Exclusive FCNC decays - Hadronic Input and Observables

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⊛ Preface

- $b \to s\ell^+\ell^-$ and $b \to d\ell^+\ell^-$ FCNC transitions,
  data on exclusive semileptonic decays being accumulated by LHCb:
  $B \to K\ell^+\ell^-$, $B \to \pi\mu^+\mu^-$, $B \to K^*\ell^+\ell^-$, $B_s \to \phi\ell^+\ell^-$, ...
- to disentangle short-distance FCNC transitions in these decays,
  to identify Standard Model contributions and search for/constrain New Physics
  one needs the hadronic input (not only form factors !)
- recent study of $B \to \pi\ell^+\ell^-$:
  [C. Hambrock, A. K. , A. Rusov, PRD **92** (2015) [arXiv:1506.07760 [hep-ph]],
  - calculate hadronic input at the large recoil of the pion
  - predict observables, including direct CP-asymmetry
- how accurate is $|V_{td}/V_{ts}|$ from the ratio
  $\Gamma(B \to \pi\ell^+\ell^-)/\Gamma(B \to K\ell^+\ell^-)$?
- brief comments on $B_{(s)} \to V\ell^+\ell^-$, $V = K^*, \rho, \phi$

⊛ FCNC transitions in Standard Model

- the $b \to d\ell^+\ell^-$ effective Hamiltonian

$$H_{\rm eff}^{b\to d} = \frac{4G_F}{\sqrt{2}}\Big[-\lambda_t(C_9\mathcal{O}_9 + C_{10}\mathcal{O}_{10} + C_7\mathcal{O}_{7\gamma})$$

$$-\lambda_t \sum_{i=3,4,5,6,8g} C_i\,\mathcal{O}_i + \lambda_c \sum_{i=1,2} C_i\,\mathcal{O}_i^c + \lambda_u \sum_{i=1,2} C_i\,\mathcal{O}_i^u\Big] + h.c.\,,$$

$\lambda_p = V_{pb}V^*_{pd},\ (p=u,c,t)\,,$ $\quad |\lambda_u| \lesssim |\lambda_c| \sim |\lambda_t|,$

- hereafter $\lambda_t = -(\lambda_u+\lambda_c)$, with $\sim \lambda_u$ and $\sim \lambda_c$ parts separated
- direct CP violation (CKM phase in λ_u) a noticeable effect in SM
- $H_{\rm eff}^{b\to s}$ governing the $b \to s\ell^+\ell^-$ transitions: CKM enhanced,
  has a less "rich" structure, with srongly suppressed $\sim \lambda_u$ part and $\lambda_t \simeq -\lambda_c$

⊛ Decay amplitude

- compact form:

$$A(B \to \pi \ell^+ \ell^-) = \frac{G_F}{\sqrt{2}} \lambda_t \frac{\alpha_{\rm em}}{\pi} f^+_{B\pi}(q^2) \Bigg[(\bar{\ell}\gamma^\mu \ell)\, p_\mu \Bigg(C_9 + \Delta C_9^{(B\pi)}(q^2) + \frac{2m_b}{m_B + m_\pi} C_7^{\rm eff} \frac{f^T_{B\pi}(q^2)}{f^+_{B\pi}(q^2)} \Bigg) + (\bar{\ell}\gamma^\mu \gamma_5 \ell)\, p_\mu C_{10} \Bigg],$$

- all "background" effects: the operators $O_{i=1,2,3,...6,8g}$ combined with e.m. lepton pair, collected in (process- and q^2-dependent)

$$\Delta C_9^{(B\pi)}(q^2) = -\frac{16\pi^2}{f^+_{B\pi}(q^2)} \left(\frac{\lambda_u}{\lambda_t} \mathcal{H}^{(u)}(q^2) + \frac{\lambda_c}{\lambda_t} \mathcal{H}^{(c)}(q^2) \right),$$

- defined via two nonlocal hadronic matrix elements

$$\mathcal{H}^{(p)}(q^2) \left[(p\cdot q) q_\mu - q^2 p_\mu \right] = i \int d^4x e^{iqx} \langle \pi(p) | \mathrm{T}\Big\{ j^{\rm em}_\mu(x), \Big[C_1 \mathcal{O}^p_1(0) + C_2 \mathcal{O}^p_2(0) + \sum_{k=3-6,8g} C_k \mathcal{O}_k(0) \Big] \Big\} | B(p+q) \rangle, \quad (p = u, c),$$

