

Annual CRC meeting 29.9. - 1.10.2025, Siegen



Collaborative Research Center  
TRR 257

1st round: 2019- 2022    **2nd round: 2023-2026**    **3rd round: 2027-2030**

Alexander Lenz

### 1. Setting the scene

- A. Current projects and papers
- B. Referees comments 2nd period
- C. Particle physics future plans
- D. New structural developments in Aachen, Karlsruhe, Siegen and Heidelberg
- E. Hot flavour topics in Community

### 2. Gudrun's questions

- 1) What was the overall impact of the CRC research in this area?
- 2) What goals have been achieved or will/should be achieved until early 2026?
- 3) What synergies have been exploited?
- 4) What is the perspective of the projects in this research area for FP3?
- 5) Does the part of the cover story related to this research area need to be modified?

### 3. New ideas

- A. Increase SM precision, Gradient Flow
- B. Charm Physics
- C. Collider Flavour connection
- D. New methods
- E. Multi-body hadronic decays/CPV/Dalitz

1st round: 2019- 2022

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### Research Area C: Flavour physics

C1a: Inclusive semileptonic, rare and radiative decays of B mesons	Huber, Mannel, Steinhauser	20
C1b: $B - \bar{B}$ mixing, CP violation, and lifetimes	Lenz, Nierste, Steinhauser	10
C1c: Non-perturbative matrix elements for $B - \bar{B}$ mixing and lifetimes	Harlander, Lenz, Nierste	10
C2a: Hadronic matrix elements and exclusive semileptonic decays	Feldmann, Mannel	11
C2b: Exclusive non-leptonic and rare b-quark decays	Feldmann, Huber	24
C3a: New sources of flavour violation at high transverse momenta	Blanke, Krämer	6
C3b: New Physics models for flavour observables	Nierste	23

Discussed here

Entries  
on our  
webpage  
for period  
2

Discussed by Michael K.

104

Write project reports - check CRC webpage if all papers are included



## Setting the scene: Entscheidungsschreiben 7.12.2022

### Teilprojekt C1b B-Mischung, CP-Verletzung und Lebensdauern (Lenz / Nierste / Steinhauser)

Das Arbeitsprogramm kann auch mit weniger Personalaufwand erfolgreich umgesetzt werden, daher werden Personalmittel nur für jeweils eine Stelle der Kategorie „Postdoktorandin/Postdoktorand und Vergleichbare“ sowie „Doktorandin/Doktorand und Vergleichbare“ bewilligt und in Aussicht gestellt.

### Teilprojekt C1c\* Nicht-perturbative Matrixelemente für B-Mischung und Lebensdauern (Harlander / Lenz / Nierste)

Den Projektleitern wird empfohlen, Herrn Witzels Kompetenzen auch in die weitere Gestaltung des Projekts einzubeziehen.

finden werden. Von herausragendem wissenschaftlichem Wert sind auch die Berechnungen zur QCD-Faktorisierung, die von den Herren Bell, Feldmann und Huber in ihrem gemeinsamen Projekt C2b durchgeführt wurden und die ebenfalls international auf große Resonanz stießen. Die Planungen für die nächste Förderperiode lassen u. a. von den Projekten C1a (Huber, Mannel, Steinhauser) und C3a (Blanke, Krämer) wegweisende Präzisionsrechnungen für inklusive Zerfälle von B-Mesonen bzw. zur Phänomenologie neuer flavour-verletzender Wechselwirkungen sowie zur Verbindung von Flavour- und Kolliderphysik erwarten, die erneut die Arbeiten des Verbunds ins internationale Rampenlicht werden stellen können.

nießen diese Sichtbarkeit zweifelsohne. Sie prägen und gestalten nationale und internationale Initiativen, wie z.B. die European Strategy for Particle Physics, ein Beratungsgremium des CERN und dort insbesondere auch das European Committee for Future Accelerators (ECFA). Die Ergebnisse der unterschiedlichen Präzisionsberechnungen, die in den verschiedenen Arbeitsgruppen des SFB/Transregio erzielt wurden, sind von essenzieller Bedeutung für die experimentellen Erfolge am LHC des CERN, für die Auswertung und das Verständnis der Daten, die dort produziert werden. Der Mehrwert dieser Präzisionsberechnungen für die detaillierte Interpretation der LHC-Daten kann kaum hoch genug eingestuft werden. Sie zählen zu den internationalen Spitzenleistungen auf diesem Forschungsgebiet und setzen weltweit Maßstäbe.

International ist der Verbund nach wie vor einzigartig. Trotz hohem Interesse an dem Forschungsgebiet gibt es aufgrund fehlender Förderinstrumente international keinen vergleichbaren Forschungsverbund, der die so immens wichtige Aufgabe übernimmt, die an den großen Beschleunigern geplanten und durchgeführten Experimente theoretisch zu begleiten, sie zu untermauern und deren Befunde zu analysieren, zu erklären und zu bewerten.

