Solving Beautiful Puzzles

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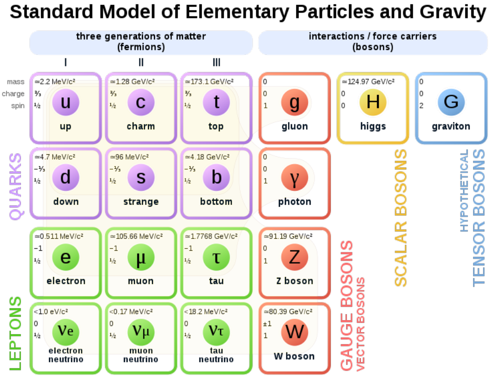
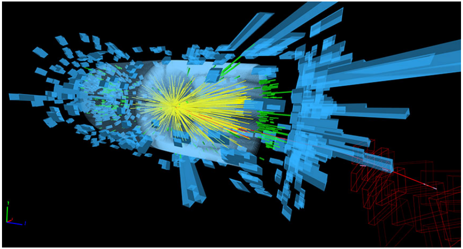
Testing the Standard Model

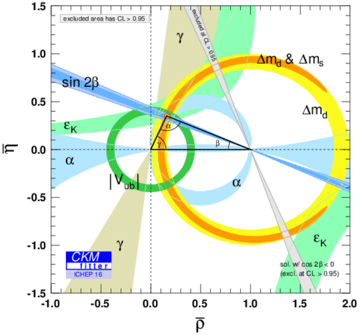


Passed all tests up to 100 GeV

Testing the Standard Model



Energy/Direct



Precision/Indirect

Precision frontier

Tiny deviations from SM predictions constrain effects of New Physics

The Flavour Puzzle

- Flavour symmetry broken by Yukawa couplings to the Higgs field
- Origin of mixing between families described by unitary CKM matrix
- Visualized by unitary triangles
- Dominant source of CP violation (antiparticle-particle asymmetry)

$$\begin{pmatrix} \boldsymbol{V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & \boldsymbol{V_{cs}} & V_{cb} \\ V_{td} & V_{ts} & \boldsymbol{V_{tb}} \end{pmatrix}$$

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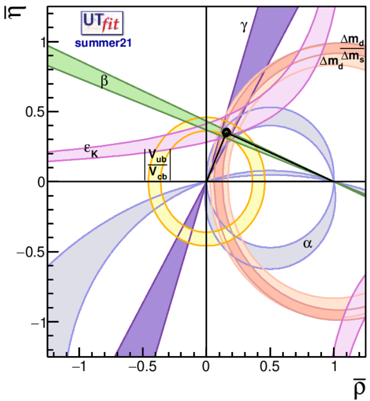
Our understanding of Flavour is unsatisfactory

The Flavour Puzzle

Thanks to Marcella Bona for providing the 2021 plots

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}$$



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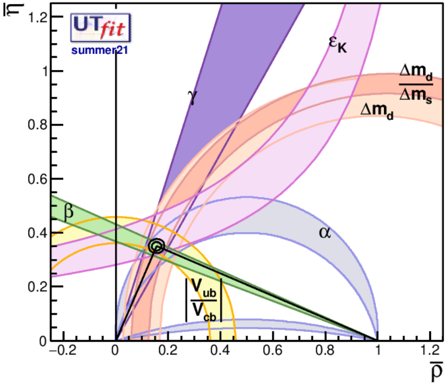

Huge amounts of data + theory advances = Precision frontier

Tiny deviations from SM predictions constrain effects of New Physics

SM or beyond?

Challenge:

Disentangle SM long-distances effects from the effects of new interactions

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- Some anomalies already spotted

SM or beyond?

Challenge:

Disentangle SM long-distances effects from the effects of new interactions

- Some anomalies already spotted
- Revise previous assumptions: reliable theory uncertainties
- Look for the cleanest observables/methods

Challenge:

Disentangle SM long-dist... effects fr... e effects ... ctions

Puzzles in semileptonic decays

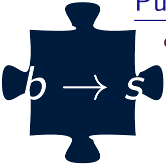
- Inclusive versus Exclusive
- V_{cb} and V_{ub}
- LFUV in R_D and R_{D*}

