Heavy Flavour Outlook

– Theory –

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LHCP 2015
St. Petersburg

Heavy Flavour (HF) Physics

According to "The Authorities" *) :

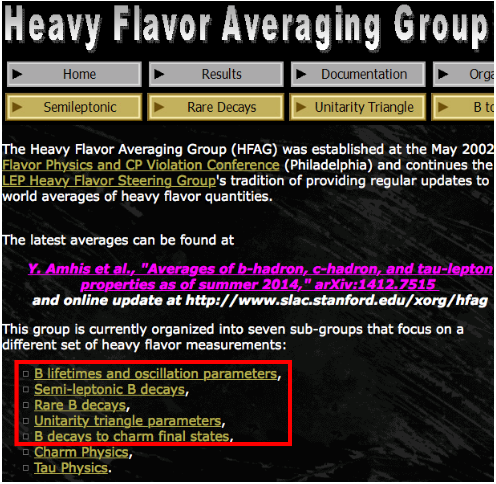
HF physics

= 5/7 × beauty physics

+ 1/7 × charm physics

+ 1/7 × τ physics

in terms of working groups



[http://www.slac.stanford.edu/xorg/hfag/]

*) Who provide an invaluable service to the community with their effort.
Thank you!!!

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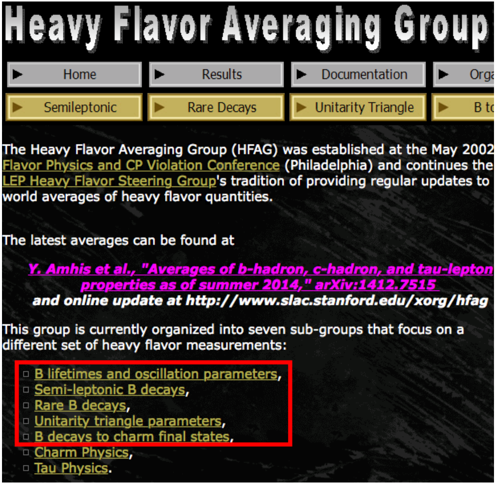

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Possible “explanations”?

b-quark has larger mass than *c*-quark

$m_c \simeq 1$ GeV $<$ $m_b \simeq 4$ GeV

- more *b*-hadrons with more decay channels as for *c*-hadrons
- larger hierarchy with QCD-binding scale $\Lambda_{\text{QCD}} \lesssim 0.5$ GeV

$\Lambda_{\text{QCD}} \ll m_b$ vs. $\Lambda_{\text{QCD}} \lesssim m_c$

⇒ **puts theory on firmer grounds for beauty physics for many important observables**

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Thank you!!!

Heavy Flavour (HF) Physics

According to "The Authorities" *):

⇒ Focus on theory outlook
for *b*-physics

Related theory talks at this conference . . .

- "Theory: overview on production (including polarization) and spectroscopy",
  Mon. 31/08, 11:30, M. Buntenschön
- "Theoretical perspective on rare and semi-rare *B* decays" ($B_s \to \bar{\mu}\mu$, $B \to K^{(*)}\bar{\ell}\ell$),
  Wed. 02/09, 11:15, C. Bobeth
- "BSM searches via rare decays in *B* physics",
  Thu. 03/09, 10:00, D. Martinez Santos

and many more experimental talks in HF-sessions

Flavour changes in the standard model (SM)

$U_i = \{u, c, t\}$:

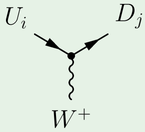
$Q_U = +2/3$

$D_j = \{d, s, b\}$:

$Q_D = -1/3$

$$\mathcal{L}_{\rm CC} = \frac{g_2}{\sqrt{2}} (\bar{u}, \bar{c}, \bar{t}) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma^\mu P_L \begin{pmatrix} d \\ s \\ b \end{pmatrix} W_\mu^+$$

~ Cabibbo-Kobayashi-Maskawa (CKM) matrix



$$\mathcal{L}_{\rm SM} = \underbrace{\mathcal{L}_{\rm gauge}}_{\text{flavour sym } G_{\rm flavour}} + \underbrace{\overline{Q}_L Y_U \tilde{\Phi} U_R + \overline{Q}_L Y_D \Phi D_R}_{\text{Yukawa's break } G_{\rm flavour}}$$

$\Uparrow$

- $Y_{U,D}$ origin of flavour in the SM = 6 + 4 parameters (+ 3 lepton masses)
- $6 \times$ quark masses $\propto vev \times \mathrm{diag}(Y_{U,D}) \Rightarrow$ very hierarchical
- $4 \times V_{\rm CKM} \Rightarrow$ off-diagonal entries strongly suppressed

$$G_{\rm flavour} = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R} \otimes SU(3)_{L_L} \otimes SU(3)_{E_R} \otimes U(1)_{\rm PQ} \otimes U(1)_Y \otimes G_{\rm SM}$$

SM still invariant under $G_{\rm SM} = U(1)_Y \otimes U(1)_B \otimes U(1)_L$

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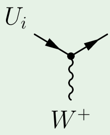
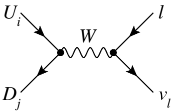


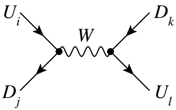
Tree: only $U_i \to D_j$ & $D_i \to U_j$

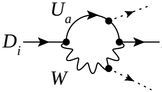
⇒ charged current (CC): $\boldsymbol{Q_i \neq Q_j}$

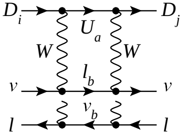
Loop: $D_i \to D_j$ (& $U_i \to U_j$)

⇒ neutral current (FCNC): $\boldsymbol{Q_i = Q_j}$









$M_1 \to \ell\bar{\nu}_\ell$

$M_1 \to M_2 + \ell\bar{\nu}_\ell$

$M_1 \to M_2 M_3$

$M_1 \to M_2 + \{\gamma, Z, g\}$

$\{\gamma, Z, g\} \to \{\bar{\ell}\ell, \bar{\nu}\nu, M_3\}$

$M_1 \to \bar{\ell}\ell$

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$M^0 \leftrightarrow \overline{M}^0$ (= mixing)

