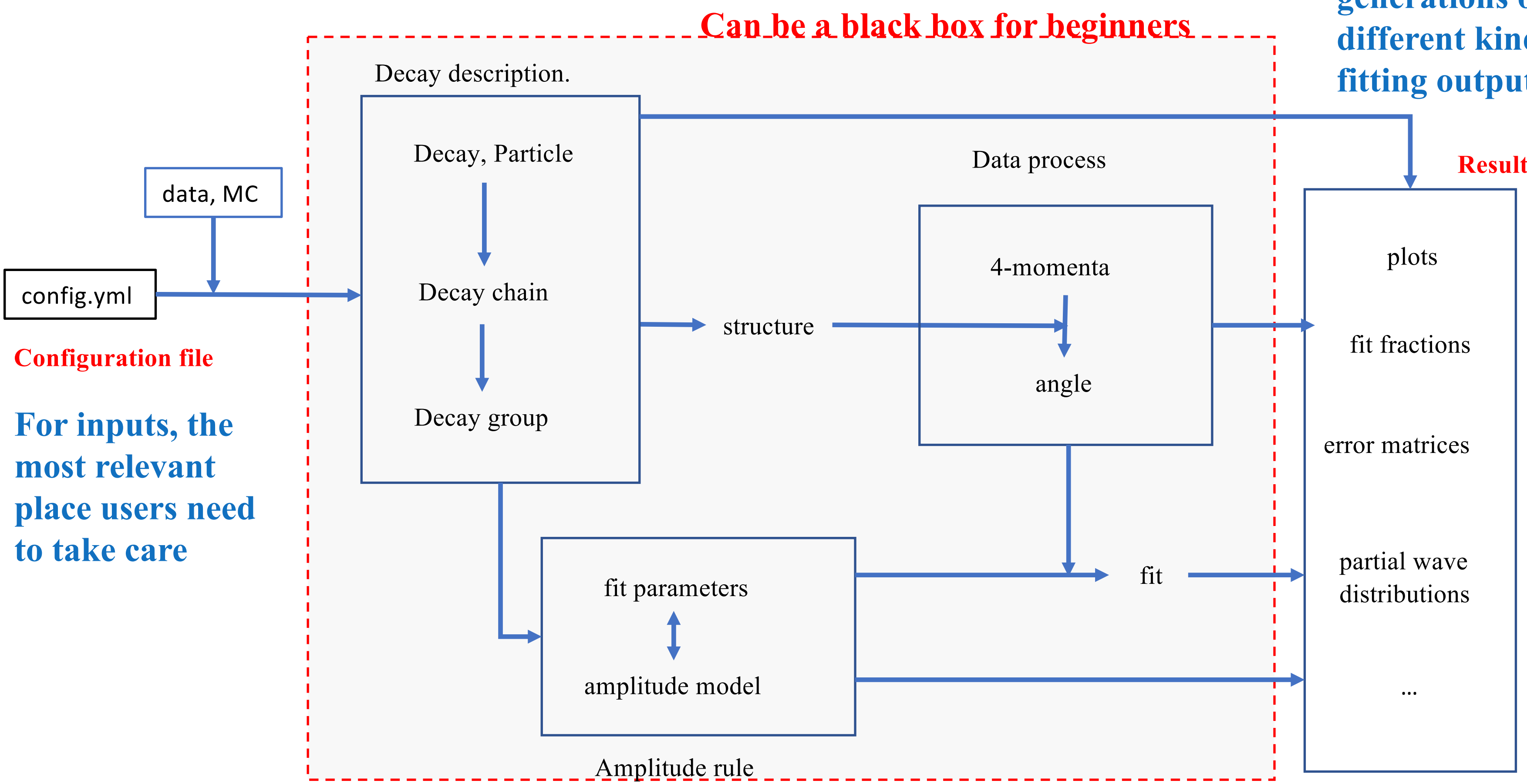
Features

- Based on Tensor-Flow v2

- Fast
  - GPU based
  - Vectorized calculation
  - Automatic differentiation
- General
  - Custom model available
- Easy to use
  - Simple configuration file
  - Automatics process
  - All necessary functions implemented
- Open access and well supported https://gitlab.com/jiangyi15/tf-pwa

