Theoretical Overview of B Physics

$\rightarrow$ personal perspectives $\leftarrow$

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Outline

Introduction

Theoretical tools for B physics

$B-\bar{B}$ mixings: $\Delta M_{s,d}$, $\Delta\Gamma_{s,d}$, $a_{\rm fs}^{s,d}$

$B_{s,d}\to\mu^+\mu^-$: powerful model killing

Semi-leptonic decays: $|V_{ub}|$, $|V_{cb}|$ and $R(D^{(*)})$

Exclusive $b\to s\ell^+\ell^-$ decays: several anomalies

Non-leptonic decays: higher-order pert. corrs

Conclusion

Why B physics:

- What is B physics: properties, productions and decays of various hadrons containing at least one bottom quark;

  $B_{u,d,s,c}$ mesons, Λ_b baryon

- Why study B physics: three main motivations;

Measure the SM parameters related to flavour;
Test of the CKM mechanism of flavor and CP violation;
Indirect probe or constrain on various New Physics;

← complementary to EWP tests (@LEP) and direct searches at high-energy frontier (@ LHC, Tevatron);

operator product expansion;
various effective field theories;
factorization theorems;

→ Deepen our understanding of strong interactions both the pert. and non-pert. aspects QCD.

Test and probe the internal hadronic structure in B-hadron and its decay products.

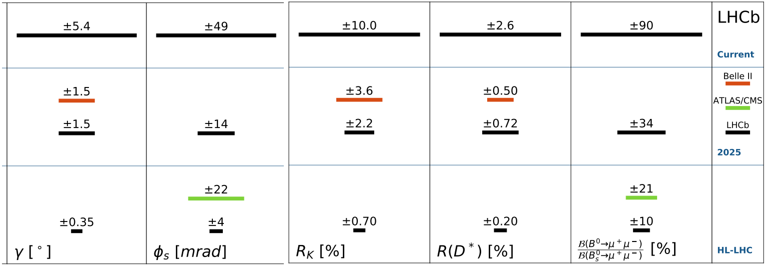
← theoretical and phenomenological input for other hadron processes;

Dedicated B-physics experiments:

- Past: first observation of $B \to X_s \gamma$ by CLEO in 1994; continued by Tevatron @ Fermilab and the two B-factories: BaBar @ SLAC and Belle @ KEK with many key measurements; [*A. J. Bevan et al., "The Physics of the B Factories," 1406.6311*]

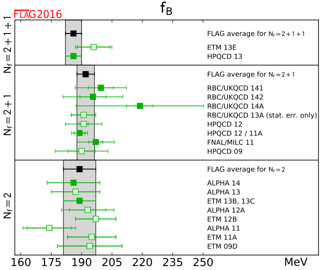
- Current: dedicated LHCb (also ATLAS and CMS) @ LHC with many exciting results; [*I. Bediaga et al., "Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era," arXiv:1808.08865*]

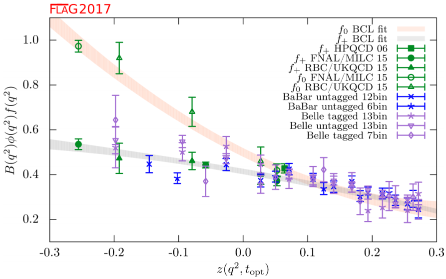
- Future: besides LHCb @ LHC, also Belle II @ SuperKEKB expected to start data taking in 2018, designed to find NP beyond the SM of particle physics; [*https://confluence.desy.de/display/BI/B2TiP+WebHome; 1808.10567*]



Theoretical tasks for B physics:

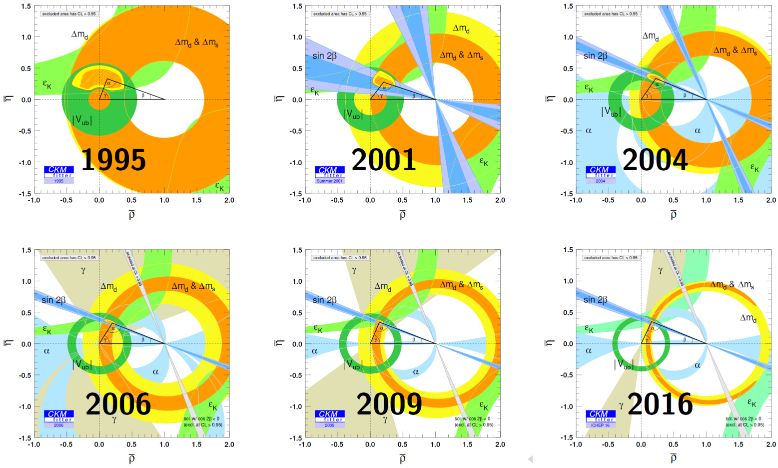
- Main task: try to improve the theory predictions to match the more and more precise exp. data;
- Many dynamical frameworks developed: HQET, SCET, NRQCD, QCDF, pQCD, $\cdots \hookrightarrow$ based on QCD, and separate pert. from non-pert. strong interaction effects $\leftrightarrow$ factorization theorem;
- For the non-pert. objects: mostly from Lattice QCD and LCSR, $\cdots$; [*for reviews see: http://flag.unibe.ch/, and https://hflav.web.cern.ch/*]





Current status of B physics:

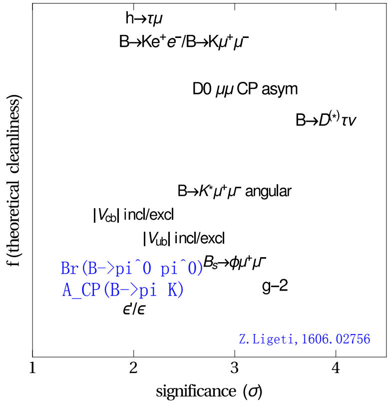
- The CKM mechanism of flavor & CP violation well established! $\hookrightarrow$ 2008 Nobel Prize for Kobayashi and Maskawa;



- Information on UT from tree- and loop-level processes well consistent!

Current status of B physics:

- Remember: $\mathcal{O}(20\%)$ NP contributions to most FCNC processes still allowed by the current data;
- Several intriguing tensions/anomalies do observed in flavour physics, might be any BSM signals?



† all of them not yet conclusive: theo. uncertainties or exp. fluctuations?

† except for theo. cleanest modes, more cross-checks needed;

† exp. measurements of related observables needed;

† indep. theory and lattice calculations needed;

How to describe B-hadron weak decays:

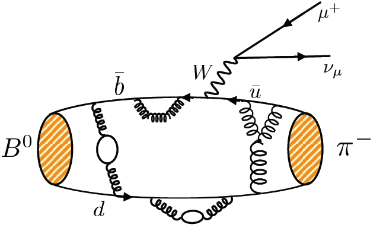
- At the quark level: B-hadron weak decays mediated by weak charged-current $J^\mu_{\rm cc}$ coupled to $W^\pm$;

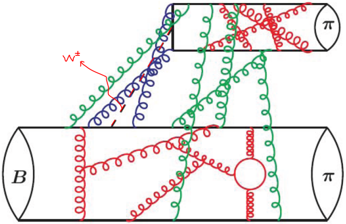
$$\mathcal{L}_{\rm cc} = -\frac{g_2}{\sqrt{2}}\, J^\mu_{\rm cc}\, W^\dagger_\mu + \text{h.c.}, \quad J^\mu_{\rm cc} = (\bar{u}_L, \bar{c}_L, \bar{t}_L)\,\gamma^\mu\, V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

↪ $V_{\rm CKM}$: describes flavor violation, and very predictive, especially for CPV!

