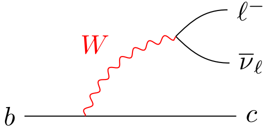
Heavy Quark Expansion for inclusive Semileptonic Decays

K. Keri Vos

Maastricht University & Nikhef

Exclusive versus Inclusive Theory



- Theory (Weak interaction): Transitions between quarks/partons

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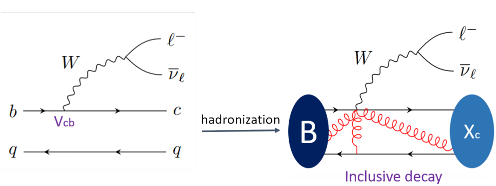


- Theory (Weak interaction): Transitions between quarks/partons
- Observation: Transitions between hadrons

Challenge:

- Dealing with QCD at large distances/small scales
- Parametrize fundamental mismatch in non-perturbative objects
  - Calculable: Lattice or Light-cone sumrules
  - Measurable: from data

Why inclusive decays?

- Set up OPE and heavy quark expansion
- Well established for B decays, precise framework
- Extract important CKM parameters V_{cb} and V_{ub}
- Extract power corrections from data
- Cross check of exclusive decays

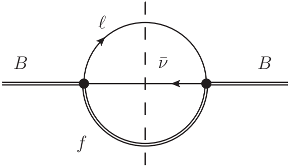
Heavy Quark Expansion

Setting up the OPE

Chay, Georgi, Bigi, Shifman, Uraltsev, Vainstain, Manohar, Wise, Neubert, Mannel, $\cdots$

- b quark mass is large compared to Λ_{QCD}
- Setting up the HQE: momentum of b quark: $p_b = m_b v + k$, expand in $k \sim iD$
- Field-redefinition of the heavy field

Operator Product Expansion (OPE)

$2\,\mathrm{Im}$ 

$= \sum_{n,i} \frac{C_i^{(n)}(\mu,\alpha_s)}{m_b^i} \langle B|\mathcal{O}_i^{(n)}|B\rangle_\mu$

- $\mathcal{C}_i(\mu)$: short distance, perturbative coeficients
- $\langle B|\mathcal{O}_i|B\rangle_\mu$: non-perturbative forward matrix elements of local operators
- operators contain chains of covariant derivatives

$$\langle B|\mathcal{O}_i^{(n)}|B\rangle = \langle B|\bar{b}_v(iD_\mu)\ldots(iD_{\mu_n})b_v|B\rangle$$

Decay rate

Γ_i are power series in $\mathcal{O}(\alpha_s)$

$$\Gamma = \Gamma_0 + \frac{1}{m_b}\Gamma_1 + \frac{1}{m_b^2}\Gamma_2 + \frac{1}{m_b^3}\Gamma_3 \cdots$$

- Γ_0: decay of the free quark (partonic contributions), $\Gamma_1 = 0$
- Γ_2: μ_π^2 kinetic term and the μ_G^2 chromomagnetic moment

$$2M_B\mu_\pi^2 = -\left\langle B|\bar{b}_v iD_\mu iD^\mu b_v|B\right\rangle$$
$$2M_B\mu_G^2 = \left\langle B|\bar{b}_v(-i\sigma^{\mu\nu})iD_\mu iD_\nu b_v|B\right\rangle$$

- Γ_3: ρ_D^3 Darwin term and ρ_{LS}^3 spin-orbit term

$$2M_B\rho_D^3 = \frac{1}{2}\left\langle B|\bar{b}_v\left[iD_\mu,[ivD, iD^\mu]\right]b_v|B\right\rangle$$
$$2M_B\rho_{LS}^3 = \frac{1}{2}\left\langle B|\bar{b}_v\left\{iD_\mu,\left[ivD, iD_\nu\right]\right\}(-i\sigma^{\mu\nu})b_v|B\right\rangle$$

- Γ_4: 9 parameters Mannel, Turczyk, Uraltsev, JHEP 1010 (2011) 109
- Γ_5: 18 parameters Mannel, Turczyk, Uraltsev, JHEP 1010 (2011) 109

Inclusive $B \to X_c$ decays

Heavy Quark Expansion

Inclusive $B \to X_c \ell \nu$: Heavy Quark Expansion (HQE)

$m_Q \sim m_q \gg \Lambda_{\rm QCD}$ OPE for $b \to c \ell \bar{\nu}$

- q is treated as a heavy degree of freedom
- two-quarks operators: $\bar{Q}_v (iD^\alpha \cdots iD^\beta) Q_v$
- IR sensitivity to mass m_q

$$\Gamma\Big|_{1/m_Q^3} = \left[\frac{34}{3} + 8 \log \rho + \ldots\right] \frac{\rho_D^3}{m_Q^3}, \quad \text{with } \rho = (m_q/m_Q)^2$$

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- HQE parameters extracted from lepton energy, hadronic mass and q^2 moments
- Recent progress: ideas for the lattice Juetner et al. [2305.14092]

Moments of the spectrum

BABAR, PRD 68 (2004) 111104; BABAR, PRD 81 (2010) 032003; Belle, PRD 75 (2007) 032005

Non-perturbative matrix elements obtained from moments of differential rate

Charged lepton energy

$$\langle E^n \rangle_{\rm cut} = \frac{\int_{E_\ell > E_{\rm cut}} dE_\ell \, E_\ell^n \, \frac{d\Gamma}{dE_\ell}}{\int_{E_\ell > E_{\rm cut}} dE_\ell \, \frac{d\Gamma}{dE_\ell}}$$

Hadronic invariant mass

$$\langle (M_X^2)^n \rangle_{\rm cut} = \frac{\int_{E_\ell > E_{\rm cut}} dM_X^2 \, (M_X^2)^n \, \frac{d\Gamma}{dM_X^2}}{\int_{E_\ell > E_{\rm cut}} dM_X^2 \, \frac{d\Gamma}{dM_X^2}}$$

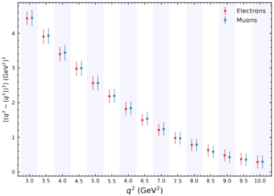
Dilepton momentum

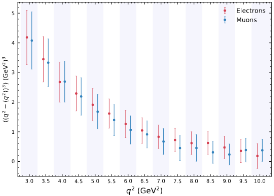
$$\langle (q^2) \rangle_{\rm cut} = \frac{\int_{q^2 > q^2_{\rm cut}} dq^2 \, \frac{d\Gamma}{dq^2}}{\int_0 dq^2 \, \frac{d\Gamma}{dq^2}}$$

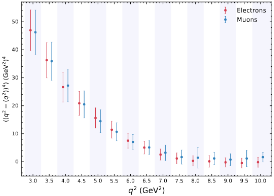
- Moments up to $n = 3, 4$ and with several energy cuts available
- Experimentally necessary to use some cut on the leptons

q^2 moments

Belle Collaboration [2109.01685, 2105.08001]







Centralized moments as function of $q^2_{\rm cut}$ [Talk by Markus Prim]