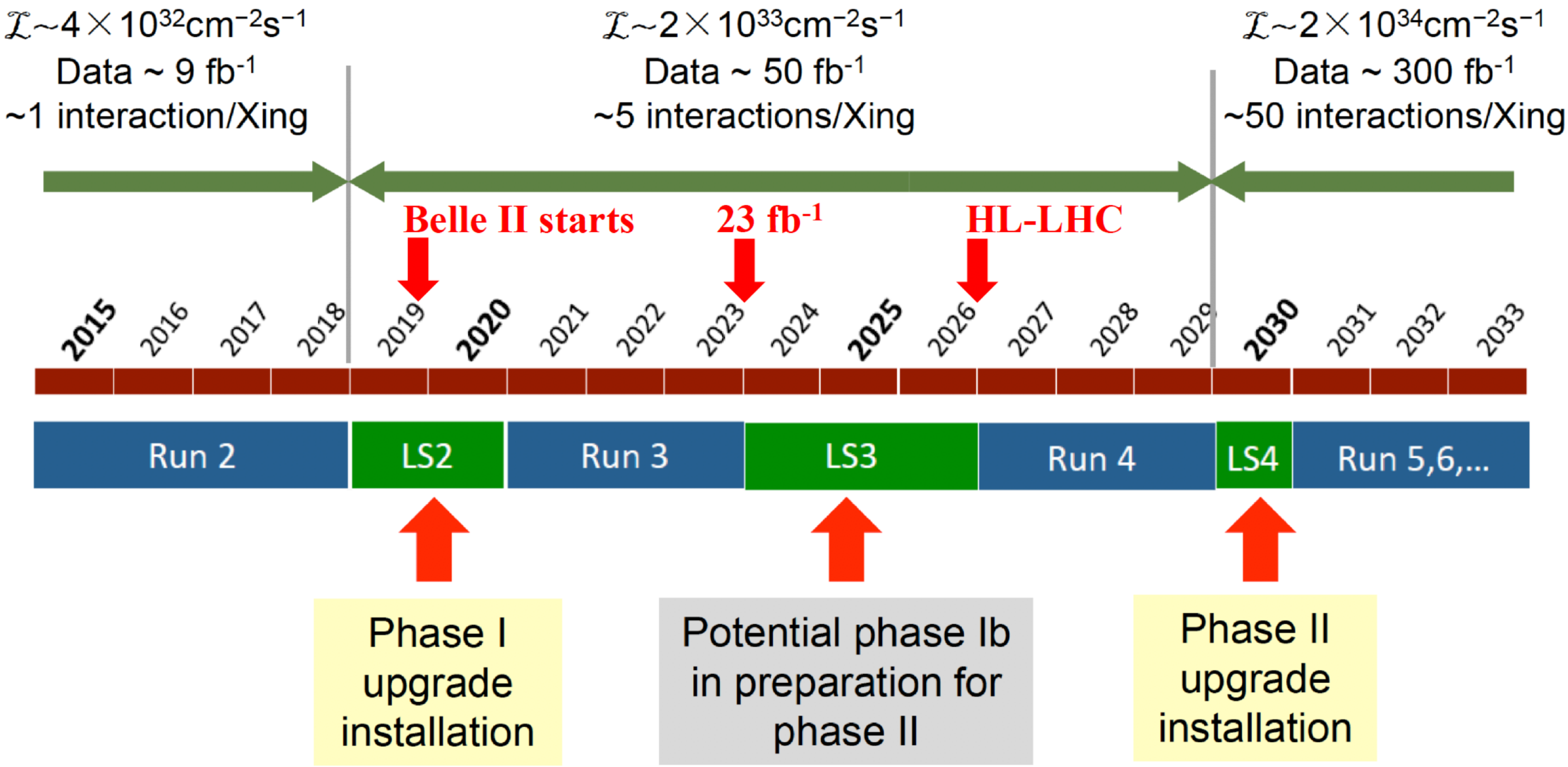
Framework

Automatic generations of different kinds of fitting outputs



For inputs, the most relevant place users need to take care

The LHCb upgrade plans

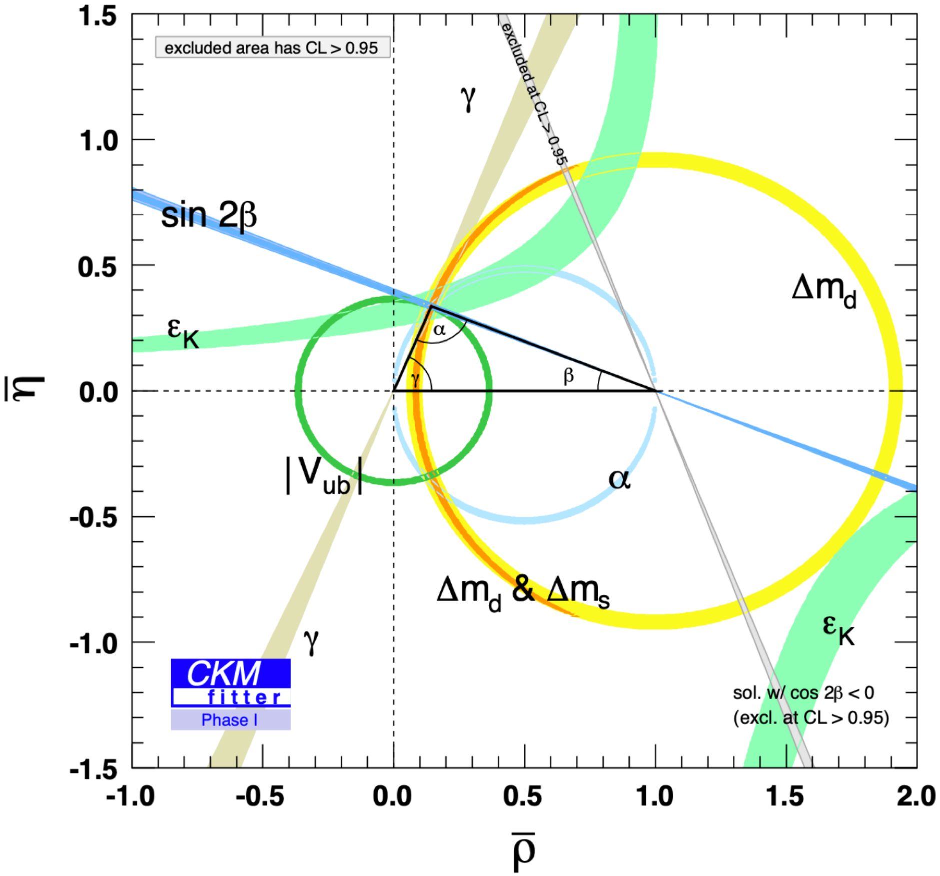


Physics potential for LHCb upgrade

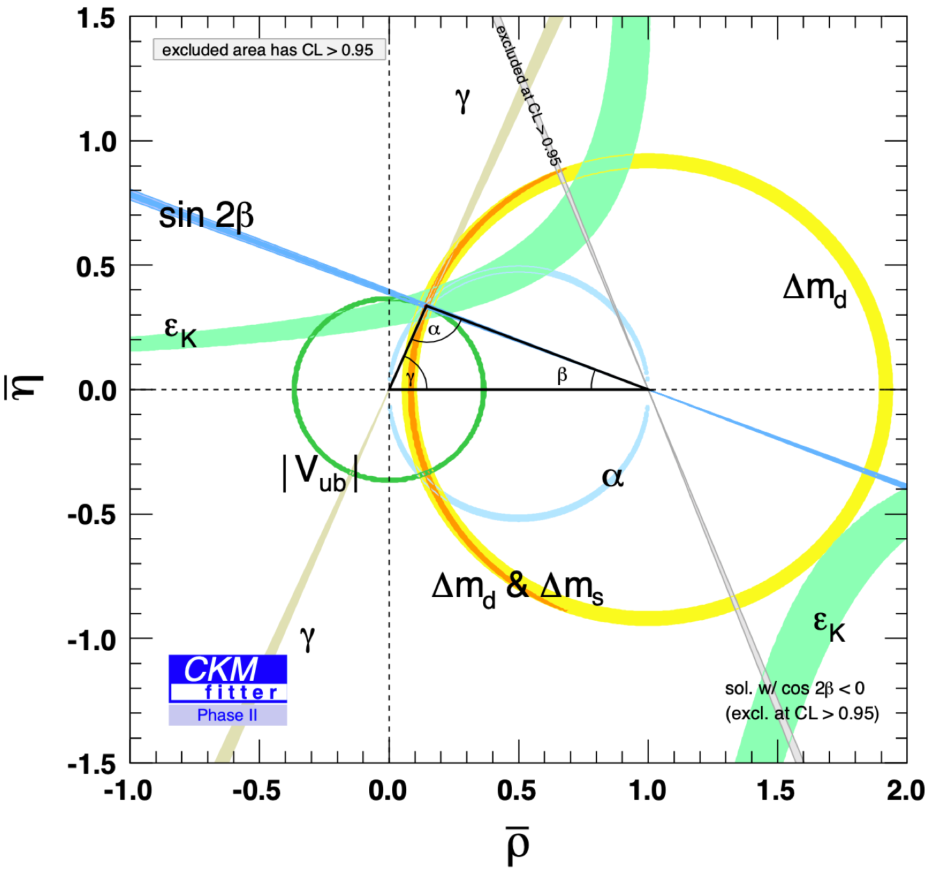
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1<q^2<6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1<q^2<6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [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%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0\to\mu^+\mu^-)/\mathcal{B}(B_s^0\to\mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0\to\mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ 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}	–