- In the real world: no free quarks due to confinement; quarks always confined inside hadrons through soft-gluon exchanges;

↪ In B physics, simple weak decays overshadowed by complex strong interactions!





Typical features for B-hadron weak decays:

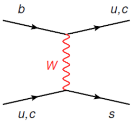
- A typical multi-scale problem and scales are highly hierarchical;

EW interaction scale	$\gg$	ext. mom'a in B rest frame	$\gg$	QCD-bound state effects
$m_W \sim 80.4\ \mathrm{GeV}$	$\gg$	$m_b \sim 4.8\ \mathrm{GeV}$	$\gg$	$\Lambda_{\mathrm{QCD}} \sim 1\ \mathrm{GeV}$

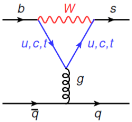
- Starting point $\mathcal{L}_{\mathrm{eff}}$: integrate out heavy d.o.f. ($m_{W,Z,t} \gg m_b$), physics above (below) $\mu \sim m_b$ contained in C_i ($\langle \mathcal{O}_i \rangle$); [*A. J. Buras, 1102.5650*]

$$\mathcal{L}_{\mathrm{eff}} \sim G_F\, V_{\mathrm{CKM}} \times \Big[\sum_{p=u,c} \sum_{i=1,2} C_i\, \mathcal{O}_i^p + \sum_{3,\dots,6} C_i\, \mathcal{O}_i + \sum_{7,\dots,10} C_i\, \mathcal{O}_i + \sum_{7\gamma,8g} C_i\, \mathcal{O}_i \Big]$$

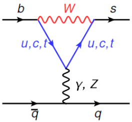
charged current

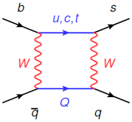


QCD-penguin

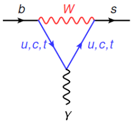


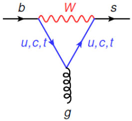
EW-penguin





electro- & chromo-mgn





- C_i: RG-improved pert. calculable;
  matching at μ_0 and running to μ_b;
  NNLL accuracy available!

Hadronic matrix elements for B-hadron weak decays:

- How to evaluate $\langle f|\mathcal{O}_i|B\rangle$: $\langle 0|\mathcal{O}_i|B\rangle$, $\langle \pi|\mathcal{O}_i|B\rangle$, $\langle \pi\pi|\mathcal{O}_i|B\rangle$, $\langle \bar{B}|\mathcal{O}_i|B\rangle$, $\cdots$;

Quark-hadron duality,
Heavy-quark mass expansion,
HQE, OPE,
…

Effective theories,
Factorization,
Approximate symmetries
Lattice QCD, LCSR, …

Inclusive decays

$B \to X_s\gamma, B \to X_s\ell^+\ell^-$

$B \to X_u\ell\nu, B \to X_c\ell\nu$

Exclusive decays

$B_s \to \mu^+\mu^- \quad \to \quad \langle 0|\mathcal{O}|B_s\rangle$

$B-\overline{B}$ mixing $\to \quad \langle B|\mathcal{O}|\overline{B}\rangle$

$B \to \pi l\nu \quad \to \quad \langle \pi|\mathcal{O}|B\rangle$

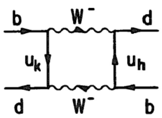
$B \to \pi\pi \quad \to \quad \langle \pi\pi|\mathcal{O}|B\rangle$

Increasingly difficult

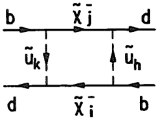
- $\langle M_1 M_2|\mathcal{O}_i|B\rangle$: not yet possible in lattice QCD; expressed in terms of (few) universal non-pert. hadronic quantities with pert. calculable coefficients;
  - dynamical approaches based on factorization theorems: PQCD, QCDF, SCET, $\cdots$; [Keum, Li, Sanda, Lü, Yang '00; Beneke, Buchalla, Neubert, Sachrajda, '00; Bauer, Flemming, Pirjol, Stewart, '01]
  - (approximate) symmetries of QCD: Isospin, U-Spin, V-Spin, and flavor SU(3) symmetries, $\cdots$; [Zeppenfeld, '81; London, Gronau, Rosner, Chiang, Cheng *et al.*]

$B - \bar{B}$ mixings:

- **Motivation**: strongly suppressed in SM; highly sensitive to BSM effects;



SM: $\frac{C_{\rm SM}}{m_W^2}$



NP: $\frac{C_{\rm NP}}{\Lambda^2}$

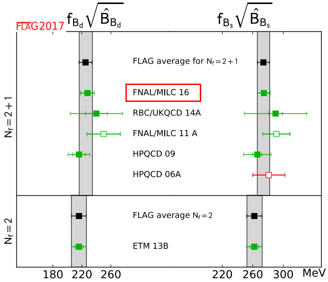
General parametrization:

$$M_{12} = M_{12}^{\rm SM} \times (1 + h\, e^{2i\sigma})$$

NP parameters

$\hookrightarrow$ $\Lambda \geq 10^3\ {\rm TeV}$

- $\Delta M_{s,d} \doteq 2|M_{12}^{s,d}|$: calculated from box diagrams with internal virtual particles; main uncertainty from Bag parameters $\langle B_q|\mathcal{O}_i|\bar{B}_q\rangle \propto f_{B_q}^2 B_{B_q}^{(i)}$;



$$\Delta M_d^{\rm SM} = (0.53^{+0.03}_{-0.04})\ \text{ps}^{-1}$$

$$\Delta M_d^{\rm HFAG} = (0.5065 \pm 0.0019)\ \text{ps}^{-1}$$

$$\Delta M_s^{\rm SM} = (18.1^{+1.1}_{-1.2})\ \text{ps}^{-1}$$

$$\Delta M_s^{\rm HFAG} = (17.757 \pm 0.021)\ \text{ps}^{-1}$$

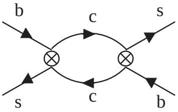
[Kirk, Lenz and Rauh, 1711.02100; T. Rauh, talk given at CKM2018]

$B - \bar{B}$ mixings:

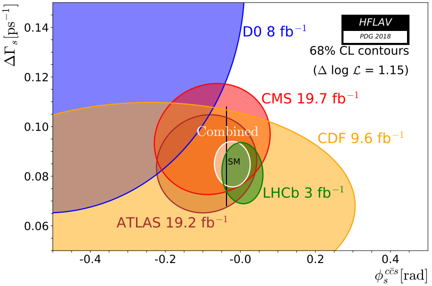
- $\Delta\Gamma_{s,d} \doteq 2|\Gamma_{12}^{s,d}| \cos\phi_{12}^{s,d}$: arise from absorptive part of box diagrams, dominated by tree-level $b \to c\bar{c}s(d)$ transitions; [Artuso/Borissov/Lenz, 1511.09466]

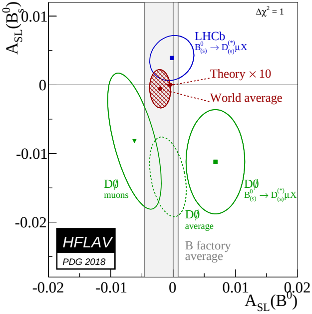
$$\Gamma_{12}^{s} = \frac{\Lambda^3}{m_b^3}\left[\Gamma_3^{s,(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{s,(1)} + \left(\frac{\alpha_s}{4\pi}\right)^2 \Gamma_3^{s,(2)} + \ldots\right]$$

$$+ \frac{\Lambda^4}{m_b^4}\left(\Gamma_4^{s,(0)} + \ldots\right) + \ldots$$ [H. M. Asatrian *et al*, 1709.02160]



