LFUV in charged-current $b \to c\ell\nu_\ell$ decays: overview

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Outline

Introduction

Theoretical tools for B physics

LFUV in $b \to c\ell\nu_\ell$ decays

NNLO correction to 2-body hadronic decays

Conclusion

Why interested in B physics:

- 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;

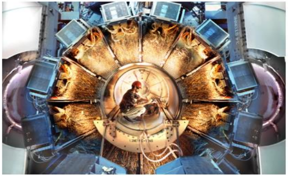
→ Deepen our understanding of strong interactions both the pert. and non-pert. aspects QCD.

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

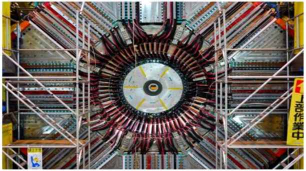
← theoretical and phenomenological input for other hadron processes;

B physics experiments:

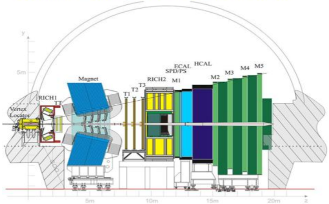
- Dedicated heavy flavour experiments: BaBar, Belle, LHCb, Belle-II



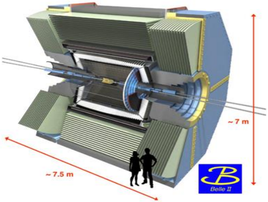
美国斯坦福直线加速器上的BaBar



日本高能加速器上的Belle



大型强子对撞机上的LHCb

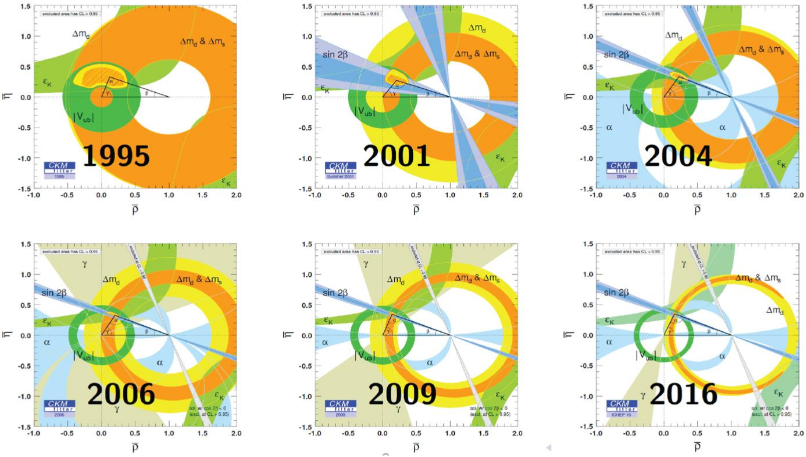


日本超级高能加速器的Belle-II

- Currently: LHCb @ LHC, Belle-II @ SuperKEKB, designed to find NP beyond the SM of particle physics; [*R. Aaij et al., 1208.3355; E. Kou et al., 1808.10567*]

Evolution in quark flavour physics:

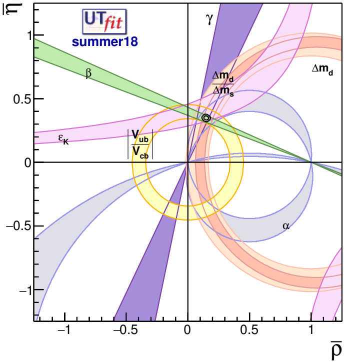
- CKM unitarity triangle: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* \equiv 0$

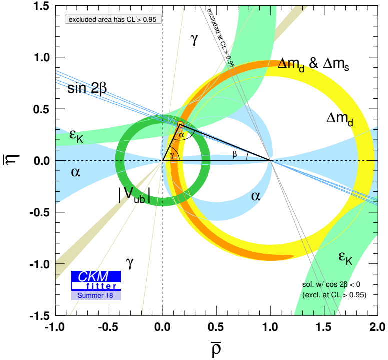


- Thanks to both exp. and theo. progress, we are now entering a promising precision flavour era!

Current status of B physics:

- The CKM mechanism of flavor & CP violation well established!;
[*UTfit, http://utfit.org/UTfit; CKMfitter, http://ckmfitter.in2p3.fr*]





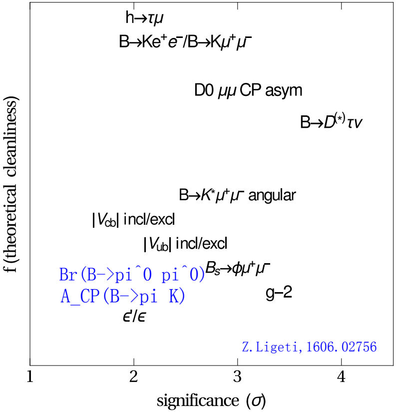
- Information on the UT sides and angles from both tree- and loop-induced processes well consistent;

- The SM source of CP violation should be the dominant one!

Current status of B physics:

- Remember: $\mathcal{O}(15\% \sim 20\%)$ NP contributions to most processes still allowed by data;
- Several intriguing tensions do observed, might be BSM signals?

$R(D^{(*)})$ anomalies, NNLO correction to 2-body hadronic B decays



† 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:

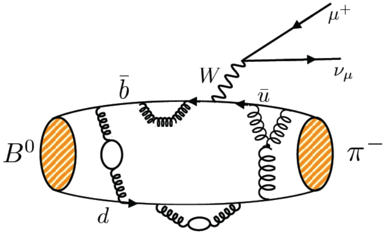
- At the quark level: B-hadron weak decays mediated by weak charged-current $J^{\mu}_{\rm CC}$ coupled to $W^{\pm}$;

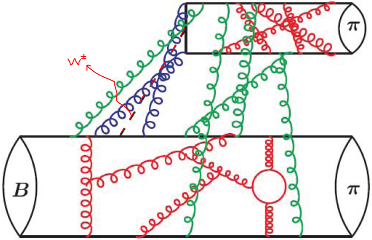
$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}}\, J^{\mu}_{\rm CC}\, W^{\dagger}_{\mu} + \text{h.c.}, \quad J^{\mu}_{\rm CC} = (\bar{u}_{\rm L}, \bar{c}_{\rm L}, \bar{t}_{\rm L})\, \gamma^{\mu}\, V_{\rm CKM} \begin{pmatrix} d_{\rm L} \\ s_{\rm L} \\ b_{\rm L} \end{pmatrix}$$

$\hookrightarrow$ $V_{\rm CKM}$: 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;

$\hookrightarrow$ In B physics, simple weak decays overshadowed by complex strong interactions!





Typical features for B-hadron weak decays:

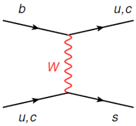
- A typical multi-scale problem and scales are highly hierarchical;

EW interaction scale	$\gg$	ext. mom'a in B rest frame	$\gg$	QCD-bound state effects
$m_W \sim 80.4$ GeV $m_Z \sim 91.2$ GeV	$\gg$	$m_b \sim 4.8$ GeV	$\gg$	$\Lambda_{\text{QCD}} \sim 1$ GeV

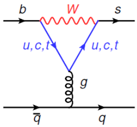
- Starting point $\mathcal{H}_{\text{eff}}$: [*Buras, hep-ph/9806471*]

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

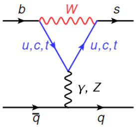
charged current

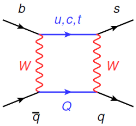


QCD-penguin

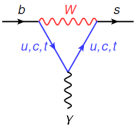


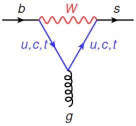
EW-penguin





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 $\langle f|\mathcal{O}_i|B\rangle$: $\langle 0|\mathcal{O}_i|B\rangle$, $\langle \pi|\mathcal{O}_i|B\rangle$, $\langle \pi\pi|\mathcal{O}_i|B\rangle$, $\langle \bar{B}|\mathcal{O}_i|B\rangle$;