C1a: exzellent

C1b: gut bis sehr gut

C1c: sehr gut

C2a: sehr gut

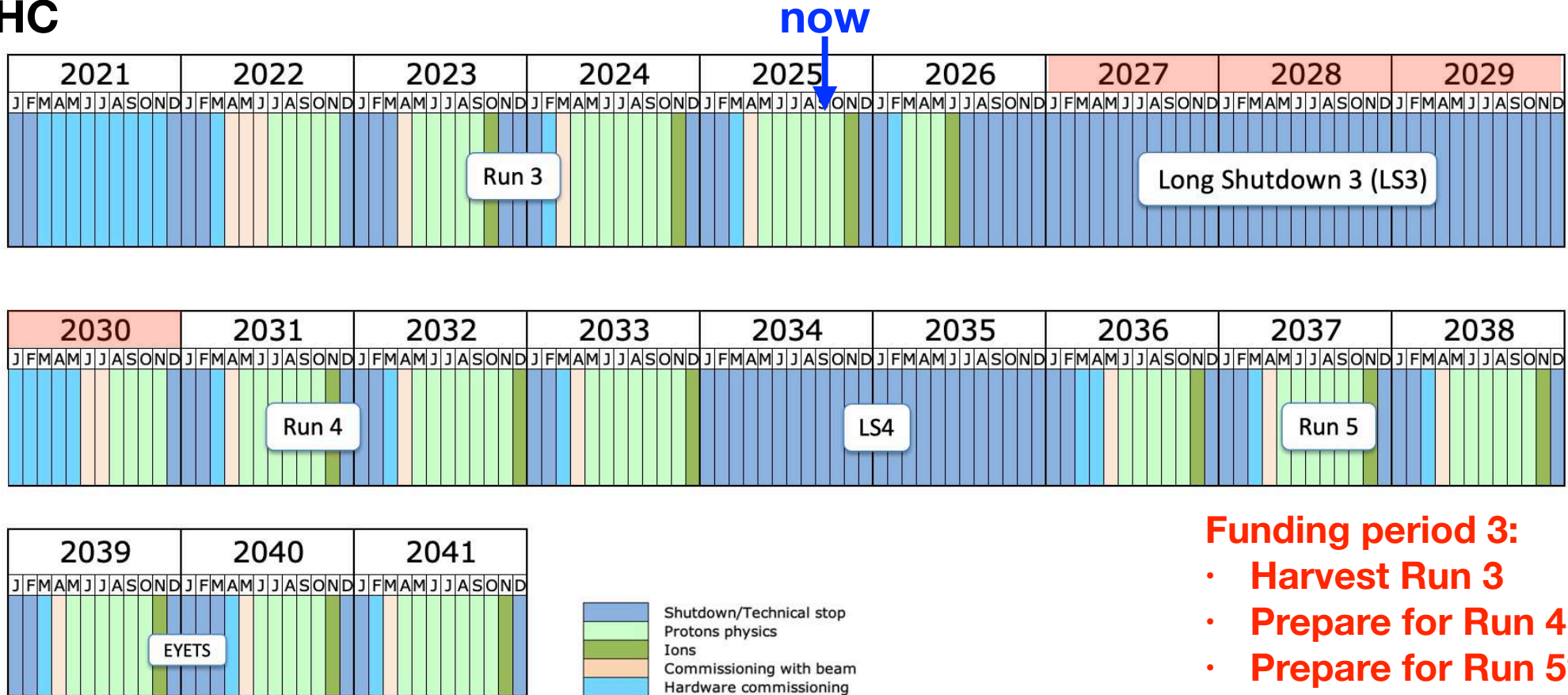
C2b: sehr gut bis exzellent

C3a: sehr gut

C3b: gut

## Setting the scene: future particle physics plans

### LHC

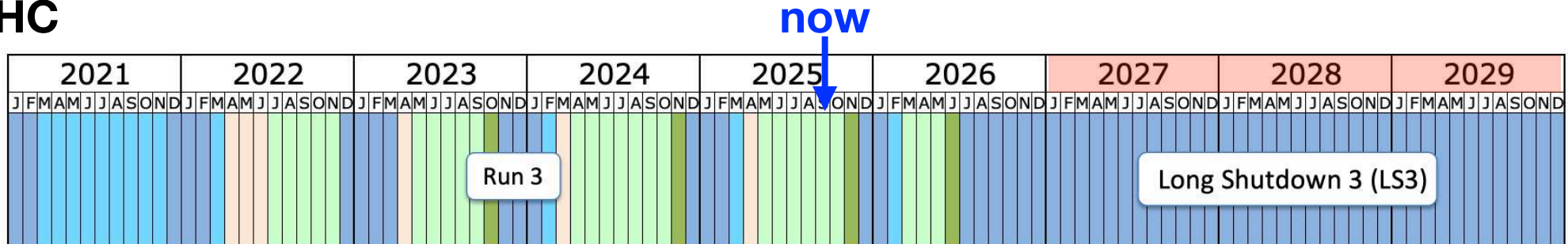


Last update: November 24

- Funding period 3:**
- Harvest Run 3
  - Prepare for Run 4
  - Prepare for Run 5?
  - Prepare for FCC?

## Setting the scene: future particle physics plans

### LHC



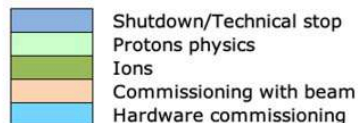
### INSTALL LHCb upgrade 2 — LHCb upgrade 2



### LHCb upgrade 2



Last update: November 24



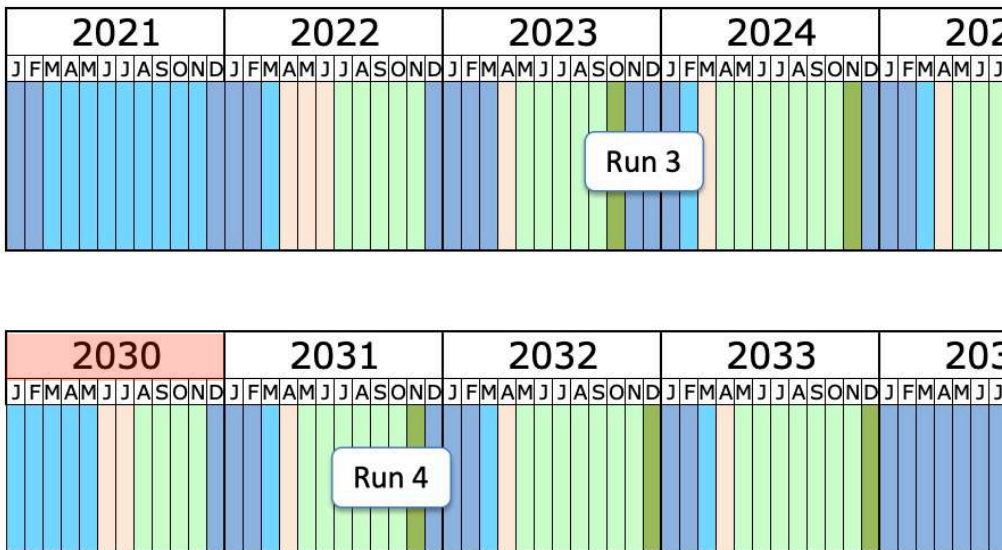
### Funding period 3:

- Harvest Run 3
- Prepare for Run 4
- Prepare for Run 5? - LHCb U2
- Prepare for FCC?

## Setting the scene: future particle physics plans

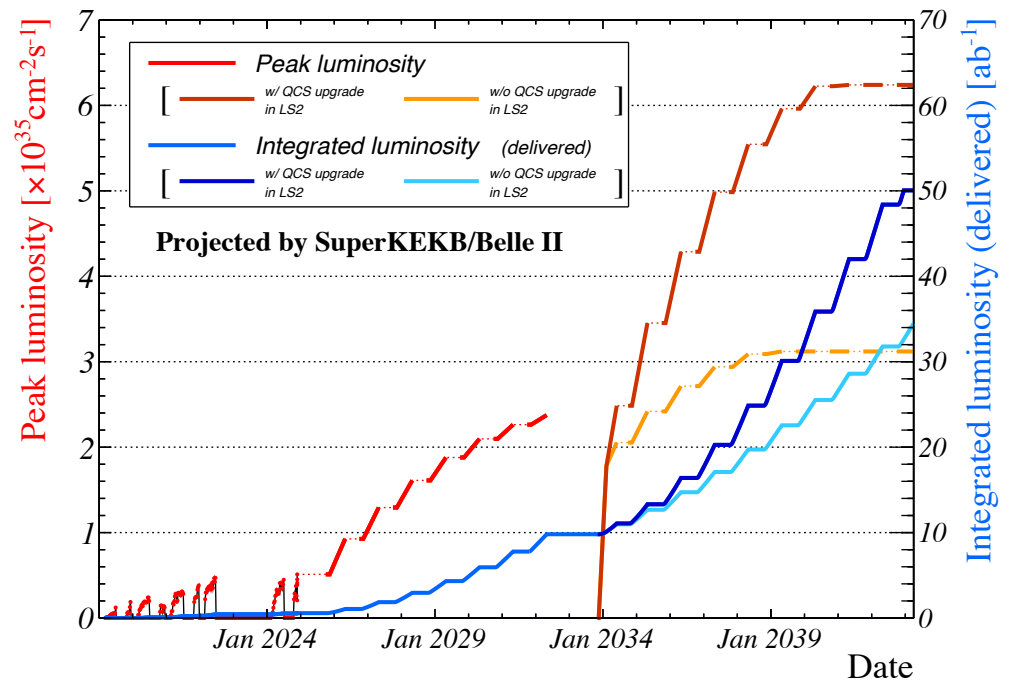
### LHC

- Harvest Run 3
- Prepare for R4
- Prepare for R5 **LHCb U2**
- Prepare for FCC?



### Belle II

- Harvest/prepare for 30 ab<sup>-1</sup>
- Prepare for 60 ab<sup>-1</sup>





## Setting the scene: future particle physics plans

### LHC

- Harvest Run 3
- Prepare for R4
- Prepare for R5 **LHCb U2**
- Prepare for FCC?

### Belle II

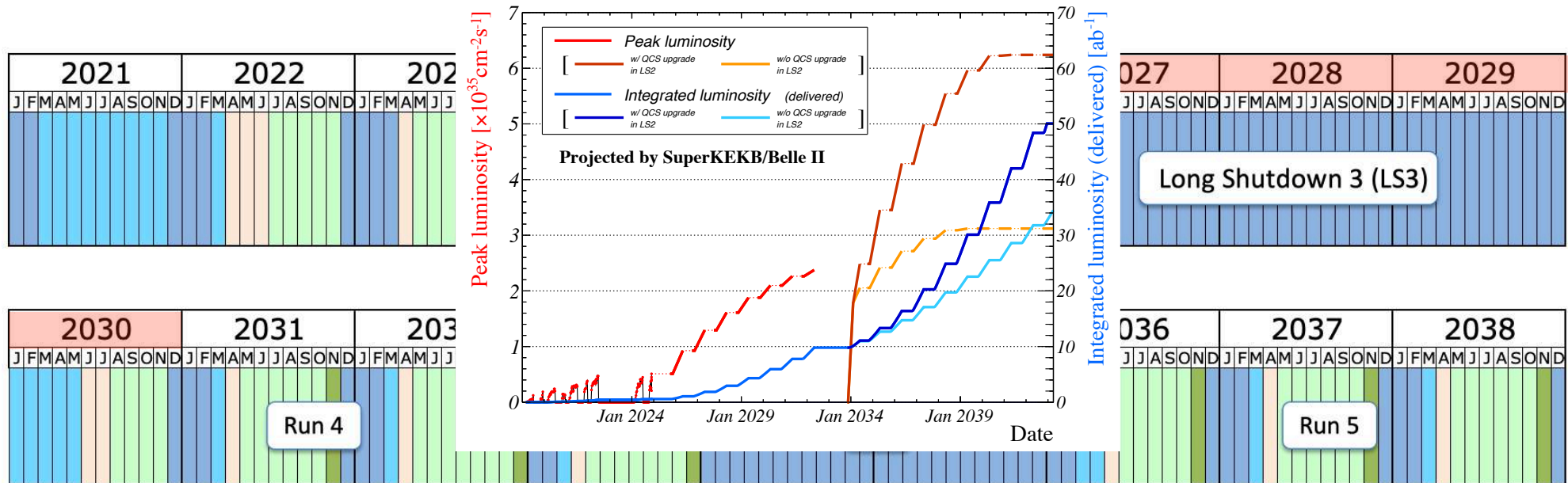
- Harvest/prepare for 30 ab<sup>-1</sup>
- Prepare for 60 ab<sup>-1</sup>