CKM triangles in two decades

Phase I



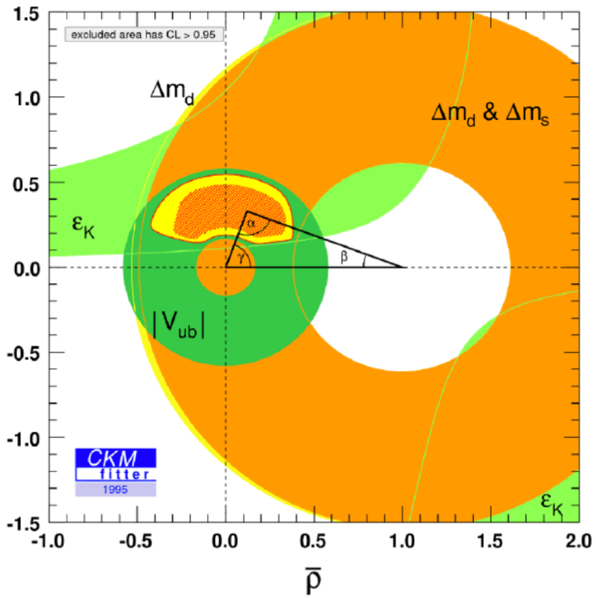
Phase II



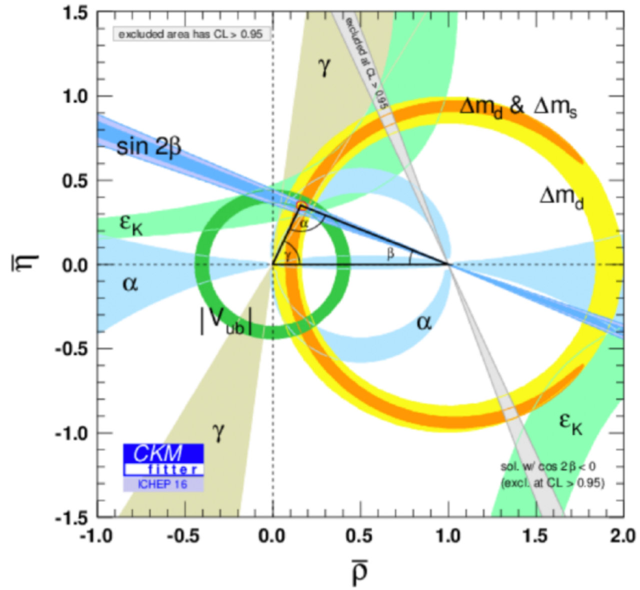
- With assumptions on improvements on lattice plus measurements from Belle II
- Central values at current fit values