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

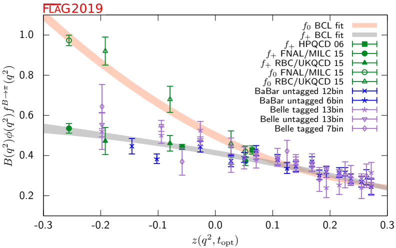
$B_s \to \mu^+\mu^-$	$\to$	$\langle 0\|\mathcal{O}\|B_s\rangle$
$B-\bar{B}$ mixing	$\to$	$\langle B\|\mathcal{O}\|\bar{B}\rangle$
$B \to \pi l\nu$	$\to$	$\langle \pi\|\mathcal{O}\|B\rangle$
$B \to \pi\pi$	$\to$	$\langle \pi\pi\|\mathcal{O}\|B\rangle$

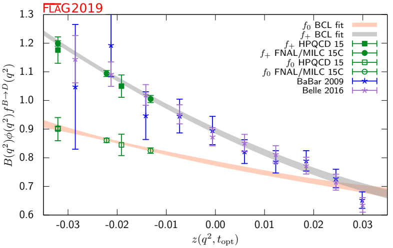
Increasingly difficult

- $\langle M_1M_2|\mathcal{O}_i|B\rangle$: not yet possible in lattice QCD;
  - dynamical approaches based on factorization theorems: PQCD, QCDF, SCET, ⋯; [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, ⋯; [Zeppenfeld, '81; London, Gronau, Rosner, Chiang, Cheng *et al.*]

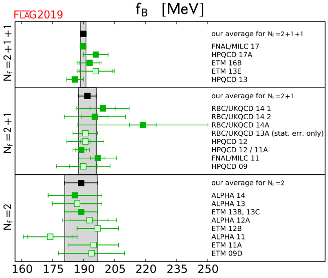
Hadronic matrix elements for B-hadron weak decays:

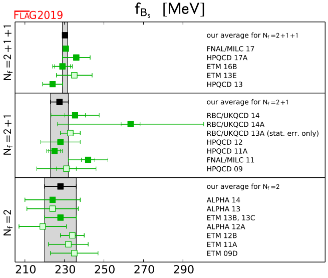
- $\langle M|\bar{c}\gamma^\mu b|B\rangle$:
  [FLAG: http://flag.unibe.ch/]





- $\langle 0|\bar{q}\gamma^\mu\gamma_5 u|B_q\rangle$:
  [FLAG: http://flag.unibe.ch/]





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

- BaBar 2012 results: [BaBar, 1205.5442, 1303.0571]

Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays

BaBar Collaboration (J.P. Lees *et al.*) 显示全部 364 名作者

May 2012 - 8 pages

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

Phys.Rev.Lett. 109 (2012) 101802
DOI: 10.1103/PhysRevLett.109.101802
BABAR-PUB-12-012, SLAC-PUB-15028
e-Print: arXiv:1205.5442 [hep-ex] | PDF
Experiment: SLAC-PEP2-BABAR

Abstract (arXiv)
Based on the full BaBar data sample, we report improved measurements of the ratios R(D(*)) = B(B -> D(*) Tau Nu)/B(B -> D(*) l Nu), where l is either e or mu. These ratios are sensitive to new physics contributions in the form of a charged Higgs boson. We measure R(D) = 0.440 +- 0.058 +- 0.042 and R(D*) = 0.332 +- 0.024 +- 0.018, which exceed the Standard Model expectations by 2.0 sigma and 2.7 sigma, respectively. Taken together, our results disagree with these expectations at the 3.4 sigma level. This excess cannot be explained by a charged Higgs boson in the type II two-Higgs-doublet model. We also report the observation of the decay B -> D Tau Nu, with a significance of 6.8 sigma.

Measurement of an Excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ Decays and Implications for Charged Higgs Bosons

BaBar Collaboration (J.P. Lees *et al.*) 显示全部 341 名作者

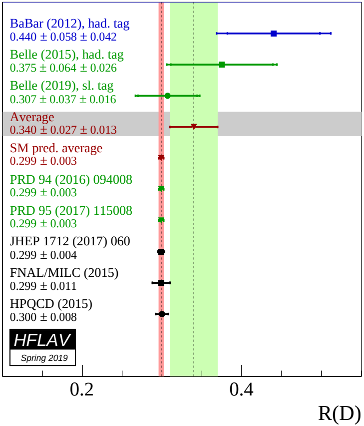
Mar 3, 2013 - 30 pages

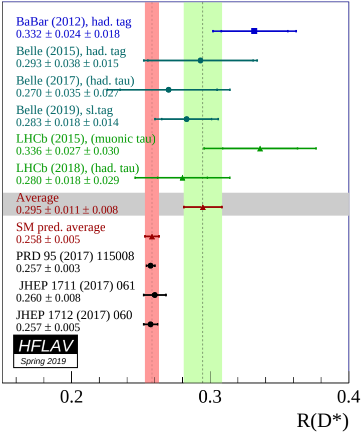
Phys.Rev. D88 (2013) no.7, 072012
(2013-10-31)
DOI: 10.1103/PhysRevD.88.072012
BABAR-PUB-13-001, SLAC-PUB-15381
e-Print: arXiv:1303.0571 [hep-ex] | PDF
Experiment: SLAC-PEP2-BABAR

Abstract (APS)
Based on the full BABAR data sample, we report improved measurements of the ratios $R(D)=B(\bar{B}\to D\tau\bar{\nu}_\tau)/B(\bar{B}\to D\ell\bar{\nu}_\ell)$ and $R(D^*)=B(\bar{B}\to D^*\tau\bar{\nu}_\tau)/B(\bar{B}\to D^*\ell\bar{\nu}_\ell)$, where ℓ refers to either an electron or muon. These ratios are sensitive to new physics contributions in the form of a charged Higgs boson. We measure $R(D)=0.440\pm0.058\pm0.042$ and $R(D^*)=0.332\pm0.024\pm0.018$, which exceed the standard model expectations by 2.0σ and 2.7σ, respectively. Taken together, the results disagree with these expectations at the 3.4σ level. This excess cannot be explained by a charged Higgs boson in the type II two-Higgs-doublet model. Kinematic distributions presented here exclude large portions of the more general type III two-Higgs-doublet model, but there are solutions within this model compatible with the results.

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

- Belle and LHCb results: [Belle, 1507.03233, 1607.07923, 1612.00529, 1709.00129, 1904.08794, 1910.05864; LHCb, 1506.08614, 1708.08856, 1711.02505]

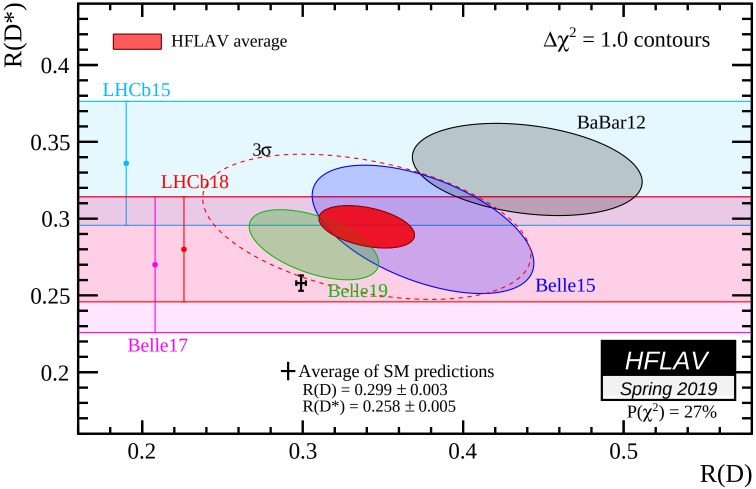




- $R(D) = 0.340 \pm 0.027 \pm 0.013$; $R(D^*) = 0.295 \pm 0.011 \pm 0.008$.