Puzzles in nonleptonic decays

- Missing CP violation
- $B \to \pi K$ puzzle
- $B \to D\pi$ puzzle

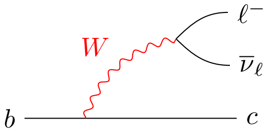
Puzzles in rare decays

- Anomalies in $b \to s\ell\ell$



Puzzles in semileptonic decays: V_{ub} and V_{cb}

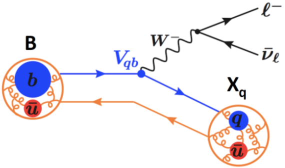
Exclusive versus Inclusive Theory



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

Exclusive versus Inclusive Theory

Figure from Marzia Bordone



- 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

Inclusive Decays

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

- b quark mass is large compared to $\Lambda_{\rm QCD}$
- Setting up the HQE: momentum of b quark: $p_b = m_b v + k$, expand in $k \sim iD$
- Optical Theorem $\to$ (local) Operator Product Expansion (OPE)

$$d\Gamma = d\Gamma_0 + \frac{d\Gamma_1}{m_b} + \frac{d\Gamma_2}{m_b^2} + \ldots \qquad d\Gamma_i = \sum_k C_i^{(k)} \left\langle B | O_i^{(k)} | B \right\rangle$$

- $C_i^{(k)}$ perturbative Wilson coefficients
- $\langle B | \ldots | B \rangle$ non-perturbative matrix elements $\to$ string of iD
- operators contain chains of covariant derivatives

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

- HQE parameters extracted from lepton energy and hadronic mass moments

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

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

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

Hadronic invariant mass

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

$$R^*(E_{\mathrm{cut}}) = \frac{\int_{E_\ell > E_{\mathrm{cut}}} dE_\ell \, \frac{d\Gamma}{dE_\ell}}{\int_0 dE_\ell \, \frac{d\Gamma}{dE_\ell}}$$

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

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,

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

- Include terms up to $1/m_b^3$* see also Gambino, Healey, Turczyk [2016]
- Recent progress: α_s^3 to total rate and kinetic mass Fael, Schonwald, Steinhauser [2020, 2021]
- Recent progress: $\alpha_s \rho_D^3$ for total rate Mannel, Pivovarov [2020]
- Includes all known α_s, α_s^2 and α_s^3 corrections!

Recent update:

$$|V_{cb}|_{\rm incl} = (42.16 \pm 0.51) \times 10^{-3}$$

Gambino, Schwanda, PRD 89 (2014) 014022;
Alberti, Gambino et al, PRL 114 (2015) 061802;
Bordone, Capdevila, Gambino, Phys.Lett.B 822 (2021) 136679

Towards the ultimate precision in inclusive V_{cb}

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

Challenge:

- 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

Alternative V_{cb} determination

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

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

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

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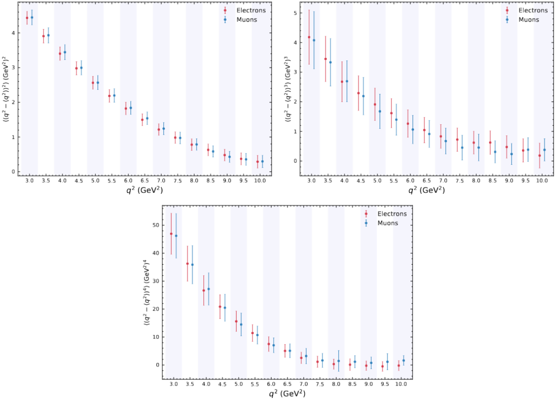
- Caveat: standard lepton energy and hadronic mass moments are not RPI quantities
- Alternative determination using only RPI q^2 moments including $1/m_b^4$
- Recent progress: First measurement of q^2 moments Belle [2109.01685], Belle II [2205.06372]

q^2 moments

Belle Collaboration [2109.01685, 2105.08001]



Centralized moments as function of q^2_{cut}

New V_{cb} Determination

$$R^*(q^2_{\rm cut}) \qquad \langle (q^2)^n \rangle_{\rm cut}$$

$$\downarrow$$

$$\mu_3, \mu_G, \tilde{\rho}_D, r_E, r_G, s_E, s_B, s_{qB}, m_b, m_c$$

$$\downarrow$$

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

$$\downarrow$$

$$V_{cb} = (41.69 \pm 0.63) \cdot 10^{-3}$$

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

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- Independent cross check of previous determinations
  - Agreement at $1 - 2\sigma$ level
  - Difference due to input on branching ratio $\rightarrow$ Need new measurements!