$\mathcal{A} \sim G_F V_{ij}$

$\sim G_F V_{ij} V^*_{lk}$

$\sim G_F g \sum_a V_{ai} V^*_{aj} f(m_a)$

$\sim G_F g^2 \sum_{a,b} V_{ai} V^*_{aj} f(m_{a,b})$

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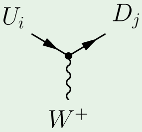

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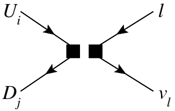

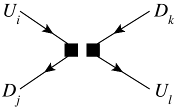

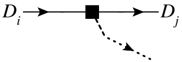

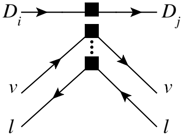

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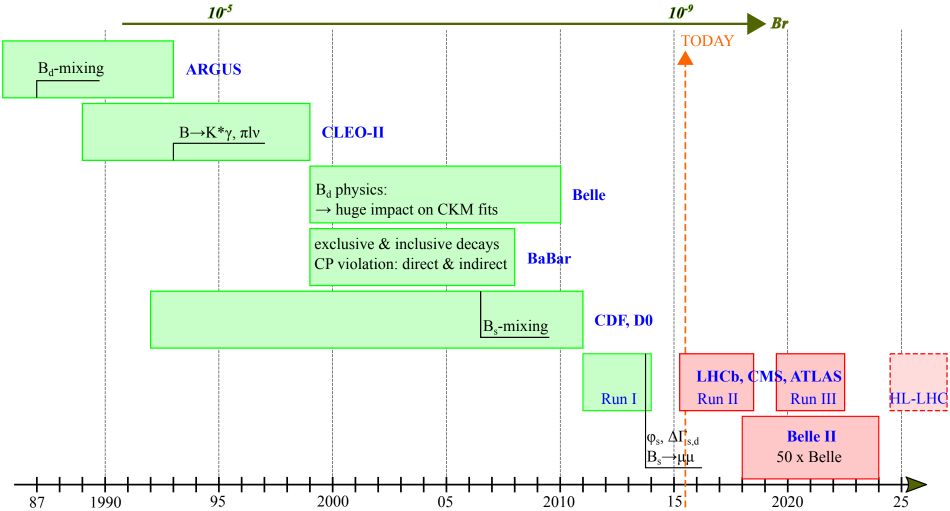
$M^0 \leftrightarrow \overline{M}^0$ (= mixing)

Decoupling for $m_M \ll m_W$ ⇒ effective theory à la Fermi

$\mathcal{A} \sim G_F V_{ij}$ $\quad \sim G_F V_{ij} V_{lk}^*$ $\quad \sim G_F\, C(V_{ij}, m_a)$ $\quad \sim G_F\, C(V_{ij}, m_a, m_b)$

Timeline of (some) *b*-physics experiments (starting late 80's)

- a few selected experimental results, testing the SM
- strong experimental program in next 10 years (2015 – 2025)



CKM-paradigm of SM is confirmed by *b*-Physics data

⇒ fit of CKM-Parameters . . .

[experimental input from CKMfitter homepage]

CKM matrix up to $\mathcal{O}(\lambda^4)$ in terms of

4 Wolfenstein parameters

$$\lambda \sim 0.22, \quad A, \quad \rho, \quad \eta$$

$$V_{ij} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

⇒ nowadays sophisticated fit:

"combine and overconstrain"

!!! numerous *b*-Physics measurements

$\|V_{ud}\|$ (nuclei)	$0.97425 \pm 0 \pm 0.00022$
$\|V_{us}\| f_+^{K\to\pi}(0)$	0.2163 ± 0.0005
$\|V_{cd}\|$ (νN)	0.230 ± 0.011
$\|V_{cs}\|$ $(W \to c\bar{s})$	$0.94^{+0.32}_{-0.26} \pm 0.13$
$\|V_{ub}\|$ (semileptonic)	$(4.01 \pm 0.08 \pm 0.22) \times 10^{-3}$
$\|V_{cb}\|$ (semileptonic)	$(41.00 \pm 0.33 \pm 0.74) \times 10^{-3}$
$\mathcal{B}(\Lambda_p \to p\mu^-\bar{\nu}_\mu)_{q^2>15}/\mathcal{B}(\Lambda_p \to \Lambda_c\mu^-\bar{\nu}_\mu)_{q^2>7}$	$(1.00 \pm 0.09) \times 10^{-2}$
$\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau)$	$(1.08 \pm 0.21) \times 10^{-4}$
$\mathcal{B}(D_s^- \to \mu^-\bar{\nu}_\mu)$	$(5.57 \pm 0.24) \times 10^{-3}$
$\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)$	$(5.55 \pm 0.24) \times 10^{-2}$
$\mathcal{B}(D^- \to \mu^-\bar{\nu}_\mu)$	$(3.74 \pm 0.17) \times 10^{-4}$
$\mathcal{B}(K^- \to e^-\bar{\nu}_e)$	$(1.581 \pm 0.008) \times 10^{-5}$
$\mathcal{B}(K^- \to \mu^-\bar{\nu}_\mu)$	0.6355 ± 0.0011
$\mathcal{B}(\tau^- \to K^-\bar{\nu}_\tau)$	$(0.6955 \pm 0.0096) \times 10^{-2}$
$\mathcal{B}(K^- \to \mu^-\bar{\nu}_\mu)/\mathcal{B}(\pi^- \to \mu^-\bar{\nu}_\mu)$	1.3365 ± 0.0032
$\mathcal{B}(\tau^- \to K^-\bar{\nu}_\tau)/\mathcal{B}(\tau^- \to \pi^-\bar{\nu}_\tau)$	$(6.431 \pm 0.094) \times 10^{-2}$
$\mathcal{B}(B_s \to \mu\mu)$	$(2.8^{+0.7}_{-0.6}) \times 10^{-9}$
$\|V_{cd}\| f_+^{D\to\pi}(0)$	0.148 ± 0.004
$\|V_{cs}\| f_+^{D\to K}(0)$	0.712 ± 0.007
$\|\varepsilon_K\|$	$(2.228 \pm 0.011) \times 10^{-3}$
Δm_d	(0.510 ± 0.003) ps^{-1}
Δm_s	(17.757 ± 0.021) ps^{-1}
$\sin(2\beta)_{[c\bar{c}]}$	0.691 ± 0.017
$(\phi_s)_{[b\to c\bar{c}s]}$	-0.015 ± 0.035
$S_{\pi\pi}^{+-}$, $C_{\pi\pi}^{+-}$, $C_{\pi\pi}^{00}$, $\mathcal{B}_{\pi\pi}$ all charges	Inputs to isospin analysis
$S_{\rho\rho,L}^{+-}$, $C_{\rho\rho,L}^{+-}$, $S_{\rho\rho}^{00}$, $C_{\rho\rho}^{00}$, $\mathcal{B}_{\rho\rho,L}$ all charges	Inputs to isospin analysis
$B^0 \to (\rho\pi)^0 \to 3\pi$	Time-dependent Dalitz analysis
$B^- \to D^{(*)}K^{(*)-}$	Inputs to GLW analysis
$B^- \to D^{(*)}K^{(*)-}$	Inputs to ADS analysis
$B^- \to D^{(*)}K^{(*)-}$	GGSZ Dalitz analysis