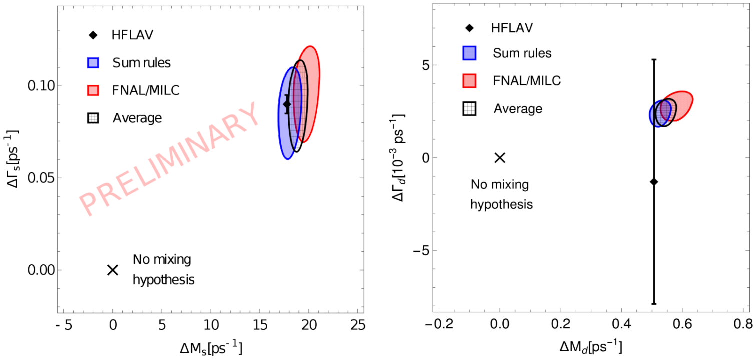
- $a_{\rm fs}^{s,d} \doteq \left|\frac{\Gamma_{12}^{s,d}}{M_{12}^{s,d}}\right| \sin\phi_{12}^{s,d}$: motivated by 2013 D0 dimuon charge asymmetry!





$B - \bar{B}$ mixing:

- $\Delta M_{s,d}$ vs $\Delta\Gamma_{s,d}$: state-of-the-art comparison; [Kirk, Lenz and Rauh, 1711.02100; T. Rauh, talk given at CKM2018]



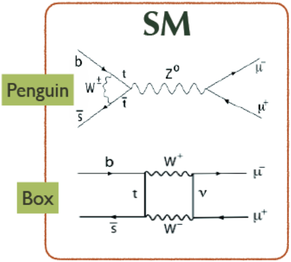
- SM predictions and exp. averages consistent with each other!

$\hookrightarrow$ Large NP effect in $B_{s,d}$ mixings now closed!

$B_{s,d} \to \mu^+\mu^-$:

- **Facts about $B_{s,d} \to \mu^+\mu^-$:** highly suppressed within the SM;
  - helicity suppressed, by a factor of $(m_\mu/m_B)^2$;
  - FCNC process, forbidden at tree-level, proceed only via loop diagrams;
  - CKM suppressed by $|V_{tb}V_{ts}^*|^2$;

  $\hookrightarrow$ very sensitive to NP, especially from $\mathcal{O}_{S(P)}$;



- **Theory status:** C_A now to NNLO QCD + NLO EW; enhanced EM correction included; [Bobeth *et al., 1311.0903; Beneke, Bobeth and Szafron, 1708.09152*]

$$\mathcal{H}_{\rm eff} = -\frac{G_F\,\alpha}{\sqrt{2}\pi s_W^2}\left[V_{tb}V_{tq}^* \sum_i^{A,S,P} \left(C_i\,\mathcal{O}_i + C_i'\,\mathcal{O}_i'\right) + \text{h.c.}\right]$$

$$\mathcal{O}_A = (\bar{q}\gamma_\mu P_L b)\,(\bar{\ell}\gamma^\mu\gamma_5\ell)\,, \quad \mathcal{O}_{S(P)} = m_b(\bar{q}P_R b)\,[\bar{\ell}(\gamma_5)\ell]$$

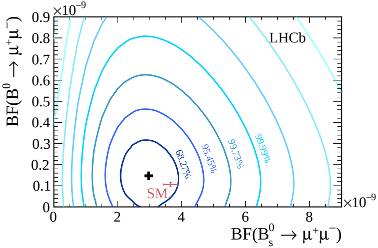
$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = (3.57 \pm 0.17) \times 10^{-9}$, $\overline{\mathcal{B}}(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

$B_{s,d} \to \mu^+\mu^-$:

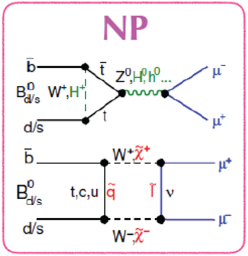
- CMS + LHCb and LHCb updated results: [1411.4413, 1703.05747]

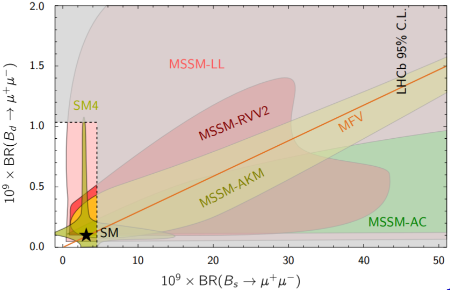
$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \cdot 10^{-9}$ (7.8σ);

$\overline{\mathcal{B}}(B_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10}$ (3.0σ);



- Powerful in model killing: good consistency between SM and exp. data; [D. Straub, 1205.6094]





$B_{s,d} \to \mu^+\mu^-$:

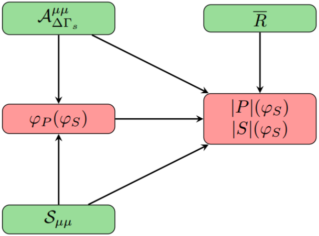
- Time-dependent observables: due to sizeable $\Delta\Gamma_s$; [De Bruyn *et al.*, 1204.1737; Fleischer *et al.*, 1703.10160; 1709.04735]

$$\mathcal{C}^{\lambda}_{\mu\mu} \equiv \frac{1-|\xi_\lambda|^2}{1+|\xi_\lambda|^2} = -\eta_\lambda \left[\frac{2|PS|\cos(\varphi_P-\varphi_S)}{|P|^2+|S|^2}\right] \equiv -\eta_\lambda \mathcal{C}_{\mu\mu}$$

$$\mathcal{S}^{\lambda}_{\mu\mu} \equiv \frac{2\,\Im(\xi_\lambda)}{1+|\xi_\lambda|^2} = \frac{|P|^2\sin(2\varphi_P-\phi_s^{\rm NP})-|S|^2\sin(2\varphi_S-\phi_s^{\rm NP})}{|P|^2+|S|^2} \equiv \mathcal{S}_{\mu\mu}$$

$$\mathcal{A}^{\mu\mu,\lambda}_{\Delta\Gamma_s} \equiv \frac{2\,\Re(\xi_\lambda)}{1+|\xi_\lambda|^2} = \frac{|P_{\mu\mu}|^2\cos(2\varphi_P^{\mu\mu}-\phi_s^{\rm NP})-|S_{\mu\mu}|^2\cos(2\varphi_S^{\mu\mu}-\phi_s^{\rm NP})}{|P_{\mu\mu}|^2+|S_{\mu\mu}|^2}$$

- With the updated LHC: these observables provide new d.o.f. for NP searches; [Fleischer, Jaarsma, Tetlalmatzi-Xolocotzi, 1703.10160; 1709.04735]



$$P_{\ell\ell} \equiv \frac{C_{10}^{\ell\ell}-C_{10}^{\ell\ell'}}{C_{10}^{\rm SM}} + \frac{M_{B_s}^2}{2\,m_\ell}\left(\frac{m_b}{m_b+m_s}\right)\left[\frac{C_P^{\ell\ell}-C_P^{\ell\ell'}}{C_{10}^{\rm SM}}\right]$$

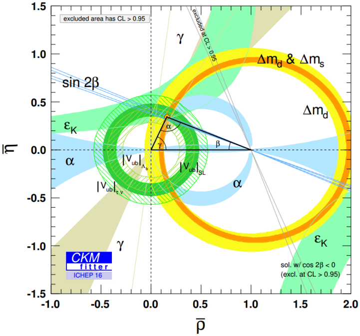
$$S_{\ell\ell} \equiv \sqrt{1-4\frac{m_\ell^2}{M_{B_s}^2}}\,\frac{M_{B_s}^2}{2\,m_\ell}\left(\frac{m_b}{m_b+m_s}\right)\left[\frac{C_S^{\ell\ell}-C_S^{\ell\ell'}}{C_{10}^{\rm SM}}\right]$$

$|V_{ub}|$ and $|V_{cb}|$ problem:

- Importance of $|V_{xb}|$: play a key role in determining the apex of UT;

  - $|V_{ub}|$ or $|V_{ub}/V_{cb}|$ constraints drectly the UT;
  - $b \to s$ induced FCNC processes $\propto |V_{tb}V_{ts}^*|^2 \simeq |V_{cb}|^2 \left[1 + \mathcal{O}(\lambda^2)\right]$;
  - $\epsilon_K \simeq x|V_{cb}|^2 + \cdots$;

  $\hookrightarrow$ More precise determination of $|V_{xb}|$ is of utmost importance!