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- First pure data extraction of $1/m_b^4$ terms
- Important to check convergence of the HQE

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

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- Inputs for calculations of $B \to X_u \ell \nu$, B lifetimes and $B \to X_s \ell \ell$

Exclusive V_{cb}

$B \to D$ and $B \to D^*$

- Form factors extracted from lattice, LC sumrules (+data)
- Knowledge on the q^2 dependence crucial
- BGL Boyd, Grinstein,Lebed or CLN/HQE Caprini, Lellouch, Neubert parametrization
  - Start of many discussions Gambino, Jung, Schacht, Bordone, van Dyck, Gubernari, ...
  - BGL: model independent parametrization using analyticity
  - CLN*: uses HQE at $1/m_b$ + assumptions *justified at time of introduction
- Improved HQE treatment including $1/m_c^2$ corrections Bordone, van Dyk, Jung [1908.09398]

$$|V_{cb}|_{\text{excl}} = (40.3 \pm 0.8) \times 10^{-3}$$

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- Recent progress: $B \to D^*$ form factors at nonzero recoil 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 challenge of V_{ub}

Exclusive $B \to \pi \ell \nu$

- Only one form factor
- Combining Lattice QCD [FNAL/MILC, RBC/UKQCD] and QCD sum rules

Recent update:

Leljak, Melic, van Dyk [2102.07233]

$$|V_{ub}|_{\text{excl}} = (3.77 \pm 0.15) \cdot 10^{-3}$$

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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]

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

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
- In progress: include known α_s^2 corrections
- 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

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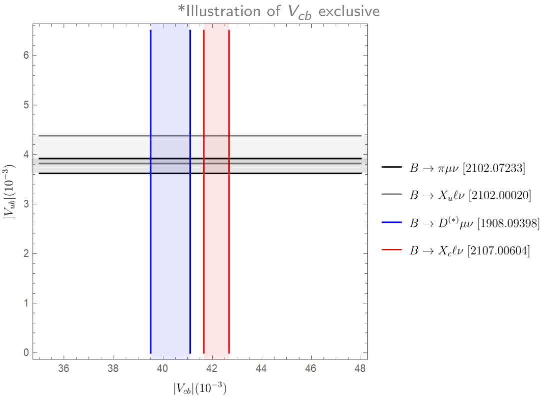
In progress:

Gunawardana, Lange, Mannel, Paz, Olschewsky, KKV [in progress]

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

Inclusive versus Exclusive semileptonic decays



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

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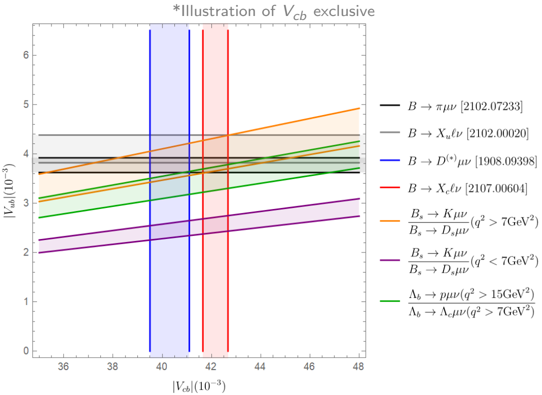

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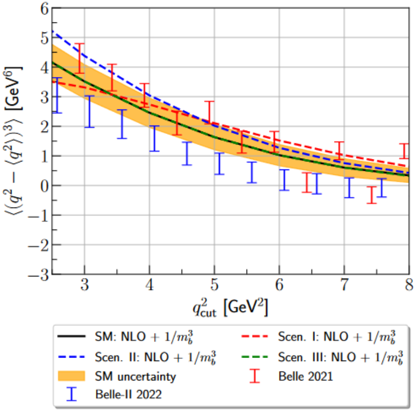
- Recent progress: $B_s \to K\mu\nu$ [LHCb [2012.05143], Khodjamirian, Rusov [2017]]
- Unlikely to be due to NP Jung, Straub [2018]
- New data necessary: stay tuned!

New Physics?

Rahimi, Fael, Vos [2208.04282]

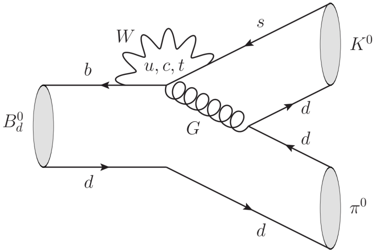


- NP would also influence the moments of the spectrum
- Requires a simultaneous fit of hadronic parameters and NP In progress..