⊛ Input: $B \to \pi$ form factors

- form factors :

$$\langle\pi(p)|\bar{d}\gamma^\mu b|B(p+q)\rangle = 2p^\mu f^+_{B\pi}(q^2) + \mathcal{O}(q^\mu),$$

$$\langle\pi(p)|\bar{d}\sigma^{\mu\nu}q_\nu b|B(p+q)\rangle = 2p^\mu q^2 \frac{if^T_{B\pi}(q^2)}{m_B+m_\pi} + O(q^\mu)$$

- the update of the vector form factor from LCSR:

I. S.Imsong, A.K., T. Mannel and D. van Dyk, JHEP **1502** (2015) 126 [arXiv:1409.7816 [hep-ph]]

$$f^+_{B\pi}(q^2) = \frac{f^+_{B\pi}(0)}{1-q^2/m^2_{B*}}\Big\{1 + b_1^+\Big[z(q^2,t_0) - z(0,t_0) - \frac{1}{3}\Big(z(q^2,t_0)^3 - z(0,t_0)^3\Big)\Big]$$
$$+ b_2^+\Big[z(q^2,t_0)^2 - z(0,t_0)^2 + \frac{2}{3}\Big(z(q^2,t_0)^3 - z(0,t_0)^3\Big)\Big]\Big\},$$

$f^+_{B\pi}(0) = 0.307 \pm 0.020$, $b_1^+ = -1.31 \pm 0.42$, $b_2^+ = -0.904 \pm 0.444$

- the ratio $f^T_{B\pi}(q^2)/f^+_{B\pi}(q^2)$ from LCSR

G. Duplancic, A.K., T. Mannel, B. Melic and N. Offen, JHEP **0804** (2008) 014 [arXiv:0801.1796 [hep-ph]].

⊛ How do we calculate $\Delta C_9^{(B\pi)}(q^2)$?

the method originally used for $B \to K\ell\ell$

[A. K., T. Mannel and Y. M. Wang, JHEP **1302** (2013) 010 [arXiv:1211.0234 [hep-ph]]]

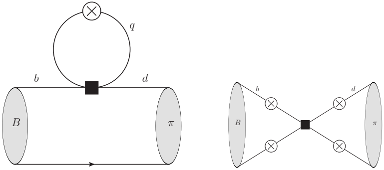
- calculate the correlation functions $\mathcal{H}^{(u,c)}(q^2 < 0)$ at $|q^2| \gg \Lambda^2_{QCD}$
- include soft-gluon nonfactorizable contributions

  A.K., T. Mannel, A. A. Pivovarov and Y.-M. Wang, JHEP **1009** (2010) 089 [arXiv:1006.4945 [hep-ph]].
- for NLO (hard-gluon) contributions we use QCD factorization (QCDF) (at $q^2 < 0$!)

  M. Beneke, T. Feldmann and D. Seidel, Nucl. Phys. B **612** (2001) 25; [hep-ph/0106067];
  Eur. Phys. J. C **41**, 173 (2005) [hep-ph/0412400].
- effect of penguin operators $O_{3,4,5,6,8g}$ at the level of $\leq 10\%$ in the observables
- $\mathcal{H}^{(u,c)}(q^2 > 0)$ obtained matching our calculation at $q^2 < 0$ to the hadronic dispersion relation in q^2
- including $V = \rho, \omega, \phi, J/\psi, \psi(2S)$ resonances; inputs: decay constants of V's, $B \to V\pi$ nonleptonic amplitudes (experimental BRs and QCDF)
- the result valid at large recoil $q^2 \ll m_b^2$, up to charmonium region

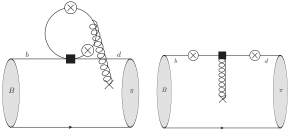
⊛ Calculating nonlocal amplitude at $q^2 < 0$

- LO diagrams: factorizable loop and weak annihilation (QCDF)



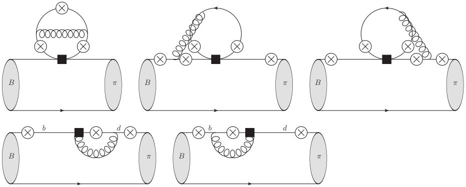
- soft-gluon nonfactorizable contraibutions

  (LCSR with *B*-meson DA):