Determining V_{cb} and the HQE elements

$$\langle E_\ell^n \rangle, \langle (M_X^2)^n \rangle \quad \langle (q^2)^n \rangle_{\rm cut}$$

$$\downarrow$$

$$m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_d^3, r_E, r_G, s_E, s_B, s_{qB}, + \cdots$$

$$\downarrow$$

$$\mathrm{Br}(\bar{B} \to X_c \ell \bar{\nu}) \propto \frac{|V_{cb}|^2}{\tau_B} \left[\Gamma_{\mu_3} \mu_3 + \Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + \Gamma_{\tilde{\rho}_D} \frac{\tilde{\rho}_D^3}{m_b^3} + \Gamma_{r_E} \frac{r_E^4}{m_b^4} + \Gamma_{r_G} \frac{r_G^4}{m_b^4} + \Gamma_{s_B} \frac{s_B^4}{m_b^4} + \Gamma_{s_E} \frac{s_E^4}{m_b^4} + \Gamma_{s_{qB}} \frac{s_{qB}^4}{m_b^4} \right]$$

$$\downarrow$$

$$V_{cb}$$

State-of-the-art in inclusive $b \to c$

Jezabek, Kuhn, NPB 314 (1989) 1; Melnikov, PLB 666 (2008) 336; Pak, Czarnecki, PRD 78 (2008) 114015; Becher, Boos, Lunghi, JHEP 0712 (2007) 062; Alberti, Gambino, Nandi, JHEP 1401 (2014) 147; Mannel, Pivovarov, Rosenthal, PLB 741 (2015) 290; Fael, Schonwald, Steinhauser, Phys Rev. D 104 (2021) 016003; Fael, Schonwald, Steinhauser, Phys Rev. Lett. 125 (2020) 052003; Fael, Schonwald, Steinhauser, Phys Rev. D 103 (2021) 014005,

$$\Gamma \propto |V_{cb}|^2 m_b^5 \left[\Gamma_0 + \Gamma_0^{(1)} \frac{\alpha_s}{\pi} + \Gamma_0^{(2)} \left(\frac{\alpha_s}{\pi}\right)^2 + \Gamma_0^{(3)} \left(\frac{\alpha_s}{\pi}\right)^3 + \frac{\mu_\pi^2}{m_b^2} \left(\Gamma^{(\pi,0)} + \frac{\alpha_s}{\pi} \Gamma^{(\pi,1)}\right) \right.$$
$$\left. + \frac{\mu_G^2}{m_b^2} \left(\Gamma^{(G,0)} + \frac{\alpha_s}{\pi} \Gamma^{(G,1)}\right) + \frac{\rho_D^3}{m_b^3} (\Gamma^{(D,0)} + \Gamma_0^{(1)} \left(\frac{\alpha_s}{\pi}\right)) + \mathcal{O}\left(\frac{1}{m_b^4}\right) + \cdots \right)$$

- Include terms up to $1/m_b^4$* see also Gambino, Healey, Turczyk [2016]
- α_s^3 to total rate and kinetic mass Fael, Schonwald, Steinhauser [2020, 2021]
- $\alpha_s \rho_D^3$ for total rate Mannel, Pivovarov [2020]
- Kinetic mass scheme 1411.6560,1107.3100; hep-ph/0401063

E_ℓ, M_X moments:

$$|V_{cb}|^{\rm BCG}_{\rm incl} = (42.00 \pm 0.51) \times 10^{-3}$$

q^2 moments*:

$$|V_{cb}|^{q^2}_{\rm incl} = (41.69 \pm 0.63) \times 10^{-3}$$

Gambino, Schwanda, PRD 89 (2014) 014022;
Alberti, Gambino et al, PRL 114 (2015) 061802;
Bordone, Capdevila, Gambino, Phys.Lett.B 822 (2021) 136679; Bernlochner, Welsch, Fael, Olschewsky, Persson, van Tonder, KKV [2205.10274]

Towards the ultimate precision in inclusive V_{cb}

$$\Gamma \propto |V_{cb}|^2 m_b^5 \left[\Gamma_0 + \Gamma_0^{(1)} \frac{\alpha_s}{\pi} + \Gamma_0^{(2)} \left(\frac{\alpha_s}{\pi}\right)^2 + \Gamma_0^{(3)} \left(\frac{\alpha_s}{\pi}\right)^3 + \frac{\mu_\pi^2}{m_b^2} \left(\Gamma^{(\pi,0)} + \frac{\alpha_s}{\pi} \Gamma^{(\pi,1)} \right) \right.$$
$$\left. + \frac{\mu_G^2}{m_b^2} \left(\Gamma^{(G,0)} + \frac{\alpha_s}{\pi} \Gamma^{(G,1)} \right) + \frac{\rho_D^3}{m_b^3} (\Gamma^{(D,0)} + \Gamma_0^{(1)} \left(\frac{\alpha_s}{\pi}\right)) + \mathcal{O}\left(\frac{1}{m_b^4}\right) + \cdots \right)$$

Challenges:

- Include higher-order $1/m_b$ and α_s corrections
- Proliferation of non-perturbative matrix elements
  - 4 up to $1/m_b^3$
  - 13 up to $1/m_b^4$ Dassinger, Mannel, Turczyk, JHEP 0703 (2007) 087
  - 31 up to $1/m_b^5$ Mannel, Turczyk, Uraltsev, JHEP 1011 (2010) 109

The advantage of q^2 moments

Mannel, KKV, JHEP 1806 (2018) 115; Fael, Mannel, KKV, JHEP 02 (2019) 177

- Standard lepton energy and hadronic mass moments are not RPI quantities
- New q^2 moments are RPI!

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Reparametrization invariant quantities:

- Setting up the HQE: momentum of b quark: $p_b = m_b v + k$, expand in $k \sim iD$
- Choice of v not unique: Reparametrization invariance (RPI)

$$v_\mu \to v_\mu + \delta v_\mu$$

$$\delta_{RP}\ v_\mu = \delta v_\mu \ \text{ and } \ \delta_{RP}\ iD_\mu = -m_b \delta v_\mu$$

  - links different orders in $1/m_b \to$ reduction of parameters
  - up to $1/m_b^4$: 8 parameters (previous 13)

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- q^2 moments could enable a full extraction up to $1/m_b^4$

q^2 moments only analysis

Bernlochner, Welsch, Fael, Olschewsky, Persson, van Tonder, KKV [2205.10274]

$$|V_{cb}|^{q^2}_{\rm incl} = (41.69 \pm 0.27|_{\mathcal{B}} \pm 0.31|_{\Gamma} \pm 0.18|_{\rm exp.} \pm 0.17|_{\rm theo} \pm 0.34|_{\rm const.}) \times 10^{-3}$$

- First extraction using q^2 moments with $1/m_b^4$ terms
- Agreement with BCG extraction (differs due to branching ratio inputs)

  Bordone,Capdevila, Gambino [2021]

$$|V_{cb}|^{\rm BCG}_{\rm incl} = (42.00 \pm 0.51) \times 10^{-3}$$

- Higher order terms reduce value by 0.25%.

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$$|V_{cb}|^{q^2}_{\mathrm{incl}} = (41.69 \pm 0.63) \times 10^{-3}$$

- Extracted ρ_D smaller than previous Bernlochner, Prim, Fael, KKV [in progress]
- Higher order coefficients important to check convergence of the HQE

$$r_E^4 = (0.02 \pm 0.34) \cdot 10^{-1}\mathrm{GeV}^4 \quad r_G^4 = (-0.21 \pm 0.69)\mathrm{GeV}^4$$

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- Inputs for $B \to X_u \ell \nu$ Next, B lifetimes and $B \to X_s \ell\ell$ KKV, Huber, Lenz, Rusov, et al.
- Additional 0.23 uncertainty due to missing higher orders

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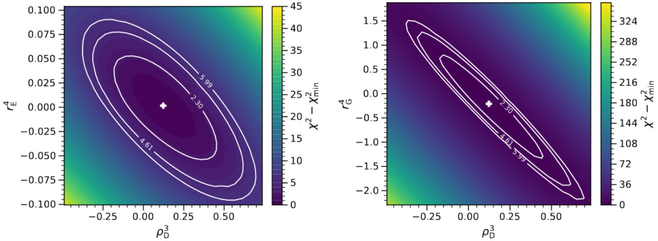

Even higher corrections?