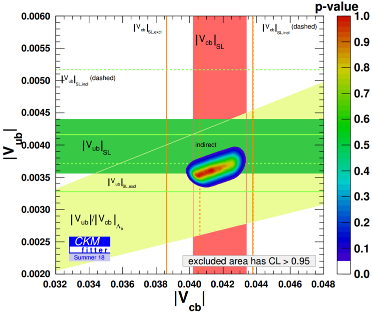


- Incl. vs excl. methods: [Nandi, Gambino, Tackmann, talks at CKM 2016]

  - Inclusive $|V_{cb}|$: OPE/HQE, dominated by theory uncertainties, especially by correlations of theoretical parameters;
  - Inclusive $|V_{ub}|$: OPE/HQE, limited knowledge of leading and subleading SFs;
  - Exclusive $|V_{xb}|$: how precise can the form factors be calculated by LQCD or LCSR;

$|V_{ub}|$ and $|V_{cb}|$ problem:

- Status of global fit for $|V_{xb}|$: [Gambino, Silva, Bona, talks at CKM2018]



- Results for CKM2018: [Silva, Bona, talks at CKM2018]

$$|V_{cb}|_{\text{incl.}} = (42.2 \pm 0.4 \pm 0.6) \cdot 10^{-3}, \qquad |V_{ub}|_{\text{incl.}} = (4.44 \pm 0.17 \pm 0.31) \cdot 10^{-3}$$

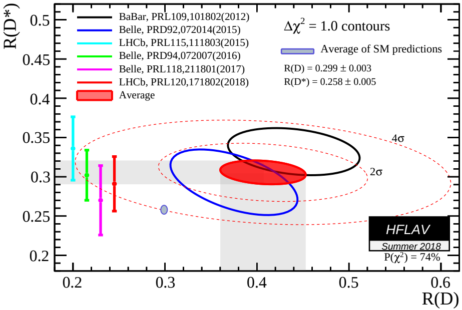
$$|V_{cb}|_{\text{excl.}} = (41.2 \pm 0.6 \pm 0.9 \pm 0.2) \cdot 10^{-3}, \qquad |V_{ub}|_{\text{excl.}} = (3.72 \pm 0.09 \pm 0.22) \cdot 10^{-3}$$

$\hookrightarrow$ $|V_{xb}|$ tension significantly reduced, especially for $|V_{cb}|$!

$\hookrightarrow$ global fit favours $|V_{ub}|_{\text{excl.}}$ & $|V_{cb}|_{\text{incl.}}$!

$R(D)$ and $R(D^*)$ anomalies:

- $B \to D^{(*)}\tau\bar{\nu}$ **decays**: tree-level processes;massive τ makes them sensitive to tree-level NP like RH currents, charged Higgs, leptoquarks, $\cdots$;
- **Current status**: $R(D^{(*)}) = \frac{\mathrm{Br}(B\to D^{(*)}\tau\nu_\tau)}{\mathrm{Br}(B\to D^{(*)}\ell\nu_\ell)}$; [BaBar, 1205.5442, 1303.0571; Belle, 1507.03233, 1607.07923, 1612.00529; LHCb, 1506.08614, 1708.08856]



▷ $R(D)_{\mathrm{SM}} = 0.299 \pm 0.003$ 2.3σ

$[0.407 \pm 0.039 \pm 0.024]$

▷ $R(D^*)_{\mathrm{SM}} = 0.258 \pm 0.005$ 3.0σ

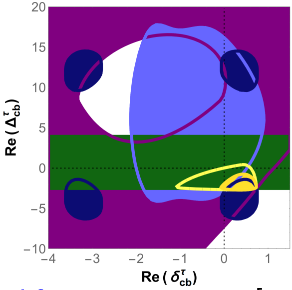
$[0.306 \pm 0.013 \pm 0.007]$

$\hookrightarrow$ combined $\sim 3.78\sigma$ deviation!

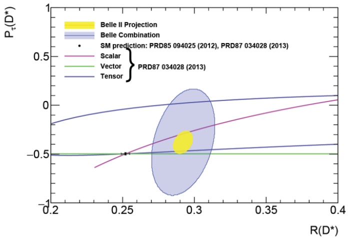
- **Theo.**: more precise lattice calculations for $B \to D^{(*)}$ FFs at non-zero recoil!
- **Exp.**: $A_\lambda^{D^{(*)}}$, $R_L^{D^*}$, $\Lambda_b \to \Lambda_c\tau\bar{\nu}$, $B_s \to D_s^{(*)}\tau\bar{\nu}$, $B_c \to J/\Psi(\eta_c)\tau\bar{\nu}$, $B \to X_c\tau\bar{\nu}$;

$R(D)$ and $R(D^*)$ anomalies:

- Importance of other observables: [Celis, Jung, Li, Pich, 1612.07757]



$$\delta^\ell_{cb} \equiv \frac{(g_L^{cb\ell} + g_R^{cb\ell})(m_B - m_D)^2}{m_\ell\,(\bar m_b - \bar m_c)}, \quad \Delta^\ell_{cb} \equiv \frac{(g_L^{cb\ell} - g_R^{cb\ell})m_B^2}{m_\ell\,(\bar m_b + \bar m_c)},$$



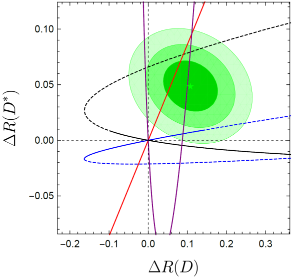
- B_c-lifetime constraint: [Li/Yang/Zhang, 1605.09308; Hu/Li/Yang, 1810.04939]

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda^2}\sum_i C_i(\Lambda) Q_i,$$

$$Q_{lq}^{(3)} = (\bar l \gamma_\mu \tau^I l)(\bar q \gamma^\mu \tau^I q), \quad Q_{lequ}^{(1)} = (\bar l^j e)\varepsilon_{jk}(\bar q^k u)$$

$$Q_{ledq} = (\bar l^j e)(\bar d q^j), \quad Q_{lequ}^{(3)} = (\bar l^j \sigma_{\mu\nu} e)\varepsilon_{jk}(\bar q^k \sigma^{\mu\nu} u)$$

$\hookrightarrow$ $V - A$ and/or tensor Lorentz structure needed!