### BESS III

- data taking till 2030/32

### Super tau charm

- Operation from 2033 onwards

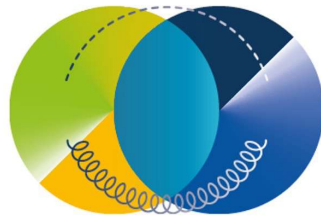




Setting the scene: structural developments at sites

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- **1.1.2026 Excellence cluster: Color meets Flavor - Siegen, Bonn, Dortmund, Jülich**



color meets flavor

- **1.1.2026 New W3 Computational Physics in Siegen**
- **New W3 Theoretical Physics Karlsruhe in Karlsruhe**
- **1.1.2026 New W1 Cosmology? In Karlsruhe**
- **Oliver Witzel permanent in Siegen**
- What else?

## Setting the scene: hot topics in flavour communities

**more than a lifetime** **22. – 25.9.2025  
Siegen, Germany**



**Organising Committee**  
Johannes Albrecht  
LHCb, Dortmund  
Florian Bernlochner  
Bella II, Bonn  
Achim Geiser  
CMS, DESY  
Robert Harlander  
Theory, Aachen  
Alexander Lenz  
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Ulrich Nierste  
Theory, Karlsruhe  
Maria Smizanska  
ATLAS, Lancaster  
Guy Wilkinson  
LHC and BES III, Oxford  
Oliver Witzel  
Theory, Siegen

**International workshop**  
Lifetimes of heavy hadrons  
– experimental and theoretical aspects

<https://indico.physik.uni-siegen.de/event/498/>

**BEYOND FLAVOUR PHYSICS**

Topical Workshop  
"Particle Physics after the Higgs Discovery"

June 23-24 2025  
Emmy Noether Campus  
University of Siegen

**Topics:**  
Top and Higgs,  
Flavour physics,  
Quantum Information/Collider interplay

**Organization:**  
Tao Han (Pittsburg)  
Wolfgang Kilian (Siegen)  
Giovanni Petrolini (Siegen)  
Arzu Ergul (Siegen)

**Contact:**  
kilian@physik.uni-siegen.de  
gpetrolini@physik.uni-siegen.de

<https://indico.physik.uni-siegen.de/event/573/>

**TP1 CPPS P<sup>3</sup>H**

color meets flavor

The 11th International  
Workshop on Charm Physics  
July 17-21, 2023

**CHARM 2023**  
Siegen, Germany  
Hörsaalzentrum am Unteren Schloss



**Topics**

- Charm facilities - Status and future
- Charmed meson and baryon spectroscopy
- Exotic hadrons
- Production of charm and charmonia
- Hidden and open charm in media
- Light hadronic spectroscopy from decays of charm and charmonia
- Leptonic, semileptonic rare charm decays (including form factors, BSM models, LFV)
- Rare charm decays to photons, neutrinos and invisibles (dark photons, axions)
- Hadronic charm decays and CP-violation
- D mixing
- Tau lepton physics
- Averages for HFLAV and PDG

**Local Organising Committee**

- J. Albrecht (TU Dortmund)
- F. Bernlochner (U Bonn)
- M. Cristofari (U Siegen)
- J. Dingfelder (U Bonn)
- A. Ergul (Secretary) (U Siegen)
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- G. Vogt (LLNL & UC Davis)
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- G. Wilkinson (U Oxford)
- B. Yabsley (U Sydney)
- Y. Zheng (UCAS Beijing)

**Website**  
<https://indico.physik.uni-siegen.de/event/1/>

The 5th edition of the workshop  
"Beyond the Flavour Anomalies"  
Siegen, Germany, 9 – 11 April 2024



**Topics**

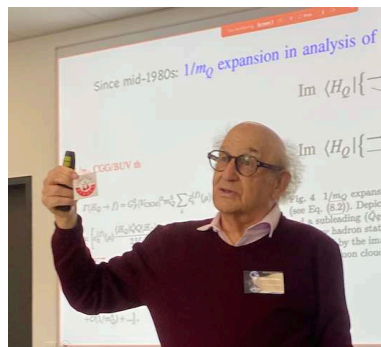
- Rare semileptonic decays
- Tree-level semileptonic decays
- Lepton flavour universality ratios
- Tree-level non-leptonic decays
- Charm sector
- Hadronic effects
- Experimental overviews and prospects
- Beyond the Standard Model

**Organising Committee**

- Alexander Lenz (Siegen University)
- Mitesh Patel (Imperial College London)
- Konstantinos Petridis (Bristol University)
- Alekssey Ruzar (Siegen University)
- Danny van Dyk (Durham University)

**Secretariat**  
Arzu Ergul (Siegen University)

**TP1 CPPS P<sup>3</sup>H**



**Lattice meets Continuum** 3<sup>rd</sup> edition  
Seminarzentrum Unteres Schloss, Universität Siegen  
September 30 – October 3, 2024

<https://indico.physik.uni-siegen.de/event/168/>

**Confirmed Speakers**

- Oliver Bär (HU Berlin)
- Alexandro Barone (U Mainz)
- Vadim Baru (U Bochum)
- Alessandro De Santis (U Roma Tor Vergata)
- Felix Eisen (U Siegen)
- Martin Gorbahn (U Liverpool)
- Christoph Hanhart (FZ Jülich)
- Robert Harlander (RWTH Aachen)
- Florian Herberich (U Zürich)
- Martin Jung (U Torino)
- Takashi Kishimoto (U Siegen)
- Alexander Khatami (U Siegen)
- Daniel Mohler (TU Darmstadt)
- Maria Laura Pascaud (U Siegen)
- Fernando Romero-Lopez (MIT)
- J. Tobias Wang (CERN)
- Raynette van Sinder (MCC)
- Alejandro Vazquez (Zaragoza U)
- Ker-Yi (Maastricht U)

**Organization Committee**

- Arzu Ergul (Secretary) (U Siegen)
- Matthew Bock (U Siegen)
- Paolo Campini (U Torino)
- Shoji Hashimoto (KNA)
- Stefan Merten (U Siegen)
- Ruth Van de Water (Fermilab)
- Oliver Witzel (U Siegen)

**Advisory Committee**

- Johannes Albrecht (TU Dortmund)
- Florian Bernlochner (U Bonn)
- Markus Cristofari (U Siegen)
- Christoph Hanhart (FZ Jülich)
- Stefan Krieg (FZ Jülich)
- Alexander Lenz (U Siegen)
- Carsten Urbach (U Bonn)

**The Gradient Flow in QCD and other Strongly Coupled Field Theories**  
Trento, 20 - 24 March 2023

**ORGANIZERS**

- Christopher Mahan (William & Mary, United States)
- Robert Harlander (RWTH Aachen University, Germany)
- Anna Hasenfratz (University of Colorado, Boulder, United States)
- Oliver Witzel (Siegen University, Germany)

**TOPICS**

- Perturbative approach
- Non-perturbative renormalization
- Electric dipole moments
- Flavor physics
- Conformal systems
- BSM physics

**CONFIRMED SPEAKERS**

- Nora Brambilla
- Luigi Del Debbio
- Julian Bui
- Fabian Lange
- Martin Lüscher
- Aleksander Ruzar
- Gerrit Scharnholt
- Andrea Sfondrini