Mannel, Mulatin, KKV [in progress]

- HQE set up with $m_c/m_b \sim \mathcal{O}(1)$
- IR sensitive terms for $m_c \to 0$ Bigi, Mannel, Turczyk, Uraltsev [0911.3322]
  - at dim-6: $1/m_b^3 \ln m_c^2$
  - at dim-8: $1/m_b^5 m_b^2/m_c^2 \sim 1/m_b^3 1/m_c^2$
- Numerically: $m_c^2 \sim m_b \Lambda_{\rm QCD}$
- New! Calculation and estimate of these effects

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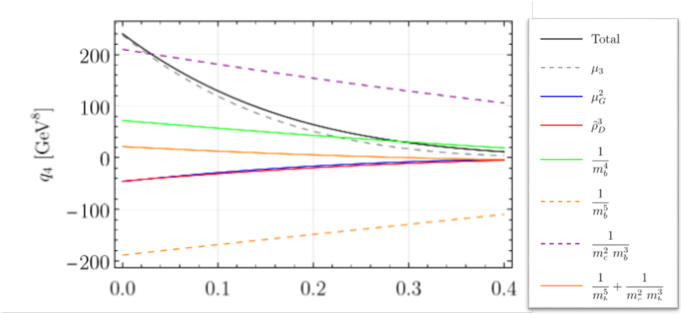
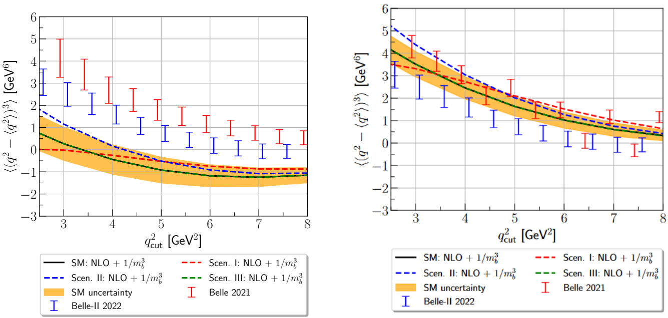


What is next?

Fael, Rahimi, KKV [2208.04282]



- Simultaneous fit of all measurements
  - α_s^2 corrections required Fael et al. [in progress], corrections are negative Steinhauser, Fael, Schoenwald [2205.03410]

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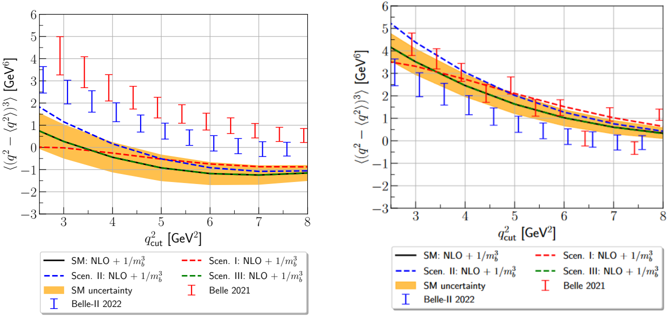

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- Requires a simultaneous fit of hadronic parameters and NP [Talk by Matteo Fael]

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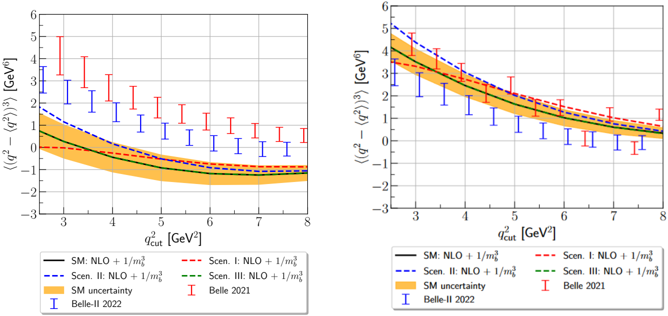

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- Ratio of inclusive $b \to u$ over $b \to c$ in OPE Fael, KKV [in progress]

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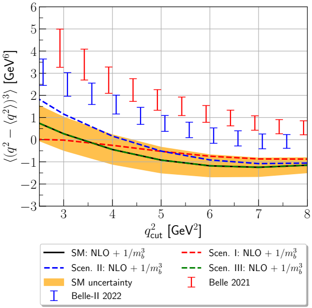

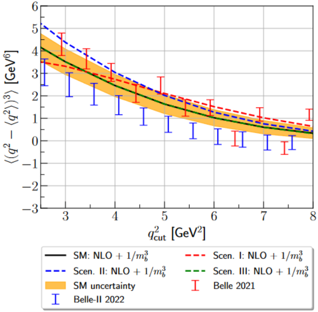

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- QED! Talk Marzia Bordone@CKM

Lepton universality in semileptonic decays

KKV, Rahimi; JHEP [2207.03432] See talk @CKM by Kowalewski

$$R_{e/\mu}(X) \equiv \frac{\Gamma(B \to X_c e \bar{\nu}_e)}{\Gamma(B \to X_c \mu \bar{\nu}_\mu)}$$

- Belle II result: $R_{e/\mu}(X) = 1.033 \pm 0.022$ PRL131 [2023] [2301.08266]
- In agreement with new SM predictions: 1.006 ± 0.001 at 1.2σ

KKV, Rahimi; JHEP [2207.03432] See talk @CKM by Kowalewski

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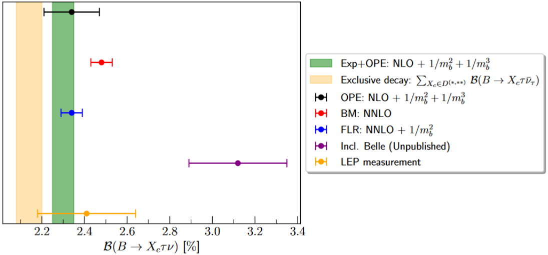
- New! Belle II result: $R_{\tau/\ell}(X) = 0.228 \pm 0.016 \pm 0.036$ @EPS
- In agreement with our SM prediction:

$$R_{\tau/\ell}(X) = 0.221 \pm 0.004$$



Inclusive $B \to X_u$ semileptonic decays

Inclusive V_{ub}

Inclusive $B \to X_u \ell \nu$

- Experimental cuts necessary to remove charm background
- Local OPE as in $b \to c$ cannot work
- Switch to different set-up using light-cone OPE
- Introduce non-perturbative shape functions ($\sim$ parton DAs in DIS)
- Different frameworks: BLNP, GGOU, DGE, ADFR

Recent update:

Belle [2102.00020]

$$|V_{ub}|_{\rm incl} = (4.10 \pm 0.28) \cdot 10^{-3}$$

Inclusive determinations need to be scrutinized

BLNP update - in progress -

Bosch, Lange, Neubert, Paz [2005]
Greub, Neubert, Pecjak [0909.1609]; Beneke, Huber, Li [0810.1230]; Becher, Neubert [2005]

Update of BLNP approach

- Systematic framework: Soft Collinear Effective Theory (SCET)
- Separates the different scales in the problem

$$d\Gamma = H \otimes J \otimes S$$

→ H: Hard scattering kernel at $\mathcal{O}(m_b)$
→ J: universal Jet function at $\mathcal{O}(\sqrt{m_b \Lambda_{\mathrm{QCD}}})$
→ S: Shape function at $\mathcal{O}(\Lambda_{\mathrm{QCD}})$

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  - $\rightarrow$ S: Shape function at $\mathcal{O}(\Lambda_{\rm QCD})$
- In progress: include known α_s^2 corrections