Conclusion

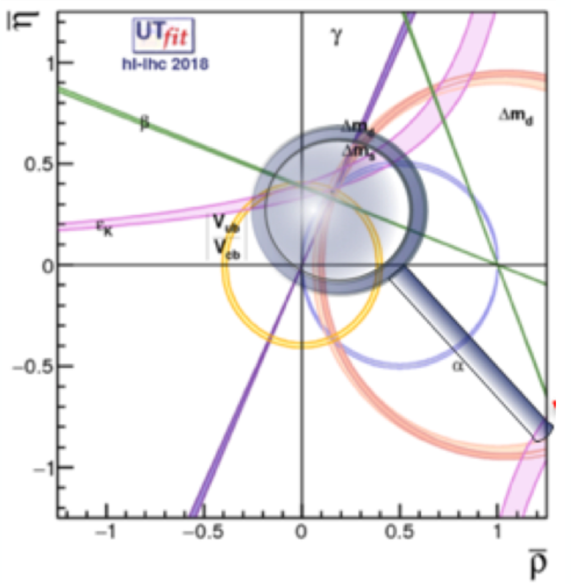
1995

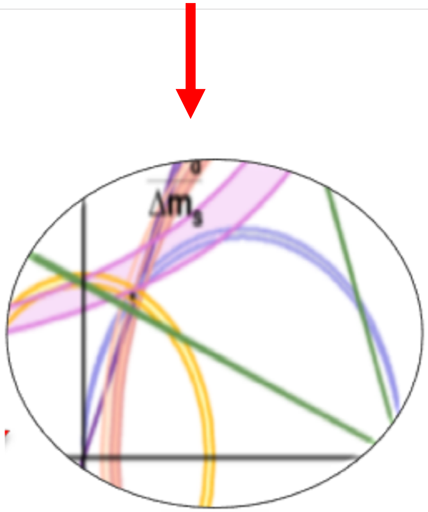


2016

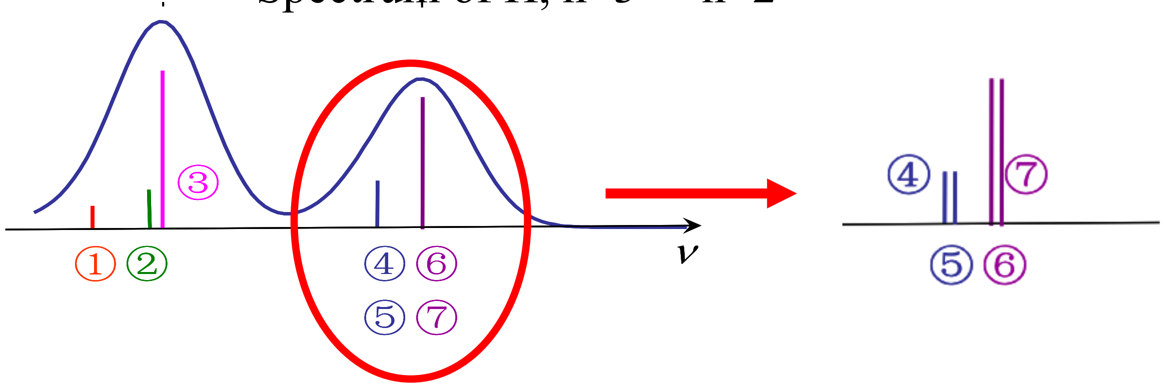


future



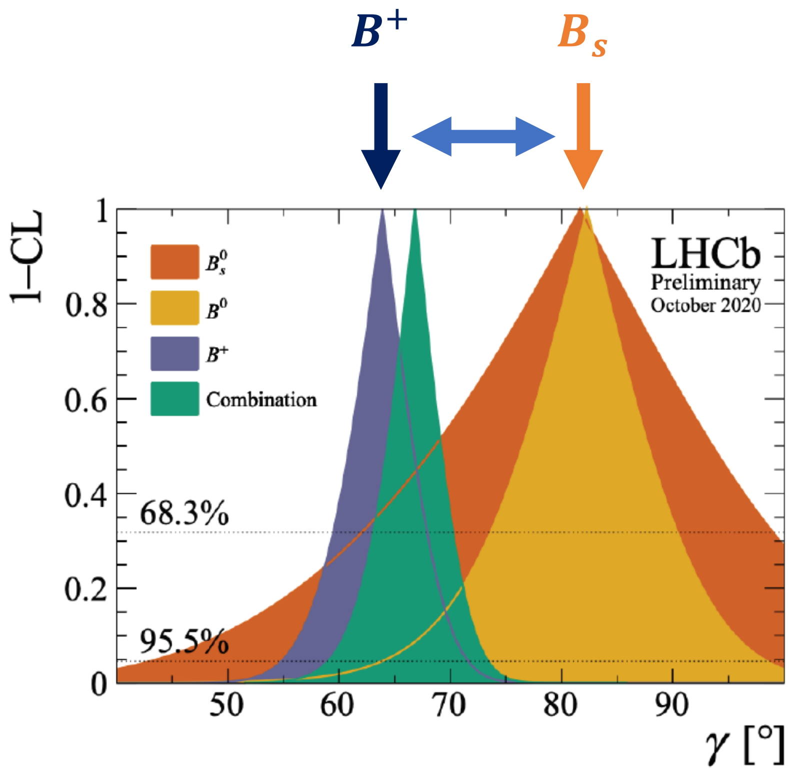


Spectrum of H, n=3 → n=2



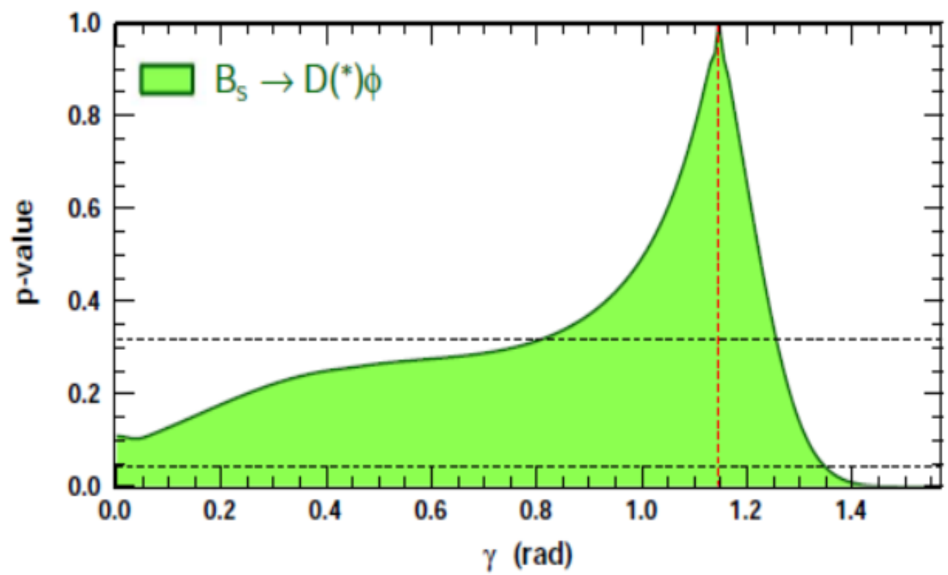
Efforts in B_s decays

D. Ao et al., CPC45 (2021) 023003



- Uncertainties of γ in B_s decays still large, potential improvements
- Important to understand discrepancies of γ measured from B^0 and B_s decays

- $B_s^0 \to \overline{D^0} K^+ K^-$和$B_s^0 \to \overline{D^{*0}} \phi$: golden channels for measuring γ in B_s decays
- Sensitivity studies performed: 10-15° with LHCb Run 1+2 data