Puzzles in nonleptonic decays

The challenge of nonleptonic B decays

- Nonleptonic decays are important probes of CP violation
  - Direct CP violation due to different strong and weak phases
  - Mixing-induced CP violation in neutral decays probe mixing phase $\phi_{d,s}$
  - Sensitivity to NP in loops (penguins)
- CP violation in the SM is too small and peculiar!
  - CKM CP violating effects only from flavour changing currents
  - Flavour diagonal CP violation tiny in SM (EDMs)
  - Large CP asymmetries with processes with tiny BRs and vice versa



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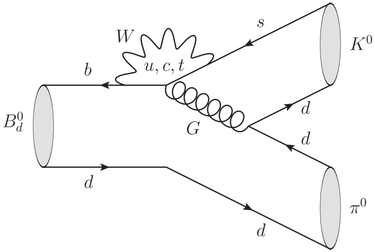
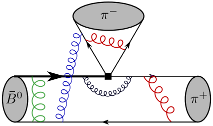


Challenge: Calculation of Hadronic matrix elements

How to handle nonleptonic B decays?



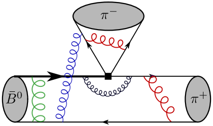
QCD Factorization Beneke, Buchalla, Neubert, Sachrajda

- Disentangle perturbative (calculable) and non-perturbative dynamics using HQE
- Systematic expansion in α_s and $1/m_b$ (studied up to α_s^2) Bell, Beneke, Huber, Li

$$\langle \pi^+\pi^- | \mathcal{Q}_i | B \rangle = T_i^I \otimes F^{B\to\pi^+} \otimes \Phi_{\pi^-} + T_i^{II} \otimes \Phi_{\pi^-} \otimes \Phi_{\pi^+} \otimes \Phi_B$$

- Non-perturbative form factors and LCDAs
  - from data, lattice or Light-Cone Sum Rules
- No systematic framework to compute power corrections (yet?)
- Strong phases suffer from large uncertainties
- Theoretical challenge: reliable computations of observables
- Include QED corrections Beneke, Boer, Toelstede, KKV [2020]

How to handle nonleptonic B decays?



QCD Factorization Beneke, Buchalla, Neubert, Sachrajda

- Disentangle perturbative (calculable) and non-perturbative dynamics using HQE
- Include QED corrections Beneke, Boer, Toelstede, KKV [2020]

Flavour symmetries (Isospin or $SU(3)$)

- Many studies e.g. Fleischer, Jaarsma, KKV, Malami [2017,2018]
- Recent progress: Global $SU(3)$ fit to $B \to PP$ decays Huber, Tetlalmatzi-Xolocotzi [2111.06418]

$B \to \pi K$ puzzle

The $B \to K\pi$ Puzzle

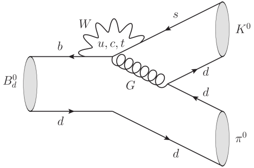
e.g. Buras, Fleischer, Recksiegel, Schwab [2004, 2007];Fleischer, Jaeger, Pirjol, Zupan [2008]
Neubert, Rosner [1998]; Beaudry, Datta, London, Rashed, Roux [2018]; Fleischer, Jaarsma, KKV [2018]

(Longstanding) Puzzling patterns in $B \to \pi K$ data

- Penguin dominated; Electroweak penguins contribute at same level as tree!

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

- Recent LHCb measurement for $A_{\rm CP}(K^- \pi^0)$
  LHCb Collaboration, PRL 126, 091802 [2021]
- Confirms and enhances the observed difference
  - $\delta(\pi K)^{\rm exp} = (11.5 \pm 1.4)\%$
  - 8σ from 0



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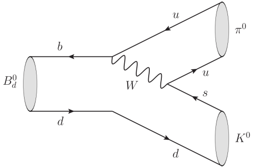

- Not clean!
  - color-suppressed tree contributes
  - $\delta(\pi K)^{\mathrm{QCDF}} = (2.1^{+2.8}_{-4.6})\%$ [Bell, Beneke, Huber, Li]
  - or via $SU(3)$ [Fleischer, Jaarsma, Malami, KKV [2018]]

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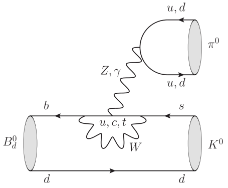
- Hint for NP in the EWP sector?



