The University of Manchester

Flavour Physics: CP Violation

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on behalf of

Aspen, 14th January 2016

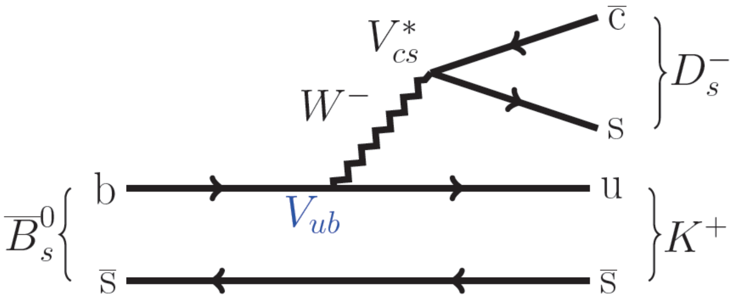
Outline

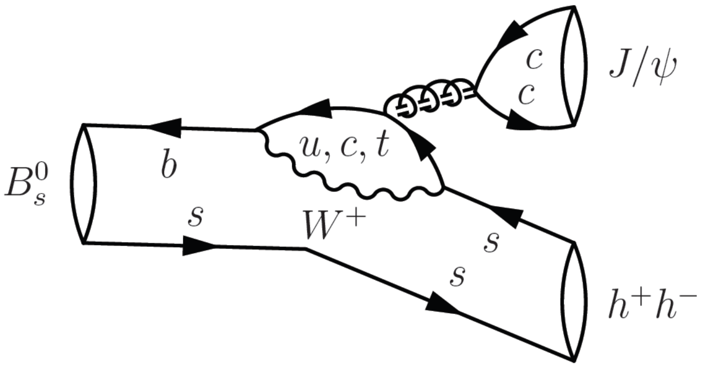
- Introduction
- CP violation and CKM physics:
  - Measurement of $|V_{ub}|$ on $\Lambda^0_b \rightarrow p\mu^- \overline{\nu}_\mu$
  - Measurement of $|V_{cb}|$ on $B \rightarrow D \ell \nu$
  - Determination of CKM γ angle
  - $\sin(2\beta)$ from $B^0 \rightarrow J/\psi K^0_S$ and $B^0 \rightarrow D^{(*)}_{CP} h^0$ decays
  - Measurement of the CP-violating weak phase φ_s
  - CP violation in B mixing
- Mixing and CPV in the charm sector
  - Mixing in $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decays
  - Search of CPV in $D^0 \rightarrow K^0_S K^0_S$
  - Mixing and search of indirect CPV in $D^0 \rightarrow h^- h^+$
  - Measurement of $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^- K^+) - A_{CP}(D^0 \rightarrow \pi^- \pi^+)$
- Conclusions

Review based on new 2015 results

Introduction to flavour physics

- In the search for physics beyond the SM, the study of beauty and charm hadron decays is complementary to direct searches for new particles
- Can discover NP due to the effect of virtual new particles in quantum loops
- NP could introduce sizeable effects in flavour changing processes and modify the Yukawa interactions
- Through the study of the interference of different quantum paths
  ➔ access to the magnitude of the couplings of NP and also to their phase (for instance, by measuring CP asymmetries).
- Precision measurements of FCNC can reveal NP even well above the TeV scale and provide key information on the couplings and phases of these new particles, if they are visible at the TeV scale

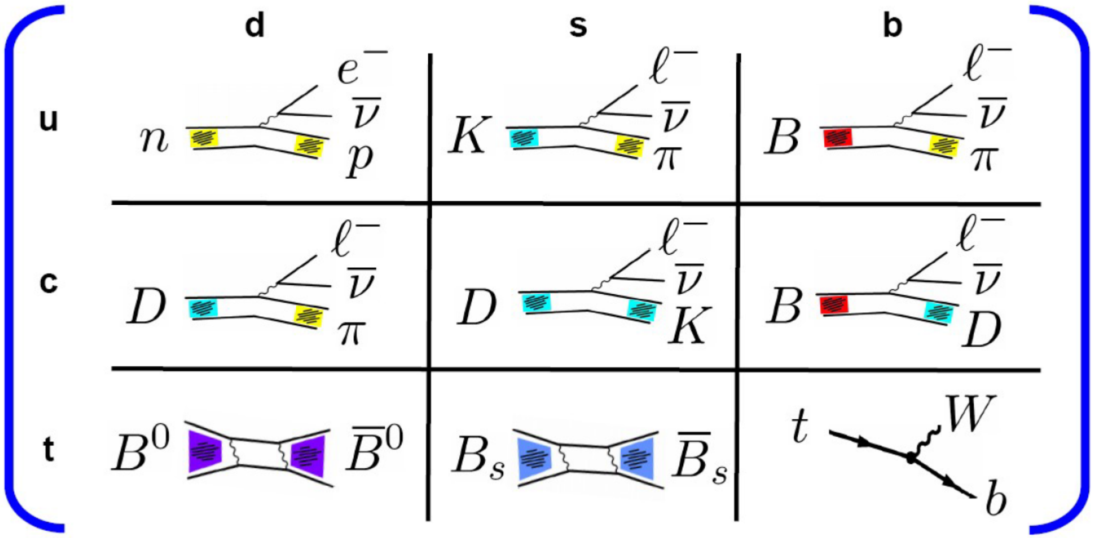




Introduction to flavour physics

- Weak interaction couples quarks through elements of the CKM mixing matrix
  - each element V_{ij} (i=u,c,t and j=d, s, b) quantify the relative i↔ j coupling strength.
- Precise measurements of the magnitudes and phases of the CKM elements provide constraints on many possible scenarios for physics BSM
- Its elements can be expressed in terms of 4 independent parameters

V_{CKM} =



Introduction to flavour physics

- Weak interaction couples quarks through elements of the CKM mixing matrix
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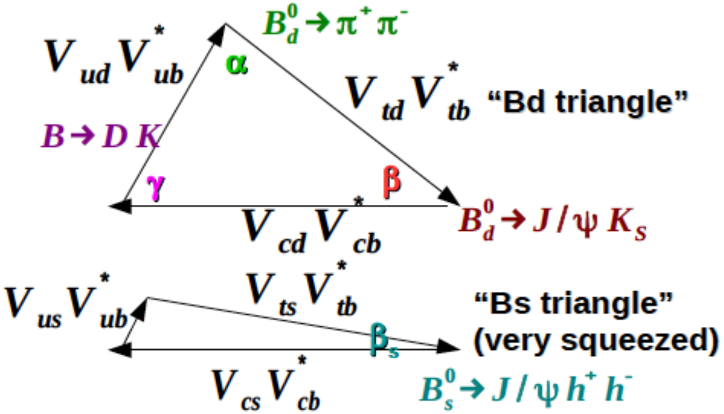
- Precise measurements of the magnitudes and phases of the CKM elements provide constraints on many possible scenarios for physics BSM
- Its elements can be expressed in terms of 4 independent parameters: λ, A, ρ, η

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

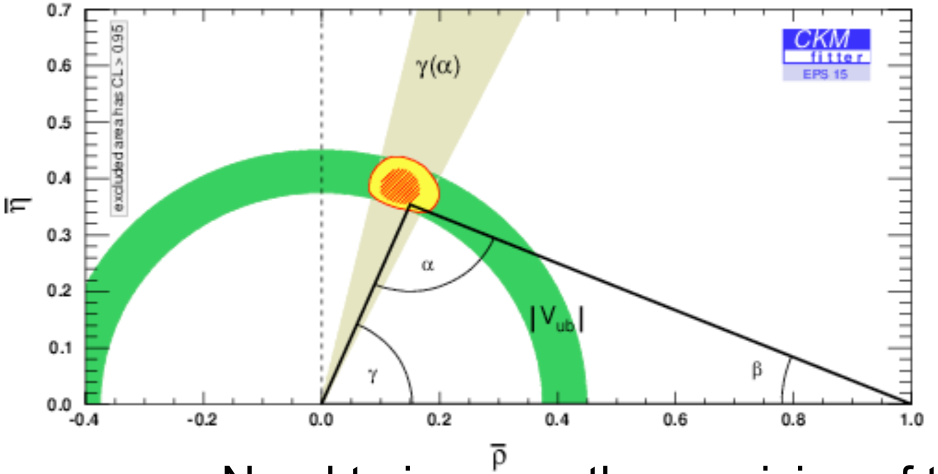
- ➢ λ, A, ρ, η not predicted by the SM ➔ to be measured
- ➢ Complex elements → CPV phases: γ, β, β_s
- ➢ Unitarity imposes relations ➔ 6 independent unitarity triangles

Introduction to flavour physics

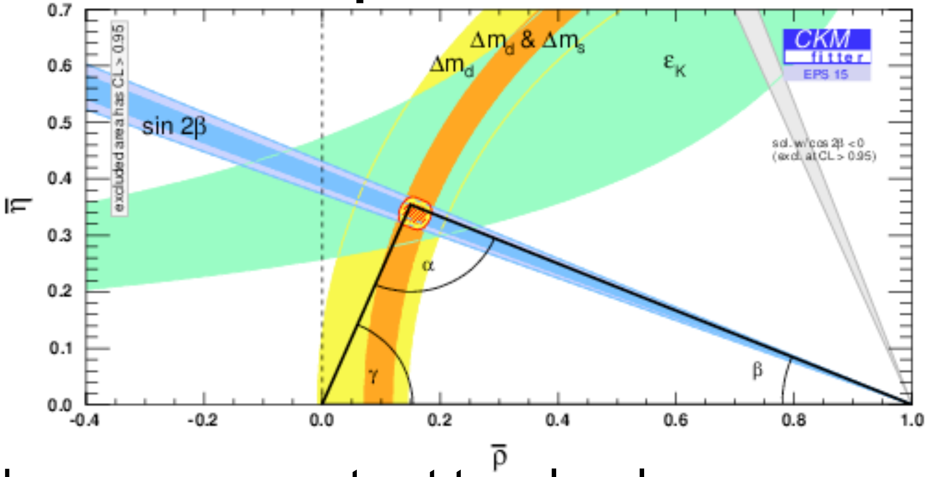
- If NP enters mainly at loop level ➔ compare the determination of the parameters (ρ, η) from processes dominated by
  - tree diagrams **(V_{ub}, V_{cb},γ,…)**
  - loop diagrams **(Δm_d&Δm_s, β, ε_k,…)**



Tree measurements



Loop measurements



Need to improve the precision of the measurements at tree level
➔ to (dis-)prove the existence of NP contributions in loops.

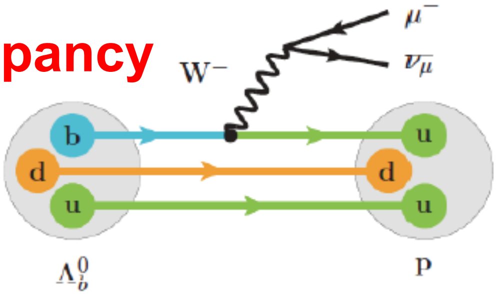
B physics results

Nature Physics 11 (2015) 743

Measurement of $|V_{ub}|$ on of $\Lambda^0_b \to p\mu^- \overline{\nu}_\mu$

- V_{ub} describes the transition b → u
- Measured via the semileptonic quark level transition $b \to u \ell \nu$
- Two complementary methods to perform the measurement: inclusive and exclusive ways
- World average V_{ub} determined by PDG 2014
  - **Inclusive: $b \to u \ell \nu$: $|V_{ub}|=[4.41\pm0.15^{+0.15}_{-0.17}]\ 10^{-3}$**
  - **Exclusive: $B \to \pi \ell \nu$: $|V_{ub}|=[3.28\pm0.29]\ 10^{-3}$**

➔ **3 σ discrepancy**



- LHCb evaluated the branching fraction of $\Lambda^0_b \to p\mu^- \overline{\nu}_\mu$

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = \boxed{\frac{|V_{ub}|^2}{|V_{cb}|^2}} \frac{G(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{G(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}}$$

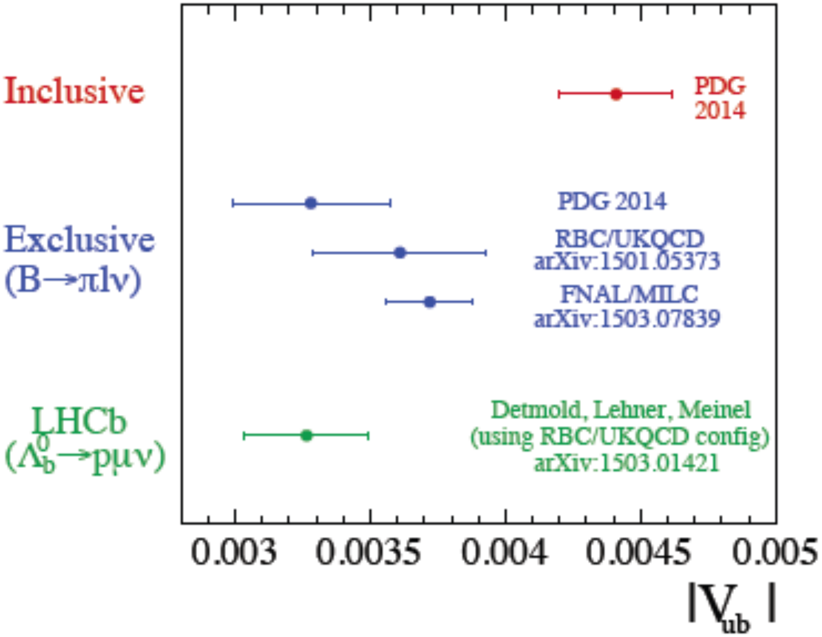
where the form factor G taken from lattice calculations from [arxiv:1503.01421(hep-lat)]

