Flavor Physics

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on behalf of the LHCb collaboration
including results from other experiments

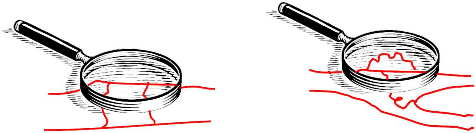
12 February 2016

Lake Louise Winter Institute
February 7 – 13, 2016, Chateau Lake Louise, Canada

Outline

Flavor physics: WHAT, WHY, HOW ?

1. WHAT: Quarks and leptons exist in 6 "flavors" (u, c, t, d, s, b) and (e, μ, τ, ν_e, ν_μ, ν_τ).
2. WHY:
    - Flavor is at the heart of the Standard Model, involving 22 of the 28 free parameters (masses and mixing of fundamental fermions, CP violation)
    - Flavor physics loop processes (box and penguins) are sensitive to energy scales well beyond the ones of the accelerators, thanks to virtual contributions



→ Indirect search for New Physics

3. HOW:
    - Compare precise theoretical predictions with precise experimental measurements
    - LHCb, Belle, BaBar, ATLAS, CMS, NA62, BESIII, neutrinos experiments, ...!

Introduction to flavor physics

Masses and mixings of quarks have a common origin in the SM, the Yukawa interactions with the Higgs doublet

$$\mathcal{L}_{\text{Yukawa}} = -Y^d_{ij}\overline{Q'_{Li}}\phi d'_{Rj} - Y^u_{ij}\overline{Q'_{Li}}\epsilon\phi^* u'_{Rj} + \text{h.c.}$$

After SSB, quark masses are obtained by diagonalizing Y.
Mass eigenstates are related to the weak eigenstates by the CKM matrix:

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}' = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}^{\text{phys}}$$

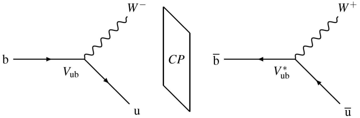
The weak current interactions between quarks and $W^\pm$ are proportional to the CKM matrix elements:

$$\mathcal{L}_{\text{CC}} = -\frac{g}{\sqrt{2}} \left(\bar{u}_{\text{L}}, \bar{c}_{\text{L}}, \bar{t}_{\text{L}}\right) \gamma^\mu W^+_\mu V_{\text{CKM}} \begin{pmatrix} d_{\text{L}} \\ s_{\text{L}} \\ b_{\text{L}} \end{pmatrix} + h.c.$$

CKM matrix and CP violation

- 3×3 unitary matrix, describes CP violation in the SM

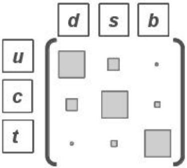
$$V_{ij} \neq V_{ij}^* \;\Rightarrow\; (CP)\mathcal{L}_{\mathrm{CC}}(CP)^\dagger \neq \mathcal{L}_{\mathrm{CC}}^\dagger \;\Rightarrow\; \cancel{CP}$$



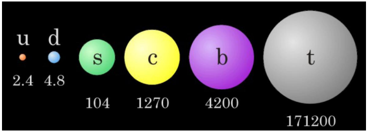
- Can be parameterized with 4 parameters A, λ, ρ and η:

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Strong hierarchy in quarks couplings:



also in masses:



Searching for New Physics

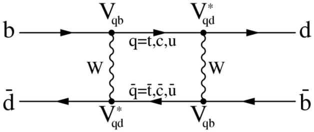
Few fundamental questions:

- Hierarchy of masses and mixing angles? why 3 generations?
- Stability of the Higgs mass? Dark matter?
- Baryon asymmetry of the Universe requires CPV beyond the SM

  (Not necessarily in flavor changing processes, nor necessarily in quark sector)

Two ways to address them:

- Direct searches: try to produce directly new real particles “on-shell”, but we don’t know their mass or lifetime and we are limited by the center-of-mass energy of accelerator.
- Indirect searches: study the effect of “off-shell” (virtual) particles within quantum loop. Compare precise theoretical predictions with precise experimental measurements. Not limited by the center-of-mass energy of accelerator.
  e.g. Argus 1987, B^0–$\bar{B}^0$ mixing ⇒ heavy top quark



→ Flavor physics exploits the second approach

Selected physics results

In 50 minutes, will concentrate on “quark flavor physics”. For neutrinos, see Jonathan Link’s talk.
Talk biased towards possible “hints” of New Physics (+ tetra&pentaquarks since no other talk on that here)

(For top, see e.g. Y. Chao talk)

- Tetra&Pentaquarks
- CP violation and CKM physics
  - γ angle
  - Mixing-induced CP violation (β, ϕ_s)
  - CP violation in B^0 and B_s^0 mixing
  - CPV in kaons
  - CPV in charm
  - V_{ub}
  - Global CKM fit
- Tests of Lepton Flavor Universality
  - $R_K = \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$
  - R_D and R_{D^*}
- Rare decays
  - $B \to \mu^+\mu^-$
  - $B^0 \to K^*\mu^+\mu^-$, $B_s^0 \to \phi\mu\mu$, $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$
- $(g-2)_\mu$

Heavy flavor experiments

Exp.	Accelerator	Beam energies	$\sigma(b\bar{b})$	Int. lumi (end 2015)
BaBar	PEP2, e^+e^-	$3.1 + 9\,\mathrm{GeV}$	1 nb	$550\,\mathrm{fb}^{-1}$
Belle	KEKB, e^+e^-	$3.5 + 8\,\mathrm{GeV}$	1 nb	$1\mathrm{ab}^{-1}$
CDF, DØ	Tevatron, $p\bar{p}$	$2 \times 0.98\,\mathrm{TeV}$	$100\,\mu$b	$10\,\mathrm{fb}^{-1}$ each
LHCb	LHC, pp	$2 \times 3.5\,\mathrm{TeV}$	$290\,\mu$b	$1\,\mathrm{fb}^{-1}$
		$2 \times 4\,\mathrm{TeV}$	$330\,\mu$b	$2\,\mathrm{fb}^{-1}$
		$2 \times 6.5\,\mathrm{TeV}$	$500\,\mu$b	$0.3\,\mathrm{fb}^{-1}$ (ongoing)
ATLAS, CMS	LHC, pp	$2 \times 3.5\,\mathrm{TeV}$	$290\,\mu$b	$5\,\mathrm{fb}^{-1}$ each
		$2 \times 4\,\mathrm{TeV}$	$330\,\mu$b	$20\,\mathrm{fb}^{-1}$ each
		$2 \times 6.5\,\mathrm{TeV}$	$500\,\mu$b	$\sim 3\,\mathrm{fb}^{-1}$ (ongoing)

+ Belle II, BESIII, NA62, KOTO, BESIII, CLEO, MEG, COMET, Mu3e, Mu2e, MUSIC, PRISM/PRIME, Project X, E989, ...

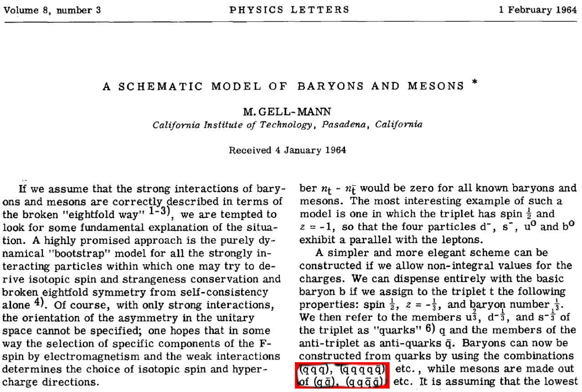
- e^+e^- collider: B and $\bar{B}$ produced coherently (good flavor tagging), clean (low background), low boost
- Hadron collider: all kinds of b-hadrons (B^+, B^0, B_s^0, B_c^+, b-baryons, ...) but produced incoherently (difficult flavor tagging), high cross-section, high boost, high background (challenging trigger, reconstruction, selection)
- Charm produced at both e^+e^- colliders (e.g. CLEO, BESIII) and hadron colliders. At the LHC, $\sigma(pp \to c\bar{c})$ is 20 times larger than $b\bar{b}$!

Tetra&Pentaquarks

- Tetraquarks
- Pentaquarks

Tetra and Pentaquarks

Known since the sixties that $qq\bar{q}\bar{q}$ and $qqqq\bar{q}$ are allowed in the quark model.



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

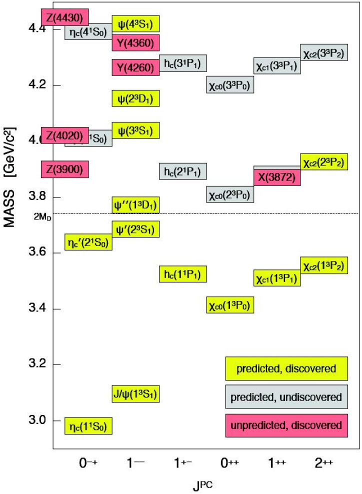
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$ etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$ etc. It is assuming that the lowest

Searches for years and many "discoveries" not confirmed

Exotics states and charmonium spectroscopy

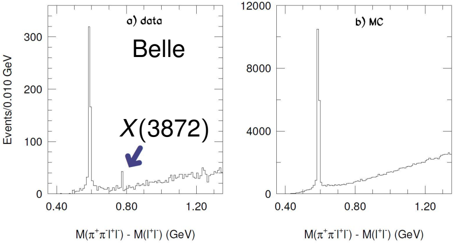
- Most charmonium states successfully described as $c\bar{c}$ resonances
- However, past decade has seen few “exotics” (names *XYZ*) that do not fit within this model

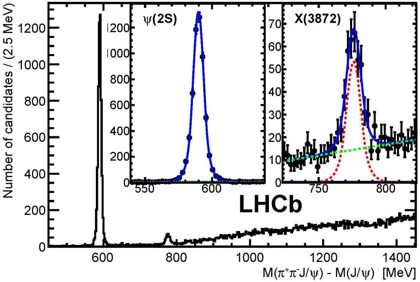


[R. Mitchell]

$X(3872)$

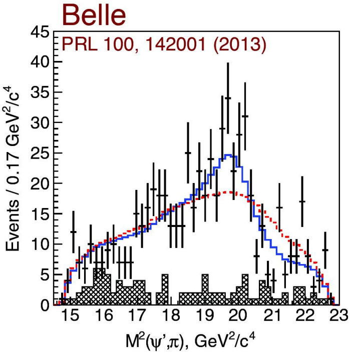
- First observed by Belle in $B^+ \to X(J/\psi\,\pi^+\pi^-)K^+$ above the $\psi(2S)$ [PRL 91 (2003) 262001]
- Then seen by 5 other experiments (BaBar, CDF, DØ, LHCb, CMS)
- LHCb determined its quantum number $J^{PC} = 1^{++}$ via angular analysis of $B \to X(J/\psi\,\pi\pi)K$ [PRL 110, 222001 (2013)] and $B^+ \to X(\rho^0 J/\psi)K^+$ [PRD92 (2015) 011102(R)]
- Nature still unclear: compatible with tetraquark, DD^* molecule or $\chi_{c1}(2^3P_1)$ hypotheses, though pure DD^* molecule disfavored at 4.4σ by LHCb [Nucl. Phys. B886 (2014) 665]





Tetraquark $Z(4430)^-$ (1)

- $Z(4430)^-$ special "tetraquark candidate", because charged: cannot be a $c\bar{c}$ state
- Belle discovered it in $B^0 \to \psi(2S)K^+\pi^-$ [PRD 80, (2009) 031104(R)] and had evidence for its J^P to be 1^+ [PRD 88 (2013) 074026]
- Using a moment analysis, BaBar claimed they do not need it in their data [PRD 79 (2009) 112001]
- LHCb redid the BaBar moment analysis using 3 fb^{-1} and clearly need something more to describe the $\psi(2S)\pi$ [PRL 112, 222002 (2014)]

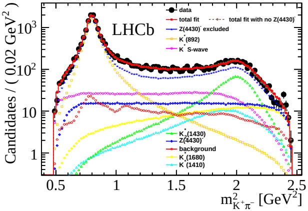


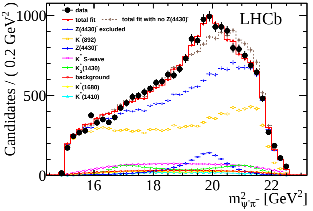
Fit without (red) and with the Z (blue)

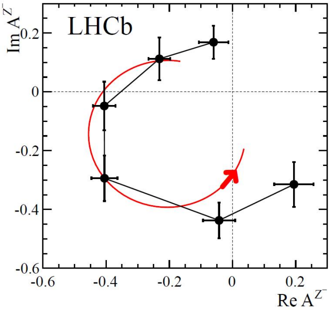
Tetraquark $Z(4430)^-$ (2)

[LHCb, PRL 112, 222002 (2014)]

- LHCb unbinned amplitude analysis of $B^0 \to \psi(2S) K^+ \pi^-$:
  $m = 4475 \pm 7^{+15}_{-25}\ \mathrm{MeV}/c^2$, $\Gamma = 172 \pm 13^{+37}_{-34}\ \mathrm{MeV}/c^2$
- J^P confirmed to be 1^+ and Argand plot shows the typical pattern for a resonance.
- Minimal quark content $c\bar{c}d\bar{u}$







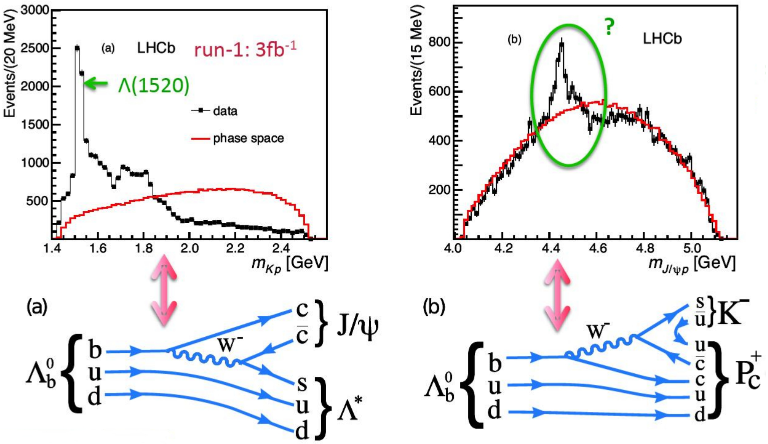
Fitted values of the Z amplitude in six $m^2_{\psi' \pi^-}$ bins.

Red is expectation from BW

Pentaquarks in $\Lambda_b^0 \to J/\psi\, pK$ decays (1) [LHCb, PRL 115 (2015) 072001]

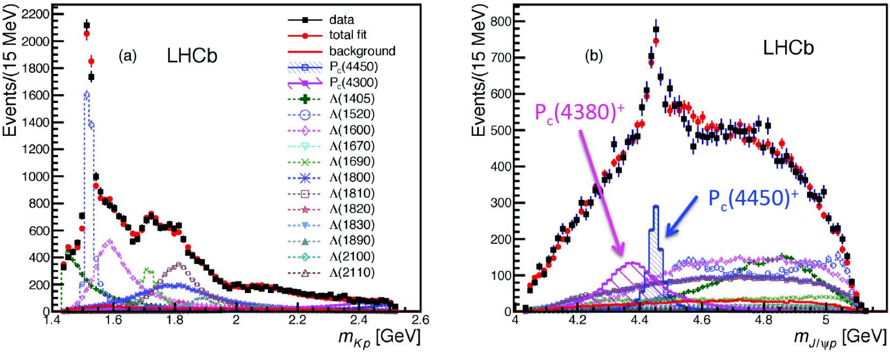
- $\Lambda_b^0 \to J/\psi\, pK$ initially studied for a precise Λ_b^0 lifetime [PRL111(2013)102003]
- Close look at the $m(Kp) - m(J/\psi\, p)$ Dalitz:
  - $m(Kp)$ with a rich structure due to Λ^* states
  - $m(J/\psi\, p)$ looks strange

Clear difference between data in black and phase space in red



Pentaquarks in $\Lambda_b^0 \to J/\psi\, pK$ decays (2) [LHCb, PRL 115 (2015) 072001]

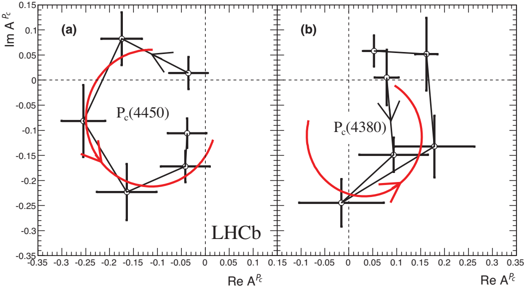
- Complex angular fit needed to describe the data: 5 decay angles, 14 possible Λ^* resonances for $m(Kp)$ and 2 "resonances" for $m(J/\psi\, p)$
- Fit prefers two opposite parities:
  $P_c(4380)^+$: $m = 4380 \pm 8 \pm 29\,\mathrm{MeV}/c^2$, $\Gamma = 205 \pm 18 \pm 86\,\mathrm{MeV}$, $J^P = \frac{3}{2}^-$
  $P_c(4450)^+$: $m = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV}/c^2$, $\Gamma = 39 \pm 5 \pm 19\,\mathrm{MeV}$, $J^P = \frac{5}{2}^+$

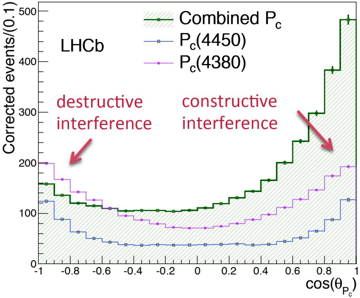


Pentaquarks in $\Lambda_b^0 \to J/\psi\, pK$ decays (3) [LHCb PRL 115 (2015) 072001]

- Argand plots show the phase motion of a resonance for $P_c(4450)$.
- For the $P_c(4380)$, one point is off by $\sim 2\sigma$.

