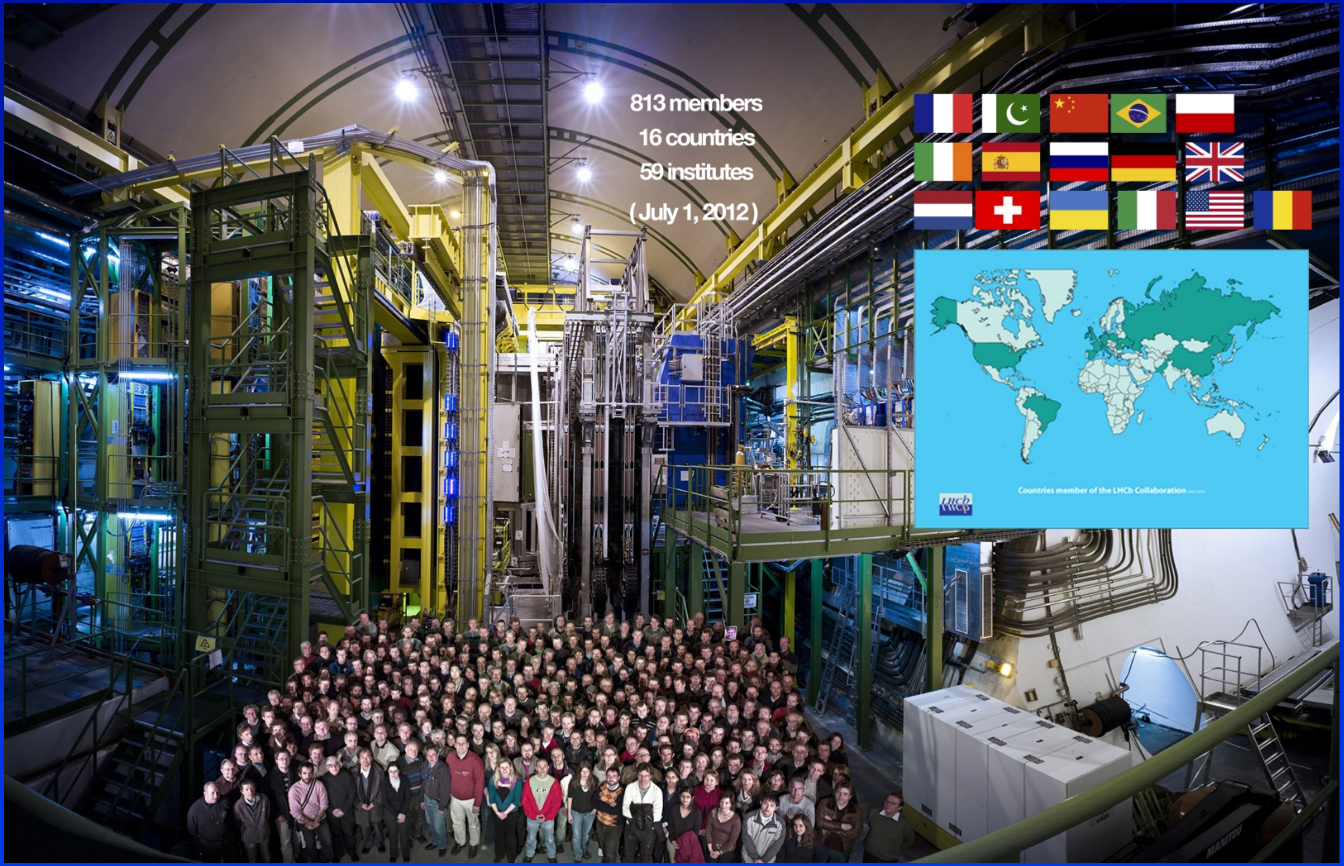
Rencontres du Vietnam 2018 August 10th, 2018

CP Violation in Heavy-Flavour Hadrons



Jörg Marks, Heidelberg University
on behalf of the LHCb collaboration

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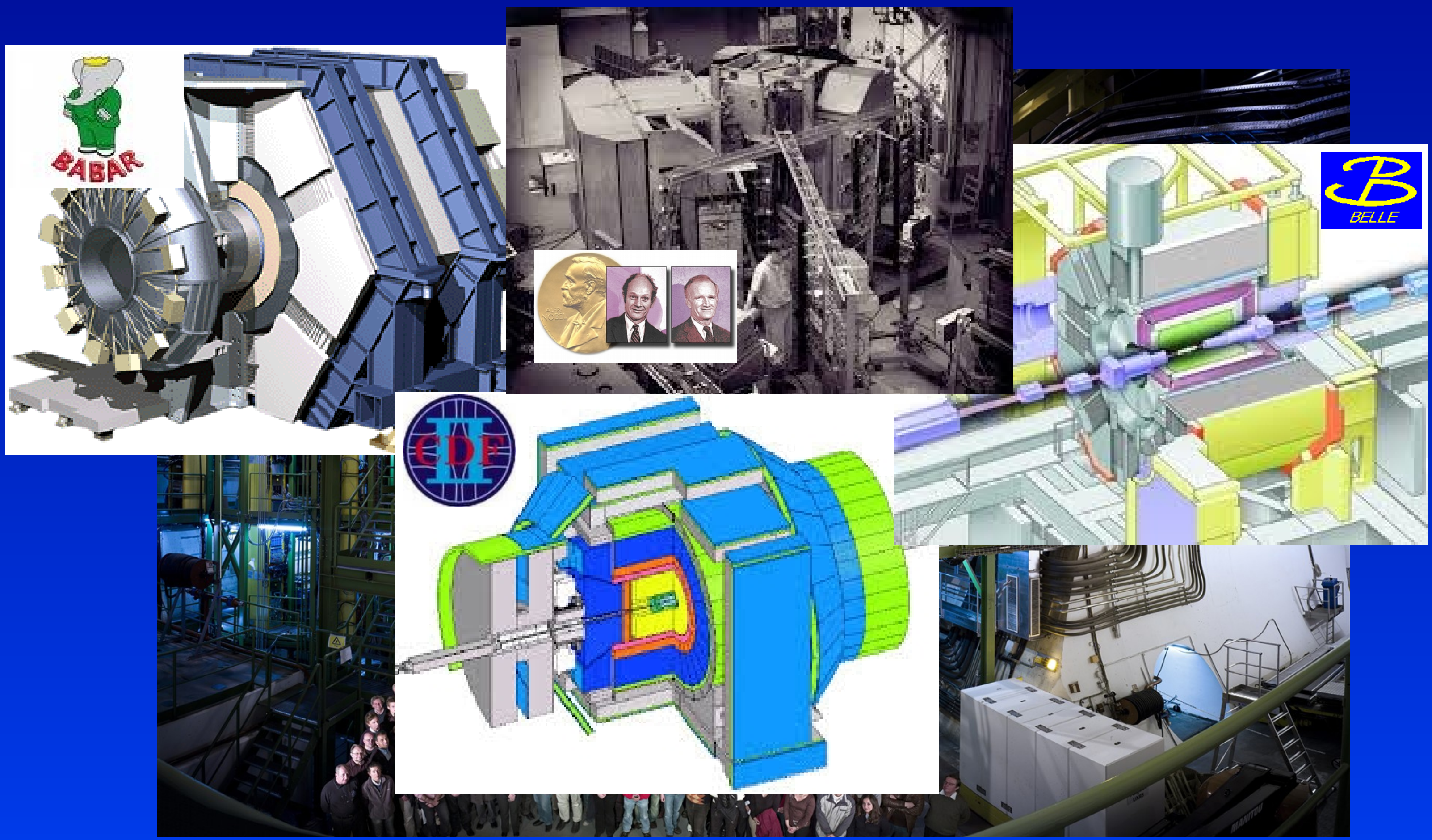

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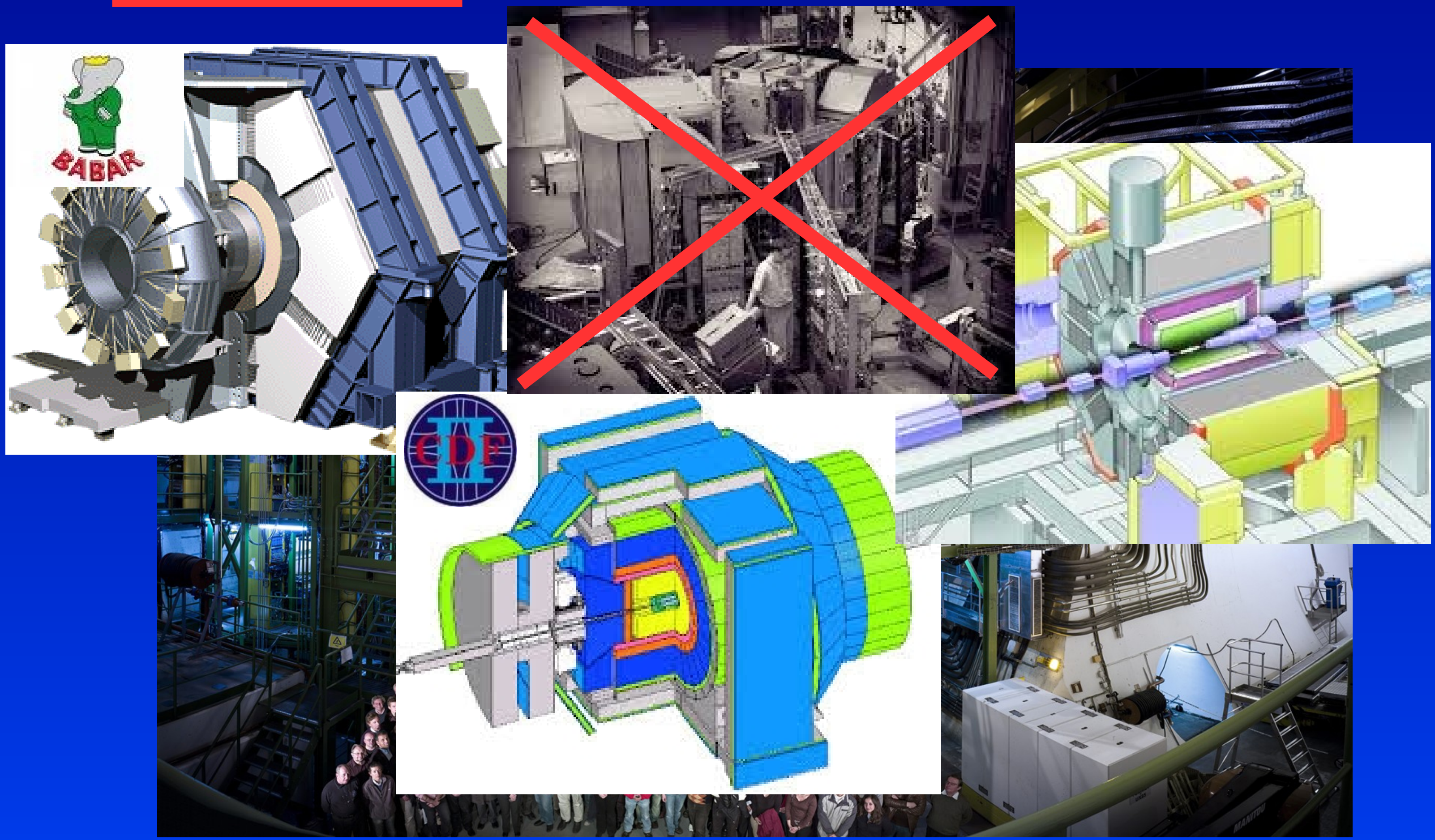

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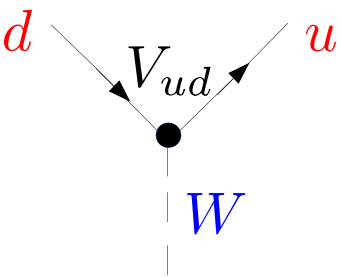
Introduction

- CP symmetry describes the invariance under charge conjugation C and parity operation P

- Diagonalizing Yukawa matrices lead to quark mass eigenstates which are mixed by virtue of the weak interactions $\rightarrow$ CKM matrix

Photo: R. Hahn, Sandbox Studio

$$\begin{pmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{\mathrm{CKM}}} \cdot \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix}$$



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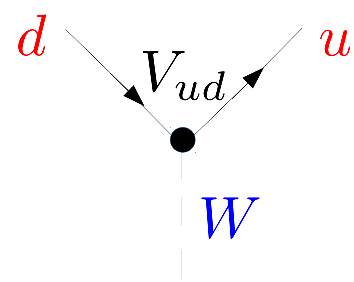

- Mixing between families is CKM suppressed
- In case of 3 families elements are complex

Introduction

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

Wolfenstein parametrization $\lambda \approx 0.22$

Only source of CPV in SM

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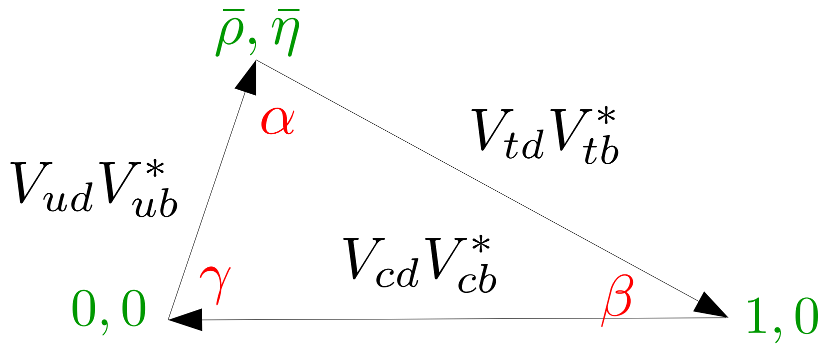
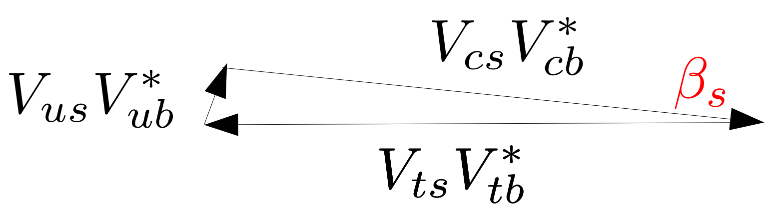
Wolfenstein parametrization $\lambda \approx 0.22$





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Only source of CPV in SM

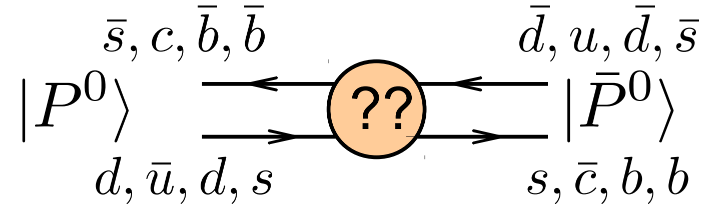
Wolfenstein parametrization $\lambda \approx 0.22$

- Decays of heavy flavoured particles are well suited to test the CKM mechanism and search for non-SM contributions to CP violation.

$\rightarrow$ focus is here on beauty and charm hadrons

Mixing in Neutral Mesons

Neutral mesons (K, D, B, B_s) are created as flavour eigenstates of the strong interaction. They can mix through weak interactions.



- The time evolution is obtained by

$$i\frac{\partial}{\partial t}\begin{pmatrix} P^0(t) \\ \bar{P}^0(t) \end{pmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}\right]\begin{pmatrix} P^0(t) \\ \bar{P}^0(t) \end{pmatrix}$$

- The physical eigenstates are P_L and P_H:

$$|P_{L,H}\rangle = p|P^0\rangle \mp q|\bar{P}^0\rangle$$

$$|P_{L,H}(t)\rangle = e^{-i(m_{L,H} - i\Gamma_{L,H}/2)t}|P_{L,H}(t=0)\rangle$$

- Define mass and lifetime differences of P_L and P_H:

$$x = \frac{\Delta m}{\Gamma} = \frac{m_H - m_L}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{2\Gamma}$$

$$\Gamma = \frac{\Gamma_L + \Gamma_H}{2}$$

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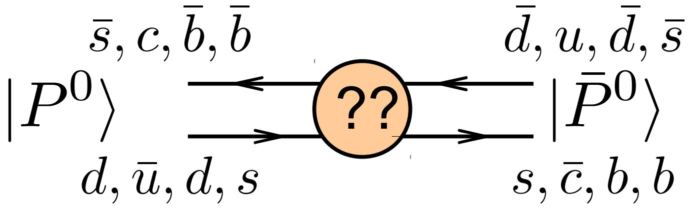
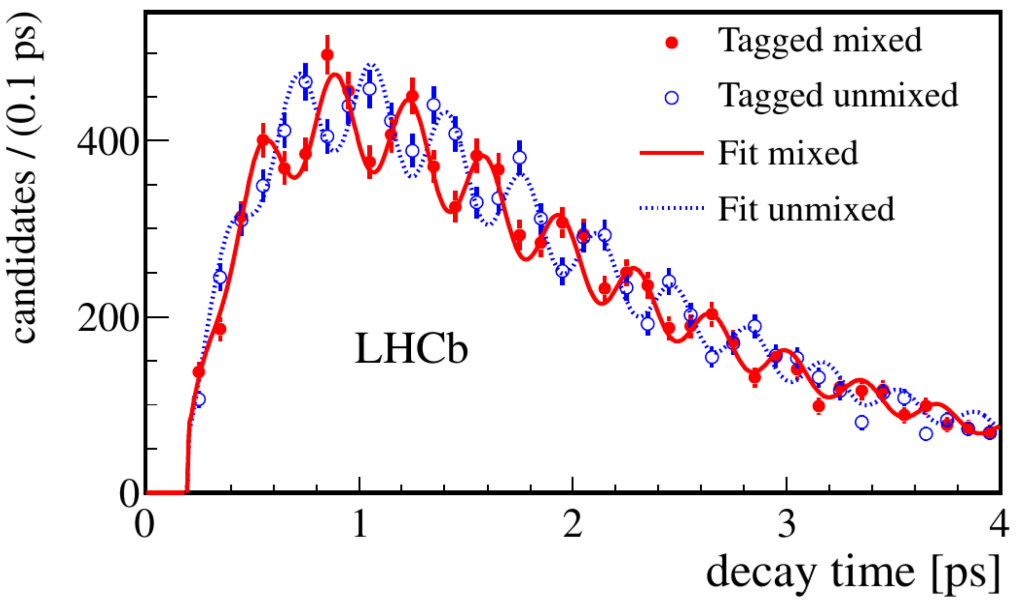


➢ $B_s^0 - \bar{B}_s^0$ oszillation frequency Δm_s measurement in $B_s^0 \rightarrow D_s^- \pi^+$ decays



NJOP 15, 053021 (2013)

$$\Delta m_s = 17.768 \pm 0.023\,(stat) \pm 0.006\,(syst)\ ps^{-1}$$

Classification of CP Violation

For CP violation need 2 interfering amplitudes with different strong δ and weak ϕ phases

Amplitudes of the decay $P \to f$ and their conjugates are $\mathcal{A}_f = \langle P|\mathcal{H}|f\rangle$, $\bar{\mathcal{A}}_{\bar{f}} = \langle \bar{P}|\mathcal{H}|\bar{f}\rangle$, $\mathcal{A}_{\bar{f}} = \langle P|\mathcal{H}|\bar{f}\rangle$ and $\bar{\mathcal{A}}_f = \langle \bar{P}|\mathcal{H}|f\rangle$

- CP violation in decay (direct CPV)

$$\Gamma(P \to f) \neq \Gamma(\bar{P} \to \bar{f}) \qquad |\mathcal{A}_f| \neq |\bar{\mathcal{A}}_{\bar{f}}|$$

- CP violation in mixing (indirect CPV)