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- Systematic framework: Soft Collinear Effective Theory (SCET)
- Separates the different scales in the problem

$$d\Gamma = H \otimes J \otimes S$$

→ H: Hard scattering kernel at $\mathcal{O}(m_b)$
→ J: universal Jet function at $\mathcal{O}(\sqrt{m_b \Lambda_{\rm QCD}})$
→ S: Shape function at $\mathcal{O}(\Lambda_{\rm QCD})$

- In progress: include known α_s^2 corrections

BLNP update - in progress -

Bosch, Lange, Neubert, Paz [2005]
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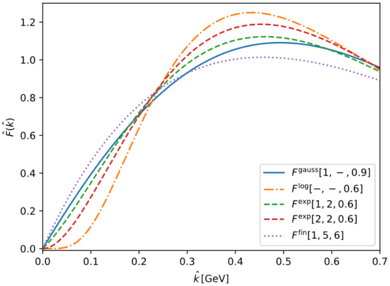
- Moments of shape functions can be linked to HQE parameters in $b \to c$
  - In progress: include higher-moments
  - kinetic mass scheme as in $b \to c$
- Shape function is non-perturbative and cannot be computed
  - In progress: new flexible parametrization

Shape function parametrization

Olschewsky, Lange, Mannel, KKV [2306.xxxx]



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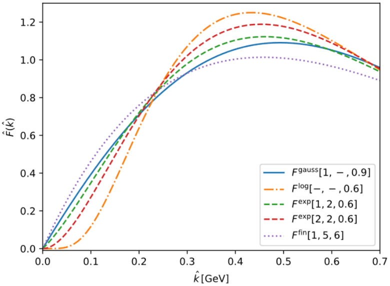

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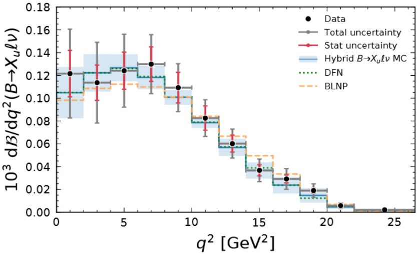
In progress:

Lange, Mannel, Olschewsky, KKV [in progress]

$$|V_{ub}|_{\text{incl}} = \quad \text{Stay Tuned!}$$

Progress on inclusive $B \to X_u$

Belle [2107.13855]



- Measurements of the shape may prove useful!
- Ongoing discussion to improve MonteCarlo framework

Heavy quark expansion for charm?

Why HQE for charm?

- Expansion parameters $\alpha_s(m_c)$ and $\Lambda_{\rm QCD}/m_c$ less than unity, but not so small ...
- Turn vice into virtue: more sensitive to higher $1/m_Q$ corrections
- Exploit the full physics potential of BES III, LHCb ...
- Constrain Weak Annihilation (WA) contributions

  $\rightarrow$ $B_d \to s\ell\ell$ [Huber, Hurth, Lunghi, Jenkins, KKV, Qin]

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Challenges:

- Valence and non-valence WA operators at higher orders
- Scale for radiative corrections
- Charm mass definition see e.g. Boushmelev, Mannel, KKV [2301.05607]

HQE for Charm revisited

$m_Q \gg m_q \sim \Lambda_{\rm QCD}$ OPE for $c \to s\ell\bar{\nu}$

- q dynamical degree of freedom
- four-quark operators remain in OPE
- no explicit $\log(m_q/m_Q)$: hidden inside new non-perturbative HQE parameters
- $\log(m_c/m_b)$ in $B \to X\ell\nu$ corresponds to $\log(\mu/m_c)$ in $D \to X\ell\nu$
- caused by mixing of four-quark operators into two-quark operators:

$$C_i^{2q}(\mu) = C_i^{2q}(m_c) + \log\left(\frac{\mu}{m_c}\right)\sum_j \hat{\gamma}_{ij}^T C_j^{4q}(m_c)$$

HQE for charm revisited

$\rho = m_s^2/m_c^2$

Fael, Mannel, KKV, hep-ph/1910.05234

$$\frac{\Gamma(D \to X_s \ell\nu)}{\Gamma_0} = \left(1 - 8\rho - 10\rho^2\right)\mu_3 + (-2 - 8\rho)\frac{\mu_G^2}{m_c^2} + 6\frac{\tilde{\rho}_D^3}{m_c^3}$$
$$+ \frac{16}{9}\frac{r_G^4}{m_c^4} + \frac{32}{9}\frac{r_E^4}{m_c^4} - \frac{34}{3}\frac{s_B^4}{m_c^4} + \frac{74}{9}\frac{s_E^4}{m_c^4} + \frac{47}{36}\frac{s_{qB}^4}{m_c^4} + \frac{\tau_0}{m_c^3}$$

- RPI quantities (q^2 moments) depend on reduced set
- Up to $1/m_c^3$ only <u>one</u> extra HQE param
- Data required to test description
- Comparison of extracted HQE parameters with B decays

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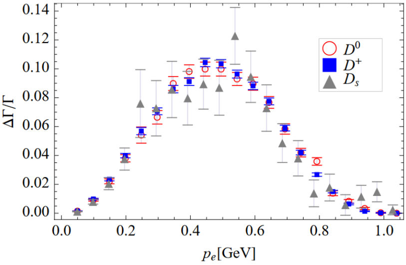
- Up to $1/m_c^3$ only <u>one</u> extra HQE param
- Data required to test description
- Comparison of extracted HQE parameters with B decays

Key question: HQE indeed applicable to inclusive charm decays?

Extracting weak annihilation from data

Gambino, Kamenik [1004.0114]



- Extrapolate data to $p_e \to 0$ and convert from lab frame to D meson rest frame
- Kinetic mass for charm at $\mu = 0.5$ GeV threshold, HQE parameters as input
- Obtain strong bounds on weak annihilation (WA) contribution
- Max 2% WA contribution to $B \to X_u \ell \nu$

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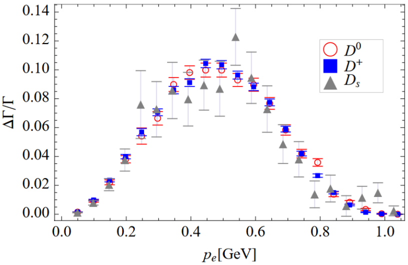

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- Max 2% WA contribution to $B \to X_u \ell \nu$
- My wish: Extract HQE and WA directly from q^2 moments at BESIII

Outlook - inclusive decays

We are in the High-precision Era in Flavour Physics!

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- Reached impressive precision

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Close collaboration between theory and experiment necessary!

Backup

Shape functions

Bigi, Shifman, Uraltsev, Luke, Neubert, Mannel, $\cdots$

- Leading order shape functions

$$2m_B f(\omega) = \langle B(v)|\bar{b}_v \delta(\omega + i(n \cdot D)) b_v |B(v)\rangle$$

- Charged Lepton Energy Spectrum (at leading order)

$$\frac{d\Gamma}{dy} \sim \int d\omega \theta(m_b(1-y) - \omega) f(\omega)$$

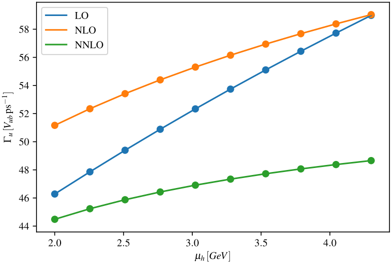
- Moments of the shapefunction are related to HQE ($b \to c$) parameters:

$$f(\omega) = \delta(\omega) + \frac{\mu_\pi^2}{6m_b^2}\delta''(\omega) - \frac{\rho_D^3}{m_b^3}\delta'''(\omega) + \cdots$$

- Shape function is non-perturbative

Shape function parametrization

Preliminary! Olschewsky, Lange, Mannel, KKV [2306.xxxx]



- α_s^2 corrections give large corrections [see also Pezcjak 2019]
- Required to make precision predictions

Contamination of the $B \to X_c \ell \nu$ signal

Rahimi, Mannel, KKV [arXiv: 2105.02163]

Avoid background subtraction by calculating the full inclusive width:

$$d\Gamma(B \to X\ell) = d\Gamma(B \to X_c \ell\bar{\nu}) + d\Gamma(B \to X_u \ell\bar{\nu}) + d\Gamma(B \to X_c(\tau \to \ell\bar{\nu}\nu)\bar{\nu})$$

- $b \to u\ell\nu$ contribution: suppressed by V_{ub}/V_{cb}
- $b \to c(\tau \to \mu\nu\bar{\nu})\bar{\nu}$ contribution: phase space suppressed
- QED effects
- Quark-hadron duality violation?