- The interference patterns confirm the opposite parities





- Significance evaluated with toy Monte Carlo :
  $P_c(4380)^+$: 9σ
  $P_c(4450)^+$: 12σ
- Those states are consistent with $c\bar{c}uud$
- Next steps: confirmation with other channels and other experiments

Unitarity triangles and CP violation

- γ-angle
- Mixing-induced CPV in B_s^0
- Mixing-induced CPV in B^0
- CP violation in B^0 and B_s^0 mixing
- V_{ub}
- CP violation in charm
- CP violation in kaons
- Global CKM fits

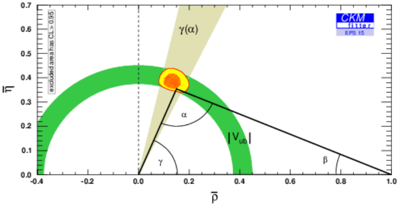
[See talks by A. Soffer, A. Chisholm, S. Harnew, B. Siddi, F. Wilson, E. Maurice]

γ angle

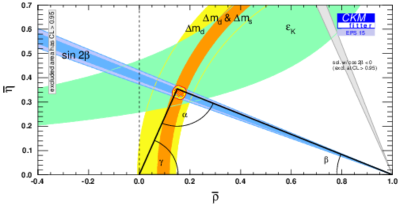
- $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is the least known of the CKM unitarity angles. Can be determined by:
  - Tree level processes, nearly insensitive to NP. Act as reference. Negligible theoretical uncertainty, using $B \to DK$, $\delta\gamma/\gamma \simeq 10^{-7}$

    [J. Brod et al, JHEP 1401 (2014) 051]
  - Loop processes, sensitive to NP
- Comparing the two can reveal NP

Unitarity triangle: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



Constraints from "Trees"



Constraints from "Loops"

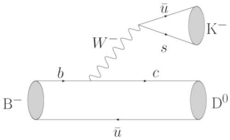
[CKMfitter (J. Charles et al.), EPJ. C41, 1-131 (2005), updated results and plots available at: `http://ckmfitter.in2p3.fr`]

γ angle measured with tree processes

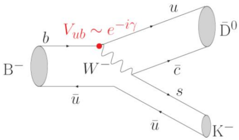
- γ-from-tree measurements use interferences between suppressed and favored $B \to Dh$ decays
- Many modes used: $D \to KK$, $D \to K\pi$, $D \to K_S^0\pi\pi$, $D \to K_S^0 K\pi$, $B_s^0 \to D_s^{\mp} K^{\pm}$

$$\begin{tikzcd}
 & D^0 K^- \arrow[dr, "\mathcal{A}_D r_D e^{i\delta_D}"] & \\
B^- \arrow[ur, "\mathcal{A}_B"] \arrow[dr, "\mathcal{A}_B r_B e^{i(\delta_B-\gamma)}"'] & & f_D \\
 & \overline{D}^0 K^- \arrow[ur, "\mathcal{A}_D"'] &
\end{tikzcd}$$

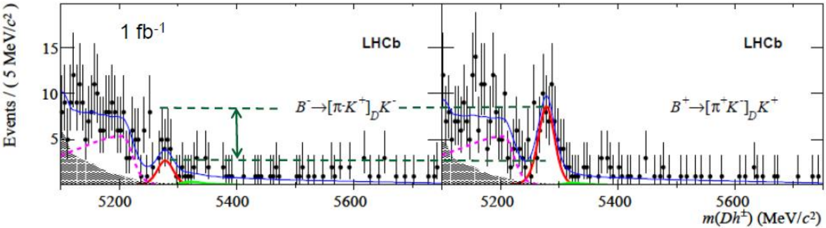
Favoured



Suppressed

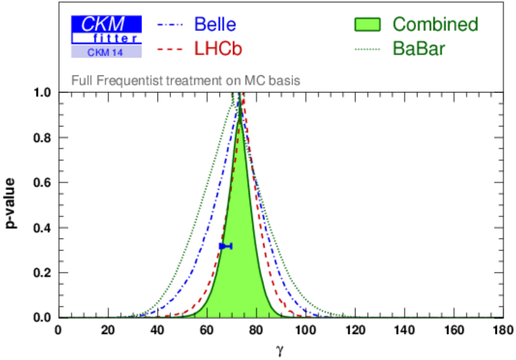


- Typical BR are small: around 10^{-7}
- e.g. "suppressed ADS mode": very clean easy to interpret information on γ:



[PLB 712 (2012) 203]

γ combination

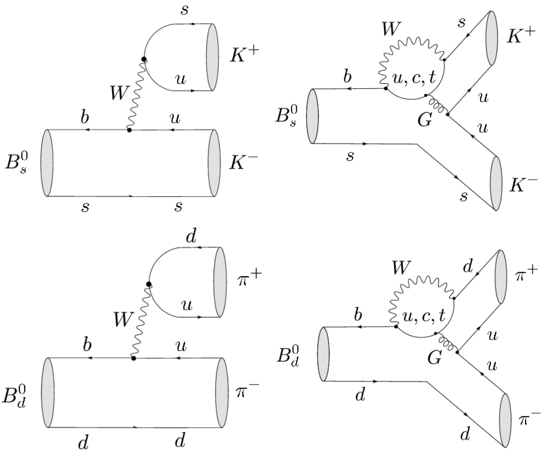


- No update since October 2014 (CKM2014): $\gamma = (73.2^{+6.3}_{-7.0})^\circ$
- Blue point is from indirect constraints: $\gamma^{\text{indirect}} = (66.9^{+1.0}_{-3.7})^\circ$
- Expect updates soon in particular with:
  - $B^\pm \to D^0 K^\pm \pi^+\pi^-$, $D^0 \to K^+K^-$, $\pi^+\pi^-$ [LHCb, PRD 92, 112005 (2015)]
  - $B^\pm \to D^0 h^\pm$, $D^0 \to K\pi\pi^0$, $\pi\pi\pi^0$, $KK\pi^0$ [LHCb, PRD 91, 112014 (2015)]
  - $B^0 \to DK^+\pi^-$, $D \to K^+\pi-$, K^+K^-, $\pi^+\pi^-$ [LHCb, arXiv:1602.03455]

γ-angle measured with loop processes

[LHCb, PLB 741 (2015) 1, 1 fb^{-1}]

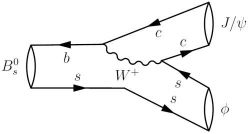
- γ extracted from $B_s^0 \to K^+K^-$, $B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$ using U-spin + isospin analyses. e.g. [R. Fleischer, PLB459 (1999) 306, Ciuchini, JHEP 10 (2012) 029]
- Experimental result: $\gamma = (63.5^{+7.2}_{-6.7})^\circ$, including U-spin breaking effects
- Compatible with "γ from tree" so far

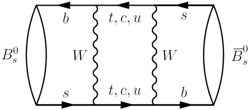


Mixing-induced CPV in B_s^0

- Interference between B_s^0 decay to $J/\psi\,\phi$ either directly or via B_s^0–$\overline{B}_s^0$ oscillation gives rise to a CP violating phase $\phi_s^{J/\psi\,\phi} \equiv \phi_s = \Phi_\mathrm{M} - 2\Phi_\mathrm{D}$

$$\begin{tikzcd}
B_s \arrow[rr, "\Phi_D"] \arrow[dr, "\Phi_M"'] & & J/\psi\phi \\
& \overline{B}_s \arrow[ur, "-\Phi_D"'] &
\end{tikzcd}$$



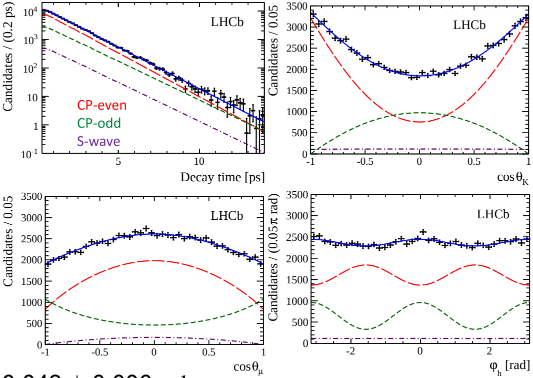


- In SM, $\phi_s \simeq -2\beta_s = -(0.0376^{+0.0007}_{-0.0008})\,\mathrm{rad}$, $\beta_s = \arg\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right)$
- Neglecting sub-leading diagrams, the same phase is expected in $B_s^0 \to D_s^+ D_s^-$ and $B_s^0 \to J/\psi\pi\pi$
- NP could enter in the $B_s^0 - \overline{B}_s^0$ mixing box diagram
- Measured by fitting differential decay rates for B_s^0 and $\overline{B}_s^0$:

$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi\phi)}{\mathrm{d}t\,\mathrm{d}\cos\theta_\mu\,\mathrm{d}\varphi_h\,\mathrm{d}\cos\theta_K} = f(\phi_s, \Delta\Gamma_s, \Gamma_s, \Delta m_s, M(B_s^0), |A_\perp|, |A_\parallel|, |A_S|, \delta_\perp, \delta_\parallel, \ldots)$$

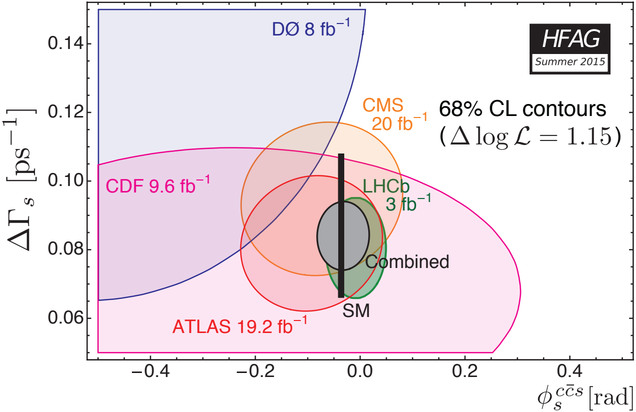
Mixing-induced CPV in $B_s^0 \to J/\psi\, h^+ h^-$ [LHCb, PRL 114, 041801 (2015)]

- Unbinned maximum likelihood fit (time, mass, angles, initial flavor)



- $\phi_s = -0.058 \pm 0.049 \pm 0.006\,\mathrm{rad}$,
- $\Gamma_s \equiv (\Gamma_\mathrm{L} + \Gamma_\mathrm{H})/2 = 0.6603 \pm 0.0027 \pm 0.0015\,\mathrm{ps}^{-1}$
- $\Delta\Gamma_s \equiv \Gamma_\mathrm{L} - \Gamma_\mathrm{H} = 0.0805 \pm 0.0091 \pm 0.0032\ \mathrm{ps}^{-1}$
- Combined with $B_s^0 \to J/\psi\pi^+\pi^-$: $\phi_s = -0.010 \pm 0.039$

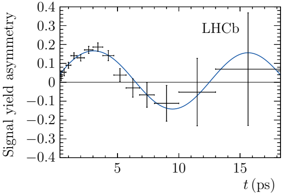
Mixing-induced CPV in B_s^0



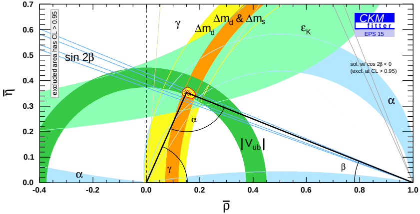
- LHCb is dominating the world average:
- $\phi_s^{\text{HFAG WA}} = -0.034 \pm 0.033\,\text{rad}$
- Compatible with SM, but still room for NP!
- Experimental constraints on penguin pollution using $B^0 \to J/\psi\,\rho^0$ and $B_s^0 \to J/\psi\,\overline{K}^{*0}$ [LHCb, PLB 742 (2015) 38, JHEP 11 (2015) 082]

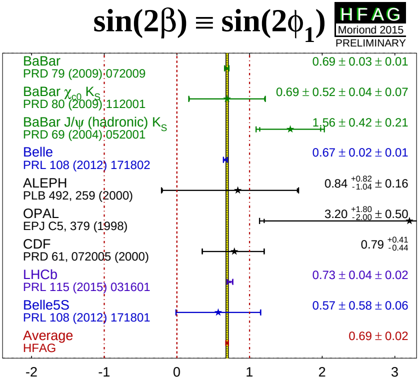
Mixing-induced CP violation in B^0

- $\mathcal{A}_f^{\rm CP}(t) = \frac{\Gamma(\bar{B}(t)\to f)-\Gamma(B(t)\to f)}{\Gamma(\bar{B}(t)\to f)+\Gamma(B(t)\to f)} \propto \sin 2\beta$
  $f = J/\psi\, K^0_{\rm S},\ J/\psi\, K^0_{\rm L},\ \eta_c K^0_{\rm S}, \ldots$
- LHCb $B^0 \to J/\psi\, K^0_{\rm S}$: [PRL 115 (2015) 031601]
  Precision similar to b-factories, excellent agreement.

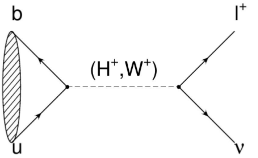


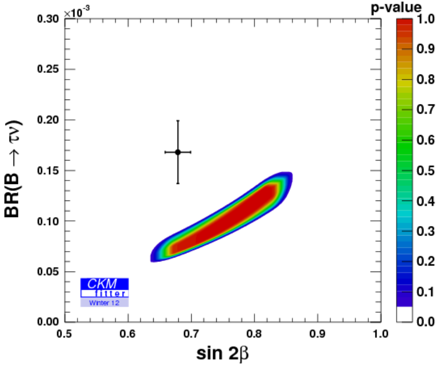
- BaBar+Belle analysis of $B^0 \to D^{(*)}_{\rm CP} h^0$, penguin-free [PRL 115 (2015) 121604].
  First combined fit to BaBar and Belle data.
  5σ observation of CPV in this mode.
  Very good agreement with world average from $B \to$ charmonium K^0 decays.
- World average in agreement with indirect SM fit.

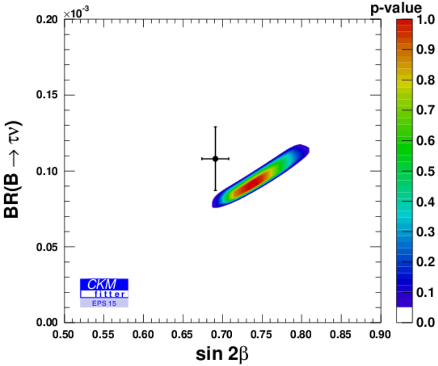




$\sin 2\beta - \mathcal{B}(B^+ \to \tau^+\nu_\tau)$ correlations







2012 → 2015: tension disappeared with more statistics

(latest Belle $B^+ \to \tau^+\nu_\tau$ result: [arXiv:1503.05613])

CP violation in B^0 and B_s^0 mixing

- Semileptonic asymmetry

  $A_{\mathrm{SL}}^q = \frac{\Gamma(\bar{B}_q \to B_q \to f) - \Gamma(B_q \to \bar{B}_q \to \bar{f})}{\Gamma(\bar{B}_q \to B_q \to f) + \Gamma(B_q \to \bar{B}_q \to \bar{f})}$

  very small in the SM [arXiv:1511.09466]

  $A_{\mathrm{SL}}^{s\ \mathrm{SM}} = (2.22 \pm 0.25) \times 10^{-5}$

  $A_{\mathrm{SL}}^{d\ \mathrm{SM}} = (-4.7 \pm 0.6) \times 10^{-4}$
- DØ measured the di-muon asymmetry, A_{SL}^b, mixture of semileptonic asymmetries in B_s^0 (A_{SL}^s) and B^0 (A_{SL}^d).

  $\sim 3\sigma$ from SM [DØ, PRD 89 (2014) 012002]
- LHCb measured individually:

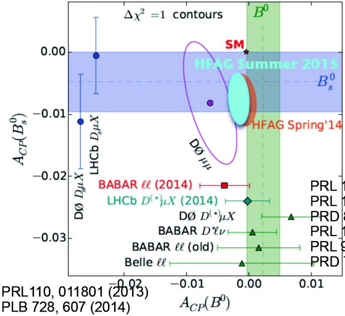
  $A_{\mathrm{SL}}^s = (-0.06 \pm 0.50 \pm 0.36)\%$, 1 fb^{-1},

  [PLB 728 (2014) 607]

  $A_{\mathrm{SL}}^d = (-0.02 \pm 0.19 \pm 0.30)\%$, 3 fb^{-1},

  [PRL 114 (2015), 041601]

  Compatible with both SM and DØ
- Explanation of DØ A_{SL}^b could be due to deviation in $\Delta\Gamma_{\mathrm{d}}$ [PRD 87 074020(2013)]

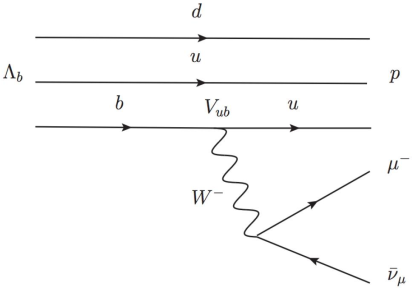


PRL 114 081801 (2015)
PRL 114, 041601 (2015)
PRD 86, 072009 (2012)
PRL 111, 101802 (2013)
PRL 96, 251802 (2006)
PRD 73, 112002 (2006)

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

V_{ub} (1)

- PDG 2014: 3σ discrepancy between the 2 ways to measure V_{ub}:
  - inclusive $b \to u\ell\nu$, $|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3}$
  - exclusive $B \to \pi\ell\nu$, $|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$
- LHCb uses $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ for the first time [Nature Physics 11, 743-747 (2015)], 2 fb^{-1}

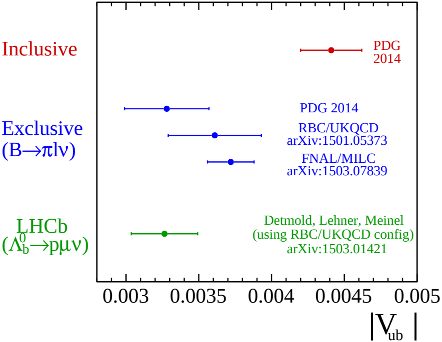


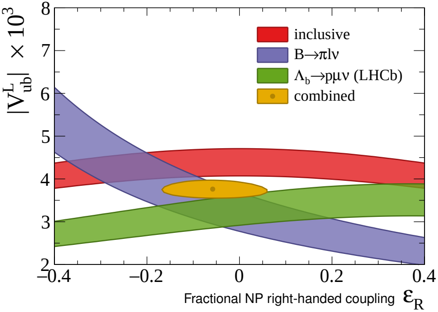
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)} R_{FF}$$

where R_{FF} is a ratio of form factors calculated using Lattice QCD [arxiv:1503.01421]

V_{ub} (2) [Nature Physics 11, 743-747 (2015)]

$$|V_{ub}| = (3.27 \pm 0.15(\text{stat}) \pm 0.16(\text{LQCD}) \pm 0.06(V_{cb})) \times 10^{-3}$$



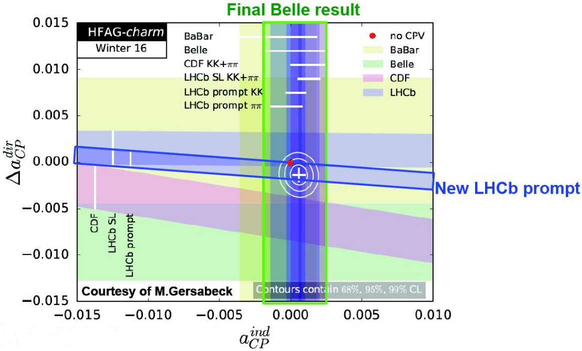


- Confirms discrepancy between inclusive and exclusive
- Disfavor NP models with significant right handed current
- Debatable world averages, depending on the input used (theory, BR of control mode, ...)