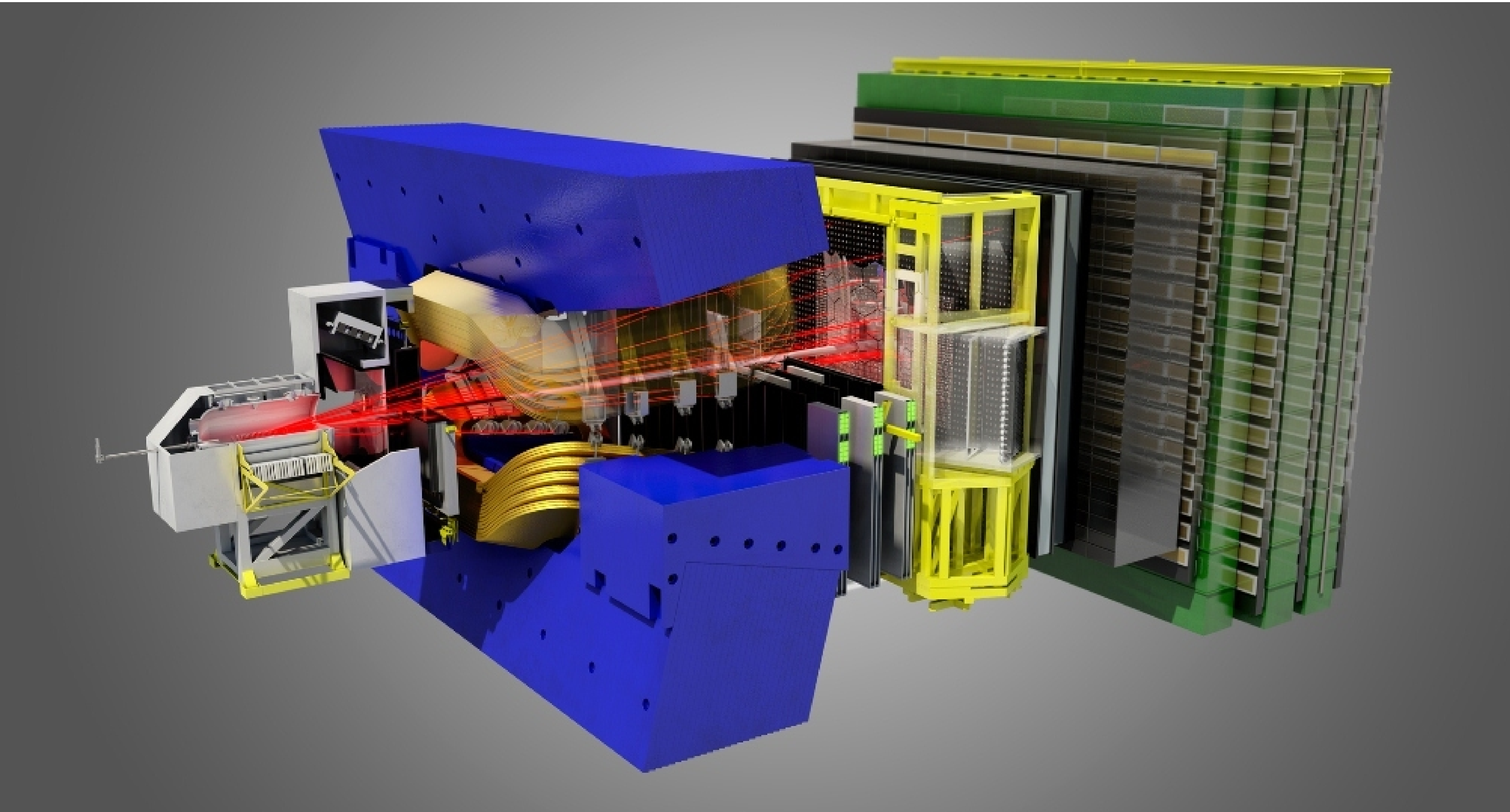
$$|\frac{q}{p}| \neq 1$$

- CP violation in interference of mixing and decay (indirect CPV)

$$arg(\lambda_f) \neq arg(\lambda_{\bar{f}}) \; , \qquad \lambda_f \equiv \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$$

Selected results

CP violation in Mixing



Introduction - CPV in $B^0_{(s)}$ Mixing

Semileptonic $B^0_{(s)}$ decays are tree-dominated transitions, CP-conserving and flavour specific.

- Provide theoretically clean measurements of CP violation in $B^0_{(s)}$ mixing by comparing probabilities $\mathcal{P}(B^0_{(s)} \to \bar{B}^0_{(s)})$ and $\mathcal{P}(\bar{B}^0_{(s)} \to B^0_{(s)})$

  - $$a^q_{sl} = \frac{\Gamma(\bar{B}^0_{(s)} \to f) - \Gamma(B^0_{(s)} \to \bar{f})}{\Gamma(\bar{B}^0_{(s)} \to f) + \Gamma(B^0_{(s)} \to \bar{f})} \approx \frac{\Delta\Gamma_{(s)}}{\Delta m_{(s)}} \tan\phi^q_{12}$$

  - Standard Model predictions are small

    $$a^s_{sl} = (2.2 \pm 0.27) \cdot 10^{-5} \quad a^d_{sl} = (-4.7 \pm 0.6) \cdot 10^{-4}$$

PRD 83 (2011) 036004
arXiv:1102.4274

- Two experimental methods

Same-sign dilepton asymmetry

$$a_{sl} = \frac{\mathcal{P}^{++}_{ll} - \mathcal{P}^{--}_{ll}}{\mathcal{P}^{++}_{ll} + \mathcal{P}^{--}_{ll}}$$

Untagged t dependent asymmetry

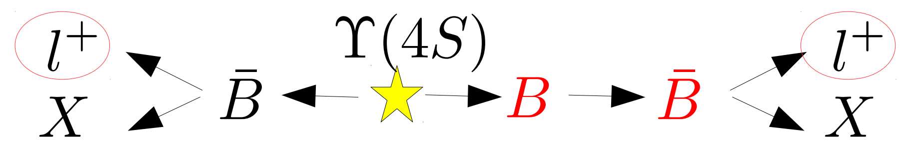
$$\frac{N(\bar{B},t) - N(B,t)}{N(\bar{B},t) + N(B,t)} = \frac{a_{sl}}{2}\left(1 - \frac{cos(\Delta m t)}{cosh(\frac{1}{2}\Delta\Gamma t)}\right)$$

BABAR - CP Violation in B^0 Mixing

- Measure the asymmetry A_{CP} in the dilepton same-sign rates using the full *BABAR* dataset

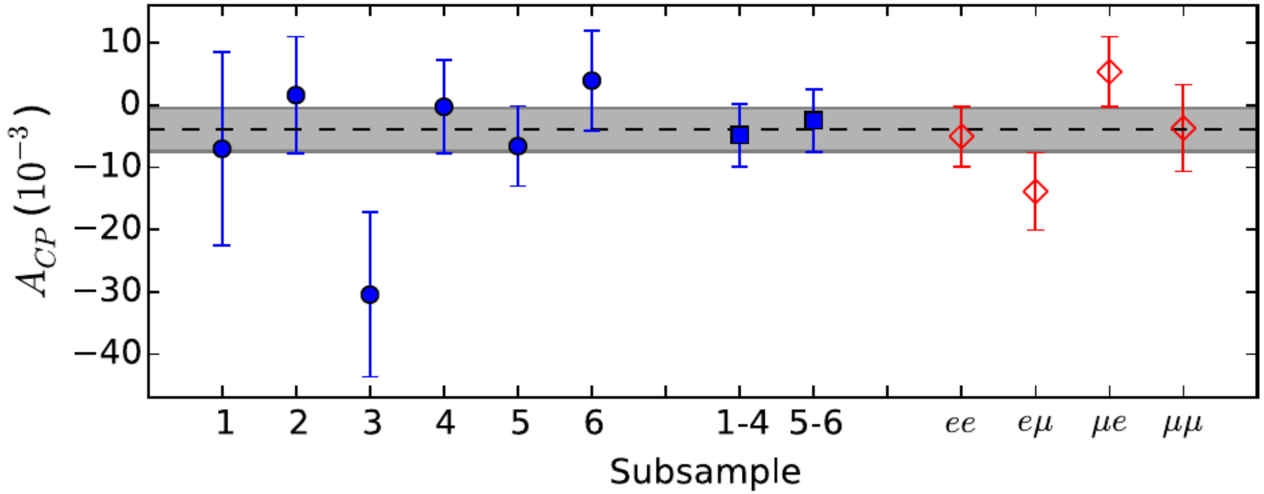
Phys. Rev. Lett. 114, 081801 (2015)

- $A_{CP} = \dfrac{\mathcal{P}_{ll}^{++} - \mathcal{P}_{ll}^{--}}{\mathcal{P}_{ll}^{++} + \mathcal{P}_{ll}^{--}}$



- Allow for 4 lepton comb.

  $l_1 l_2 = \{ee, e\mu, \mu e, \mu\mu\}$



- Asymmetry in $B^0 - \bar{B}^0$ mixing from semileptonic decays in $\Upsilon(4S)$

$A_{CP} = (-3.9 \pm 3.5 \pm 1.9) \cdot 10^{-3}$

HFLAV $A_{CP}^{\Upsilon(4S)} = (-1.9 \pm 2.7) \cdot 10^{-3}$

LHCb - CP Violation in B_s^0 Mixing

Phys. Rev. Lett. 117, 061803 (2016)

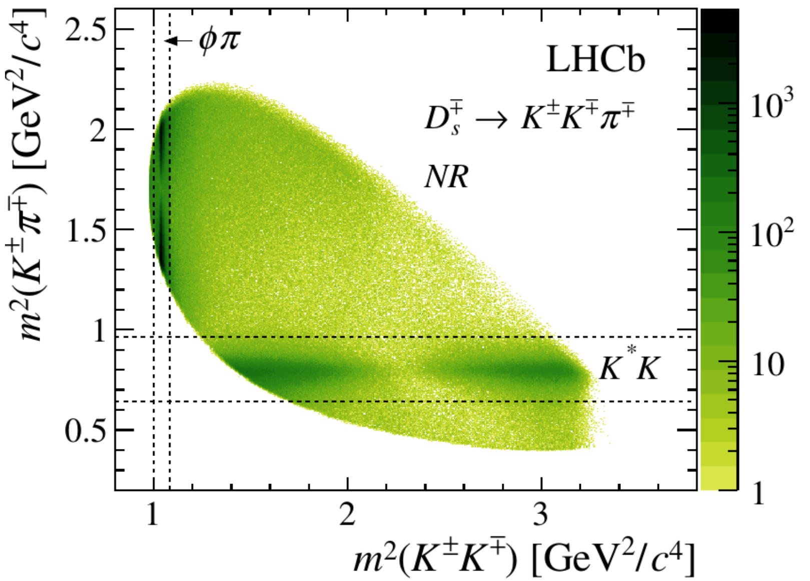
- Measure a_{sl}^s in semileptonic $B_s^0 \to D_s^-(\to K^+K^-\pi^-)\mu^+\nu_\mu X$ decays
  - No determination of the initial flavour and integrate over the B_s^0 decay time

$$A_{raw} = \frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)}{N(D_s^-\mu^+) + N(D_s^+\mu^-)} = \frac{a_{sl}}{2}$$

  - No dependency on the production rate of B_s^0 and $\bar{B}_s^0$ due to the high mixing frequency of Δm_s
  - Fit D_s^- mass for various subsamples (magnet polarity, Dalitz region, data taking period)
  - Asymmetry in B_s^0 mixing

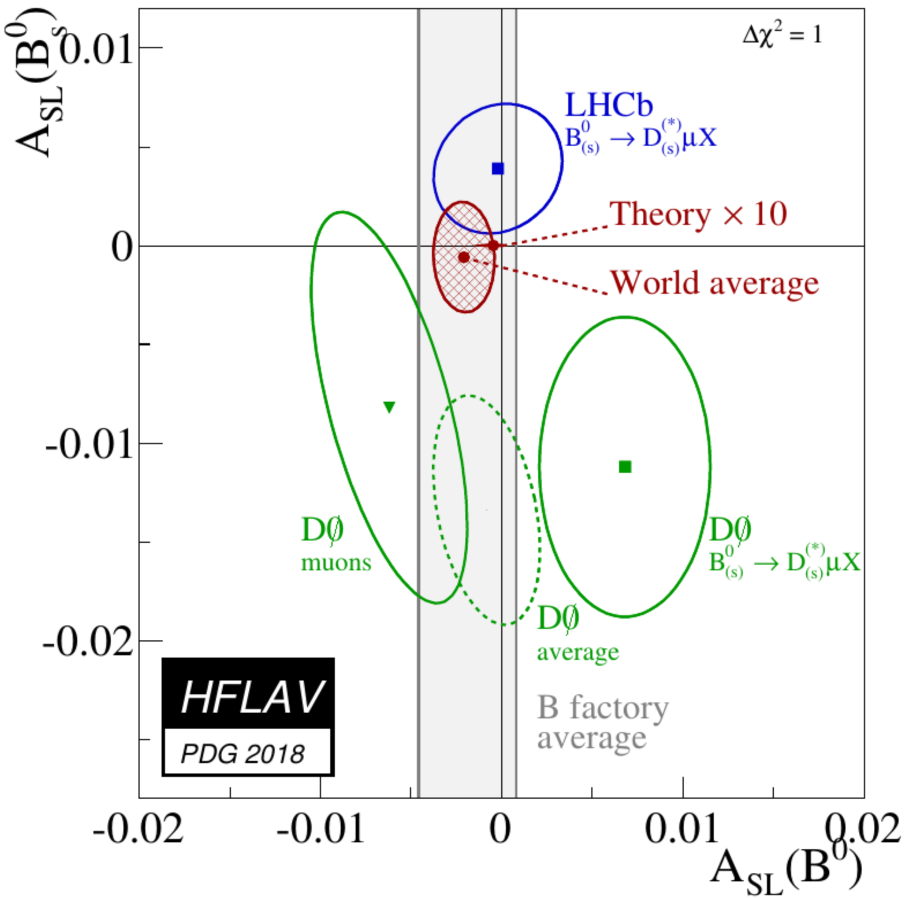
$$a_{sl}^s = (0.39 \pm 0.26 \pm 0.20)\%$$

$\int \mathcal{L} \approx 3 fb^{-1}$



Summary of CPV in $B^0_{(s)}$ Mixing

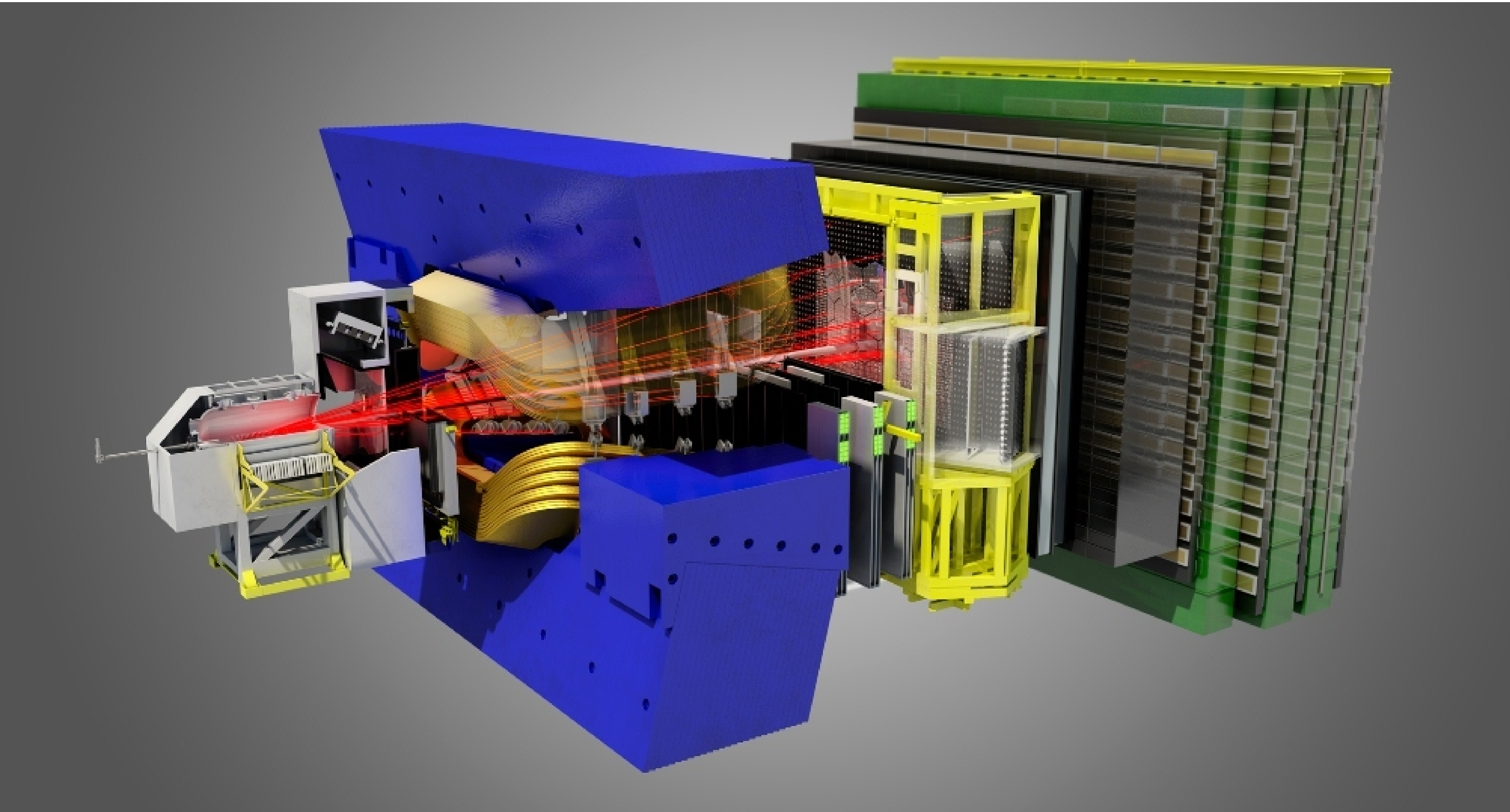
- Measurements of a^d_{sl} and a^s_{sl} are fully compatible with SM predictions



No significant CP violation in mixing of B^0 and B^0_s

Selected results

Direct CP violation



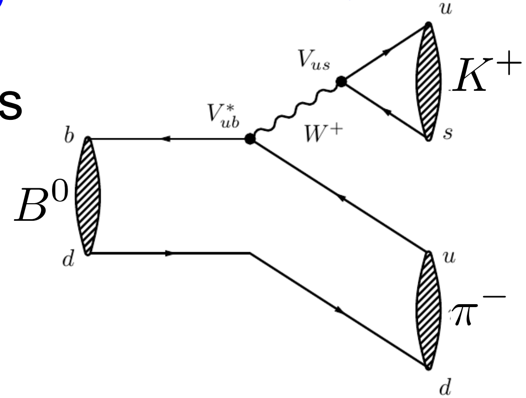
Direct CPV in Charmless $B^0_{(s)}$ Decays

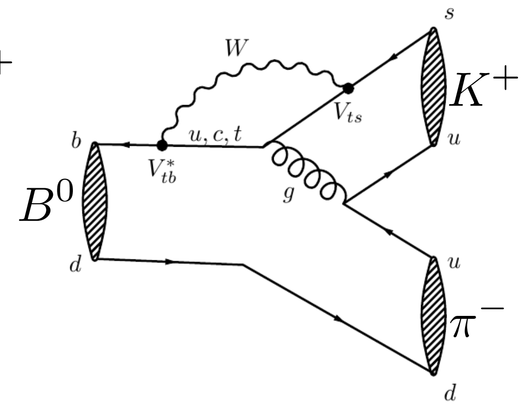
➢ The interference between $b \to u$ tree and $b \to s(d)$ loop processes gives access to direct CP violation in $B^0_{(s)} \to K\pi$ decays

