C1a: Inclusive semileptonic, rare and radiative decays of *B* Mesons

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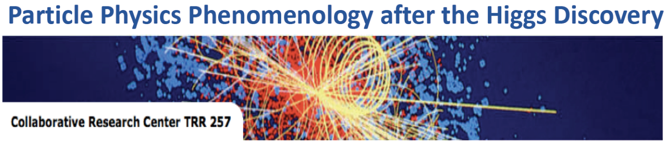

SFB Kick Off Meeting, March 18th/19th , 2019

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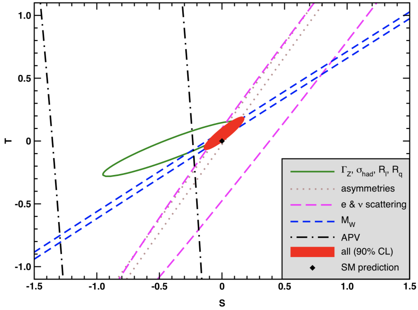
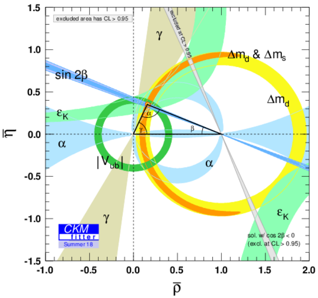
The role of Flavour Physics

Flavour Physics provides a complementary test of the SM:





Gauge Structure

Flavour Stucture

Indirect searches for new physics with a high sensitivity!

Heavy Quark Expansion in a Nutshell

Inclusive Decays

$$d\Gamma = d\Gamma_0 + d\Gamma_1/m_Q + d\Gamma_2/m_Q^2 + \cdots$$

with

$$d\Gamma_i = \sum_k C_i^{(k)}(\alpha_s, \mu/m_Q)\langle O_i^{(k)}\rangle_\mu$$

- $O_i^{(k)}$: Local operator(s) of dimension $i+3$
- $\langle \ldots \rangle_\mu$: Forward matrix element, normalized at μ
- $C_i^{(k)}(\alpha_s, \mu/m_Q)$: (perturbative) Wilson coefficient

Heavy Quark Expansion parameters

- $d\Gamma_0$ is the decay of a free quark ("Parton Model")
- $d\Gamma_1$ vanishes due to Heavy Quark Symmetries
- $d\Gamma_2$ is expressed in terms of two parameters

$$\begin{aligned} 2M_H\mu_\pi^2 &= -\langle H(v)|\bar{Q}_v(iD)^2 Q_v|H(v)\rangle \\ 2M_H\mu_G^2 &= \langle H(v)|\bar{Q}_v\sigma_{\mu\nu}(iD^\mu)(iD^\nu)Q_v|H(v)\rangle \end{aligned}$$

μ_π: Kinetic energy and μ_G: Chromomagnetic moment

- $d\Gamma_3$ two more parameters

$$\begin{aligned} 2M_H\rho_D^3 &= -\langle H(v)|\bar{Q}_v(iD_\mu)(ivD)(iD^\mu)Q_v|H(v)\rangle \\ 2M_H\rho_{LS}^3 &= \langle H(v)|\bar{Q}_v\sigma_{\mu\nu}(iD^\mu)(ivD)(iD^\nu)Q_v|H(v)\rangle \end{aligned}$$

ρ_D: Darwin Term and ρ_{LS}: Spin-Orbit Term

A few Remarks

- Local OPE is well established for $b \to c\ell\bar{\nu}$
- For $b \to u\ell\bar{\nu}$ a light-cone expansion has to be used
- For $b \to s\gamma$ and $b \to s\ell\ell$ some terms do not have an OPE: Charm loops

Project Plan

- WA1: Kinetic Mass to N^{3}LO accuracy
- WA2: Charm Quark Mass Dependence of $B \to X_s \gamma$
- WA3: Perturbative Corrections to higher order terms in the $1/m$ expansion
- WA4: Improvement of the HQE parameters
- WA5: Increasing the precision of $B \to X_{s/d} \ell\ell$
- WA6: Multi Parton Contributions to $B \to X_{s/d} \gamma$
- WA7: Re-Summations of the HQE
- WA8: Realistic Models of Duality Violations