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

- 2019 WA results: [HFLAV: https://hflav.web.cern.ch/]



- $R(D)$: 1.4σ; $R(D^*)$: 2.5σ; combined: $\sim 3.08\sigma$.

Key observations:

- $R(D)$ and $R(D^*)$ anomalies: hint at LFUV, first signal of NP?

- Remember: LFU well tested in τ leptonic decays, EW sector, and light pseudoscalar-meson decays; [Bifani *et al., 1809.06229*]

$$g_\mu/g_e = 1.0018 \pm 0.0014 \qquad \frac{\Gamma_{Z\to\mu^+\mu^-}}{\Gamma_{Z\to e^+e^-}} = 0.9974 \pm 0.0050$$

$$g_\tau/g_\mu = 1.0011 \pm 0.0015$$

$$g_\tau/g_e = 1.0030 \pm 0.0015 \qquad \frac{2\Gamma_{W^-\to\tau^-\overline{\nu}_\tau}}{\Gamma_{W^-\to e^-\overline{\nu}_e} + \Gamma_{W^-\to\mu^-\overline{\nu}_\mu}} = 1.066 \pm 0.025$$

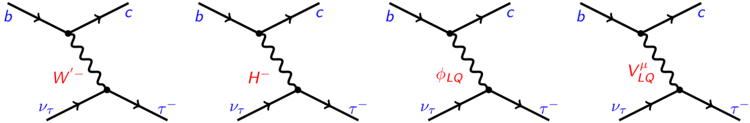
$$\left(\frac{\Gamma_{K^-\to e^-\overline{\nu}_e}}{\Gamma_{K^-\to\mu^-\overline{\nu}_\mu}}\right)^{\rm SM} = (2.477 \pm 0.001)\times 10^{-5} \qquad \left(\frac{\Gamma_{\pi^-\to e^-\overline{\nu}_e}}{\Gamma_{\pi^-\to\mu^-\overline{\nu}_\mu}}\right)^{\rm SM} = (1.2352 \pm 0.0001)\times 10^{-4}$$

$$\left(\frac{\Gamma_{K^-\to e^-\overline{\nu}_e}}{\Gamma_{K^-\to\mu^-\overline{\nu}_\mu}}\right)^{\rm exp} = (2.488 \pm 0.009)\times 10^{-5} \qquad \left(\frac{\Gamma_{\pi^-\to e^-\overline{\nu}_e}}{\Gamma_{\pi^-\to\mu^-\overline{\nu}_\mu}}\right)^{\rm exp} = (1.230 \pm 0.004)\times 10^{-4}$$

- If confirmed, LFU violated between the 3rd and the first two generations, and also only in B decays!

What should we do:

- $B \to D^{(*)}\tau\nu_\tau$ decays: tree-level processes, mediated by $W^\pm$ in SM; massive τ makes them sensitive to other mediators like $W'^\pm$, $H^\pm$, LQs, $\cdots$;



- Check the SM predictions! [BGL vs CLN parametrizations of $B \to D^{(*)}$ FFs, Bigi/Gambino(/Schacht) '16 '17; Gambino/Jung/Schacht '19; ...]

data+lattice/LCSR+unitarity bounds+HQE to higher orders

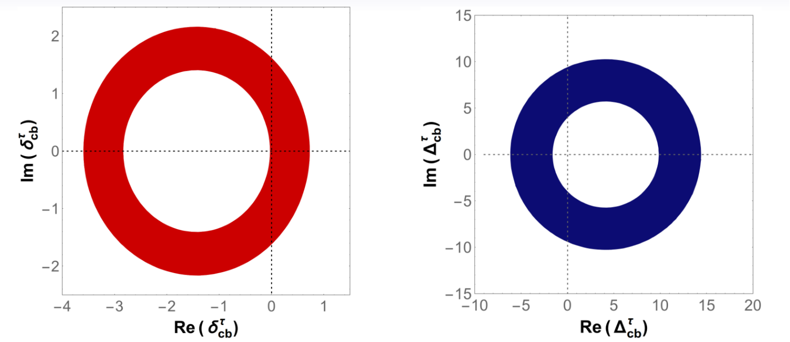
	R(D)	R(Di*)
D.Bigi, P.Gambino, Phys.Rev. D94 (2016) no.9, 094008 [arXiv:1606.08030 [hep-ph]]	0.299 ± 0.003	
F.Bernlochner, Z.Ligeti, M.Papucci, D.Robinson, Phys.Rev. D95 (2017) no.11, 115008 [arXiv:1703.05330 [hep-ph]]	0.299 ± 0.003	0.257 ± 0.003
D.Bigi, P.Gambino, S.Schacht, JHEP 1711 (2017) 061 [arXiv:1707.09509 [hep-ph]]		0.260 ± 0.008
S.Jaiswal, S.Nandi, S.K.Patra, JHEP 1712 (2017) 060 [arXiv:1707.09977 [hep-ph]]	0.299 ± 0.004	0.257 ± 0.005

- EM corrections to $R(D)$ and $R(D^*)$ by 5% and 3%, for soft-photon energy cut at 20-40 MeV; [Boer/Kitahara/Nisandzic, 1803.05881]

Scalar NP: Celis/Jung/Li/Pich, 1612.07757

- Effective low-energy Lagrangian with scalar currents:

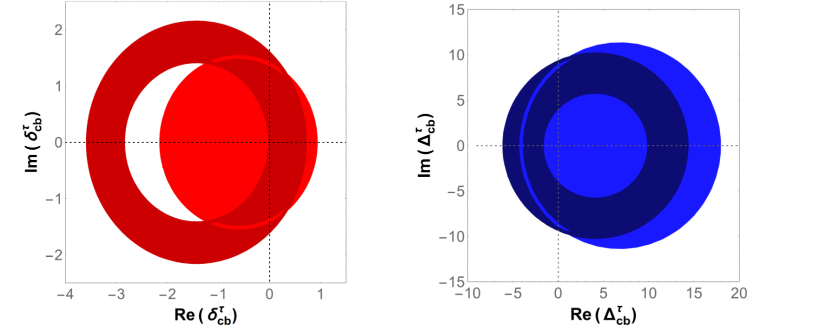
$$\mathcal{L}_{\rm eff} = -\frac{4G_F V_{q_u q_d}}{\sqrt{2}} \left[\bar{q}_u (g_L^{q_u q_d \ell} \mathcal{P}_L + g_R^{q_u q_d \ell} \mathcal{P}_R) q_d\right] [\bar{\ell} \mathcal{P}_L \nu_\ell]$$



- $R(D)$: $\delta^\ell_{cb} \equiv \frac{(g_L^{cb\ell}+g_R^{cb\ell})(m_B-m_D)^2}{m_\ell\,(\bar{m}_b-\bar{m}_c)}$; $R(D^*)$: $\Delta^\ell_{cb} \equiv \frac{(g_L^{cb\ell}-g_R^{cb\ell})m_B^2}{m_\ell\,(\bar{m}_b+\bar{m}_c)}$
- $R(D^{(*)})$ can be trivially explained, but not in the NFC 2HDMs!