- Measure the t-integrated asymmetries

$$A_{CP} = \frac{N_{\bar{B}\to\bar{f}} - N_{B\to f}}{N_{\bar{B}\to\bar{f}} + N_{B\to f}}$$

$$B \to f = \begin{pmatrix} B^0 \to K^+\pi^- \\ B^0_s \to K^-\pi^+ \end{pmatrix}$$





- Test Standard Model prediction in a model independent way by

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B^0_s \to K^-\pi^+)} + \frac{\mathcal{B}(B^0_s \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} \underbrace{\equiv}_{\text{SM}} 0$$

LHCb measurements — external averages

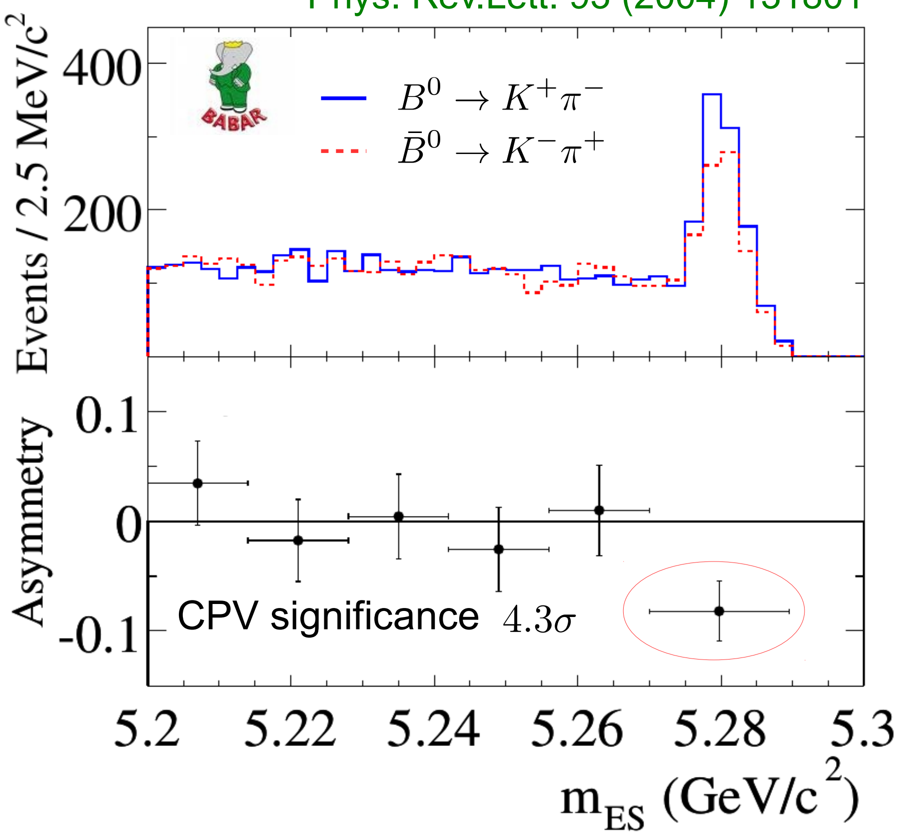
H.J. Lipkin, Phys. Lett. B 621 (2005) 126

CP Violation in $B^0 \to K^+\pi^-$ Decays

➤ First CP asymmetry measurements by B factory experiments in 2004

- First evidence CPV in $B^0 \to K^+\pi^-$

Phys. Rev.Lett. 93 (2004) 131801



- Results after updates to the full datasets compared to CDF and LHCb

$A_{CP} = -0.107 \pm 0.016\,(stat)^{+0.006}_{-0.004}\,(syst)$

Phys. Rev. D87 (2013) 05009

$A_{CP} = -0.083 \pm 0.013\,(stat) \pm 0.004\,(syst)$

Phys. Rev. D87 (2013) 031103

$A_{CP} = -0.069 \pm 0.014\,(stat) \pm 0.007\,(syst)$

Phys. Rev. Lett.113 (2014) 242001

$A_{CP} = -0.084 \pm 0.004\,(stat) \pm 0.003\,(syst)$

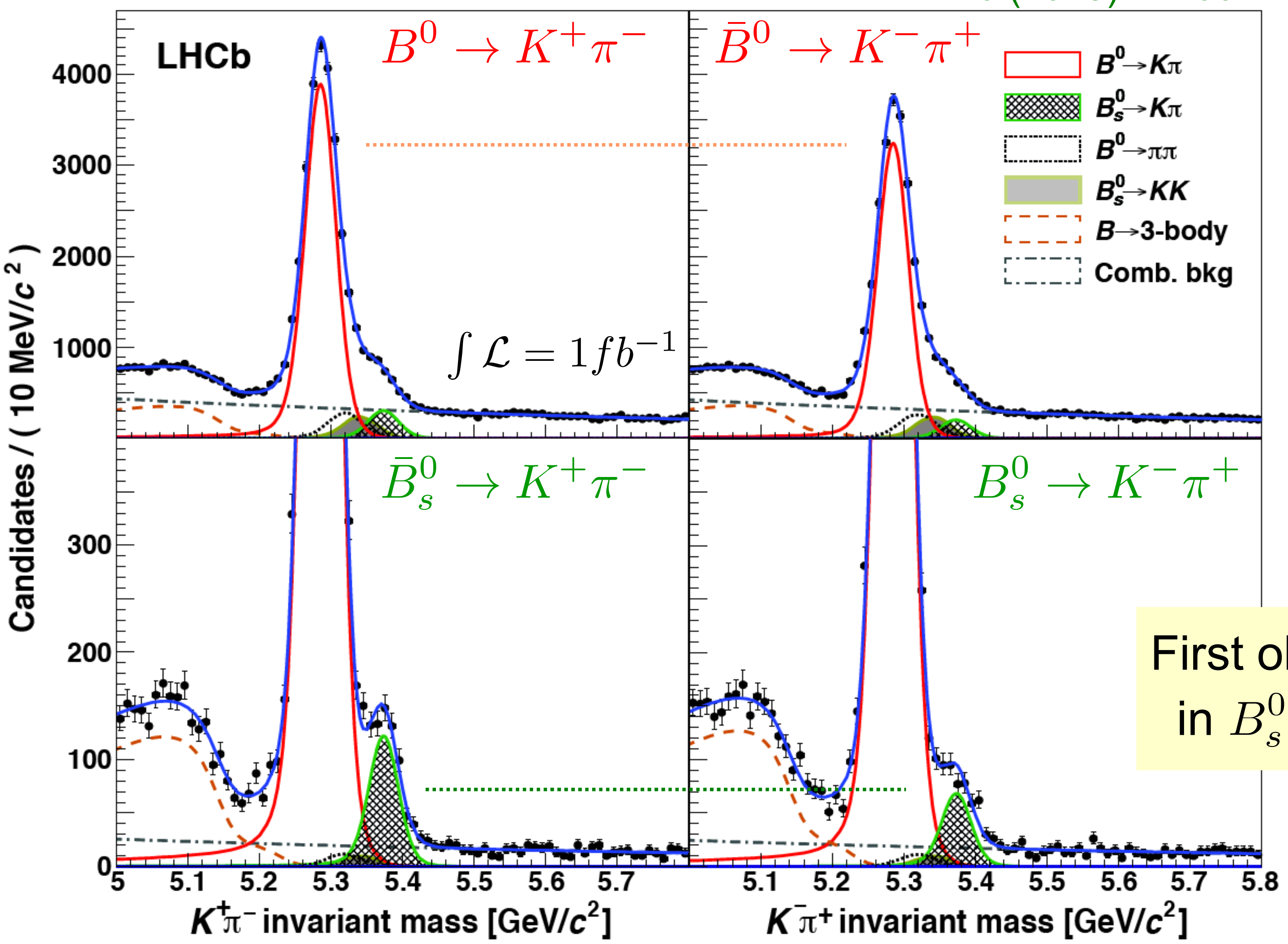
arXiv:1805.06759

new $\int \mathcal{L} \approx 3 fb^{-1}$

uncertainties decreased significantly

Direct CP Violation in B_s^0 Decays

PRL 110 (2013) 221601

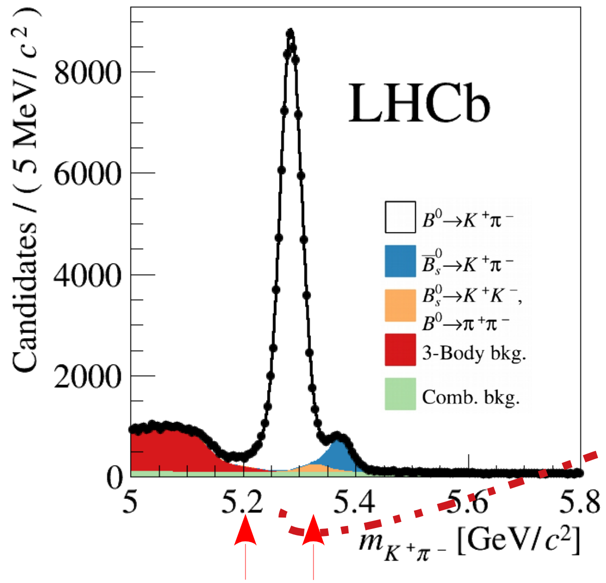


First observation of CPV in $B_s^0 \to K^-\pi^+$ (2013)

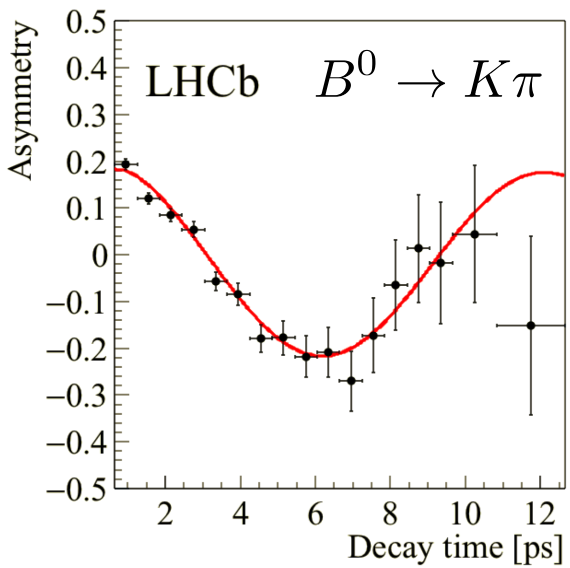
Direct CP Violation in $B^0_{(s)}$ Decays

arXiv:1805.06759

➢ Mass and time dependent asymmetry of $B^0 \to K^+\pi^-$



$\int \mathcal{L} \approx 3 fb^{-1}$



➢ Results after correcting for detection and production asymmetries

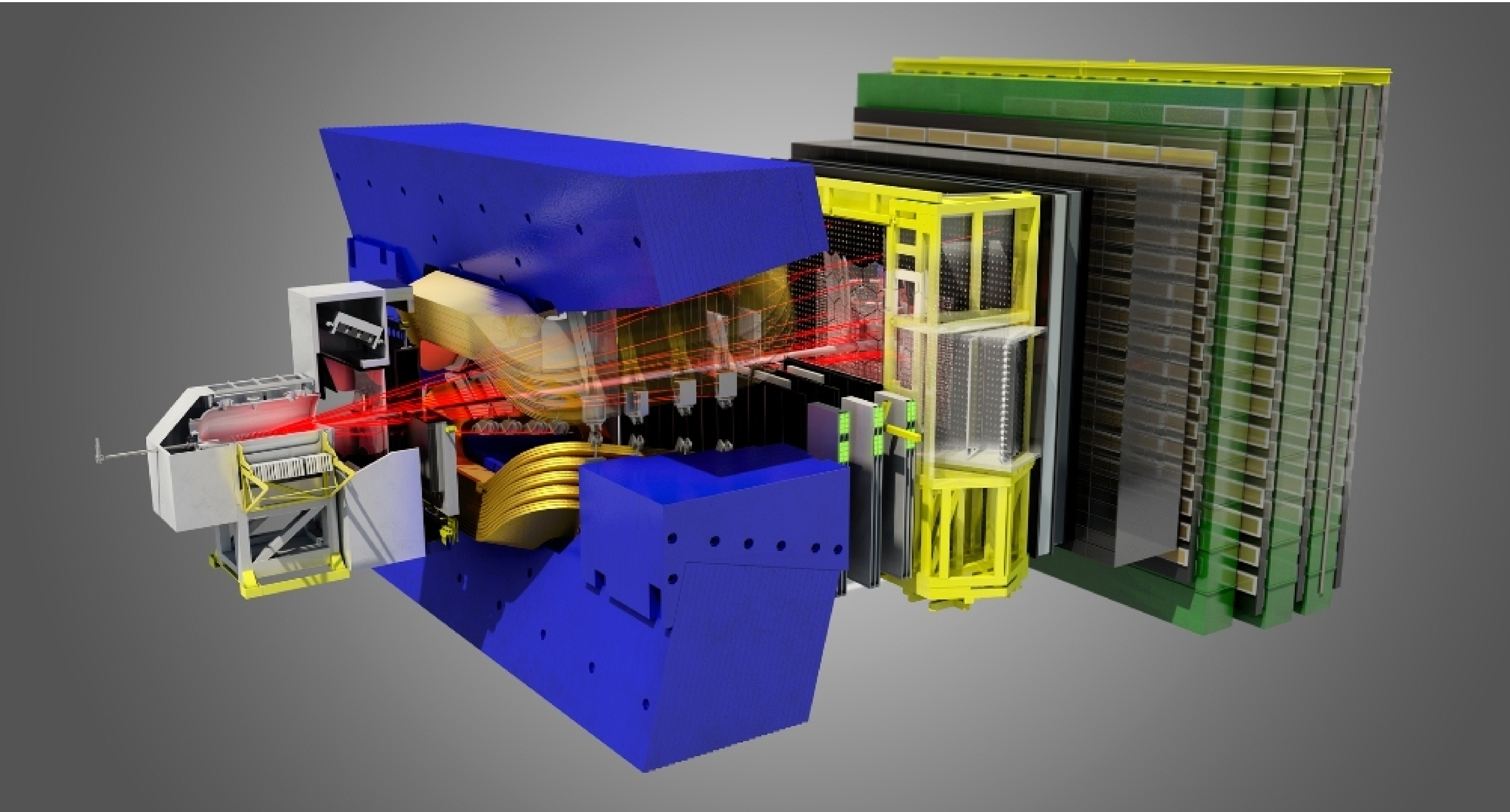
- $A_{CP}(B_s^0 \to K^-\pi^+) = 0.213 \pm 0.015\,(stat) \pm 0.007\,(sys)$
- $A_{CP}(B^0 \to K^+\pi^-) = -0.084 \pm 0.004\,(stat) \pm 0.003\,(sys)$

HFLAV averages + JHEP 04 (2013) 001
arXiv:1612.07233

- $\Delta = -0.11 \pm 0.04 \pm 0.03 \quad \to$ compatible with SM expectation

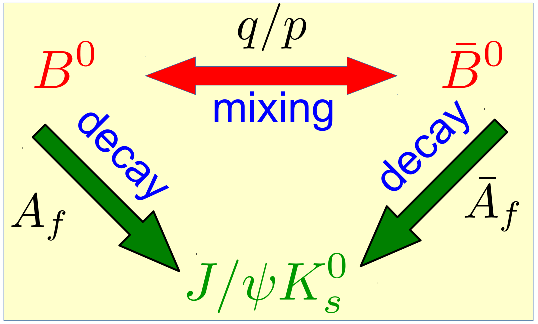
Selected results

CP Violation in the Interference of Mixing and Decay



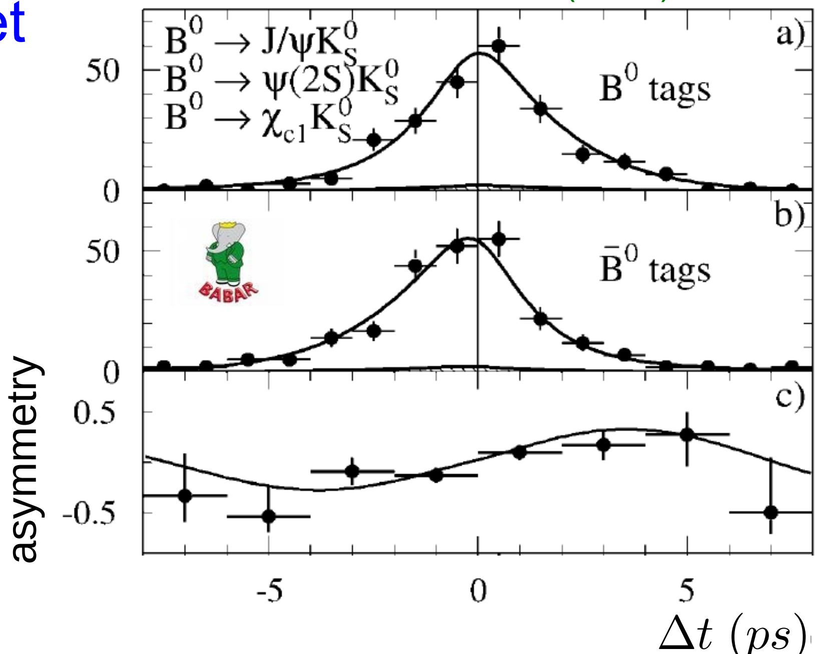
First Observation of CPV in B System

CP violation in the B^0 System was observed in 2001 at the B factories in $B^0/\bar{B}^0$ decays to a CP eigenstate



- The interference between $B^0 \to J/\Psi\, K_s^0$ decays and $B^0 \to \bar{B}^0 \to J/\Psi\, K_s^0$ mixed decays gives access to CP violation in the Interference of mixing and decay

