Project A.8: Charmless Exclusive B Decays

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as lecturer) (PhD students)

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Methodology

"Charmless exclusive B decays" means: final state with energetic particles $E \sim \mathcal{O}(m_B)$, initial state with heavy quark and soft stuff.

$$B \to \pi\ell\nu,\ \gamma\ell\nu,\ V\gamma,\ K^{(*)}\ell\ell,\ M_1M_2,\ M_1M_2M_3,\ X_u(\text{jet})\ell\nu,\ X_s(\text{jet})\gamma,\ \ldots$$

- High-energy physics technology of collinear factorization, soft-collinear effective theory (SCET) [originally developed for this purpose!], renormalization group.
- But contrary to collinear factorization in high-energy scattering (DIS, DY, $\gamma^*\gamma^*\pi$, pion form factor), soft physics does not cancel at leading power.
- Isolate strong coupling physics from calculable weak coupling physics [$\alpha_s(m_b)$, $\alpha_s(\sqrt{m_b\Lambda}) \ll 1$].
  Expansion in Λ/m_b and α_s at the hard (m_b) and hard-collinear scale ($\sqrt{m_b\Lambda}$).

$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb}V_{pD}^{*}\Big(C_1\mathcal{O}_1 + C_2\mathcal{O}_2 + \sum_{i=\text{pen}} C_i\mathcal{O}_{i,\text{pen}}\Big) \qquad \Rightarrow \qquad \langle f|\mathcal{O}|\bar{B}\rangle_{\text{QCD+QED}}$$

Project A.8 Overview

I Phenomenology of (quasi-) two-body charmless final states

- Analysis of complete sets of final states, NNLO phenomenology with QCD factorization
- Dedicated CP violation studies

II $B \to \gamma\ell\nu$ and the inverse moment λ_B of the B-meson light-cone distribution amplitude (LCDA)

- NLO QCD sum rule analysis of λ_B
- Factorization in SCET at next-to-leading power

III Electromagnetic corrections to B decays

- Factorization theorem for QED corrections to charmless two-body decays and computation of the leading logarithms
- Electromagnetic corrections to $B \to \ell\ell$, $B \to K^{(*)}\ell\ell$

IV Three-body hadronic B decays

- QCD factorization and hadronic models

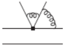
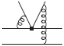
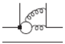
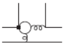
I. Phenomenology of (quasi-) two-body charmless final states

Status of NNLO QCD factorization calculations

$$\langle M_1 M_2 | C_i O_i | \bar{B} \rangle_{\mathcal{L}_{\rm eff}} = \sum_{\rm terms} C(\mu_h) \times \Big\{ F_{B\to M_1} \times \underbrace{T^{\rm I}(\mu_h, \mu_s)}_{1+\alpha_s+\ldots} \star f_{M_2} \Phi_{M_2}(\mu_s)$$

$$+ f_B \Phi_B(\mu_s) \star \Big[\underbrace{T^{\rm II}(\mu_h, \mu_I)}_{1+\ldots} \star \underbrace{J^{\rm II}(\mu_I, \mu_s)}_{\alpha_s+\ldots} \Big] \star f_{M_1} \Phi_{M_1}(\mu_s) \star f_{M_2} \Phi_{M_2}(\mu_s) \Big\}$$

$$+ 1/m_b\text{-suppressed terms}$$

Status	2-loop vertex corrections (T_i^I)	1-loop spectator scattering (T_i^{II})
Trees	 [GB 07, 09] [Beneke, Huber, Li 09]	 [Beneke, Jäger 05] [Kivel 06] [Pilipp 07]
Penguins	 in progress	 [Beneke, Jäger 06] [Jain, Rothstein, Stewart 07]

from G. Bell [FPCP 2010]

Missing NNLO penguin amplitude partially computed (tree operator matrix elements) [Bell, MB, Huber, Li, 2015], penguin operator matrix elements still in progress.

$\Rightarrow$ Global QCDF phenomenology project not yet started.