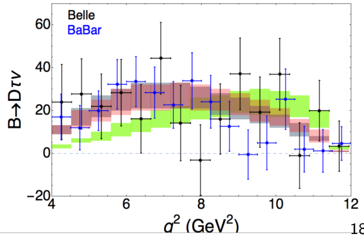
Scalar NP: Celis/Jung/Li/Pich, 1612.07757

- Constraints from other $b \to c\tau\nu$ observables:



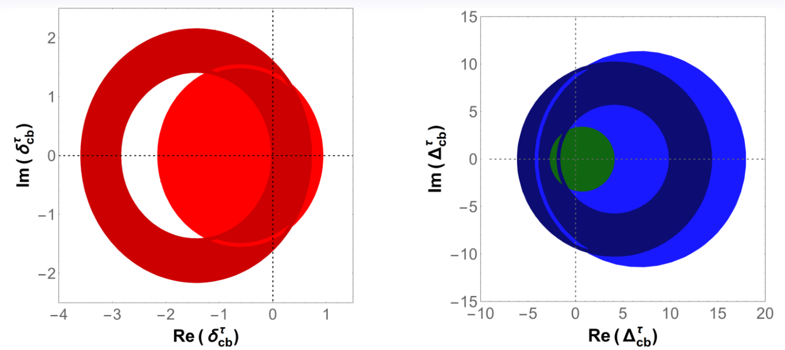
Differential rates:

- compatible with SM and NP
- already now constraining, especially in $B \to D\tau\nu$
- "theory-dependence" of data needs addressing [Bernlochner+'17]



Scalar NP: Celis/Jung/Li/Pich, 1612.07757

- Constraints from other $b \to c\tau\nu$ observables:



Total width of B_c: $\Gamma(B_c^- \to \tau^- \bar{\nu}_\tau) = \frac{G_F^2}{8\pi} |V_{cb}|^2 f_{B_c}^2 m_{B_c}^3 \frac{m_\tau^2}{m_{B_c}^2} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left| C_V - C_S \frac{m_{B_c}^2}{m_\tau [m_b(\mu_b) + m_c(\mu_b)]} \right|^2$

- $B_c \to \tau\nu$ is an obvious $b \to c\tau\nu$ transition
  - ➥ not measurerable in foreseeable future
  - ➥ can oversaturate total width of B_c! [X.Li+'16]
- Excludes second real solution in Δ^τ_{cb} plane (even scalar NP for $R(D^*)$? [Alonso+'16, Akeroyd+'17])

Scalar NP: Celis/Jung/Li/Pich, 1612.07757

- Global fits with scalar NP:

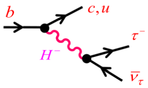
$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{q_u q_d} \left[\bar{q}_u \left(g_L^{q_u q_d \ell} \mathcal{P}_L + g_R^{q_u q_d \ell} \mathcal{P}_R\right) q_d\right] \left[\bar{\ell} \mathcal{P}_L \nu_\ell\right]$$

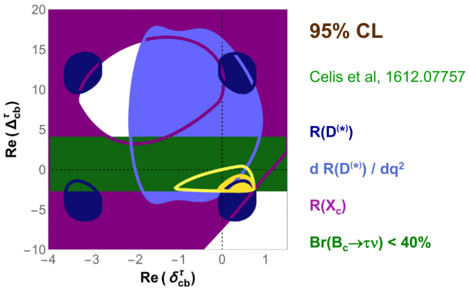
Scalar Form Factors

$$\delta R(D) \longleftrightarrow \delta_{cb}^{\ell} \equiv \left(g_L^{cb\ell} + g_R^{cb\ell}\right) \frac{(m_B - m_D)^2}{m_\ell \, (\bar{m}_b - \bar{m}_c)}$$

$$\delta R(D^*) \longleftrightarrow \Delta_{cb}^{\ell} \equiv \left(g_L^{cb\ell} - g_R^{cb\ell}\right) \frac{m_B^2}{m_\ell \, (\bar{m}_b + \bar{m}_c)}$$

Real Couplings





Scalar LQ: Li/Yang/Zhang, 1605.09308

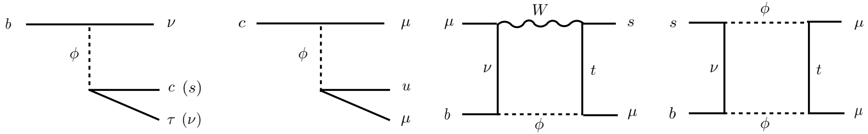
- The LQ model: one single scalar LQ with $M_\phi \sim 1$ TeV and $(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$ added to SM; [M. Bauer and M. Neubert, 1511.01900]

$$\mathcal{L}_\phi = (D_\mu \phi)^\dagger D_\mu \phi - M_\phi^2 \, |\phi|^2 - g_{h\phi} \, |\Phi|^2 |\phi|^2$$

$$+ \bar{Q}^c \boldsymbol{\lambda}^L i\tau_2 L \, \phi^* + \bar{u}_R^c \, \boldsymbol{\lambda}^R e_R \, \phi^* + \text{h.c.} \,,$$

- ϕ interactions with fermions: rotating from the weak to the mass basis for quarks and charged leptons, to get $\mathcal{L}_{\text{int}}^\phi$;

$$\mathcal{L}_{\text{int}}^\phi = \bar{u}_L^c \boldsymbol{\lambda}_{ul}^L l_L \phi^* - \bar{d}_L^c \boldsymbol{\lambda}_{d\nu}^L \nu_L \phi^* + \bar{u}_R^c \boldsymbol{\lambda}_{ul}^R l_R \phi^* + \text{h.c.} \,,$$



- Both tree- and loop-level $(\bar{u}_i d_j)(\bar{\nu}\ell)$, $(\bar{u}_i u_j)(\ell^+\ell^-)$ and $(\bar{d}_i d_j)(\bar{\nu}\nu)$ generated;
$\hookrightarrow$ $\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau$, $B_c^- \to \tau^-\bar{\nu}_\tau(\gamma)$, $D^0 \to \mu^+\mu^-$, $D^+ \to \pi^+\mu^+\mu^-$, $B \to X_s\nu\bar{\nu}$, $B \to K^{(*)}\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$, $(g-2)_\mu$; [Bauer/Neubert, 1511.01900]

Scalar LQ: Li/Yang/Zhang, 1605.09308

- $\mathcal{H}_{\text{eff}}$ for $b \to c\tau\nu_\tau$ transitions: after integrating out ϕ;

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[C_V(M_\phi)\, \bar{c}\gamma_\mu P_L b\, \bar{\tau}\gamma^\mu P_L \nu_\tau + C_S(M_\phi)\, \bar{c} P_L b\, \bar{\tau} P_L \nu_\tau - \frac{1}{4} C_T(M_\phi)\, \bar{c}\sigma_{\mu\nu} P_L b\, \bar{\tau}\sigma^{\mu\nu} P_L \nu_\tau \Big]$$

- C_V, C_S, C_T: the WCs at the matching scale $\mu = M_\phi$;

$$C_V(M_\phi) = 1 + \frac{\lambda^L_{b\nu_\tau}\lambda^{L*}_{c\tau}}{4\sqrt{2}G_F V_{cb} M_\phi^2}, \quad C_S(M_\phi) = C_T(M_\phi) = -\frac{\lambda^L_{b\nu_\tau}\lambda^{R*}_{c\tau}}{4\sqrt{2}G_F V_{cb} M_\phi^2}$$

- Four best-fit solutions for $R(D^{(*)})$ along with acceptable q^2 spectra: $M_\phi = 1\ \text{TeV}$; [M. Freytsis, Z. Ligeti, J. T. Ruderman, 1506.08896]

$$(\lambda^L_{b\nu_\tau}\lambda^{L*}_{c\tau}, \lambda^L_{b\nu_\tau}\lambda^{R*}_{c\tau}) = (C''_{S_R}, C''_{S_L}) = \begin{cases} (\ \ 0.35, & -0.03), \quad P_A \\ (\ \ 0.96, & \ \ 2.41), \quad P_B \\ (-5.74, & \ \ 0.03), \quad P_C \\ (-6.34, & -2.39), \quad P_D \end{cases}$$

Scalar LQ: Li/Yang/Zhang, 1605.09308

- Solution P_A: explain in a natural way $R(D^{(*)})$, $R(K)$ and $(g-2)_\mu$, while satisfying other constraints without fine-tuning; [Bauer and Neubert, 1511.01900]

One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

Martin Bauer[a] and Matthias Neubert[b,c]
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We show that by adding a single new scalar particle to the Standard Model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \to \bar{K}\ell^+\ell^-$ decays, the enhanced $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \to \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit value.

- Question: these four best-fit solutions can be discriminated from each other using other processes mediated by the same quark-level $b \to c\tau\nu_\tau$ transition?