**Status and prospects of Non-leptonic B meson decays**

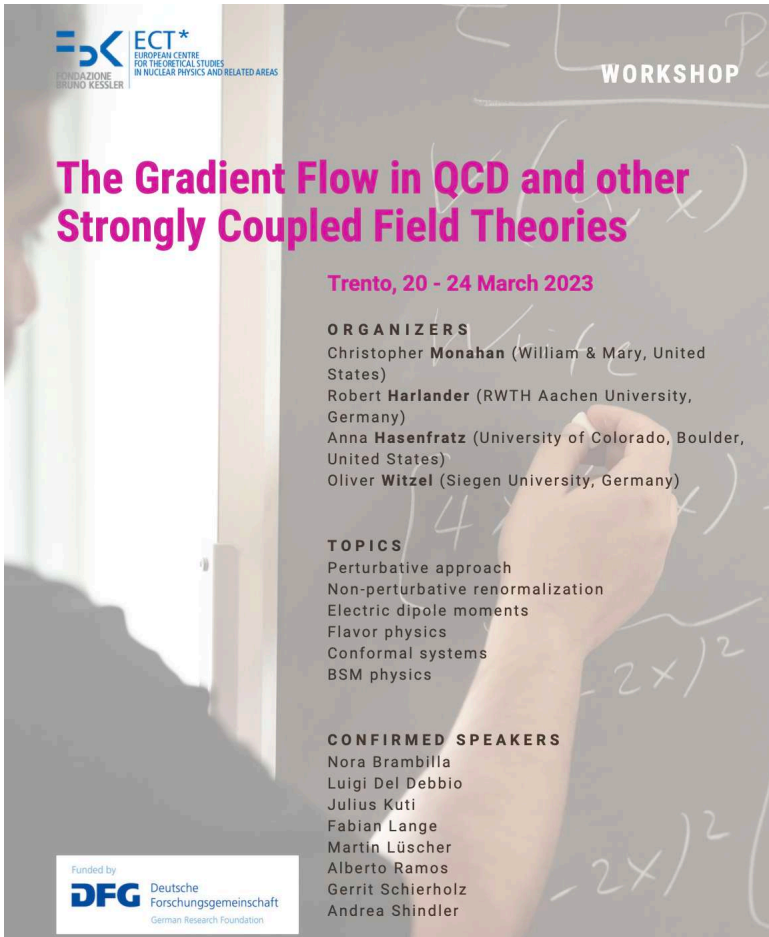


The mascots of Siegen, miner Henner and iron industry worker Frieder, meet the Higgs particle

Collaborative Research Center SFB 237

May 31, 2022 to June 2, 2022  
Europe/Berlin timezone

Enter your search term



**ECT\***  
EUROPEAN CENTRE  
FOR THEORETICAL STUDIES  
IN NUCLEAR PHYSICS AND RELATED AREAS

**WORKSHOP**

### The Gradient Flow in QCD and other Strongly Coupled Field Theories

**Trento, 20 - 24 March 2023**

**ORGANIZERS**  
Christopher Monahan (William & Mary, United States)  
Robert Harlander (RWTH Aachen University, Germany)  
Anna Hasenfratz (University of Colorado, Boulder, United States)  
Oliver Witzel (Siegen University, Germany)

**TOPICS**  
Perturbative approach  
Non-perturbative renormalization  
Electric dipole moments  
Flavor physics  
Conformal systems  
BSM physics

**CONFIRMED SPEAKERS**  
Nora Brambilla  
Luigi Del Debbio  
Julius Kuti  
Fabian Lange  
Martin Lüscher  
Alberto Ramos  
Gerrit Schierholz  
Andrea Shindler

Funded by  
**DFG** Deutsche Forschungsgemeinschaft  
German Research Foundation

**Start of a new series:**

**2023: Trento (Harlander, Witzel)**

**2025: Zürich (Fabian Lange -> PhD Aachen, post-doc KIT)**

**2026: Edinburgh (Matthew Black -> PhD Siegen)**

## Setting the scene: hot topics in flavour communities

- **Origin of anomalies:**
  - Hadronic contributions to  $b \rightarrow s\ell\ell$
  - $V_{cb} - V_{ub}$  puzzle
  - Precision of QCD factorisation in B decays/LCSR
- **Match experimental precision:**
  - Mixing:  $\Delta M_s$  limited by dim 6 Bag parameter
  - $\Delta\Gamma_s$  limited by dim 7 contributions
  - Penguin pollution in gold-plated modes
  - Lifetimes limited by dim 6/7 Bag-parameter
- **Conceptual issues**
  - Convergence properties of HQE: charm
  - Quark mass concepts
  - Gradient-flow
- **Elephants in the room?**  $\Delta A_{CP} : D^0 \rightarrow \pi^+\pi^-, K^+K^-, D\text{-mixing}$
- **What else?**

Observable	Current LHCb (up to 9 fb <sup>-1</sup> )	Upgrade I (23 fb <sup>-1</sup> )	Upgrade I (50 fb <sup>-1</sup> )	Upgrade II (300 fb <sup>-1</sup> )
<b>CKM tests</b>				
$\gamma$ ( $B \rightarrow DK$ , etc.)	2.8° [20, 21]	1.3°	0.8°	0.3°
$\phi_s$ ( $B_s^0 \rightarrow J/\psi\phi$ )	20 mrad [24]	12 mrad	8 mrad	3 mrad
$ V_{ub} / V_{cb} $ ( $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$ , etc.)	6% [56, 57]	3%	2%	1%
<b>Charm</b>				
$\Delta A_{CP}$ ( $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ )	$29 \times 10^{-5}$ [27]	$13 \times 10^{-5}$	$8 \times 10^{-5}$	$3.3 \times 10^{-5}$
$A_\Gamma$ ( $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ )	$11 \times 10^{-5}$ [31]	$5 \times 10^{-5}$	$3.2 \times 10^{-5}$	$1.2 \times 10^{-5}$
$\Delta x$ ( $D^0 \rightarrow K_S^0\pi^+\pi^-$ )	$18 \times 10^{-5}$ [58]	$6.3 \times 10^{-5}$	$4.1 \times 10^{-5}$	$1.6 \times 10^{-5}$
<b>Rare decays</b>				
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	69% [32, 33]	41%	27%	11%
$S_{\mu\mu}$ ( $B_s^0 \rightarrow \mu^+\mu^-$ )	—	—	—	0.2
$A_\Gamma^{(2)}$ ( $B^0 \rightarrow K^{*0}e^+e^-$ )	0.10 [59]	0.060	0.043	0.016
$S_{\phi\gamma}$ ( $B_s^0 \rightarrow \phi\gamma$ )	0.32 [60]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \rightarrow \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [61]	0.148	0.097	0.038

**LHCb upgrade II documents....**

### • BSM interpretation of potential anomalies

- Connection to collider physics

**See talk by Michael K.**



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## Overall impact

C1a: Inclusive semileptonic, rare and radiative decays of B mesons  
C1b:  $\mathbf{B} - \bar{\mathbf{B}}$  mixing, CP violation, and lifetimes  
C1c: Non-perturbative matrix elements for  $\mathbf{B}$ —mixing and lifetimes

**Heavy Quark Expansion:** for total decay rates (sl&nl), lifetime ratios and mixing  $\Gamma_{12}$

$$\Gamma(B_q) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_q}}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_q}}{m_b^3} + \dots + 16\pi^2 \left[ \tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_q}}{m_b^4} + \dots \right]$$

with perturbative coefficients  $\Gamma_i = \Gamma_i^{(0)} + \frac{\alpha_s(m_b)}{4\pi} \Gamma_i^{(1)} + \left( \frac{\alpha_s(m_b)}{4\pi} \right)^2 \Gamma_i^{(2)} + \dots$

and non-perturbative matrix elements  $\langle \mathcal{O}_i \rangle_{B_q}$  and  $\langle \tilde{\mathcal{O}}_i \rangle_{B_q}$

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C1c: Non-perturbative matrix elements for  $\mathbf{B}$ -mixing and lifetimes

**HQE: state of the art dominated by CRC-TRR 257 contributions**

**for non-leptonic decays:**

$$\Gamma(B_q) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_q}}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_q}}{m_b^3} + \dots + 16\pi^2 \left[ \tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_q}}{m_b^4} + \dots \right]$$

Already on the arxiv/published

Should be done by the end of 2026

## Overall impact

C1a: Inclusive semileptonic, rare and radiative decays of B mesons  
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**HQE: state of the art dominated by CRC-TRR 257 contributions**

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Diagram illustrating the contributions to the decay rate  $\Gamma(B_q)$  and the associated theoretical uncertainties, categorized by the CRC-TRR 257 contributions:

- $\Gamma_3$  (KIT) is associated with the term  $\Gamma_3$ .
- $\Gamma_5^{(0)}$  (Siegen, penguins+ BSM) and  $\Gamma_5^{(1)}$  (Siegen, SM - tree-level op) are associated with the term  $\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_q}}{m_b^2}$ .
- $\Gamma_6^{(0)}$  (Siegen, penguins+ BSM) is associated with the term  $\Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_q}}{m_b^3}$ .
- $\tilde{\Gamma}_6^{(2)}$  (KIT) is associated with the term  $\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3}$ .
- $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$  (Siegen, HQET - SM/BSM) is associated with the term  $\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3}$ .
- $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$  (Aachen/Siegen, GF-matching) is associated with the term  $\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3}$ .
- $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$  (Aachen/Siegen, GF-lattice) is associated with the term  $\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3}$ .