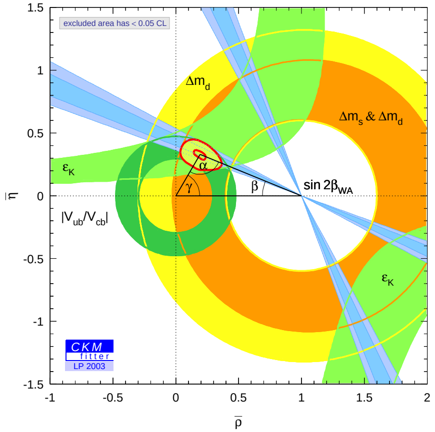
CKM-paradigm of SM is confirmed by *b*-Physics data

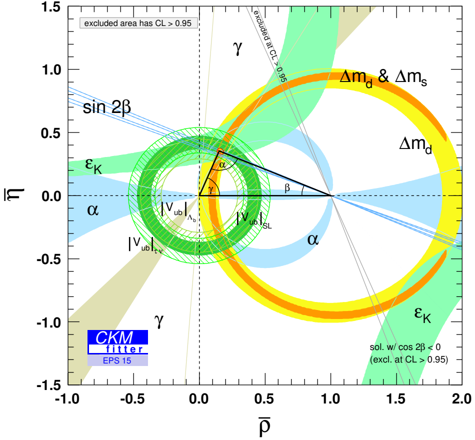
⇒ fit of CKM-Parameters . . . 2003 → 2015 works "frustratingly (?)" well

improved by *B*-factories, Tevatron, LHC

CKMfitter results [`http://ckmfitter.in2p3.fr/`]

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





See also "UTfit collaboration" [`http://www.utfit.org/UTfit/`]

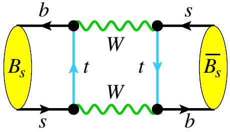
See also "SCAN Method" [Eigen et al. arXiv:1301.5867 + 1503.02289]

b-Physics is a window to New Physics . . .

Example: Neutral B_q-meson mixing ($q = d, s$) – mass difference Δm_q

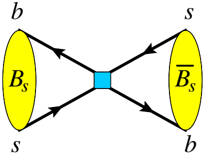
- SM contribution is loop and CKM suppressed + GIM-enhancement

$$\Delta m_q|_{\mathrm{SM}} \propto \frac{g^4}{(4\pi)^2} \left(V_{tb} V_{tq}^*\right)^2 \frac{S_0(m_t/m_W)}{32 m_W^4}$$



- (Generic) New Physics contribution suppressed by new physics scale

$$\Delta m_q|_{\mathrm{NP}} \propto \frac{1}{\Lambda_{\mathrm{NP}}^2}$$



⇒ can probe high scales via $\Delta m_q|_{\mathrm{exp}} = \Delta m_q|_{\mathrm{SM}} + \Delta m_q|_{\mathrm{NP}}$

$$\Lambda_{\mathrm{NP}} \sim \frac{4\pi}{g^2} \frac{1}{|V_{tb} V_{tq}^*|} \times 0.28\,\mathrm{TeV} \sim \begin{cases} 1100\ \mathrm{TeV} & B_d - \text{mixing} \\ 220\ \mathrm{TeV} & B_s - \text{mixing} \end{cases}$$

. . . some minor deviations from SM

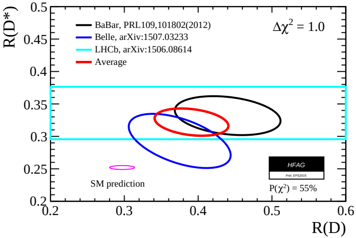
- **CP-violation:** like-sign dimuon asymmetry by DØ at 3σ [DØ1310.0447]
  from SM "interpretation" [Borissov/Hoeneisen 1303.0175]

- tensions between **exclusive** and **inclusive** determinations of V_{ub} and V_{cb}

- **breaking** of lepton flavour universality (LFU) at **"tree"** and **"loop"** level ?

tree) $$R(D^{(*)}) \equiv \frac{\mathcal{B}[B \to D^{(*)}\tau\bar{\nu}_\tau]}{\mathcal{B}[B \to D^{(*)}\ell\bar{\nu}_\ell]} \quad (\ell = e,\, \mu)$$

combination of Babar, Belle, LHCb at 3.9σ



loop) $$R_K \equiv \frac{\mathcal{B}[B^+ \to K^+\bar{\mu}\mu]}{\mathcal{B}[B^+ \to K^+\bar{e}e]} = 0.745^{+0.097}_{-0.082}$$