PRL 87 (2001) 091802



- Measure time-dependent asymmetry to get the CP violating phase

$$\mathcal{A}(t) \equiv \frac{\Gamma(\bar{B}^0(t) \to J/\Psi K_s^0) - \Gamma(B^0(t) \to J/\Psi K_s^0)}{\Gamma(\bar{B}^0(t) \to J/\Psi K_s^0) + \Gamma(B^0(t) \to J/\Psi K_s^0)}$$

$$\approx \sin(2\beta)\sin(\Delta m_{(s)} t))$$

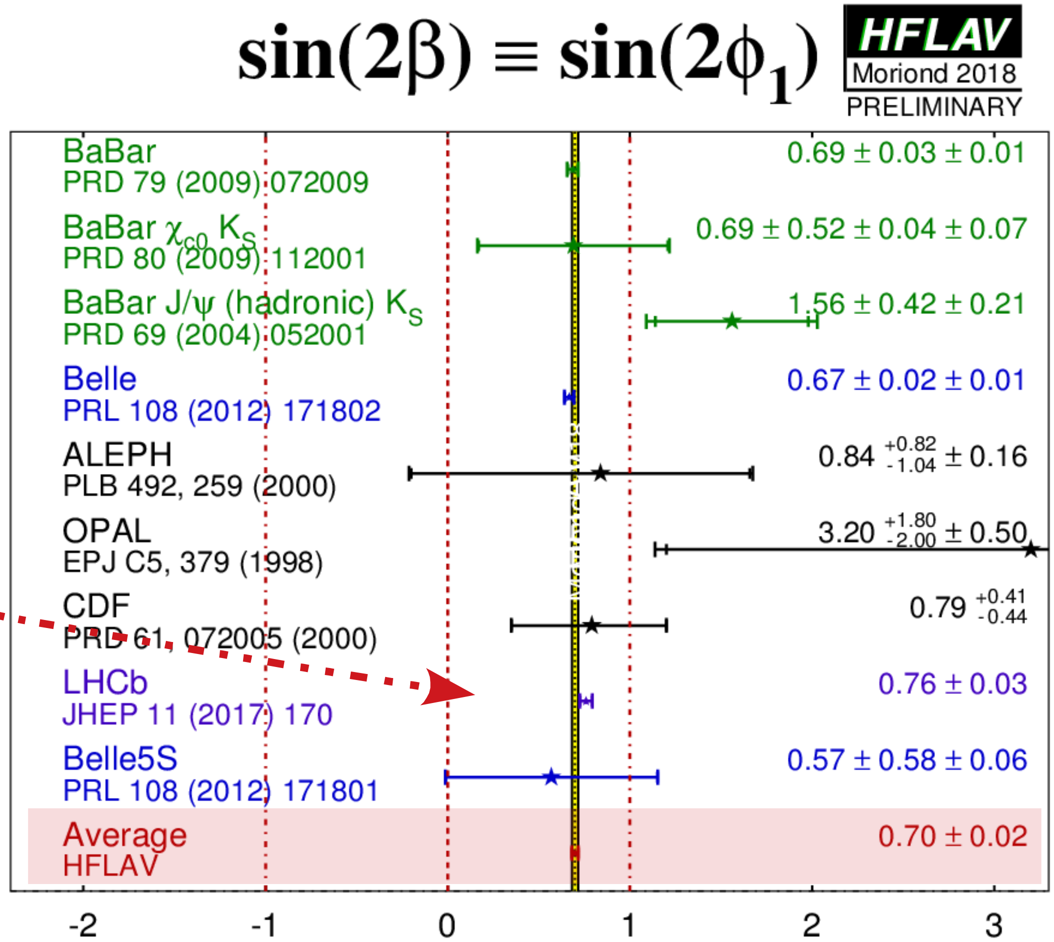
- Requires flavor tagging

$$\sin(2\beta_{B\ fac}) = 0.679 \pm 0.020$$

PRD 79 (2009) 072009, PRL 108 (2012) 171802

Summary - $\sin(2\beta)$ Measurements

- World average as compiled by the Heavy FLavour AVeraging group
  - Compatible with indirect prediction from CKMfitter(2016)
    $\sin(2\beta_{indirect}) = 0.740^{+0.020}_{-0.025}$
  - Uncertainty of the LHCb result with $\int \mathcal{L} = 3fb^{-1}$ is competitive with Belle and *BABAR* JHEP 11 (2017) 170



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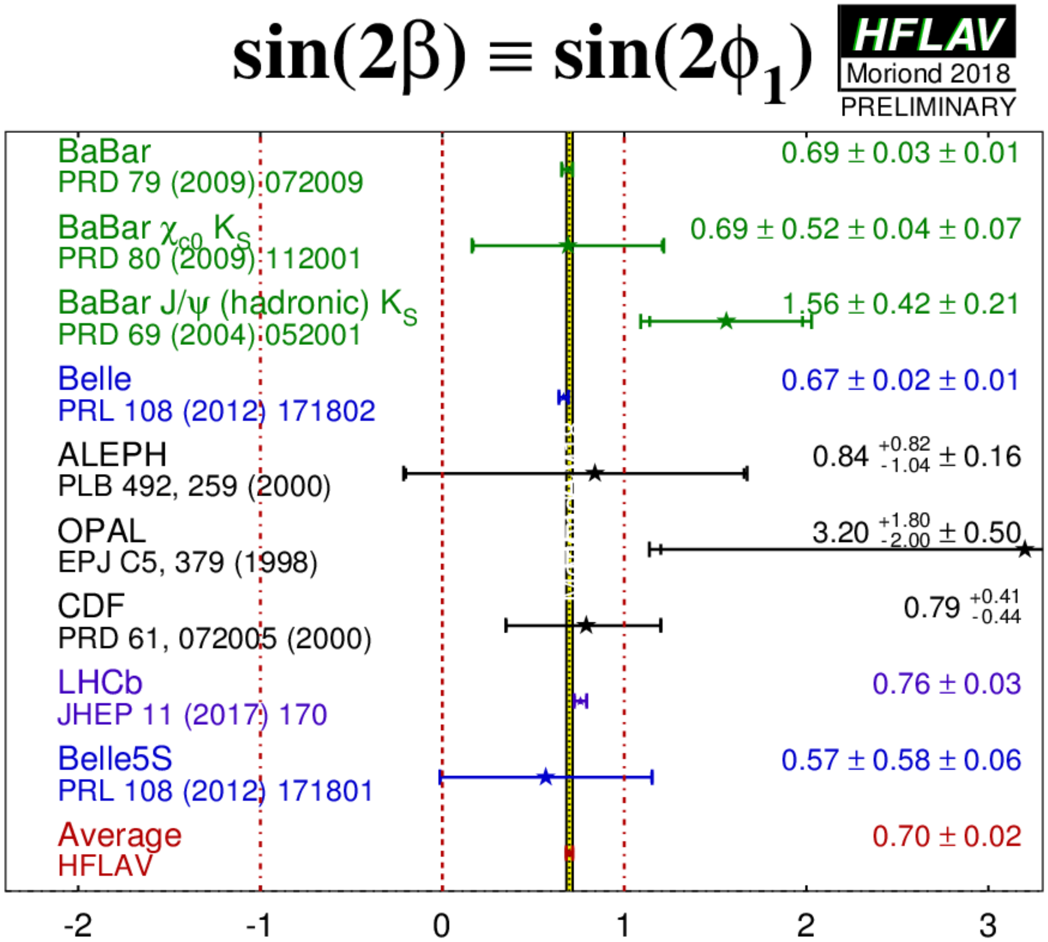
- Current average allows for two solutions in $[0, \pi]$
  $\sin(2\beta_{HFLAV}) = 0.699 \pm 0.017$
  $\beta = (22.2 \pm 0.7)^\circ \quad \beta = (67.8 \pm 0.7)^\circ$



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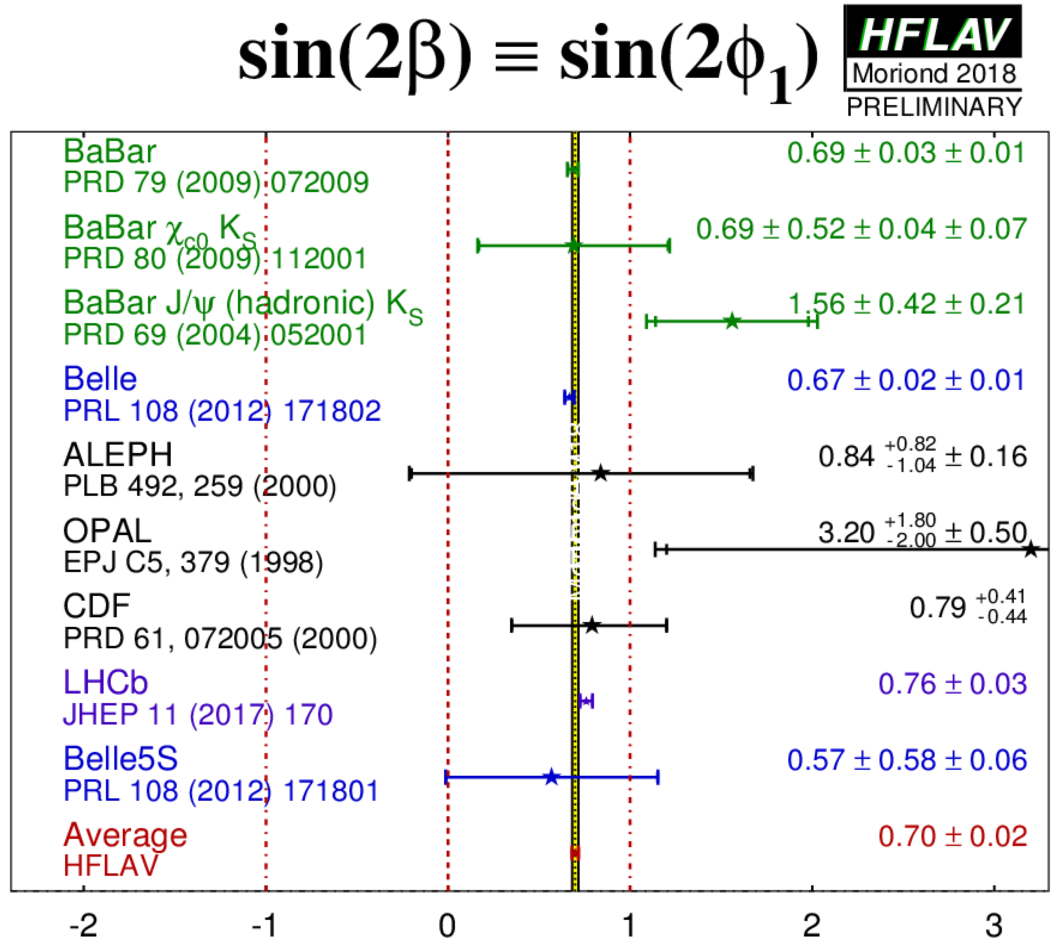
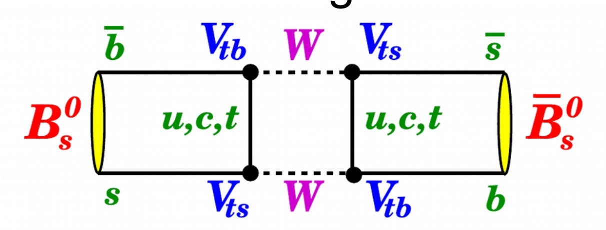
  $\beta = (22.2 \pm 0.7)^\circ$ ~~$\beta = (67.8 \pm 0.7)^\circ$~~ $7.3\,\sigma$
  recent combined Belle and *BABAR* analysis measures $\cos(2\beta) > 0$
  arXiv:1804.06152, arXiv:1804.06153



$\sin(2\beta_s)$ Measurements

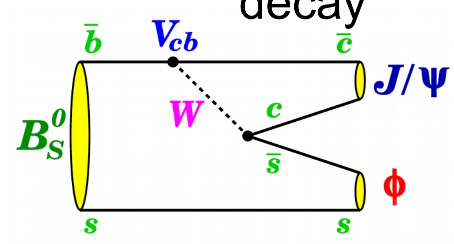
Similar to the B^0 system the interference of mixing and decay gives access to the CP violating phase $\phi_s \equiv -2\beta_s$ in the B_s^0 system

mixing

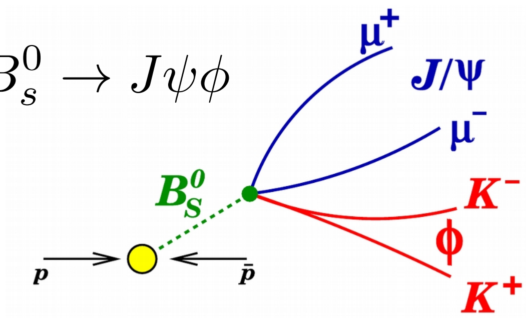


+

decay



$B_s^0 \to J\psi\phi$



PRD 85 (2012) 072002

- Measurements of $B_s^0 \to J/\psi\phi\,,\ J/\psi K^+K^-\,,\ J/\psi\pi^+\pi^-$ first by CDF and D0 then by LHCb, Atlas and CMS

- Access new physics contributions by deviations from SM
  - $\phi_s = \phi_s^{SM} + \Delta\phi_s\ , \quad \Delta\phi_s = arg(M_{12}/M_{12}^{SM})$
  - Get ϕ_s^{SM} from global fit ignoring penguin contribution, CKM fitter arXiv:1501.05013
    $\phi_s^{SM} = -0.0364 \pm 0.0016\ rad$

LHCb - ϕ_s , $\Delta\Gamma_s$ in $B_s \to J/\psi\phi$

➢ Need an angular analysis to statistically separate CP eigenstates

$\phi \to K^+K^-$ in P wave $\to$ CP-even, CP-odd

$\phi \to K^+K^-$ in S wave $\to$ CP-odd

depending on rel. orbital momentum of J/ψ and ϕ

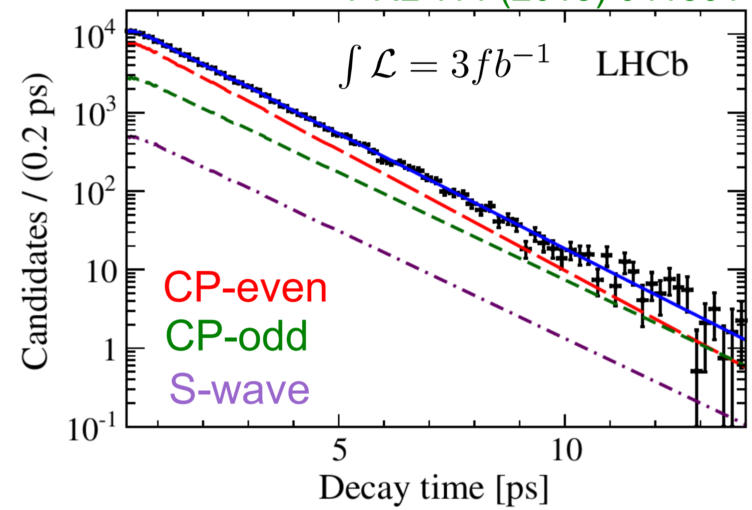
helicity angles $\Omega = (\theta_\mu, \theta_K, \phi_h)$

➢ LHCb determines in a max. likelihood fit to $\frac{d^4\Gamma(B_s^0 \to J\psi KK)}{dt\, d\Omega}$ the physics quantities ϕ_s , $\Delta\Gamma_s$, Γ_s , ...

- Key ingredients to t – dependent flavour tagged angular analysis

  - probability of getting the initial B flavour wrong
  - decay time measurement
  - event by event decay time resolution
  - knowledge of Δm_s

PRL 114 (2015) 041801



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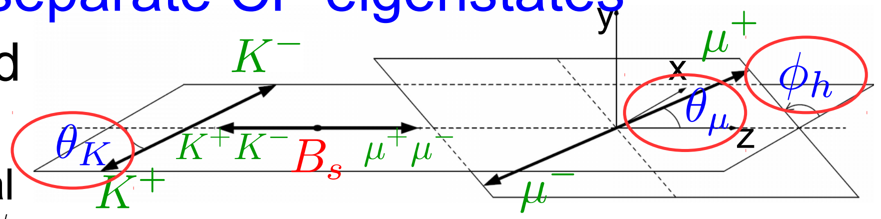
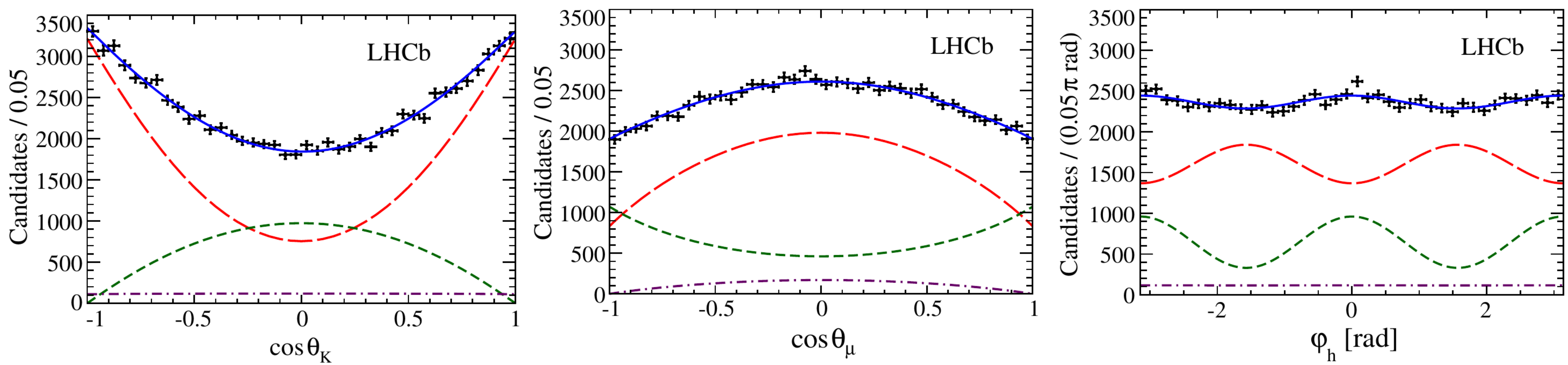


$$\frac{d^4\Gamma(B_s^0 \to J\psi KK)}{dt\, d\Omega}$$

- LHCb determines in a max. likelihood fit to the physics quantities ϕ_s , $\Delta\Gamma_s$, Γ_s , ...

PRL 114 (2015) 041801



CP-even CP-odd S-wave

Summary - ϕ_s , $\Delta\Gamma_s$ in $B_s \to J/\psi\phi$

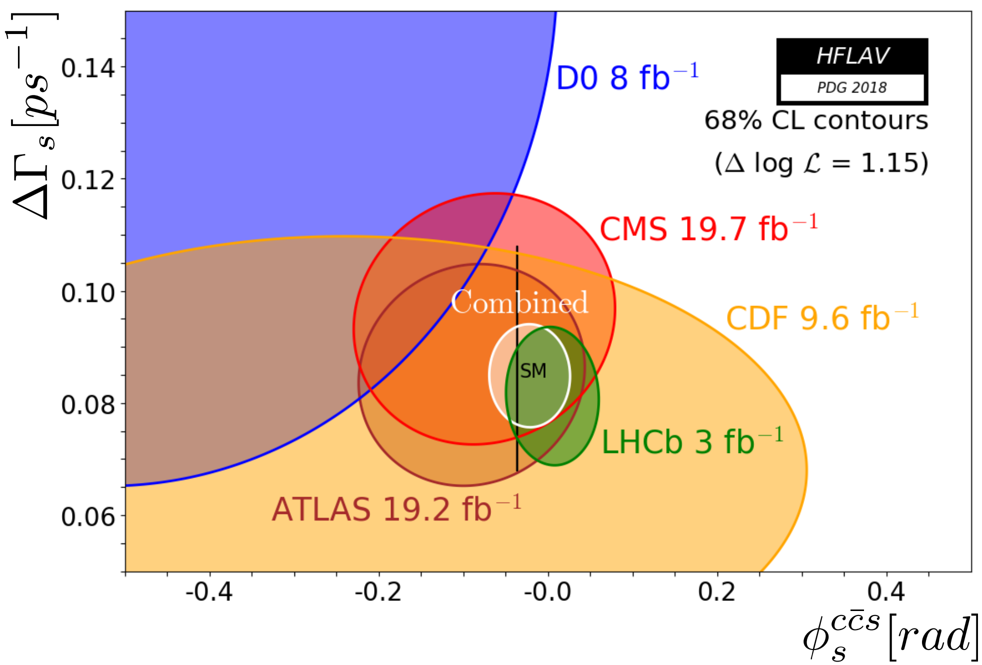
- LHCb results for $B_s \to J/\psi K^+K^-, J/\psi\pi^+\pi^-, J/\psi\phi(K^+K^-)$ JHEP 08 (2017) 037

  $\phi_s = -25 \pm 45 \pm 8\, mrad \quad \Delta\Gamma_s \equiv \Gamma_L - \Gamma_H = 0.0813 \pm 0.0073 \pm 0.0036\; ps^{-1}$

  $\Gamma_s = 0.6588 \pm 0.0022 \pm 0.0015\; ps^{-1}$ $|\lambda| = 0.978 \pm 0.013 \pm 0.003$ no evidence for CPV