Goal:
provide theoretical description and compare with Monte-Carlo data used by Belle (II)

Challenge:
estimate how much this description would improve V_{cb} determination

Short-Distances Masses

Bigi, Shifman, Uraltsev, Vainshtein, hep-ph/9704245, hep-ph/9405410; Czarnecki, Melnikov, Uraltsev, hep-ph/9708372.

- Renormalon issues require short-distance mass
- $\overline{\mathrm{MS}}$ for scales μ above heavy quark mass
- Kinetic mass: relating hadron versus quark mass
  QCD corrections using hard cut off μ

$$m_Q(\mu)^{\mathrm{kin}} = m_Q^{\mathrm{Pole}} - \left[\overline{\Lambda}\right]_{\mathrm{pert}} + \left[\frac{\mu_\pi^2}{2m_Q}\right]_{\mathrm{pert}} + \dots$$

$$[\overline{\Lambda}]_{\mathrm{pert}} = \frac{4}{3} C_F \frac{\alpha_s(m_c)}{\pi}\mu \qquad [\mu_\pi^2]_{\mathrm{pert}} = C_F \frac{\alpha_s(m_c)}{\pi}\mu^2$$

- Higher-order terms in the HQE generate corrections $(\alpha_s/\pi)\mu^n/m_Q^n$.

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- Higher-order terms in the HQE generate corrections $(\alpha_s/\pi)\mu^n/m_Q^n$.
- **$\Lambda_{\mathrm{QCD}} < \mu < m_Q$**: expansion parameters μ/m_Q
  - Well established for m_B: $\mu/m_B \simeq 0.2$
  - Charm??

    $\rightarrow$ $\mu = 1$ GeV $\rightarrow \mu/m_c \simeq 1$

    $\rightarrow$ $\mu = 0.5$ GeV $\rightarrow \mu/m_c \simeq 0.4$

Kinetic Mass

Putting all power corrections to zero!

- $m_c^{\mathrm{kin}}(1\ \mathrm{GeV}) = 1.16\ \mathrm{GeV}$ ($m_s \to 0$ limit)

$$\Gamma(c \to s\ell\nu)^{\mathrm{kin}} = \Gamma_0 \left[1 + 7.7\frac{\alpha_s(m_c)}{\pi} + 69\left(\frac{\alpha_s(m_c)}{\pi}\right)^2\right]$$

- $m_c^{\mathrm{kin}}(0.5\ \mathrm{GeV}) = 1.4\ \mathrm{GeV}$ ($m_s \to 0$ limit)

$$\Gamma(c \to s\ell\nu)^{\mathrm{kin}} = \Gamma_0 \left[1 + 1.2\frac{\alpha_s(m_c)}{\pi} + 17\left(\frac{\alpha_s(m_c)}{\pi}\right)^2\right]$$

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$\mu = 0.5$ GeV touches upon the non-perturbative regime?

Spectral-Density Mass

Chetyrkin, Kuehn, Steinhauser hep-ph/9705254, Penin, Pivovarov hep-ph/9805344

- m_c not observable $\to$ no physical meaning
- Extracted from data: moments of the spectral density in $e^+e^- \to$ hadrons

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

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- Start from vacuum correlator

$$\int d^4x\, e^{-iqx}\langle 0|T[j_\mu(x)j_\nu(0)]|0\rangle = (g_{\mu\nu}q^2 - q_\mu q_\nu)\Pi(q^2)$$

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- Expand around $q^2 = 0$: $(\bar{C}_n = \bar{C}_n^{(0)} + \frac{\alpha_s(\mu)}{\pi}\bar{C}_n^{(1)} + \ldots)$

$$\Pi(q^2) = \Pi(0) + \frac{4}{9}\frac{3}{16\pi^2}\sum_{n=1}^{\infty}\bar{C}_n\left(\frac{q^2}{4m_c^2}\right)$$

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- $\bar{C}_n$ known up to α_s^2 and related to moments

$$\bar{C}_n = (4m_c^2)^n M_n \quad \text{with} \quad M_n = \int\frac{ds}{s^{n+1}}R(s) \tag{1}$$

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$$\bar{C}_n = (4m_c^2)^n M_n \quad \text{with} \quad M_n = \int\frac{ds}{s^{n+1}}R(s) \qquad (1)$$

- Replace m_c:

$$m_c = \frac{1}{2}\left(\frac{\bar{C}_n}{M_n}\right)^{1/(2n)}$$

Spectral-Density Mass

Chetyrkin, Kuehn, Steinhauser [hep-ph/9705254], Penin, Pivovarov [hep-pp/9805344]

Boushmelev, Mannel, KKV [2301.05607]

$$\Gamma(c \to s\ell\nu) = \frac{G_F^2|V_{cs}|^2}{192\pi^3}\left(\frac{1}{2}\left(\frac{\bar{C}_n}{M_n}\right)^{1/2}\right)^5\left(1+\frac{\alpha_s(\mu)}{\pi}a_1+\left(\frac{\alpha_s(\mu)}{\pi}\right)^2 a_2+\cdots\right)$$

$$= \frac{G_F^2|V_{cs}|^2}{6144\pi^3}\left(\frac{\bar{C}_n^{(0)}}{M_n}\right)^{5/2}\left(1+\frac{\alpha_s(\mu)}{\pi}\left[a_1+\frac{5}{2n}\frac{\bar{C}_n^{(1)}}{\bar{C}_n^{(0)}}\right]\right.$$

$$\left.+\left(\frac{\alpha_s(\mu)}{\pi}\right)^2\left[a_2+\frac{5}{2n}a_1\frac{\bar{C}_n^{(1)}}{\bar{C}_n^{(0)}}+\frac{5}{2n}\frac{\bar{C}_n^{(2)}}{\bar{C}_n^{(0)}}+\frac{5}{4n}\left(\frac{5}{4n}-1\right)\left(\frac{\bar{C}_n^{(1)}}{\bar{C}_n^{(0)}}\right)^2\right]+\cdots\right)$$

- Conclusion for B: pert. series improves a bit
- Scale at which α_s^2 vanishes rather low: 0.7 m_b
- In progress: Similar approach for the charm + power corrections

$b \to u\ell\nu$ contribution: Local OPE

Neubert (1994); Bosch, Paz, Lange, Neubert (2004,2005)

- Can be analyzed in local OPE as $B \to X_c\ell\nu$ by taking $m_c \to 0$ limit
- For V_{ub} determination
  - large charm background requires experimental cuts
  - reduces the inclusivity and local OPE no longer converges
  - spectrum described by non-local OPE
  - convolution of pert. coefficients with shape function

Goal:

provide theoretical description and compare with Monte-Carlo data used by Belle (II)