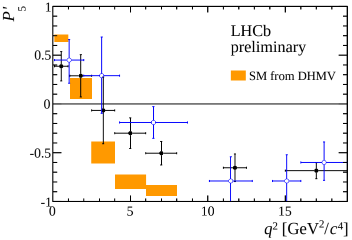
from $R_K|_{\text{SM}} \approx 1$ at 2.6σ [LHCb 3/fb 1406.6482]

- $b \to s(\gamma,\, \bar{\ell}\ell)$ **global fits** for $\ell = \mu$

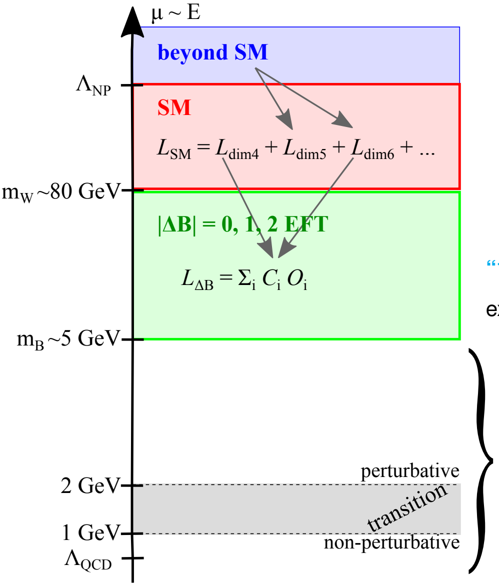
  with/without $\ell = e$ (i.e. R_K)
  (also known as "$B \to K^*\bar{\mu}\mu$ anomaly" in angular observable P_5')

  prefer non-SM value of eff. coupling

  $$C_9 = C_9^{\text{SM}} + \Delta C_9 \text{ with } C_9^{\text{SM}} \approx +4 \text{ and } \Delta C_9 \approx -1$$



Central theme: factorisation via stack of effective theories (EFT)



"$1/m_b$ expansions": (QCD laboratory)

exploit hierarchies $\Lambda_1 \ll \Lambda_2 \ll \ldots \ll m_B$

- Λ_i =process-specific scales, sometimes non-perturbative $\sim \Lambda_{QCD} \approx 0.5$ GeV

$\Rightarrow$ factorization of matrix-elements into hard coefficients and hadronic objects (decay constants, form factors, distribution amplitudes)

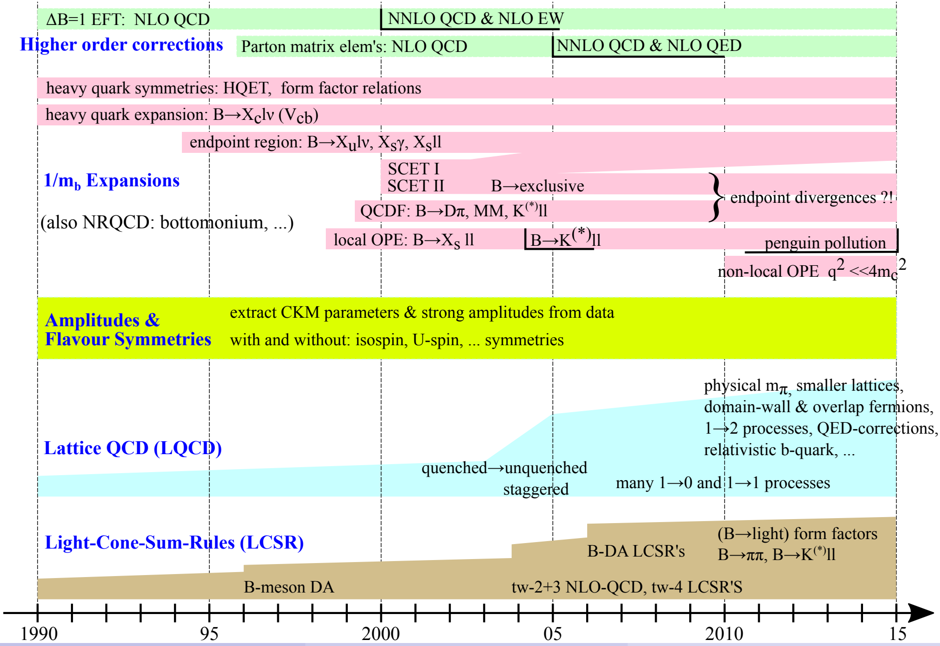
!!! @ leading order in $1/m_b$ usually a few universal hadronic objects

$\Downarrow$

from data or non-pertubative methods

Timeline of theoretical methods in *b*-physics

(starting early 90's)



. . . review some selected topics

V_{ub} and V_{cb} in the SM in 2015

New results for $b \to (u, c) + \ell\bar{\nu}_\ell$ $(\ell = e, \mu)\ldots$

- new inclusive $|V_{cb}|_{\rm incl} = (42.21 \pm 0.78) \cdot 10^{-3}$ [Alberti/Gambino/Healey/Nandi 1411.6560]
- new $B \to D\ell\bar{\nu}_\ell$ measurement *(preliminary)* [Belle @ EPS-HEP 2015, R. Glattauer]
- new $B \to D$ FF's from 2 lattice groups [FNAL/MILC 1503.07237, HPQCD 1505.03925]
- new $B \to \pi$ FF's from lattice [FNAL/MILC 1503.07839]

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. . . and **consequences for** V_{cb}

- simultaneous fit of $|V_{cb}|$ and FF-parametes (z-exp.) to lattice and data *(preliminary)*

  $|V_{cb}|_{B\to D} = (41.08 \pm 0.95) \cdot 10^{-3}$ (data = Babar '09 + Belle '15) [P. Gambino @ EPS-HEP 2015]

  $|V_{cb}|_{B\to D} = (42.09 \pm 1.07) \cdot 10^{-3}$ (data = Belle '15) [R. Glattauer @ EPS-HEP 2015]