Huber | Mannel | Steinhauser

Quark Mass (WA1 and WA2)

Strong dependence on the quark mass:

$$d\Gamma \propto m_b^5 G_F^2 \left(c_0 + \frac{\alpha_s}{\pi} c_1 + \cdots + \mathcal{O}(1/m) \right)$$

- **Pole mass m_b^{pole}:**
  Renormalon ambiguity of order Λ_{QCD}
  Renders the $1/m_b$ expansion undetermined
- **$\overline{\mathrm{MS}}$ mass $m_b^{\overline{\mathrm{MS}}}(\mu)$:**
  Short-distance mass (no renormalon)
  Useful only at scales $\mu > m_b$
- **Kinetic Mass m_b^{kin}:**
  Short-distance mass (no renormalon)
  Valid for $\mu < m_b$

Kinetic Mass

$$m^{\rm kin}(\mu) = m_b^{\rm pole} - \Lambda_{\rm QCD}|_{\rm pert} - \frac{\mu_\pi^2|_{\rm pert}}{2m^{\rm kin}}$$

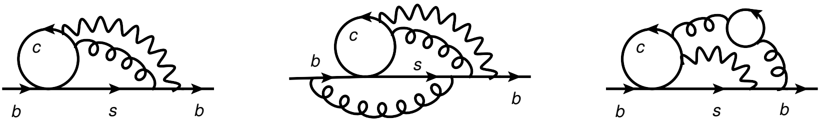
The parameters $\Lambda_{\rm QCD}|_{\rm pert}$ and $\mu_\pi^2|_{\rm pert}$ are obtained from the (perturbative) evaluation of the correlator

$$T(q_0, \vec{q}\,) = \frac{i}{2m_Q} \int {\rm d}^4x\, e^{-iqx} \langle Q| TJ(x)J^\dagger(0)|Q\rangle$$

Project Goal:
Evaluate the relation between $m^{\rm kin}$ and $m_b^{\rm pole}$ to NNNLO
$\rightarrow$ Improvement of the V_{cb} determination

Charm Quark Mass Dependence of $B \to X_s\gamma$

The $O_{1/2} - O_7$ term depend on the charm mass:



Project Goal:
Compute the $O_{1/2} - O_7$ term to NNLO
$\to$ Improvement of $B \to X_s\gamma$

CC Semileptonics (WA3, WA4, WA7 WA8)

Various Aspects of the Heavy Quark Expansion

- Perturbative Corrections at higher orders in $1/m$
- Improvement of the HQE Parameters
- Resummations of the HQE
- Duality Violation

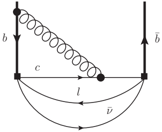
Perturbative Corrections at higher orders in $1/m$

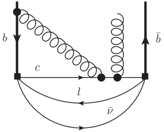
Known are

- leading order: $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$
- $\mu_\pi^2\alpha_s$ and $\mu_G^2\alpha_s$
- Anything else only at tree level

Project Goal 1:
Compute the $\mathcal{O}(\alpha_s)$ contributions at $1/m_b^3$
$\rightarrow$ Improvement of the V_{cb} determination
Project Goal 2:
Include the QCD corrections to higher orders using RPI
$\rightarrow$ Improvement of the V_{cb} determination

First results on $\rho_D \alpha_s$ (total rate) (ThM, Pivovarov, QFET 2018-23)





$$\Gamma = \Gamma_0 \left(C_0(\rho) \left[1 + \frac{\mu_\pi^2}{2m_b^2} \right] + C_G(\rho) \frac{\mu_G^2}{2m_b^2} + C_{rD}(\rho) \frac{\rho_D^3}{6m_b^3} + \cdots \right)$$

$$\begin{aligned} C_{rD} &= -57.1588 + \frac{\alpha_s}{4\pi}(-56.5941 C_A + 446.793 C_F) \\ &= -57.1588 + \frac{\alpha_s}{4\pi}(425.942) \\ &= -57.1588(1 - \frac{\alpha_s}{4\pi} 7.4519 \ldots) \\ &= -57.1588(1 - 0.12) \end{aligned}$$

Improvement of the HQE parameters

Current status

Problem: Number of HQE parameters in higher orders!