⊛ NLO contributions

- generate Im- part at $q^2 < 0$ dual to FSI
- NLO factorizable effects

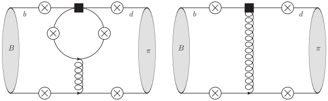


two-loop diagrams with c and massless u loops

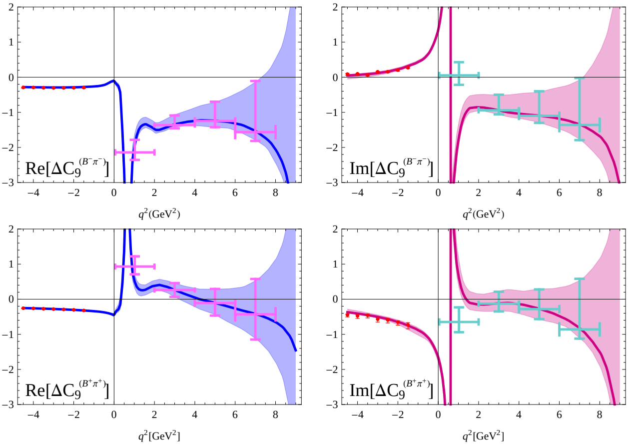
H. H. Asatryan, H. M. Asatrian, C. Greub and M. Walker, Phys. Rev. D **65** (2002) 074004 [hep-ph/0109140];

H. M. Asatrian, K. Bieri, C. Greub and M. Walker, Phys. Rev. D **69** (2004) 074007 [hep-ph/0312063].

- Nonfactorizable hard spectator scattering



⊛ Numerical results: $\Delta C_9(q^2)$ for $B^\pm \to \pi^\pm \ell^+ \ell^-$



points: calculated $\Delta C_9^{(B\pi)}(q^2 < 0)$, crosses: binned $\Delta C_9^{(B\pi)}(q^2 > 0)$,

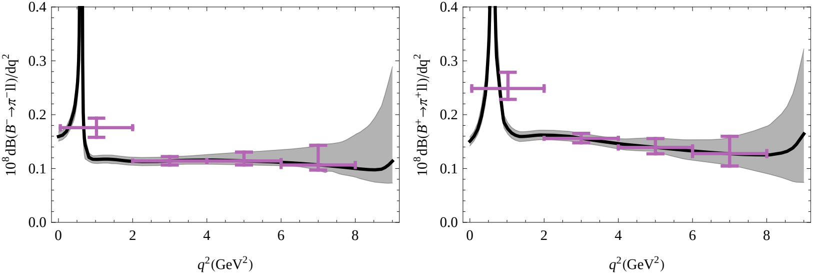
solid line/shaded area - fit/errors

⊛ Observables in $B \to \pi \ell^+ \ell^-$

- the dilepton invariant mass spectrum:

$$\frac{d\mathrm{Br}(B \to \pi \ell^+ \ell^-)}{dq^2} = \frac{G_F^2 \alpha_{\rm em}^2 |\lambda_t|^2}{1536\pi^5 m_B^3} |f^+_{B\pi}(q^2)|^2 \lambda^{3/2}(m_B^2, q^2, m_\pi^2)$$

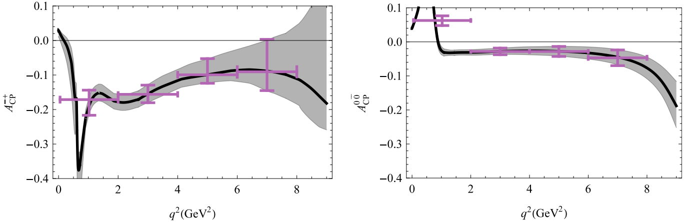
$$\times \left\{ \left| C_9 + \Delta C_9^{B\pi}(q^2) + \frac{2m_b}{m_B + m_\pi} C_7 \frac{f^T_{B\pi}(q^2)}{f^+_{B\pi}(q^2)} \right|^2 + |C_{10}|^2 \right\} \tau_B \, .$$