  $\Rightarrow$ reduces tension to $|V_{cb}|_{\rm incl}$ to 0.9σ and 0.1σ

- !!! still large tension to $B \to D^*\ell\bar{\nu}_\ell$

  $|V_{cb}|_{B\to D^*} = (39.04 \pm 0.75) \cdot 10^{-3}$ [FNAL/MILC 1403.0635]

  2.9σ for $|V_{cb}|_{\rm incl}$, 1.7σ for $|V_{cb}|_{B\to D}$ from Babar + Belle, 2.3σ for $|V_{cb}|_{B\to D}$ from only Belle

  $\Rightarrow$ based on zero-recoil extrapolation (uses CNL-parameterisation (heavy quark limit))

  !!! need lattice results away from zero-recoil

V_{ub} and V_{cb} in the SM in 2015

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. . . and **consequences for** V_{ub}

- $|V_{ub}|_{B\to\pi} = (3.72 \pm 0.16) \cdot 10^{-3}$ $\Rightarrow$ some reduction of tension to 1.9σ w.r.t.
  $|V_{ub}|_{\rm incl} = (4.45 \pm 0.36) \cdot 10^{-3}$ (average of DGE, BLNP, GGOU from CKMfitter)
  !!! confirmation by other lattice groups of $B \to \pi$ FF's desirable
- $|V_{ub}|_{\Lambda_b\to p} = (3.27 \pm 0.23) \cdot 10^{-3}$ from LHCb (NEW) [LHCb 1504.01568]
  from $|V_{ub}|/|V_{cb}|$ measured in $\Lambda_b \to p\mu\bar{\nu}_\mu / \Lambda_b \to \Lambda_c\mu\bar{\nu}_\mu$, assuming $|V_{cb}| = (39.5 \pm 0.8) \cdot 10^{-3}$

? other theory approaches to inclusive V_{ub} under investigation
"shape functions from data of $B \to X_u\ell\bar{\nu}_\ell + B \to X_s\gamma$"
[SIMBA Bernlocher/Lacker/Ligeti/Stewart/2×Tackmann, NNVub Healey/Mondino/Gambino]

? V_{ub} and right-handed currents from angular analysis of $B \to \rho(\to \pi\pi)\ell\bar{\nu}_\ell$
(even with B-factory data) [Bernlocher/Ligeti/Turczyk 1408.2516]

? alternative decays $B \to \omega\ell\bar{\nu}_\ell$, $B_s \to K^{(*)}\ell\bar{\nu}_\ell$ lack either precise theory input or data

New physics in CKM angle γ

"CKM-γ extraction from tree-level decays corresponds to pure SM value"

$\Rightarrow$ based on **assumption:** absence of weak phases other then γ

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

Can we exclude this in view of expected $\delta\gamma \simeq 1^\circ$ at LHCb and Belle II ?

- γ measured in $B^\pm \to DK^\pm$ due to interference of $b \to c\bar{u}s$ and $b \to u\bar{c}s$ where D^0 and $\bar{D}^0 \to$ common final state
- mediated by color-octet and singlet $O_{1,2} \propto (\bar{u}_1 b)_{(V-A)}(\bar{d}_1 u_2)_{(V-A)}$

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{u_1 b} V^*_{u_2 d_1} \left[C_1 O_1 + C_2 O_2\right] \qquad u_{1,2} = u,\, c,\ \text{and}\ d_1 = d,\, s$$

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New physics in $C_{1,2} = C_{1,2}^{\rm SM} + \Delta C_{1,2}$ leads to

[Brod/Lenz/Tetlamatzi-Xolocotzi/Wiebusch 1412.1446]

$$\gamma \quad \to \quad (\gamma + \Delta\gamma) \approx \gamma + (r_A - r_{A'})\frac{\text{Im}(\Delta C_1)}{C_2}$$

$$r_{A'} \equiv \frac{\langle \bar{D}^0 K^- | \mathcal{O}_1^{c\bar{u}s} | B^- \rangle}{\langle \bar{D}^0 K^- | \mathcal{O}_2^{c\bar{u}s} | B^- \rangle} \qquad r_A \equiv \frac{\langle D^0 K^- | \mathcal{O}_1^{u\bar{c}s} | B^- \rangle}{\langle D^0 K^- | \mathcal{O}_2^{u\bar{c}s} | B^- \rangle}$$

Estimate

$(r_A - r_{A'}) \approx -0.6$

what are the model-independent constraints on $\Delta C_{1,2}$?

New physics in CKM angle γ

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? constraints on $\Delta C_{1,2}$ $\Rightarrow$ various possibilities, **but** large theory uncertainties:

[CB/Haisch/Lenz/Pecjak/Tetlamatzi-Xolocotzi/Wiebusch 1404.2531, Brod/Lenz/Tetlamatzi-Xolocotzi/Wiebusch 1412.1446]

- $b \to c\bar{u}d$: $B \to D\pi$ and $B \to D^{(*)0}h^0$
- $b \to u\bar{u}d$: $B \to \pi\pi$ $(S_{\pi\pi},\ R_{\pi^-\pi^0})$
- total b lifetime and lifetime difference: $\Gamma_{\rm tot}$ and $\Delta\Gamma_s$
- via mixing of $b \to c\bar{c}(d,s)$ into $B \to X_{d,s}\gamma$
- semi-leptonic CP asymmetries $a_{\rm sl}^{d,s}$

Combination yields

$$\text{Im}\Delta C_1 \in [-0.62,\ +0.14]$$
$$\text{Im}\Delta C_2 \in [-0.19,\ +0.11]$$
$$\text{Re}\Delta C_1 \in [-0.19,\ +0.13]$$
$$\text{Re}\Delta C_2 \in [-0.07,\ +0.02]$$

With $\text{Im}[\Delta C_1(m_b)] \simeq \pm 0.1 \Rightarrow \Delta\gamma \simeq \mp 4^\circ$