- 4 up to $1/m^3$
- 13 up to $1/m^4$ (tree level)
- 31 up to order $1/m^5$ (tree level)
- Factorial Proliferation

Reparametrization Invariance: Reduction (ThM, Vos 2018)

- 8 Parameters up to $1/m_b^4$

Still there will be a factorial proliferation ...

Need an estimate of the matrix elements

Preliminary work in QFET (Uraltsev 2013, Heinonen, ThM 2018)

Lowest Lying State Saturation Ansatz (LLSSA): e.g.

$$\langle B|\bar{h}_v (iD)^2 (iD)^2 h_v|B\rangle \sim \langle B|\bar{h}_v (iD)^2 h_v|B\rangle \langle B|\bar{h}_v (iD)^2 h_v|B\rangle \sim \mu_\pi^4$$

This can be inferred from the sum rule:

$$\sum_{k=0}^{\infty} \sum_n (2\pi)^3 \delta^3(p_n^\perp) \left(\frac{-\epsilon_n}{\omega}\right)^k \langle B(p_B)|\bar{b}_v \mathcal{P}_1 Q_v|n\rangle \langle n|\bar{Q}_v \mathcal{P}_2 \Gamma b_v|B(p_B)\rangle$$

$$= \sum_{k=0}^{\infty} \left\langle B(p_B)|\bar{b}_v \mathcal{P}_1 \left(\frac{iv\cdot D}{\omega}\right)^k \left(\frac{1+\not{v}}{2}\right) \mathcal{P}_2 \Gamma b_v|B(p_B)\right\rangle$$

where $\mathcal{P}_{1,2}$ are products of $(iD)_\perp$

Project Goal: Study the QCD corrections to the sum rule.

HQE Resummations and Duality Violations

Higher orders in $1/m$: Partial Resummations of the HQE

- Partial Resummations of the HQE (ThM, Vos 2018)
- Duality Violations:
  $1/m$ Expansion as an asymptotic series

Radiative and Rare Decays

Precision Calculations of $B \to X_{s/d}\gamma$ and $B \to X_{s/d}\ell\ell$:

- Increasing the precision in $B \to X_{s/d}\ell\ell$
- Multi-Parton contributions to $B \to X_{s/d}\gamma$

Increasing the precision in $B \to X_{s/d}\ell\ell$

- Revisiting the $c\bar{c}$ and $u\bar{u}$ resonances
  - Improving the Krüger Sehgal Ansatz for the charm loop (ongoing)
  - Include non-factorizable contributions
- Introduce an m_X cut: Shape function region
  - SCET analysis
  - Power corrections
- CP Violation in $B \to X_d\ell\ell$
- QED corrections to $B \to X_{s/d}\ell\ell$
  - $\ell = \mu$ vs. $\ell = e$

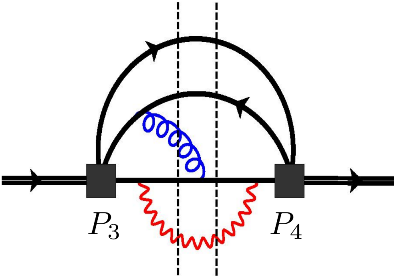
Multi-Parton contributions to $B \to X_{s/d}\gamma$

Preliminary work:

- Huber, Poradzinski, Virto 2014: NLO corrections to $b \to sq\bar{q}\gamma$
- Huber, Qin, Vos 2018: Five particle contributions $b \to sq\bar{q}\ell\ell$

Project goals:

Complete the missing NLO piece



The Role of C1a within the CRC

Questions within C1:

- Is the kinetic scheme reparametrization invariant?
- If not, can it be modified in a RP invariant fashion?
- 1S scheme vs. kinetic scheme
- Can we set up an alternative determination of inclusive V_{cb}?
- How can we improve the inclusive V_{ub} determination?

Questions within C:

- Comparison between different mass schemes
- Link to the NP models in C3
- Exclusive sum vs. inclusive calculations

Overall Questions

- Methods
- Collider vs. Flavour: Top Bottom link