**HQE: state of the art dominated by CRC-TRR 257 contributions**

for mixing:

$$\Gamma_{12} = 16\pi^2 \left[ \tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_q}}{m_b^4} + \dots \right]$$

$\tilde{\Gamma}_6^{(2)}$   
KIT/  
Siegen

Previous (2022 and earlier) predictions:

$\tilde{\Gamma}_6^{(1)}$  KIT/Siegen

$\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$  HQET-SR: Siegen

+ different lattice groups, including Siegen

## Overall impact

C1a: Inclusive semileptonic, rare and radiative decays of B mesons  
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C1c: Non-perturbative matrix elements for  $\mathbf{B}$ -mixing and lifetimes

**HQE: state of the art dominated by CRC-TRR 257 contributions**

for semi-leptonic decays:

$$\Gamma(B_q) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_q}}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_q}}{m_b^3} + \dots + 16\pi^2 \left[ \tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_q}}{m_b^4} + \dots \right]$$



$\Gamma_3^{(2)}$   
 KIT  
Arbitrary  $m_q$



$\Gamma_8^{(0)}$   
 Siegen

**HQE: state of the art dominated by CRC-TRR 257 contributions**

for rare decays:

$$\Gamma(B_q) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_q}}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_q}}{m_b^3} + \dots + 16\pi^2 \left[ \tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}}{m_b^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle_{B_q}}{m_b^4} + \dots \right]$$

$\Gamma_3^{(2)}$   
KIT

$\Gamma_3^{(2)}$   
Aachen/  
Siegen/  
KIT

$\Gamma_3^{(1)}$   
Siegen

Hadronic mass spectrum for  $\bar{B} \rightarrow X_s \ell^+ \ell^-$

$Q_{1,2} - Q_7$  interference for  $b \rightarrow s\gamma$

Phenomenology

Inclusive  $\bar{B} \rightarrow X_s \ell^+ \ell^-$  at the LHC: theory predictions and new-physics reach  
Tobias Huber (Siegen U.), Tobias Hurth (U. Mainz, PRISMA and Mainz U., Inst. Phys.), Jack Jenkins (Siegen U.), Enrico Lunghi (Indiana U.), Qin Qin (Hua-Zhong U. Sci. Tech.) et al. (Nov 22, 2024)  
Published in: JHEP 11 (2024) 130, JHEP 05 (2025) 099 (erratum) • e-Print: 2404.03517 [hep-ph]

## Overall impact

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## Phenomenology:

Total decay rates of B mesons at NNLO-QCD

Manuel Egner (KIT, Karlsruhe, TTP), Matteo Fael (U. Padua, Dept. Phys. Astron. and INFN, Padua), Alexander Lenz (Siegen U.), Maria Laura Piscopo (Siegen U. and Nikhef, Amsterdam and Vrije U., Amsterdam), Aleksey V. Rusov (Siegen U. and Munich, Tech. U.) et al. (Dec 18, 2024)

Published in: *JHEP* 04 (2025) 106 • e-Print: [2412.14035](#) [hep-ph]

**KIT/  
Siegen**

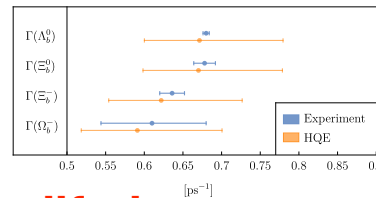
## world-leading precision in lifetimes&ratios

$$\Gamma(B_d) = 0.63_{-0.07}^{+0.11} \text{ ps}^{-1} \rightarrow 0.636_{-0.037}^{+0.028} \text{ ps}^{-1}$$

Quark-hadron duality at work: lifetimes of bottom baryons

James Gratrex (Boskovic Inst., Zagreb), Alexander Lenz (Siegen U.), Blaženka Melić (Boskovic Inst., Zagreb), Ivan Nišandžić (Boskovic Inst., Zagreb), Maria Laura Piscopo (Siegen U.) et al. (Jan 18, 2023)

Published in: *JHEP* 04 (2023) 034 • e-Print: [2301.07698](#) [hep-ph]



## world-leading precision in baryon lifetimes

Current-current operator contribution to the decay matrix in  $B$ -meson mixing at next-to-next-to-leading order of QCD

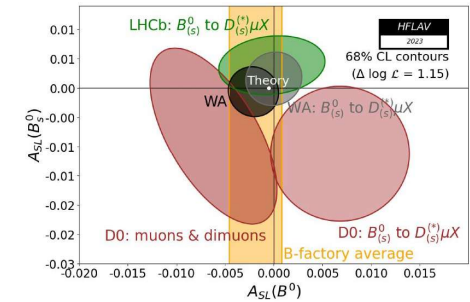
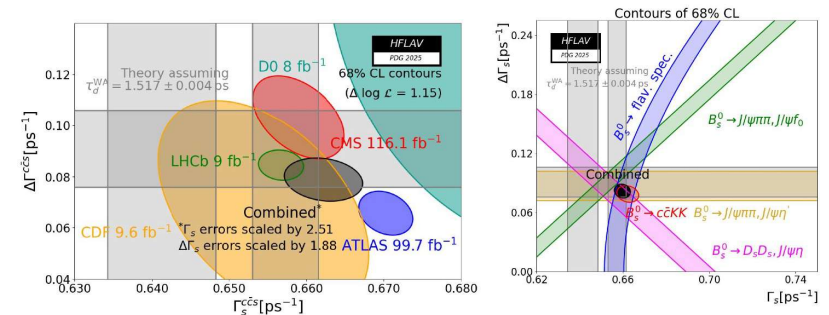
Marvin Gerlach (KIT, Karlsruhe, TTP), Ulrich Nierste (KIT, Karlsruhe, TTP), Pascal Reek (KIT, Karlsruhe, TTP), Vladyslav Shtabovenko (Siegen U.), Matthias Steinhauser (KIT, Karlsruhe, TTP) (May 28, 2025)

## world-leading precision in mixing

$$\Delta\Gamma_s = \left( 7.58_{-0.66}^{+0.63}_{\text{scale}} \pm 0.16_{-0.34}^{+0.16}_{\text{scale}}, 1/m_b \pm 0.20_{B\tilde{B}_S} \pm 1.39_{1/m_b} \pm 0.09_{\text{input}} \right) \times 10^{-2} \text{ ps}^{-1} \text{ (PS)}.$$

**KIT/  
Siegen**

## TRR 257 is the HFLAV theory reference



## Reviews:

Charm physics

David Friday (Manchester U.), Evelina Gersabeck (Freiburg U.), Alexander Lenz (Siegen U.), Maria Laura Piscopo (Nikhef, Amsterdam and Vrije U., Amsterdam) (Jun 18, 2025)

e-Print: [2506.15584](#) [hep-ph]

Lifetimes of b-hadrons and mixing of neutral B-mesons: theoretical and experimental status

Johannes Albrecht (Dortmund U.), Florian Bernlochner (Bonn U.), Alexander Lenz (Siegen U.), Aleksey Rusov (Siegen U.) (Feb 6, 2024)

Published in: *Eur.Phys.JST* 233 (2024) 2, 359-390 • e-Print: [2402.04224](#) [hep-ph]



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Published in: *JHEP* 04 (2025) 106 • e-Print: [2412.14035](https://arxiv.org/abs/2412.14035) [hep-ph]