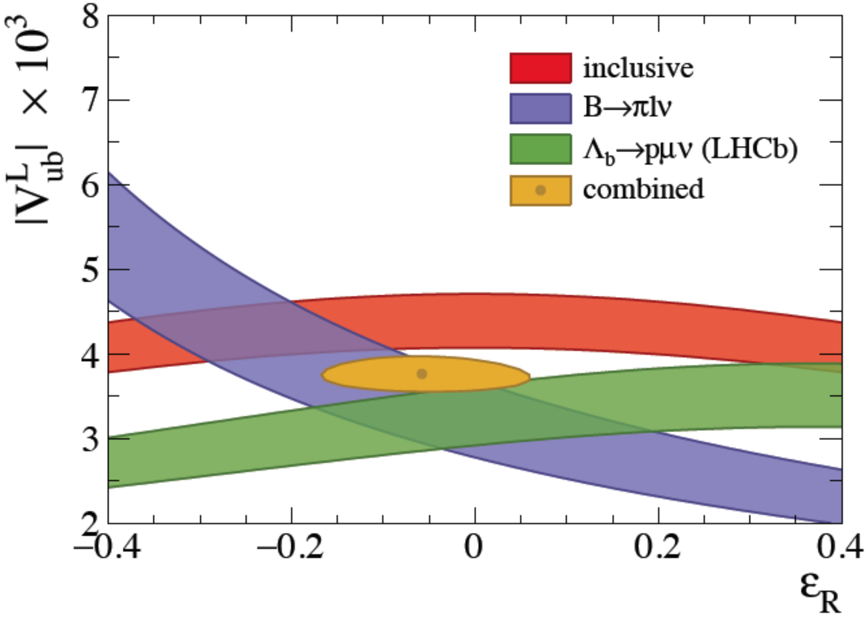
Nature Physics 11 (2015) 743

Measurement of $|V_{ub}|$ on of $\Lambda^0_b \to p\mu^- \overline{\nu}_\mu$

- Result: $\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$
- Using the world average $|V_{cb}|=[39.5\pm0.8]\ 10^{-3}$ by exclusive decays

  $|V_{ub}|=[3.27\pm0.15_{(exp)}\pm0.16_{(LQCD)}+0.06_{(norm)}]10^{-3}$
- Confirms **discrepancy** between inclusive and exclusive
- Inconsistent with a significant right handed current





arXiv:1510.03657
submitted to PRD

Measurement of $|V_{cb}|$ on $B\to D\ell\nu$

- V_{cb} describes the transition b → c
- Measured via the semileptonic quark level transition $b\to c\,\ell\nu$
- World average V_{cb}
  - Inclusive: $B\to X_c\ell\nu$: $|V_{cb}|=[42.21\pm0.78]\ 10^{-3}$
  - Exclusive: $B\to D\ell\nu$: $|V_{cb}|=[40.0\pm1.4]\ 10^{-3}$ and $B\to D^*\ell\nu$: $|V_{cb}|=[38.94\pm0.76]\ 10^{-3}$

2-3 σ discrepancy

- Recent measurements by Belle on $B\to D\ell\nu$
- V_{cb} via differential decay width:

$$\frac{d\Gamma}{dw}=\frac{G_F^2 m_D^3}{48\pi^3}(m_B+m_D)^2(w^2-1)^{3/2}\underset{\text{electroweak correction}}{\eta_{\mathrm{EW}}^2}|V_{\mathrm{cb}}|^2\underset{\text{form factor}}{\mathcal{G}(w)^2}$$

Kinematics: $w=v_B\cdot v_D$

- For form factor $\mathcal{G}(w)$, two parameterisations considered:
  - CLN [Nucl. Phys. B 530, 153 (1998)]
  - BGL [Phys. Rev. Lett. 74, 4603 (1995)]

arXiv:1510.03657
submitted to PRD

Belle Measurement of $|V_{cb}|$ on $B\rightarrow D\ell\nu$

- Using the CLN parameterisation and assuming the value of $\mathcal{G}(1)=1.0541\pm0.0083$ [arXiv:1503.07237]

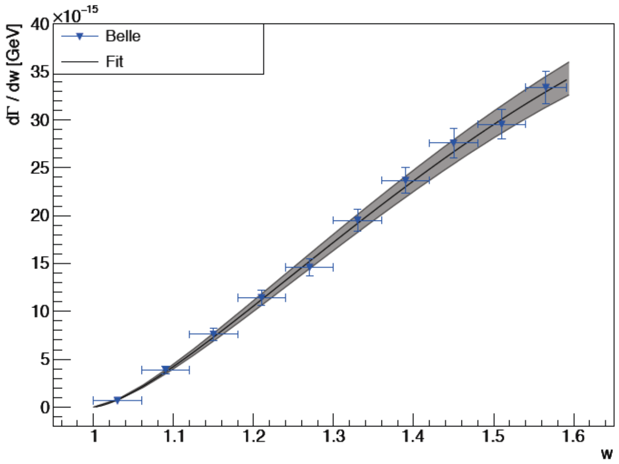
  $|V_{cb}|\eta_{EW}(\mathrm{CLN})=(40.12\pm1.34)\ 10^{-3}$

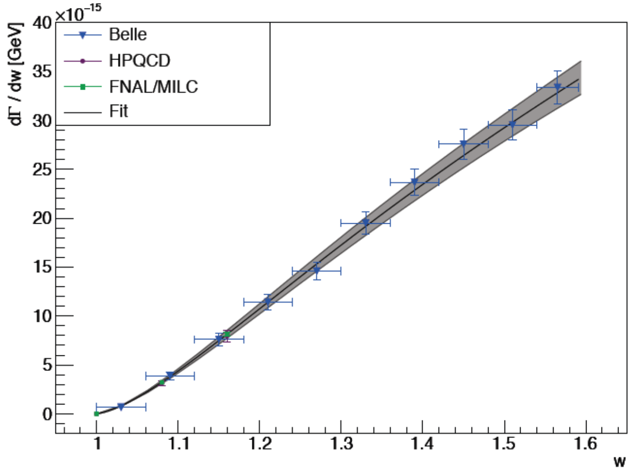
- Using the BGL method to perform a combined fit to the model-independent form-factor parameterisation

  $|V_{cb}|\eta_{EW}(\mathrm{BGL})=(41.10\pm1.14)\ 10^{-3}$

➔ Error significantly reduced from previous measurements

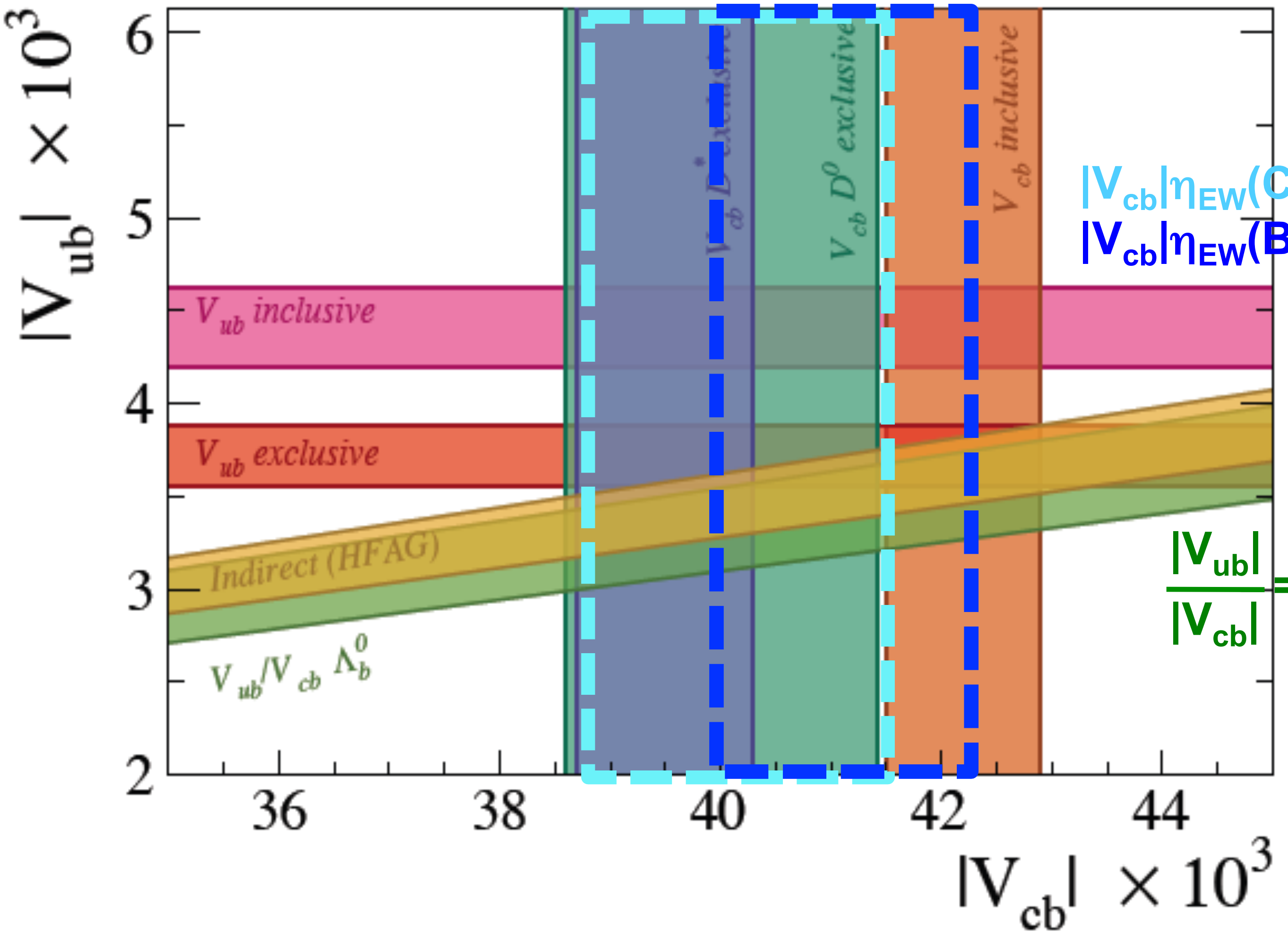
➔ Result is in between inclusive and exclusive results





LHCb: Nature Physics 11 (2015) 743
Belle: arXiv:1510.03657 (submitted to PRD)

Overview of $|V_{ub}|$ and $|V_{cb}|$ measurements



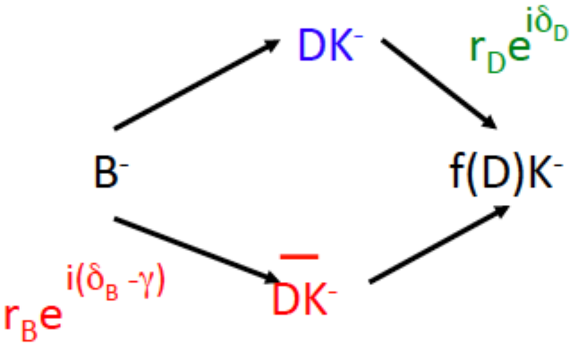
$|V_{cb}|\eta_{EW}$(CLN)=(40.12±1.34) 10^{-3}

$|V_{cb}|\eta_{EW}$(BGL) =(41.10±1.14) 10^{-3}

$\frac{|V_{ub}|}{|V_{cb}|}$=(0.083±0.004±0.004)