$R(D)$ and $R(D^*)$ anomalies:

- The observed tension is model independent: exclusive already over-saturates inclusive; [M. Freytsis, Z. Ligeti, J. Ruderman, 1506.08896]
  - The data on $R(D)$ and $R(D^*)$ imply:

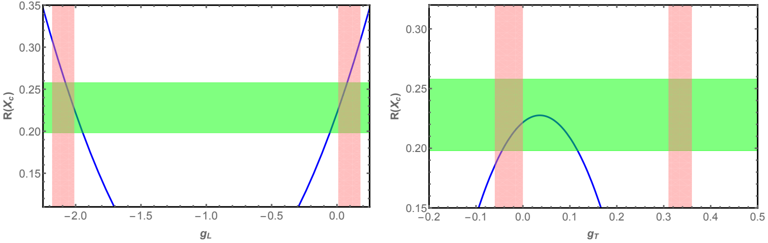
$$\mathrm{Br}(\bar{B} \to D^* \tau \bar{\nu}) + \mathrm{Br}(\bar{B} \to D \tau \bar{\nu}) = (2.78 \pm 0.25)\%$$

  - Including the four lightest orbitally excited D meson states:

$$\mathrm{Br}(\bar{B} \to D^{(*)} \tau \bar{\nu}) + \mathrm{Br}(\bar{B} \to D^{**} \tau \bar{\nu}) \sim 3\%$$

  - From inclusive=$\sum$exclusive: $\mathrm{Br}(b \to X_c \tau \bar{\nu}) = (2.35 \pm 0.23)\%$ (LEP)

- $R(X_c)$ constraint: [Kamali/Rashed/Datta,1801.08259; Lai/Li/Li/Yang, w.i.p.]

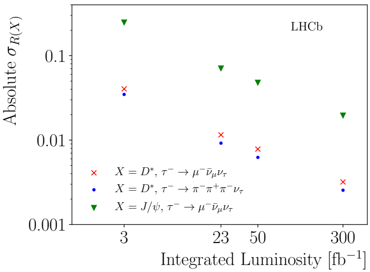


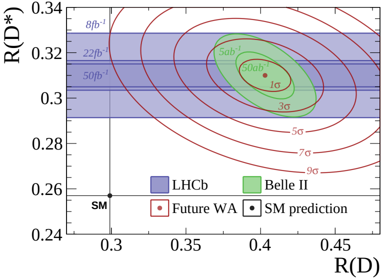
$R(D)$ and $R(D^*)$ anomalies:

- Another hint of LFUV: around 1.7σ above SM; [LHCb, 1711.05623; Cohen/Lamm/Lebed, 1807.02730; Wang/Zhu, 1808.10830]

$$R(J/\psi) = \frac{\mathrm{Br}(B_c \to J/\psi \tau \nu_\tau)}{\mathrm{Br}(B_c \to J/\psi \ell \nu_\ell)} = 0.71 \pm 0.17 \pm 0.18 \quad \text{vs} \quad 0.20 \sim 0.39 \text{ (theo.)}$$

- Future prospects with Belle-II and LHCb very promising! [Albrecht *et al., 1709.10308; I. Bediaga et al., 1808.08865*]



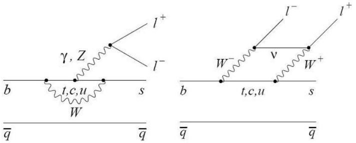


- Maybe the first tantalizing hint for BSM? Let's stay tuned!

Exclusive $b \to s\ell^+\ell^-$ decays:

- $\mathcal{H}_{\rm eff}$ for $b \to s\ell^+\ell^-$: [Bobeth, Gambino, Gorbahn, Haisch, hep-ph/0312090]

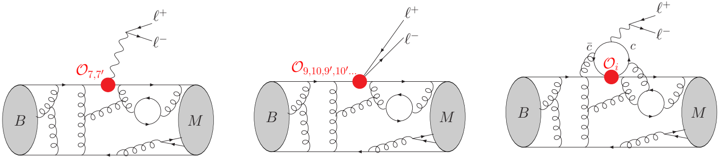
$$\mathcal{H}_{\rm eff}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \left(C_i O_i + C_i' \mathcal{O}_i'\right), \quad \mathcal{O}_7^{(\prime)} = \frac{e}{16\pi^2} \bar{m}_b \left(\bar{s}\sigma^{\mu\nu} P_{R(L)} b\right) F_{\mu\nu}$$



$$\mathcal{O}_9^{(\prime)} = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma^\mu P_{L(R)} b\right)\left(\bar{\ell}\gamma_\mu \ell\right)$$

$$\mathcal{O}_{10}^{(\prime)} = \frac{e^2}{16\pi^2} \left(\bar{s}\gamma^\mu P_{L(R)} b\right)\left(\bar{\ell}\gamma_\mu \gamma_5 \ell\right)$$

- Amplitudes for exclusive decays: [Descotes-Genon, talk at FPCP 2016; Bobeth, Chrzaszcz, Dyk, and Virto, arXiv:1707.07305]



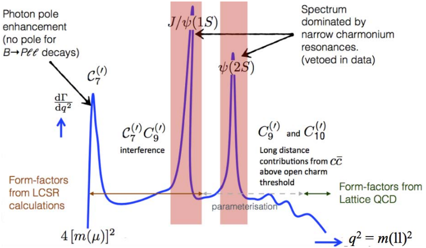
$$\mathcal{A}_\lambda^{(\ell)\,L,R} = \mathcal{N}_\lambda^{(\ell)} \left\{ (C_9^{(\ell)} \mp C_{10}^{(\ell)}) \mathcal{F}_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[C_7^{(\ell)} \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

Exclusive $b \to s\ell^+\ell^-$ decays:

- Hadronic matrix elements of $\mathcal{O}_i$: [Beneke/Feldmann/Seidel, 0106067, 0412400; Grinstein/Pirjol, hep-ph/0404250; Beylich/Buchalla/Feldmann, 1101.5118]

† Large recoil (low-q^2)

- very low-q^2 ($\lesssim 1\ \mathrm{GeV}^2$) dominated by $\mathcal{O}_7$;
- low-q^2 ($[1,6]\ \mathrm{GeV}^2$) dominated by $\mathcal{O}_{9,10}$;
- QCDF or SCET, LCSR;



† Small recoil (high-q^2) - dominated by $\mathcal{O}_{9,10}$; - local OPE + HQET;

- Key issues: how large of power corrs from $b \to sc\bar{c} \to s\ell^+\ell^-$ for $q^2 \le 6\ \mathrm{GeV}^2$ and from fact. FF terms? [Descotes-Genon *et al., 1510.04239*]

$$h_\lambda(q^2) = \frac{\epsilon_\mu^*(\lambda)}{m_B^2}\int d^4x\, e^{iq\cdot x}\left\langle K_\lambda^{(*)}\right|\mathrm{T}\left\{j_\mu^{\mathrm{em}}(x), \sum_i C_i\mathcal{O}_i(0)\right\}\left|B(p)\right\rangle$$

$$\approx \underbrace{[\text{LO in } 1/m_b]}_{\text{QCDF}} + h_\lambda^{(0)} + \frac{q^2}{1\mathrm{GeV}^2}h_\lambda^{(1)} + \frac{q^4}{1\mathrm{GeV}^4}h_\lambda^{(2)}, \qquad h_\lambda^{(0,1,2)} \in \mathbb{C}$$

$$F(q^2) = F^{\mathrm{soft}}(\xi_{\perp,\parallel}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F\frac{q^2}{m_B^2} + \ldots$$

Exclusive $b \to s\ell^+\ell^-$ decays:

- Parametrisation of $\mathcal{H}_\lambda(q^2)$: [Khodjamirian *et al., 1006.4945; Bobeth et al., 1707.07305;*]