Penguin pollution in $B_q \to J/\psi M$ from local OPE

$B_q - \overline{B}_q$ mixing phases $\phi_d = 2\beta$ and $\phi_s = -2\beta_s$ can be measured in $B \to J/\psi K_S$ and $B_s \to J/\psi\phi$

$$A_{CP}[B_q \to f](t) = \frac{S_f \sin(\Delta m_q t) - C_f \cos(\Delta m_q t)}{\cosh(\Delta\Gamma_q t/2) + A^f_{\Delta\Gamma} \sinh(\Delta\Gamma_q t/2)}$$

$$S_f = -\eta_f \sin(\underbrace{\phi_q + \phi_q^{\rm NP} + \Delta\phi_q^f}_{\equiv\, \phi_f})$$

$\Delta\phi_q$ = process-specific **penguin pollution** suppressed by $\epsilon \approx 0.02$
SM-bkg to new physics searches

$$\tan(\Delta\phi_q^f) \approx 2\,\epsilon\,\sin\gamma\,\frac{P_f}{T_f} + \mathcal{O}(\epsilon^2) \qquad \epsilon \equiv \left|\frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\right|$$

with T_f and P_f in amplitude $\quad A(B \to f) = V_{cb}V_{cs}^* T_f + V_{ub}V_{us}^* P_f$

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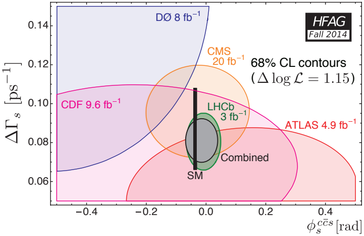
Example ϕ_s

[talks @ LHCP '15: M. Vesterinen (LHCb), V. Nikoleanko (ATLAS), J. Pazzini (CMS)]

- $\phi_s = (-2.08^{+0.07}_{-0.08})^\circ$ in SM [HFAG]
- $\phi_f = (-0.86 \pm 2.01)^\circ$ from $f = J/\psi\phi$ [HFAG]

  $\phi_f = (-2.01 \pm 1.89)^\circ$ from $f = J/\psi(KK,\, \pi\pi,\, D_sD_s)$
  [talk @ LHCP '15: M. Vesterinen]
- $\delta\phi_f \approx 0.46^\circ$ LHCb-prospects 50 fb^{-1} from $f = J/\psi\phi$
  [LHCb 1208.3355]



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with T_f and P_f in amplitude $\quad A(B \to f) = V_{cb}V_{cs}^* T_f + V_{ub}V_{us}^* P_f$

$\Delta\phi_q$ via local OPE

[Frings/Nierste/Wiebusch 1503.00859]

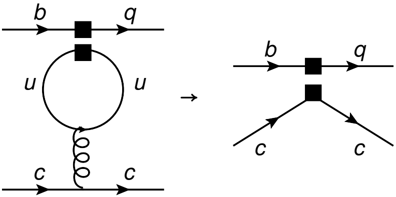
input: branching fraction measurements $B_q \to f$

- $|\Delta\phi_d^{J/\psi K}| < 0.68°$
- $|\Delta\phi_s^{(J/\psi\phi)_{0,\perp}}| < 0.99°, \quad |\Delta\phi_s^{(J/\psi\phi)_\parallel}| < 1.22°$
- also S_f and C_f for $f = J/\psi + (K, \pi^0, \rho, K^*, \phi)$

$\Rightarrow$ alternative to $SU(3)_{\rm flavour}$ + control channels
$\Rightarrow$ improveable: better knowledge of matrix elements

local OPE of $\langle f|C_1 O_1^u + C_2 O_2^u|B_q\rangle$

since $\Lambda_{QCD} \ll q^2 \sim m^2_{J\psi}$



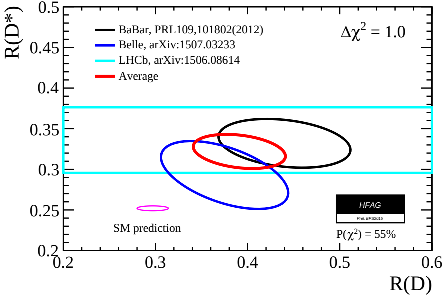
$R(D)$ & $R(D^*)$ in SM

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu}_\ell)}$$

- new results from Belle and LHCb 2015
- **persistent deviation of 3.9σ** (combined)
- new lattice predictions for $R(D)$ in SM

$R(D)|_{\rm SM} = 0.299 \pm 0.011$ [FNAL/MILC 1503.07237]

$R(D)|_{\rm SM} = 0.300 \pm 0.008$ [HPQCD 1505.03925]



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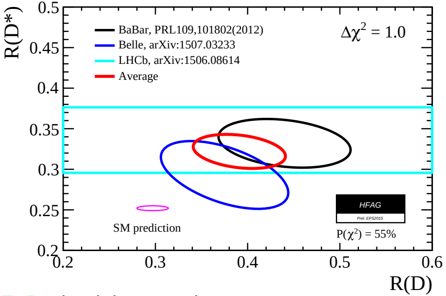


. . . the authors of Greljo/Isidori/Marzocca 1506.01705 raised the question:

1) when taking serious the 30% enhancement of $b \to c\tau\bar{\nu}_\tau$, this could mean that . . .

2) inclusive $\mathcal{B}(B \to X_c\ell\bar{\nu}_\ell)$ ($\ell = e, \mu$) could be too large **if** experimentalists subtract backgrounds from $B \to X_{u,c}\tau\bar{\nu}_\tau$ followed by $\tau \to X\ell\nu\nu$ **by** using SM predictions of $B \to X_{u,c}\tau\bar{\nu}_\tau$ in monte-carlo's $\Leftarrow$ is this really the case ?

". . . we urge the experimental collaborations to reanalyze all semi-leptonic charged-current B decays without imposing LFU, both as far as signal and as far as background are concerned . . ."

3) could explain (in part) the tension $|V_{cb}|_{\rm excl} < |V_{cb}|_{\rm incl}$

??? would that help to solve the "gap-problem": $\sum_{\rm excl} \mathcal{B}(b \to c\ell\bar{\nu}_\ell) < \mathcal{B}(B \to X_c\ell\bar{\nu}_\ell)$ by 3σ

[Bernlocher/Biedermann/Lacker/Lück, 1402.2849, T. Lück at EPS-HEP 2015]

New physics interpretation of anomalies . . .