Determination of CKM γ

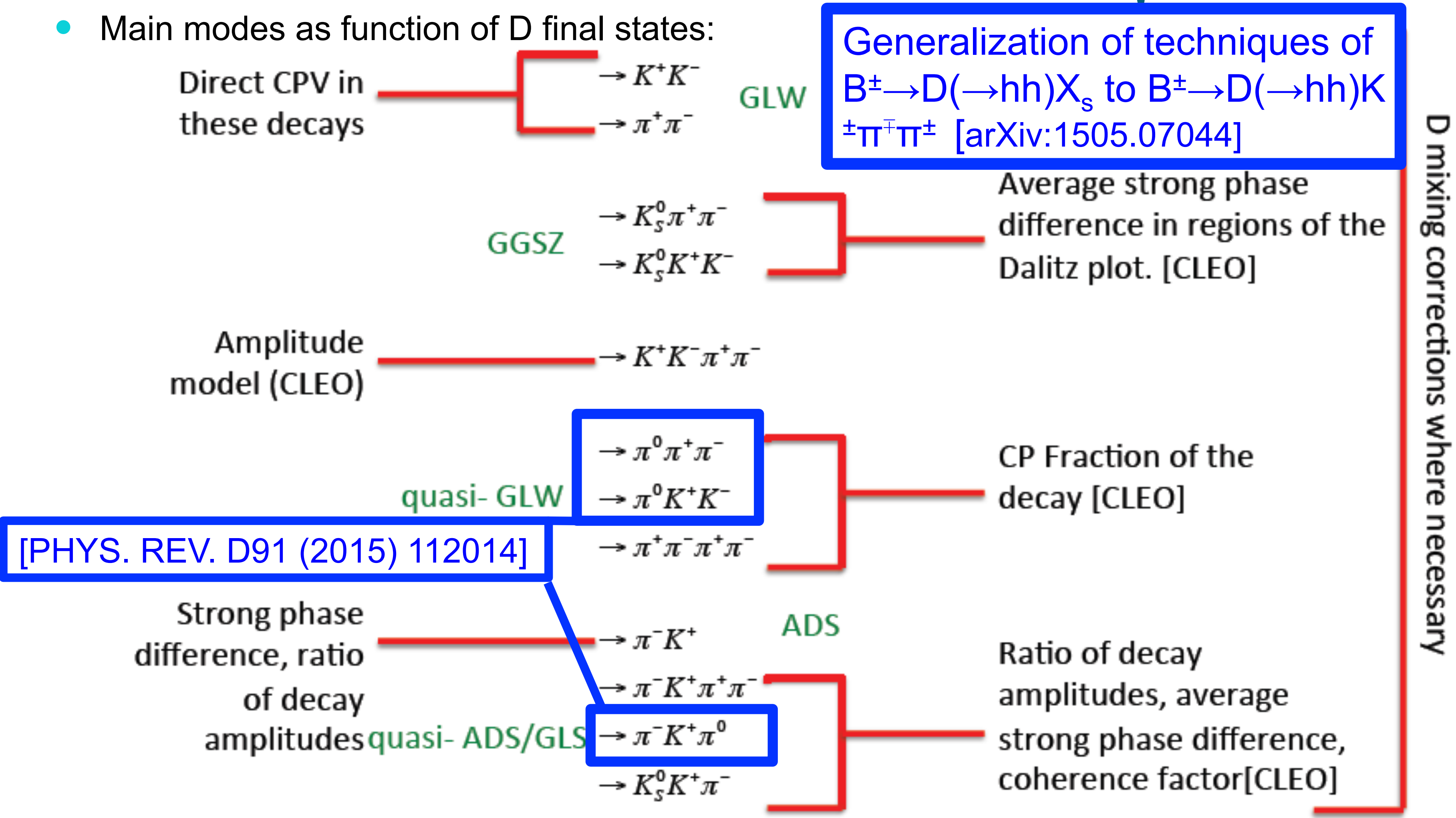
- The least well measured phases is $$\gamma = -\arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$
- Sensitivity to γ from b→u and b→c interference
- Magnitude of the interference is governed by γ, r_B amplitude ratio and δ_B CP-conserving strong phase difference
- Crucial point: D^0 and $\overline{D}^0$ to decay to same final state



- γ measurements from $B^\pm \to DK^\pm$ (r_B~0.1)
  - $B^\pm \to D\pi^\pm$ also possible but needed higher statistics (r_B~0.01)

Determination of CKM γ

- Main modes as function of D final states:



Generalization of techniques of $B^{\pm}\to D(\to hh)X_s$ to $B^{\pm}\to D(\to hh)K^{\pm}\pi^{\mp}\pi^{\pm}$ [arXiv:1505.07044]

Direct CPV in these decays

GLW

$\to K^+K^-$

$\to \pi^+\pi^-$

GGSZ

$\to K_S^0\pi^+\pi^-$

$\to K_S^0K^+K^-$

Average strong phase difference in regions of the Dalitz plot. [CLEO]

Amplitude model (CLEO)

$\to K^+K^-\pi^+\pi^-$

quasi- GLW

$\to \pi^0\pi^+\pi^-$

$\to \pi^0K^+K^-$

$\to \pi^+\pi^-\pi^+\pi^-$

CP Fraction of the decay [CLEO]

[PHYS. REV. D91 (2015) 112014]

Strong phase difference, ratio of decay amplitudes

ADS

$\to \pi^-K^+$

quasi- ADS/GLS

$\to \pi^-K^+\pi^+\pi^-$

$\to \pi^-K^+\pi^0$

$\to K_S^0K^+\pi^-$

Ratio of decay amplitudes, average strong phase difference, coherence factor[CLEO]

D mixing corrections where necessary

- Other interesting modes with vector mesons, e.g. $B\to D^*K$, $\overline{B}\to D\overline{K}^{*0}$, $B^{\pm}\to D\varphi$ and as well b-baryon decays (e.g. $\Lambda_b\to D\Lambda$ decays) and other multi-body final states

arXiv: 1505.07044
Submitted to PRD

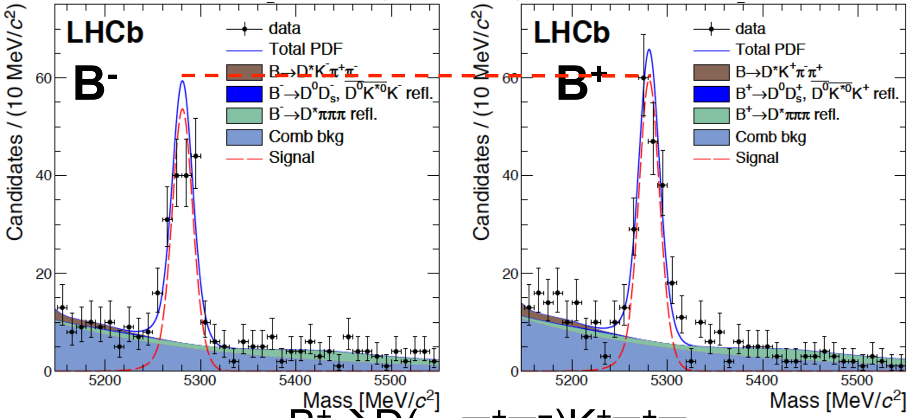
Determination of CKM γ

- First ADS and GLW analyses of the decay $B^- \to D(\to hh)h^-\pi^+\pi^-$
- Global fit for all $D \to h^+h^-$ modes gives:

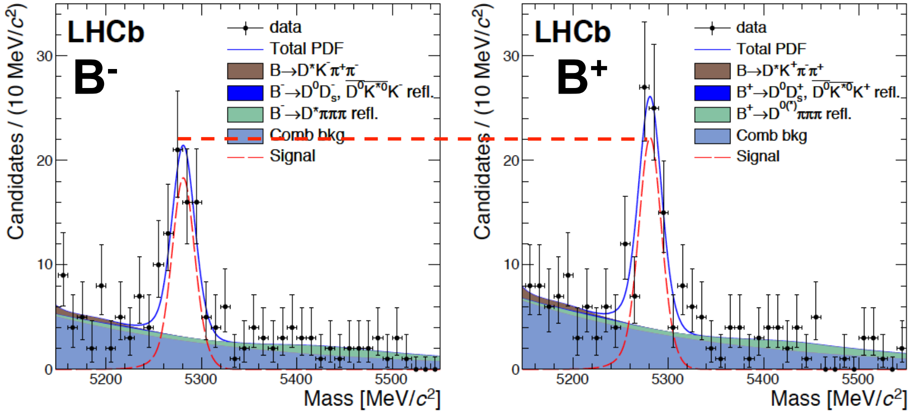
  $\gamma = (74^{+20}_{-18})^\circ$ at 68.3% CL

- Compatible with the global average published in LHCb-CONF-2014-004
- Contribution to improve the precision on γ from combined measurements

$B^\pm \to D(\to K^-K^+)K^\pm\pi^+\pi^-$



$B^\pm \to D(\to \pi^+\pi^-)K^\pm\pi^+\pi^-$

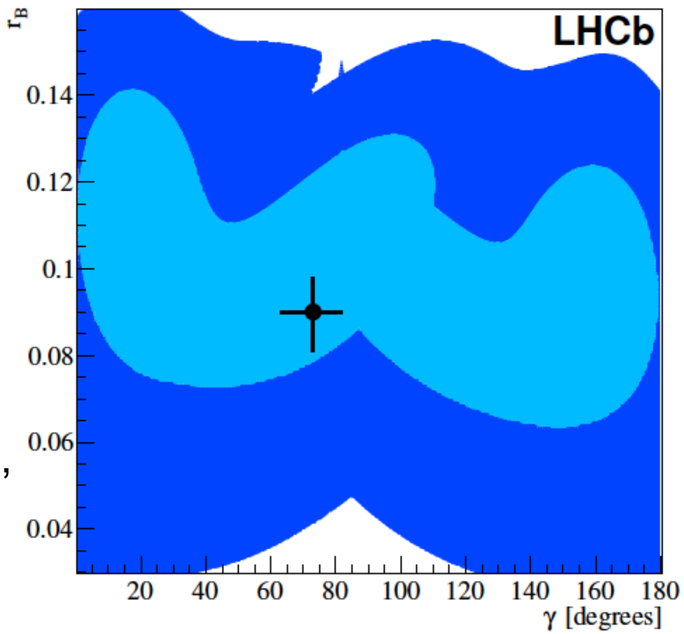


First significant signals in D CP modes
First evidence of ADS DCS $B^- \to D(\to K^+\pi^-)K^-\pi^+\pi^-$

Phys. Rev. D 91, 112014 (2015)

Determination of CKM γ

- This method uses $B^{\pm} \to D^0 h^{\pm}$ decays:
  - **ADS channel $D^0 \to K \pi \pi^0$**
  - **Quasi-GLW $D^0 \to \pi\pi\pi^0$ and $D^0 \to KK\pi^0$ First time!**
- Dilution factors measured by CLEO-c [PLB 731(2014) 197] [Phys. Lett. B740 (2015) 1]
- Measured observables by the ratio and asymmetry ➔ constraints on γ, r_B and δ_B
- **Higher sensitivity** compared with the results of BaBar and Belle [Phys. Rev. D84 (2011) 012002, Phys. Rev. D88 (2013) 091104, Phys. Rev. Lett. 99 (2007) 251801]
- No evidence of CPV obtained with the current experimental precision
- The results exhibit **good consistency with other LHCb measurements.** [LHCb-CONF-2014-004]



Best-fit value **$r_B = 0.11 \pm 0.03$**

No strong constraints on γ or δ_B with these statistics

Combining γ measurements

- No update since CKM 2014
- Ultimate theoretical error $<10^{-7}$
- **Direct measurement**, world average:

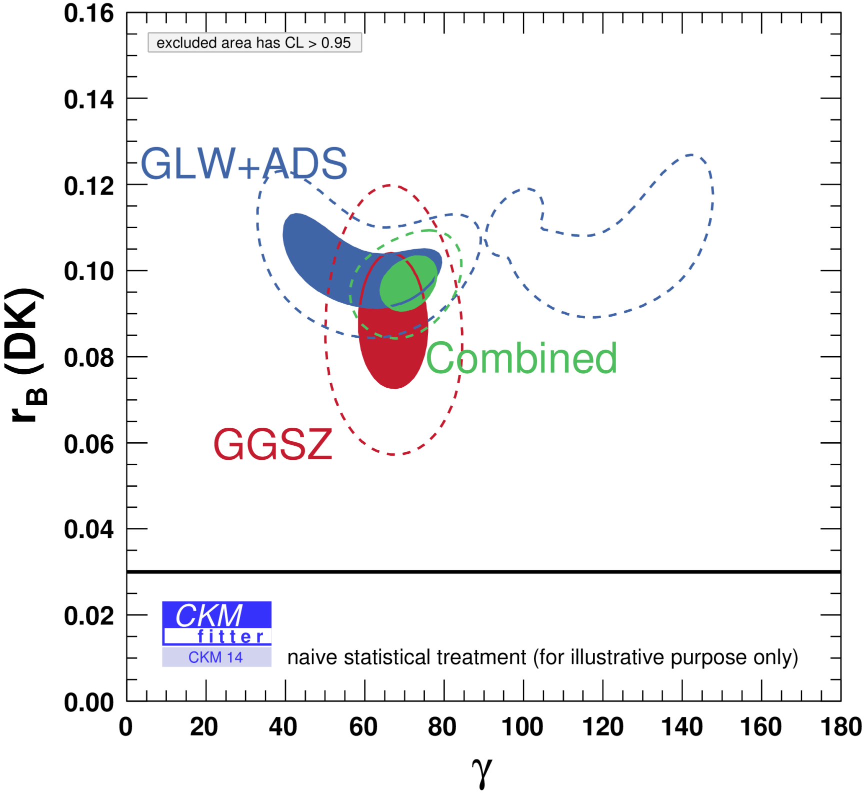
  $\gamma=(73.2^{+6.3}_{-7.0})^{o}$

  $r_B=(0.097\pm0.006)$

  $\delta_B=(125.4^{+7.0}_{-7.8})^{o}$

- **Indirect determination** from global CKM fit, including loop based measurements

  $\gamma=(66.9^{+1.0}_{-3.7})^{o}$



Phys. Rev. Lett. 115(2015) 031601

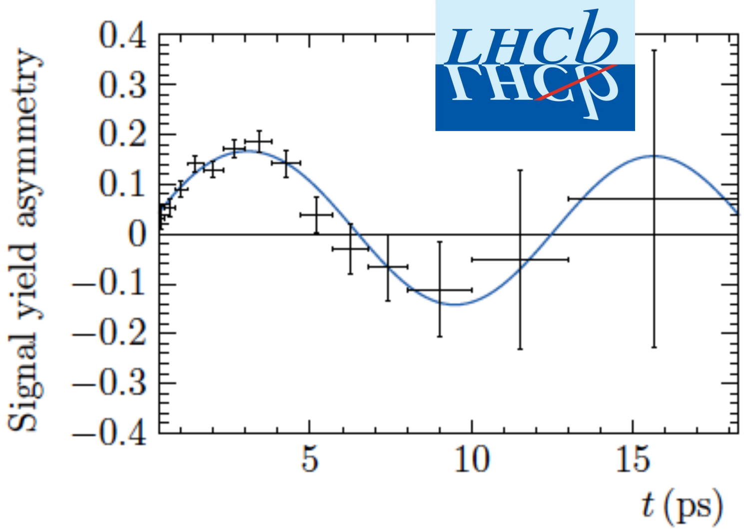
sin(2β) from $B^0 \to J/\psi K^0_S$ decays at LHCb