Analysis of two-body decays in other approaches [C.D. Lü and collaborators]

"Topological amplitudes"

$$T, C, P, P_{\mathrm{EW}}, S, E, PA, \ldots$$

Factorization relies on Λ_{QCD} expansion, usually leading order only in $\Lambda_{\mathrm{QCD}}/m_b$.
SU(2), SU(3) [Zeppenfeld, 1981] light flavour symmetries provide amplitude relations.
Usually leading order only in $m_q \ll \Lambda_{\mathrm{QCD}}$

Can combine som of this information in topological amplitude fits to data.

- Charmless $B_s \to VV$ Decays in Factorization-Assisted Topological-Amplitude Approach [C. Wang, Q.-A. Zhang, Y. Li, C.-D. Lü, 1701.01300]
- Analysis of Charmless Two-body B decays in Factorization Assisted Topological Amplitude Approach [S.-H. Zhou, Q.-A. Zhang, W.-R. Lyu, C.-D. Lü, 1608.02819]
- Global Analysis of Charmless B Decays into Two Vector Mesons in Soft-Collinear Effective Theory [C. Wang, Q.-A. Zhang, Y. Li, C.-D. Lü, 1708.04861]

Global fits to PP, PV [double no. of amplitudes], VV [triple no. of amplitudes, needs polarisation measurements] including B_s decays.

Global Fit for all B→PP, VP and PV decays (100 Channels)

35 branching Ratios and 11 CP violation observations data are used for the fit with $\chi^2/\text{d.o.f} = 45.2/34 = 1.3.$

$$\chi^C = 0.48 \pm 0.06, \quad \phi^C = -1.58 \pm 0.08,$$
$$\chi^{C'} = 0.42 \pm 0.16, \quad \phi^{C'} = 1.59 \pm 0.17,$$
$$\chi^E = 0.057 \pm 0.005, \quad \phi^E = 2.71 \pm 0.13,$$
$$\chi^P = 0.10 \pm 0.02, \quad \phi^P = -0.61 \pm 0.02.$$
$$\chi^{P_C} = 0.048 \pm 0.003, \quad \phi^{P_C} = 1.56 \pm 0.08,$$
$$\chi^{P'_C} = 0.039 \pm 0.003, \quad \phi^{P'_C} = 0.68 \pm 0.08,$$
$$\chi^{P_A} = 0.0059 \pm 0.0008, \quad \phi^{P_A} = 1.51 \pm 0.09,$$

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{x_i^{\text{th}} - x_i}{\Delta x_i} \right)^2 .$$

χ^2 is smaller than previous topology diagram approach. Number of free parameters is much reduced.

Global fit for charmless B→ VV decays
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18 branching fractions, 20 polarization fractions, 6 relative phases, and 2 direct CP asymmetries as input

10 free parameters to be fitted

$$\chi_C^0 = 0.23 \pm 0.05, \quad \phi_C^0 = 0.48 \pm 0.29; \quad \chi_E^0 = 0.082 \pm 0.026, \quad \phi_E^0 = 1.69 \pm 0.16;$$

$$\chi_S^0 = 0.018 \pm 0.003, \quad \phi_S^0 = 1.29 \pm 0.22; \quad \chi_{P_A}^0 = 0.012 \pm 0.002, \quad \phi_{P_A}^0 = -0.07 \pm 0.18;$$

$$\chi_{P_A}^{\parallel,\perp} = 0.0098 \pm 0.0003, \quad \phi_{P_A}^{\parallel,\perp} = -0.21 \pm 0.09;$$

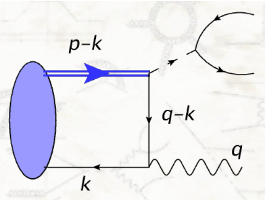
The $\chi^2/\text{d.o.f} = 82.0/(46-10)$ is 2.28.

Well explanation of the transverse polarization puzzle with minimum number of free parameters.