  ↪ in addition to $\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau$, we examined the scalar LQ effects on $B_c^- \to \tau^-\bar{\nu}_\tau$, $B_c^- \to \gamma\tau^-\bar{\nu}_\tau$ and $B \to X_c\tau\bar{\nu}_\tau$ decays.

Scalar LQ: Li/Yang/Zhang, 1605.09308

- Decay width of $B_c^- \to \tau^- \bar{\nu}_\tau$ with LQ-exchanged contribution:

$$\Gamma(B_c^- \to \tau^- \bar{\nu}_\tau) = \frac{G_F^2}{8\pi} |V_{cb}|^2 f_{B_c}^2 m_{B_c}^3 \frac{m_\tau^2}{m_{B_c}^2} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left| C_V - C_S \frac{m_{B_c}^2}{m_\tau \left[m_b(\mu_b) + m_c(\mu_b)\right]} \right|^2$$

- Numerical results with the four best-fit solutions:

$$\Gamma(B_c^- \to \tau^- \bar{\nu}_\tau) = \begin{cases} 2.22 \times 10^{-2}\, \Gamma_{B_c}, & \text{SM} \\ 2.45 \times 10^{-2}\, \Gamma_{B_c}, & P_A \\ 1.33\, \Gamma_{B_c}, & P_B \\ 2.39 \times 10^{-2}\, \Gamma_{B_c}, & P_C \\ 1.31\, \Gamma_{B_c}, & P_D \end{cases}$$

- Conclusion: P_B and P_D already excluded by $\Gamma(B_c^- \to \tau^- \bar{\nu}_\tau)$;

  $\hookrightarrow$ needs only consider P_A and P_C! [Alonso+'16, Akeryd+'17, Blanke+'19]

Model-independent analysis: Hu/Li/Yang, 1810.04939

- Most general $SU(3)_C \times U(1)_Q$-invariant $\mathcal{L}_{\text{eff}}$ at m_b scale:

$$\mathcal{L}^{(6)}_{\text{SM}} = -\frac{4G_F}{\sqrt{2}} V_{cb}\, \mathcal{O}_{V_L} + \text{H.c.},$$

$$\mathcal{L}^{(6)}_{\text{NP}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left(C_{V_L}\mathcal{O}_{V_L} + C_{V_R}\mathcal{O}_{V_R} + C_{S_L}\mathcal{O}_{S_L} + C_{S_R}\mathcal{O}_{S_R} + C_T\mathcal{O}_T \right) + \text{H.c.},$$

其中

$$\mathcal{O}_{V_{L(R)}} = (\bar{c}\gamma^\mu P_{L(R)} b)(\bar{\tau}\gamma_\mu P_L \nu_\tau),$$

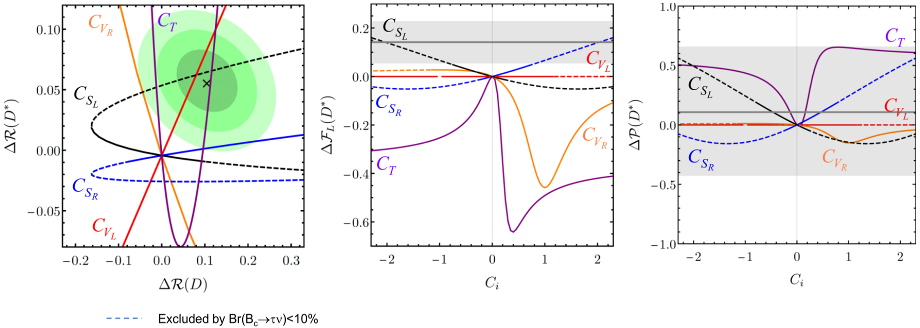
$$\mathcal{O}_{S_{L(R)}} = (\bar{c} P_{L(R)} b)(\bar{\tau} P_L \nu_\tau),$$

$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau).$$

- Observables considered:
  - $R(D)$ and $R(D^*)$;
  - $d\Gamma(B \to D^{(*)}\tau\nu_\tau)/dq^2$;
  - $\mathcal{B}(B_c \to \tau\nu_\tau) \leq 10\ (30)\%$;
  - $R(X_c) = \frac{\Gamma(B\to X_c\tau\nu_\tau)}{\Gamma(B\to X_c\ell\nu_\ell)}$;
  - τ longitudinal polarization fraction $P_\tau(D^*)$.
  - D^* longitudinal polarization fraction $F_L^{D^*}$.

Model-independent analysis: Hu/Li/Yang, 1810.04939

- Global fit results: [Murgui, Penuelas, Jung, Pich, 1904.09311]



- Main observations:
  - ▷ With $R(D^{(*)})$, $d\Gamma/dq^2$, and $\Gamma(B_c)$, three minima obtained;
  - ▷ The 3rd with large C_T disfavored by distributions, removed by $F_L^{D^*}$;
  - ▷ Central value of $F_L^{D^*}$ cannot be accommodated, exp. confirmation!

Model-independent analysis: Hu/Li/Yang, 1810.04939

- Possible NP mediators: [Murgui, Penuelas, Jung, Pich, 1904.09311]

	Min 1	Min 2	Min 3	Min 1	Min 2	Min 3
$\mathcal{B}(B_c \to \tau\nu)$	10%			30%		
$\chi^2_{\rm min}$/d.o.f.	34.1/53	37.5/53	58.6/53	33.8/53	36.6/53	58.4/53
C_{V_L}	$0.17^{+0.13}_{-0.14}$	$0.41^{+0.05}_{-0.06}$	$-0.57^{+0.23}_{-0.24}$	$0.19^{+0.13}_{-0.17}$	$0.42^{+0.06}_{-0.06}$	$-0.54^{+0.23}_{-0.24}$
C_{S_R}	$-0.39^{+0.38}_{-0.15}$	$-1.15^{+0.18}_{-0.08}$	$0.06^{+0.59}_{-0.19}$	$-0.56^{+0.49}_{-0.17}$	$-1.33^{+0.25}_{-0.08}$	$-0.14^{+0.69}_{-0.18}$
C_{S_L}	$0.36^{+0.11}_{-0.35}$	$-0.34^{+0.12}_{-0.19}$	$0.64^{+0.13}_{-0.49}$	$0.54^{+0.10}_{-0.46}$	$-0.16^{+0.13}_{-0.22}$	$0.81^{+0.12}_{-0.58}$
C_T	$0.01^{+0.06}_{-0.05}$	$0.12^{+0.04}_{-0.04}$	$0.32^{+0.02}_{-0.03}$	$0.01^{+0.07}_{-0.05}$	$0.12^{+0.04}_{-0.04}$	$0.32^{+0.02}_{-0.03}$

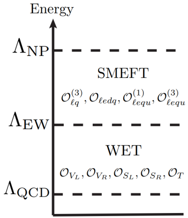
- Min 1 $\mathcal{O}_{V_L}$
  - W' boson, $M'_W \sim 0.2$ TeV ruled out by direct searches
  - Leptoquarks: $U_3 \sim (3, 3, 2/3)$
  - Scalar leptoquarks: $S_1 \sim (\bar{3}, 3, 1/3)$
- Min 2 $\mathcal{O}_{S_{L,R}}, \mathcal{O}_{V_L}, \mathcal{O}_T$
  - Combination of several candidates, e.g, leptoquark $S_1 \sim (\bar{3}, 3, 1/3)$ and scalar boson $H_2 \sim (1, 21/3)$
- Min 3 $\mathcal{O}_{S_L}, \mathcal{O}_T$
  - Scalar leptoquarks $R_2 \sim (3, 2, 7/6)$ or $S_1 \sim (\bar{3}, 1, 1/3)$

- Quite useful for specific UV-complete NP model constructions.