$b \to s\bar{\mu}\mu$ global fits

R_K

$R(D^{(*)})$

New physics interpretation of anomalies ...

$b \to s\bar{\mu}\mu$ global fits | **R_K** | **$R(D^{(*)})$**

Model-IN-dependently via $|\Delta B| = 1$ EFT

Prefer **non-SM value** of effective coupling

$$C_i^\mu(m_b) = C_i^{\rm SM} + \Delta C_i^\mu$$

A) $\Delta C_9^\mu \approx -1$

B) $\Delta C_9^\mu \approx -\Delta C_{10}^\mu \approx -0.5$

in A) and B) **destructive to SM**:

$$C_9^{\rm SM} \approx -C_{10}^{\rm SM} \approx +4$$

$$O_{9\,(10)} \propto [\bar{s}\gamma_\mu P_L b][\bar{\ell}\gamma_\mu(\gamma_5)\ell]$$

[Descotes-Genon et al. 1307.5683, Altmannshofer/Straub 1308.1501, Beaujean/CB/van Dyk 1310.2478, Hurth/Mahmoudi 1312.5267]

1) tensor (T) op's excluded

2) $\ell = e$ (pseudo)-scalar (S) op's only in part
($\ell = \mu$ excluded by $B_s \to \bar{\mu}\mu$)

3) (axial)-vector op's favoured

[Hiller/Schmaltz 1408.1627]

⇓

Not decisive if NP in $\ell = e$ or $\ell = \mu$ — in principle in both

!!! need combined fit of $\ell = e, \mu$

Latest total and diff. rate's

1) single op-scenario:

$$V_L, \quad T, \quad -\tfrac{1}{2}S + \tfrac{1}{8}T$$

2) two op-scenario:

$$(S_L, S_R), (V_L, S_R), (V_L, -\tfrac{1}{2}S + \tfrac{1}{8}T)$$

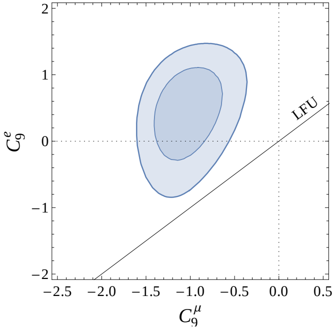
[Freytis/Ligeti/Ruderman 1506.08896]

New physics interpretation of anomalies . . .

$b \to s\bar{\mu}\mu$ global fits **R_K** **$R(D^{(*)})$**

Model-IN-dependently via $|\Delta B| = 1$ EFT

$\Rightarrow$ combined fit of $b \to s\bar{\mu}\mu$ and $b \to s\bar{e}e$ prefers



no relations exist to

$b \to s(\bar{\mu}\mu, \bar{e}e)$ and R_K

NP in $\ell = \mu$ and SM in $\ell = e$

[Ghosh/Nardecchia/Renner 1408.4097, Hurth/Mahmoudi/Neshatpour 1410.4545, Altmannshofer/Straub 1411.3161]

New physics interpretation of anomalies . . .

$b \to s\bar{\mu}\mu$ **global fits** | R_K | $R(D^{(*)})$

Model-dependently

✗ Z models: Z-coupl. implies $\Delta C_9/\Delta C_{10} = (1 - 4s_W^2) \ll 1$

✗ MSSM: Z-peng. dominated no large $\Delta C_9 = -1$

[Altmannshofer/Straub 1308.1501, Mahmoudi/Neshatpour/Virto 1401.2145]

✓ Leptoquark models

✓ Z' models

✓ Leptoquark models

✓ Composite Higgs models

✓ SM-EFT $(SU(2)_L \times U(1)_Y) \to$ 2 op's $O_{\ell q}^{1(3)} = [\bar{\ell}_p \gamma_\mu (\tau^a) \ell_r][\bar{q}_s \gamma^\mu (\tau^a) q_t]$

[Bhattacharya et al. 1412.7164, Alonso et al. 1505.005164, Greljo et al. 1506.01705, Calibbi et al. 1506.02661]

$\Rightarrow$ dynamical realisation via spin-1 Leptoquark, $SU(2)_L$ singlet [1505.005164] or triplet [1506.01705]

New physics interpretation of anomalies ...

$b \to s\bar{\mu}\mu$ global fits | **R_K** | **$R(D^{(*)})$**

Proposed checks / future signals

- angular analysis of $B \to K^* \bar{\mu}\mu$ with 3 fb^{-1}
- measure $R_{K^*,\, X_s,\, K_0(1430),\, K_1}$ and **no-rate ratios** like

  ... $A_{\text{FB}}(\bar{\mu}\mu)/A_{\text{FB}}(\bar{e}e)$ ratios of zero-crossings
- measure differential rates, angular observables and CP-aysmmetries in $B \to D^{(*)}\tau\bar{\nu}_\tau$
- check $R_{M_1}/R_{M_2} = 1 \Rightarrow$ model discriminator
- search for LFV decays: $B_q \to \bar{\ell}_a \ell_b$, $B \to K^{(*)}\bar{\ell}_a \ell_b$
- in specific models additional non-b-physics pheno affected

  for example links with $h \to \tau\mu$, $Z' \to \bar{e}e$ vs. $Z' \to \bar{\mu}\mu$, $\ell_a \to \ell_b \gamma$, ... many more

$\Rightarrow$ see original works for details

Inclusive $B \to X_s\gamma$

$$\Gamma(B \to X_q\gamma) = \Gamma(b \to q\gamma)_{\rm p} + \delta\Gamma_{\rm np}$$

$$\propto (|C_7|^2 + |C_7'|^2)$$

$$O_{7\,(7')} \propto m_b \left[\bar{s}\sigma_{\mu\nu} P_{R(L)} b\right] F^{\mu\nu}$$