CP violation in charm

$$A_{\rm CP}(D^0 \to f) = \frac{\Gamma(D^0\to f)-\Gamma(\overline{D}^0\to f)}{\Gamma(D^0\to f)+\Gamma(\overline{D}^0\to f)}$$ with $f = K^+K^-$ and $\pi^+\pi^-$

[LHCb, arXiv:1602.03160], [Belle, PLB 753 (2016) 412]



New world average:

$$a_{\rm CP}^{\rm ind} = (0.056 \pm 0.040)\%$$
$$\Delta a_{\rm CP}^{\rm dir} = (-0.137 \pm 0.070)\%$$

Consistent with no CPV at 6.5% CL.

Direct CPV in kaons: ϵ'/ϵ

- 1999: discovery of direct CP violation in $K \rightarrow \pi\pi$ (NA48, KTeV)

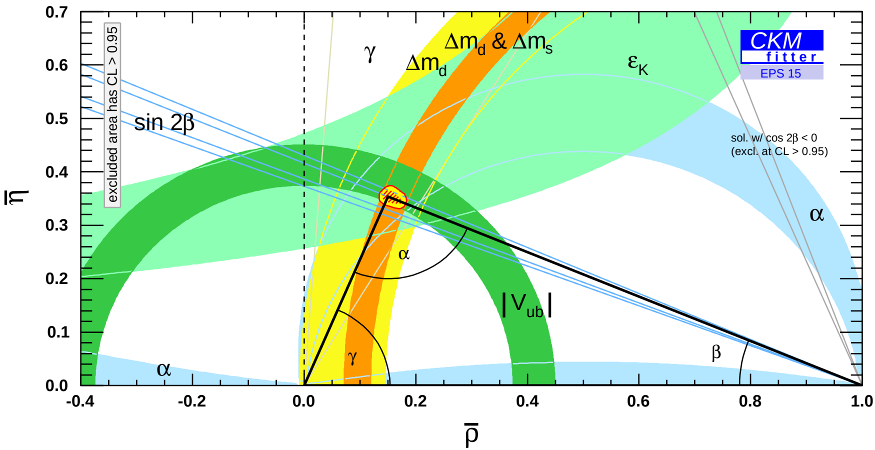
- 2001: Combined experimental average of the two above experiments: $Re\,(\epsilon'/\epsilon) = (16.6 \pm 2.3) \times 10^{-4}$, compatible with SM
  Experimental precision much better than the theoretical prediction.

- 2015: Fantastic progresses in lattice QCD. Can now compute all relevant long-distance effects that used to dominate the theoretical uncertainty
  [RBC-UKQCD, PRL 115, 212001 (2015)] [Ishizuka et al., PRD 92, 074503 (2015)]
  [A. J., Buras et al, arXiv:1507.06345] $Re\,(\epsilon'/\epsilon)^{\mathrm{SM}} = (1.9 \pm 4.5) \times 10^{-4}$

- A new 2.9σ discrepancy emerges!

- Good lattice prospects to improve even further the theoretical uncertainty

Global CKM fit



Excellent consistency of the various CKM measurements so far

[CKMfitter (J. Charles et al.), EPJ. C41, 1-131 (2005), updated results and plots available at: `http://ckmfitter.in2p3.fr`]

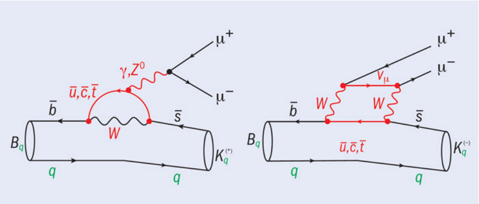
Tests of Lepton Flavor Universality

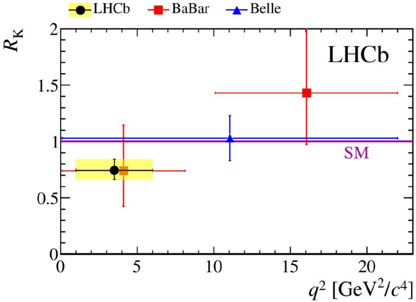
- R_K, $B^+ \to K^+\ell^+\ell^-$
- R_D, R_{D^*}, $B^0 \to D^{(*)-}\tau^+\nu_\tau$

See talks by B. Siddi, A. Palladino

Test of Lepton Universality with $B^+ \to K^+\ell^+\ell^-$

[PRL,113, 151601 (2014)]





- Search for NP in the above loops $(q^2 = m^2_{\ell\ell})$

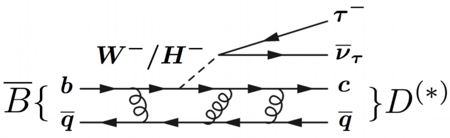
$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1.0003 \pm 0.0001 \text{ in the SM}$$ [Bobeth et al., JHEP0712:040(2007)]

- $R_K(\text{LHCb}, 1 < q^2 < 6\,\text{GeV}^2/c^4) = 0.745^{+0.090}_{-0.074} \pm 0.036$ (2.6σ from SM)
- To monitor with more statistics

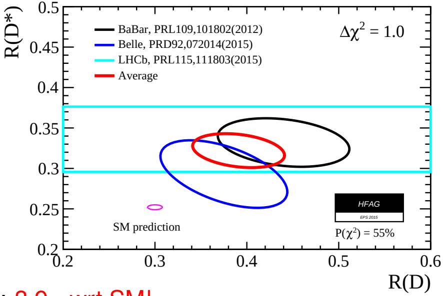
$\mathcal{B}(B^0 \to D^{(*)-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{(*)-}\ell^+\nu_\ell)$

$$R_D = \frac{\mathcal{B}(B^0 \to D^-\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^-\ell^+\nu_\ell)}, \quad R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell)}, \ \ell = \mu, e$$

- Sensitive to NP at the tree level!
- Theoretical predictions:
  - $R_D = 0.300 \pm 0.008$, [HPQCD, PRD 92, 054510 (2015)]
  - $R_{D*} = 0.252 \pm 0.003$, [S.Fajfer et al., PRD 85(2012) 094025]



[updated by M. Rotondo Feb 2016]



- Combination of LHCb, Belle and BaBar: 3.9σ wrt SM!
- Interestingly, CMS sees a slight excess in $h \to \tau\mu$ [CMS, PLB 749 (2015) 337]

Rare decays

- Effective field theory
- $B \to \mu^+\mu^-$
- $B^0 \to K^*\mu^+\mu^-$
- $B \to \phi\mu^+\mu^-$
- $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$

See talks by G. Andreassi, Y.T. Lai, H. Schreeck, S. Yang, I. Nugent, F. Wilson, R. Cheaib

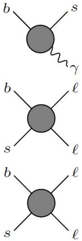
Effective field theory

Transition $B \to f$ described by an effective Hamiltonian $\langle f|\mathcal{H}_{\mathrm{eff}}|B\rangle$, with

$$\mathcal{H}_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \sum_i \Big(\underbrace{C_i \mathcal{O}_i}_{\mathrm{Left-handed}} + \underbrace{C_i' \mathcal{O}_i'}_{\mathrm{Right-handed}} \Big)$$

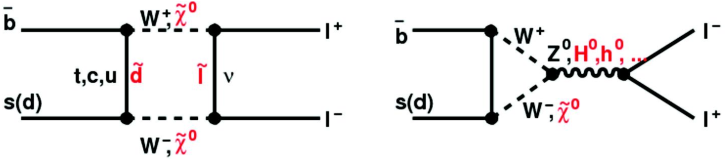
Computed by splitting into:

- C_i (Wilson coefficients): short distance (perturbative) effective couplings, can be computed in terms of fundamental couplings of the SM and beyond
- $\langle f|\mathcal{O}_i|B\rangle$: long distance (non perturbative), computed using QCD at low energy or extracted by phenomenological analysis. $\mathcal{O}_i$ are local operators:



	$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{O}_7^{(\prime)}$ photon penguin	✓		✓
$\mathcal{O}_9^{(\prime)}$ vector coupling			✓
$\mathcal{O}_{10}^{(\prime)}$ axialvector coupling		✓	✓
$\mathcal{O}_{S,P}^{(\prime)}$ (pseudo)scalar penguin		✓	

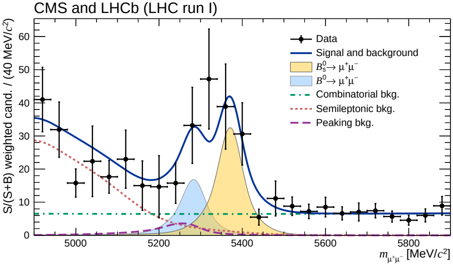
$B \to \mu^+\mu^-$

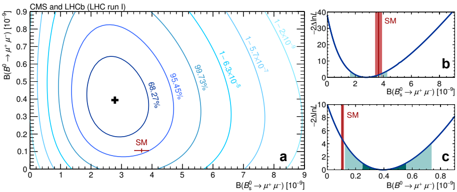


- $B^0_{s,d} \to \mu^+\mu^-$ are loop processes very suppressed in the SM.
  Involved Wilson coefficients $C^{(\prime)}_{S,P}$ and $C^{(\prime)}_{10}$
  Precise theoretical prediction [C. Bobeth et al, PRL 112 (2014) 101801]:
  $\mathcal{B}^{\mathrm{SM}}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23)^{-9}$
  $\mathcal{B}^{\mathrm{SM}}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09)^{-10}$
- Sensitive to new physics
  e.g. $\mathcal{B}^{\mathrm{MSSM}}(B^0_s \to \mu^+\mu^-) \propto \tan^6\beta$, where $\tan\beta = v_2/v_1$ is the ratio of neutral Higgs field vacuum expectation values
- Intensive searches over the past 30 years...

$B \to \mu^+\mu^-$ combined analysis of CMS and LHCb

[CMS and LHCb, Nature 522 (2015) 68]

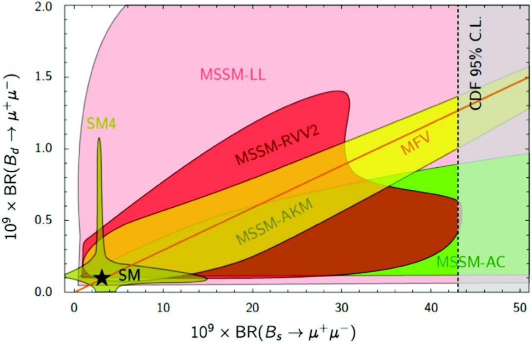




- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$ (6.2σ), first observation!
- $\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$ (3.2σ) evidence for $B^0 \to \mu^+\mu^-$
- $\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = 0.14^{+0.08}_{-0.06}$ (2.3σ of SM)

$B \to \mu^+\mu^-$ consequences

Modified from [D. Straub, Nuovo Cim. C035N1 (2012) 249]

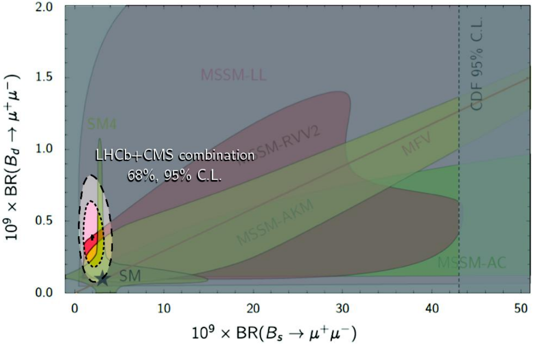


- SM4: Standard Model with a sequential fourth generation
- Left-handed currents only (MSSM-LL)
- Ross, Velasco-Sevilla and Vives (MSSM-RVV2)
- Antusch, King and Malinsky (MSSM-AKM)
- RSc: Randall-Sundrum model with custodial protection
- Agashe and Carone (MSSM-AC)

$B \to \mu^+\mu^-$ consequences

Strong constraints on many NP models, in particular those with large tan β

Modified from [D. Straub, Nuovo Cim. C035N1 (2012) 249]



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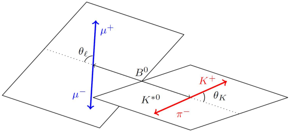
$B^0 \to K^{*0}\mu^+\mu^-$ [LHCb, arXiv:1512.04442]

- Same motivations as $B^- \to K^-\ell^+\ell^-$.
  Same SM loops, but with a vector in the final state, sensitive to $C_7^{(\prime)}$, $C_9^{(\prime)}$ and $C_{10}^{(\prime)}$
- Complicated angular analysis with many observables:



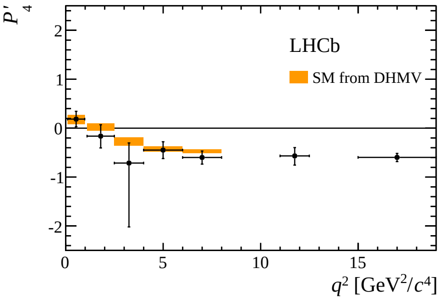
$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi \;+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

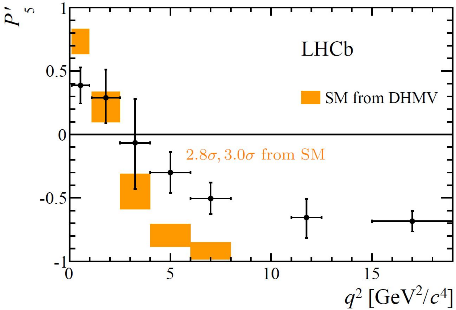
- Can parameterize the angular coeff to be largely free of form factor uncertainties

[Descotes-Genon et al, JHEP, 1305:137, (2013)]

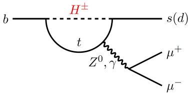
e.g. $\boxed{P_5' = \frac{S_5}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}}$ where F_L is the fraction of longitudinal polarization

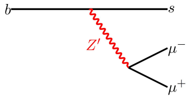
$B^0 \to K^{*0}\mu^+\mu^-$ [LHCb, arXiv:1512.04442], [DHMV = Descotes-Genon et al., JHEP 12 (2014) 125]





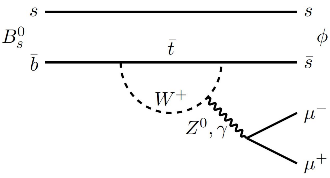
- Mainly compatible with the SM except one angular variable
- Local 2.8–3.0σ discrepancy with SM prediction in bins $q^2 \equiv m^2_{\mu\mu} \in [4,8]\,\mathrm{GeV}^2/c^4$ of P'_5
- LHCb fit of the EW penguin Wilson coeff C_9, including $S_3 - S_9, F_\mathrm{L}, A_\mathrm{FB}$: 3.4σ from SM
- Theoretical work ongoing to better understand this effect: NP or unexpectedly large hadronic effect? See e.g. [Descotes-Genon et al., arXiv:1510.04239]
- Channel also studied by BaBar [arXiv:1508.07960], Belle [PRL 103, 171801], CMS [PLB 753(2016)424], ATLAS [ATLAS-CONF-2013-038] and CDF [PRL 108, 081807]

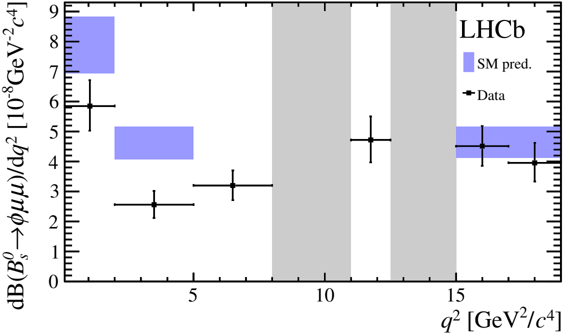




$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$ [JHEP 09 (2015) 179]

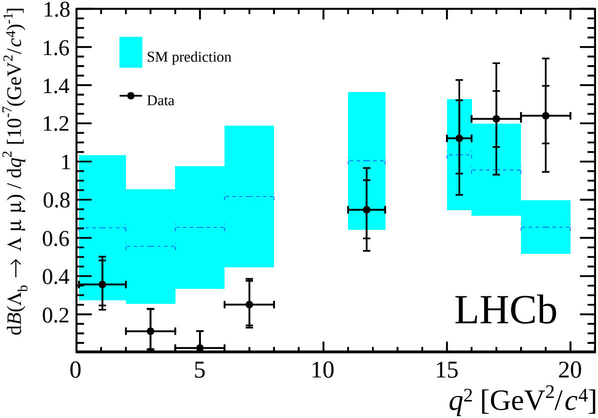
- Similar to $B^0 \to K^*\mu^+\mu^-$, but not self-tagged (no CP observable accessible)
- Narrow ϕ resonance gives clean signal peak
- Full angular analysis
- At low q^2, BR also below SM [Altmannshofer, Straub, EPJ C75 (2015) 382], [Bharucha et al, arXiv:1503.05534]





$\mathcal{B}(\Lambda_b^0 \to \Lambda^0 \mu^+ \mu^-)$ [JHEP 06 (2015) 115]

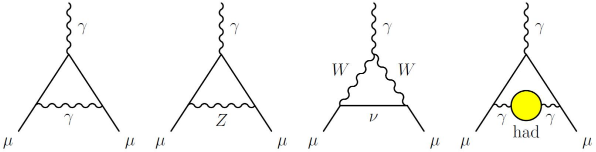
- Similar to $B^0 \to K^* \mu^+ \mu^-$
- Baryonic system provides sensitivity to additional observables
- Rate still too low to preform a full angular analysis.
- Again, BR lower than SM at low q^2: deficit of muons?



SM from [Detmold et al., PRD 87, (2013) 074502]

Muon anomalous magnetic moment $(g-2)_\mu$

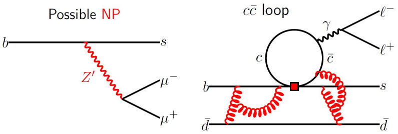
- Dirac equation predicts a muon magnetic moment $\vec{M} = g_\mu \frac{e}{2m_\mu} \vec{S}$ with gyromagnetic ratio $g_\mu = 2$. But experimentally, $g_\mu > 2$.
- This "anomaly", $a_\mu = (g_\mu - 2)/2$, arises from calculable quantum fluctuations, largest contributions:



- SM value: $a_\mu^{\mathrm{SM}} = (116\,591\,803 \pm 49) \times 10^{-11}$ [PDG 2014]
- Experiment: $a_\mu^{\mathrm{E821}} = (116\,592\,091 \pm 63) \times 10^{-11}$ [PRD 73:072003 (2006), Brookhaven E821 + PDG2014]
- Difference: $a_\mu^{\mathrm{E821}} - a_\mu^{\mathrm{SM}} = (288 \pm 80) \times 10^{-11}$ 3.6σ deviation [PDG 2014]
- Underestimated uncertainties? SUSY?
- Fermilab E989 should reduce the experimental uncertainty to $\pm 16 \times 10^{-11}$

Interpretations of flavor anomalies

- We see tensions in both:
    - Charged Current $b \to c\tau\nu$: R_D, R_{D*}
    - FCNC $b \to s\ell\ell$: R_K, $B^0 \to K^* \mu^+\mu^-$, $B^0_s \to \phi\mu\mu$, $\Lambda^0_b \to \Lambda^0\mu^+\mu^-$, ...
- Statistical fluctuations? Under-estimated uncertainties? theory? experiment? NP!?
- Many attempts to perform global fit of "flavor anomalies" and explain them, e.g. on next slide, [Altmannshofer et al., EPJ C 75 (2015) 382], [Descotes-Genon et al., arXiv:1510.04239]
- $b \to s\ell\ell$ anomalies point to NP in C_9. Unfortunately it is a place where SM uncertainties are debatable (charm loop)

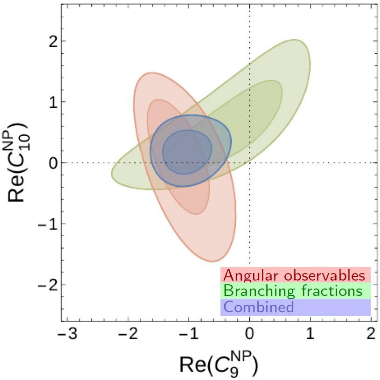


- Two Higgs Doublet Models type II seem disfavored by $R(D^{(*)})$ [PRD D 88, 072012 (2013)] But type III possible [Crivellin et al., PRD 86, 054014 (2012)], ...
- Leptoquark could explain $R_{D(*)}$, R_K and $(g-2)_\mu$ [Bauer, Neubert arXiv:1511.01900], [Dorsner et al., JHEP 2013:84], [Sakaki et al., PRD 88, 094012 (2013)], ...
- Introducing a Z' that allows FCNC at the tree level could explain $B^0 \to K^{*0}\mu\mu$, R_K and $h \to \tau\mu$. e.g. [Crivellin et al, PRL 114, 151801 (2015)], ...