Model-independent EFT analysis: Hu/Li/Yang, 1810.04939

- All available collider data show no NP signals up to TeV scale!
- SMEFT: parametrize any NP effects by higher-dim. operators; [Buchmuller, Wyler, '86; Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884]

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda} C_{ll\varphi\varphi} Q_{ll\varphi\varphi} + \frac{1}{\Lambda^2} \sum_i C_i Q_i + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$



与 $b \to c\tau\nu_\tau$ 过程最相关的六维算符

$$Q_{lq}^{(3)} = (\bar{l}\gamma_\mu \tau^I l)(\bar{q}\gamma^\mu \tau^I q)\,, \qquad Q_{ledq} = (\bar{l}^j e)(\bar{d} q^j)\,,$$

$$Q_{lequ}^{(1)} = (\bar{l}^j e)\varepsilon_{jk}(\bar{q}^k u)\,, \qquad Q_{lequ}^{(3)} = (\bar{l}^j \sigma_{\mu\nu} e)\varepsilon_{jk}(\bar{q}^k \sigma^{\mu\nu} u)$$

- $\Lambda \to \mu_{\rm EW}$，重整化群演化[A. Manohar et al., *Dimension-Six Renormalization Group Equations*. http://einstein.ucsd.edu/smeft/]
- $\mu_{\rm EW}$，匹配[J. Aebischer et al., JHEP05(2016)037; A. Manohar et al., JHEP03(2018)016]

$$C_{V_L} = -\frac{\sqrt{2}}{2G_F\Lambda^2} \sum_n \left[C_{lq}^{(3)}\right]_{332n} \frac{V_{nb}}{V_{cb}}, \qquad C_{S_R} = -\frac{\sqrt{2}}{4G_F\Lambda^2} \frac{1}{V_{cb}} \left[C_{ledq}\right]^*_{3332}\,,$$

$$C_{S_L} = -\frac{\sqrt{2}}{4G_F\Lambda^2} \sum_n \left[C_{lequ}^{(1)}\right]^*_{33n2} \frac{V_{nb}}{V_{cb}}, \qquad C_T = -\frac{\sqrt{2}}{4G_F\Lambda^2} \sum_n \left[C_{lequ}^{(3)}\right]^*_{33n2} \frac{V_{nb}}{V_{cb}}$$

- $\mu_{\rm EW} \to \mu_b$，重整化群演化[J. Aebischer, et al., JHEP09(2017)158; E.E Jenkins et al., JHEP01(2018)084]

采用三圈的 QCD 和一圈的 EW/QED 演化，

$$C_{V_L}(\mu_b) = -1.503 \left[C_{lq}^{(3)}\right]_{3323}(\Lambda),$$

$$C_{V_R}(\mu_b) = 0,$$

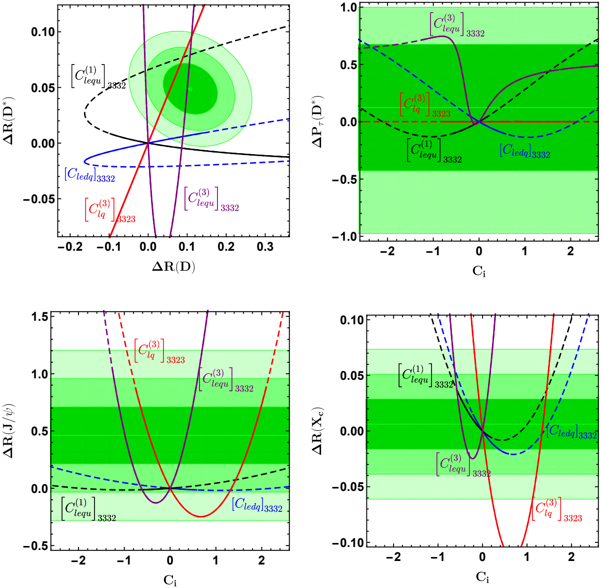
$$C_{S_L}(\mu_b) = -1.257 \left[C_{lequ}^{(1)}\right]_{3332}(\Lambda) + 0.2076 \left[C_{lequ}^{(3)}\right]_{3332}(\Lambda),$$

$$C_{S_R}(\mu_b) = -1.254 \left[C_{ledq}\right]_{3332}(\Lambda),$$

$$C_T(\mu_b) = 0.002725 \left[C_{lequ}^{(1)}\right]_{3332}(\Lambda) - 0.6059 \left[C_{lequ}^{(3)}\right]_{3332}(\Lambda),$$

Model-indep. EFT analysis: Hu/Li/Yang, 1810.04939

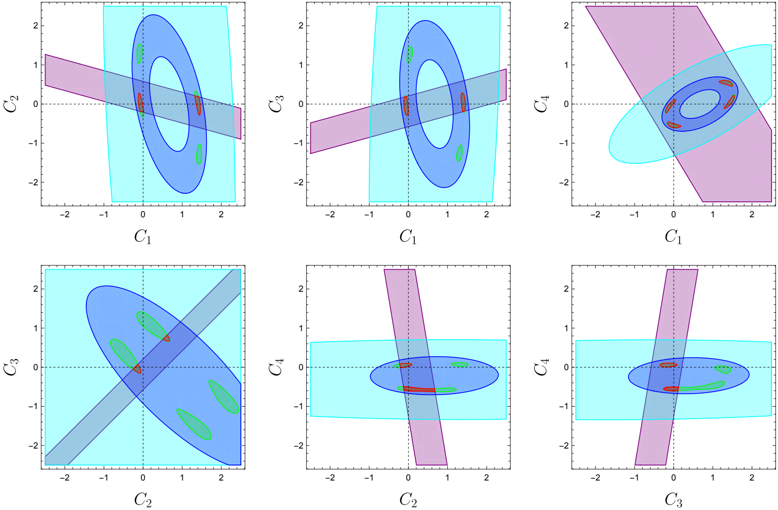
- Fit results with a single WC:



- ▷ $[C_{lequ}^{(1)}]_{3332}$ (C_{S_L}) already ruled out by $\Delta R(D^{(*)})$ at 3σ;
- ▷ $[C_{ledq}]_{3332}$ (C_{S_R}) can only marginally at 2σ;
- ▷ $[C_{lq}^{(3)}]_{3323}$ (C_{V_L}) or $[C_{lequ}^{(3)}]_{3332}$ (C_{S_L} and C_T) can explain $R(D^{(*)})$ at 1σ;

Model-independent EFT analysis: Hu/Li/Yang, 1810.04939

- With two WCs: green, $R(D^{(*)})$; cyan, $R(J/\Psi)$; blue, $R(X_c)$; purple, $\Gamma(B_c)$



$$C_1 \equiv \left[C_{lq}^{(3)}\right]_{3323}, \quad C_2 \equiv \left[C_{ledq}\right]_{3332}, \quad C_3 \equiv \left[C_{lequ}^{(1)}\right]_{3332}, \quad C_4 \equiv \left[C_{lequ}^{(3)}\right]_{3332}$$

Model-independent EFT analysis: Hu/Li/Yang, 1810.04939

- How to discriminate 11 most optimal scenarios?