  - Measurements include the mass range above $\phi(1020)$

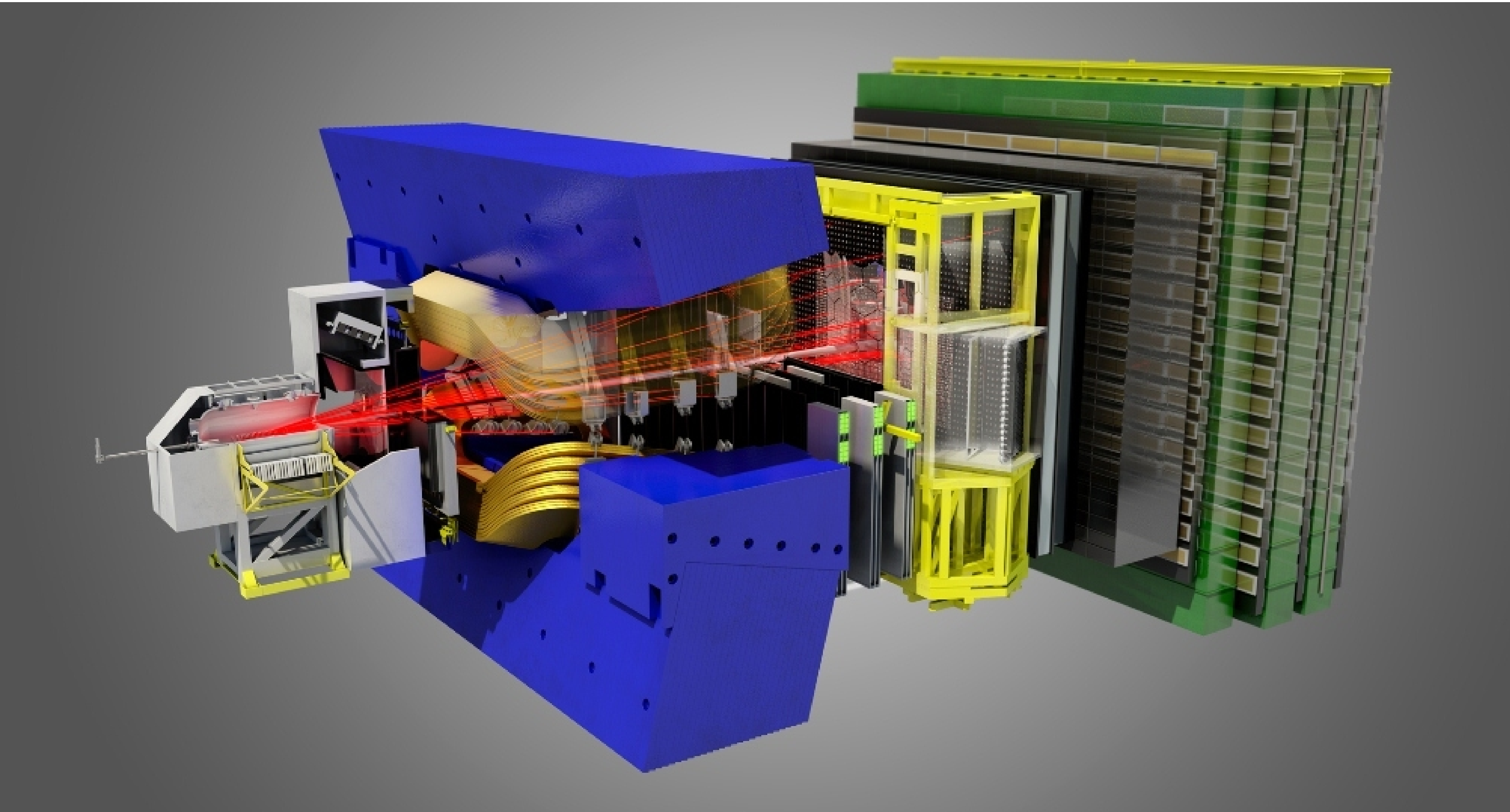
- HFLAV average for $\phi_s^{c\bar{c}s}$ vs $\Delta\Gamma_s$



- Reached a precision of $33\; mrad$ with LHC run 1 data, which includes also ATLAS PLB 757 (2016) 97 and CMS JHEP 08 (2016) 147 data
- Good agreement with Standard Model expectations

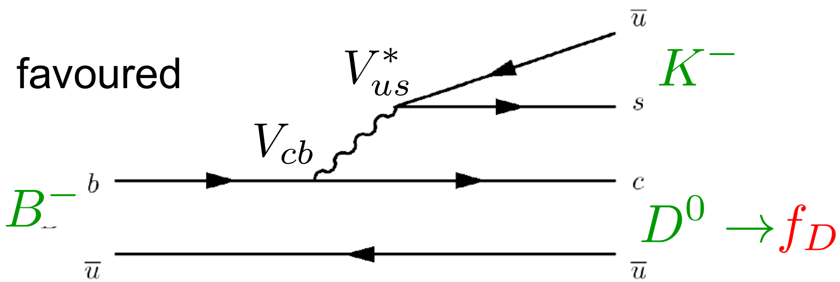
Selected results

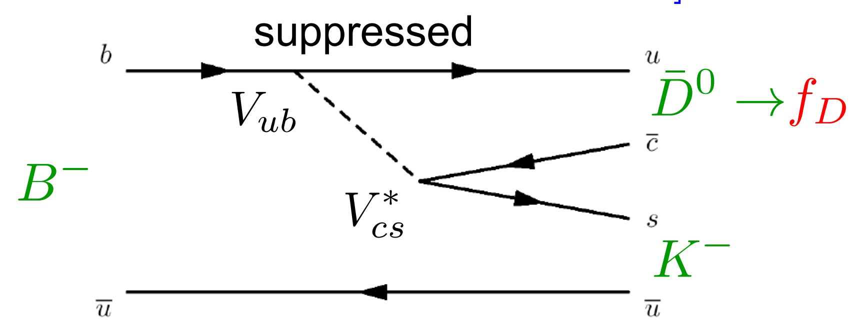
Measurement of the CKM angle γ



Introduction - γ in $B \to DK$ Decays

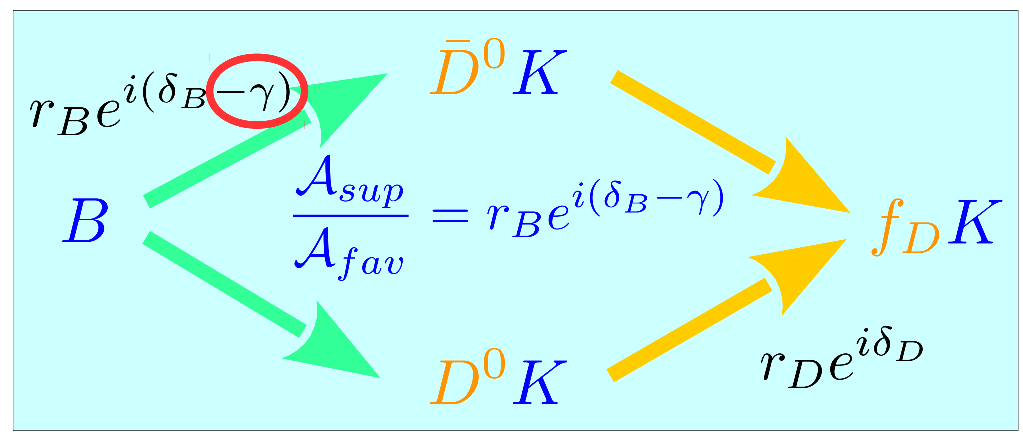
$b \to c$ and $b \to u$ transitions are sensitive to $\gamma \equiv arg[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}]$





Reconstruct $D^{0}/\bar{D}^{0}$ in a final state f_{D} accessible to both to achieve interference

- Interference allows to determine
  - weak phase γ
  - relative strong phase δ_{B}
  - magnitude ratio of the amplitudes r_{B}
- Hadronic parameters (r_{D}, δ_{D}) of f_{D} (either determined or external input)



δ_{D}, δ_{B}: Strong phases r_{B}, r_{D}: Amplitude ratios

- Considered as SM benchmark since only tree level processes are involved

γ Measurement in $B \to DK$ Decays

Depending on the final state $D^0 \to f_D$ distinguish methods of γ extraction

- Measure CP asymmetries and charge averaged partial decay rate ratios
  $\to$ fit for (γ, r_B, δ_B)

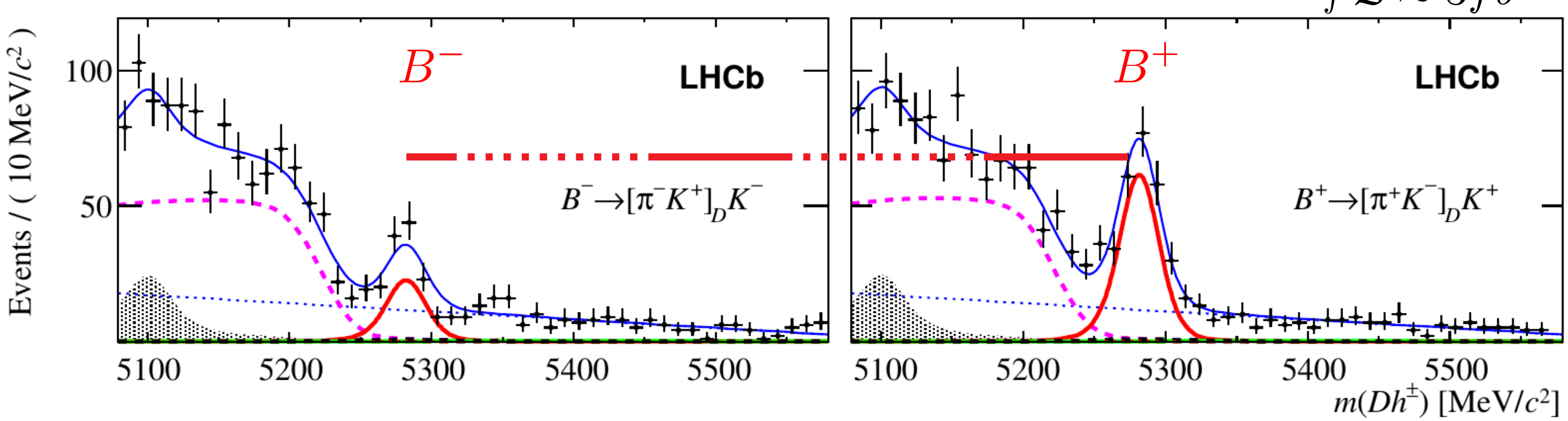
➢ GLW (Gronau, London, Wyler) [1991]): $f_D = [K^+K^-], [\pi^+\pi^-], [K_s^0\pi^0]$

- f_D is a suppressed CP eigenstate

➢ ADS (Atwood, Dunietz, Soni [1997,2001]): $f_D = [K^-\pi^+], [K^+\pi^-]$

- Interference of suppressed B / favoured D decays and favoured B / doubly suppressed D decays

$\int \mathcal{L} \approx 3 fb^{-1}$



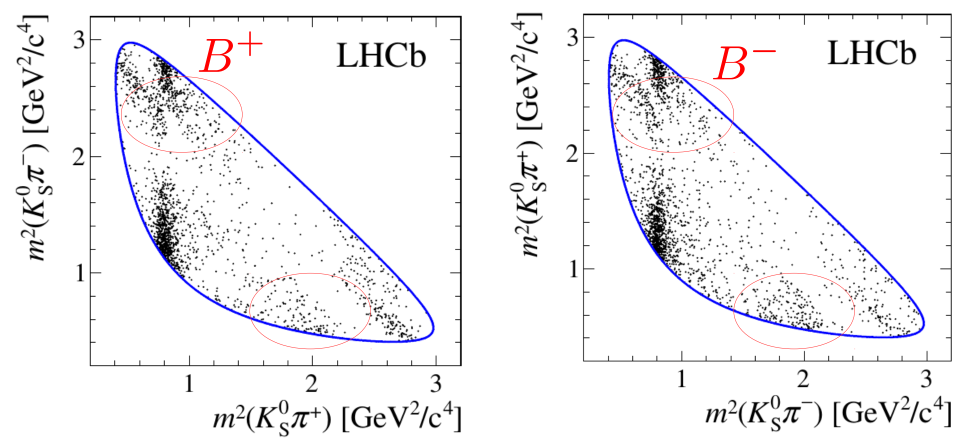
PLB 760 (2016) 117

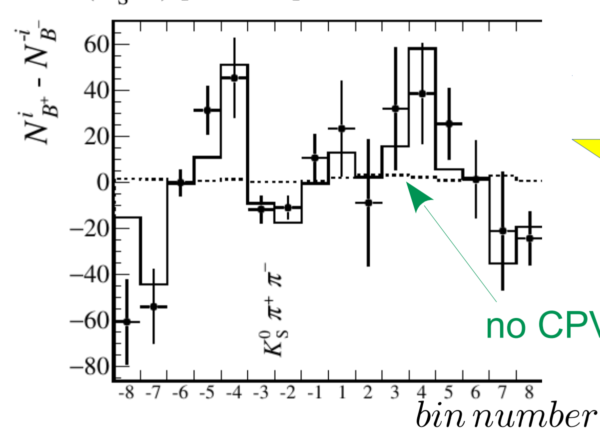
γ Measurement in $B \to DK$ Decays

- GGSZ(Giri, Grossman, Sofer, Zupan) [2003]): $f_D = [K_s^0\pi^+\pi^-, K_s^0K^+K^-]$
  - f_D is a multibody selfconjugate state, which contains different quasi 2-body final states ($D^0 \to K^{*-}\pi^+$, $D^0 \to K^{*+}\pi^-$, $D^0 \to K_s^0\rho^0$)
  - Interference of suppressed and favoured B decays followed by D decays provide amplitude and phase variations across the Dalitz plane
  - Measure yields in bins across the Dalitz plane and compare B^+ and B^-

    Use strong D phase measurement, CLEO-c PRD 82 (2010) 112006

arXiv:1806.01202

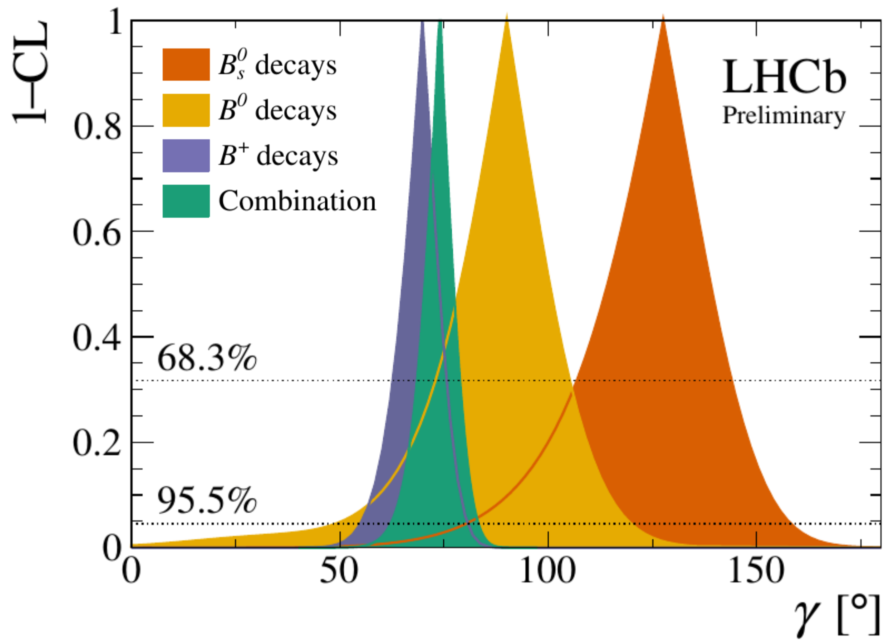




new

LHCb - Results of γ Measurements

- Combine 16 γ measurements to obtain global LHCb average
  - Determine γ and hadronic amplitude ratio and phase difference
  - To achieve optimal sensitivity, use 94 observables with a likelihood ansatz for the combination



$B^+ \to DK^+$	$D \to h^+h^-$	GLW	Run 1 & 2
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	Run 1
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	Run 1
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	Run 1
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	Run 2
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	Run 1
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	Run 1 & 2
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	Run 1 & 2
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	Run 1
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	Run 1
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	Run 1
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	Run 1
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	Run 1
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	Run 1

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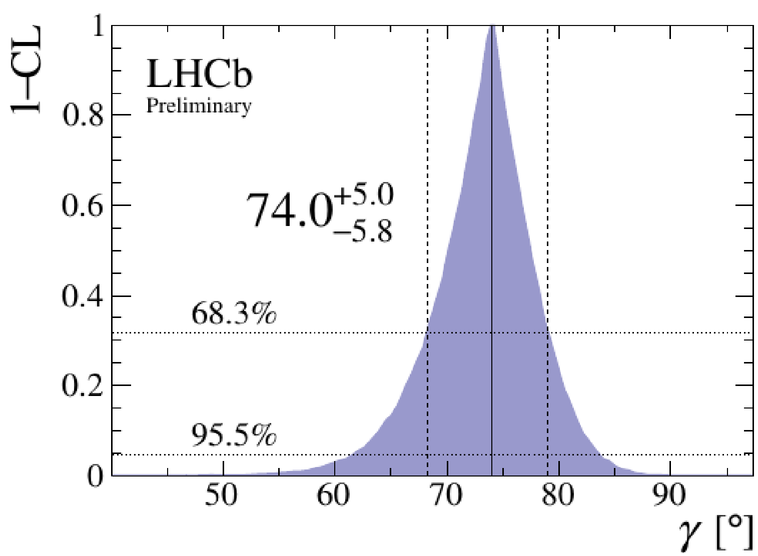
  - Determine γ and hadronic amplitude ratio and phase difference
  - To achieve optimal sensitivity, use 94 observables with a likelihood ansatz for the combination



LHCb-CONF-2018-002

- Uncertainty of γ decreased by a factor of 3 from 2013 to 2018 combining more and more measurements
- Most precise determination from a single experiment to date

$$\gamma_{LHCb} = (74.0^{+5.0}_{-5.8})^\circ$$

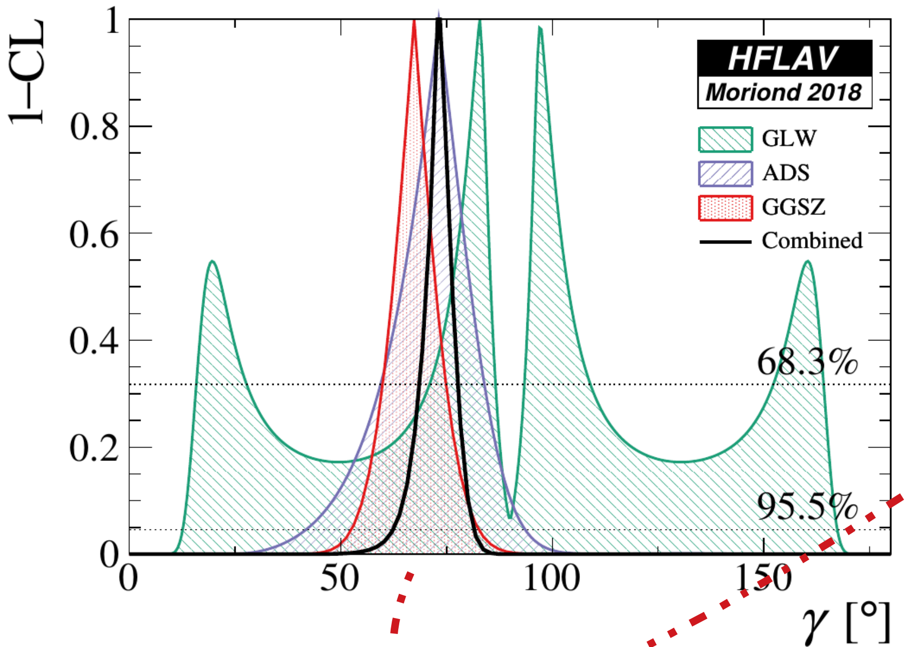
- *BABAR* result using the full dataset

$$\gamma_{BABAR} = (69^{+17}_{-16})^\circ$$

PRD 87 (2013) 052015

World Average of γ Measurements

- All experiments performed measurements with the various methods
  - Determine γ and hadronic amplitude ratio and phase difference
  - Uncertainties of the averages are dominated by the LHCb results