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Siegen**

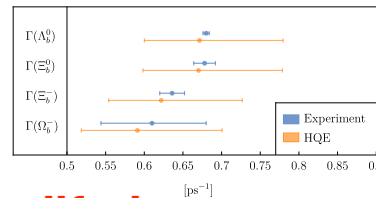
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**KIT/  
Siegen**

## New, dominant uncertainties

Bag parameters  $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$

already done with HQET sum rule

gradient flow/lattice: Aachen/KIT/Siegen

Dimension 7  $\tilde{\Gamma}_7 \langle \tilde{\mathcal{O}}_7 \rangle_{B_q}$

$\tilde{\Gamma}_7^{(1)}$ : will be done by KIT

$\langle \tilde{\mathcal{O}}_7 \rangle_{B_q}$ : will be done with HQET-SR: Siegen

## Overall impact

C1a: Inclusive semileptonic, rare and radiative decays of B mesons  
C1b:  $\mathbf{B} - \bar{\mathbf{B}}$  mixing, CP violation, and lifetimes  
C1c: Non-perturbative matrix elements for  $\mathbf{B}$ -mixing and lifetimes

**HQE: state of the art dominated by CRC-TRR 257 contributions**

## Phenomenology:

$$b \rightarrow s\gamma$$

$$\bar{B} \rightarrow X_s \ell^+ \ell^-$$

Combined semi-  
leptonic &  
Lifetime fit

crucial constraint on  
BSM Models, e.g. 2HDM:

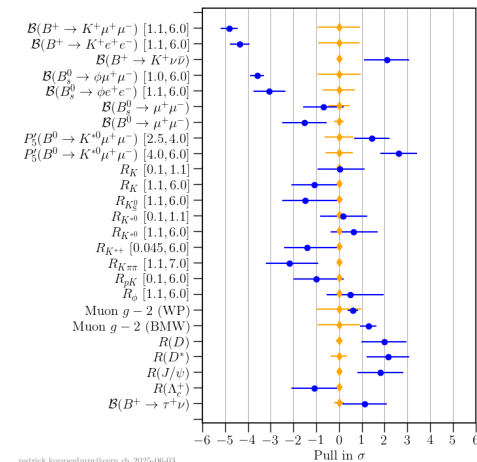
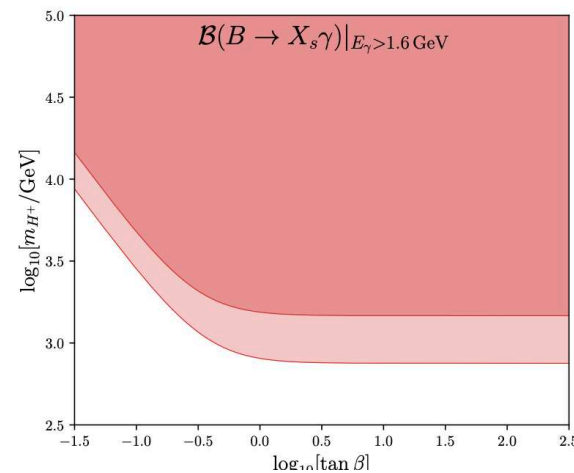
Independent cross-check of  
anomalies in exclusive decays



**A holistic view on the heavy quark expansion**

**A combined  $B \rightarrow X_s \ell^+ \ell^-$  and  $B$  lifetime analysis**

F. Bernlochner, M. Fael, I. Milutin, M. Prim, K.K. Vos

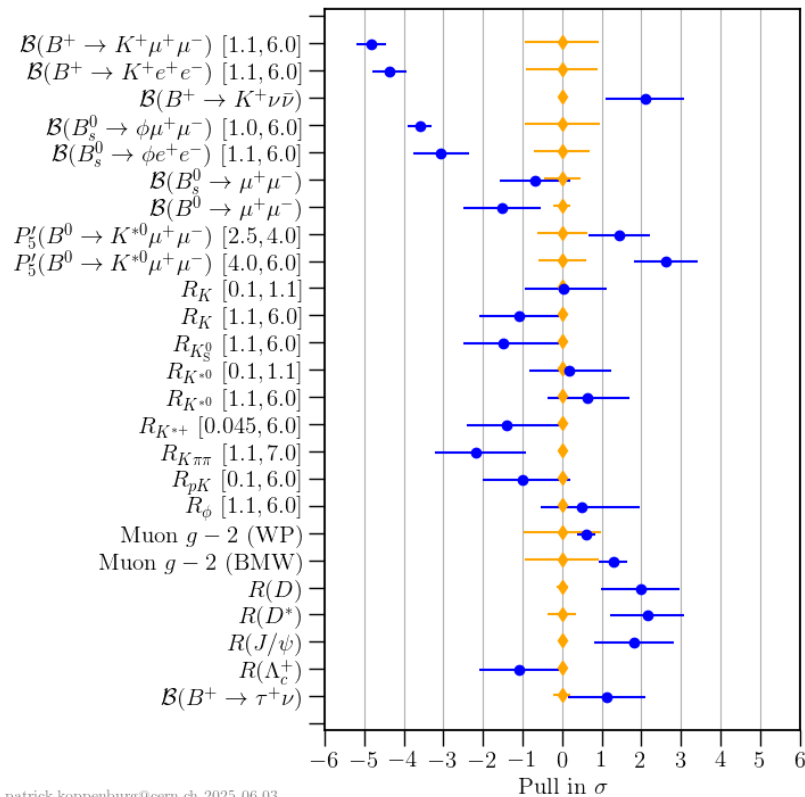


patrick.koppensberg@cern.ch 2025-06-03

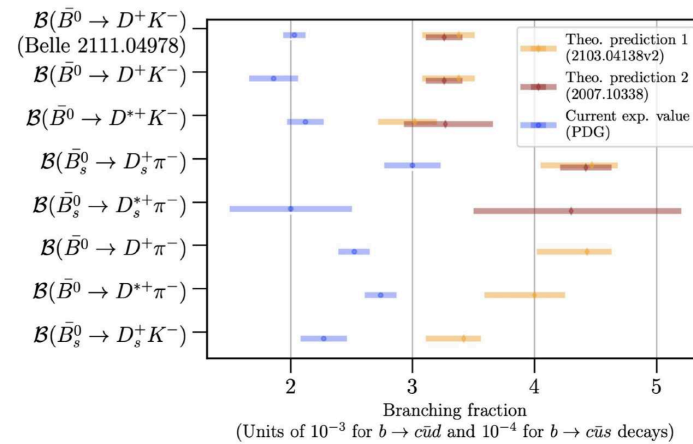
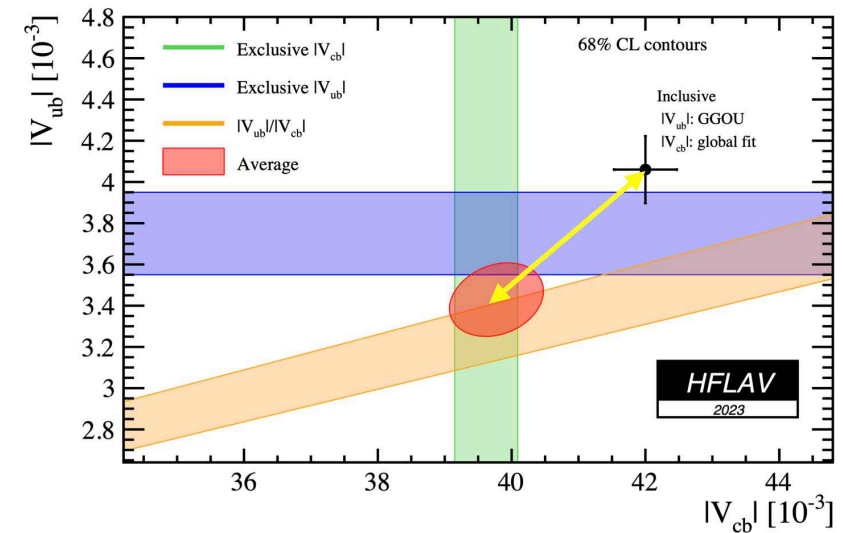
## Motivation:

C2a: Hadronic matrix elements and exclusive semileptonic decays

C2b: Exclusive non-leptonic and rare b-quark decays



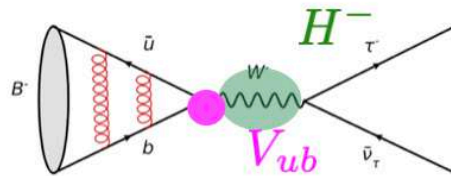
patrick.koppenburg@cern.ch 2025-06-03



## Motivation:

C2a: Hadronic matrix elements and exclusive semileptonic decays  
C2b: Exclusive non-leptonic and rare b-quark decays

### • Leptonic Decays



$$\langle 0 | \bar{b} \gamma^\mu \gamma_5 u | B_q(p) \rangle = i f_{B_q} p^\mu$$

Decay constant

$$\langle D^0(p_D) | \bar{c} \gamma_\mu b | B^-(p_B) \rangle = f_+^{B^- \rightarrow D^0}(q^2) \left( p_B^\mu + p_D^\mu - \frac{m_B^2 - m_D^2}{q^2} q^\mu \right)$$

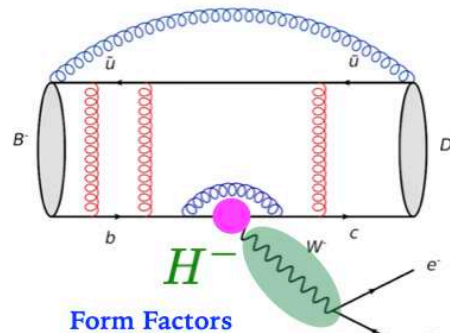
Form Factors

Factorisation

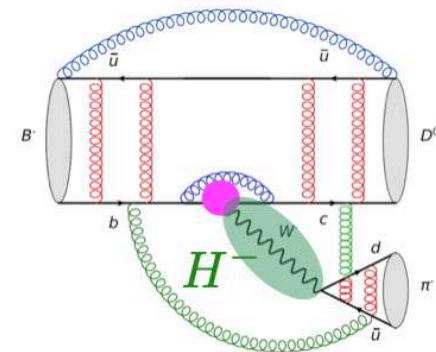
$$\langle D^0 \pi^- | \bar{c} \gamma_\mu (1 - \gamma_5) b \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d | B^- \rangle$$

$$\approx \langle D^0 | \bar{c} \gamma_\mu (1 - \gamma_5) b | B^- \rangle \cdot \langle \pi^- | \bar{u} \gamma^\mu (1 - \gamma_5) d | 0 \rangle$$

### • Semileptonic Decays



### • Non-leptonic Decays



I) Imaginary part of CKM-elements = CP Violation

II) Instead of a W-Boson a charged Higgs particle could be exchanged

III) QCD effects are crucial! Perturbative QCD corrections  
Non-perturbative: decay constants, form factors, factorisation

IV) Determination of SM-Parameter



## Overall impact

C2a: Hadronic matrix elements and exclusive semileptonic decays  
C2b: Exclusive non-leptonic and rare b-quark decays

For semi-leptonic and non-leptonic decays

### C2a hadronic matrix elements relevant for exclusive b-decays.

- mesonic & baryonic transition form factors in the framework of **QCD light-cone sum rules (LCSR)**
- improve understanding of **light-cone distribution amplitudes (LCDA)** for light & heavy hadrons

1. QCD factorisation and light-cone distribution amplitudes

2. QCD sum rules and related methods

3. New Channels and multi-hadron final states

4. Inclusive rates and sum over exclusive channels, semi-inclusive decays

For semi-leptonic and non-leptonic decays

## Overall impact

C2a: Hadronic matrix elements and exclusive semileptonic decays  
C2b: Exclusive non-leptonic and rare b-quark decays

- Overall impact of the CRC research in this area?
- What goals have been achieved or will/should be achieved until early 2026?

- Better understanding of hadronic input functions in factorisation-based approaches to exclusive  $b$  decays
- Extension/generalisation of sum-rule methods to new channels

**$B$  anomalies**

**Charm physics**

**Hadronic anomalies**

**$V_{cb}$  puzzle**

### WA1:

- perturbative tail for  $\Lambda_b$  LCDA ✓
- strange-quark mass effects in  $B_s$  LCDA ✓
- 2-loop-improved parametrization of  $B$ -meson LCDA [in progress]

### WA2:

- $B_c \rightarrow J/\psi$  form factors from sum rules ✓
- dispersive analysis of  $B \rightarrow K^*$  and  $B_s \rightarrow \phi$  form factors ✓
- HQET analysis of  $B_{(s)} \rightarrow D_{(s)}^{(*)}$  form factors / lattice / LCSR ✓
- dispersive approach to rare decay  $D \rightarrow \pi \ell^+ \ell^-$  ✓

### WA3:

- $S$ -wave contribution to  $B \rightarrow K^*(\rightarrow K\pi)\ell^+\ell^-$  from LCSR ✓
- form factors for exotic  $B$  decays into "dark baryons" ✓
- Dalitz distribution for CP violation in  $B \rightarrow K\pi\pi$  ✓

### WA4:

- sum-rule analysis of orbitally excited  $D$  mesons and their role in  $b \rightarrow c$  spectrum [in progress] ✓
- shape function vs. light-cone distribution amplitudes [in progress]

## Overall impact

C2a: Hadronic matrix elements and exclusive semileptonic decays  
C2b: Exclusive non-leptonic and rare b-quark decays

### 3. Synergies

- C2b  $\leftrightarrow$  impact of hadronic input functions on non-leptonic/rare decays
- C2b  $\leftrightarrow$  rescattering effects in multi-body channels
- C1a  $\leftrightarrow$  inclusive rates vs. Orbitally excited  $D$ -states

### 4. What is the perspective of the projects in this research area for FP3?

- WA1: systematic parameterization for 2- and 3-particle LCDAs, generalized soft functions; constraining  $B$ -meson LCDAs from  $B \rightarrow \gamma \ell \nu$ .
- WA2/WA3: more focus on lattice simulations for local hadronic matrix elements; inclusion of low-energy hadronic rescattering effects
- WA3: exploiting relations between shape functions and light-cone distribution amplitudes in analyses of inclusive and exclusive  $b$ -decays.

TM will not be a PI in FP3 anymore:

**Option 1:** keep C2a structure, replace sum rules by lattice; add Oliver Witzel as new PI

**Option 2:** merge C2a with QCD aspects of C2b  
TH new PI in C2a, replacing TM; associate OW

### 5. Modification of cover story?

- Less emphasis on sum rules - more emphasis on latte

## Overall impact

C2a: Hadronic matrix elements and exclusive semileptonic decays  
C2b: Exclusive non-leptonic and rare b-quark decays

### **C2b: Exclusive non-leptonic and rare semi-leptonic and radiative $b$ -quark decays (theoretical predictions and phenomenological implications)**

- use factorisation and effective-field-theory methods to understand hadronic uncertainties
  - phenomenological updates for angular observables and partial decay rates
  - extend our studies to possible flavour structures of physics beyond the Standard Model.
1. NNLO QCD corrections: two loop corrections to scalar penguin amplitude in non-leptonic decays;  
higher-order corrections to annihilation topologies
  2. QED corrections in the factorization framework:  
Semi-leptonic operators in  $B \rightarrow K^* \ell \ell$ ; hadronic operators in  $B \rightarrow K^* \ell \ell$  - and non-leptonic decays;  
QED corrections to heavy-to-light form factors; isospin-violating observables and violation of lepton-flavour universality.
  3. Power corrections in exclusive B meson decays:  
factorization of endpoint divergencies in  $B \rightarrow \pi$  form factor; extension to non-leptonic and rare decays
  4. Phenomenology of non-leptonic Decays:  
comprehensive NNLO analysis of  $B \rightarrow PP, VP, VV$  decays; combination of QCDF with flavour-symmetries of the light quarks;  
two-body decays beyond the quasi-particle approximation;
  5. Phenomenology of rare semi-leptonic and radiative decays:  
precision phenomenology for  $B \rightarrow K^* \ell \ell$  at large hadronic recoil realistic parametrization of hadronic resonances beyond  
factorization, rare radiative decays of  $B_s, B_c$  and  $\Lambda_b$ .