II. $B \to \gamma\ell\nu$ and the inverse moment λ_B of the B-meson light-cone distribution amplitude (LCDA)

with Y.-B. Wei and V.M. Braun, Y. Ji (U. Regensburg)

Motivation



$$\Gamma(\ell\nu) \propto f_B^2 \left(\frac{m_\ell}{m_B}\right)^2$$

$$\Gamma(\gamma\ell\nu) \propto f_B^2 \, \frac{\alpha_{\rm em}}{4\pi} \left(\frac{m_B}{\lambda_B}\right)^2$$

No helicity suppression.
Simplest, non-trivial, hard-exclusive B decay when $2E_\gamma = \mathcal{O}(m_b)$.
Involves B meson light-cone distribution amplitude:

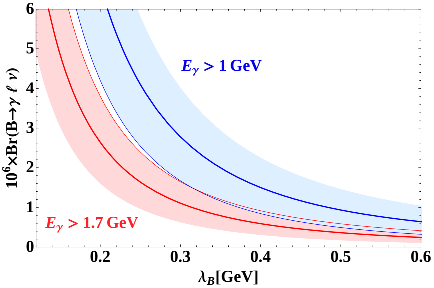
$$iF_{\rm stat}(\mu)\Phi_{B+}(\omega,\mu) = \frac{1}{2\pi}\int dt\, e^{it\omega}\, \langle 0|(\bar{q}_s Y_s)(tn_-)\not{n}_-\gamma_5 (Y_s^\dagger h_v)(0)|\bar{B}_v\rangle_\mu$$

$$\frac{1}{\lambda_B(\mu)} = \int_0^\infty \frac{d\omega}{\omega}\,\Phi_{B+}(\omega,\mu), \qquad \sigma_n(\mu) = \lambda_B(\mu)\int_0^\infty \frac{d\omega}{\omega}\,\ln^n\frac{\mu_0}{\omega}\,\Phi_{B+}(\omega,\mu)$$

Crucial quantity for the colour-suppressed tree amplitude in charmless B decays and other exclusive B decays (see III.)

$$\Gamma(\pi\pi) \propto f_\pi \Phi_\pi \left[C_2 F^{B\pi} + C_1\,\frac{\alpha_s f_B f_\pi \Phi_\pi}{m_B \lambda_B}\right]^2$$

Branching fraction for $E_\gamma > E_{\gamma,\min} \gg \Lambda_{\rm QCD}$ is very sensitive to λ_B



First significant measurement from BELLE [1504.05831]
Expect BELLE II to measure λ_B. Hypothetical example:

$$\mathrm{Br}\left(B^- \to \gamma\ell\bar{\nu}, E_\gamma > 1.7\,\mathrm{GeV}\right) = (2.0 \pm 0.4) \times 10^{-6} \quad \to \quad \lambda_B = 228^{+76}_{-61}\,\mathrm{MeV}$$

Dominant theoretical uncertainty about equally from σ_1, σ_2 and power-suppressed form factor ξ.

Theoretical description

Hadronic physics contained in

$$iT_{\nu\mu}(p,q) = \int d^4x\, e^{ipx} \langle 0|\mathrm{T}\{j^{\nu}_{\mathrm{em}}(x)(\bar{u}\gamma_\mu(1-\gamma_5)b)(0)\}|B^-\rangle$$
$$\equiv i\epsilon_{\mu\nu\rho\sigma}v^\rho p^\sigma\, F_V(E_\gamma) + (g_{\mu\nu}v\cdot p - v_\nu p_\mu)\,\hat{F}_A(E_\gamma) + \frac{v_\nu v_\mu}{v\cdot p} f_B m_B + p_\nu\text{-terms}$$

$$F_V(E_\gamma) = \underbrace{\frac{Q_u m_B f_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma,\mu)}_{\text{leading power}} + \underbrace{\left[\xi(E_\gamma) + \frac{Q_b m_B f_B}{2E_\gamma m_b} + \frac{Q_u m_B f_B}{(2E_\gamma)^2}\right]}_{\text{next}-\text{to}-\text{leading power}},$$

$$F_A(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B(\mu)} R(E_\gamma,\mu) + \left[\xi(E_\gamma) - \frac{Q_b m_B f_B}{2E_\gamma m_b} - \frac{Q_u m_B f_B}{(2E_\gamma)^2} + \frac{Q_\ell f_B}{E_\gamma}\right].$$

- R is a radiative correction factor. Known to NLO+NLL
- Both form factors idential to all order at leading power (helicity conservation)
- Next-to-leading power terms parameterized by $\xi(E_\gamma)$. Irreducible uncertainty in determination of λ_B.