- Average from HFLAV

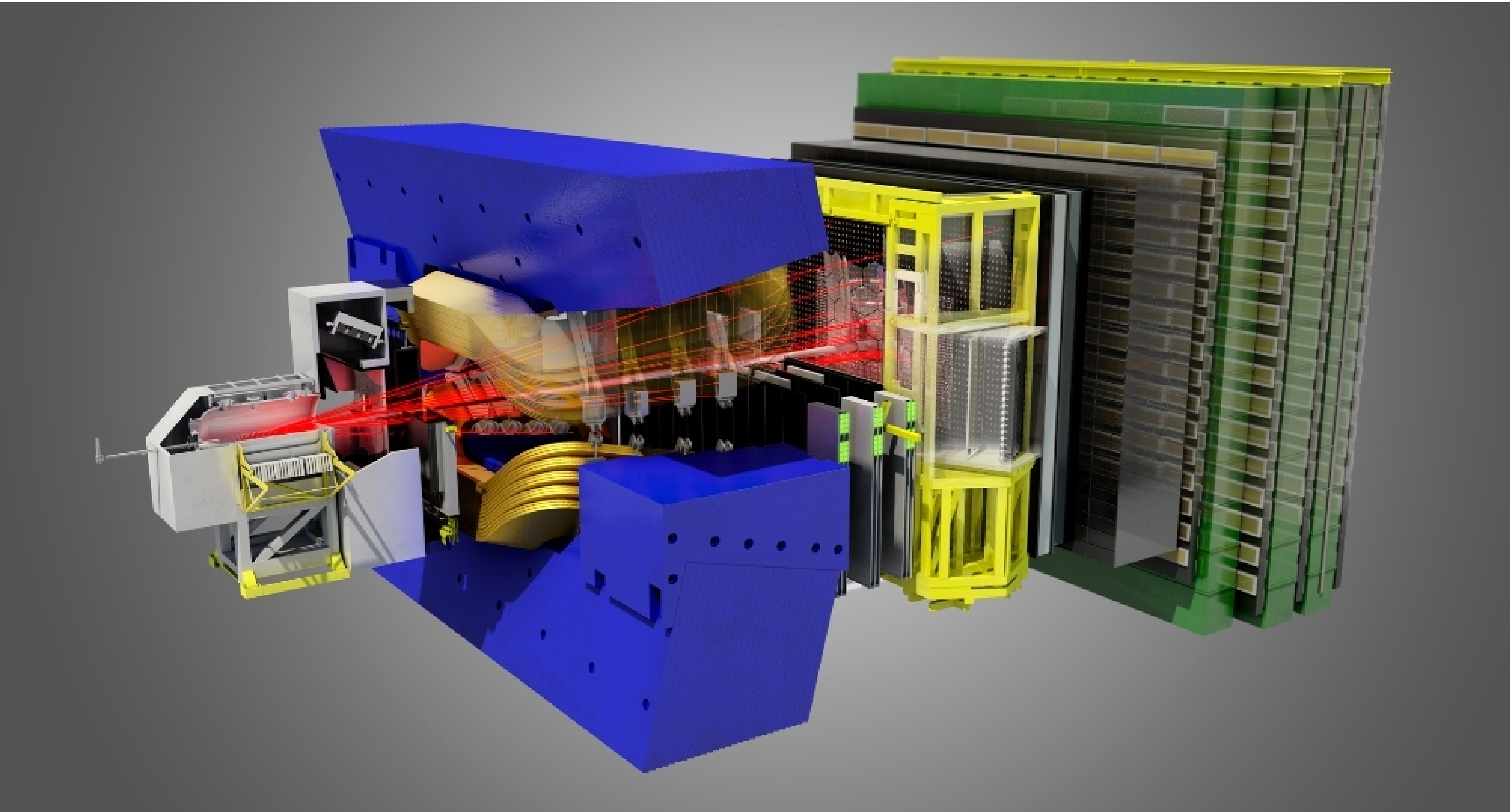
$$\gamma_{HFLAV} = (73.5^{+4.2}_{-5.1})^\circ$$

- Compatible with indirect prediction from CKMfitter(2016)

$$\gamma_{predicted} = (65.1^{+1.0}_{-2.5})^\circ$$

Selected results

CP violation in the Baryon Sector



CPV in Charmless 2-body Λ_b^0 Decays

Phys. Rev. Lett. 113, 242001 (2014)

CDF measured the first time in 2014 CP asymmetries in baryonic decays, $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$, using the full dataset ($9.3\ fb^{-1}$)

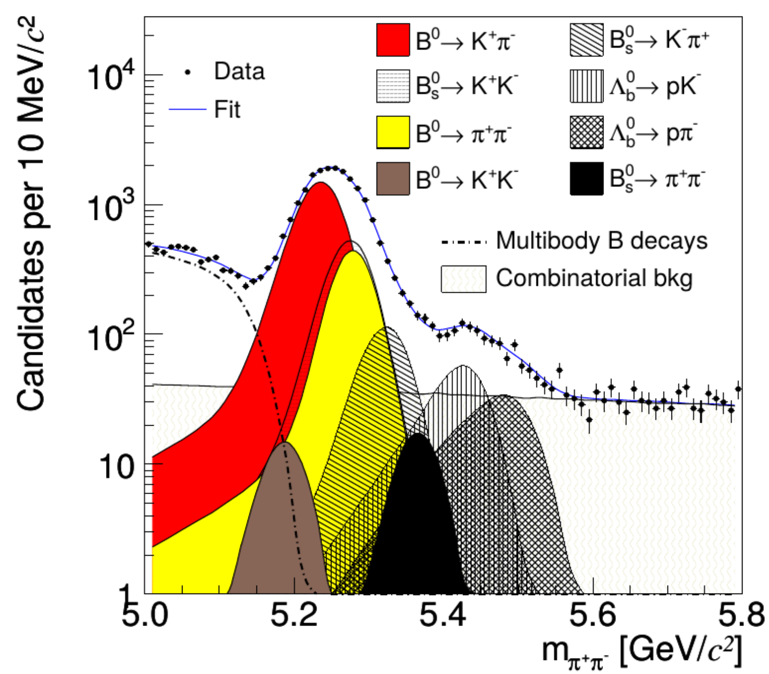
$$A_{CP}^{dir} = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\bar{\Lambda}_b^0 \to \bar{f})}{\Gamma(\Lambda_b^0 \to f) + \Gamma(\bar{\Lambda}_b^0 \to \bar{f})} = \frac{N_{b\to f} - c_f N_{\bar{b}\to\bar{f}}}{N_{b\to f} + c_f N_{\bar{b}\to\bar{f}}}$$

Phys. Rev. D 80, 034011 (2009)

- While theory predicted 30 % asymmetries the measurements are compatible with no direct CP violation

$$A_{CP}^{dir}(\Lambda_b^0 \to p\pi^-) = +0.06 \pm 0.07 \pm 0.03$$

$$A_{CP}^{dir}(\Lambda_b^0 \to pK^-) = -0.10 \pm 0.08 \pm 0.04$$



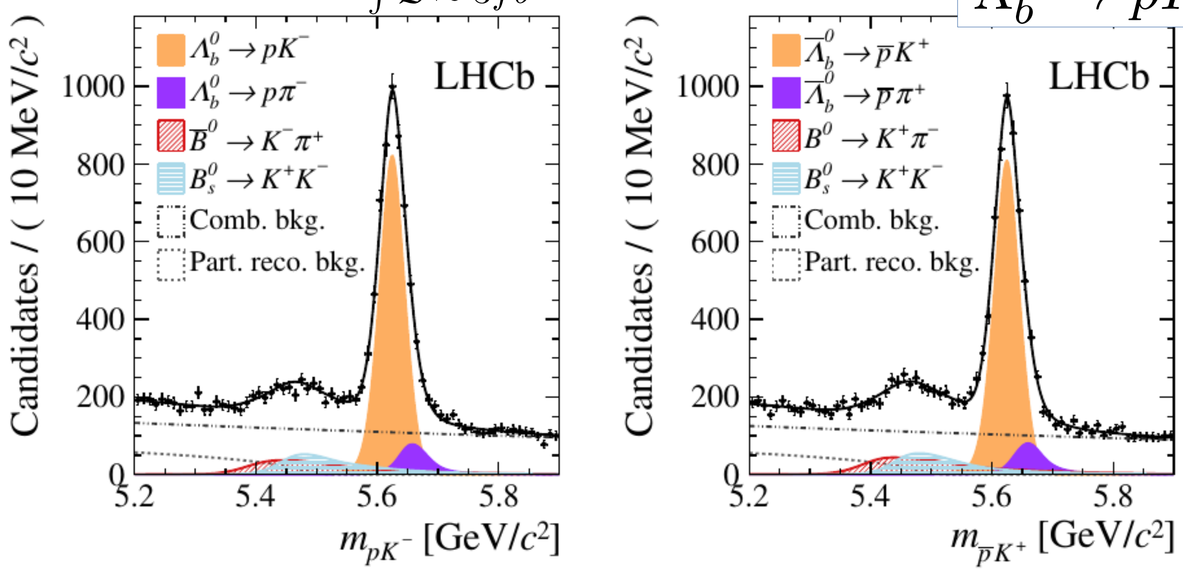
CPV in Charmless 2-body Λ_b^0 Decays

arXiv: 1807.06544 (2018) new

- LHCb measurement of direct CP asymmetries in $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$ using all run 1 data

$\int \mathcal{L} \approx 3 fb^{-1}$

$\Lambda_b^0 \to pK^-$



- Most precise measurement to date, compatible with no direct CP violation

$$A_{CP}^{p\pi^-} = -0.035 \pm 0.017 \pm 0.020$$

$$A_{CP}^{pK^-} = -0.020 \pm 0.013 \pm 0.019$$

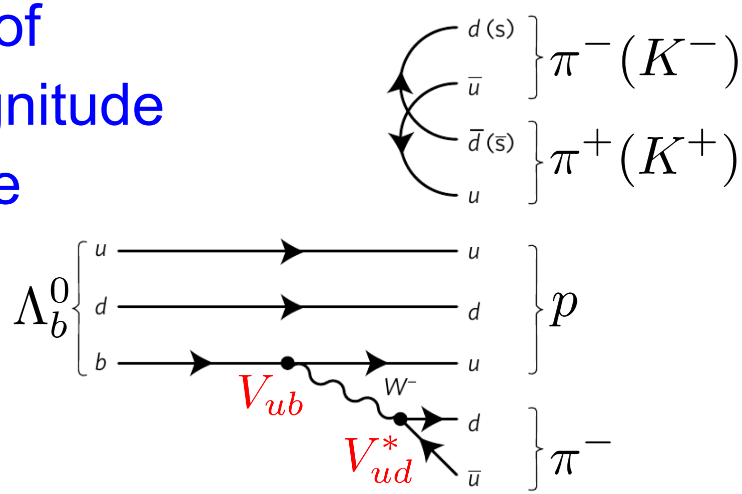
$$A_{CP}^{pK^-} - A_{CP}^{p\pi^-} = 0.014 \pm 0.022 \pm 0.013$$

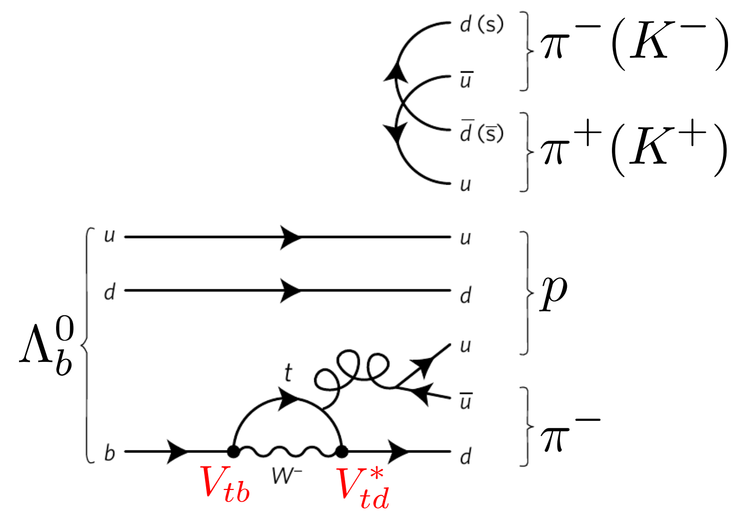
cancels most systematic uncertainties

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ Decays

Nature Physics 13,391-396 (2017)

- Two amplitudes of comparable magnitude interfere and give access to CP violation

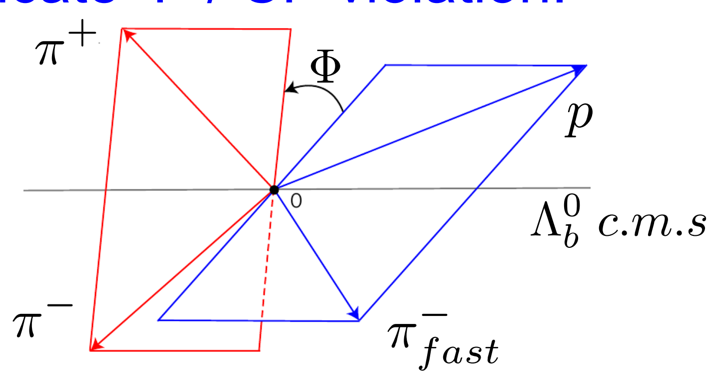




- Measure P and CP violation observables $a_{P/CP}^{T-odd} = 1/2(A_{\hat{T}} \pm \bar{A}_{\hat{T}})$ using triple products of final state particle momenta in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays in the Λ_b^0 $c.m.s.$ Non-zero values indicate P / CP violation.

$$\Lambda_b^0 : \; C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$$

$$\bar{\Lambda}_b^0 : \; \bar{C}_{\hat{T}} \equiv \vec{p}_{\bar{p}} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$



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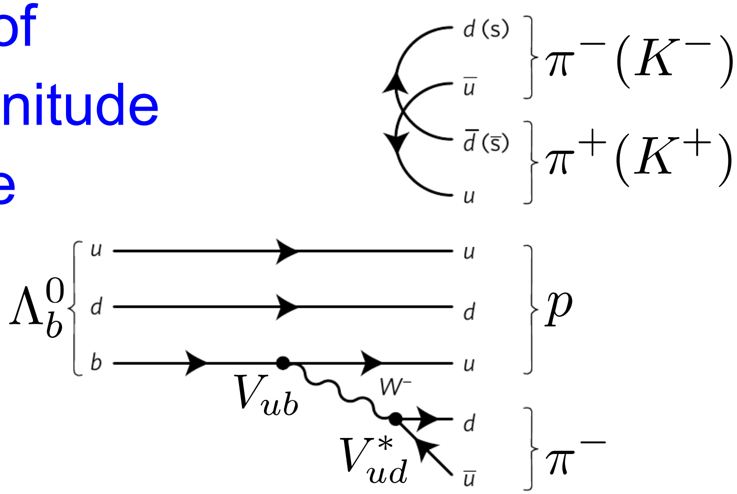

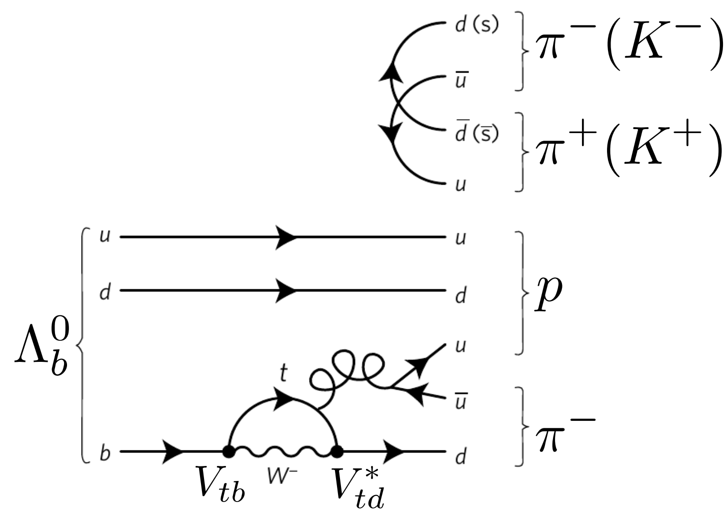

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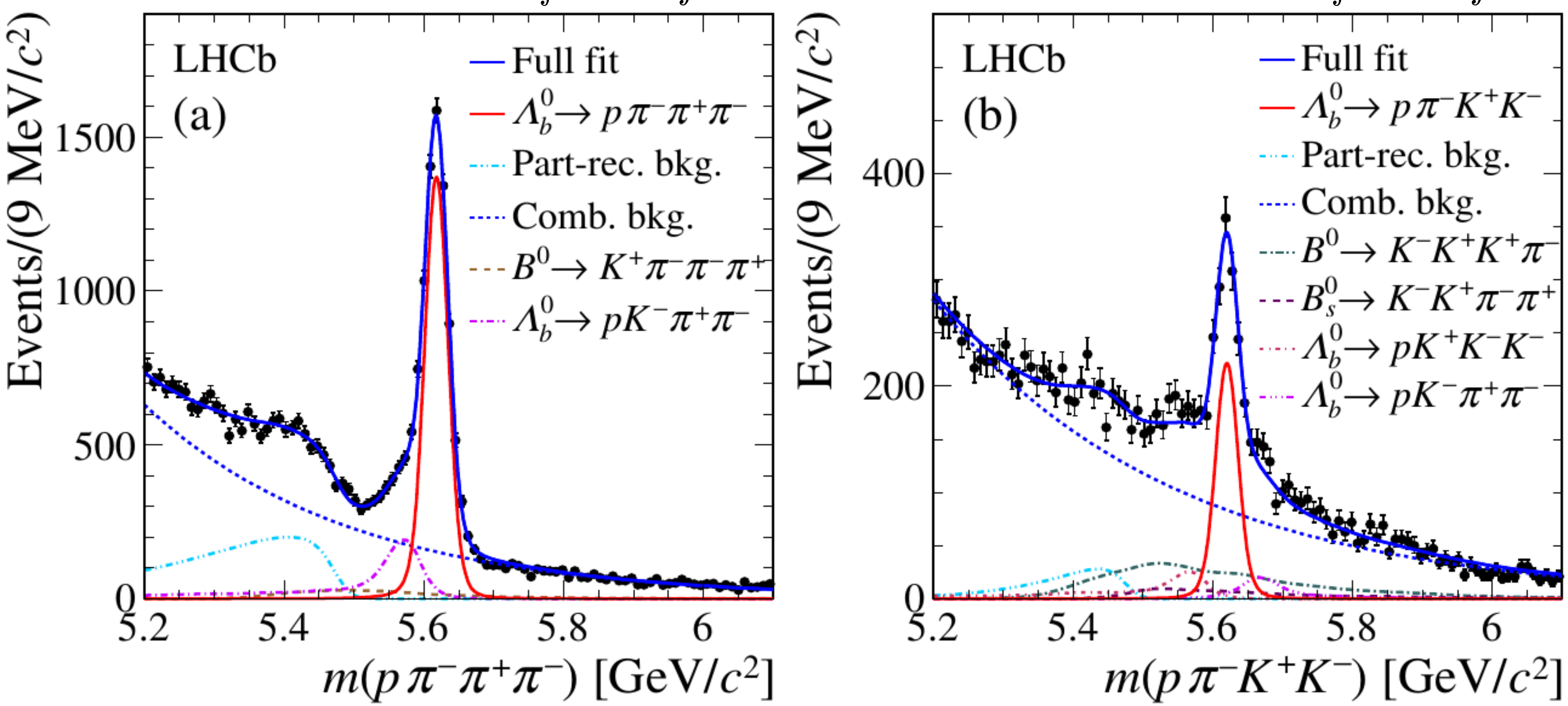
$$\Lambda_b^0 : \ C_{\hat{T}} \equiv \vec{p}_p \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}) \qquad A_{\hat{T}} \equiv \frac{N(C_{\hat{T}} > 0) - N(C_T < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

$$\bar{\Lambda}_b^0 : \ \bar{C}_{\hat{T}} \equiv \vec{p}_{\bar{p}} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \qquad \bar{A}_{\hat{T}} \equiv \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_T < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}$$

CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ Decays

- Signal Distributions

$N = 6646 \pm 105$ $\int\mathcal{L} \approx 3fb^{-1}$ $N = 1030 \pm 56$ $\int\mathcal{L} \approx 3fb^{-1}$



NP 13, (2017) 39

- The Λ_b^0 four body decays have a rich resonance structure dominated in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ by $\Delta(1232)^{++} \to p\pi^+$ and $\rho^0(770) \to \pi^+\pi^-$ decays

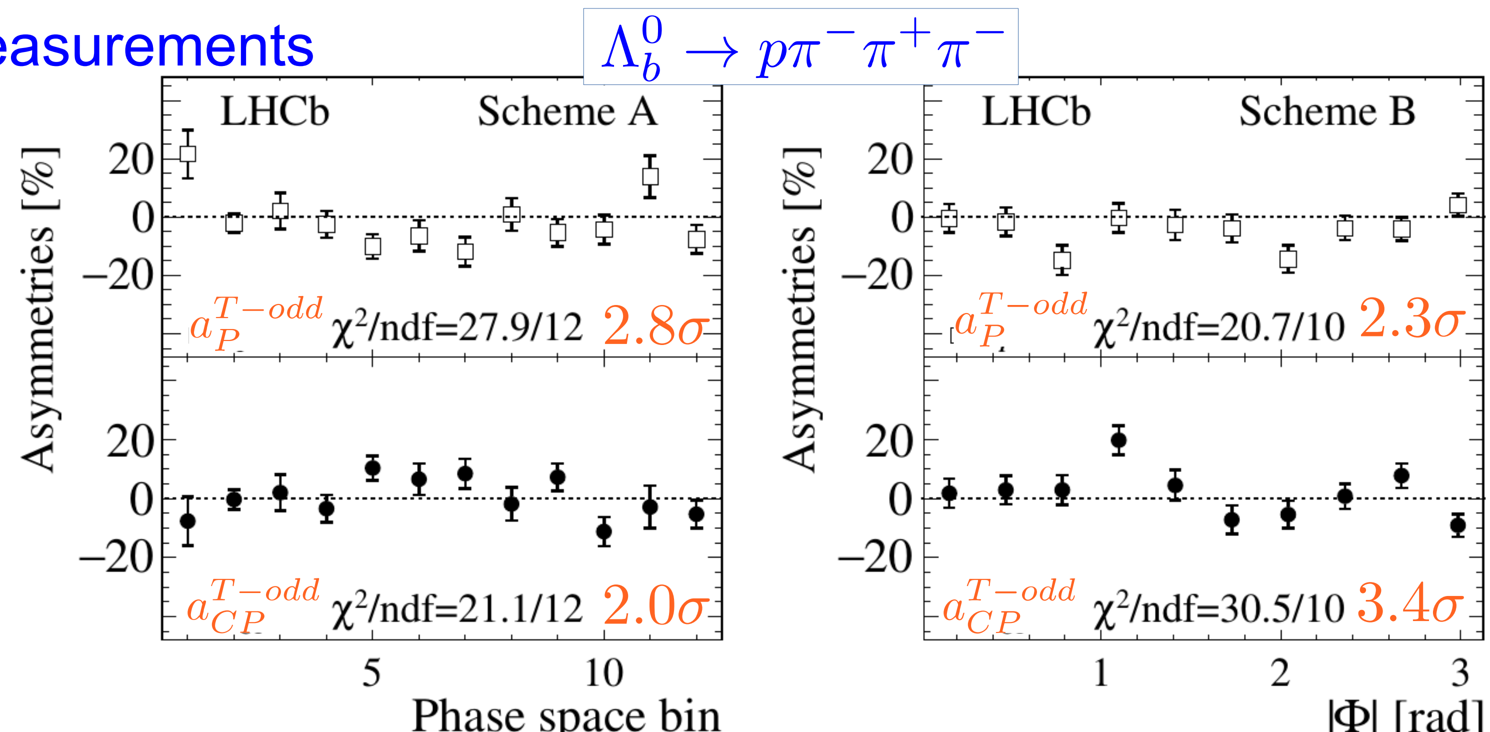
CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ Decays

CP asymmetries vary strongly over the phase space, therefore determine $a_{P/CP}^{T-odd}$ in a phase space and Φ dependent binning.

- Asymmetry measurements over the entire phase space do not show P / CP violation
- First evidence for CPV in the baryon sector at 3.3 σ is found in localized asymmetry measurements

P

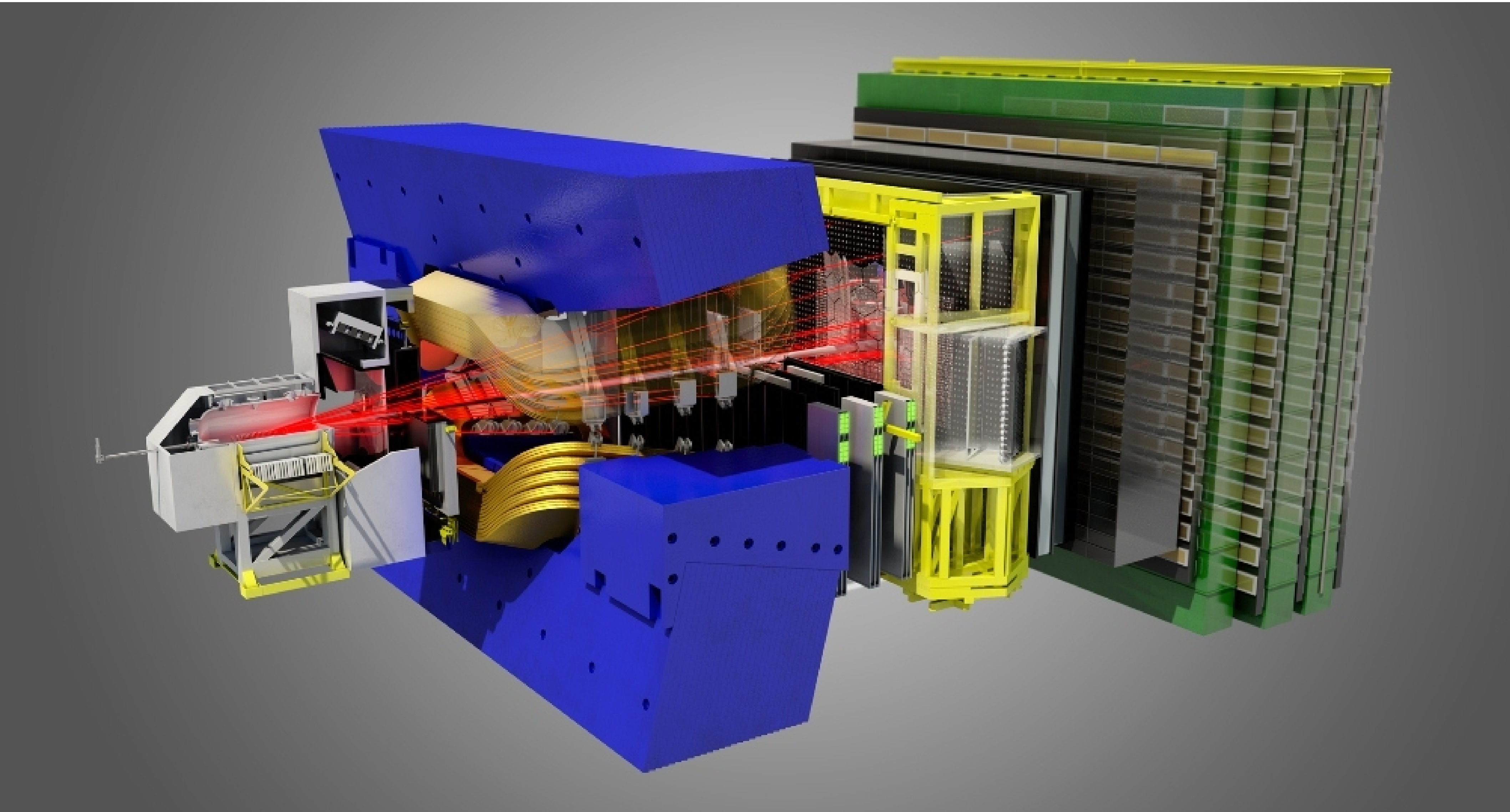
CP



NP 13, (2017) 39

Selected results

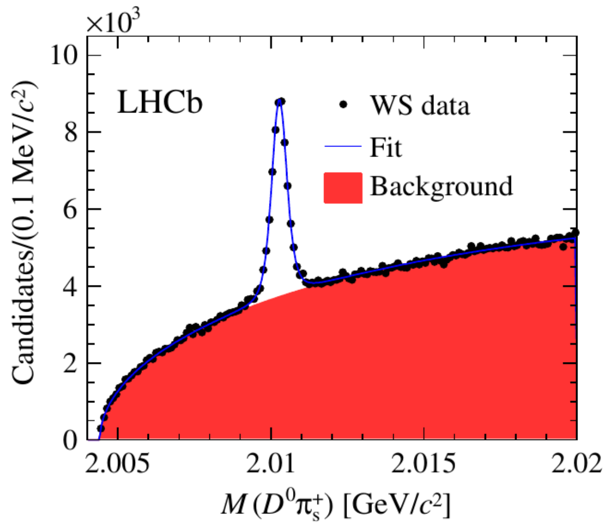
Mixing and CP violation in Charm

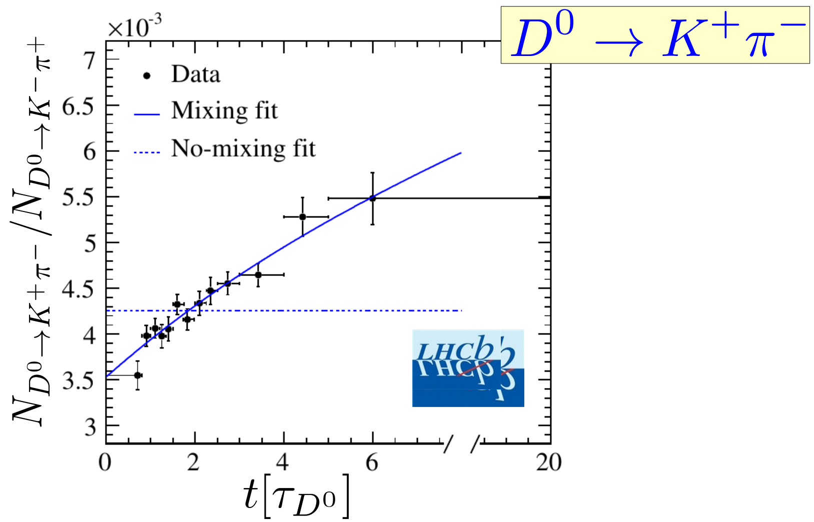


Mixing and CPV in the D System

- SM predicts small effects $(\sim 10^{-3})$ in mixing and CP violation
  - Complement K and B systems, access to new physics coupling to up-type sector
  - D mixing first observed at hadron colliders by LHCb in 2013
    - Established earlier by combining many B factory results

PRL 110 (2013) 101802





no mixing excluded at $9.1\,\sigma$

- Not a precision testing ground, since calculations are difficult due to the intermediate mass range

LHCb - CPV in $D^0 \to K^+\pi^-$

A determination of mixing parameters for D^0 and $\bar{D}^0$ gives access to CPV

- Using data of 2011 – 2016 LHCb determined the time dependent $D^0 \to K^+\pi^- / D^0 \to K^-\pi^+$ rate $R^{\pm}(t)$

PRD 97 (2018) 031101

- Mixing parameter

$$R^{\pm}(t) \propto e^{-\Gamma t}\left(R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm}\,\Gamma t + \frac{x'^{2\pm} + y'^{2\pm}}{4}|\frac{q}{p}|^2(\Gamma t)^2\right)$$

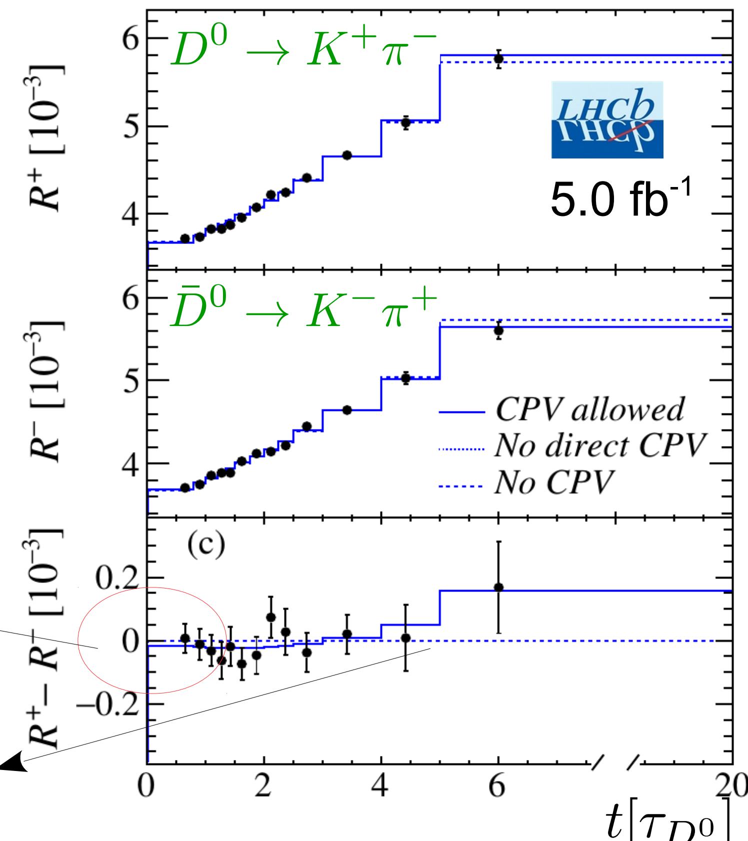
$$y'^{\pm} = |\frac{q}{p}|^{\pm 1}[y\,cos(\delta \pm \phi) \mp x\,sin(\delta \pm \phi)]$$

$$x'^{\pm} = |\frac{q}{p}|^{\pm 1}[x\,cos(\delta \pm \phi) \pm y\,sin(\delta \pm \phi)]$$

$$R_D^{\pm} = R_D(1 \pm A_D)$$

$\neq 0 \to$ direct CPV

$\neq 0 \to$ indirect CPV



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PRD 97 (2018) 031101

- Results

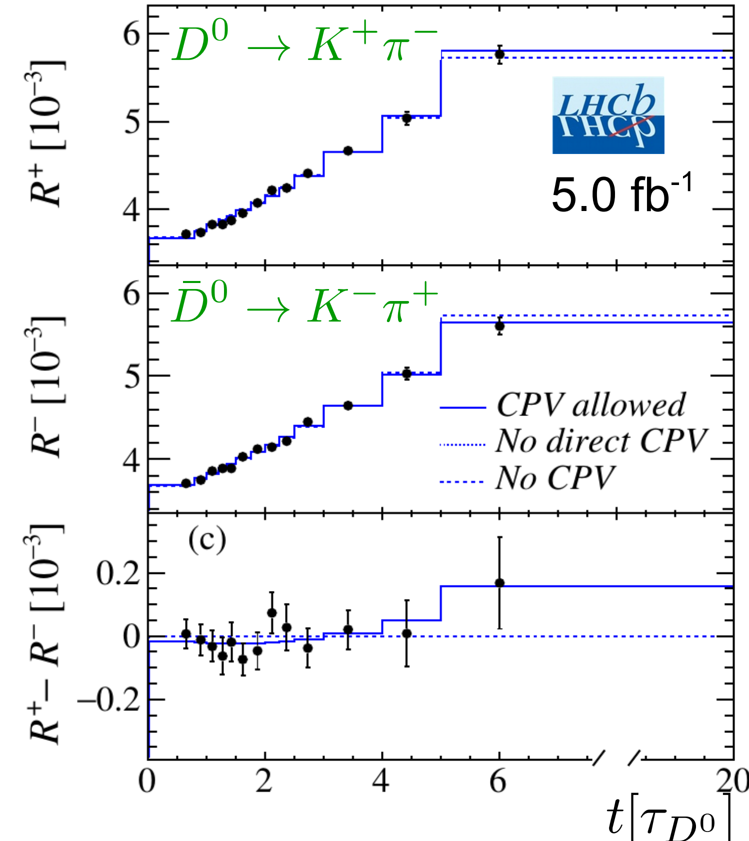
  - CPV in mixing

    $$1.00 < |q/p| < 1.35 \;\; @\, 68.3\,\%\, CL$$

  - direct CPV

    $$A_D = \frac{R^+ - R^-}{R^+ + R^-} = (-0.1 \pm 9.1) \cdot 10^{-3}$$

No indication for direct or indirect CPV



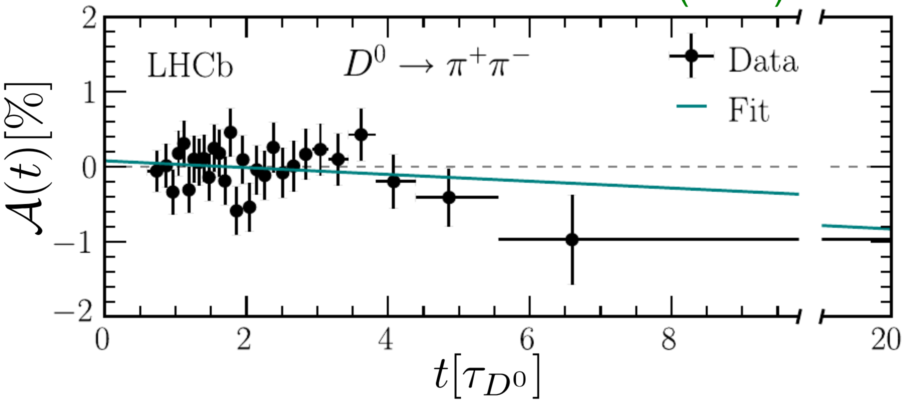
t-dependent CPV in $D^0 \to K^+K^-/\pi^+\pi^-$

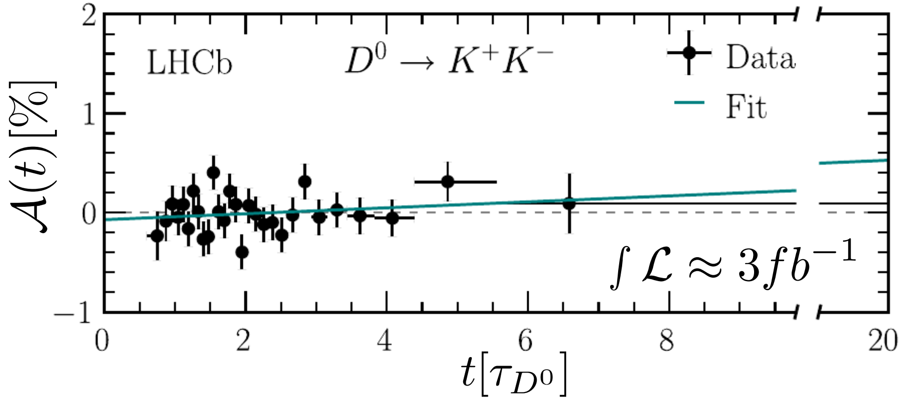
- Access CPV through decay time dependent asymmetry measurements