- $\Gamma(b \to q\gamma)_{\rm p}$ = perturbatively calculable part @ NNLO
- $\delta\Gamma_{\rm np}$ = non-perturbative part
  around 5% uncertainty @ $E_\gamma \geq 1.6$ GeV
  [Benzke/Lee/Neubert/Paz arXiv:1003.5012]
- $b \to d u \bar{u} \gamma$ sizeable in $b \to d\gamma$
  [Asatrian/Greub et al. arXiv:1305.6464]

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  [Asatrian/Greub et al. arXiv:1305.6464]

Latest SM updates @ NNLO QCD for $E_\gamma \geq 1.6$ GeV [Misiak et al. arXiv:1503.01789]

$$\mathcal{B}(B \to X_s\gamma)|_{\rm SM} = (3.36 \pm 0.23) \times 10^{-4}$$

$$\mathcal{B}(B \to X_d\gamma)|_{\rm SM} = (1.73^{+0.12}_{-0.22}) \times 10^{-5}$$

uncertainty budget due to:

- 5% non-perturbative
- 3% higher order
- 3% interpolation of m_c-dep. in NNLO corr.
- 2% parametric

Better adopted for actual measurement without strange tagging $\Rightarrow X_{s+d}$:

$$R_\gamma \equiv \frac{\mathcal{B}(B \to X_s\gamma) + \mathcal{B}(B \to X_d\gamma)}{\mathcal{B}(B \to X_x \ell \bar{\nu}_\ell)} = (3.31 \pm 0.22) \times 10^{-3}$$

Current world averages

$$\mathcal{B}(B \to X_s\gamma)|_{\rm Exp} = (3.43 \pm 0.22) \times 10^{-4}$$

$$\mathcal{B}(B \to X_d\gamma)|_{\rm Exp} = (1.41 \pm 0.57) \times 10^{-5}$$

$\Rightarrow$ bound on charged Higgs mass in 2HDM (type-II) $m_{H^\pm} > 480$ GeV @ 95% CL

Inclusive $B \to X_s \bar{\ell}\ell$ (at Belle II)

3 observables in angular analysis $\qquad Br \propto (H_L + H_T)$ and $A_{\rm FB} \propto H_A$

$$\frac{8}{3}\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = \left(1+\cos^2\theta_\ell\right) H_T(q^2) + 2\left(1-\cos^2\theta_\ell\right) H_L(q^2) + 2\cos\theta_\ell H_A(q^2)$$

different dependence on short-distance $C_{7,9,10}$ – **complementary to $B \to K^{(*)}\bar{\ell}\ell$ at low q^2**

$(\hat{s} = q^2/m_b^2)$

$$H_T \propto \hat{s}(1-\hat{s})^2\left[\left|C_9 + \frac{2}{\hat{s}}C_7\right|^2 + |C_{10}|^2\right] \qquad H_L \propto (1-\hat{s})^2\left[|C_9 + 2C_7|^2 + |C_{10}|^2\right]$$

$$H_A \propto -4\,\hat{s}(1-\hat{s})^2 \mathrm{Re}\left[(C_9 + \frac{2}{\hat{s}}C_7)C_{10}^*\right]$$

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$$H_A \propto -4\hat{s}(1-\hat{s})^2 \mathrm{Re}\left[(C_9 + \frac{2}{\hat{s}}C_7)C_{10}^*\right]$$

SM predictions @ NNLO QCD and NLO QED [Huber/Hurth/Lunghi arXiv:1503.04849]

- theory unc. for $\mathcal{B}$ and $H_{L,T}$: 6 – 9 % in $q^2 \in [1, 3.5], [3.5, 6], [1, 6]$ GeV^2
- theory unc. for H_A: from 5 – 70 %, depend strongly on q^2-binning around zero-crossing
- zero-crossing of H_A predicted with $\lesssim 4\,\%$
- QED corrections lead to **pronounced differences** for $\ell = e$ and $\ell = \mu$
- at high-q^2 uncertainties larger: $\mathcal{B}$ about 30 %
- PHOTOS gives satisfactory approximation of explicite QED results

Effects of M_{X_s}-cuts analysed in SCET at level of sub-leading shape functions $\Rightarrow$ require combination of $B \to X_s\gamma$, $B \to X_s\bar{\ell}\ell$ and $B \to X_u \ell\bar{\nu}_\ell$ [Lee et al. hep-ph/0511334, 0512191, 0812.0001, Bernlocher et al.1101.3310, Bell et al. 1007.3758]

Summary

Theory outlook

- **short-distance** conceptually understood, in practice involved 2- and 3-loop calculations
- **advances in lattice QCD** can be expected (predictions from several groups with different systematics)
  - $\Rightarrow$ high accuracy for B-decay constants and bag factors: Δm_q, $B_q \to \bar{\ell}\ell$ and $B \to \ell\bar{\nu}_\ell$
  - $\Rightarrow$ $B_{(s)} \to \pi, D, (K)$ FF's: excl. $b \to (u, c) + \ell\bar{\nu}_\ell$ and $B \to (\pi, K) + (\bar{\ell}\ell, \bar{\nu}\nu)$ @ high q^2
  - $(\Rightarrow)$ perhaps subleading matrix elements for $B \to X_c\ell\bar{\nu}_\ell$ and $|\Delta B| = 2$ for $\Delta\Gamma_q$
  - ? FF's for ($B \to$ unstable resonance $\to PP$) (a la $B \to K^* \to K\pi$) possible
  - ? isospin and QED corrections
- conceptual progress on **power-corrections** in QCDF/SCET desirable:

  excl. $B \to PP, VP, VV$ and hadr. contr. to $B \to K^{(*)}\bar{\ell}\ell$ @ low q^2
- process-specific **QED corrections** ?
- continue model-(in)dependent **New Physics** analysis
- **new phenomenological sector** emerged to study flavour: tests of Yukawa couplings via inclusive (c, b) and exclusive via $h \to V\gamma$

We need both complementary experiments: **LHC (LHCb, CMS, ATLAS) and Belle II**

Backup Slides