crosses: binned BRs, solid line/shaded area - fit/errors

⊛ Observables in $B \to \pi \ell^+ \ell^-$

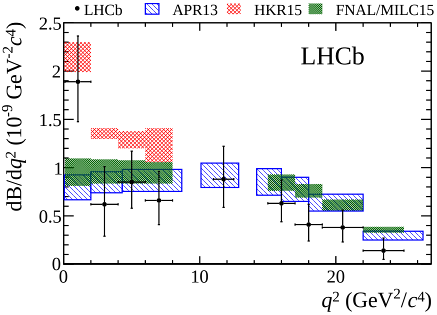
- direct CP-asymmetry



- Binned observables: *CP*-asymmetry and isospin asymmetry

Bin $[GeV^2]$	[0.05, 2.0]	[2.0, 4.0]	[4.0, 6.0]	[6.0, 8.0]	[1.0, 6.0]
$\mathcal{A}_{CP}^{(-+)}$	$-0.171^{+0.027}_{-0.045}$	$-0.156^{+0.027}_{-0.024}$	$-0.099^{+0.047}_{-0.025}$	$-0.091^{+0.093}_{-0.053}$	$-0.143^{+0.035}_{-0.029}$
$\mathcal{A}_{CP}^{(\bar{0}0)}$	$0.063^{+0.014}_{-0.015}$	$-0.028^{+0.010}_{-0.010}$	$-0.028^{+0.015}_{-0.015}$	$-0.047^{+0.023}_{-0.023}$	$-0.008^{+0.013}_{-0.013}$
$\mathcal{A}_I$	$-0.195^{+0.033}_{-0.035}$	$-0.020^{+0.031}_{-0.032}$	$-0.021^{+0.035}_{-0.053}$	$-0.021^{+0.060}_{-0.100}$	$-0.063^{+0.033}_{-0.040}$

⊛ recent measurement of $B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ at LHCb



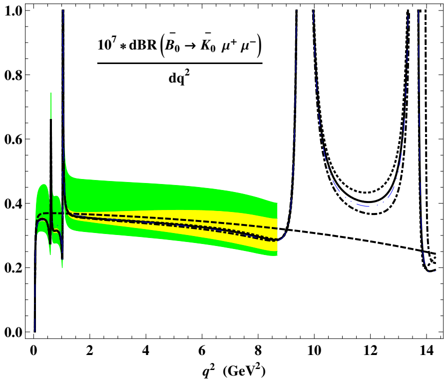
from [LHCb collaboration, ArXiv:1509.00414 [hep-ex]]

measured total $\mathcal{A}(B^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}) = -0.11 \pm 0.12 \pm 0.01$

⊛ earlier analysis of $B \to K\ell\ell$

- the dilepton invariant mass spectrum:

from A. K., T. Mannel and Y. M. Wang, JHEP **1302** (2013) 010 [arXiv:1211.0234 [hep-ph]],



green (yellow) band -uncertainties of $B \to K$ form factors (of nonlocal effects)

- a larger error of $B \to K$ form factor, less complicated nonlocal effects , binned BR somewhat larger than central exp. [LHCb'12] values

⊛ Can one extract $|V_{td}/V_{ts}|$ from the ratio of FCNC decays ?

- the ratio of the differential widths:

$$R(q^2) = \frac{d\Gamma(B\to\pi\ell^+\ell^-)/dq^2}{d\Gamma(B\to K\ell^+\ell^-)/dq^2} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{|f^+_{B\pi}(q^2)|^2}{|f^+_{BK}(q^2)|^2}\frac{\lambda^{3/2}(m_B^2,q^2,m_\pi^2)}{\lambda^{3/2}(m_B^2,q^2,m_K^2)}$$

$$\times\frac{\left|C_9+\Delta C_9^{B\pi}(q^2)+\frac{2m_b}{m_B+m_\pi}C_7\frac{f^T_{B\pi}(q^2)}{f^+_{B\pi}(q^2)}\right|^2+|C_{10}|^2}{\left|C_9+\Delta C_9^{BK}(q^2)+\frac{2m_b}{m_B+m_\pi}C_7\frac{f^T_{BK}(q^2)}{f^+_{BK}(q^2)}\right|^2+|C_{10}|^2}$$

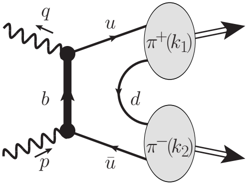
- the ratio in the second line contains different nonlocal contributions, the numerator also depends on V_{ub} !
- we plan to calculate this ratio more accurately
  (need correlated theoretical uncertainties in both hadronic inputs)

⊛ $B \to K^*\ell\ell$, current status

- a complete calculation of nonlocal hadronic effects not yet available (separate parts, in different approaches)
- a systematic account of nonlocal effects at $q^2 \ll 0 \oplus$ hadronic dispersion relation at $q^2 > 0$
- before that the accuracy of the form factors has to be improved $B \to K\pi(K^*)$, $B \to \pi\pi(\rho)$ etc.
- how important are $\ell \neq 1$ partial waves in dimeson system; how dominant is K^* vs nonresonant background in the P-wave?