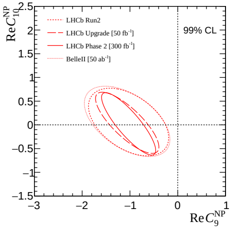
$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

$$\mathcal{H}_\lambda(z) = \frac{1 - z\, z_{J/\psi}^*}{z - z_{J/\psi}} \frac{1 - z\, z_{\psi(2S)}^*}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z), \quad \hat{\mathcal{H}}_\lambda(z) = \left[\sum_{k=0}^{K} \alpha_k^{(\lambda)} z^k \right] \mathcal{F}_\lambda(z)$$

$$z(q^2) \equiv \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

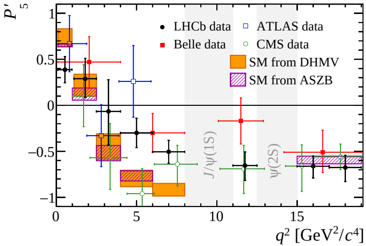
- Based on analyticity + data and valid for $-7 \leq q^2 \leq m_{\psi(2S)}^2$: [Bobeth *et al., 1707.07305; Chrzaszcz et al., 1805.06378; Mauri et al., 1805.06401*]

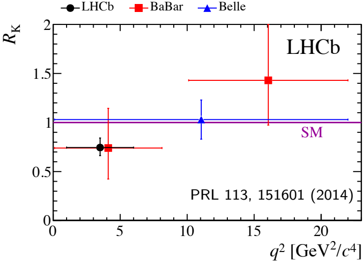
k	0	1	2
$\mathrm{Re}[\alpha_k^{(\perp)}]$	-0.06 ± 0.21	-6.77 ± 0.27	18.96 ± 0.59
$\mathrm{Re}[\alpha_k^{(\parallel)}]$	-0.35 ± 0.62	-3.13 ± 0.41	12.20 ± 1.34
$\mathrm{Re}[\alpha_k^{(0)}]$	0.05 ± 1.52	17.26 ± 1.64	–
$\mathrm{Im}[\alpha_k^{(\perp)}]$	-0.21 ± 2.25	1.17 ± 3.58	-0.08 ± 2.24
$\mathrm{Im}[\alpha_k^{(\parallel)}]$	-0.04 ± 3.67	-2.14 ± 2.46	6.03 ± 2.50
$\mathrm{Im}[\alpha_k^{(0)}]$	-0.05 ± 4.99	4.29 ± 3.14	–

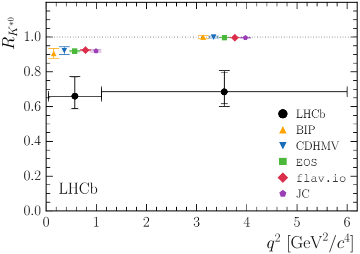


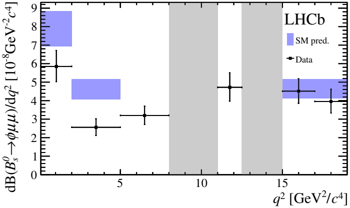
Exclusive $b \to s\ell^+\ell^-$ decays:

- Observed anomalies: [Dettori, Langenbruch, talks at Moriond 2018]









- Comments: 1, P'_5 stat. fluctuation unlikely; 2, precise evaluation of QED effect in $R_K^{(*)}$ very necessary; 3, cross-checks about hadronic nuisance parameters needed;

Exclusive $b \to s\ell^+\ell^-$ decays:

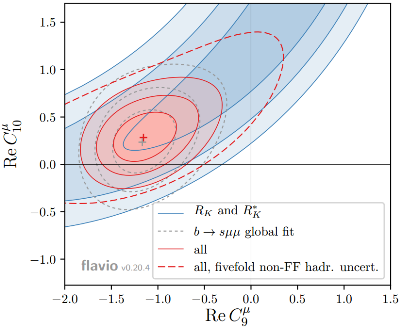
- Global fits to $b \to s\ell^+\ell^-$ data: [Danny van Dyk, talk at CKM2018]

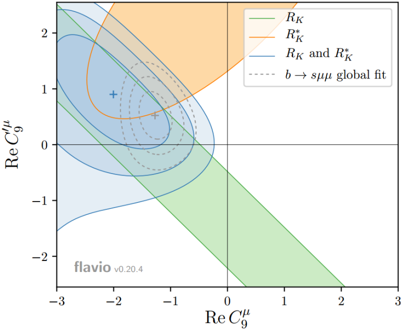
who	approach	data set	references
		global fits	
AS+	QCDF+	$b \to s\mu\mu$ / LFU	Altmannshofer, Straub et al. [1703.09189] [1704.05435]
CJ+	QCDF++	$b \to s\mu\mu$ + LFU	Camalich, Jäger et al. [1412.3183] [1704.05446]
DGMV+	QCDF+	$b \to s\mu\mu$ + LFU	Descotes-Genon, Matias, Virto et al. [1510.04329] [1704.05340]
HM+	QCDF++	$b \to s\mu\mu$ + LFU	Hurth, Mahmoudi et al. [1603.00865] [1806.02791]
Rome	QCDF++	$b \to s\mu\mu$ + LFU	Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli [1704.05447]
		fits to $B \to K^*\mu\mu$ only	
BCvDV	z-param	$B \to K^*\mu\mu$ (LHCb)	Bobeth, Chrzaszcz, DvD, Virto

- Conclusion: while different in the treatment of local and non-local hadronic contributions, all groups agree on a negative shift to C_9 by $-1.1 \ldots -1.76 \simeq -25 \ldots 40\%$ of the SM value, although other contributions are also possible.

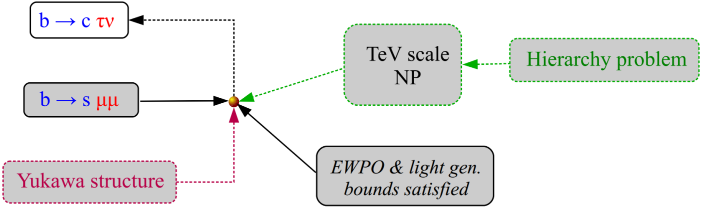
Exclusive $b \to s\ell^+\ell^-$ decays:

- New global fits: [Capdevila *et al., 1704.05340; D. Straub, talk at CKM2018*]





- New directions for model builders: [G. Isodro, talk at CKM2018]



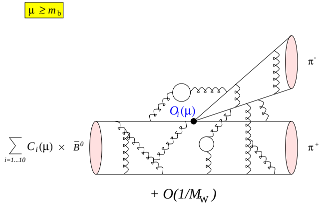
Non-leptonic B decays:

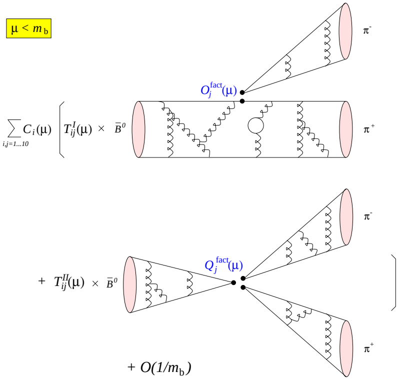
- To leading power in the heavy-quark expansion, $\langle M_1 M_2 | \mathcal{O}_i | \bar{B} \rangle$ obeys the following factorization formula: [*Beneke, Buchalla, Neubert, Sachrajda, '99-'04*]

$$\langle M_1 M_2 | \mathcal{O}_i | \bar{B} \rangle \simeq m_B^2 \, F_+^{BM_1}(0) \, f_{M_2} \int du \; T_i^I(u) \, \phi_{M_2}(u) + (M_1 \leftrightarrow M_2)$$

$$+ f_B \, f_{M_1} \, f_{M_2} \int d\omega dv du \; T_i^{II}(\omega, v, u) \, \phi_B(\omega) \, \phi_{M_1}(v) \, \phi_{M_2}(u)$$

$$+ \mathcal{O}(1/m_b)$$





- Systematic framework to all orders in α_s, but limited accuracy by $1/m_b$ corrs.