$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \approx \underbrace{a_{CP}^{dir}(f)}_{\text{CPV in decay}} - \underbrace{\frac{t}{\tau} A_\Gamma}_{\text{CPV in mixing + interfer.}}$$

CP eigenstate

PRL 118 (2017) 261803





- World best measurement using $\mathcal{L}_{int} \approx 3\ fb^{-1}$

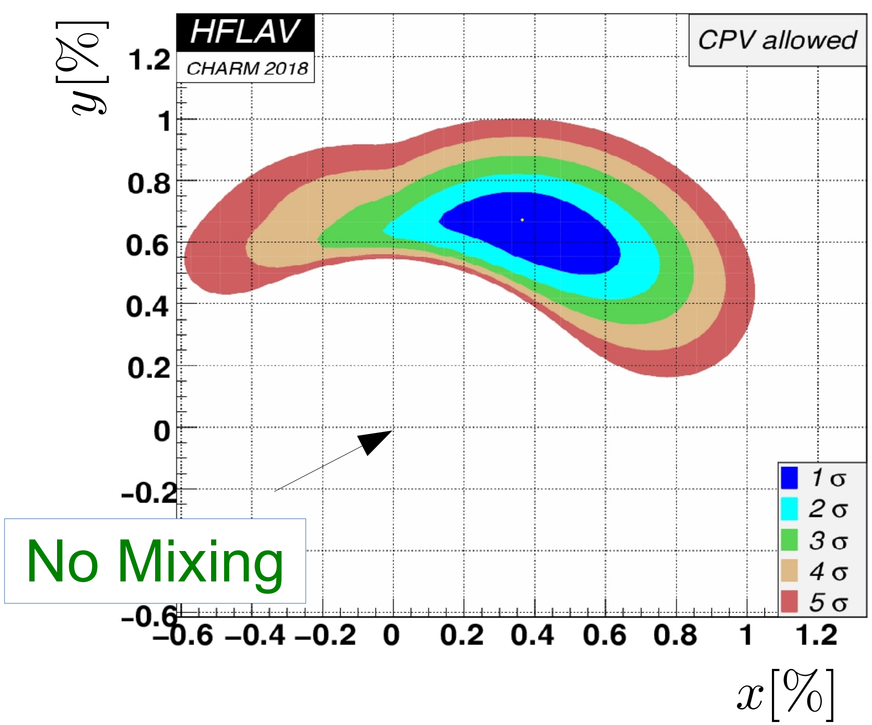
$A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \cdot 10^{-3}$

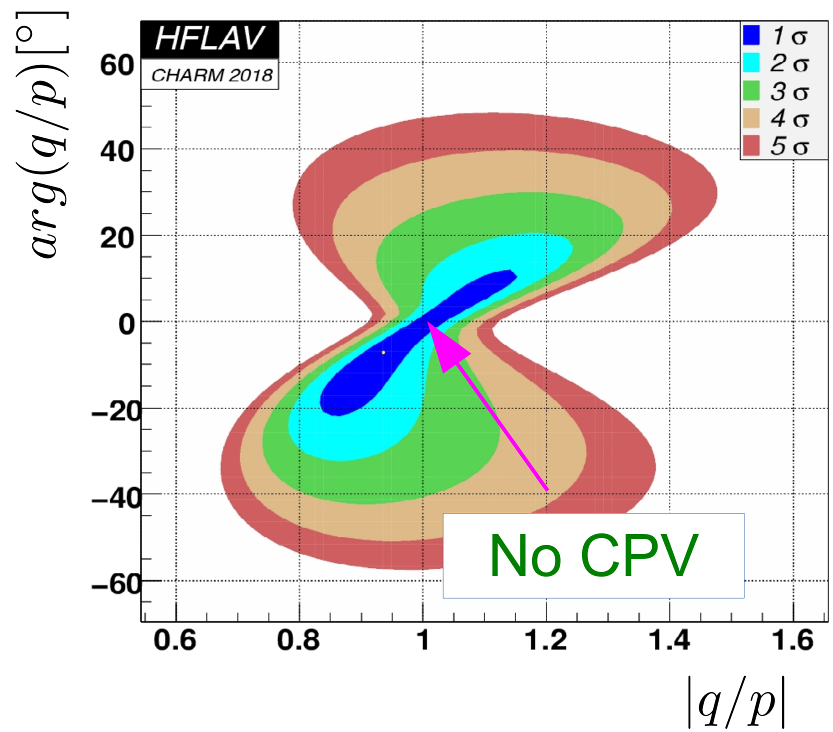
$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \cdot 10^{-3}$

No indirect CPV, level of precision 10^{-3}

Summary - CPV in Charm

- ➢ LHCb takes the fine results of the B factories and Tevatron in charm physics to an even higher precision





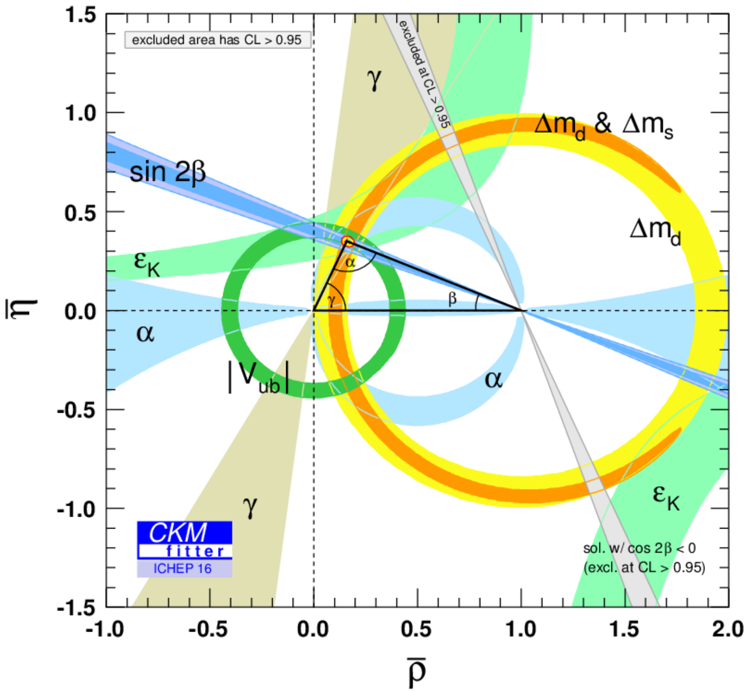
- Experimental data indicates mixing
- No indication for CP violation

- ➢ All results are compatible with Standard Model expectations

Summary

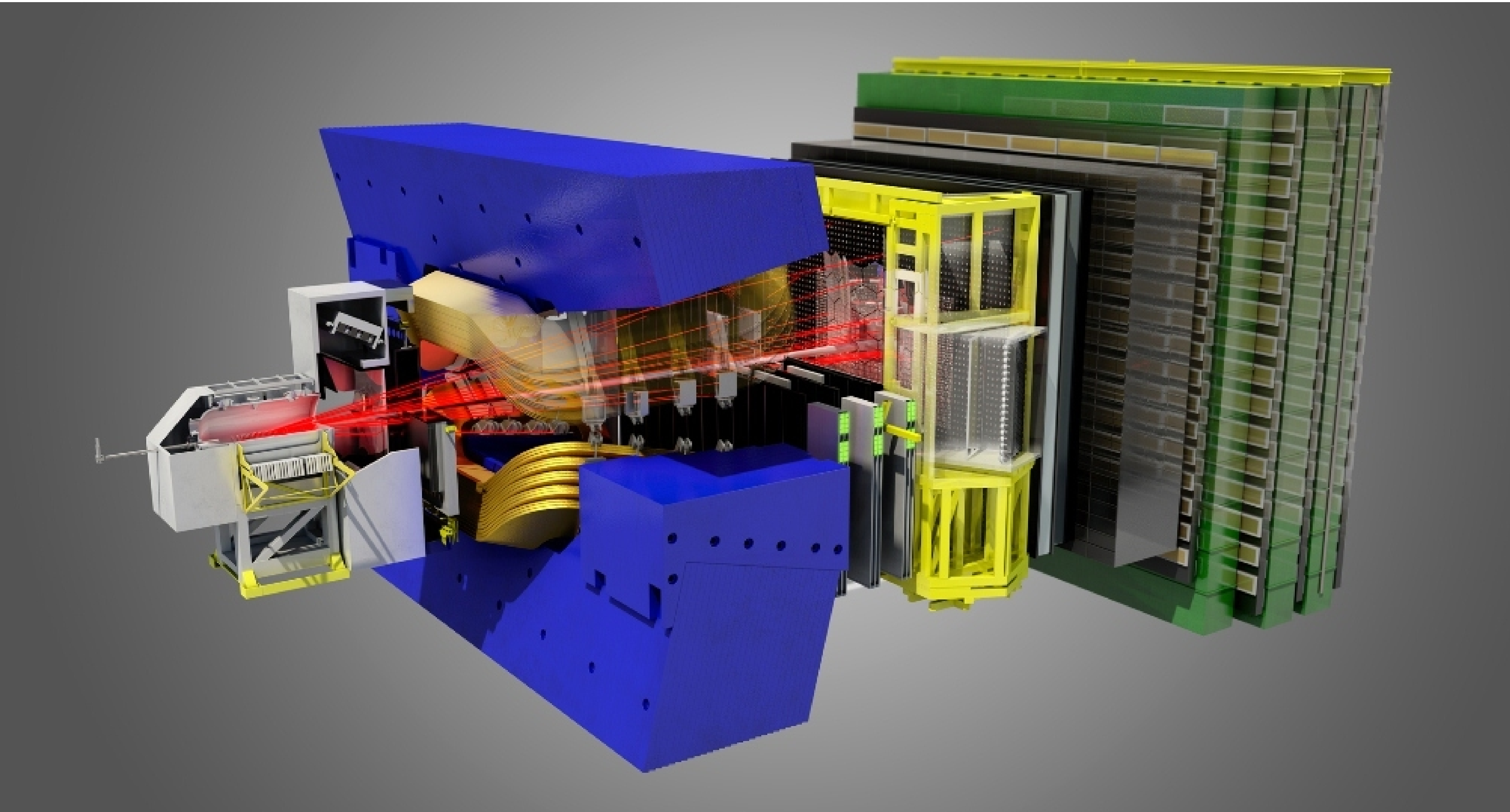
- Measurements of the CKM triangle made an enormous progress in the LHC era and are a very important tool in the search for new physics
- All measurements of CP violation are consistent with the predictions of the CKM mechanism of the Standard Model

  → no evidence for new physics contributions



- First evidence of CPV in the baryon sector is found by LHCb in localized asymmetry measurements → many more measurements to come
- BELLE II and LHCb Upgrade will further improve the precision in CPV measurements → stay tuned

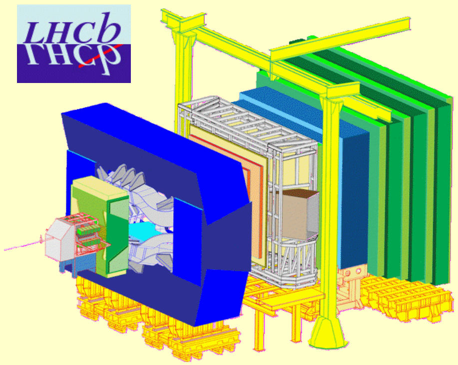
Backup



Contributors Beauty / Charm Physics

B physics experiments are also well suited for charm physics

hadron collider



LHCb at LHC

$\int_{run1} \mathcal{L} \approx 3fb^{-1}$

$\int_{run2} \mathcal{L} \approx 5fb^{-1}$

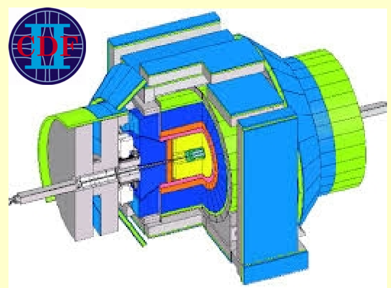
$3.9 \cdot 10^{12}\ b\bar{b}$

world's largest B sample

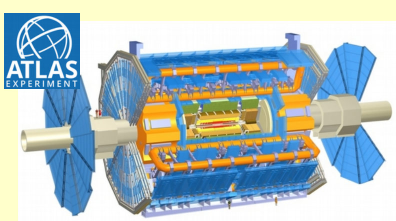
CDF at TEVATRON

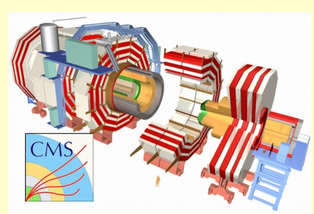
$\int \mathcal{L} \approx 9.6fb^{-1}$

$1.3 \cdot 10^{10}\ b\bar{b}$

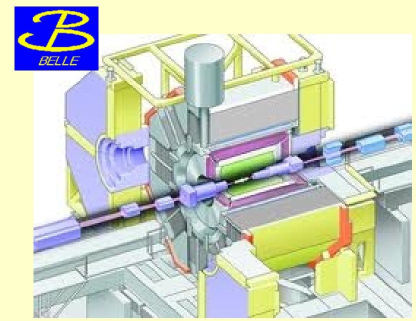


General Purpose Experiments





e^+e^- collider



Belle at KEKB

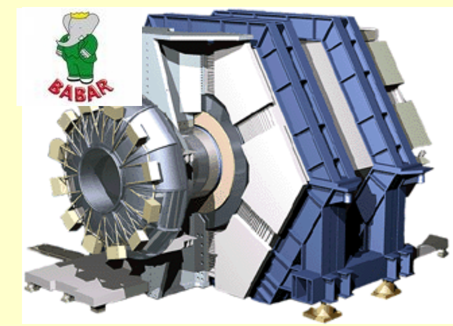
$\int \mathcal{L} \approx 1atb^{-1}$

$1.2 \cdot 10^{9}\ b\bar{b}$

BABAR at PEPII

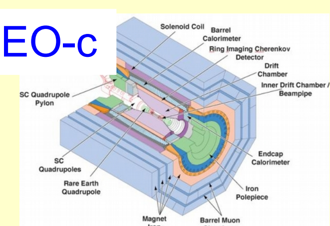
$\int \mathcal{L} \approx 550fb^{-1}$

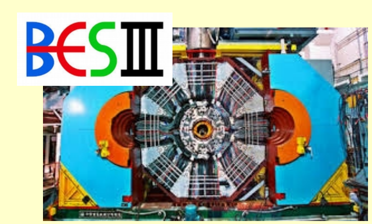
$6.6 \cdot 10^{8}\ b\bar{b}$



Charm Facilities $\psi(3770)$

CLEO-c





Experimental Aspects

Different experimental requirements at pp and e^+e^- facilities

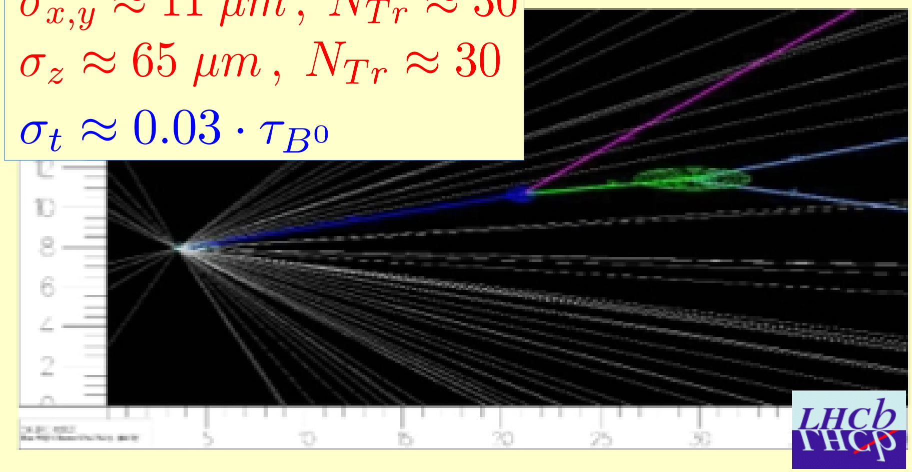
hadron collider

PV resolution

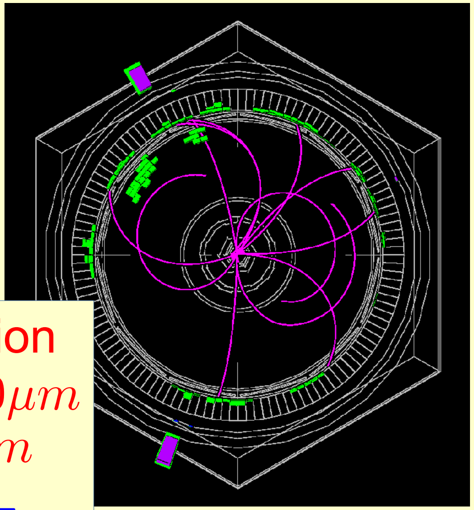
$\sigma_{x,y} \approx 11\ \mu m\,,\ N_{Tr} \approx 30$

$\sigma_z \approx 65\ \mu m\,,\ N_{Tr} \approx 30$

$\sigma_t \approx 0.03 \cdot \tau_{B^0}$



e^+e^- collider

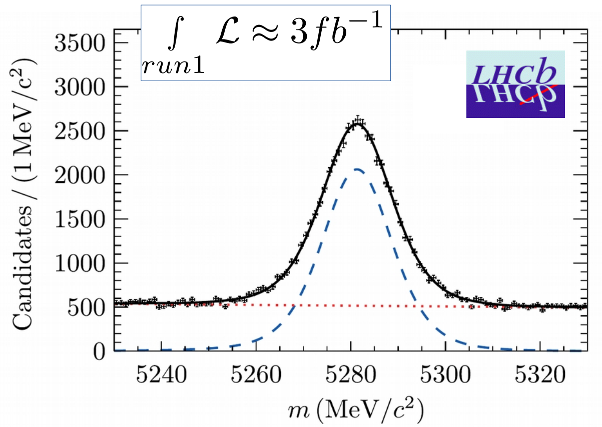


PV resolution

$\sigma_{x,y} \approx 130 \mu m$

$\sigma_z \approx 80\ \mu m$

$\sigma_t \approx 0.3 \cdot \tau_{B^0}$



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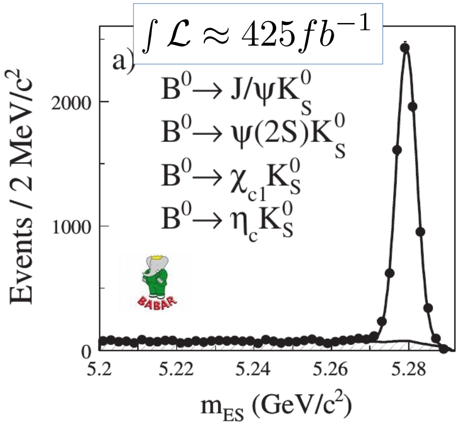
$m(B^0 \to J/\Psi\, K_s)$

B^0 CP violation measurement



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Asymmetry Measurements

Measure CP asymmetries at $10^{-3} \rightarrow$ control systematic uncertainties at a similar level

- Determine raw asymmetries A_{raw} by comparing partial decay rates of a process and its CP conjugate

$$A_{raw} = \frac{N(x) - N(\bar{x})}{N(x) + N(\bar{x})}$$

- Systematic uncertainties cancel, 2 contributions in case of LHCb
  - production rate asymmetries, A_P (measurements for $B^0, B_s^0, B^+, \Lambda_b^0$)
  - asymmetries due to particle / anti-particle detection, A_D

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- For LHCb A_P and A_D are determined by
  - use of control samples
  - regularly reverse magnet polarity
  - remove fiducial volumes contributing to asymmetries

- CP asymmetry: $A_{CP} = A_{raw} - A_P - A_D$