- NLO $+ 1/m_b^2 + 1/m_b^3$
- In agreement with partonic calc of DFN De Fazio, Neubert (1999); Gambino, Ossola, Uraltsev (2005)
- First study: no α_s for $1/m_b^2$, no additional uncert. due to missing higher orders
- Inputs HQE parameters from $B \to X_c\ell\nu$ study Gambino, Schwanda [2014]; Gambino, Healey, Turczy [2016]

Monte Carlo versus HQE

Rahimi, Mannel, KKV [arXiv: 2105.02163]; De Fazio, Neubert 1999; Bosch, Lange, Neubert, Paz 2005

Compare local OPE with generator level Monte-Carlo data provided by Cao, Bernlochner

Monte Carlo:

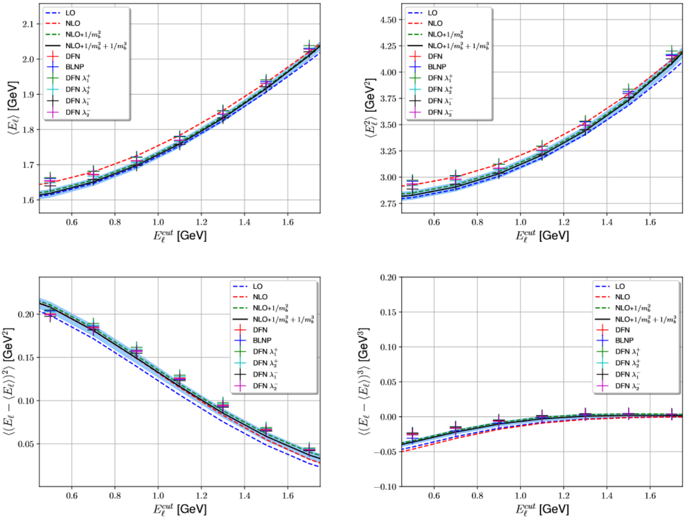
- BLNP: specific shape function input parameters shape function parameters $b = 3.95$ and $\Lambda = 0.72$
- DFN: α_s corrections convoluted with the exponential shape function model
  - Inputs from $B \to X_c \ell\nu$ and $B \to X_s\gamma$ data using KN-scheme Kagan, Neubert 1998
  - $(\lambda_1^+, \lambda_2^+, \lambda_1^-, \lambda_2^-)$ are obtained by varying $\bar{\Lambda}$ and μ_π^2 within 1σ Buchmuller, Flacher, 2006

Hadronic contributions: "hybrid Monte Carlo" Belle Collabroation [arXiv:2102.00020.]

- convolution with hadronization simulation based on PYTHIA
- plus explicit resonances: $\bar{B} \to \pi\ell\bar{\nu}$ and $\bar{B} \to \rho\ell\bar{\nu}$

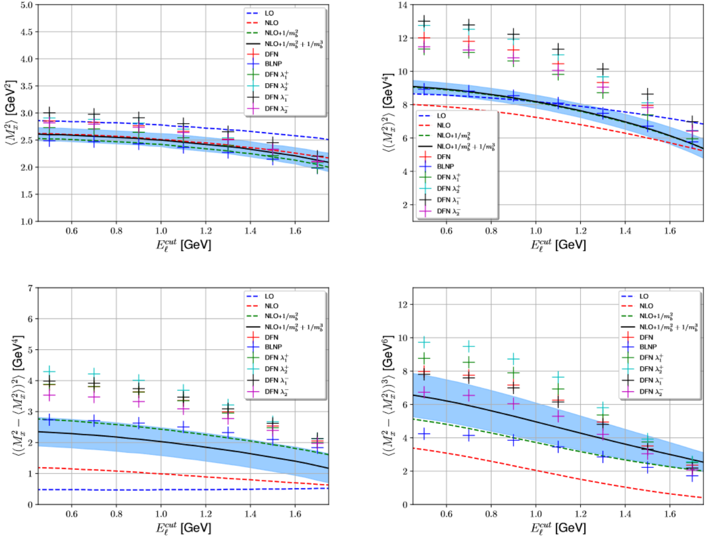
Monte Carlo versus HQE

Rahimi, Mannel, KKV [arXiv: 2105.02163]; MC data by Lu Cao and Florian Bernlochner



MC-results are in good agreement with the HQE results

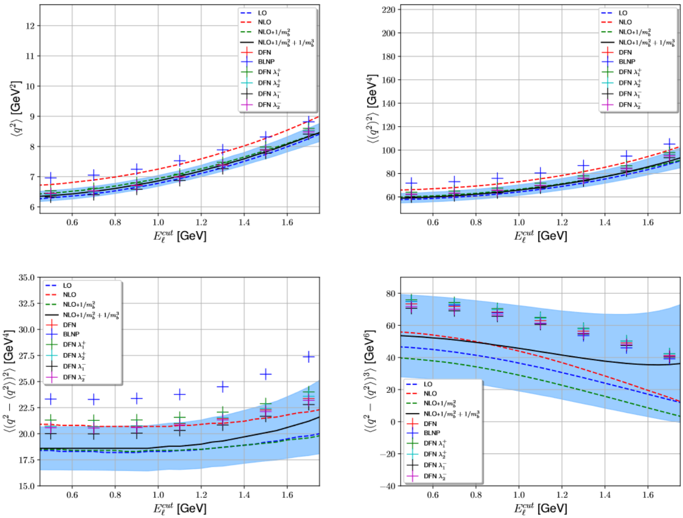
Rahimi, Mannel, KKV[arXiv: 2105.02163]; MC data by Lu Cao and Florian Bernlochner



Wide spread between MC for higher moments

Monte Carlo versus HQE

Rahimi, Mannel, KKV[arXiv: 2105.02163]; MC data by Lu Cao and Florian Bernlochner



Monte Carlo versus local OPE: remarks

Rahimi, Mannel, KKV[arXiv: 2105.02163];

Remarks:

- DFN: Smearing corresponding to a shape function, mimicking some non-perturbative effects; may not capture all
- BLNP: should reproduce the HQE, with parameters adjusted to local HQE prediction
  - should include higher moments of the shape-function model?
  - include subleading shape functions?
- our HQE: interesting to include α_s to HQE parameters, α_s^2?

Five-body τ contribution

Rahimi, Mannel, KKV[arXiv: 2105.02163];

Contribution from five-body charm decay to $b \to c\ell\nu$ via

$$B(p_B) \to X_c(p_{X_c})(\tau(q_{[\tau]}) \to \mu(q_{[\mu]})\nu_\mu(q_{[\bar{\nu}_\mu]})\nu_\tau(q_{[\nu_\tau]}))\bar{\nu}_\tau(q_{[\bar{\nu}_\tau]})$$

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$$\frac{\Gamma_{\rm tot}(b \to c\tau(\to \ell\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau)}{\Gamma_{\rm tot}(b \to c\ell\bar{\nu})} \sim 4.0\%$$

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  - $L_{\mu\nu}$ five-body leptonic tensor (narrow-width limit for τ)
  - $W_{\mu\nu}$ standard hadronic tensor including HQE parameters

- Interesting to search for new physics! Mannel, Rusov, Shahriaran (2017); Mannel, Rahimi, KKV [in progress]

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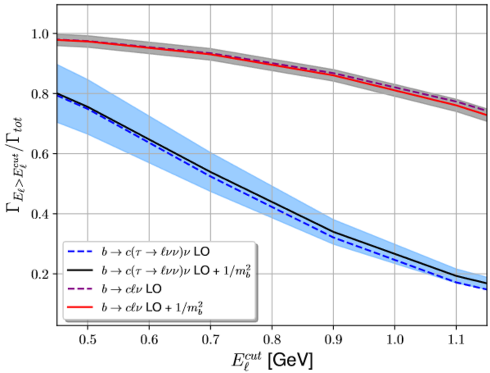