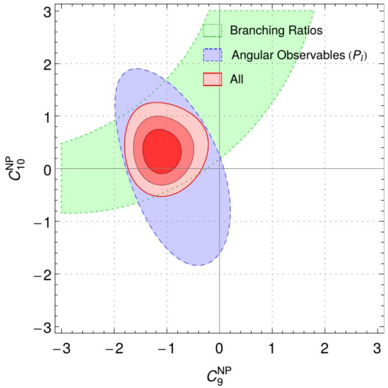
Interpretations of flavor anomalies

Global fit of Wilson coefficients to $b \to s$ data (e.g):

[Altmannshofer et al., EPJ C 75 (2015) 382]



[Descotes-Genon et al., arXiv:1510.04239]



- Tension reduced with $\Delta\mathrm{Re}(C_9) \simeq -1$, significances around 4σ.
- Consistency between angular observables and branching fractions

Future plans

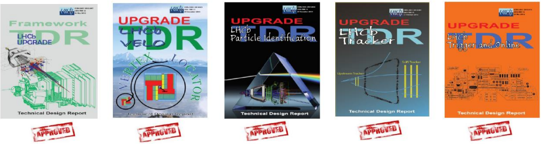
- LHCb
- Belle II
- ATLAS and CMS

LHCb plans

- Run 2 (2016-2018): 5 fb^{-1} at $\sqrt{s} = 13\,\mathrm{TeV}$, improved trigger
- Some major experimental measurements (e.g. γ, $B_s^0 \to \phi\phi$) are not yet at the level of theoretical prediction
- Above a luminosity of $\sim 4 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, LHCb efficiency to trigger hadronic modes saturates, because of the L0-trigger bottleneck which can not cope with more than 1 MHz output rate.

$\Rightarrow$ upgrade the LHCb experiment in 2018–2019:

- Full software trigger: read all detector at 40 MHz $\to$ $\times 2$ efficiency for hadronic final state.
- Luminosity up to $2\times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, new challenges: high pile-up, large occupancies, radiation damages
- Detector upgrades: VELO (pixels), tracker (Silicon strips and scintillating fibers), RICH (multi-anode PMTs), CALO& MUON (new electronics), ...
- Aim to collect $\sim$50 fb^{-1}. Annual yields wrt published analyses: $\times$10 for muonic final states and $\times$20 for hadronic modes.



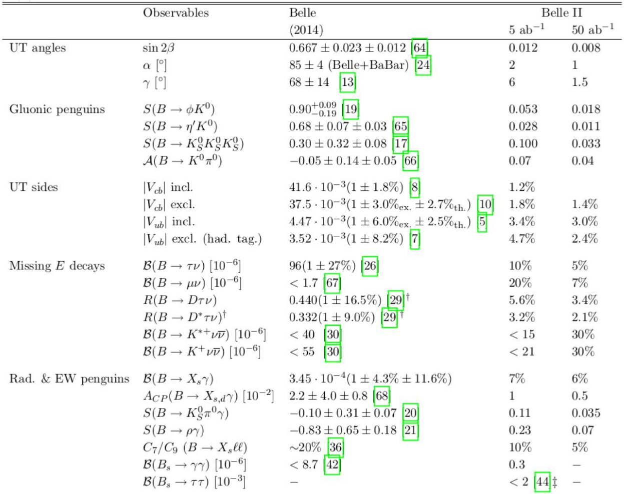
Expected performances of LHCb upgrade [LHCb-PUB-2014-040]

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 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)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	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%
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 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°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^\mp K^\pm)$	17°	11°	**2.0°**	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	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

- $\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ with a precision of 0.018
- γ with a precision below 1°

Future, Belle II (See talks by D. Greenwald, T. Luo)

- Belle II plans to take data from 2018 to 2024
- Physics complementary and competitive with LHCb



	Observables	Belle	Belle II	
		(2014)	5 ab^{-1}	50 ab^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$ [64]	0.012	0.008
	α [°]	85 ± 4 (Belle+BaBar) [24]	2	1
	γ [°]	68 ± 14 [13]	6	1.5
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$ [19]	0.053	0.018
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$ [65]	0.028	0.011
	$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$ [17]	0.100	0.033
	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$ [66]	0.07	0.04
UT sides	$\lvert V_{cb} \rvert$ incl.	$41.6 \cdot 10^{-3}(1 \pm 1.8\%)$ [8]	1.2%	
	$\lvert V_{cb} \rvert$ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\rm ex.} \pm 2.7\%_{\rm th.})$ [10]	1.8%	1.4%
	$\lvert V_{ub} \rvert$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\rm ex.} \pm 2.5\%_{\rm th.})$ [5]	3.4%	3.0%
	$\lvert V_{ub} \rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 8.2\%)$ [7]	4.7%	2.4%
Missing E decays	$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$96(1 \pm 27\%)$ [26]	10%	5%
	$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7 [67]	20%	7%
	$R(B \to D\tau\nu)$	$0.440(1 \pm 16.5\%)$ [29]†	5.6%	3.4%
	$R(B \to D^*\tau\nu)^\dagger$	$0.332(1 \pm 9.0\%)$ [29]†	3.2%	2.1%
	$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ $[10^{-6}]$	< 40 [30]	< 15	30%
	$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ $[10^{-6}]$	< 55 [30]	< 21	30%
Rad. & EW penguins	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%
	$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$ [68]	1	0.5
	$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$ [20]	0.11	0.035
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$ [21]	0.23	0.07
	C_7/C_9 $(B \to X_s \ell\ell)$	~20% [36]	10%	5%
	$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	< 8.7 [42]	0.3	–
	$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	–	< 2 [44]‡	–

[Wiechczynski at EPS'2015]. See also [P. Urquijo, NPPP, 263-264 (2015) 15]

Flavor future of ATLAS and CMS

ATLAS and CMS will continue to collect data with an instantaneous luminosity 10 to 40 larger than LHCb. However, since their priority is the high-$p_{\rm T}$ physics, they cannot afford a too low $p_{\rm T}$ threshold at the trigger level, hence a compromise is to be done for *b*-physics.

In ATLAS, New Inner B Layer (already in run2) interesting for flavor physics: improve decay resolution and flavor tagging.

Modified from [ECFA/13/284, 21 Nov 2013]

Expected sensitivities that can be achieved on key heavy flavor physics observables, using the total integrated luminosity recorded until the end of each LHC run period. The values for flavor-changing neutral-current top decays are expected 95% confidence level upper limits in the absence of signal.

		LHC era			HL-LHC era	
		Run 1 2010–12	Run 2 2015–17	Run 3 2019–21	Run 4 2024–26	Run 5+ 2028–30+
$\int \mathcal{L} dt$	LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	70 fb^{-1} (?)
$\int \mathcal{L} dt$	ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	...	3000 fb^{-1}
$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B^0_s\to\mu^+\mu^-)}$	CMS	$>$ 100%	71%	47%	...	21%
	LHCb	220%	110%	60%	40%	28%
$q_0^2\ A_{\rm FB}(K^{*0}\mu^+\mu^-)$	LHCb	10%	5%	2.8%	1.9%	1.3%
	Belle II	—	50%	7%	5%	—
$\phi_s(B^0_s \to J/\psi\phi)$	ATLAS	0.11	0.05–0.07	0.04–0.05	...	0.020
	LHCb	0.05	0.025	0.013	0.009	0.006
$\phi_s(B^0_s \to \phi\phi)$	LHCb	0.18	0.12	0.04	0.026	0.017
γ	LHCb	7°	4°	1.7°	1.1°	0.7°
	Belle II	—	11°	2°	1.5°	—
$A_\Gamma(D^0 \to K^+K^-)$	LHCb	3.4×10^{-4}	2.2×10^{-4}	0.9×10^{-4}	0.5×10^{-4}	0.3×10^{-4}
	Belle II	—	18×10^{-4}	$4–6 \times 10^{-4}$	$3–5 \times 10^{-4}$	—
$t \to qZ$	ATLAS	...	...	23×10^{-5}	...	$4.1–7.2 \times 10^{-5}$
	CMS	100×10^{-5}	...	27×10^{-5}	...	10×10^{-5}
$t \to q\gamma$	ATLAS	...	...	7.8×10^{-5}	...	$1.3–2.5 \times 10^{-5}$

Conclusions and prospects (1)

Tantalizing tensions with respect to the SM:

Observable	Tension wrt SM	Limited by
$B \to D^{(*)}\tau\nu / B \to D^{(*)}\ell\nu,\ \ell = \mu, e$	3.9σ	experiment
$(g-2)_\mu$	3.6σ	exp. & theo.
$B^0 \to K^{*0}\mu\mu$ angular dist., BR	3.4σ	exp. & theo.
$B_s^0 \to \phi\mu\mu$ BR	3.0σ	experiment
Dimuon CP asymmetry	3.0σ	experiment
V_{ub} exclusive versus inclusive	3.0σ	exp. & theo.
ϵ'/ϵ (direct CPV in K)	2.9σ	theory
$B^+ \to K^+ee / B^+ \to K^+\mu\mu$	2.6σ	experiment
$h \to \tau\mu$	2.4σ	experiment

Many other interesting results exhibit no tension today, but put strong constraints on NP models.
They remain fundamental for future searches, e.g.: γ, B^0-D^0-K^0-mixing, ϕ_s, $\sin 2\beta$, $B_s^0 \to \mu\mu$, $B \to X_s\gamma$, V_{cb}, $B \to \tau\nu$, CPV in charm, CLVF, $K \to \pi\nu\bar{\nu}$, ...

Conclusions and prospects (2)

- Flavor physics is at the heart of the SM and a powerful tool to look for NP. It probes scales beyond the TeV, thanks to virtual processes.
- Intriguing hints of Lepton Flavor non Universality in semi-leptonic *b*-decays $+$ other “flavors anomalies”:
  statistical fluctuations, New Physics or under-estimated uncertainties?
- Many NP explanation attempts, but no single picture has emerged yet. Not easy to explain them all together in a simple and natural way.
- The situation will be clarified with
  - improvements in theory (Lattice QCD, LCSR, ...)
  - more experimental results soon (LHC, BelleII, NA62, BESIII, E989, ...)
- Expect many new exiting results in the coming years!

Apologies for the hundred of very nice flavor results not mentioned here...

Backup

Phenomenology

Why going beyond the Standard Model?

- SM describes very well existing data, however:
  - Gravity is not included
  - Higgs mass diverges quadratically
  - Why 28 free parameters?
  - Why such a hierarchy in CKM? Link with MNS?

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix} \qquad V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

  - Where does CP violation comes from?
    - MS CPV to small to explain baryonic asymmetry
    - New source of CPV?
- Hence we expect new particles, new couplings and new CP violating sources...

Fundamental parameters of the Standard Model

The 28 parameters of the Standard Model are:

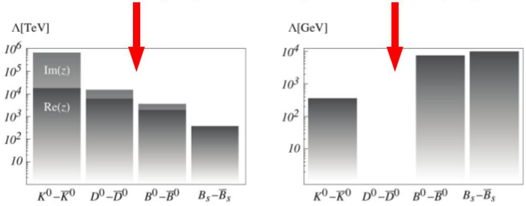
- the 3 coupling constant associated to $SU(2)_L \times U(1)_Y$ and $SU(3)_c$,
- the 2 Higgs field potential parameters μ and λ,
- the six quark masses and the six lepton masses,
- the four CKM parameters
- the six MNS parameters
- the possible QCD CP violating phase θ_{QCD}.

Constraining NP with flavors

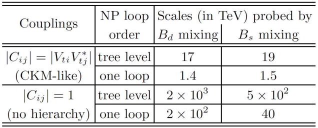
e.g. [J. Kamenik, Mod.Phys.Lett. A29 (2014) 1430021]

Limits on NP scale

Generic coupling MFV (i.e. SM-like) coupling



also: [J. Charles et al, arXiv:1309.2293] $\frac{C_{ij}^2}{\Lambda^2}(\bar{q}_{i,L}\gamma^\mu q_{j,L})^2$



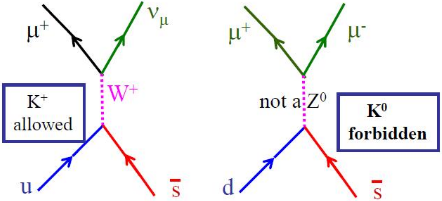
Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$	tree level	17	19
(CKM-like)	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$	tree level	2×10^3	5×10^2
(no hierarchy)	one loop	2×10^2	40

TABLE II. The scale of the operator in Eq. (2) probed by B_d and B_s mixings at Stage II (if the NP contributions to them are unrelated). The impact of CKM-like hierarchy of couplings and/or loop suppression is indicated.

Historical power of Flavor Physics

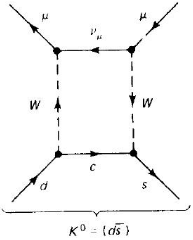
In the past, flavour physics lead to several «indirect» discoveries:

- 1970: Kaon semileptonic branching fractions



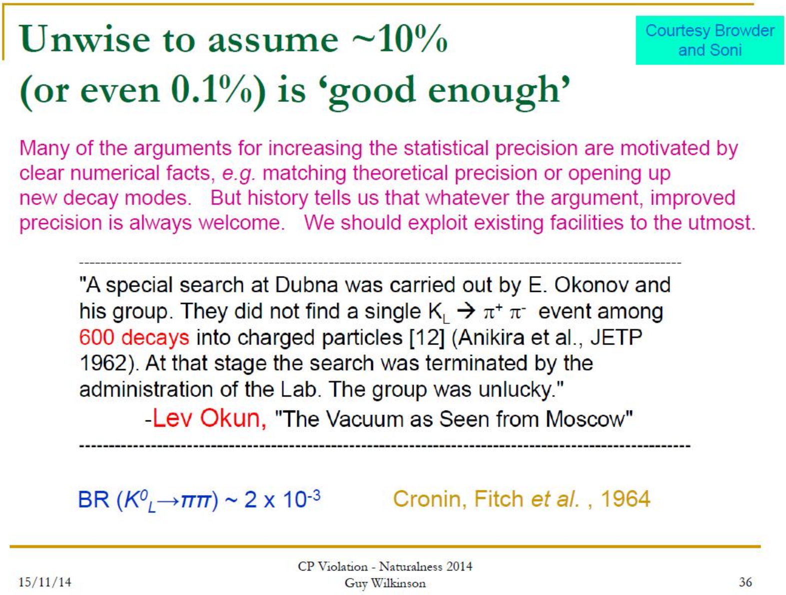
$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

Glashow, Iliopoulos, Maiani (GIM) proposed a solution
⇒ No flavor changing neutral current (FCNC)
⇒ FCNC are suppressed by loop diagrams
⇒ charm quark prediction



Observed in 1973

Why precision?



Unwise to assume ~10% (or even 0.1%) is 'good enough'

Courtesy Browder and Soni

Many of the arguments for increasing the statistical precision are motivated by clear numerical facts, *e.g.* matching theoretical precision or opening up new decay modes. But history tells us that whatever the argument, improved precision is always welcome. We should exploit existing facilities to the utmost.

> "A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \to \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."
>
> -Lev Okun, "The Vacuum as Seen from Moscow"

BR ($K^0_L \to \pi\pi$) ~ 2 x 10^{-3} Cronin, Fitch *et al.* , 1964

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CP Violation - Naturalness 2014
Guy Wilkinson

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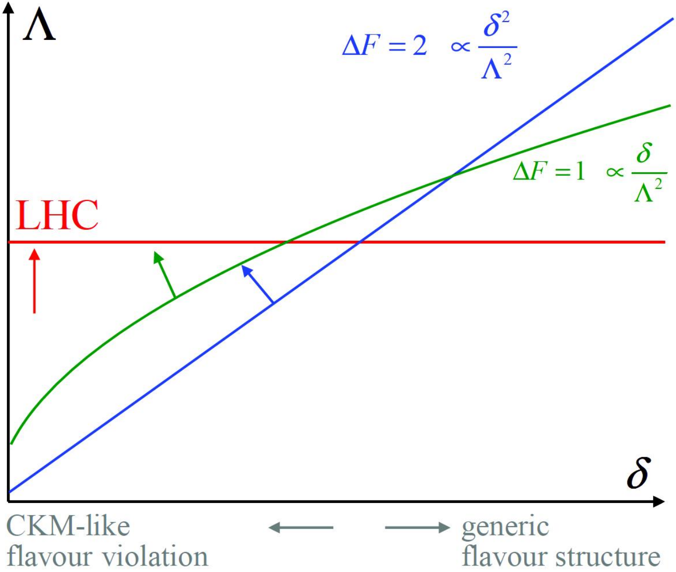
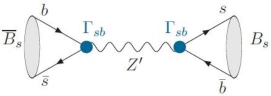
Complementarity of direct/indirect NP searches

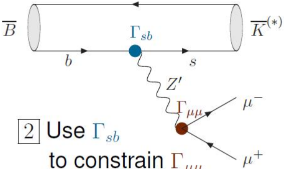


Constraining Z' couplings with different channels

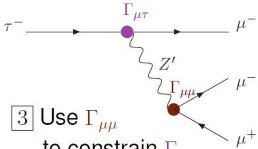
[Crivellin et al, arXiv:1504.07928]



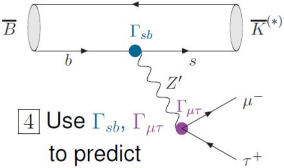
$\boxed{1}$ Constrain Γ_{sb}
from $B_s - \overline{B}_s$ mixing



$\boxed{2}$ Use Γ_{sb}
to constrain $\Gamma_{\mu\mu}$
from $B \to K^{(*)}\mu^+\mu^-$

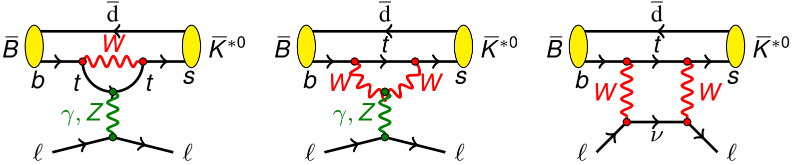


$\boxed{3}$ Use $\Gamma_{\mu\mu}$
to constrain $\Gamma_{\mu\tau}$
from $\tau^- \to \mu^-\mu^+\mu^-$

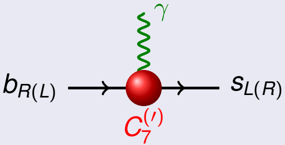


$\boxed{4}$ Use Γ_{sb}, $\Gamma_{\mu\tau}$
to predict
$B \to K^{(*)}\tau^+\mu^-$
⇒ Large effects possible?