Isospin sumrule

e.g. Gronau [2005]; Gronau, Rosner [2006]

$$\Delta(\pi K) \equiv A_{\rm CP}(\pi^+ K^-) + \frac{\Gamma(\pi^- \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^- \bar{K}^0) - \frac{2\Gamma(\pi^0 K^-)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^0 K^-) - \frac{2\Gamma(\pi^0 \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^0 \bar{K}^0) \equiv \Delta(\pi K)^{\rm QCD} + \delta\Delta(\pi K)$$

- Sensitive to new physics effects: $\Delta(\pi K)^{\rm QCD} = (0.5 \pm 1.1)\%$ [Bell, Beneke, Huber, Li]
- QED effects: $\delta\Delta(\pi K) = -0.42\%$ [Beneke, Boer, Toelstede, KKV [2020]]
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- Isospin sumrule also robust against QED effects!
- Updates of modes with neutral pions necessary $\rightarrow$ Belle II
- Mixing-induced CP asymmetry in $B \rightarrow \pi^0 K^0$ provides additional test Fleischer, Jaarsma, Malami, KKV [2016,2018]

$B \to D\pi$ puzzle

$B_s^0 \to D_s^+\pi$ and $B_d^0 \to D^+K^-$ puzzle

see also Cai, Deng, Li, Yang [2103.04138], Endo, Iguro, Mishima [2109.10811], Gershon, Lenz, Rusov, Skidmore [2111.04478]

Discrepancies between data and theory for $B_s \to D_s^{+(*)}\pi^-$ and $B \to D^{+(*)}K^-$

- pure tree decays (no color-suppressed nor penguin contributions)
- NNLO predictions in QCDF Huber, Kraenkl [1606.02888]
- Same form factors as for exclusive V_{cb}
- Updated and extended calculations give $\sim 4\sigma$ deviation Bordone, Gubernari, Huber, Jung and van Dyk, [2007.10338]

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- QED corrections cannot explain the tension* Beneke, Boer, Finauri, KKV [2107.03819]
- Possible NP explanations have been studied Iguro, Kitahara [2008.01086], Bordone, Greljo, Marzocca [2103.10332]
- Also puzzling patterns in $B_s \to D_s K$ are revealed Fleischer, Malami [2110.04240]

Interesting puzzle that requires both experimental and theoretical attention!

The Challenge of QED Corrections

Electromagnetic Effects

Beneke, Boer, Toelstede, KKV, JHEP 11 (2020) 081 [2008.10615]

$$\Gamma[\bar{B} \to M_1 M_2](\Delta E) \equiv \Gamma[\bar{B} \to M_1 M_2 + X_s]\big|_{E_{X_s} \leq \Delta E},$$

- IR finite observable (width) must include ultra-soft photon radiation
- X_s are soft photons with total energy less than ultrasoft scale ΔE
- Factorizes in non-radiative amplitude and ultrasoft function

$$\Gamma[\bar{B} \to M_1 M_2](\Delta E) = |\mathcal{A}(\bar{B} \to M_1 M_2)|^2 \sum_{X_s} |\langle X_s | (\bar{S}_v^{(Q_B)} S_{v_1}^{\dagger(Q_{M_1})} S_{v_2}^{\dagger(Q_{M_2})}) | 0 \rangle|^2 \, \theta(\Delta E - E_{X_s})$$

Simple classification:

- Ultra-soft photons: eikonal approximation, well understood

$$\Delta E \ll \Lambda_{\mathrm{QCD}}$$

- NEW: Non-universal, structure dependent corrections Beneke, Boer, Toelstede, KKV [2020]
- Both effects important: virtual photons can resolve the structure of the meson!

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- Often done: Assume pointlike approximation up to the scale m_B [Baracchini, Isidori]
  - $\rightarrow$ fails to account for all large logarithms (and scales)!
  - $\rightarrow$ photons with energy $\gtrsim \Lambda_{\mathrm{QCD}}$ probe the partonic structure of the mesons

Ultrasoft Contribution

- Ultrasoft effects dress braching ratio

$$U(M_1 M_2) = \left(\frac{2\Delta E}{m_B}\right)^{-\frac{\alpha_{\rm em}}{\pi}\left(Q_B^2 + Q_{M_1}^2\left[1+\ln\frac{m_{M_1}^2}{m_{B_q}^2}\right] + Q_{M_2}^2\left[1+\ln\frac{m_{M_2}^2}{m_B^2}\right]\right)}$$

- Recover the standard eikonal/QED factor Beneke, Boer, Toelstede, KKV [2020]
- ΔE is the window of the πK invariant mass around m_B
- Theory requires $\Delta E \ll \Lambda_{\rm QCD} = 60\,\text{MeV}$

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  $\rightarrow$ $U(\pi^+ K^-) = 0.914$, $U(\pi^0 K^-) = U(K^- \pi^0) = 0.976$ and $U(\pi^- \bar{K}^0) = 0.954$

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- Experimentally usoft effects included using PHOTOS
- Challenging to compare theory with experiment! In progress...