No MC data available to test with

Theory guidance to include power corrections

Lowest State Saturation Approximation (LSSA)

$$\langle B|O_1 O_2|B\rangle = \sum_n \langle B|O_1|n\rangle\langle n|O_2|B\rangle$$

$$\rho_D^3 = \varepsilon\mu_\pi^2, \qquad \rho_{LS}^3 = -\varepsilon\mu_G^2, \qquad \varepsilon \sim 0.4 \text{ GeV}$$

Mannel, Turczyk, Uraltsev JHEP 1011 (2010) 109; Heinonen, Mannel, NPB 889 (2014) 46

- LSSA estimated as priors (60% gaussian uncertainty)
- $\mathcal{O}(1/m_b^4, 1/m_b^5)$ can then be included in fit Healey, Turczyk, Gambino, PLB 763 (2016) 60

$$|V_{cb}|_{\text{incl}} = (42.00 \pm 0.64) \times 10^{-3}$$

- -0.25% shift due to power corrections

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Towards the Ultimate Precision in $|V_{cb}|$

- Include α_s corrections to for ρ_D^3 Mannel, Pivovarov [in progress]; Gambino [in progress]
- Full determination up to $1/m_b^4$ from data possible?

Theory guidance to include power corrections

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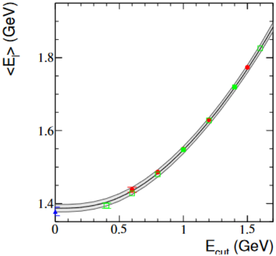
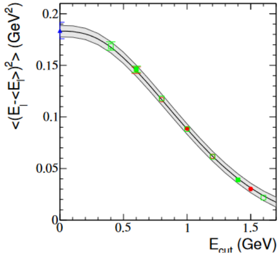
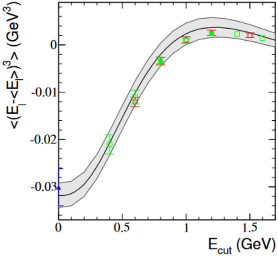
Moments of the spectrum

Gambino, Schwanda Phys. Rev. D 89, 014022 (2014)

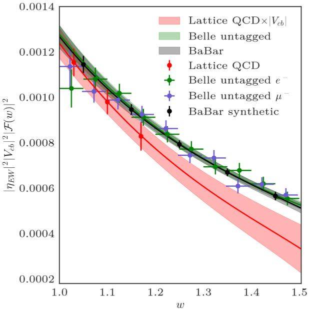






$B \to D^*$ form factors

Fermilab-MILC [2105.14019]



- Tension between the slope of the lattice and experimental data
- Same form factors determine SM predictions for $R_{D^{(*)}}$
- New experimental and lattice data needed!

The V_{cb} puzzle: Inclusive versus Exclusive decays

Exclusive $B \to D^{(*)}\ell\bar{\nu}$

- Form factor required (only for $B \to D$ available at different kinematic points)
- Different parametrizations for form factors: CLN Caprini, Lellouch, Neubert [1997] and BGL Boyd, Grinstein, Lebed [1995]
  - BGL: model independent based on unitarity and analyticity
  - CLN: Simple parametrization using HQE relations
- Some inconsistencies in the Belle data were pointed out see e.g. van Dyk, Jung, Bordone, Gubernari [2104.02094]

Inclusive $B \to X_c\ell\nu$

- Determined fully data driven including $1/m_b$ power corrections

Recently a lot of attention for the V_{cb} puzzle! Bigi, Schacht, Gambino, Jung, Straub, Bernlochner, Bordone, van Dyk, Gubernari

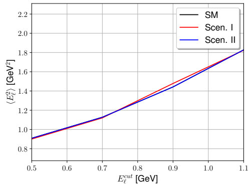
Stay tuned!

Inclusive $b \to c$

Mannel, Rahimi, KKV [in progress]

NP in the τ sector

- Affects also inclusive $B \to X_c \tau \nu$ Rusov, Mannel, Shahriaran [2017]
- Lepton and hadronic moments challenging to measure
- Recently moments of the five-body decay $B \to X_c \tau (\to \mu \nu \nu) \nu$ investigated Mannel, Rahimi, KKV [2105.02163]
- Would also be influenced by NP [in progress]
- Specific NP scenarios from global fit Mandal, Murgui, Penuela, Pich [2004.06726]



Preliminary!

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Rahimi, Mannel, KKV JHEP 09 (2021) 051 [arXiv: 2105.02163];

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Shape functions

Bigi, Shifman, Uraltsev, Luke, Neubert, Mannel, $\cdots$

- Leading order shape functions

$$2m_B f(\omega) = \langle B(v)|\bar{b}_v \delta(\omega + i(n \cdot D)) b_v |B(v)\rangle$$

- Charged Lepton Energy Spectrum (at leading order)

$$\frac{d\Gamma}{dy} \sim \int d\omega \theta(m_b(1-y) - \omega) f(\omega)$$

- Moments of the shapefunction are related to HQE ($b \to c$) parameters:

$$f(\omega) = \delta(\omega) + \frac{\mu_\pi^2}{6m_b^2}\delta''(\omega) - \frac{\rho_D^3}{m_b^3}\delta'''(\omega) + \cdots$$

- Shape function is non-perturbative and cannot be computed

Shape functions

Lange, Neubert, Bosch, Paz

- Systematic framework: Soft Collinear Effective Theory (SCET)
- Separates the different scales in the problem

$$d\Gamma = H \otimes J \otimes S$$

→ H: Hard scattering kernel at $\mathcal{O}(m_b)$
→ J: universal Jet function at $\mathcal{O}(\sqrt{m_b \Lambda_{\rm QCD}})$
→ S: Shape function at $\mathcal{O}(\Lambda_{\rm QCD})$

- Framework to include radiative corrections (+ NNLL resummation)
- Introduces 3 subleading shape functions

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- Other approach: OPE with hard-cutoff μ Gambino, Giordano, Ossola, Uraltsev
  - Use pert. theory above cutoff and parametrize the infrared
  - Different definition of the shape functions
- Shape functions have to be parametrized and obtained from data

q^2 moments only analysis

Bernlochner, Welsch, Fael, Olschewsky, Persson, van Tonder, KKV [2205.10274]

$$|V_{cb}|^{q^2}_{\rm incl} = (41.69 \pm 0.63) \times 10^{-3}$$

- Higher order coefficients important to check convergence of the HQE

$$r_E^4 = (0.02 \pm 0.34) \cdot 10^{-1} \mathrm{GeV}^4 \quad r_G^4 = (-0.21 \pm 0.69) \mathrm{GeV}^4$$

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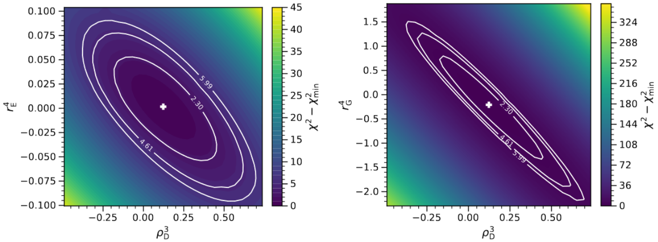
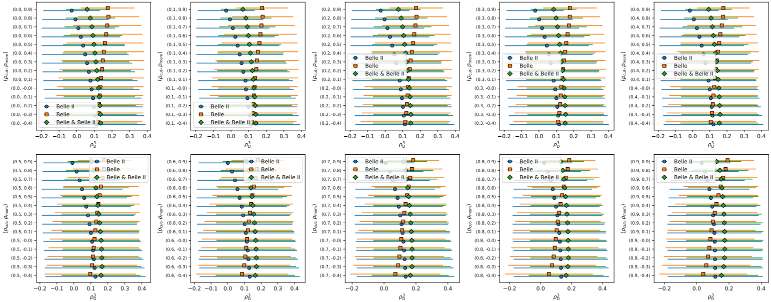


What about theory correlations?