Effective field theory

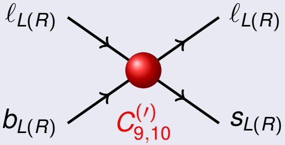


Magnetic dipole operators



$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$

Semileptonic operators

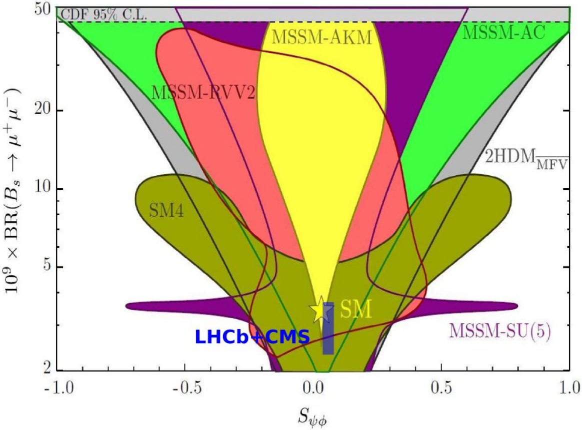


$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell)$$
$$\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

ϕ_s and $B_s^0 \to \mu^+\mu^-$ implications

- $S_{\psi\phi} = -\sin\phi_s$
- Modified from [D. Straub, Nuovo Cim. C035N1 (2012) 249 and arXiv:1012.3893] UNOFFICIAL
- Blue: 68% CL LHCb+CMS

  2014 constraints

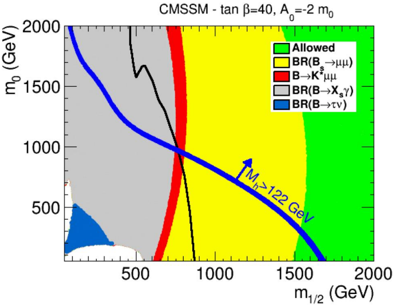


Strong constraints on many NP models:

- SM4: Standard Model with a sequential fourth generation
- Left-handed currents only (MSSM-LL)
- Ross, Velasco-Sevilla and Vives (MSSM-RVV2)
- Antusch, King and Malinsky (MSSM-AKM)
- RSc: Randall-Sundrum model with custodial protection
- Agashe and Carone (MSSM-AC)

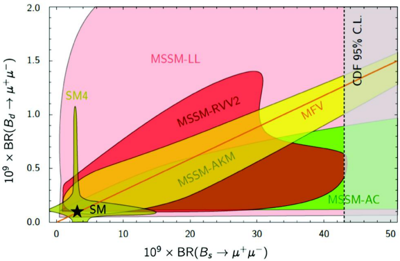
$B \to \mu^+\mu^-$ consequences

[Mahmoudi et al, EPJ C74 (2014) 2927]



Black line corresponds to the direct limit by ATLAS 20.3 fb^{-1}

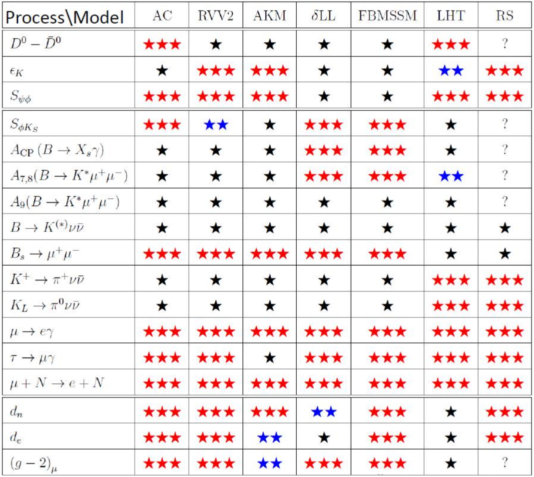
Modified from [D. Straub, Nuovo Cim. C035N1 (2012) 249]



Strong constraints on many NP models, in particular those with large tan β

Sensitivity to NP of various models

[Altmannshofer, Burus, Gori, Paradisi, Straub, 0909.1333]



Process\Model	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}\,(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

AC	U(1) flavor symmetry
RVV2	Non-abelian SU(3)-flavored MSSM
AKM	SU(3)-flavored SUSY
δLL	LH CKM-like currents
FBMSSM	Flavor-blind MSSM
LHT	Little Higgs w/T parity
RS	Randall-Sundrum

★★★ Large effect

★★ Small but visible effect

★ No observable effect

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More on R_D and R_D^* [BaBar, PRL109,101802(2012), PRD88,072012(2013)]

- Type II 2HDM can describe the higgs sector in the MSSM
- Differential decay rates

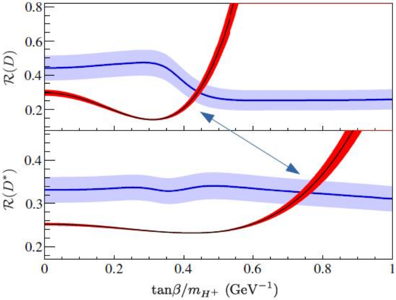
$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2|V_{cb}|^2|\boldsymbol{p}^*_{D^{(*)}}|q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\left[(|H_+|^2+|H_-|^2 + |H_0|^2)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3m_\tau^2}{2q^2}|H_s|^2\right],$$

are modified by a charged higgs

$$H_s^{\text{2HDM}} \approx H_s^{\text{SM}}\times\left(1+(S_R\pm S_L)\frac{q^2}{m_\tau(m_b\mp m_c)}\right).$$

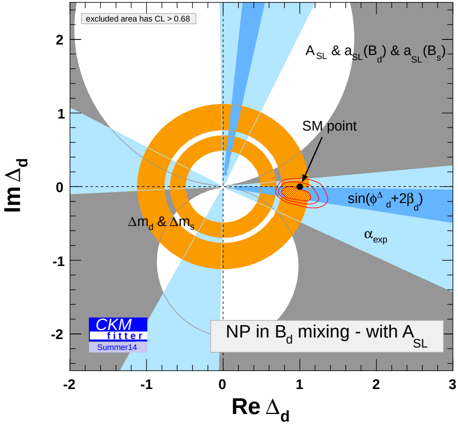
in a q^2 dependent manner

- Consider different values of tanβ/m_{H^+}: generate new signal shapes and measure $R(D^{(*)})$, compare with SM prediction
- Result is incompatible with 2HDM



G. Simi at WHEPP - IIT Kanpur, India, Dec 2015

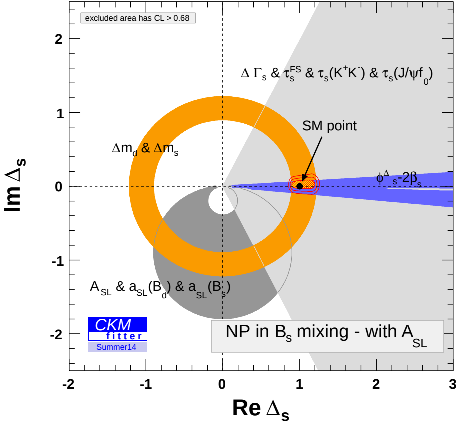
NP in B^0 mixing



$$M_{12}^{d} = M_{12}^{\mathrm{SM},d}\Delta_d\,, \quad \Delta_d = |\Delta_d| e^{i\phi_d^\Delta}$$

[CKMfitter (J. Charles et al.), EPJ. C41, 1-131 (2005), updated results and plots available at: `http://ckmfitter.in2p3.fr`]

NP in B_s^0 mixing

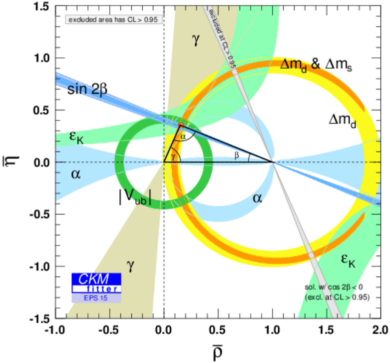


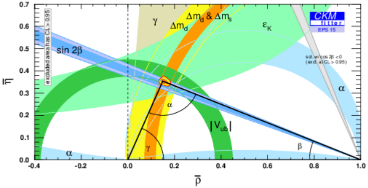
$$M_{12}^{s} = M_{12}^{\mathrm{SM},s}\Delta_s\,, \quad \Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

[CKMfitter (J. Charles et al.), EPJ. C41, 1-131 (2005), updated results and plots available at: `http://ckmfitter.in2p3.fr`]

CP violation in beauty and charm hadrons

CKMfitter plots

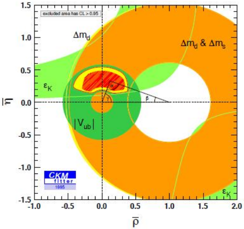




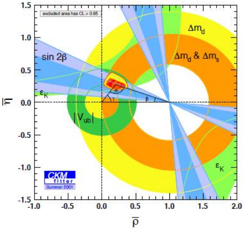
[CKMfitter (J. Charles et al.), EPJ. C41, 1-131 (2005), updated results and plots available at: `http://ckmfitter.in2p3.fr`]

20 years of CKM fits

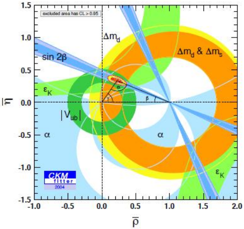
[CKMfitter, LEP, KTeV, NA48, BaBar, Belle, CDF, DØ, LHCb, CMS, ...]



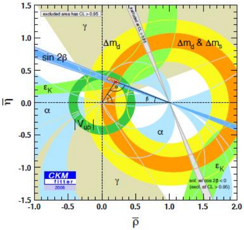
1995



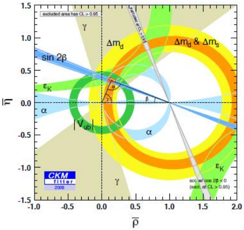
2001



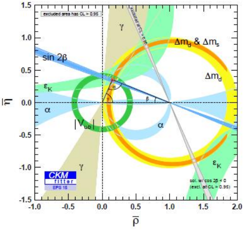
2004



2006

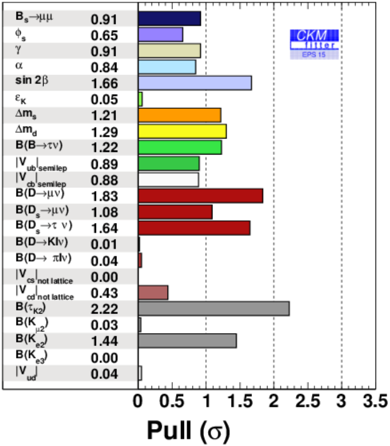


2009



2015

CKMfitter plots



A way to introduce β_s

V_{CKM} can be written with 4 independent parameters:

- the « usual » Wolfenstein parameters λ, A, ρ, η

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Or $|V_{us}|$, $|V_{ub}|$, $|V_{cb}|$, $|V_{td}|$ [Branco 1988]
- Or 4 independent phases: γ, β, β_s, β_K

$$\gamma = \arg\left(-\frac{V_{\mathrm{ud}}V_{\mathrm{ub}}^*}{V_{\mathrm{cd}}V_{\mathrm{cb}}^*}\right)$$

$$\beta = \arg\left(-\frac{V_{\mathrm{cd}}V_{\mathrm{cb}}^*}{V_{\mathrm{td}}V_{\mathrm{tb}}^*}\right)$$

$$\beta_{\mathrm{s}} = \arg\left(-\frac{V_{\mathrm{ts}}V_{\mathrm{tb}}^*}{V_{\mathrm{cs}}V_{\mathrm{cb}}^*}\right)$$

$$\beta_{\mathrm{K}} = \arg\left(-\frac{V_{\mathrm{us}}V_{\mathrm{ud}}^*}{V_{\mathrm{cs}}V_{\mathrm{cd}}^*}\right)$$

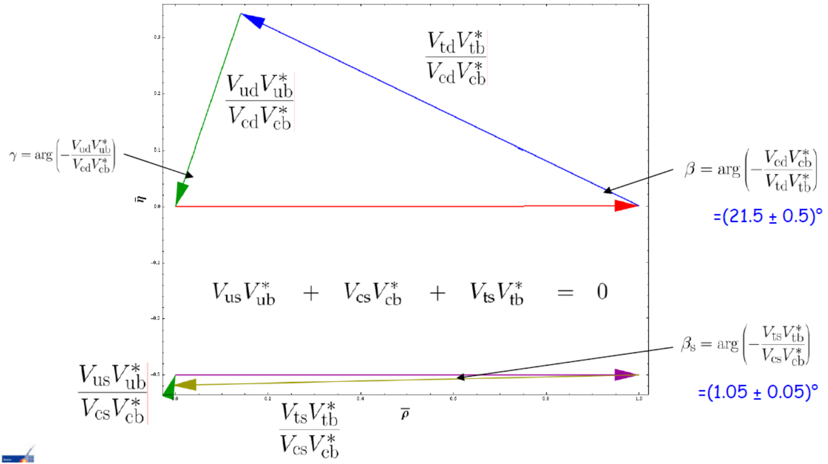
- References:
  - G. C. Branco and L. Lavoura, Phys. Lett. B 208, 123 (1988).
  - G. C. Branco et al., CP violation, Oxford University Press, (1999)
  - R. Aleksan, B. Kayser, and D. London. Determining the Quark Mixing Matrix from CP-Violating Asymmetries. *Phys. Rev. Lett.*, 73:18.20, 1994, hep-ph/9403341
  - See also: J. Silva, hep-ph/0410351

b–d and b–s unitarity triangles

SM values, both triangles on the same scale, bs triangle shifted by etabar-0.3 to be visible

b-d triangIde divided by VcdVcb*; while bs triangle divided by VcsVcb*

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



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

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

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

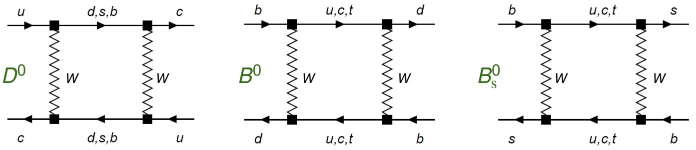
=(21.5 ± 0.5)°

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

=(1.05 ± 0.05)°

Mixing and CP violation

In Standard Model, neutral mesons (H^0) mix with their antiparticles ($\bar{H}^0$) via box diagrams ($H^0 = K^0, D^0, B^0, B_s^0$)



3 types of CP violation:

- "In the mixing": rates of $H^0 \to \overline{H}^0$ and $\overline{H}^0 \to H^0$ differ
- "In the decay": amplitudes from a process and its conjugate differ
- "In the interference between mixing and decay"

B mixing and lifetime I

The neutral B_q $(q = d, s)$ system is described by the following equation

$$i \frac{d}{dt} \begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left(\hat{M}^q - \frac{i}{2} \hat{\Gamma}^q \right) \begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

The famous box diagrams give rise to off-diagonal elements M_{12}^q and Γ_{12}^q in the mass matrix $\hat{M}^q$ and the decay rate matrix $\hat{\Gamma}^q$

Diagonalization of $\hat{M}^q$ and $\hat{\Gamma}^q$ gives the mass eigenstates

$$\text{CP-odd:} \quad B_H := p\, B + q\, \bar{B} \quad , \quad \text{CP-even:} \quad B_L := p\, B - q\, \bar{B}$$

$$\text{with} \qquad |p|^2 + |q|^2 = 1$$

with the corresponding masses M_H^q, M_L^q and decay rates Γ_H^q, Γ_L^q

B mixing and lifetime II

$|M_{12}^q|$, $|\Gamma_{12}^q|$ and $\phi_{12q} = \arg(-M_{12}^q/\Gamma_{12}^q)$ are related to three observables:

- **Mass difference:** $\Delta M_q := M_H^q - M_L^q = 2|M_{12}^q| \left(1 + \frac{1}{8}\frac{|\Gamma_{12}^q|^2}{|M_{12}^q|^2}\sin^2\phi_{12q} + ...\right)$
  $|M_{12}^q|$: heavy virtual particles: t, SUSY, ...
- **Decay rate difference:**
  $\Delta\Gamma_q := \Gamma_L^q - \Gamma_H^q = 2|\Gamma_{12}^q|\cos\phi_{12q}\left(1 - \frac{1}{8}\frac{|\Gamma_{12}^q|^2}{|M_{12}^q|^2}\sin^2\phi_{12q} + ...\right)$
  $|\Gamma_{12}^q|$: light real particles: u, c, ... no NP – below hadronic uncertainties
- **Flavor specific / semileptonic CP asymmetries:**

$$A_{\mathrm{SL}}^q = \mathrm{Im}\frac{\Gamma_{12}^q}{M_{12}^q} + \mathcal{O}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)^2 = \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_{12q} + \mathcal{O}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)^2$$

New physics effects

General parametrization of new physics effects in mixing

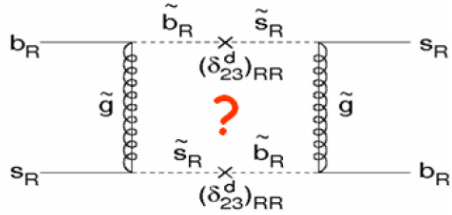
$$\Gamma_{12,s} = \Gamma_{12,s}^{\mathrm{SM}}\,, \qquad M_{12,s} = M_{12,s}^{\mathrm{SM}} \cdot \Delta_s\,; \qquad \Delta_s = |\Delta_s| e^{i\phi_s^{\Delta}}$$

leads to the following relations for observables

$$\begin{aligned}
\Delta M_s &= 2|M_{12,s}^{\mathrm{SM}}| \cdot |\Delta_s| \\
\Delta \Gamma_s &= 2|\Gamma_{12,s}| \cdot \cos\left(\phi_{12s}^{\mathrm{SM}} + \phi_s^{\Delta}\right) \\
A_{\mathrm{SL}}^{s} &= \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\mathrm{SM}}|} \cdot \frac{\sin\left(\phi_{12s}^{\mathrm{SM}} + \phi_s^{\Delta}\right)}{|\Delta_s|} \\
\phi_s^{J/\Psi\phi} &= -2\beta_s + \phi_s^{\Delta} + \delta_{\mathrm{Peng.}}^{\mathrm{SM}} + \delta_{\mathrm{Peng.}}^{\mathrm{NP}}
\end{aligned}$$

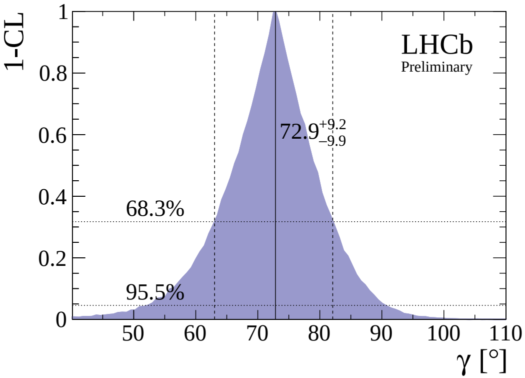
Remember: $\phi_{12s}^{\mathrm{SM}} = \arg(-M_{12}^{s}/\Gamma_{12}^{s})$ and $\beta_s = \arg\left(-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*}\right)$

New physics in B_s^0-mixing



- **Examples of NP affecting Φ and being compatible with $\Delta m_s = 17.8 ps^{-1}$**
  - hep-ph/0703117 (little higgs model with T parity)
  - hep-ph/0703112 (susy, extra Z', little Higgs)
  - Hou et al., hep-ph/0810.3396 (4th generation; top')
  - ...