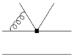
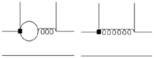
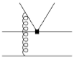
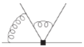
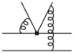
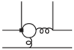
Non-leptonic B decays:

- Status of the hard kernels $T^{I,II}$: [*Bell/Beneke/Huber/Li, from '09*]

Two hard-scattering kernels for each operator insertion: T^I (vertex), T^{II} (spectator)

$$\langle M_1 M_2 | \mathcal{O}_i | B \rangle \simeq F^{BM_1} T_i^I \otimes \phi_{M_2} + T_i^{II} \otimes \phi_B \otimes \phi_{M_1} \otimes \phi_{M_2}$$

and two classes of topological amplitudes: "Tree", "Penguin".

	T^I, tree	T^I, penguin	T^{II}, tree	T^{II}, penguin
LO: $\mathcal{O}(1)$				
NLO: $\mathcal{O}(\alpha_s)$ BBNS '99-'04				
NNLO: $\mathcal{O}(\alpha_s^2)$	 Bell '07,'09 Beneke, Huber, Li '09	 Kim, Yoon '11, Bell Beneke, Huber, Li '15	 Beneke, Jager '05 Kivel '06, Pilipp '07	 Beneke, Jager '06 Jain, Rothstein, Stewart '07

- Missing NNLO pieces: 2-loop tree with insertion of penguin operators Q_{3-6}; 2-loop penguin with insertion of penguin operators Q_{3-6}; work in progress!

Non-leptonic B decays:

- How to deal with power corrections of order $\mathcal{O}(1/m_b)$;

  Main limitation of QCDF approach, e.g. weak annihilation

  $$\sim \int d\omega\, du\, dv\; T(\omega, u, v)\; \phi_B(\omega)\; \phi_{M_1}(v)\; \phi_{M_2}(u) \quad ?$$

  - convolutions diverge at endpoints $\Rightarrow$ non-factorisation in SCET-2
  - currently modelled with arbitrary soft rescattering phase

  Pure annihilation decays

  HFAG averages including LHCb Collaboration, (R. Aaij etal), LHCB-PAPER-2016-036

  0.084+/-0.024

  $10^6\,\mathrm{Br}(B_d \to K^+K^-) = 0.13 \pm 0.05$ ($\Delta D = 1$, exchange topology)

  0.671+/-0.083

  $10^6\,\mathrm{Br}(B_s \to \pi^+\pi^-) = 0.76 \pm 0.13$ ($\Delta S = 1$, penguin annihilation)

  $\Rightarrow$ extract weak annihilation amplitudes from data [Wang, Zhu 13; Bobeth, Gorbahn, Vickers 14; Chang, Sun, Yang, Li 14]

- New insights from collider-physics applications like collinear anomaly/rapidity divergence? [*Becher/Neubert '10; Becher/Bell '11; Chiu/Jain/Neill/Rothstein '12*]

  $\hookrightarrow$ our next task: how to evaluate the power corrections?

Non-leptonic B decays:

- Tree-dominated decays: Brs $[\times 10^{-6}]$ [Beneke, Huber, Li '09]

	Theory I	Theory II	Experiment
$B^- \to \pi^- \pi^0$	$5.43^{+0.06}_{-0.06}{}^{+1.45}_{-0.84}$ $(\star)$	$5.82^{+0.07}_{-0.06}{}^{+1.42}_{-1.35}$ $(\star)$	$5.59^{+0.41}_{-0.40}$
$\bar{B}^0_d \to \pi^+ \pi^-$	$7.37^{+0.86}_{-0.69}{}^{+1.22}_{-0.97}$ $(\star)$	$5.70^{+0.70}_{-0.55}{}^{+1.16}_{-0.97}$ $(\star)$	5.16 ± 0.22
$\bar{B}^0_d \to \pi^0 \pi^0$	$0.33^{+0.11}_{-0.08}{}^{+0.42}_{-0.17}$	$0.63^{+0.12}_{-0.10}{}^{+0.64}_{-0.42}$	1.55 ± 0.19
		BELLE CKM 14:	0.90 ± 0.16
$B^- \to \pi^- \rho^0$	$8.68^{+0.42}_{-0.41}{}^{+2.71}_{-1.56}$ $(\star\star)$	$9.84^{+0.41}_{-0.40}{}^{+2.54}_{-2.52}$ $(\star\star)$	$8.3^{+1.2}_{-1.3}$
$B^- \to \pi^0 \rho^-$	$12.38^{+0.90}_{-0.77}{}^{+2.18}_{-1.41}$ $(\star)$	$12.13^{+0.85}_{-0.73}{}^{+2.23}_{-2.17}$ $(\star)$	$10.9^{+1.4}_{-1.5}$
$\bar{B}^0 \to \pi^+ \rho^-$	$17.80^{+0.62}_{-0.56}{}^{+1.76}_{-2.10}$ $(\star)$	$13.76^{+0.49}_{-0.44}{}^{+1.77}_{-2.18}$ $(\star)$	15.7 ± 1.8
$\bar{B}^0 \to \pi^- \rho^+$	$10.28^{+0.39}_{-0.39}{}^{+1.37}_{-1.42}$ $(\star\star)$	$8.14^{+0.34}_{-0.33}{}^{+1.35}_{-1.49}$ $(\star\star)$	7.3 ± 1.2
$\bar{B}^0 \to \pi^\pm \rho^\mp$	$28.08^{+0.27}_{-0.19}{}^{+3.82}_{-3.50}$ $(\dagger)$	$21.90^{+0.20}_{-0.12}{}^{+3.06}_{-3.55}$ $(\dagger)$	23.0 ± 2.3
$\bar{B}^0 \to \pi^0 \rho^0$	$0.52^{+0.04}_{-0.03}{}^{+1.11}_{-0.43}$	$1.49^{+0.07}_{-0.07}{}^{+1.77}_{-1.29}$	2.0 ± 0.5
$B^- \to \rho_L^- \rho_L^0$	$18.42^{+0.23}_{-0.21}{}^{+3.92}_{-2.55}$ $(\star\star)$	$19.06^{+0.24}_{-0.22}{}^{+4.59}_{-4.22}$ $(\star\star)$	$22.8^{+1.8}_{-1.9}$
$\bar{B}^0_d \to \rho_L^+ \rho_L^-$	$25.98^{+0.85}_{-0.77}{}^{+2.93}_{-3.43}$ $(\star\star)$	$20.66^{+0.68}_{-0.62}{}^{+2.99}_{-3.75}$ $(\star\star)$	$23.7^{+3.1}_{-3.2}$
$\bar{B}^0_d \to \rho_L^0 \rho_L^0$	$0.39^{+0.03}_{-0.03}{}^{+0.83}_{-0.36}$	$1.05^{+0.05}_{-0.04}{}^{+1.62}_{-1.04}$	$0.55^{+0.22}_{-0.24}$

Theory I: $f_+^{B\pi}(0) = 0.25 \pm 0.05,\ A_0^{B\rho}(0) = 0.30 \pm 0.05,\ \lambda_B(1\,\text{GeV}) = 0.35 \pm 0.15\,\text{GeV}$