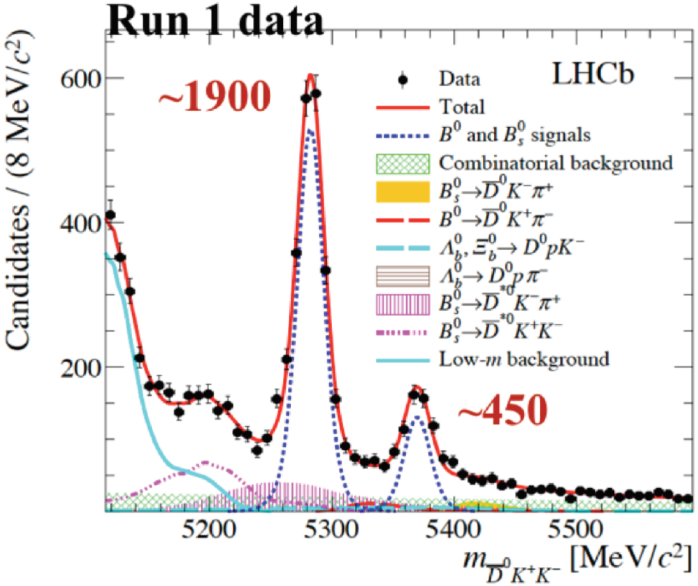


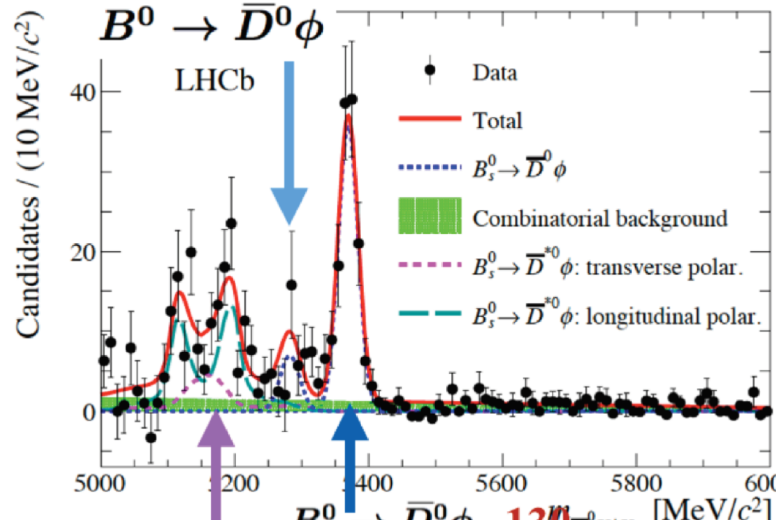
Finding these decays in LHCb

Phys. Rev. D98 (2018) 072006
Phys. Rev. D98 (2018) 071103(R)

- $B^0 \to D^0\overline{K}K$ and $B_s \to D^0\overline{K}K$ 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

Run 1 data





$B_s^0 \to \overline{D}^0\phi$ ~130

$B_s^0 \to \overline{D}^{*0}\phi$ **(Partially reconstructed, Two polarization components)** ~160

- Not only on B_s decays, efforts also ongoing to use new methods to measure old golden channels (EPJC78 (2018) 121)

CP violation results

LHCb-PAPER-2019-017
LHCb-PAPER-2019-018

- Fit fractions:

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$55.5 \pm 0.6 \pm 0.7 \pm 2.5$	$56.5 \pm 0.7 \pm 1.5 \pm 3.1$	$54.8 \pm 1.0 \pm 1.9 \pm 1.0$
$\omega(782)$	$0.50 \pm 0.03 \pm 0.03 \pm 0.04$	$0.47 \pm 0.04 \pm 0.01 \pm 0.03$	$0.57 \pm 0.10 \pm 0.12 \pm 0.12$
$f_2(1270)$	$9.0 \pm 0.3 \pm 0.8 \pm 1.4$	$9.3 \pm 0.4 \pm 0.6 \pm 2.4$	$9.6 \pm 0.4 \pm 0.7 \pm 3.9$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 0.4 \pm 1.9$	$10.5 \pm 0.7 \pm 0.8 \pm 4.5$	$7.4 \pm 0.5 \pm 3.9 \pm 1.1$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.0 \pm 0.1 \pm 0.5 \pm 0.1$
S-wave	$25.4 \pm 0.5 \pm 0.7 \pm 3.6$	$25.7 \pm 0.6 \pm 2.6 \pm 1.4$	$26.8 \pm 0.7 \pm 2.0 \pm 1.0$

- Dominant contributions from S-wave and $\rho(770)$

- CP asymmetries:

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$+0.7 \pm 1.1 \pm 1.2 \pm 1.5$	$+4.2 \pm 1.5 \pm 2.6 \pm 5.8$	$+4.4 \pm 1.7 \pm 2.3 \pm 1.6$
$\omega(782)$	$-4.8 \pm 6.5 \pm 6.6 \pm 3.5$	$-6.2 \pm 8.4 \pm 5.6 \pm 8.1$	$-7.9 \pm 16.5 \pm 14.2 \pm 7.0$
$f_2(1270)$	$+46.8 \pm 6.1 \pm 3.6 \pm 4.4$	$+42.8 \pm 4.1 \pm 2.1 \pm 8.9$	$+37.6 \pm 4.4 \pm 6.0 \pm 5.2$
$\rho(1450)^0$	$-12.9 \pm 3.3 \pm 7.0 \pm 35.7$	$+9.0 \pm 6.0 \pm 10.8 \pm 45.7$	$-15.5 \pm 7.3 \pm 14.3 \pm 32.2$
$\rho_3(1690)^0$	$-80.1 \pm 11.4 \pm 13.5 \pm 24.1$	$-35.7 \pm 10.8 \pm 8.5 \pm 35.9$	$-93.2 \pm 6.8 \pm 8.0 \pm 38.1$
S-wave	$+14.4 \pm 1.8 \pm 2.1 \pm 1.9$	$+15.8 \pm 2.6 \pm 2.1 \pm 6.9$	$+15.0 \pm 2.7 \pm 4.2 \pm 7.0$

- Large CPV from S-wave and $f_2(1270)$ (first observation)