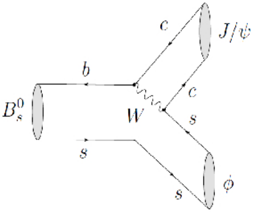
γ-angle measured with tree processes [LHCb-CONF-2014-004]

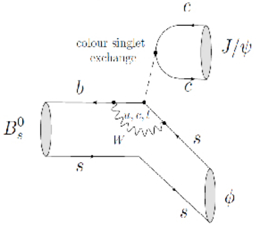


- LHCb combination of many modes, using $B_{(s)} \to D_{(s)} K^{(*)}$ (mixture of 1 and 3 fb^{-1})
- $\gamma = (72.9^{+9.2}_{-9.9})^\circ$, world best measurement, better than *B*-factories legacy!

Penguin pollution in $B_s^0 \to J/\psi\phi$

- In the SM, $B_s \to J/\psi\phi$ decay is dominated by a single weak phase: $V_{cs}V_{cb}^*$





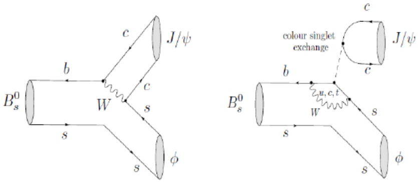
$$\begin{aligned} A(\overline{\mathrm{b}} \to \overline{\mathrm{c}}\mathrm{c}\overline{\mathrm{s}}) &= V_{\mathrm{cs}}V_{\mathrm{cb}}^*(A_T + P_{\mathrm{c}}) + V_{\mathrm{us}}V_{\mathrm{ub}}^*P_{\mathrm{u}} + V_{\mathrm{ts}}V_{\mathrm{tb}}^*P_{\mathrm{t}} \\ &= V_{\mathrm{cs}}V_{\mathrm{cb}}^*(A_T + P_{\mathrm{c}} - P_{\mathrm{t}}) + V_{\mathrm{us}}V_{\mathrm{ub}}^*(P_{\mathrm{u}} - P_{\mathrm{t}}) \end{aligned}$$

$\boxed{V_{\mathrm{ts}}V_{\mathrm{tb}}^* = -V_{\mathrm{us}}V_{\mathrm{ub}}^* - V_{\mathrm{cs}}V_{\mathrm{cb}}^*}$ $\boxed{\sim A\lambda^2(1 - \lambda^2/2)}$ $\boxed{\sim A\lambda^4(\rho + i\eta)}$

- Various penguin pollution estimates:
  - δP~10^4 [H. Boos et al., Phys.Rev. D70 (2004) 036006]
  - δP~10^3 [M. Gronau et al., arXiv:0812.4796]
  - δP up to ~0.1 [S. Faller et al., arXiv:0810.4248v1]

Penguin pollution in $B_s^0 \to J/\psi\phi$

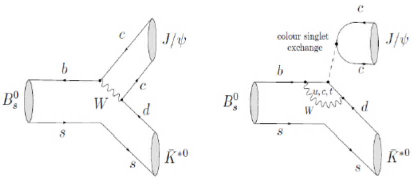
[S. Faller et al. arXiv:0810.4248]



$$\bar{b} \to \bar{s}c\bar{c}$$

Penguins suppressed by λ^2

$$A(B_s^0 \to (J/\psi\phi)_f) = \left(1 - \frac{\lambda^2}{2}\right) \mathcal{A}_f \left[1 + \epsilon a_f e^{i\theta_f} e^{i\gamma}\right] \qquad \epsilon \equiv \lambda^2/(1-\lambda^2)$$



$$\bar{b} \to \bar{d}c\bar{c}$$

Penguins NOT suppressed
wrt tree

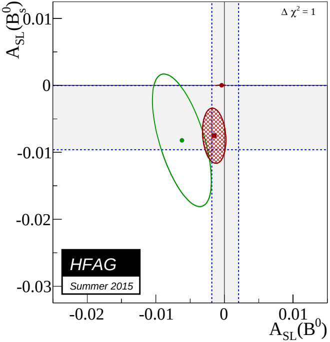
$$A(B_s^0 \to (J/\psi \bar{K}^{*0})_f) = \lambda \mathcal{A}'_f \left[1 - a'_f e^{i\theta'_f} e^{i\gamma}\right]$$

Penguin pollution in $B_s^0 \to J/\psi\phi$

- LHCb, arXiv:1411.1634 (PLB). Using $B^0 \to J/\psi\,\rho^0$, shift on ϕ_s due to penguin pollution = 0.009 $\pm$ 0.031 rad at 95% CL (including 50% SU(3) breaking effects).
- Method proposed in [S. Faller et al. arXiv:0810.4248], using $B_s^0 \to J/\psi\overline{K}^{*0}$
- Other approaches to reduce penguin pollution:
  B. Bhattacharya et al., Int.J.Mod.Phys. A28 (2013) 1350063.
  M. Jung, arXiv:1212.4789.

CPV in B^0 and B_s^0 mixing

Tension in the measurement of the SL CP asym seen by DØ.
Not confirmed by latest LHCb measurements:
$A_{\mathrm{SL}}^s = (-0.06 \pm 0.50 \pm 0.36)\%$, 1 fb^{-1}, [LHCb, PLB 728 (2014) 607]
$A_{\mathrm{SL}}^d = (-0.02 \pm 0.19 \pm 0.30)\%$, 3 fb^{-1}, [arXiv:1409.8586]



Latest BaBar result on asld: arXiv:1411.1842

CPV in B_s^0 and B^0 mixing

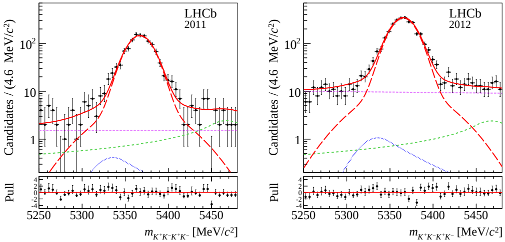
$$A_{SL}^d = \frac{N(\bar{B}^0(t) \to \ell^+ \nu_\ell X) - N(B^0(t) \to \ell^- \bar{\nu}_\ell X)}{N(\bar{B}^0(t) \to \ell^+ \nu_\ell X) + N(B^0(t) \to \ell^- \bar{\nu}_\ell X)} = \frac{|p/q|_{\mathrm{d}}^2 - |q/p|_{\mathrm{d}}^2}{|p/q|_{\mathrm{d}}^2 + |q/p|_{\mathrm{d}}^2}$$

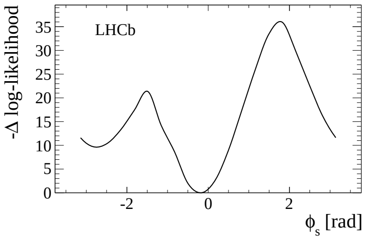
DØ measures [PRD84, 052007 (2011)] :

$$A_{SL}^b = \frac{f_{\mathrm{d}} Z_{\mathrm{d}} A_{SL}^d + f_{\mathrm{s}} Z_{\mathrm{s}} A_{SL}^s}{f_{\mathrm{d}} Z_{\mathrm{d}} + f_{\mathrm{s}} Z_{\mathrm{s}}} \quad = \quad -0.00787 \pm 0.00172(\mathrm{stat}) \pm 0.00093(\mathrm{syst})$$

where $Z_{\mathrm{q}} = 1/(1 - y_{\mathrm{q}}^2) - 1/(1 + x_{\mathrm{q}}^2) = 2\chi_{\mathrm{q}}/(1 - y_{\mathrm{q}}^2)$, $q = d, s$

$B_s^0 \to \phi\phi$ [PRD 90 (2014) 052011]

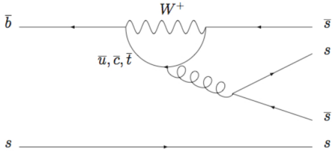




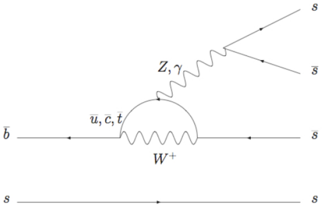
- Pure $b \to s\bar{s}s$ penguin mode
- SM expectation for CP violating weak phase $|\phi_s^{s\bar{s}s}| < 0.02^{\dagger}$
- Tagged time-dependent angular analysis, 3 fb^{-1} , 4000 $B_s^0 \to \phi\phi$ candidates
- $\phi_s^{s\bar{s}s} = -0.17 \pm 0.15 \pm 0.03$

† Bartsch et al., arXiv:8010.0249, Beneke et al., Nucl.Phys. B774 (2007)64, Cheng et al., PRD 80 (2009) 114026.

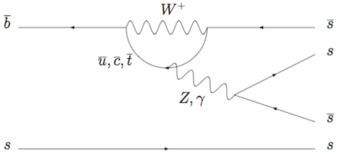
$B_s^0 \to \phi\phi$



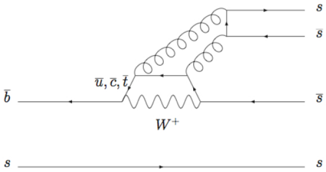
(a) gluonic penguin



(b) colour-allowed electroweak penguin



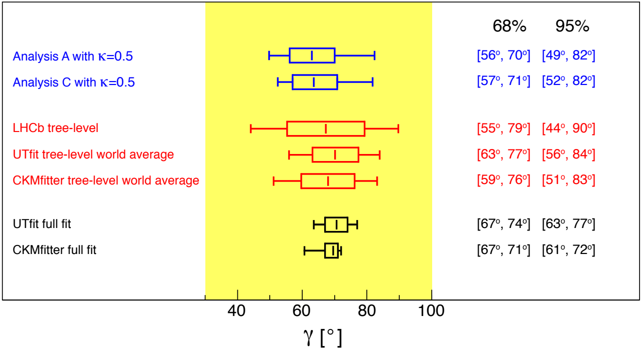
(c) colour-suppressed electroweak penguin



(d) singlet penguin

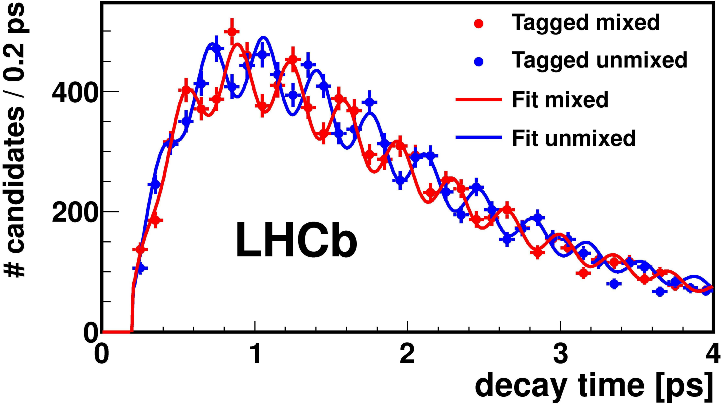
γ-angle measured with loop processes [arXiv:1408.4368, 1 fb^{-1}]

- γ extracted from $B_s^0 \to K^+K^-$, $B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$ using U-spin + isospin analyses. [e.g. R. Fleischer, PLB459 (1999) 306, Ciuchini, JHEP 10 (2012) 029]
- Experimental result: $\gamma = (63.5^{+7.2}_{-6.7})^\circ$
- Compatible with "γ from tree" so far:



LHCb, New J. Phys. 15 (2013) 053021

1 fb^{-1} $B_s^0 \to D_s^- \pi^+$



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

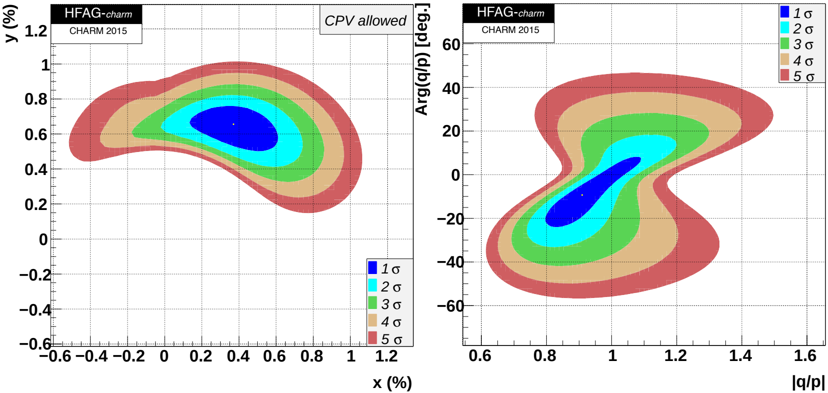
Charm mixing and CPV

Specificity of charm:

- CPV expected below $\mathcal{O}(0.1\%)$ in SM.
  Higher value means New Physics or strong hadronic effects
- FCNC with down-type quark in the loop:
  constrains NP coupling that can't be reached by B/K decays
- At LHC ($7\,\mathrm{TeV}$): $\sigma(pp \to c\bar{c}X) \simeq 20 \times \sigma(pp \to b\bar{b}X) \simeq 6\,mb$
- Complete view implies 38 observables and 10 physics parameters.
  Simplification here:

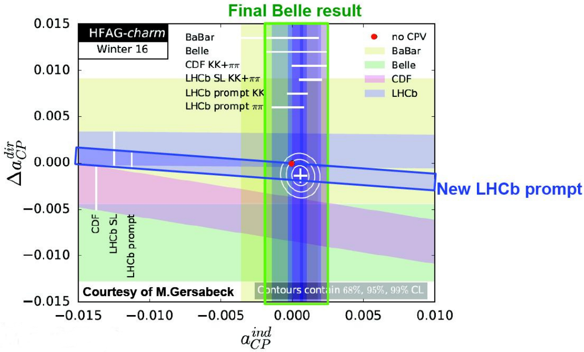
$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$
$$x = \frac{m_2 - m_1}{\Gamma}$$
$$y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$
$$\phi = arg(q/p)$$

Charm mixing and CPV



Charm CPV $\Delta A_{CP}(D^0 \to K^+K^-, \pi^+\pi^-)$

Measure the difference of CP asymmetries $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$
with $A_{\rm CP}(D^0 \to f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$



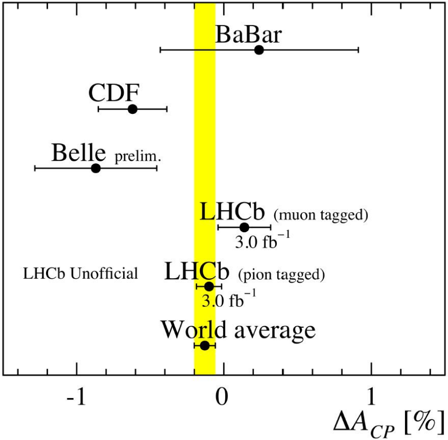
$$\Delta A_{CP} = \underbrace{(a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+))}_{\text{direct CP asymmetry}} + \underbrace{\frac{\Delta\langle t\rangle}{\tau_{D^0}} a_{CP}^{ind}}_{\text{indirect CP asymmetry}}$$

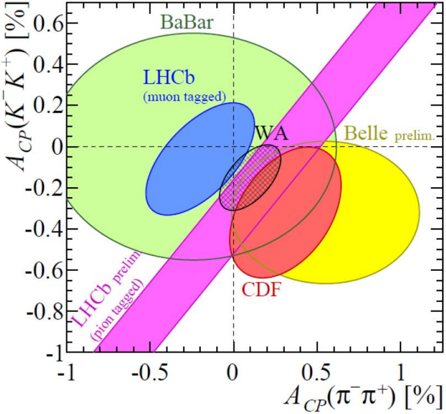
$\langle t\rangle$ is the average reconstructed decay time. $\Delta\langle t\rangle = \langle t\rangle(KK) - \langle t\rangle(\pi\pi)$

e.g. [LHCb, PRL 108, 111602 (2012)], [CDF, Public Note 10784, 2012]

Charm ΔA_{CP}

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





$$\Delta A_{CP} = (-0.10 \pm 0.08 \pm 0.03)\%$$

Direct CPV in kaons

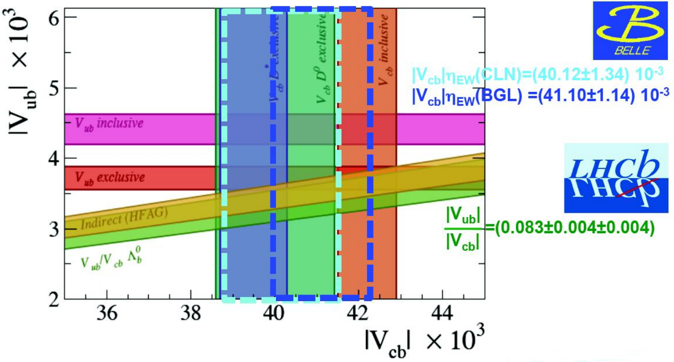
$$\eta_{+-} = A(K^0_{\mathrm{L}} \to \pi^+\pi^-)/A(K^0_{\mathrm{S}} \to \pi^+\pi^-)$$

$$\eta_{00} = A(K^0_{\mathrm{L}} \to \pi^0\pi^0)/A(K^0_{\mathrm{S}} \to \pi^0\pi^0)$$

$$\mathrm{Re}(\epsilon'/\epsilon) \simeq \epsilon'/\epsilon \simeq \frac{1}{3}(1 - |\eta_{00}/\eta_{+-}|)$$