QCD sum rule calculation of the power-suppressed form factor

Idea [Braun, Khodjamirian, 1210.4453] (similar to $\gamma\gamma^*\pi^0$ form factor): compute hadronic tensor for negative $p^2 \sim \mathcal{O}(m_b\Lambda)$ and apply a dispersion relation.

Augments the hard-collinear SCET contributions by a dispersive representation of the soft contribution from $\omega \sim \Lambda^2/E_\gamma$ and in this way provides a representation of $\xi(E_\gamma)$.

- twist-2, tree-level [Braun, Khodjamirian, 1210.4453]

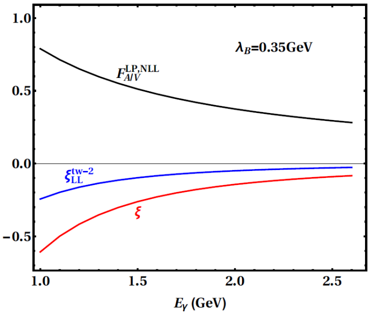
$$\xi_{\rm BK}(E_\gamma) = \frac{Q_u f_B}{2E_\gamma} \times \frac{m_B}{2E_\gamma} \times \hat{\xi}(E_\gamma)$$

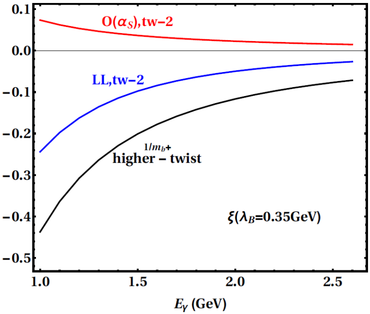
  where $\hat{\xi}$ is negative, nearly energy-independent, but depends strongly on λ_B.

- twist-2, one-loop [Y. Wang, 1606.03080]
  treatment of higher-twist not correct

- This project: three-particle B-meson LCDAs, twist-4 two-particle, $1/m_b$ correction, four-particle contributions proportional to quark condensate, better parameterization of the B-meson LCDA.

  Following plots show PRELIMINARY (unpublished) results





Appears that $1/E_\gamma$ expansion requires at least $E_\gamma > 1.5$ GeV.
λ_B analysis forth-coming.

In addition to $B \to \gamma$ with the same technique the $B \to \pi$ [Shen, Wei, Lü, 1607.08727] and $B \to D$ [Wang, Wei, Shen, Lü, 1701.06810] form factors are obtained (up to less complete higher-twist contributions).

III. Electromagnetic corrections to B decays

with C. Bobeth, R. Szafron

Motivation

- Electromagnetic corrections violate isospin symmetry.
  Can fake small electroweak penguin amplitudes in charmless B decays

- Large logarithmic enhancements $\ln m_b^2/\Lambda^2$, $\ln m_b^2/m_\ell^2$ possible

- Existing treatment of electromagnetic effects uses traditional soft photon approximation, but the logarithmic structure is more complicated in SCET

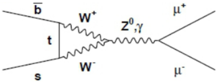
- Expected precision of measurements require inclusion of electromagnetic effects, even if small

Factorization theorems for electromagnetic correction don't exist. Theory still needs to be developed.

- Start with the simplest decay $B_s \to \ell^+\ell^-$ (+soft γ).

- Theory framework: SCET with electromagnetism, fermion masses and power-suppressed interactions

Status of $B_s \to \mu^+\mu^-$



$$\mathrm{Br}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}$$
$$\times \left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) |C_S - C_S'|^2 + \left|(C_P - C_P') + \frac{2m_\mu}{m_{B_s}}(C_{10} - C_{10}')\right|^2 \right\}$$

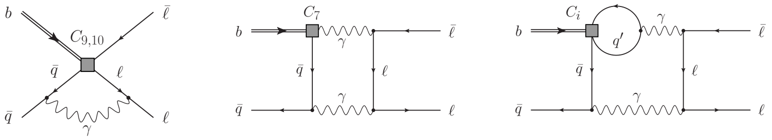
- SM only C_{10} $\Rightarrow$ helicity suppression Sensitive to scalar couplings.
- LHCb [1703.05747] $(3.0^{+0.7}_{-0.6}) \times 10^{-9}$ vs. Theory [Bobeth et al., 1311.0903] $(3.65 \pm 0.23) \times 10^{-9}$

Theory

- Includes NNLO QCD, NLO EW matching corrections at EW scale, NNLL renormalization-group evolution including QED logarithms down to the b-quark mass scale
- QED corrections below the m_b scale not included, estimated to be 0.3%.
- QCD corrections below the m_b scale all contained in the single non-perturbative parameter f_{B_s}. Known from lattice QCD with 1.5% accuracy.