Bernlochner, Welsch, Fael, Olschewsky, Persson, van Tonder, KKV [2205.10274]

- Flexible correlations between moments ρ_{mom} and different cuts ρ_{cut}
- Included by adding a penalty term to the χ^2
- Scan over large range of values
- V_{cb} constant w.r.t. theory correlations

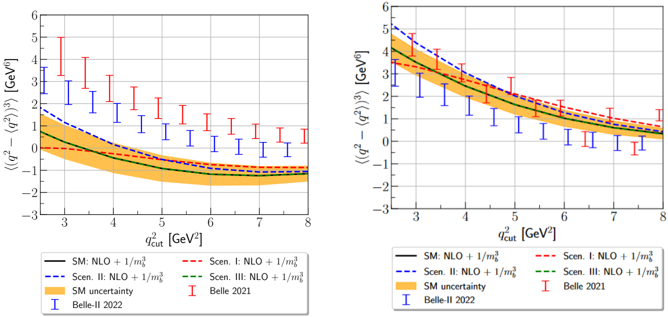


What about ρ_D^3?

Bernlochner, Welsch, Fael, Olschewsky, Persson, van Tonder, KKV [2205.10274]

- Large uncertainties on HQE elements
- Important: ρ_D^3 much smaller than previous!
- α_s^2 corrections to moments not yet included

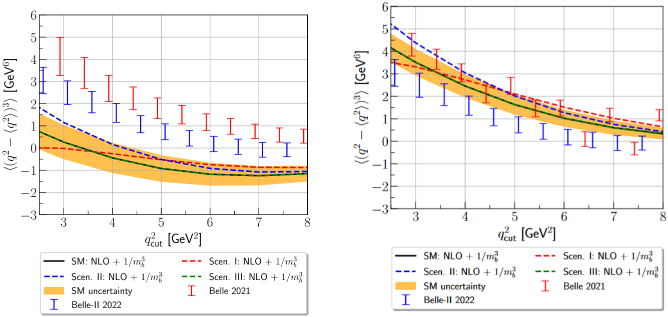
Rahimi, Fael, Vos [2208.04282]



Bernlochner, Welsch, Fael, Olschewsky, Persson, van Tonder, KKV [2205.10274]

- Large uncertainties on HQE elements
- Important: ρ_D^3 much smaller than previous!
- α_s^2 corrections to moments not yet included
- Corrections are negative Steinhauser, Fael, Schoenwald [2205.03410]
- Full analysis including all data is necessary! Bernlochner, Fael, Prim, KKV [in progress]

Rahimi, Fael, Vos [2208.04282]



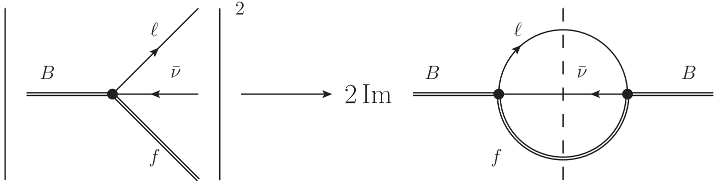
Even higher corrections?

Mannel, Mulatin, KKV [in progress]

- HQE set up with $m_c/m_b \sim \mathcal{O}(1)$
- IR sensitive terms for $m_c \to 0$ Bigi, Mannel, Turczyk, Uraltsev [0911.3322]
  - at dim-6: $1/m_b^3 ln m_c^2$
  - at dim-8: $1/m_b^5 m_b^2/m_c^2 \sim 1/m_b^3 1/m_c^2$
- Numerically: $m_c^2 \sim m_b \Lambda_{\rm QCD}$
- in progress: Calculation and estimate of these effects

Inclusive B decays

Chay, Georgi, Bigi, Shifman, Uraltsev, Vainstain, Manohar, Wise, Neubert, Mannel, · · ·



Optical Theorem

$$\Gamma \propto \sum_X (2\pi)^4 \delta^4(P_B - P_X) |\langle X | \mathcal{H}_{eff} | B(v) \rangle|^2$$

$$= \int d^4x \, \langle B(v) | \mathcal{H}_{eff}(x) \mathcal{H}^\dagger_{eff}(0) | B(v) \rangle$$

$$= 2 \, \mathrm{Im} \int d^4x \; e^{-iq\cdot x} \, \langle B(v) | \, T \left\{ \mathcal{H}_{eff}(x) \mathcal{H}^\dagger_{eff}(0) \right\} | B(v) \rangle$$

where $\mathcal{H}_{eff} = J^\mu_c L_\mu, \quad J^\mu_c = \bar{b}\gamma^\mu P_L c$

Chay, Georgi, Bigi, Shifman, Uraltsev, Vainstain, Manohar, Wise, Neubert, Mannel, · · ·

Heavy Quark Expansion

- B meson: $p_B = m_B v$
- Split the momentum b quark: $p_b = m_b v + k$, expand in $k \sim iD\, Q_v$
- Field-redefinition of the heavy field $Q(x) = exp(-im(v \cdot x))Q_v(x)$

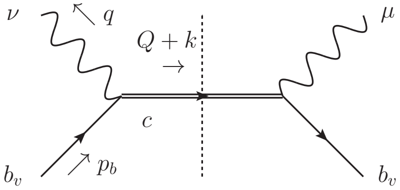
$$\begin{aligned}\Gamma \quad &= 2\,\mathrm{Im} \int d^4x\, e^{-iq\cdot x}\, \langle B(v)|\, T\left\{\mathcal{H}_{eff}(x)\mathcal{H}^\dagger_{eff}(0)\right\}|B(v)\rangle \\ &= 2\,\mathrm{Im} \int d^4x\, e^{i(m_b v - q)\cdot x} \langle B(v)|\, T\left\{\widetilde{\mathcal{H}}_{eff}(x)\widetilde{\mathcal{H}}^\dagger_{eff}(0)\right\}|B(v)\rangle\end{aligned}$$

where $\widetilde{\mathcal{H}}_{eff} = \tilde{J}^\mu_c L_\mu, \quad \tilde{J}^\mu_c = \bar{b}_v \gamma^\mu P_L c, \quad \Gamma \propto 2\mathrm{Im}\, T^{\mu\nu} L_{\mu\nu}$

$$\Gamma(B \to X_c \ell \nu_\ell) \propto 2\mathrm{Im}\, T^{\mu\nu} L_{\mu\nu}$$

$$T^{\mu\nu} = i \int dx^4 e^{i(m_b v - q)\cdot x} T \left\{ \bar{b}_v(x) \gamma^\mu P_L c(x), \bar{c}(0) \gamma^\nu P_L b_v(0) \right\}$$

$$Q = m_b v - q$$



$$= \bar{b}_v \gamma_\mu P_L \left[\frac{i}{\not{Q} + i\not{D} - m_c} \right] \gamma_\nu P_L b_v$$

$$\frac{i}{\not{Q}+i\not{D}-m_c} = \frac{i}{\not{Q}-m_c} + \frac{i}{\not{Q}-m_c}(-i\not{D})\frac{i}{\not{Q}-m_c} + \frac{i}{\not{Q}-m_c}(-i\not{D})\frac{i}{\not{Q}-m_c}(-i\not{D})\frac{i}{\not{Q}-m_c} + \dots$$