V_{ub} and V_{cb}

- 2.5σ discrepancy between the different ways to measure V_{cb}:
    - inclusive $B \rightarrow X_c \ell \nu$, $|V_{ub}| = (42.21 \pm 0.78) \times 10^{-3}$
    - exclusive $B \rightarrow D \ell \nu$, $|V_{ub}| = (40.0 \pm 1.4) \times 10^{-3}$
    - exclusive $B \rightarrow D^* \ell \nu$, $|V_{ub}| = (38.94 \pm 0.76) \times 10^{-3}$



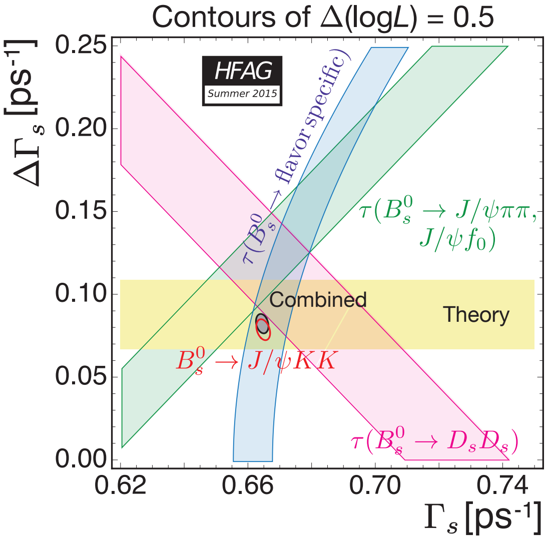
$|V_{cb}|\eta_{EW}$(CLN)=$(40.12 \pm 1.34)\ 10^{-3}$

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

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

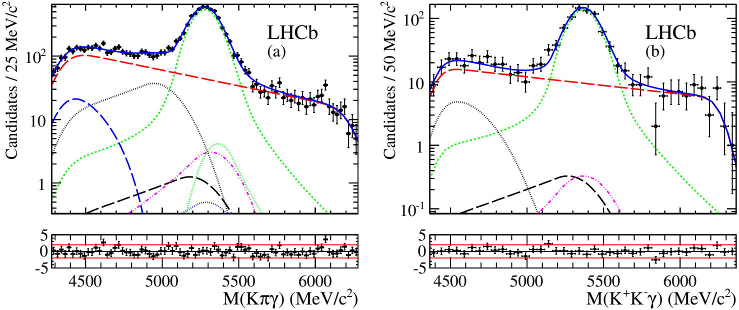
Belle, V_{cb} with $B \rightarrow D \ell \nu$ [arXiv:1510.03657]
Uncertainty significantly reduced wrt previous measurements
Results in between inclusive and exclusive results

B_s^0 lifetimes



World best measurement of A_{CP} in $B^0 \to K^*\gamma$

[Nucl. Phys. B 867 (2013) 1-18]



Most precise measurement to date (1 fb^{-1}):
$\mathcal{A}_{CP}(B^0 \to K^*\gamma) = 0.008 \pm 0.017(\text{stat}) \pm 0.009(\text{syst})$

Two Higgs Doublet models

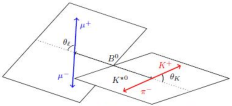
See e.g. [Branco et al., arXiv:1106.0034]

- Type I: all quarks couple to just one of the Higgs doublets (conventionally chosen to be Φ_2)
- Type II: the $Q = 2/3$ right-handed (RH) quarks couple to one Higgs doublet. (conventionally chosen to be Φ_1) and the $Q = -1/3$ RH quarks couple to the other (Φ_1).
- Type III: FCNC at the tree level.

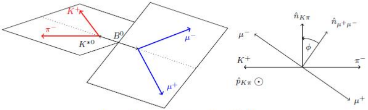
Rare decays

Definition of angles in the $B^0 \to \mu^+\mu^- K^{*0}$ analysis

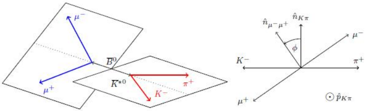
[arXiv:1304.6325]



(a) θ_K and θ_ℓ definitions for the B^0 decay



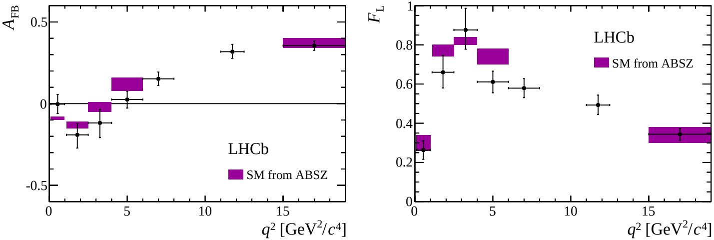
(b) ϕ definition for the B^0 decay

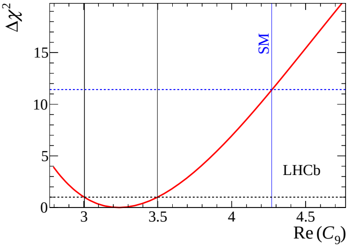


(c) ϕ definition for the $\overline{B}^0$ decay

Figure 7: Graphical representation of the angular basis used for $B^0 \to K^{*0}\mu^+\mu^-$ and $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$ decays in this paper. The notation $\hat{n}_{ab}$ is used to represent the normal to the plane containing particles a and b in the B^0 (or $\overline{B}^0$) rest frame. An explicit description of the angular basis is given in the text.

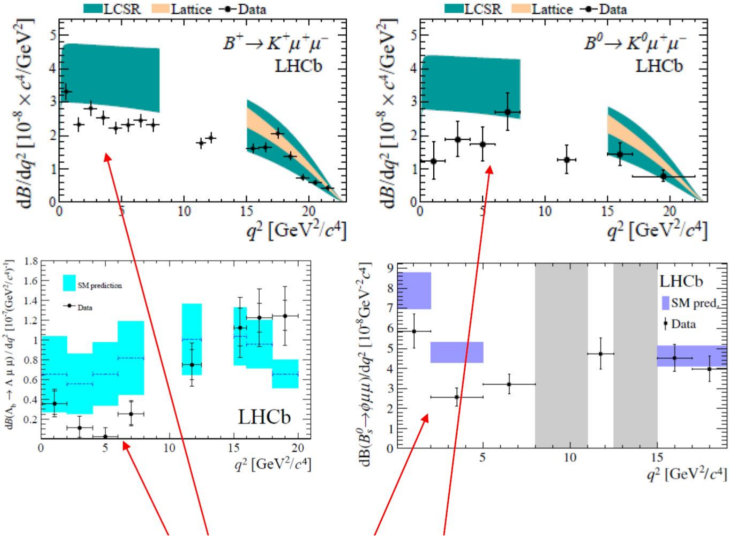
$B^0 \to K^{*0}\mu^+\mu^-$ [LHCb, arXiv:1512.04442], [ABSZ = Altmannshofer et al., EPJ C75 (2015) 382]





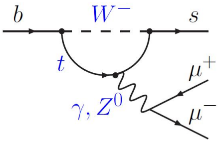
χ^2 fit to $F_{\rm L}$, $A_{\rm FB}$ and $S_3 - S_9$, gives $\Delta{\rm Re}(C_9) = -1.04 \pm 0.25$

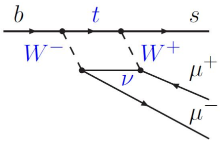
$b \to s\mu^+\mu^-$ Branching Ratios



Branching ratios tend to lie below SM predictions..? Deficit of muons?

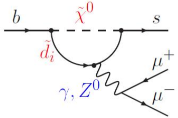
Test of lepton universality with $B^+ \to K^+ \ell^+ \ell^-$ [PRL,113, 151601 (2014)]

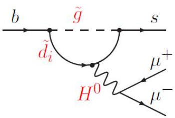


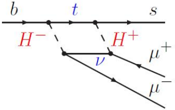


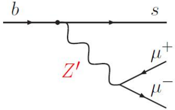
$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

(2.6σ from SM)







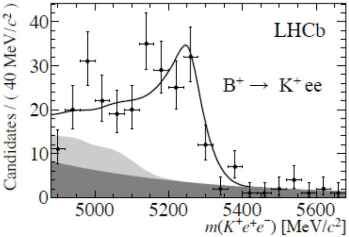


Test of lepton universality with $B^+ \to K^+\ell^+\ell^-$ [PRL,113, 151601 (2014)]

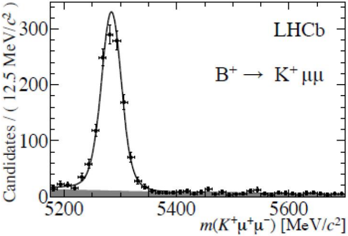
R_K measure using double ratio to minimize uncertainties:

$$R_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi\,(e^+e^-)K^+}}{\mathcal{N}_{J/\psi\,(\mu^+\mu^-)K^+}}\right)\left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi\,(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi\,(e^+e^-)K^+}}\right)$$

$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\Gamma[B^+\to K^+\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\Gamma[B^+\to K^+e^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}\,,\ (1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$$



triggered by signal electron



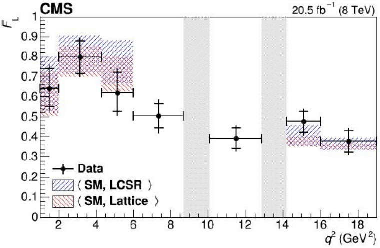
$B^0 \to K^* \mu^+ \mu^-$ at CMS [PLB 753(2016)424]

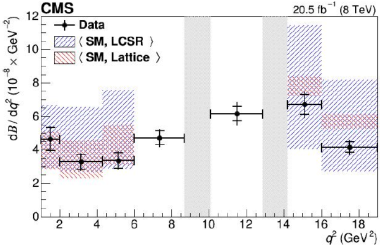
CMS result on 2012 data (8 TeV)

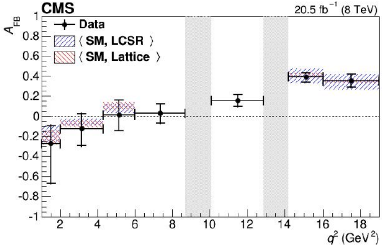
- → 20.5 fb^{-1}
- → 1400 signal events
- → integrated over Φ
- → fit s-wave component : F_s and A_s
- → determine : $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$, A_{FB}, F_{L}

SM,LCSR ← [JHEP 09 (2010) 089, JHEP 02 (2013) 010]

SM,Lattice ← [PRD 89 (2014) 094501]







$B \to K^{(*)0}\mu^+\mu^-$ isospin asymmetry

[JHEP 06 (2014) 133]

$$A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

$$= \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - (\tau_0/\tau_+)\cdot\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + (\tau_0/\tau_+)\cdot\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)},$$

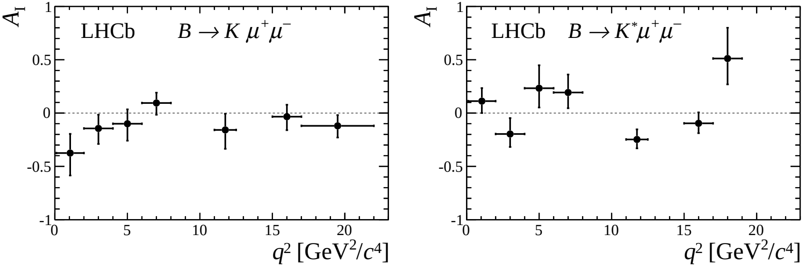
A_I consistent with SM expectations [PLB 539:227 (2002), JHEP 01 (2003) 074]

Although the isospin asymmetry for $B \to K\mu\mu$ decays is negative in all but one q^2 bin, results are more consistent with the SM compared to the previous measurement in [LHCb-PAPER-2012-011], which quoted a 4.4 σ significance to differ from zero, using a test statistic that explicitly tested for A_I to be negative in all bins. The lower significance quoted here is due to four effects: the change of the test statistic in the calculation of the significance itself, which reduces the previous discrepancy to 3.5 σ; the assumption that the isospin asymmetry of $B \to J/\psi K^{(*)}$ is zero which reduces the significance further to 3.2 σ; a re-analysis of the 2011 data with the updated reconstruction and event selection that reduces the significance to 2.5 σ; and finally the inclusion of the 2012 data set reduces the significance further to 1.5 σ.

$B \to K^{(*)0}\mu^+\mu^-$ isospin asymmetry

[JHEP 06 (2014) 133]

$$A_I = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$
$$= \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - (\tau_0/\tau_+)\cdot\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + (\tau_0/\tau_+)\cdot\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)},$$

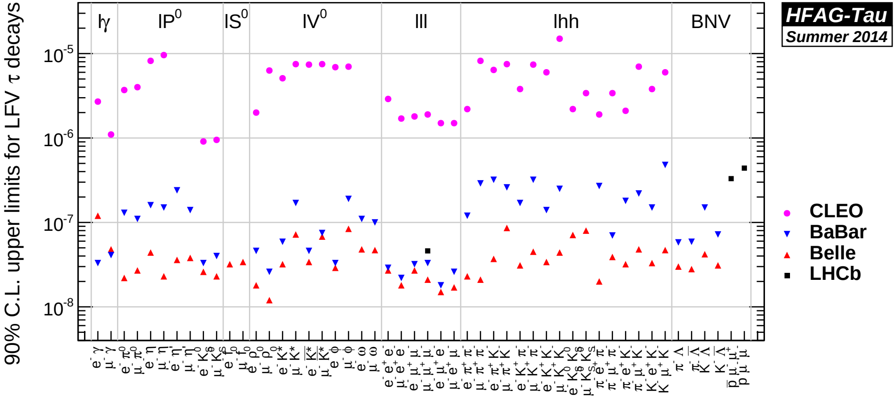


A_I consistent with SM expectations [PLB 539:227 (2002), JHEP 01 (2003) 074]

Few searches for Lepton Flavor Violating decays

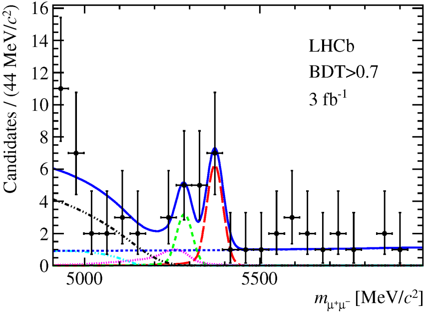
- $B^0_{(s)} \to e^\pm \mu^\mp$
  [LHCb, PRL 108, 231801 (2012)]:
  $\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 2.8 \times 10^{-9}$ at 90% CL
  $\mathcal{B}(B^0_s \to e^\pm\ \mu^\mp) < 1.1 \times 10^{-9}$ at 90% CL
  20 times better than previous limits. Constraints on leptoquarks
- $D^0 \to e^\pm \mu^\mp$
  [LHCb, PLB 745 (2016) 167] Set a limit 20 times better than Belle's one:
  $\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.3 \times 10^{-8}$ at 90% CL
- $\tau^- \to \mu^- \mu^+ \mu^-$
  Best limits by Belle and BaBar. Also [LHCb, JHEP 1502 (2015) 121]

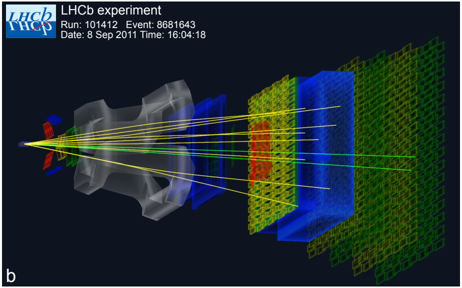
Upper limits on τ LFV branching fractions



First evidence for $B_s^0 \to \mu^+\mu^-$ by LHCb

[PRL 111, 101805 (2013)]

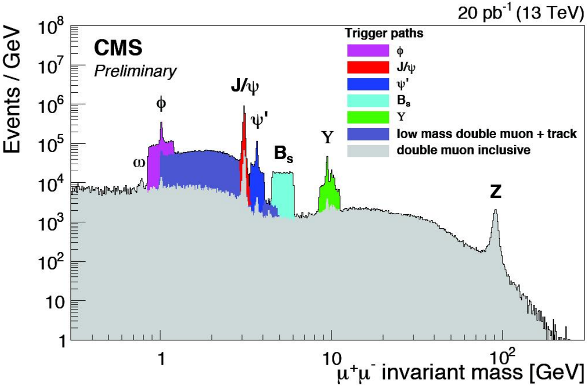




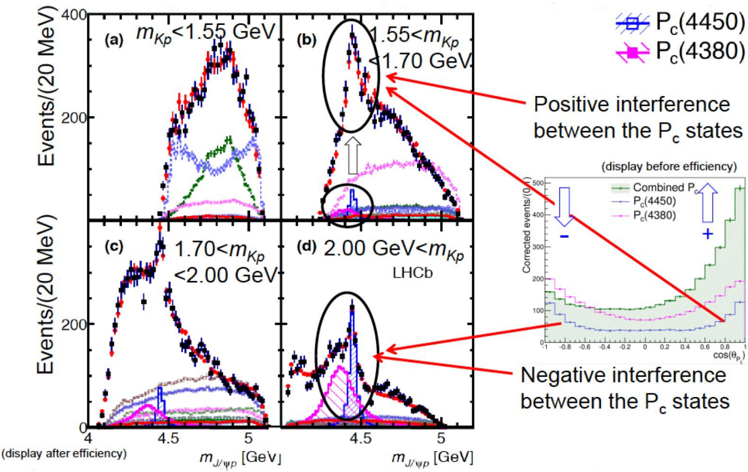
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.9^{+1.1}_{-1.0} \times 10^{-9}$
- $\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95% CL
- $\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = 0.14^{+0.08}_{-0.06}$

Other physics: spectroscopy, QCD, ...

$\mu\mu$ invariant mass



More about pentaquark (1) [LHCb, PRL 115 (2015) 072001]



Positive interference between the P$_c$ states

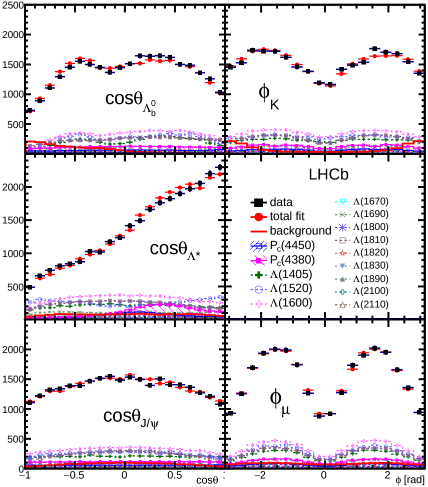
(display before efficiency)

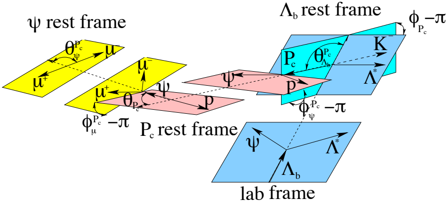
Negative interference between the P$_c$ states

(display after efficiency)

The components shown are the phase space integrals of the squares of the matrix elements. The sum of all backgrounds would not really have a physical meaning since it would take no account of interference. The two Pc states have negative interferences between themselves for high m(Kp) masses, which correspond to cos(θ_{P_c}) $<$ 0, and positive interferences for low *m*(*Kp*) (cos(θ_{P_c}) $>$ 0). This is a consequence of the opposite parities. This is why in Fig (d) the two Pcs plotted without interferences seem to be too large for what is seen in the data and in Fig (b) too small for the size of the peak in the data.