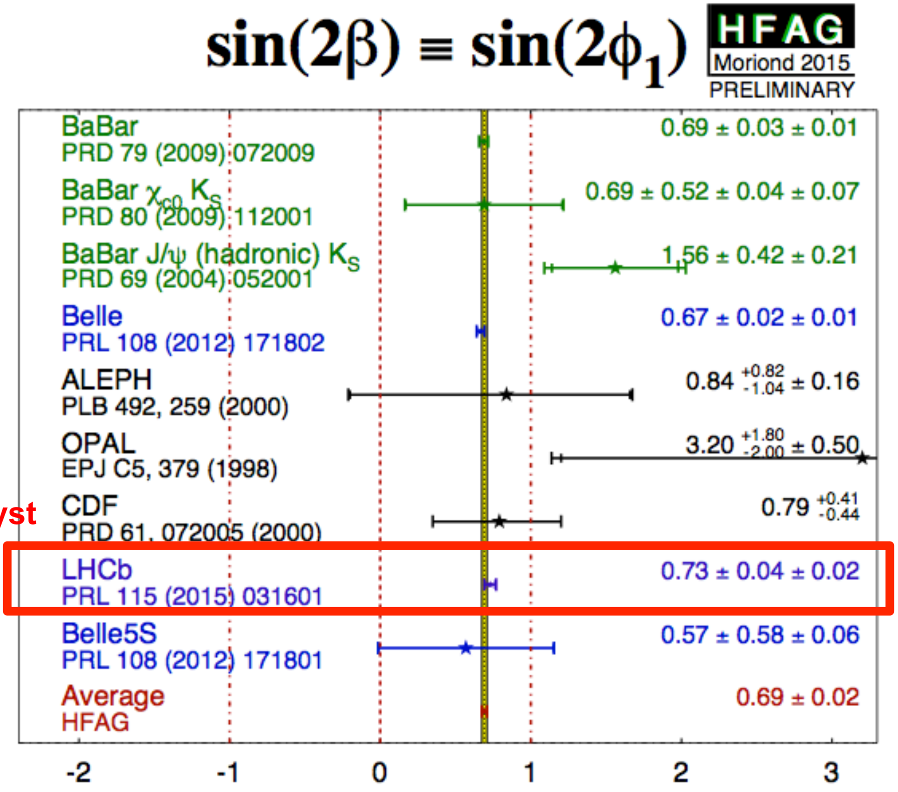
- Decay time dependent CP asymmetry between B^0 and $\overline{B}^0$ in $B^0 \to J/\psi K^0_S$
- In this decay CPV expected negligible decays

$$\mathcal{A}(t) \equiv \frac{\Gamma(\overline{B}^0(t)\to J/\psi K^0_S) - \Gamma(B^0(t)\to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t)\to J/\psi K^0_S) + \Gamma(B^0(t)\to J/\psi K^0_S)}$$

$$\mathcal{A}(t) = S\sin(\Delta m\, t) - C\cos(\Delta m\, t)$$

$S \approx \sin(2\beta) = 0.731 \pm 0.035_{stat} \pm 0.020_{syst}$





- Similar statistical precision as B-factories
- Excellent agreement with expectation from other measurements

Phys. Rev. Lett. 115 (2015) 121604

B-factory combined result: sin(2β) in $B^0 \to D^{(*)}_{CP} h^0$ decays

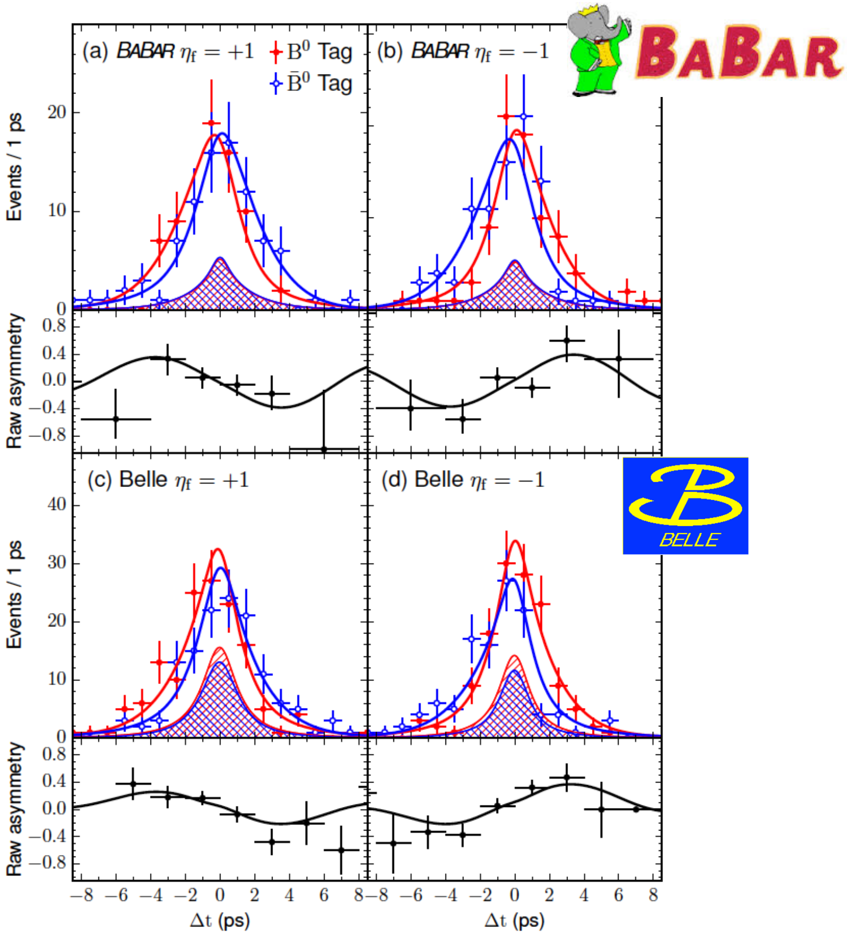
- $B^0 \to D^{(*)}_{CP} h^0$ decays **proceed mainly through tree amplitudes**
- Penguin free ($b \to c\bar{u}$) measurement
- If D decays to CP-eigenstate (K^-K^+, $K_s\pi^0$, $K_s\omega$) with $h^0 = \pi^0, \eta, \omega$

➔ time dependent CPV can occur via interference with oscillation

- **First combined fit** to BaBar and Belle data

$\sin(2\beta) = 0.66 \pm 0.10_{stat} \pm 0.006_{syst}$

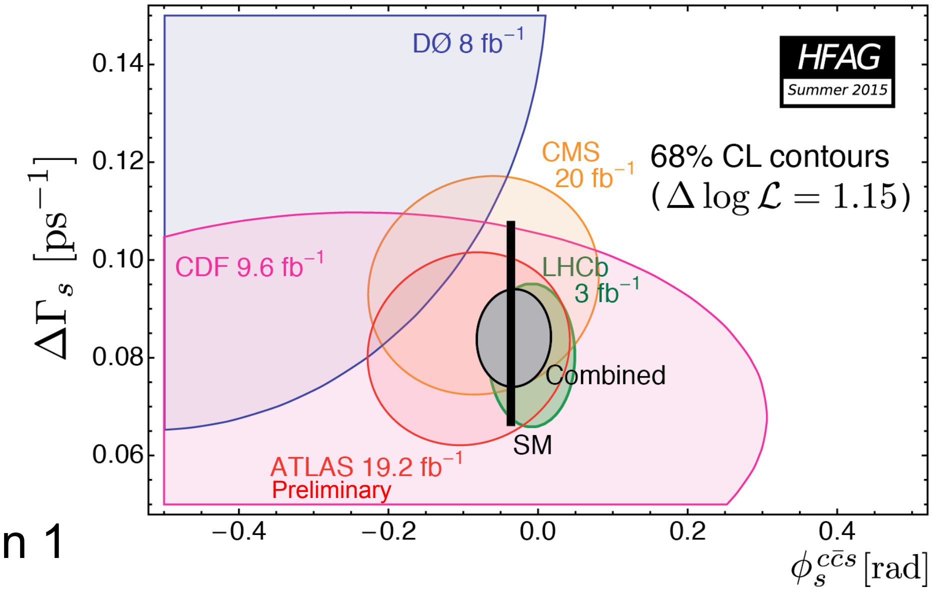
- 5 σ observation of CPV in this decay mode
- Very good agreement with the world average from B→ charmonium K^0 decays



LHCb: Phys. Rev. Lett. 114, 041801 (2015)
CMS: arXiv:1507.07527; Submitted to Phys. Lett. B
ATLAS: arXiv:1601.03297; Submitted to JHEP

Measurement of the CP-violating weak phase φ_s

- Angular analysis is needed in $B_s \rightarrow J/\psi\phi$ decays, to disentangle statistically the CP-even and CP -odd components.
- LHCb includes also $B_s \rightarrow J/\psi\pi\pi$ [Phys. Lett B736 (2014)186] and even $B_s \rightarrow D^+_s D^-_s$ [Phys. Rev. Lett. 113 (2014) 211801]
- ATLAS and CMS analyses have measured φ_s in $B_s \rightarrow J/\psi\phi$ with full Run 1 statistics



$B_s \rightarrow J/\psi\phi$	ATLAS	CMS	LHCb
	arXiv: 1601.03297	arXiv: 1507.07527	PRL 114 (2015) 041801
L (fb^{-1})	19	20	3
φ_s[mrad]	-98±84±40	-75±97±31	-58±49±6
$\Delta\Gamma_s$[fs-1]	83±11±7	95±13±7	80.5±9.1±3.3

- Combining all measurements

φ_s=(-34±33) mrad = (-2.01±1.89)°

- To be compared with the prediction, neglecting penguin contribution: **φ_s= (-2.1±0.1)°**.
- Uncertainty needs to be further reduced for a meaningful comparison

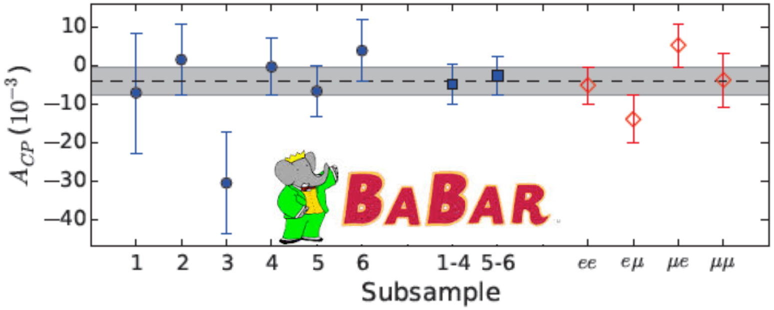
Phys. Rev. Lett. 114 (2015) 081801

CP violation in B mixing

- CP violation in dilepton samples from semileptonic *B* decays
- Assuming e-μ universality

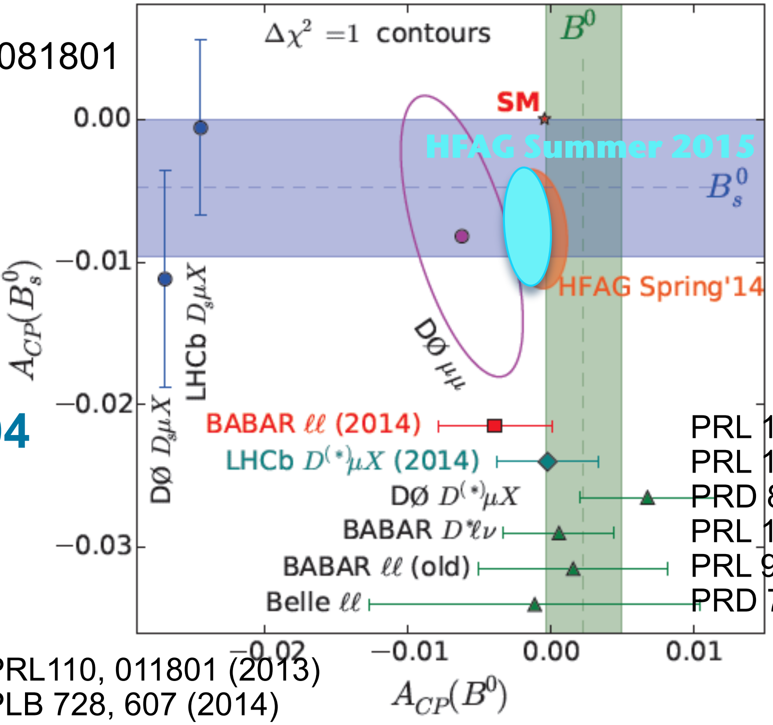
$$A_{CP} = \frac{\mathcal{P}_{\ell\ell}^{++} - \mathcal{P}_{\ell\ell}^{--}}{\mathcal{P}_{\ell\ell}^{++} + \mathcal{P}_{\ell\ell}^{--}} = \frac{1-|q/p|^4}{1+|q/p|^4}.$$