$B \to \pi\pi$ form factors

- form factors in $B \to \pi\pi\ell\nu_\ell$,
  partial wave expansion & resonances: ρ (P-wave) , f_0 (S-wave), ...
  regions of Dalitz plot with specific QCD dynamics
  [S. Faller, T. Feldmann, A. Khodjamirian, T. Mannel and D. van Dyk, (2013)]
- calculating the $B \to \pi\pi$ form factors in $B \to \pi\pi\ell\nu_\ell$ at low 2-pion mass and small q^2 from LCSR C. Hambrock and A. K., arXiv:1511.02509 [hep-ph].



- the region: $q^2 \ll m_b^2$ (b-quark virtual)
  $k^2 \ll m_b^2$ (2-pion system produced near the LC)

- new nonperturbative input: dipion distribution amplitudes (including resonances)

Conclusions

- hadronic input and observables in $B \to \pi \ell\ell$ and $B \to K \ell\ell$ calculated in the large recoil region, $0 < q^2 \lesssim m^2_{J/\psi}$
- "systematic error": dependence on the hadronic ansatz in the dispersion relation
- accuracy improvable, common input , correlations , more data on nonleptonic $B \to VP$ decays
- most interesting - binned direct CP -asymmetry in $B \to \pi \ell^+ \ell^-$
  less dependent on the input
- $B \to PP(V)\ell\ell$, still a lot of work ahead !

BACKUP SLIDES

⊛ Hierarchy of effective operators in $b \to d\ell\ell$

- "direct" $b \to d\ell\ell$, $b \to d\gamma$ operators:

$$O_{9(10)} = \frac{\alpha_{em}}{4\pi}[\bar{d}_L\gamma_\mu b_L]\ell\gamma^\mu(\gamma_5)\ell, \quad C_9(m_b) \simeq 4.4, \quad C_{10}(m_b) \simeq= -4.7,$$

$$O_{7\gamma} = -\frac{em_b}{8\pi^2}[\bar{d}\sigma_{\mu\nu}(1+\gamma_5)b]F^{\mu\nu}, \quad C_7(m_b) \simeq -0.3$$

- quark-gluon operators, combined with quark e.m. current:

$$O_1^{(c)} = [\bar{d}_L\gamma_\rho c_L][\bar{c}_L\gamma^\rho b_L], \qquad C_1(m_b) \simeq 1.1$$
$$O_2^{(c)} = [\bar{c}_L\gamma_\rho c_L][\bar{d}_L\gamma^\rho b_L], \qquad C_2(m_b) \simeq -0.25$$

$$O_1^{(u)} = [\bar{d}_L\gamma_\rho u_L][\bar{u}_L\gamma^\rho b_L],$$
$$O_2^{(u)} = [\bar{u}_L\gamma_\rho u_L][\bar{d}_L\gamma^\rho b_L],$$

$$O_{8g} = -\frac{m_b}{8\pi^2}\bar{d}\sigma_{\mu\nu}(1+\gamma_5)bG^{\mu\nu}, \quad C_8(m_b) \simeq 0.2$$

O_{3-6} - quark-penguin operators, $\quad C_{3,4,5,6} < 0.03$

- in $b \to s\ell\ell$: $O_{1,2}^{(u)}$ multiplied by strongly suppressed CKM factor and neglected

⊛ Accessing $\Delta C_9(q^2 > 0)$

- hadronic dispersion relation

$$\mathcal{H}^{(p)}(q^2) = \mathcal{H}^{(p)}(q_0^2) + (q^2 - q_0^2)\left[\sum_{V=\rho,\omega,\phi,J/\psi,\psi(2S)} \frac{f_V A^p_{BV\pi}}{(m_V^2 - q_0^2)(m_V^2 - q^2 - i m_V \Gamma_V^{\rm tot})} + \int\limits_{s_h^p}^{\infty} ds \frac{\rho_h^{(p)}(s)}{(s - q_0^2)(s - q^2 - i\epsilon)}\right], \quad (p = u, c)\,.$$

- one subtraction at $q_0^2 = -1.0$ GeV^2 for a better convergence
- f_V -decay constants of vector mesons,
  $A^{u,c}_{BV\pi}$ are the $\sim \lambda_{u,c}$ parts of $B \to V\pi$ nonleptonic amplitudes ,
  their moduli fixed using experimental information and QCDF
- integral over continuum/excited states replaced with semi-local duality approximation (LO contributions)) up to $s = 4m_D^2$, the tail $4m_D^2 < s < \infty$ fitted in polynomial form
- relative phases emerging, to be fitted by matching to l.h.s.
- finally obtain $\Delta C_9^{(B\pi)}(q^2 > 0)$, adding up the calculated $\mathcal{H}^{(u,c)}(q^2 > 0)$ weighted by $\lambda_{u.c}$, divided by $f^+_{B\pi}(q^2)$