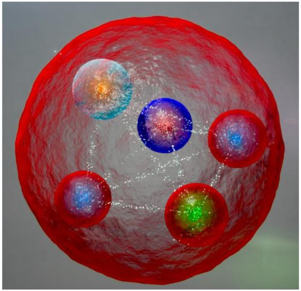
More about pentaquark (2) [LHCb, PRL 115 (2015) 072001]

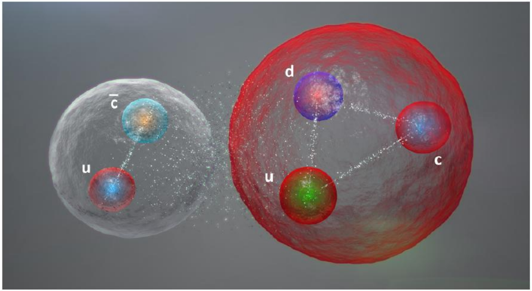


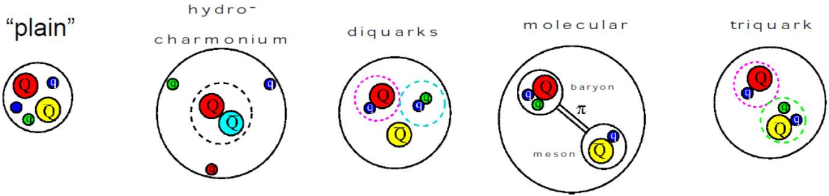


Phenomenological interpretations, e.g. [T. Burns, EPJ. A51 (2015) 11, 152]

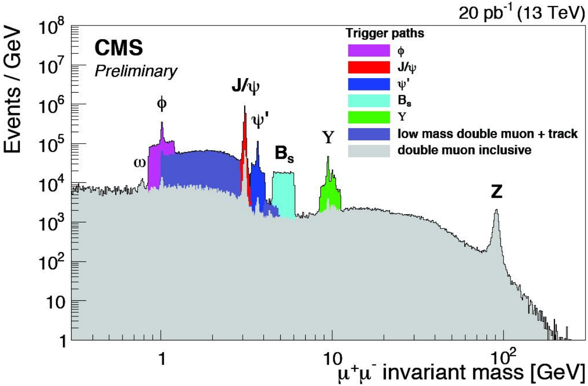
What is a pentaquark?







$\mu\mu$ invariant mass

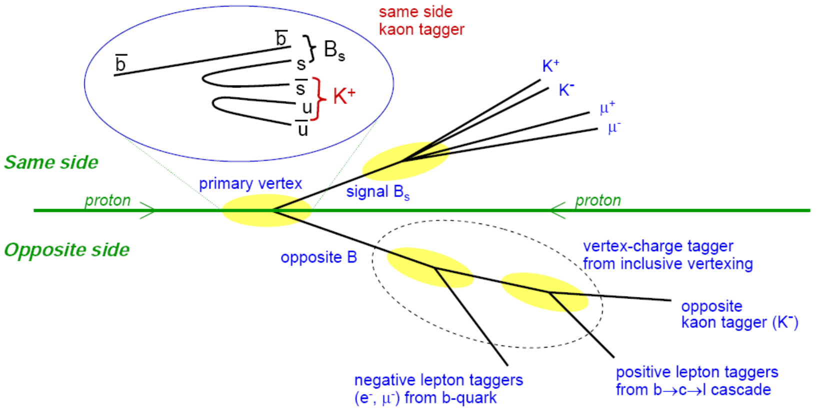


Few other physics results (amongst ~ 250 LHCb papers...!)

- First of observation of the excited baryons $\Xi_b^{('*)-}$ (bsd), [PRL 113, 242002 (2014)]
- First observation of of a heavy flavored spin-3 particle: $D_{sJ}^*(2860)^-$, [PRD 90 (2014) 072003]
- First observation of Z production in proton-lead collisions at LHCb, [JHEP 09 (2014) 030]
- Quantum numbers of the first confirmed tetraquark ($cu\bar{c}\bar{d}$) $Z(4430)^-$, [PRL 112, 222002 (2014)]
- First observation of photon polarization in $b \to s\gamma$ transition, [PRL 112, 161801 (2014)]
- Search for direct and indirect CP violation and measurement of mixing parameter in charm, [PRL 111, 251801 (2013), PRL 112, 041801 (2014), PRL 110, 101802 (2013)]
- Determination of the $X(3872)$ meson quantum numbers, [PRL 110, 222001 (2013)]
- First observation of CP violation in B_s^0, [PRL 110 (2013) 221601]
- World best limit on $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$, [JHEP 01 (2013) 090]
- Electroweak physics in the forward region, [arXiv:1411.1264, JHEP 02 (2013) 106, JHEP 01 (2013) 111, JHEP 06 (2012) 058]

Detector and upgrade

Tag initial B_s^0 flavor

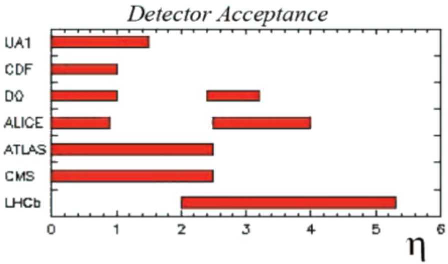


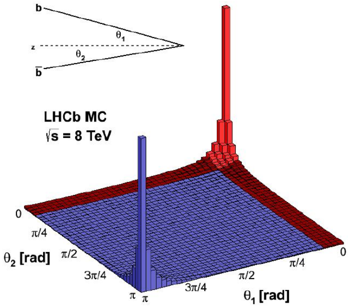
- $\varepsilon_{\text{tag}} = \frac{R+W}{R+W+U}$, $\omega = \frac{W}{R+W}$, Tagging power = $\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} D^2 = \varepsilon_{\text{tag}}(1-2\omega)^2$
- Mistag fraction, ω, estimated event by event
- Tagging algorithm optimized and calibrated on real data with $B^0 \to D^* \mu^+ \nu_\mu$, $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$

LHCb: super *b* and *c* factory at the LHC

- LHC is a proton-proton collider, $\sqrt{s} = 7\,\mathrm{TeV}$ (2011), $8\,\mathrm{TeV}$ (2012)
- Large $b\bar{b}$ production cross-section: $\sigma(pp \to b\bar{b}) = 286\mu$b at 7 TeV

  [PLB 694 (2010) 209]
- $\sigma(pp \to c\bar{c})$ 20 times larger!
- All kinds of *b*-hadrons produced (B^+, B^0, B_s^0, B_c^+, *b*-baryons, ...)
- *b*-hadrons produced mainly at low angle: LHCb detector installed in the forward region; unique pseudo-rapidity range





The LHCb detector [JINST 3 (2008 S08005)]

- Single-arm forward spectrometer:
  - Tracking system

    IP resolution $\sim 15\mu$m (at high p_T)

    $\delta p/p \sim 0.45\%$
  - RICH system

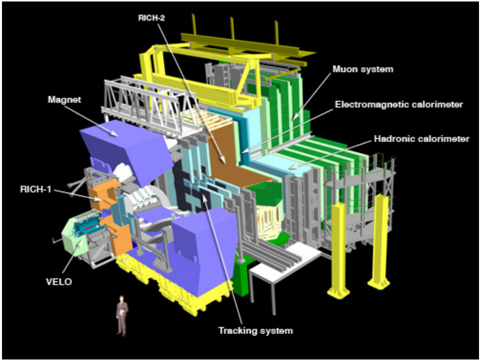
    Very good $K-\pi$ identification for

    $p \sim 2 - 100\,\mathrm{GeV}/c$
  - Calorimeters

    Energy measurement, identify π^0,γ,e

    + trigger
  - Muon detector

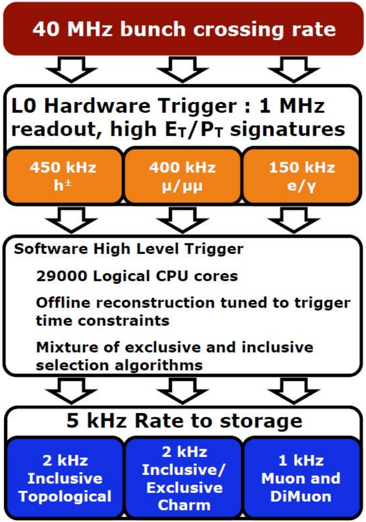
    muon identification + trigger



- Integrated lumi 1 fb^{-1} (2011), 2 fb^{-1} (2012)
  Instantaneous lumi $\sim 1 - 4 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

The LHCb Trigger in 2011–2012

- L0 hardware trigger:
  - Find lepton, hadron with high p_{T}
  - Reduce the rate from 40 MHz to 1 MHz
- HLT1 software trigger:
  - Finds vertices in VELO
  - Tracks with high IP & p_{T}
- HLT2 software trigger:
  - Reconstruct all tracks in event
  - Select inclusive/exclusive b-hadrons
  - Output rate = 5 kHz



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

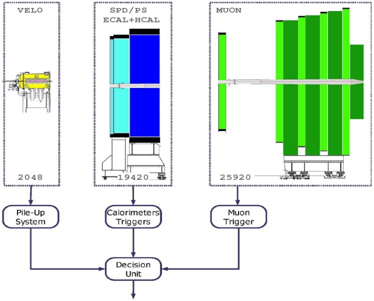
Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

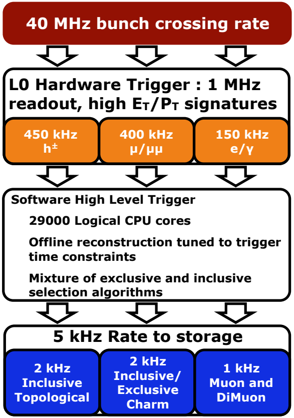
2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

Trigger

- L0 hardware trigger:
    - Find lepton, hadron with high p_T
    - Reduce the rate from 40 MHz to 1 MHz
- HLT1 software trigger:
    - Finds vertexes in VELO
    - Tracks with high IP & p_T
- HLT2 software trigger:
    - Reconstruct all tracks in event
    - Select inclusive/exclusive B meson
    - Output rate = 5 kHz



Trigger in 2012



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

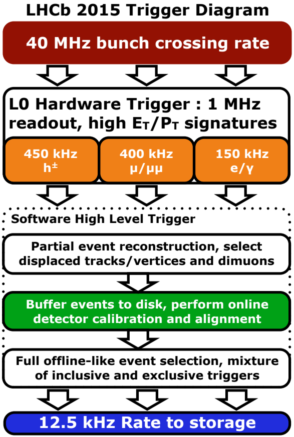
Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

Trigger in 2015



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

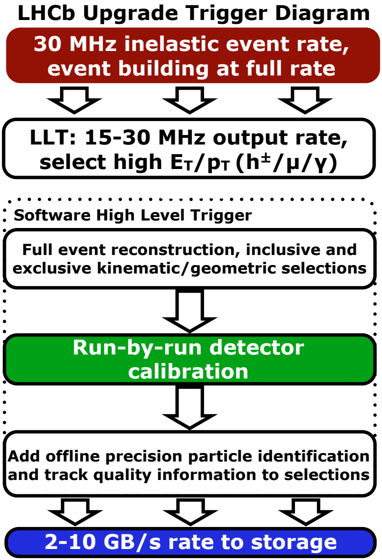
Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage

LHCb upgrade trigger (2020)



LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate, event building at full rate

LLT: 15-30 MHz output rate, select high E_T/p_T ($h^\pm/\mu/\gamma$)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Run-by-run detector calibration

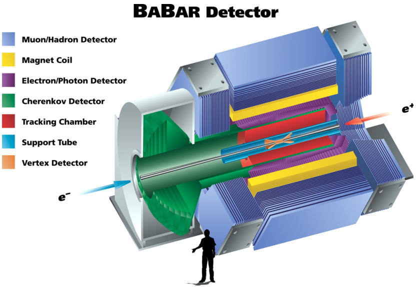
Add offline precision particle identification and track quality information to selections

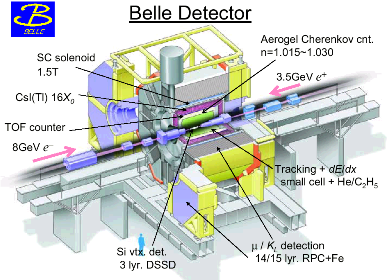
2-10 GB/s rate to storage

The LHCb detector

Other heavy flavor detectors

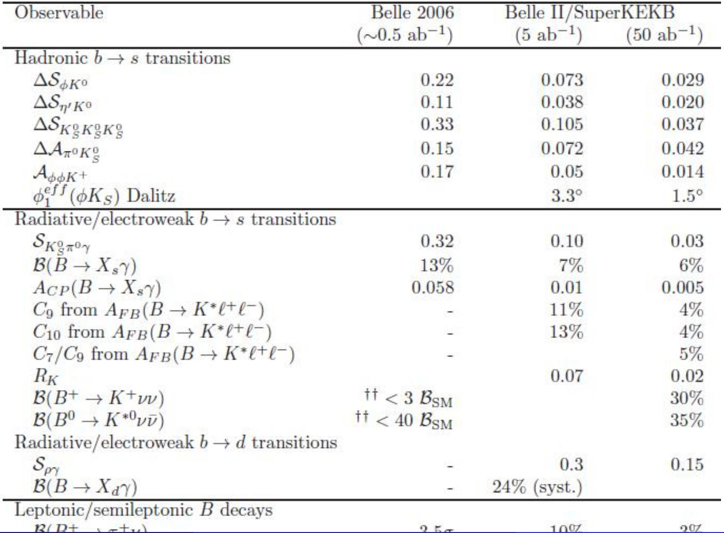
Detectors at the e^+e^- b-factories





Belle II expected performance (1)

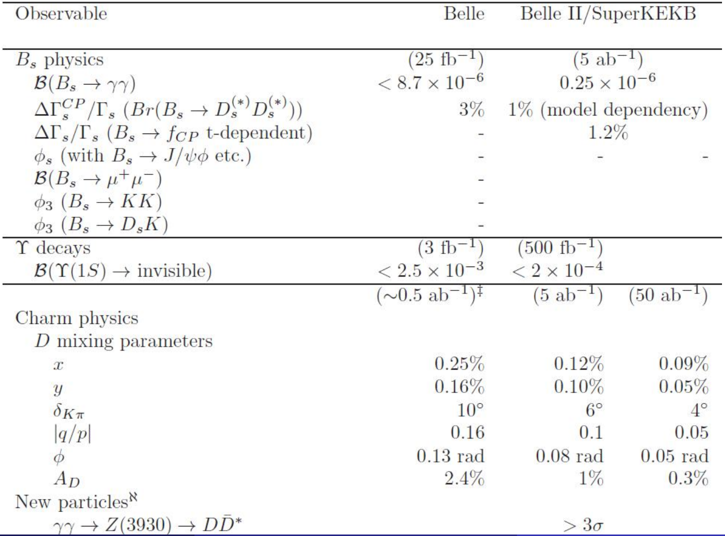
- Belle II plans to start data taking in 2018
- Physics complementary and competitive with LHCb



Observable	Belle 2006	Belle II/SuperKEKB	
	(~0.5 ab^{-1})	(5 ab^{-1})	(50 ab^{-1})
Hadronic $b \to s$ transitions			
$\Delta\mathcal{S}_{\phi K^0}$	0.22	0.073	0.029
$\Delta\mathcal{S}_{\eta' K^0}$	0.11	0.038	0.020
$\Delta\mathcal{S}_{K^0_S K^0_S K^0_S}$	0.33	0.105	0.037
$\Delta\mathcal{A}_{\pi^0 K^0_S}$	0.15	0.072	0.042
$\mathcal{A}_{\phi\phi K^+}$	0.17	0.05	0.014
$\phi_1^{eff}(\phi K_S)$ Dalitz		3.3°	1.5°
Radiative/electroweak $b \to s$ transitions			
$\mathcal{S}_{K^0_S \pi^0 \gamma}$	0.32	0.10	0.03
$\mathcal{B}(B \to X_s\gamma)$	13%	7%	6%
$A_{CP}(B \to X_s\gamma)$	0.058	0.01	0.005
C_9 from $A_{FB}(B \to K^*\ell^+\ell^-)$	-	11%	4%
C_{10} from $A_{FB}(B \to K^*\ell^+\ell^-)$	-	13%	4%
C_7/C_9 from $A_{FB}(B \to K^*\ell^+\ell^-)$	-		5%
R_K		0.07	0.02
$\mathcal{B}(B^+ \to K^+\nu\nu)$	†† $< 3\ \mathcal{B}_{\rm SM}$		30%
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	†† $< 40\ \mathcal{B}_{\rm SM}$		35%
Radiative/electroweak $b \to d$ transitions			
$\mathcal{S}_{\rho\gamma}$	-	0.3	0.15
$\mathcal{B}(B \to X_d\gamma)$	-	24% (syst.)	
Leptonic/semileptonic B decays			
$\mathcal{B}(B^+ \to \tau^+\nu)$	3.5σ	10%	3%

Belle II expected performance (1)

- Belle II plans to start data taking in 2018
- Physics complementary and competitive with LHCb



Observable	Belle	Belle II/SuperKEKB	
B_s physics	(25 fb^{-1})	(5 ab^{-1})	
$\mathcal{B}(B_s \to \gamma\gamma)$	$< 8.7 \times 10^{-6}$	0.25×10^{-6}	
$\Delta\Gamma_s^{CP}/\Gamma_s$ $(Br(B_s \to D_s^{(*)} D_s^{(*)}))$	3%	1% (model dependency)	
$\Delta\Gamma_s/\Gamma_s$ ($B_s \to f_{CP}$ t-dependent)	-	1.2%	
ϕ_s (with $B_s \to J/\psi\phi$ etc.)	-	-	-
$\mathcal{B}(B_s \to \mu^+\mu^-)$	-		
ϕ_3 $(B_s \to KK)$	-		
ϕ_3 $(B_s \to D_s K)$	-		
Υ decays	(3 fb^{-1})	(500 fb^{-1})	
$\mathcal{B}(\Upsilon(1S) \to \text{invisible})$	$< 2.5 \times 10^{-3}$	$< 2 \times 10^{-4}$	
	$(\sim 0.5\ \text{ab}^{-1})^{\ddagger}$	(5 ab^{-1})	(50 ab^{-1})
Charm physics			
D mixing parameters			
x	0.25%	0.12%	0.09%
y	0.16%	0.10%	0.05%
$\delta_{K\pi}$	10°	6°	4°
$\lvert q/p \rvert$	0.16	0.1	0.05
ϕ	0.13 rad	0.08 rad	0.05 rad
A_D	2.4%	1%	0.3%
New particles$^{\aleph}$			
$\gamma\gamma \to Z(3930) \to D\bar{D}^*$		$> 3\sigma$	