- BaBar measurement PRL 114 (2015) 081801
  A_{CP}=(-0.39±0.35±0.19)%



World average

- CPV in B^0 mixing
  |q/p| = 1.0007 ± 0.0009
  A_{CP} = (−0.15 ± 0.17)%
  $Re(\varepsilon_B)/(1+|\varepsilon_B|^2) = −0.0004 ± 0.0004$
- CPV in B_s mixing
  |q/p| = 1.0038 ± 0.0021
  A_{CP} = (−0.75 ± 0.41)%
- SM expectation ~0.01%



PRL 114 081801 (2015)
PRL 114, 041601 (2015)
PRD 86, 072009 (2012)
PRL 111, 101802 (2013)
PRL 96, 251802 (2006)
PRD 73, 112002 (2006)

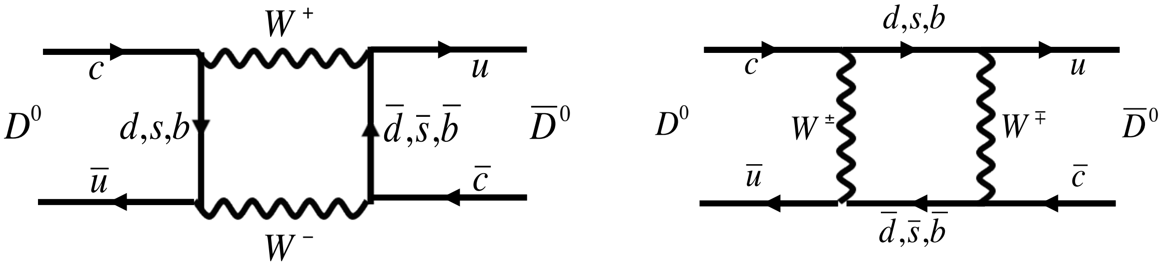
PRL110, 011801 (2013)
PLB 728, 607 (2014)

Mixing and CPV in the charm sector

D^0 mixing

- D^0 oscillation is characterized by:
  - mixing parameters: $x \equiv \frac{(m_2 - m_1)}{\Gamma}$ and $y \equiv \frac{(\Gamma_2 - \Gamma_1)}{2\Gamma}$ $\quad \Gamma \equiv (\Gamma_2 + \Gamma_1)/2$

    mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$



- Theoretical expectation: $|x|, |y| \lesssim O(10^{-2})$
- Experimental status
  - First evidence in 2007 by BaBar and Belle [arXiv:hep-ex/0703020; arXiv:hep-ex/0703036]
  - Mixing well established with more than 10 σ. Most recent and precise measurements at LHCb [PRL 110 (2013) 101802], CDF[PRL 111 (2013) 231802] and Belle [PRL 112 (2014) 111801]

arXiv: 1510.01664
Submitted to JHEP

Mixing in $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decays

- Different superposition of amplitudes at each point in phase-space. Interfering amplitudes enhance the sensitivity to mixing
- Time dependent decay rate:

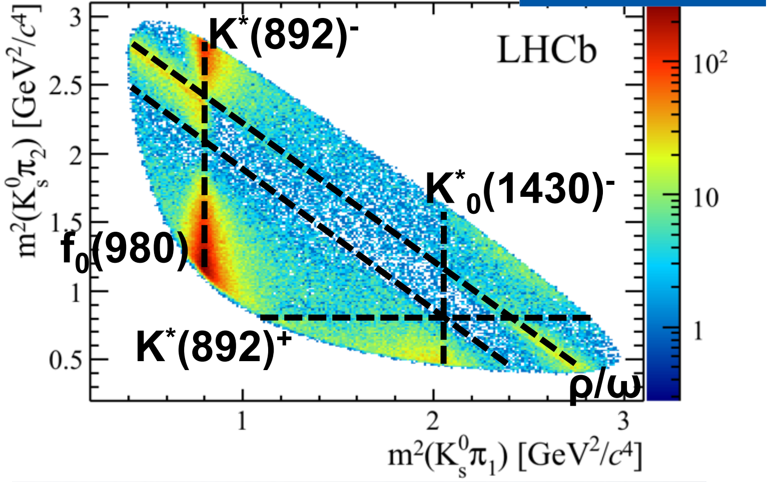
$$\mathcal{P}_{D^0} = e^{-\Gamma t}\left[T_i - \Gamma t\sqrt{T_i T_{-i}}\left(y c_i + x s_i\right)\right]$$

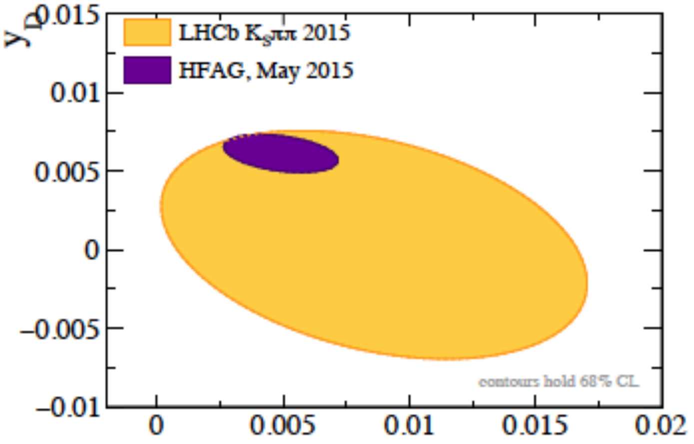
- Constrain hadronic parameters (T_i, c_i, s_i) to CLEO measurements [PRD 82 (2010) 112006]
- **First model-independent** measurement of *x* and *y* in $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decays on 1 fb^{-1} data sample

$x = (0.86 \pm 0.53 \pm 0.17) \times 10^{-2}$

$y = (0.03 \pm 0.46 \pm 0.13) \times 10^{-2}$

- Compatible with current world averages (but not yet competitive) with other experiments
- Already collected ~20 time more data for this channel





Courtesy M Gersabeck

CP violation in charm

- CP-violating asymmetries in the charm sector provide a unique probe for physics beyond the Standard Model (SM)
- In the SM CP violation is expected to be small
- New Physics can enhance CP violating observables
- CP violation contributions:
  - In decay: amplitudes for a process and its conjugate differ $\left|\frac{\bar{A}_f}{A_f}\right|^{\pm 2} \approx 1 \pm A_d \quad \text{with } A_d \neq 0$

    ➔ **direct CP violation** $a_{CP}^{dir} \approx -\frac{1}{2} A_d$
  - In mixing: rate of $\overline{D^0} \rightarrow D^0$ and $D^0 \rightarrow \overline{D^0}$ differ: $\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m \quad \text{with } A_m \neq 0$
  - In interference between mixing and decay diagrams $\phi = \left[\frac{q\bar{A}_f}{pA_f}\right] - \delta \neq 0$

    ➔ **indirect CP violation** $a_{CP}^{ind} = -\frac{A_m}{2} y \cos\phi + x \sin\phi$

New result

Phys. Lett. B 753 (2016) 412

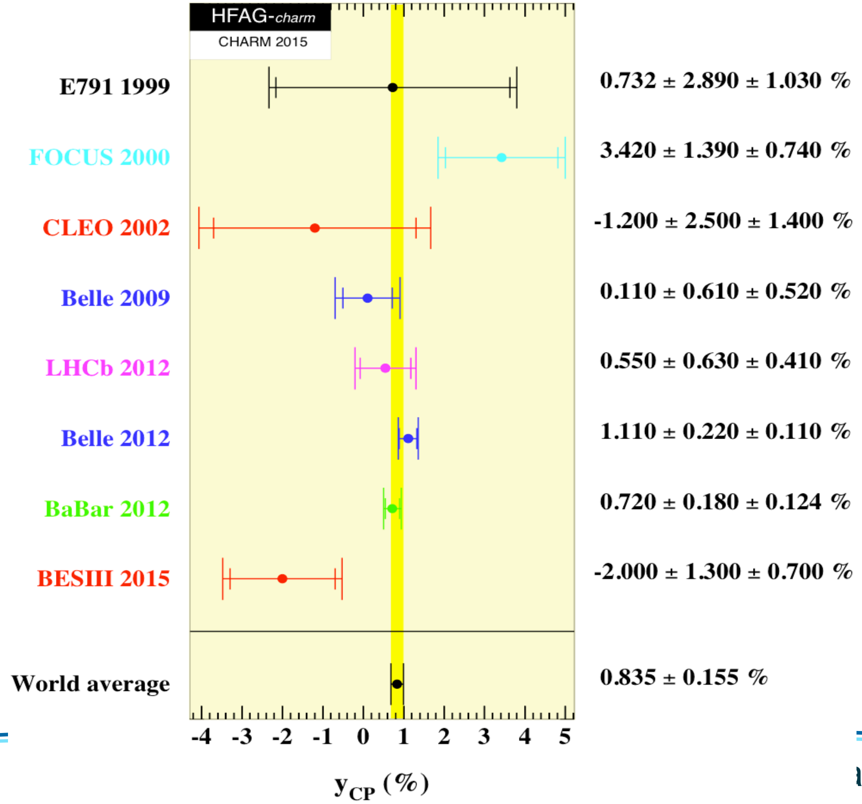
Indirect CP violation and mixing

- Mixing parameter, if no CPV $y_{CP}=y$

$$\mathbf{y}_{\mathbf{CP}}=\frac{\tau\left(D^0\to K^-\pi^+\right)}{\tau\left(D^0\to h^-h^+\right)}-1\cong y\cos\phi+\frac{1}{8}\mathbf{A}_{\mathbf{m}}^{2}\,y\cos\phi-\frac{1}{2}\mathbf{A}_{\mathbf{m}}x\sin\phi$$

- The final Belle results on 976fb^{-1}

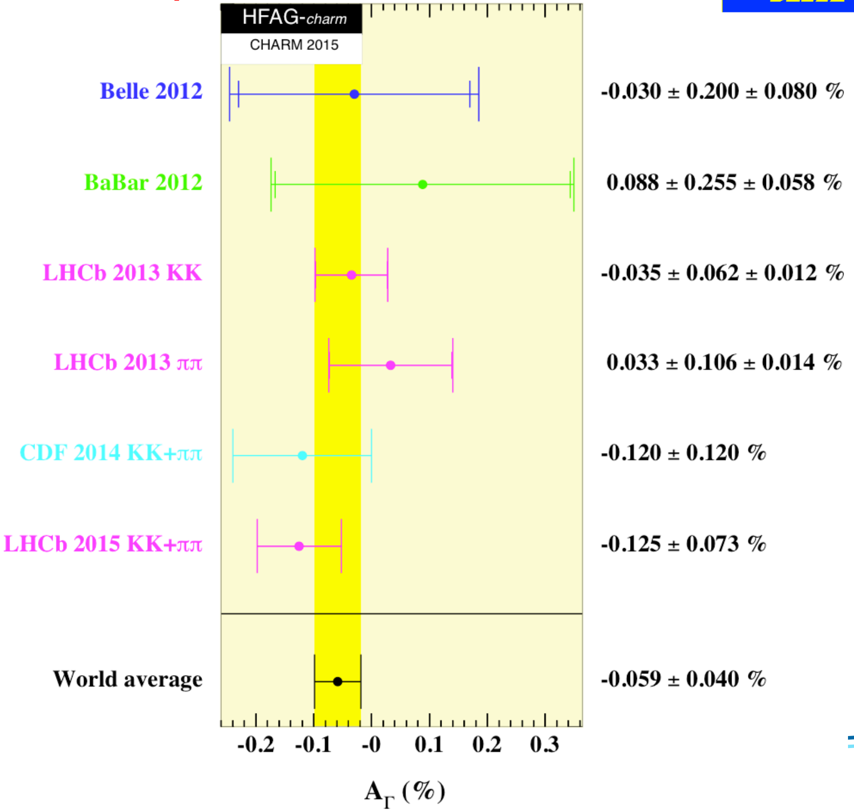
y_{CP}=(1.11 ±0.22 ±0.09)%



- Indirect CPV evaluated by

$$\mathbf{A}_\Gamma=\frac{\tau\left(\overline{D}^0\to h^-h^+\right)-\tau\left(D^0\to h^-h^+\right)}{\tau\left(\overline{D}^0\to h^-h^+\right)+\tau\left(D^0\to h^-h^+\right)}\approx\frac{\mathbf{A}_{\mathbf{M}}}{2}y\cos\phi-x\sin\phi$$

A_Γ =(−0.03 ±0.20 ±0.07)%



JHEP 10 (2015) 055

Search of CPV in $D^0 \rightarrow K^0_S K^0_S$

- Measurement of CP asymmetry

  $A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})$

  where the A_D and A_P are of O(1%) determined by control channels

- Experimentally challenging: vertexing of two (very) long-lived particles

- Results:

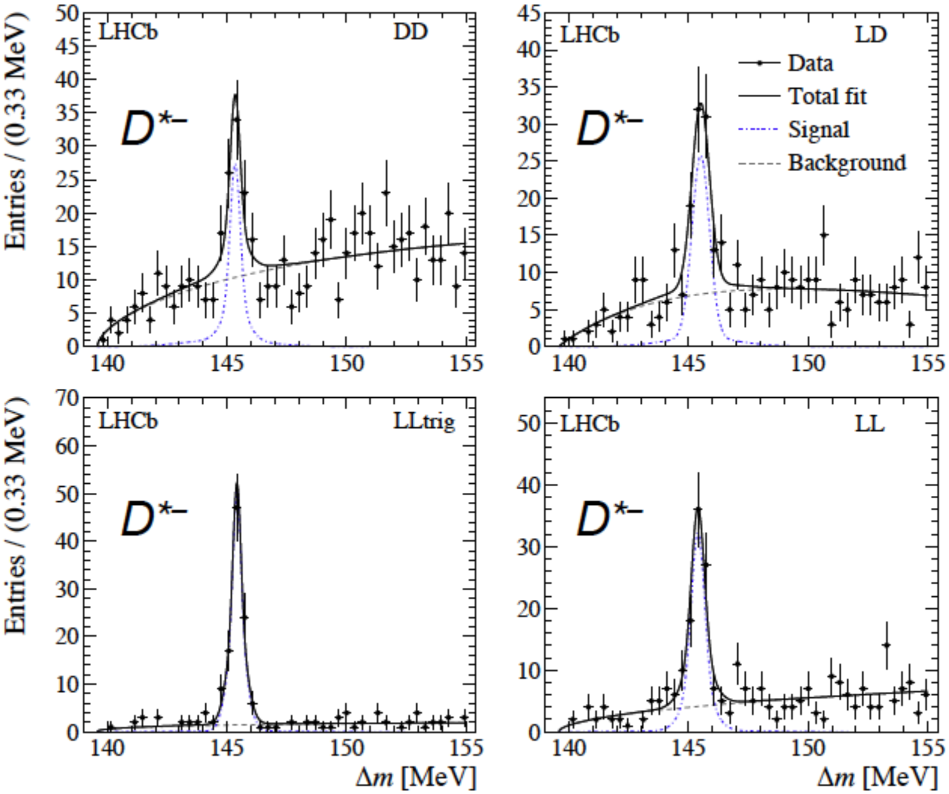
  $A_{CP}=(-2.9\pm5.2\pm2.2)\ 10^{-2}$

→ No indication of CP violation

- Single previous measurement from CLEO [PRD 63 (2001) 071101]

  $A_{CP}=(23\pm19)\times10^{-2}$

→ Significant improvement over previous measurement



Measurement of $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^-K^+) - A_{CP}(D^0 \rightarrow \pi^-\pi^+)$

- The measured asymmetry is:

$$A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\pi_s/\mu) + A_P(D^{*+}/B)$$

- **Detection** asymmetry **A_D(f)** for self-conjugate final states is usually negligible
- D^* or B **production** asymmetries d to be taken into account in pp interaction
- In $A_{RAW}(K^-K^+)^*$ - $A_{RAW}(\pi^+\pi^-)^*$ the **production** and **detection** asymmetries cancel:

$$A_{RAW}(K^-K^+)^* - A_{RAW}(\pi^-\pi^+)^* = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \equiv \Delta A_{CP}$$

➔ CP asymmetry difference very robust against systematics

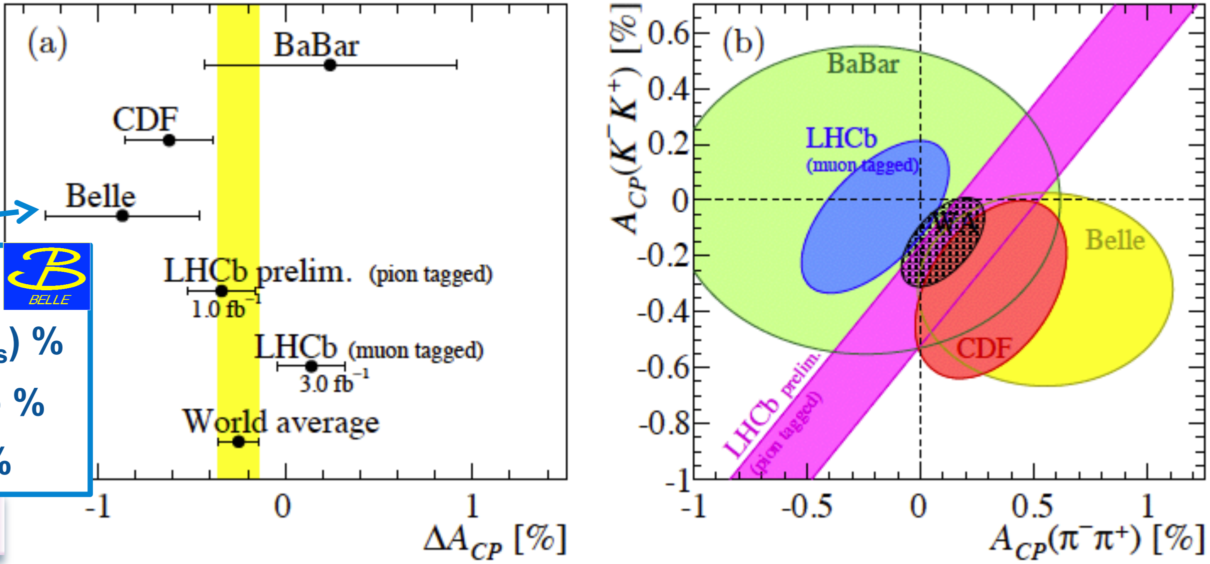
Belle final results

$A_{CP}(KK) = (-0.32 \pm 0.21_{stat} \pm 0.09_{sys})$ %

$A_{CP}(\pi\pi) = (0.55 \pm 0.36_{stat} \pm 0.09_{sys})$ %

$\Delta A_{CP} = (-0.87 \pm 0.41_{stat} \pm 0.06_{sys})$ %

arXiv:1509.04130



New result

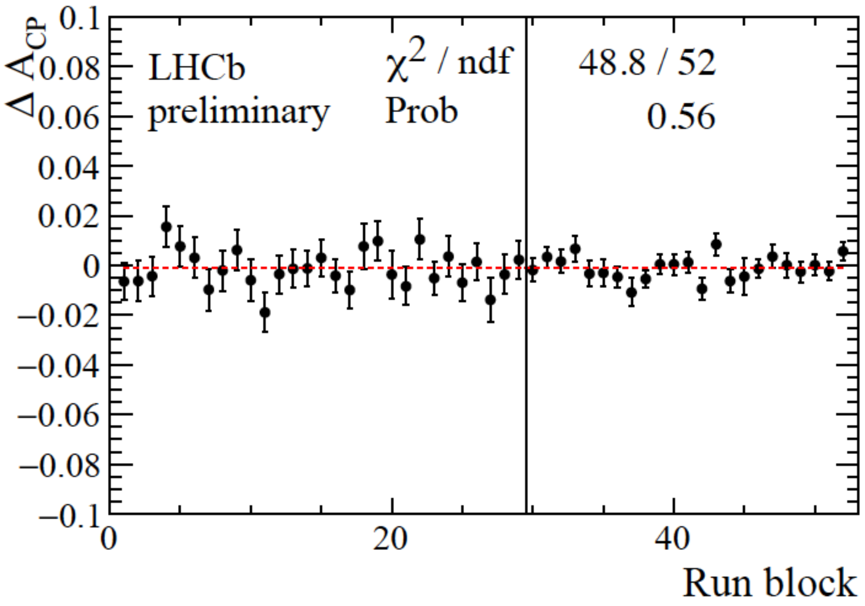
LHCb-PAPER-2015-055

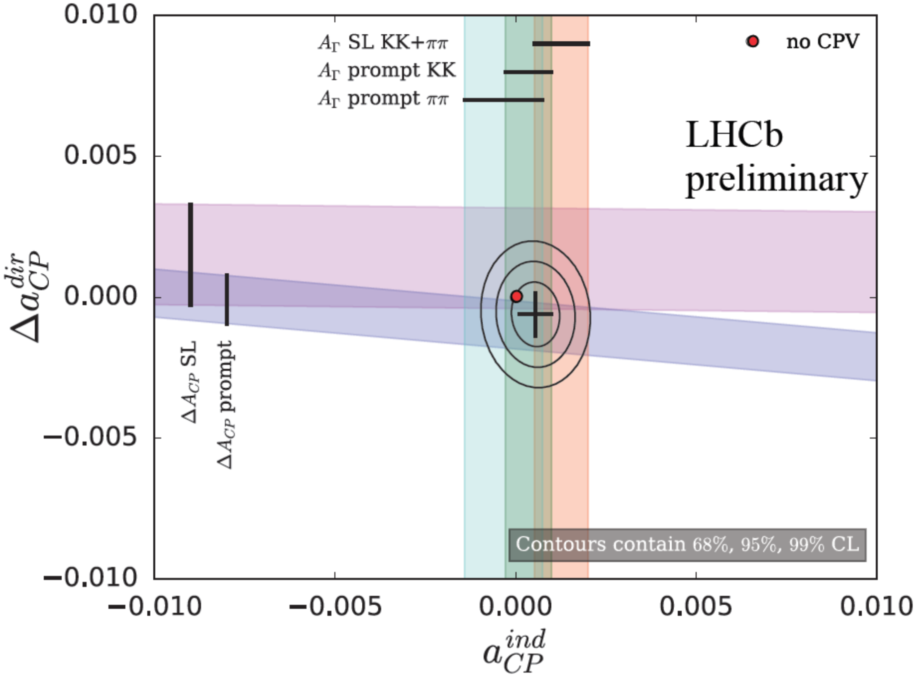
Measurement of $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^- K^+) - A_{CP}(D^0 \rightarrow \pi^- \pi^+)$

- Result with L_{int}=3 fb^{-1} of full data in Run1:

  $\Delta A_{CP} = (-0.10 \pm 0.08_{stat} \pm 0.03_{sys})$ % **Preliminary**

- Most precise measurement of direct CPV in charm decays
- No CPV evidence



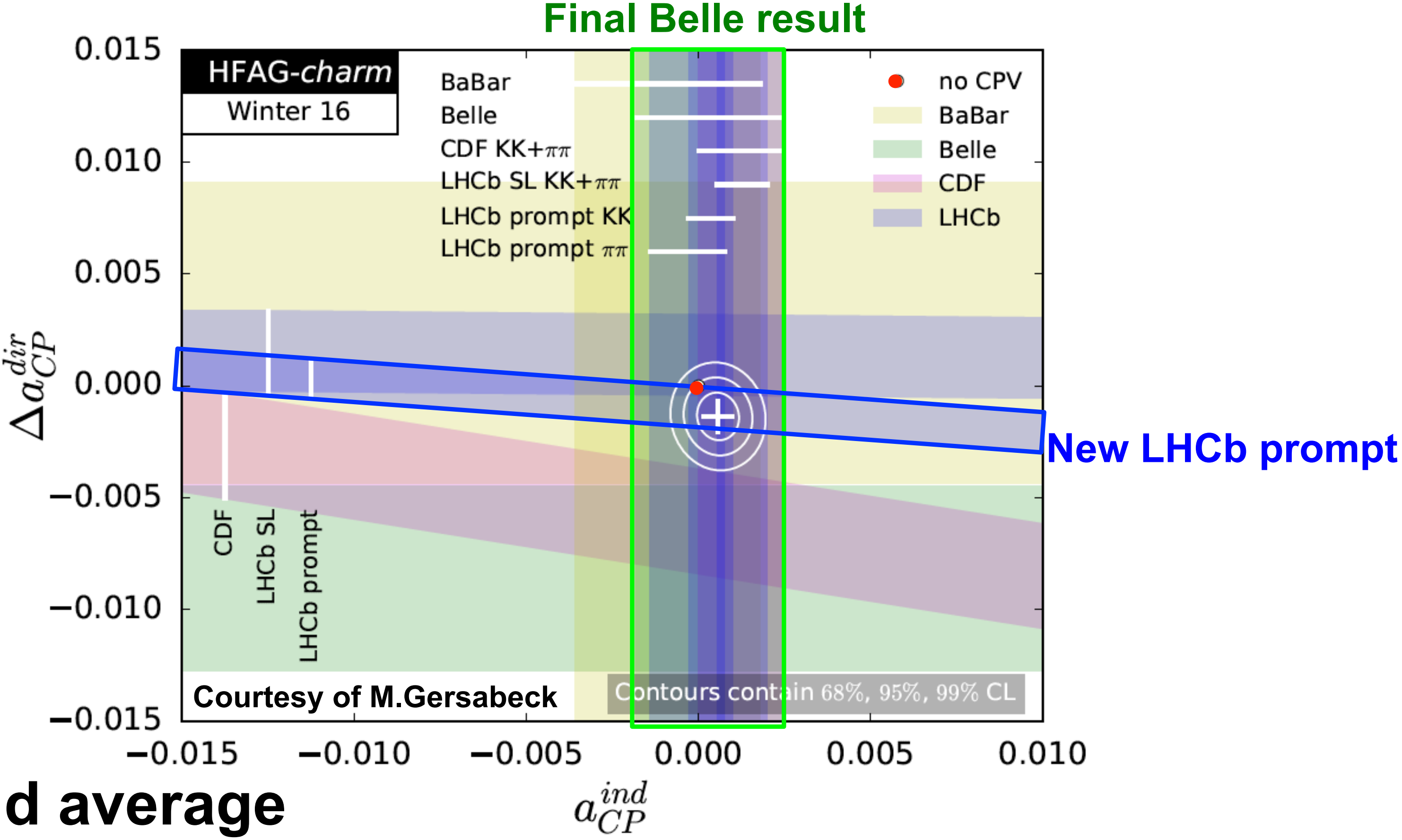


New result

LHCb: LHCb-PAPER-2015-055;
Belle: Phys. Lett. B 753 (2016) 412

Direct and indirect CP violation

Final Belle result



Courtesy of M.Gersabeck

New World average

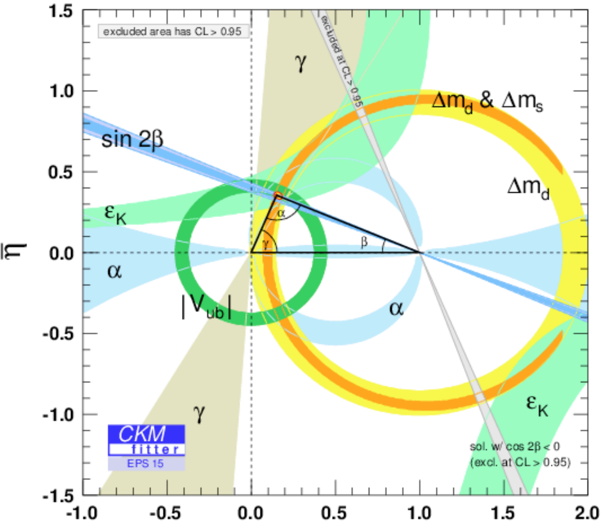
a_{CP}^{ind} = (0.056 ± 0.040)% and Δa_{CP}^{dir} = (−0.137 ± 0.070)%

➔ Consistent with no CP violation at 6.5% C.L.