Solving Beautiful Puzzles

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

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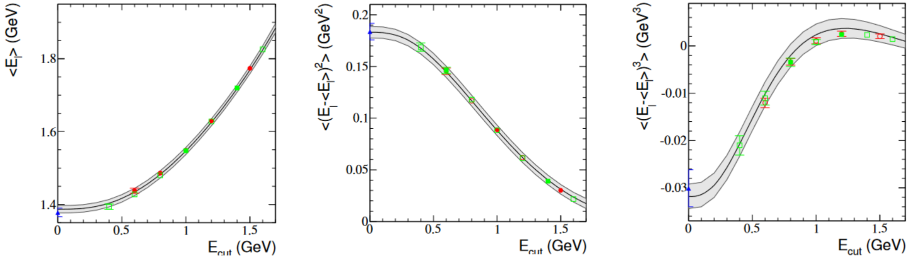
Close collaboration between theory and experiment necessary!

Backup

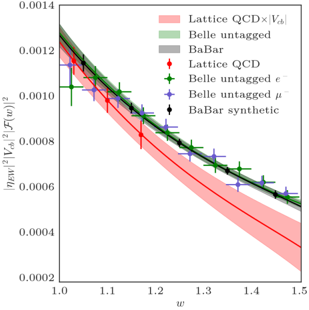
Moments of the spectrum

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!

Ratios and isospin sumrules

Beneke, Boer, Toelstede, KKV, JHEP 11 (2020) 081 [2008.10615]

- QED gives sub-percent corrections to Branching ratios

Ratios and isospin sumrules

Beneke, Boer, Toelstede, KKV, JHEP 11 (2020) 081 [2008.10615]

- Beneficial to consider ratios in which QCD is suppressed

$$R_L = \frac{2\mathrm{Br}(\pi^0 K^0) + 2\mathrm{Br}(\pi^0 K^-)}{\mathrm{Br}(\pi^- K^0) + \mathrm{Br}(\pi^+ K^-)} = R_L^{\mathrm{QCD}} + \cos\gamma \mathrm{Re}\, \delta_{\mathrm{E}} + \delta_U$$

- new structure dependent QED corrections enter linearly, QCD only quadratically

$$\delta_E = (-1.12 + 0.16i) \cdot 10^{-3}$$

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- Combined QED effect larger than QCD uncertainty!

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

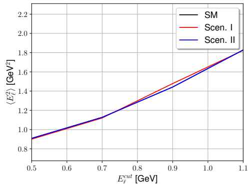
Recently a lot of attention for the V_{cb} puzzle! Bigi, Schacht, Gambino, Jung, Straub, Bernlochner, Bordone, van Dyk, Gubernari

Stay tuned!

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!

Five-body τ contribution

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

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

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

:

- Phase space suppressed:

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

- Experimentally effects diminished by cutting on the invariant mass of the B
- Can be calculated exactly in the HQE

$$\frac{\mathrm{d}^8\Gamma}{\mathrm{d}q^2\,\mathrm{d}q^2_{\nu\bar{\nu}}\,\mathrm{d}p^2_{X_c}\,\mathrm{d}^2\Omega\,\mathrm{d}\Omega^*\,\mathrm{d}^2\Omega^{**}} = -\frac{3G_F^2|V_{cb}|^2\sqrt{\lambda}(q^2-m_\tau^2)(m_\tau^2-q^2_{\nu\bar{\nu}})\mathcal{B}(\tau\to\mu\nu\nu)}{2^{17}\pi^5 m_\tau^8 m_b^3 q^2} W_{\mu\nu}L^{\mu\nu}$$

  - $L_{\mu\nu}$ 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]

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

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

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

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

- 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

New Physics explanation?

- Too many to count: exclusive $B \to D^{(*)}$ in combination with

$$R_{D^{(*)}} = \frac{B \to D^{(*)}\tau\nu}{B \to D^{(*)}\mu\nu}$$

- For inclusive $b \to c$ less analyses
  - RH-current, scalar and tensor NP contributions to rate Jung, Straub [2018]
  - RH-current to moments Feger, Mannel, et. al. [2010]
  - NP for moments KKV, Fael, Rahimi [in progress]