Electromagnetic correction

Surprise: m_B/Λ power-enhanced and logarithmically enhanced, purely virtual correction



$$
\begin{aligned}
i\mathcal{A} \;=\; & m_\ell f_{B_q} \mathcal{N}\, C_{10}\, \bar{\ell}\gamma_5 \ell \\
& + \frac{\alpha_{\rm em}}{4\pi} Q_\ell Q_q\, m_\ell m_B f_{B_q} \mathcal{N}\, \bar{\ell}(1+\gamma_5)\ell \times \Bigg\{ \int_0^1 du\,(1-u)\, C_9^{\rm eff}(u m_b^2) \int_0^\infty \frac{d\omega}{\omega}\, \phi_{B+}(\omega) \left[\ln\frac{m_b\omega}{m_\ell^2} + \ln\frac{u}{1-u} \right] \\
& - Q_\ell C_7^{\rm eff} \int_0^\infty \frac{d\omega}{\omega}\, \phi_{B+}(\omega) \left[\ln^2\frac{m_b\omega}{m_\ell^2} - 2\ln\frac{m_b\omega}{m_\ell^2} + \frac{2\pi^2}{3} \right] \Bigg\} + \ldots
\end{aligned}
$$

The virtual photon probes the B meson structure. Annihilation is “smeared out” over hard-collinear distance $1/\sqrt{m_B\Lambda}$. B-meson LCDA and $1/\lambda_B$ enters.

$$
m_B/\lambda_B \sim 20 \qquad \ln\frac{m_b\omega}{m_\mu^2} \sim 6
$$

Logarithms are not the standard soft logarithms, but due to hard-collinear, collinear and soft regions, involving also soft lepton exchange for the box graph.

Include through the substitution

$$C_{10} \to C_{10} + \frac{\alpha_{\rm em}}{4\pi} Q_\ell Q_q \Delta_{\rm QED}$$

where

$$\Delta_{\rm QED} = (33 \ldots 119) + i\,(9 \ldots 23)$$

- Reduction of the branching fraction by

$$0.3 - 1.1\%$$

  Cancellation of a factor of three between the $C_9^{\rm eff}(um_b^2)$ and $C_7^{\rm eff}$ term. Uncertainty entirely due to B-meson LCDA.

- Significantly larger than previously estimated QED correction.
  QED uncertainty almost as large as other non-parametric uncertainties (1.2%)

- New SM value for the un-tagged, time-integrated branching fraction (including parameter up-date)

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.57 \pm 0.17) \cdot 10^{-9}$$

IV. Three-body hadronic B decays

Motivation [LHCb, 1306.1246]

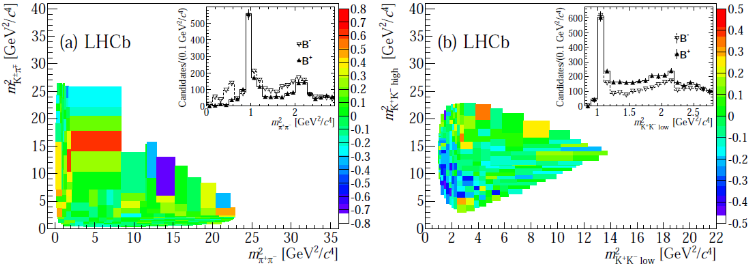


FIG. 2. Asymmetries of the number of signal events in bins of the Dalitz plot, A^N_{CP}, for (a) $B^\pm \to K^\pm\pi^+\pi^-$ and (b) $B^\pm \to K^\pm K^+ K^-$ decays. The inset figures show the projections of the number of background-subtracted events in bins of (left) the $m^2_{\pi^+\pi^-}$ variable for $m^2_{K^\pm\pi^\mp} < 15\,\mathrm{GeV}^2/c^4$ and (right) the $m^2_{K^+K^-\,\mathrm{low}}$ variable for $m^2_{K^+K^-\,\mathrm{high}} < 15\,\mathrm{GeV}^2/c^4$. The distributions are not corrected for acceptance.