⊛ Input: Nonleptonic decays $B \to V\pi$

- $B \to \rho(\omega)\pi$ decays, separate $\sim \lambda_u$ and $\sim \lambda_c$ parts of the amplitudes calculated from QCDF; cross-check with experiment:

Channel	Observable	Experiment	QCDF*)	QCDF, this work
$B^\pm \to \rho^0\pi^\pm$	$\mathrm{BR} \times 10^{-6}$	8.3 ± 1.2	$11.9^{+7.8}_{-6.1}$	$9.4^{+2.9}_{-1.9}$
	$\mathcal{A}_{CP}$	$0.18^{+0.09}_{-0.17}$	0.04 ± 0.19	0.08 ± 0.14
$B^\pm \to \omega^0\pi^\pm$	$\mathrm{BR} \times 10^{-6}$	6.9 ± 0.5	$8.8^{+5.4}_{-4.3}$	$8.8^{+2.8}_{-1.7}$
	$\mathcal{A}_{CP}$	-0.04 ± 0.06	-0.02 ± 0.04	-0.06 ± 0.06

*) M. Beneke and M. Neubert, Nucl. Phys. B **675** (2003) 333 [hep-ph/0308039].

- $B \to J/\psi\pi$ and $B \to \psi(2S)\pi$ not well described by QCDF, but $\sim \lambda_u$ part is small (originating from quark-penguins), we use BR's and upper limits for A_{CP};

- moduli of nonleptonic amplitudes used in the dispersion relation

Mode	$\lvert A^u_{BV\pi}\rvert$	$\lvert A^c_{BV\pi}\rvert$
$B^\pm \to \rho\pi^\pm$	$20.7^{+2.6}_{-2.1}$	$1.2^{+0.9}_{-0.4}$
$B^\pm \to \omega\pi^\pm$	$19.1^{+2.7}_{-2.0}$	$0.3^{+0.3}_{-0.1}$
$B^\pm \to J/\psi\pi^\pm$	$0.1^{+1.3}_{-0.1}$	29.2 ± 1.7
$B^\pm \to \psi(2S)\pi^\pm$	$2.8^{+6.7}_{-2.8}$	32.9 ± 2.2
$B^\pm \to \varphi^0\pi^\pm$	0	0

Mode	$\lvert A^u_{BV\pi}\rvert$	$\lvert A^c_{BV\pi}\rvert$
$B^0 \to \rho\pi^0$	$3.6^{+0.4}_{-0.5}$	0
$B^0 \to \omega\pi^0$	0	0
$B^0 \to J/\psi\pi^0$	$0.0^{+0.9}_{-0.0}$	19.8 ± 1.1
$B^0 \to \psi(2S)\pi^0$	$2.0^{+4.7}_{-2.0}$	23.3 ± 1.6
$B^0 \to \varphi^0\pi^0$	0	0

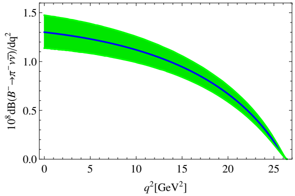
⊛ pure FCNC decay $B \to \pi\nu\bar{\nu}$

- only one effective operator in SM, nonlocal effects absent

($B \to K\nu\bar{\nu}$, M. Bartsch, M. Beylich, G. Buchalla and D.-N. Gao, JHEP **0911** (2009) [arXiv:0909.1512])

$$\mathcal{H}_{\rm eff}^{b\to d\nu\bar{\nu}} = -\frac{4G_F}{\sqrt{2}}\lambda_t C^\nu \mathcal{O}^\nu, \quad \mathcal{O}^\nu = \frac{\alpha_{\rm em}}{4\pi}(\bar{d}_L\gamma_\mu b_L)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

$$\sum_{\ell=e,\mu,\tau}\frac{d{\rm Br}(B\to\pi\nu_\ell\bar{\nu}_\ell)}{dq^2} = \tau_B\frac{G_F^2\alpha_{\rm em}^2}{256\pi^5 m_B^3}|V_{td}V_{tb}^*|^2\lambda^{3/2}(q^2)|C^\nu|^2|f_+^{(B\pi)}(q^2)|^2$$



$q^2 = m_B^2 + m_\pi^2 - 2m_B E_\pi$