Obs.	S1, S2	S3	S4, S5	S6, S7	S8, S9	S10	S11
$R(D)$	0.3625(40)	0.3986(42)	0.4016(46)	0.4007(45)	0.3956(43)	0.4015(48)	0.4015(48)
$A_{\rm FB}(D)$	0.3597(3)	0.4297(4)	0.3485(4)	0.3504(4)	0.3695(4)	0.3130(5)	0.3072(4)
$P_\tau(D)$	0.3222(22)	0.0280(28)	0.4087(21)	0.3956(21)	0.3016(23)	0.5275(17)	0.5364(17)
$\mathcal{X}_1(D)$	0.2465(27)	0.2850(30)	0.2708(30)	0.2706(30)	0.2709(29)	0.2636(31)	0.2624(31)
$\mathcal{X}_2(D)$	0.1161(13)	0.1137(12)	0.1308(16)	0.1302(16)	0.1247(14)	0.1379(17)	0.1391(18)
$\mathcal{X}_3(D)$	0.2397(29)	0.2049(21)	0.2829(35)	0.2796(34)	0.2574(30)	0.3067(39)	0.3085(39)
$\mathcal{X}_4(D)$	0.1229(12)	0.1937(22)	0.1187(12)	0.1211(12)	0.1381(14)	0.0949(9)	0.0931(9)
$R(D^*)$	0.3119(35)	0.3042(43)	0.3049(35)	0.3050(35)	0.3057(35)	0.3057(34)	0.3058(35)
$A_{\rm FB}(D^*)$	−0.0559(22)	0.0312(15)	−0.0468(22)	−0.0634(22)	−0.0827(23)	0.0010(20)	−0.0280(20)
$P_\tau(D^*)$	−0.5039(37)	0.1808(33)	−0.4867(40)	−0.5176(33)	−0.5173(42)	−0.4432(37)	−0.4973(21)
$P_{\rm L}(D^*)$	0.4552(31)	0.1415(13)	0.4614(32)	0.4501(30)	0.4612(31)	0.4556(32)	0.4280(27)
$R(J/\psi)$	$0.3012^{+0.0073}_{-0.0066}$	$0.1980^{+0.0215}_{-0.0167}$	$0.2939^{+0.0073}_{-0.0066}$	$0.2949^{+0.0069}_{-0.0064}$	$0.2935^{+0.0080}_{-0.0069}$	$0.2953^{+0.0067}_{-0.0064}$	$0.2971^{+0.0062}_{-0.0063}$
$R(\eta_c)$	$0.3412^{+0.0219}_{-0.0185}$	$0.3159^{+0.0304}_{-0.0261}$	$0.3766^{+0.0268}_{-0.0227}$	$0.3760^{+0.0264}_{-0.0223}$	$0.3692^{+0.0216}_{-0.0181}$	$0.3780^{+0.0324}_{-0.0277}$	$0.3788^{+0.0332}_{-0.0285}$
$R(X_c)$	0.2381(40)	0.2439(39)	0.2388(39)	0.2391(39)	0.2405(39)	0.2366(40)	0.2365(40)
$\mathcal{B}(B_c\to\tau\nu)[\%]$	$2.87^{+0.26}_{-0.29}$	$5.32^{+0.47}_{-0.54}$	$5.36^{+0.48}_{-0.55}$	$1.29^{+0.11}_{-0.13}$	$3.27^{+0.29}_{-0.33}$	$8.02^{+0.71}_{-0.82}$	$7.68^{+0.68}_{-0.78}\times 10^{-3}$

K. Adamczyk, B to semitauonic decays at Belle/Belle II, Talk given at CKM2018, 1903.03102

$$F_L^{D^*} = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$$

$$(F_L^{D^*})_{\rm SM} = 0.457 \pm 0.010$$

S3 can be distinguished from other ones.

distinguish the scenario S11 from the other ones.

Non-leptonic B decays:

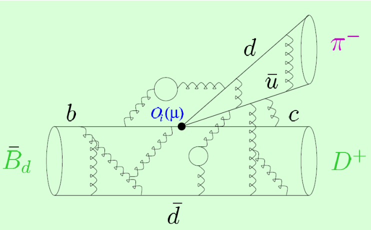
- Motivations: important inputs for the CKM UT angles α, β and γ;

- Main issue: how to evaluate precisely the hadronic matrix element $\langle M_1 M_2|\mathcal{O}_i|\bar{B}\rangle$;

$\hookrightarrow$ 3 scales involved: m_b, $\sqrt{m_b\Lambda_{\rm QCD}}$, $\Lambda_{\rm QCD}$;

$\hookrightarrow$ 4 modes: hard, hard-collinear, collinear, soft;

$\hookrightarrow$ factorization: separating scales;



- QCDF: To leading power in $1/m_b$, $\langle M_1 M_2|\mathcal{O}_i|\bar{B}\rangle$ obeys the following factorization formula: [*Beneke, Buchalla, Neubert, Sachrajda, '99-'04*]

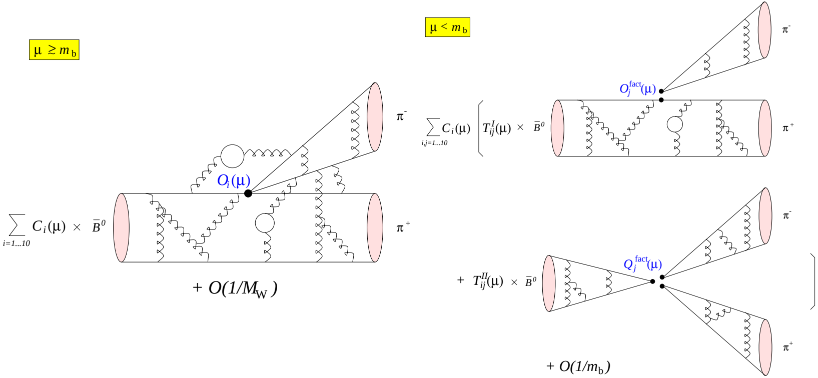
$$\langle M_1 M_2|\mathcal{O}_i|\bar{B}\rangle \simeq m_B^2\, F_+^{BM_1}(0)\, f_{M_2} \int du\; T_i^I(u)\, \phi_{M_2}(u) + (M_1 \leftrightarrow M_2)$$

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

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

QCDF approach:

- QCDF formula: [*Beneke, Buchalla, Neubert, Sachrajda, '99-'04*]



- A rigorous and systematic framework to all orders in α_s, but limited by $1/m_b$ corrections.

- Soft-collinear factorization proof more transparent in the SCET formalism; [Bauer, Flemming, Pirjol, Stewart, '01; Beneke, Chapovsky, Diehl, Feldmann, '02]

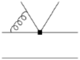
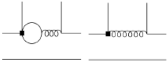
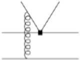
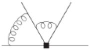
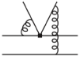
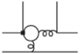
Status of QCDF/SCET:

- ## 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)

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

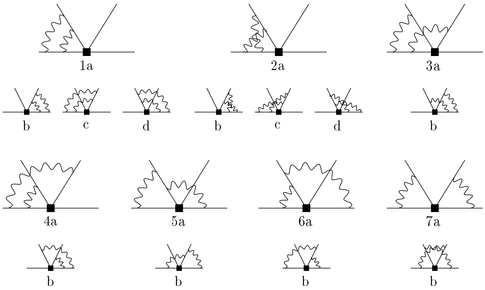
and two classes of topological amplitudes: "Tree", "Penguin".

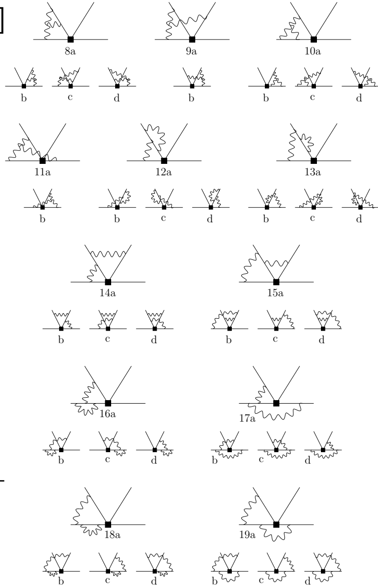
	T^I, tree	T^I, penguin	T^{II}, tree	T^{II}, penguin
LO: $\mathcal{O}(1)$				
NLO: $\mathcal{O}(\alpha_s)$ BBNS '99-'04				
NNLO: $\mathcal{O}(\alpha_s^2)$	 Bell '07,'09 Beneke, Huber, Li '09	 Kim, Yoon '11, Bell Beneke, Huber, Li '15	 Beneke, Jager '05 Kivel '06, Pilipp '07	 Beneke, Jager '06 Jain, Rothstein,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

- **Status**: 2-loop vertex and penguin amplitudes with all $\mathcal{O}_i$ insertions finished!