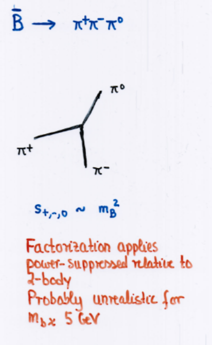
Contrary to two-body decay large local CP asymmetries.

- Enhanced sensitivity to direct CP violation and CP phases.
- Can the hadronic physics be understood to sufficient degree to make this useful?

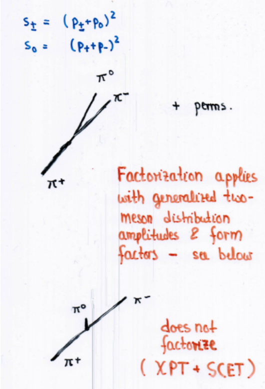
Three-body factorization theory ($B \to M_a M_b M_c$)

[MB (2006); Stewart (2006); Kränkl, Mannel, Virto, 1505.04111]

- Different factorization theorems and power-counting in different regions of the Dalitz plot
  - Central region power-suppression
  - Side-bands two-body like but long-distance rescattering in two-meson LCDA and $B \to$ two meson form factor
- Central region probably non-existent for real m_b due to spill-over of power-enhanced contributions [Kränkl, Mannel, Virto, 1505.04111]



[MB (Three-body Workshop, Paris, 2006)]



- Contrary to two-body strong interaction phases from long-distance interactions at leading power
  $\rightarrow$ can be large
  $\rightarrow$ enhanced sensitivity to direct CP violation and CP phases.

- Probably requires a combination of rigorous (factorization) and phenomenological approaches [Klein, Mannel, Virto, Keri Vos, 1708.02047]

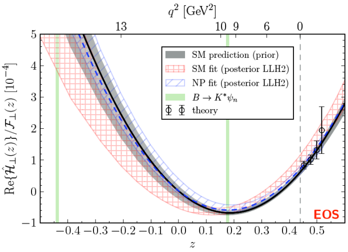
  Also [Cheng, Chua, 1308.5139; Wang et al. 1402.5501]

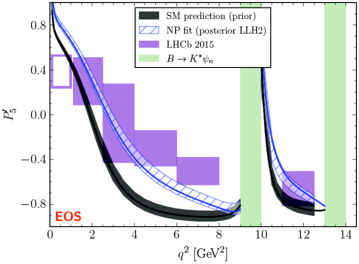
Three-body project not yet started. Javier Virto joined TUM July 2017, jointly with MIT until end of 2018, then at TUM.
Project should profit from expertise on low-energy hadron scattering within this CRC.

V. Other results and developments

Other results

- Dispersive approach to the non-factorizable charm-loop contributions to $B \to K^{(*)}\ell\ell$ (QCD factorization in the Euclidian + resonance constraints) [Bobeth, Chrzaszcz, van Dyk, Virto, 1707.07305]





- Model-independent and specific model studies of New Flavour Physics:
  - "Patterns of Flavour Violation in Models with Vector-Like Quarks" [Bobeth, Buras, Celis, Jung, 1609.04783]
  - "Yukawa enhancement of Z -mediated new physics in $S = 2$ and $B = 2$ processes" [Bobeth, Buras, Celis, Jung, 1703.04753]

Other developments

New (August 2017) Emmy-Noether Junior Research Group at TUM, led by Danny van Dyk

"Anomalies in semileptonic b-decays as antennas of New Physics"

+ A. Kokulu (PostDoc), N. Gubernari (PhD student)

- Physics focus on strong interaction and New Physics sensitivity from $B \to D^{(*)} \ell\nu$, $B \to K^{(*)} \ell\ell$, $B_c \to D^0 \ell^- \bar{\nu}$, form factors, baryonic semileptonic decays
- Expertise in statistical analysis, author of the EOS flavour observable analysis tool

Complementary to A.8 research programme and reinforcement of the Flavour Physics group

Group has been associated with the CRC 110