C2a: Hadronic matrix elements and exclusive semileptonic decays  
C2b: Exclusive non-leptonic and rare b-quark decays

2. What goals have been achieved or will/should be achieved until early 2026?

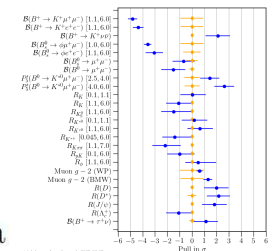
[start in Oct'25]

- detailed investigations on  $B \rightarrow D\pi$  puzzle ✓
- optimized observables for penguin-dominated non-leptonic decays ✓
- sensitivity to hadronic input functions ✓
- impact of certain BSM scenarios ✓
- interplay of QCD flavour symmetries and QCDF [in progress]

- QED corrections in  $B_s \rightarrow \mu^+ \mu^-$
  - BSM effects in  $b \rightarrow s \ell^+ \ell^-$
  - non-factorizable effects in  $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$
  - complementarity of collider, EWP and flavour data
  - implementation of flavour structure into AUTO-EFT
- pull in  $\sigma$

✓  
✓  
✓  
✓

[in progress]





## Overall impact

C2a: Hadronic matrix elements and exclusive semileptonic decays  
C2b: Exclusive non-leptonic and rare b-quark decays

### 3. Synergies

- C2a ↔ hadronic input functions
- C2a ↔ rescattering effects in multi-body channels
- B1e ↔ factorisation and endpoint divergencies

### 4. What is the perspective of the projects in this research area for FP3?

- WA1 will not be continued in FP3
- WA2: focus on pheno potential of multi-body decays and anomalies in non-leptonic decays
- WA3: baryonic decays,  
BSM flavour structures between MFV and FN

**Option 1:** keep C2b as it is, same PIs,  
slightly reduced resources (2 PD → 1 PD + 1 PhD)  
Robert Harlander as potential associated PI

**Option 2:** merge QCD aspects of C2b with C2a  
(TH new PI in C2a, replacing TM)  
join BSM flavour aspects with C3b (Nierste),  
new C3b with 3 PIs (UN, TF, RH) – **true KA-SI-AC connection!**

### 5. Modification of cover story?

- QCD precision in rare and non-leptonic decays: how much room for improvement?
- Phone of flavour anomalies: future prospects (to be self-critically discussed)
- BSM flavour structure: what can we learn from bottom-up/EFT approaches?



Overall impact: conceptual developments in C1 & C2

## Gradient flow:

- Develop formalism to calculate Bag parameter for lifetimes on the lattice - here any development was dormant for about 25 years despite huge experimental progress

Aachen/  
Siegen

- Develop the program **ftint** to calculate Feynman integrals that occur in the gradient flow formalism numerically

Aachen

## Quark masses:

- Quark masses plus gradient flow

Aachen/  
Siegen

- Replace  $m_q$  by observables

Siegen

- Quark hadron duality violations

Siegen

Overall impact: conceptual developments in C1 & C2

## Perturbation theory:

- Expand and match
- four-loop massless form factors
- $2 \rightarrow 2$  processes with massive internal particles

application to  $H \rightarrow b\bar{b}$

KIT/  
Siegen

- Massive three-loop form factors:  
Anomaly contribution  
Heavy to light

KIT/  
Siegen

KIT

KIT

KIT

KIT

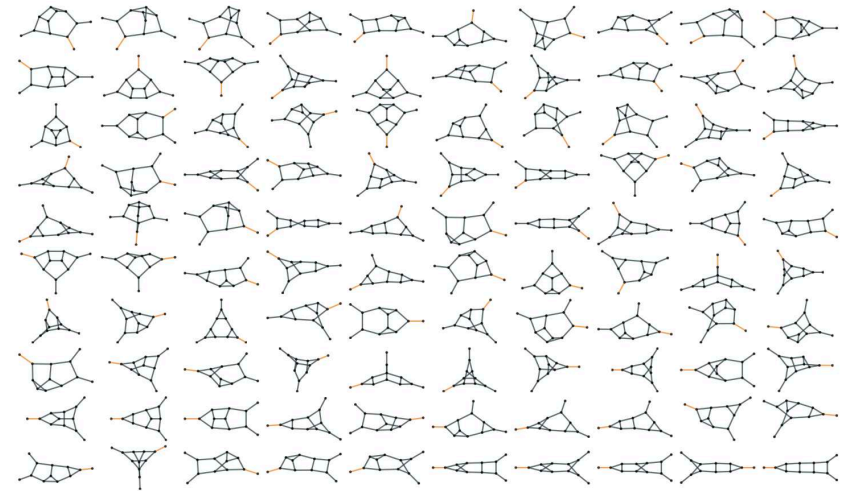


Figure 1. Reducible and irreducible topologies for four-loop form factor integrals with one off-shell leg.

## Mathematical Structures in Feynman Integrals

Feb 13 – 16, 2023  
Emmy Noether Campus  
Europe/Berlin timezone

Enter your search term

Overview

Timetable

Contribution List

Registration

Participant List

Workshop venue, travel  
information

Accommodation

Meals

The workshop aims at bringing together experts from Mathematics and Physics to discuss the latest developments and future directions in unraveling the Mathematical Structures in Feynman Integrals. Topics will include among others Structures of Feynman integrals, Integral reduction, Applications from algebraic geometry, Finite fields and rational reconstruction, Differential equations, etc.

The program will feature dedicated talks, but will also leave ample time for discussions among workshop participants.

February 11, 2023 marks the 100th anniversary of the death of the mathematician **Wilhelm Killing**, born in Burbach, only 20km from Siegen. Killing formulated a research program that is still relevant today and has significantly influenced mathematical research for a century. The 100th anniversary of Killing's death is an appropriate opportunity to honour his merits with an inaugural talk.

### 1. Setting the scene

- A. Current projects and papers
- B. Referees comments 2nd period
- C. Particle physics future plans
- D. New structural developments in Aachen, Karlsruhe, Siegen and Heidelberg
- E. Hot flavour topics in Community

### 2. Gudrun's questions

- 1) What was the overall impact of the CRC research in this area?
- 2) What goals have been achieved or will/should be achieved until early 2026?
- 3) What synergies have been exploited?
- 4) What is the perspective of the projects in this research area for FP3?
- 5) Does the part of the cover story related to this research area need to be modified?

### 3. New ideas

- A. Increase SM precision, Gradient Flow
- B. Charm Physics
- C. Collider Flavour connection
- D. Multi-body hadronic decays/CPV/Dalitz

1st round: 2019- 2022

**2nd round: 2023-2026**

**3rd round: 2027-2030**

## New ideas

- A. **Increase SM precision** - continue to provide world-leading precision develop new concepts like Gradient Flow
- **C1 obvious**
  - $b \rightarrow s\ell\ell$ : revisit form factors and non-local contributions/charm-loops  
**Include more lattice? - how? In what collaborations?**
  - $\Lambda_b$  decays - polarisation for FCC and  $V_{ub}$  determination from  $\Lambda_b \rightarrow p\ell\nu$  (form factors, lattice?)
  - LCSR for non-leptonic decays
- Gradient Flow**
- Continue lifetimes and mixing (eye-contractions)
  - Conceptual issues like quark masses? any connection between cut-off of kinetic mass with flow-time (cut-off) in gradient flows - Matching  $\overline{\text{MS}}$  already done by Robert and Oliver and friends
  - Robert: most GF matching calculations might be done with technology of Matthias one order higher
- B. **Charm Physics** - test applicability of the B physics tools in the charm sector
- Lifetimes
  - Inclusive, Semi-leptonic
  - Mixing
  - $\Delta A_{CP}$  — — Connection with multi body CPV  $B \rightarrow K\pi\pi$  (Methods by Kubis)
- C. **Collider Flavour connection**
- Re-think: was an important part of the cover story
- Thorsten/Robert/ Tom Tong -> collaboration with SMEFT fitte - bring structure in the 2499 operators
  - Uli: Connection to single top FCNC-  $t \rightarrow bW, cZ, uZ, \dots$  and  $B_s \rightarrow \mu\mu$
  - Uli: 3b more general and bottom-up; additional PI from Aachen and/or Siegen
- D. **Multi-body hadronic decays/CPV/Dalitz**
- $B \rightarrow K\pi\pi$  methods by Kubis

Let's work hard to get a referee feedback in the style of

...the internationally outstanding PIs managed to give their successful and impactful full project “Particle Physics Phenomenology after the Higgs Discovery” a new, exciting twist which deserves unconditional funding... we actually suggest to increase the requested number of positions by....