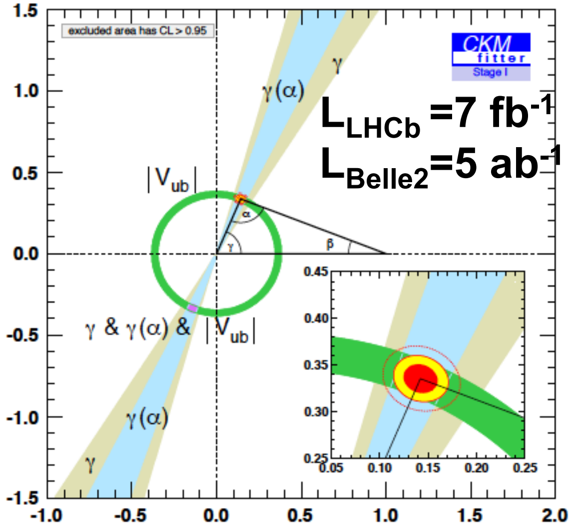
arXiv:1309.2293;
arXiv:1011.0352; LHCb-TDR-12

Looking at the future

EPS 2015

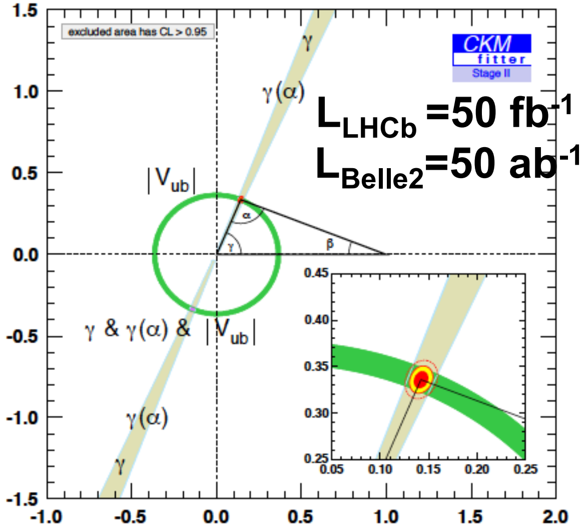


Around 2019



L_{LHCb} =7 fb^{-1}
L_{Belle2}=5 ab^{-1}

Around 2027



L_{LHCb} =50 fb^{-1}
L_{Belle2}=50 ab^{-1}

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025

LHCb Run II
Expected L=8 fb^{-1}

Detector
upgrade

LHCb Run III
Expected L=25 fb^{-1} by 2023

Collect >50 fb^{-1}
within ~10 years

2015 2016 2017 2018 2019 2020 2021 2022 2024 2025

1st collision
with partial
detector

Data taking
for physics

Expected L=50 ab^{-1}
by 2024

Conclusions

- Very large amount of new results last year
  - Both in b- and c-sector
  - Higher precision measurements
  - New decay modes
- In general the results in good agreement with the SM predictions
- Much more to come in the short and longer terms:
  - Run 2 has just started at LHC (LHCb & ATLAS &CMS)
  - LHCb upgrade & Belle II will take over

MANCHESTER
1824

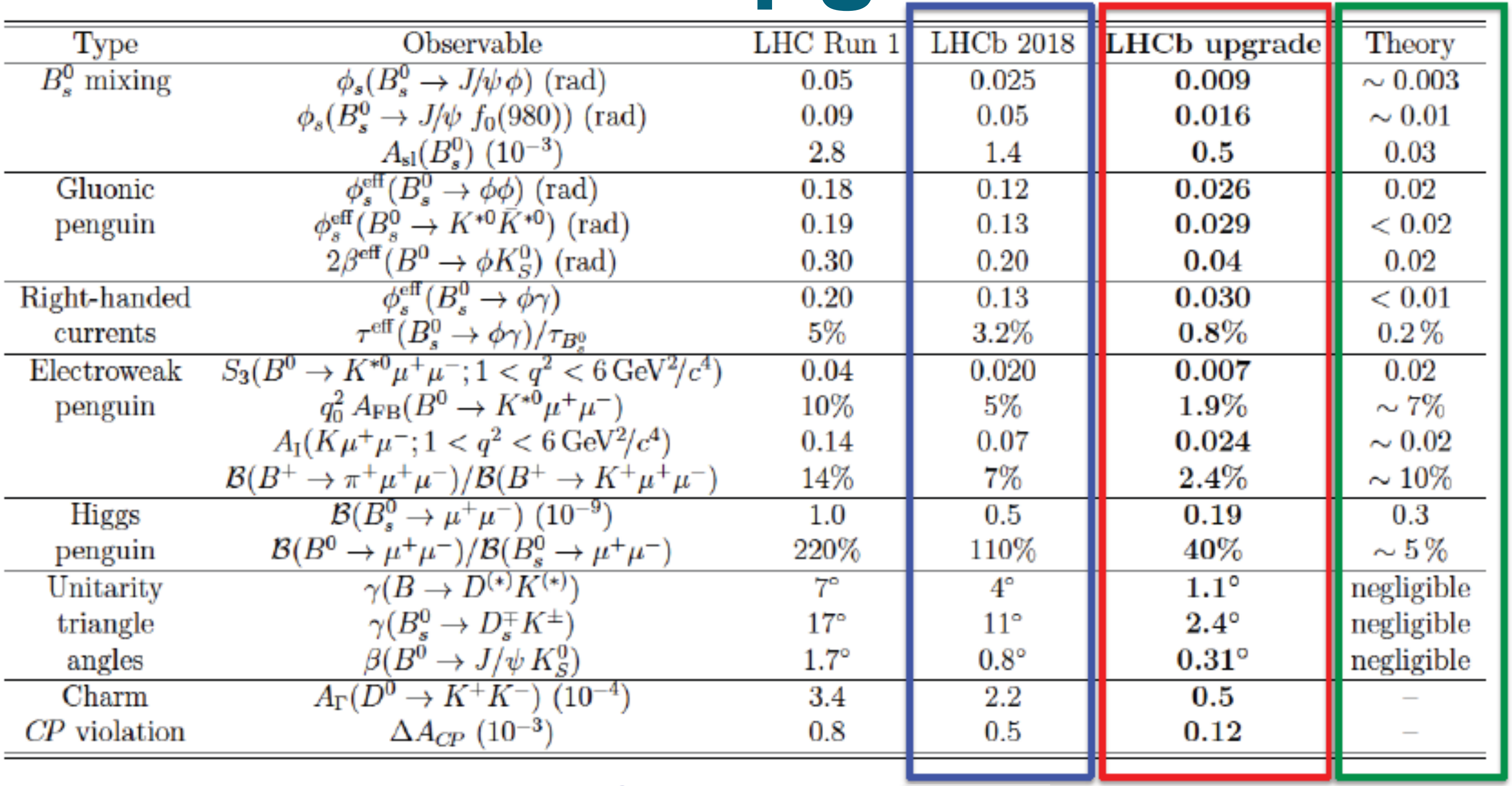
The University of Manchester

Thank you!

Backup

LHCb-PUB-2013-015

LHCb upgrade

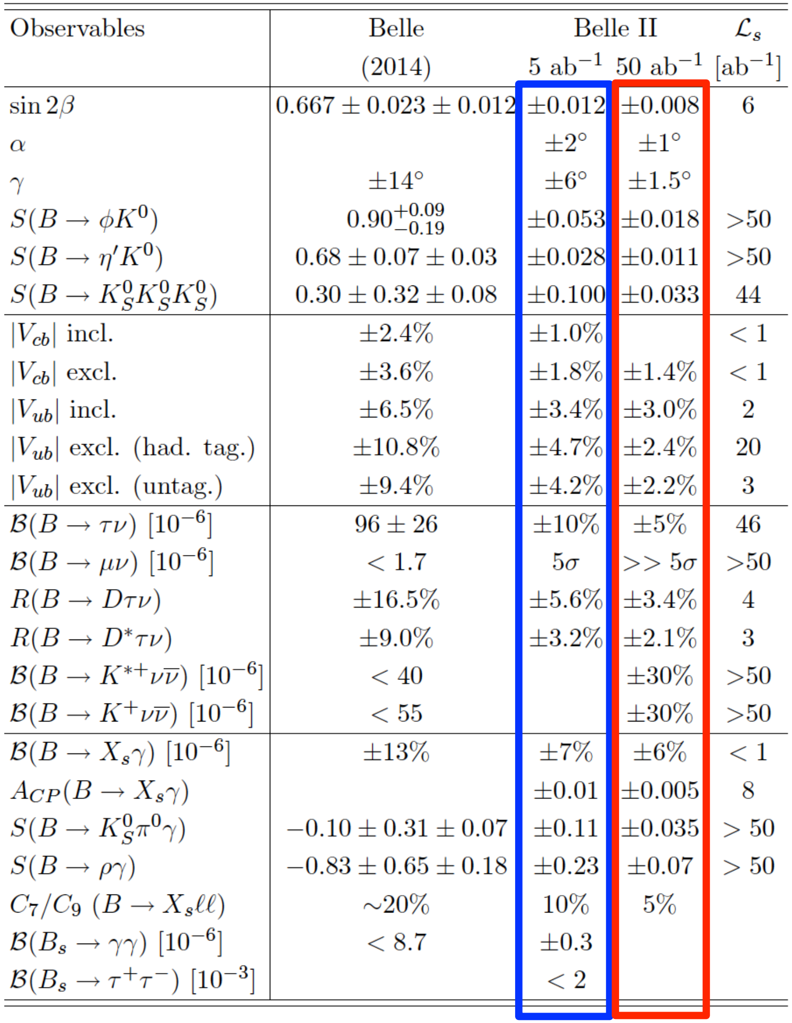


Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

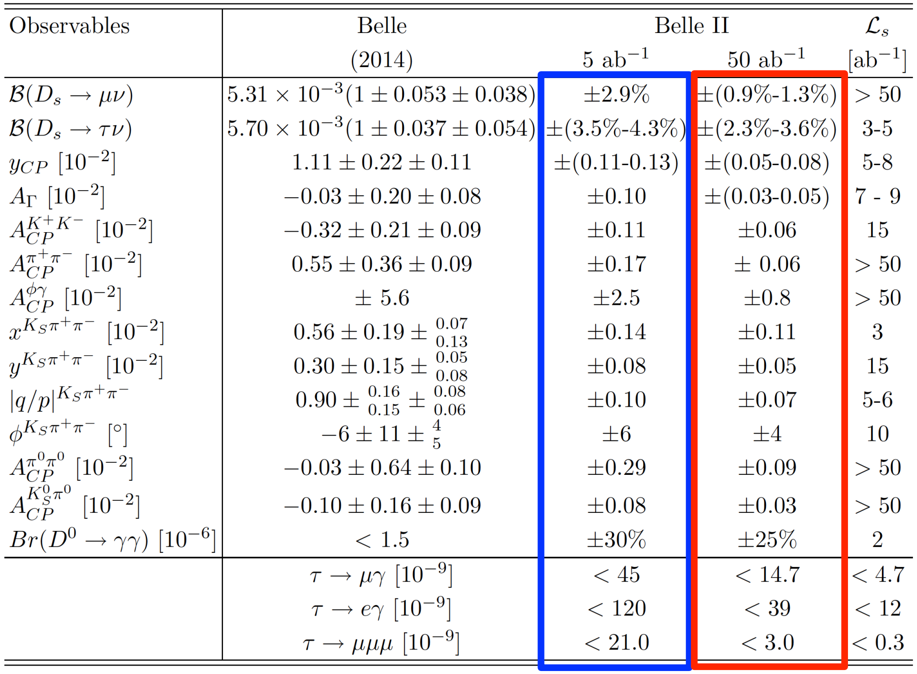
- Before the upgrade (8 fb^{-1})
- After the upgrade (50 fb^{-1})
- Theory uncertainty (as far as we know today)