Two-loop Feynman diagrams for tree amplitudes:

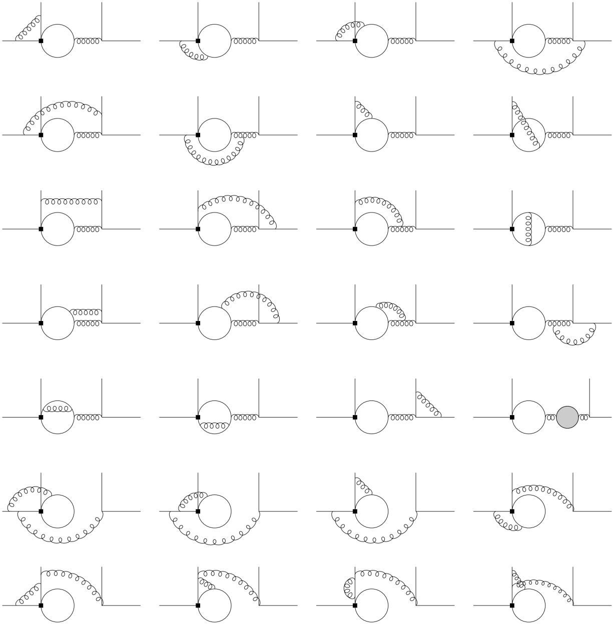
- Two-loop non-fact. diagrams: [*BBNS '00*]





  - ▷ totally 62 "non-factorizable" diagrams;
  - ▷ vacuum polarization insertions in gluon propagators;
  - ▷ the one-loop counter-term insertions;

Two-loop Feynman diagrams for penguin amplitude:



- totally more than a hundred diagrams;
- one-loop $\mathcal{O}(\alpha_s^2)$ insertion of Q_{8g};
- insertion with both $Q_{1,2}$ and Q_{3-6};

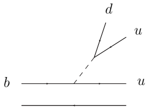
Motivation for NNLO calculation:

- Motivation for these nontrivial NNLO calculations:
  - ▷ conceptually: check if factorization theorem still held at the NNLO? needed to check the reliability of the pert. expansion and reduce scale uncertainties.
  - ▷ phenomenologically: strong phases are of $\mathcal{O}(\alpha_s)$ or of $\mathcal{O}(1/m_b)$, both of $\mathcal{O}(1/10)$, unclear whether direct CP dominated by short- or long-distance.

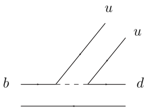
$\hookrightarrow$ NNLO is only the LO correction, quite relevant for short-distance direct CP!

  - ▷ exp. data driven: α_2 seems to be too small, and the $A_{CP}(\pi K)$ puzzle;

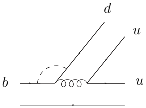
- For a 2-body decay, three topological amplitudes most relevant:



colour-allowed tree α_1



colour-suppressed tree α_2



QCD penguins α_4

Final numerical results:

- Numerical results for the tree amplitudes a_1 and a_2:

$$a_1(\pi\pi) = 1.009 + [0.023 + 0.010\,i]_{\rm NLO} + [0.026 + 0.028\,i]_{\rm NNLO}$$

$$- \left[\frac{r_{\rm sp}}{0.445}\right] \Big\{[0.014]_{\rm LOsp} + [0.034 + 0.027i\,]_{\rm NLOsp} + [0.008]_{\rm tw3}\Big\}$$

$$= 1.000^{+0.029}_{-0.069} + (0.011^{+0.023}_{-0.050})i$$

$$a_2(\pi\pi) = 0.220 - [0.179 + 0.077\,i]_{\rm NLO} - [0.031 + 0.050\,i]_{\rm NNLO}$$

$$+ \left[\frac{r_{\rm sp}}{0.445}\right] \Big\{[0.114]_{\rm LOsp} + [0.049 + 0.051i\,]_{\rm NLOsp} + [0.067]_{\rm tw3}\Big\}$$

$$= 0.240^{+0.217}_{-0.125} + (-0.077^{+0.115}_{-0.078})i$$

- Large cancellation between LO and NLO for α_2, particularly sensitive to NNLO;

- NNLO to vertex and spectator terms separately significant, but tend to cancel!

Final numerical results:

- Numerical results for the leading penguin amplitudes a_4^p:

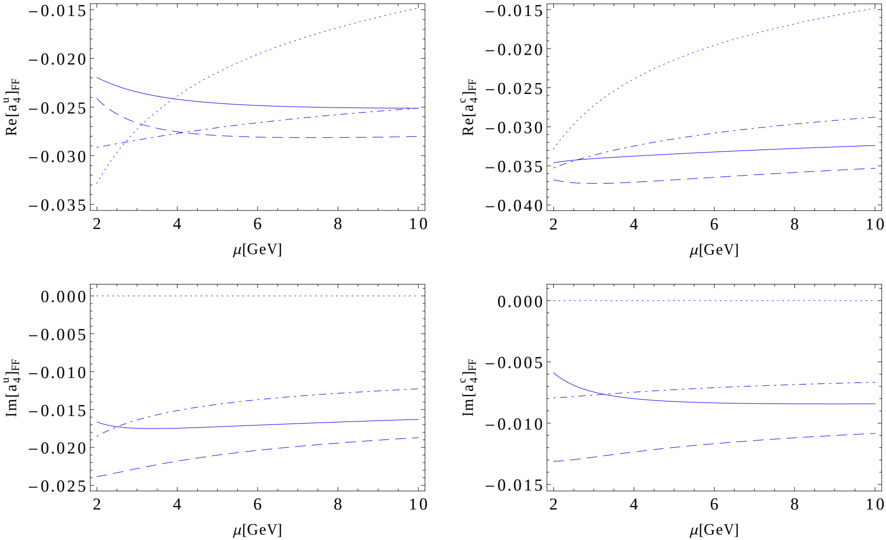
$$a_4^u(\pi\bar{K})/10^{-2} = -2.87 - [0.09 + 0.09i]_{\mathrm{V}_1} + [0.49 - 1.32i]_{\mathrm{P}_1}$$
$$- [0.32 + 0.71i]_{\mathrm{P}_2,\,\mathrm{Q}_{1,2}} + [0.33 + 0.38i]_{\mathrm{P}_2,\,\mathrm{Q}_{3-6,8}}$$
$$+ \left[\frac{r_{\mathrm{sp}}}{0.434}\right] \left\{[0.13]_{\mathrm{LO}} + [0.14 + 0.12i]_{\mathrm{HV}} - [0.01 - 0.05i]_{\mathrm{HP}} + [0.07]_{\mathrm{tw3}}\right\}$$
$$= (-2.12^{+0.48}_{-0.29}) + (-1.56^{+0.29}_{-0.15})i$$

$$a_4^c(\pi\bar{K})/10^{-2} = -2.87 - [0.09 + 0.09i]_{\mathrm{V}_1} + [0.05 - 0.62i]_{\mathrm{P}_1}$$
$$- [0.77 + 0.50i]_{\mathrm{P}_2,\,\mathrm{Q}_{1,2}} + [0.33 + 0.38i]_{\mathrm{P}_2,\,\mathrm{Q}_{3-6,8}}$$
$$+ \left[\frac{r_{\mathrm{sp}}}{0.434}\right] \left\{[0.13]_{\mathrm{LO}} + [0.14 + 0.12i]_{\mathrm{HV}} + [0.01 + 0.03i]_{\mathrm{HP}} + [0.07]_{\mathrm{tw3}}\right\}$$
$$= (-3.00^{+0.45}_{-0.32}) + (-0.67^{+0.50}_{-0.39})i$$

- Large cancellation between $Q_{1,2}$ and $Q_{3-6,8}$ insertions;
- Further detailed pheno. analyses for all 130 decay modes in progress.

Scale dependence of a_4^p on μ_b:

Dotted: LO; Dash-dotted: NLO; Dashed: NNLO$_{Q_{1,2}}$; Solid line: NNLO$_{Q_{1,2,3-6,8}}$



Conclusion and outlook

- High-luminosity frontier 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, $15\% \sim 20\%$ NP effect in most FCNC processes often possible;
- LFUV observed in B decays might be the first hint of NP! $\rightarrow$ hot topic in B physics!
- Non-trivial NNLO calculations in QCDF at leading power finished; NLO short-distance direct CP available.

Thank You for Your Attention!