Theory II: $f_+^{B\pi}(0) = 0.23 \pm 0.03,\ A_0^{B\rho}(0) = 0.28 \pm 0.03,\ \lambda_B(1\,\text{GeV}) = 0.20^{+0.05}_{-0.00}\,\text{GeV}$

- Theory II: small λ_B and form-factor hypothesis are more favoured;
- Colour-allowed modes well described, but colour-suppressed modes less;

Non-leptonic B decays:

- Penguin-dominated decays: A_{CP} $[\times 10^{-2}]$ [*Bell, Beneke, Huber, Li '15*]

f	NLO	NNLO	NNLO + LD	Exp
$\pi^- \bar{K}^0$	$0.71\,^{+0.13}_{-0.14}\,^{+0.21}_{-0.19}$	$0.77\,^{+0.14}_{-0.15}\,^{+0.23}_{-0.22}$	$0.10\,^{+0.02}_{-0.02}\,^{+1.24}_{-0.27}$	-1.7 ± 1.6
$\pi^0 K^-$	$9.42\,^{+1.77}_{-1.76}\,^{+1.87}_{-1.88}$	$10.18\,^{+1.91}_{-1.90}\,^{+2.03}_{-2.62}$	$-1.17\,^{+0.22}_{-0.22}\,^{+20.00}_{-\ 6.62}$	4.0 ± 2.1
$\pi^+ K^-$	$7.25\,^{+1.36}_{-1.36}\,^{+2.13}_{-2.58}$	$8.08\,^{+1.52}_{-1.51}\,^{+2.52}_{-2.65}$	$-3.23\,^{+0.61}_{-0.61}\,^{+19.17}_{-\ 3.36}$	-8.2 ± 0.6
$\pi^0 \bar{K}^0$	$-4.27\,^{+0.83}_{-0.77}\,^{+1.48}_{-2.23}$	$-4.33\,^{+0.84}_{-0.78}\,^{+3.29}_{-2.32}$	$-1.41\,^{+0.27}_{-0.25}\,^{+5.54}_{-6.10}$	1 ± 10
$\delta(\pi\bar{K})$	$2.17\,^{+0.40}_{-0.40}\,^{+1.39}_{-0.74}$	$2.10\,^{+0.39}_{-0.39}\,^{+1.40}_{-2.86}$	$2.07\,^{+0.39}_{-0.39}\,^{+2.76}_{-4.55}$	12.2 ± 2.2
$\Delta(\pi\bar{K})$	$-1.15\,^{+0.21}_{-0.22}\,^{+0.55}_{-0.84}$	$-0.88\,^{+0.16}_{-0.17}\,^{+1.31}_{-0.91}$	$-0.48\,^{+0.09}_{-0.09}\,^{+1.09}_{-1.15}$	-14 ± 11

$$\delta(\pi\bar{K}) = A_{\rm CP}(\pi^0 K^-) - A_{\rm CP}(\pi^+ K^-)$$

$$\Delta(\pi\bar{K}) = A_{\rm CP}(\pi^+ K^-) + \frac{\Gamma_{\pi^-\bar{K}^0}}{\Gamma_{\pi^+K^-}} A_{\rm CP}(\pi^-\bar{K}^0) - \frac{2\Gamma_{\pi^0K^-}}{\Gamma_{\pi^+K^-}} A_{\rm CP}(\pi^0 K^-) - \frac{2\Gamma_{\pi^0\bar{K}^0}}{\Gamma_{\pi^+K^-}} A_{\rm CP}(\pi^0\bar{K}^0)$$

- "NLO" and "NNLO": including only pert. calculable SD contribution;
- "NNLO+LD": power-suppressed spectator and annihilation terms included back;
- For πK, NNLO change minor, since the total penguin $\hat{\alpha}_4^c = a_4^c + r_\chi^\pi a_6^c + \beta_3^c$;
- NNLO correction does not help resolving the observed πK CP asymmetry puzzle;

Non-leptonic B decays:

- Brs and ratios: 10^{-3} $(b \to c\bar{u}d)$, 10^{-4} $(b \to c\bar{u}s)$ [*Huber, Kränkl, Li '16*]

Decay mode	LO	NLO	NNLO	Exp.
$\bar{B}_d \to D^+\pi^-$	3.58	$3.79^{+0.44}_{-0.42}$	$3.93^{+0.43}_{-0.42}$	2.68 ± 0.13
$\bar{B}_d \to D^{*+}\pi^-$	3.15	$3.32^{+0.52}_{-0.49}$	$3.45^{+0.53}_{-0.50}$	2.76 ± 0.13
$\bar{B}_d \to D^+\rho^-$	9.51	$10.06^{+1.25}_{-1.19}$	$10.42^{+1.24}_{-1.20}$	7.5 ± 1.2
$\bar{B}_d \to D^{*+}\rho^-$	8.45	$8.91^{+0.74}_{-0.71}$	$9.24^{+0.72}_{-0.71}$	6.0 ± 0.8
$\bar{B}_d \to D^+K^-$	2.74	$2.90^{+0.33}_{-0.31}$	$3.01^{+0.32}_{-0.31}$	1.97 ± 0.21
$\bar{B}_d \to D^{*+}K^-$	2.37	$2.50^{+0.39}_{-0.36}$	$2.59^{+0.39}_{-0.37}$	2.14 ± 0.16
$\bar{B}_d \to D^+K^{*-}$	4.79	$5.07^{+0.65}_{-0.62}$	$5.25^{+0.65}_{-0.63}$	4.5 ± 0.7
$\bar{B}_d \to D^{*+}K^{*-}$	4.30	$4.54^{+0.41}_{-0.40}$	$4.70^{+0.40}_{-0.39}$	—
$\Lambda_b \to \Lambda_c^+\pi^-$	2.60	$2.75^{+0.53}_{-0.53}$	$2.85^{+0.54}_{-0.54}$	$4.30^{+0.36}_{-0.35}$
$\Lambda_b \to \Lambda_c^+\rho^-$	7.46	$7.88^{+1.44}_{-1.43}$	$8.17^{+1.47}_{-1.47}$	—
$\Lambda_b \to \Lambda_c^+a_1^-$	9.57	$10.11^{+1.75}_{-1.72}$	$10.47^{+1.78}_{-1.77}$	—
$\Lambda_b \to \Lambda_c^+K^-$	2.02	$2.14^{+0.40}_{-0.39}$	$2.21^{+0.40}_{-0.40}$	3.42 ± 0.33
$\Lambda_b \to \Lambda_c^+K^{*-}$	3.86	$4.07^{+0.74}_{-0.73}$	$4.22^{+0.75}_{-0.75}$	—

- For $\bar{B}_d$ decays, NNLO Brs higher than the data; for Λ_b decays, NNLO Brs smaller than the data; $\hookrightarrow$ non-negligible power corrections with natural size $\sim 10-15\%$?

Conclusion and outlook

- High-luminosity frontier is very complementary to high-energy frontier, especially for NP searches;
- Great progress achieved in both theo. and exp. sides for B physics, and also a very promising future (LHCb and Belle II, $\cdots$);
- CKM mechanism of flavor and CP violation well established. However, 20% NP effects in most FCNC processes often possible;
- Several deviations observed at $2 \sim 4\sigma$ in $b \to c\tau\bar{\nu}$ and $b \to s\mu\mu$ decays, implications of LFUV? Lets stay tuned!
- QCDF at leading power and at NNLO in QCD established and almost complete. Any further breakthroughs welcome;

Thank You for Your Attention!