BELLE2-NOTE-0021
BELLE2-NOTE-PH-2015-002

Belle II



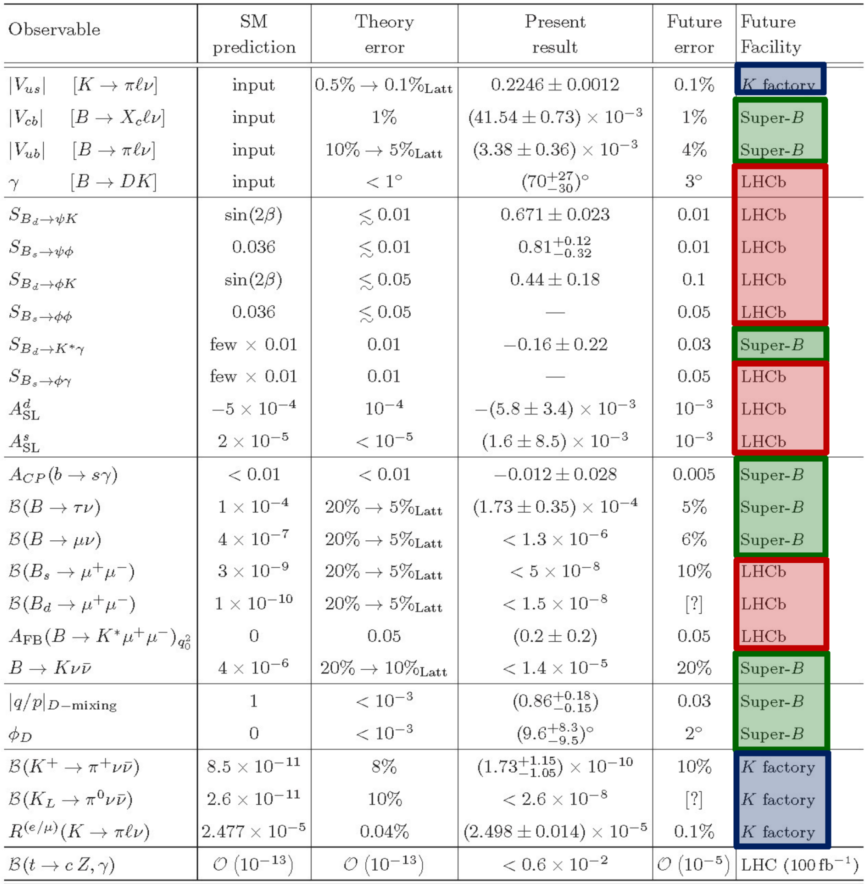
Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008	6
α		$\pm 2^\circ$	$\pm 1^\circ$	
γ	$\pm 14^\circ$	$\pm 6^\circ$	$\pm 1.5^\circ$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011	>50
$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033	44
$\|V_{cb}\|$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\|V_{cb}\|$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\|V_{ub}\|$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\|V_{ub}\|$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\|V_{ub}\|$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$	3
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	96 ± 26	$\pm 10\%$	$\pm 5\%$	46
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7	5σ	$>> 5\sigma$	>50
$R(B \to D\tau\nu)$	$\pm 16.5\%$	$\pm 5.6\%$	$\pm 3.4\%$	4
$R(B \to D^*\tau\nu)$	$\pm 9.0\%$	$\pm 3.2\%$	$\pm 2.1\%$	3
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ $[10^{-6}]$	< 40		$\pm 30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ $[10^{-6}]$	< 55		$\pm 30\%$	>50
$\mathcal{B}(B \to X_s\gamma)$ $[10^{-6}]$	$\pm 13\%$	$\pm 7\%$	$\pm 6\%$	< 1
$A_{CP}(B \to X_s\gamma)$		± 0.01	± 0.005	8
$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 0.11	± 0.035	> 50
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	± 0.23	± 0.07	> 50
C_7/C_9 $(B \to X_s \ell\ell)$	$\sim$20%	10%	5%	
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	< 8.7	± 0.3		
$\mathcal{B}(B_s \to \tau^+\tau^-)$ $[10^{-3}]$		< 2		



Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm 2.9\%$	$\pm(0.9\%$-$1.3\%)$	> 50
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm(3.5\%$-$4.3\%)$	$\pm(2.3\%$-$3.6\%)$	3-5
y_{CP} $[10^{-2}]$	$1.11 \pm 0.22 \pm 0.11$	$\pm(0.11$-$0.13)$	$\pm(0.05$-$0.08)$	5-8
A_Γ $[10^{-2}]$	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm(0.03$-$0.05)$	7 - 9
$A_{CP}^{K^+K^-}$ $[10^{-2}]$	$-0.32 \pm 0.21 \pm 0.09$	± 0.11	± 0.06	15
$A_{CP}^{\pi^+\pi^-}$ $[10^{-2}]$	$0.55 \pm 0.36 \pm 0.09$	± 0.17	$\pm$ 0.06	> 50
$A_{CP}^{\phi\gamma}$ $[10^{-2}]$	$\pm$ 5.6	± 2.5	± 0.8	> 50
$x^{K_S\pi^+\pi^-}$ $[10^{-2}]$	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	± 0.14	± 0.11	3
$y^{K_S\pi^+\pi^-}$ $[10^{-2}]$	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	± 0.08	± 0.05	15
$\|q/p\|^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ $[^\circ]$	$-6 \pm 11 \pm {}^{4}_{5}$	± 6	± 4	10
$A_{CP}^{\pi^0\pi^0}$ $[10^{-2}]$	$-0.03 \pm 0.64 \pm 0.10$	± 0.29	± 0.09	> 50
$A_{CP}^{K^0_S\pi^0}$ $[10^{-2}]$	$-0.10 \pm 0.16 \pm 0.09$	± 0.08	± 0.03	> 50
$Br(D^0 \to \gamma\gamma)$ $[10^{-6}]$	< 1.5	$\pm 30\%$	$\pm 25\%$	2
	$\tau \to \mu\gamma$ $[10^{-9}]$	< 45	< 14.7	< 4.7
	$\tau \to e\gamma$ $[10^{-9}]$	< 120	< 39	< 12
	$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0	< 3.0	< 0.3

- Soon after startup (5 ab^{-1})
- By the end of the present programme (50 ab^{-1})

Physics at Belle II and LHCb upgrade



Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$\lvert V_{us}\rvert$ $[K \to \pi \ell \nu]$	input	$0.5\% \to 0.1\%_{\rm Latt}$	0.2246 ± 0.0012	0.1%	K factory
$\lvert V_{cb}\rvert$ $[B \to X_c \ell \nu]$	input	1%	$(41.54 \pm 0.73) \times 10^{-3}$	1%	Super-B
$\lvert V_{ub}\rvert$ $[B \to \pi \ell \nu]$	input	$10\% \to 5\%_{\rm Latt}$	$(3.38 \pm 0.36) \times 10^{-3}$	4%	Super-B
γ $[B \to DK]$	input	$< 1^\circ$	$(70^{+27}_{-30})^\circ$	3°	LHCb
$S_{B_d \to \psi K}$	$\sin(2\beta)$	$\lesssim 0.01$	0.671 ± 0.023	0.01	LHCb
$S_{B_s \to \psi \phi}$	0.036	$\lesssim 0.01$	$0.81^{+0.12}_{-0.32}$	0.01	LHCb
$S_{B_d \to \phi K}$	$\sin(2\beta)$	$\lesssim 0.05$	0.44 ± 0.18	0.1	LHCb
$S_{B_s \to \phi \phi}$	0.036	$\lesssim 0.05$	—	0.05	LHCb
$S_{B_d \to K^* \gamma}$	few $\times$ 0.01	0.01	-0.16 ± 0.22	0.03	Super-B
$S_{B_s \to \phi \gamma}$	few $\times$ 0.01	0.01	—	0.05	LHCb
$A^d_{\rm SL}$	-5×10^{-4}	10^{-4}	$-(5.8 \pm 3.4) \times 10^{-3}$	10^{-3}	LHCb
$A^s_{\rm SL}$	2×10^{-5}	$< 10^{-5}$	$(1.6 \pm 8.5) \times 10^{-3}$	10^{-3}	LHCb
$A_{CP}(b \to s\gamma)$	< 0.01	< 0.01	-0.012 ± 0.028	0.005	Super-B
$\mathcal{B}(B \to \tau \nu)$	1×10^{-4}	$20\% \to 5\%_{\rm Latt}$	$(1.73 \pm 0.35) \times 10^{-4}$	5%	Super-B
$\mathcal{B}(B \to \mu \nu)$	4×10^{-7}	$20\% \to 5\%_{\rm Latt}$	$< 1.3 \times 10^{-6}$	6%	Super-B
$\mathcal{B}(B_s \to \mu^+ \mu^-)$	3×10^{-9}	$20\% \to 5\%_{\rm Latt}$	$< 5 \times 10^{-8}$	10%	LHCb
$\mathcal{B}(B_d \to \mu^+ \mu^-)$	1×10^{-10}	$20\% \to 5\%_{\rm Latt}$	$< 1.5 \times 10^{-8}$	[?]	LHCb
$A_{\rm FB}(B \to K^* \mu^+ \mu^-)_{q_0^2}$	0	0.05	(0.2 ± 0.2)	0.05	LHCb
$B \to K \nu \bar{\nu}$	4×10^{-6}	$20\% \to 10\%_{\rm Latt}$	$< 1.4 \times 10^{-5}$	20%	Super-B
$\lvert q/p\rvert_{D-\rm mixing}$	1	$< 10^{-3}$	$(0.86^{+0.18}_{-0.15})$	0.03	Super-B
ϕ_D	0	$< 10^{-3}$	$(9.6^{+8.3}_{-9.5})^\circ$	2°	Super-B
$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$	8.5×10^{-11}	8%	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	10%	K factory
$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})$	2.6×10^{-11}	10%	$< 2.6 \times 10^{-8}$	[?]	K factory
$R^{(e/\mu)}(K \to \pi \ell \nu)$	2.477×10^{-5}	0.04%	$(2.498 \pm 0.014) \times 10^{-5}$	0.1%	K factory
$\mathcal{B}(t \to c\, Z, \gamma)$	$\mathcal{O}\,(10^{-13})$	$\mathcal{O}\,(10^{-13})$	$< 0.6 \times 10^{-2}$	$\mathcal{O}\,(10^{-5})$	LHC ($100\,{\rm fb}^{-1}$)
$B(B \to Xs\gamma)$				6%	Super-B
$B(B \to Xd\gamma)$				20%	Super-B
$S(B \to \rho\gamma)$				0.15	Super-B
$B(\tau \to \mu\gamma)$				$3 \cdot 10^{-9}$	Super-B (90% U.L.)
$B(B+ \to D\tau\nu)$				3%	Super-B
$B(Bs \to \gamma\gamma)$				$0.25 \cdot 10^{-6}$	Super-B (5 ab-1)
$\sin 2\theta W$ @ $Y(4S)$				$3 \cdot 10^{-4}$	Super-B

- Physics at Super B factory: *arXiv:1002.5012* *arXiv:1008.1541*
- Belle II and LHCb will provide complementary information

Adopted from *G. Isidori et al., Ann.Rev.Nucl.Part.Sci. 60, 355 (2010)*

🟩 Super B factory

🟥 LHCb

🟦 K experiments

Phys. Rev. Lett. 115, 121604 (2015)

Measurement of the CP-violating weak phase φ_s

- $\varphi_q^{meas} = \varphi_q + \Delta\varphi_{penguin} + \Delta\varphi_{BSM}$
- Measure $\Delta\varphi_{penguin}$ in processes where penguin decays are not suppressed $B^0 \to J/\psi h^0$ with $h^0 = K^{*0}, \rho$

$$A \sim -\lambda A_{(i)}\left[1 - a'_{(i)} e^{i\theta'_{(i)}} e^{i\gamma}\right]$$

- New results from LHCb, fit for |A'/A| to limit sensitivity to hadronic uncertainties, assuming:

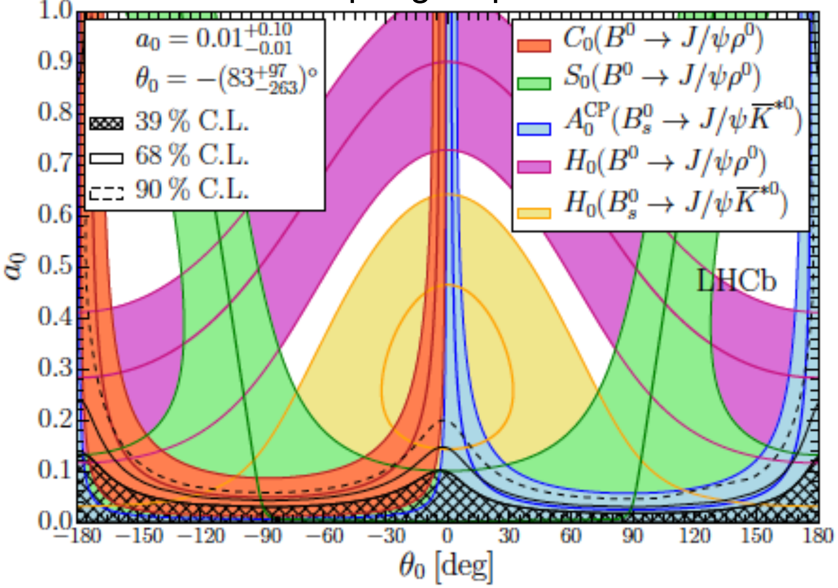
$$\left|A'_{(i)}/A_i\right|\left(B_s^0 \to J/\psi\overline{K}^{*0}\right) = \left|A'_{(i)}/A_i\right|\left(B_d^0 \to J/\psi\rho^0\right)$$

- Dominated by the input from the CP asymmetries in $B^0_s \to J/\psi\overline{K}^{*0}$

➔ penguin pollution in the determination of φ_s is small

- Compatible with previous results

Limits on the penguin parameters



$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})\ ^{+0.004}_{-0.009}\,(\text{syst})\,\text{rad}$$

$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\,\text{rad}$$

$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\,\text{rad}$$