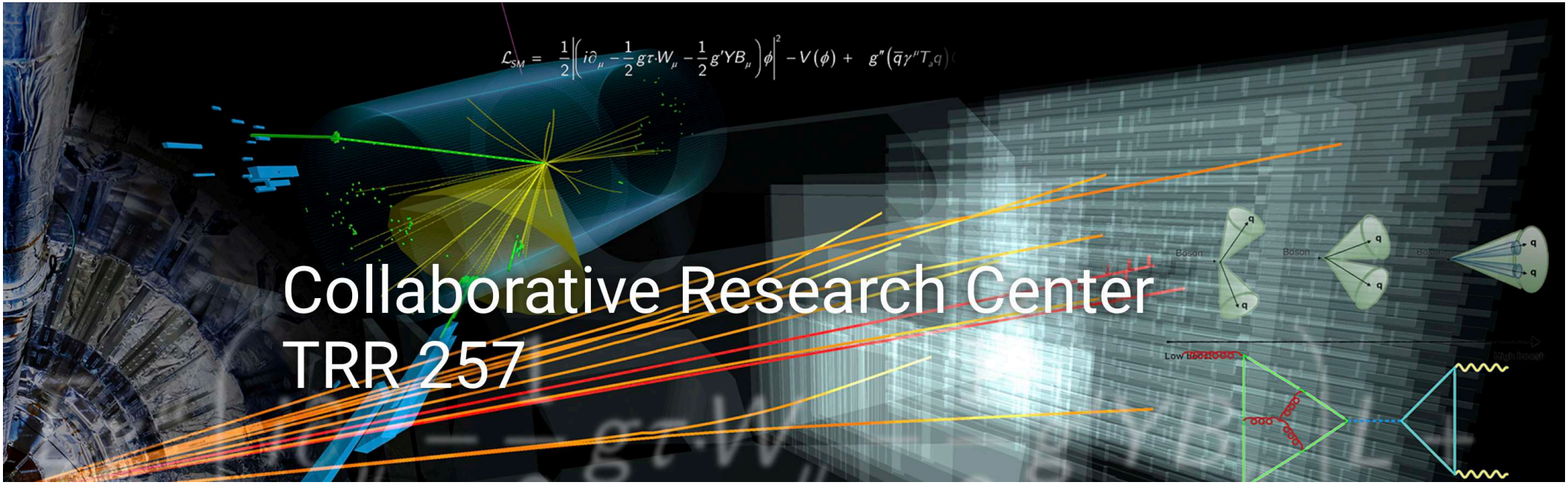
Flavour Physics

Annual CRC meeting 29.9. -1.10.2025, Siegen



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

Alexander Lenz

Flavour Physics

Outline

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

2nd round: 2023-2026

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Flavour Physics

Setting the scene

Discussed here

Entries on our webpage for period 2

Research Area C: Flavour physics

C1a: Inclusive semileptonic, rare and radiative decays of B mesons	Huber, Mannel, Steinhauser	20
C1b: $\mathbf{B} - \overline{\mathbf{B}}$ mixing, CP violation, and lifetimes	Lenz, Nierste, Steinhauser	10
C1c: Non-perturbative matrix elements for $\mathbf{B}$—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 by Michael K.

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

Flavour Physics

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 flavourverletzender 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

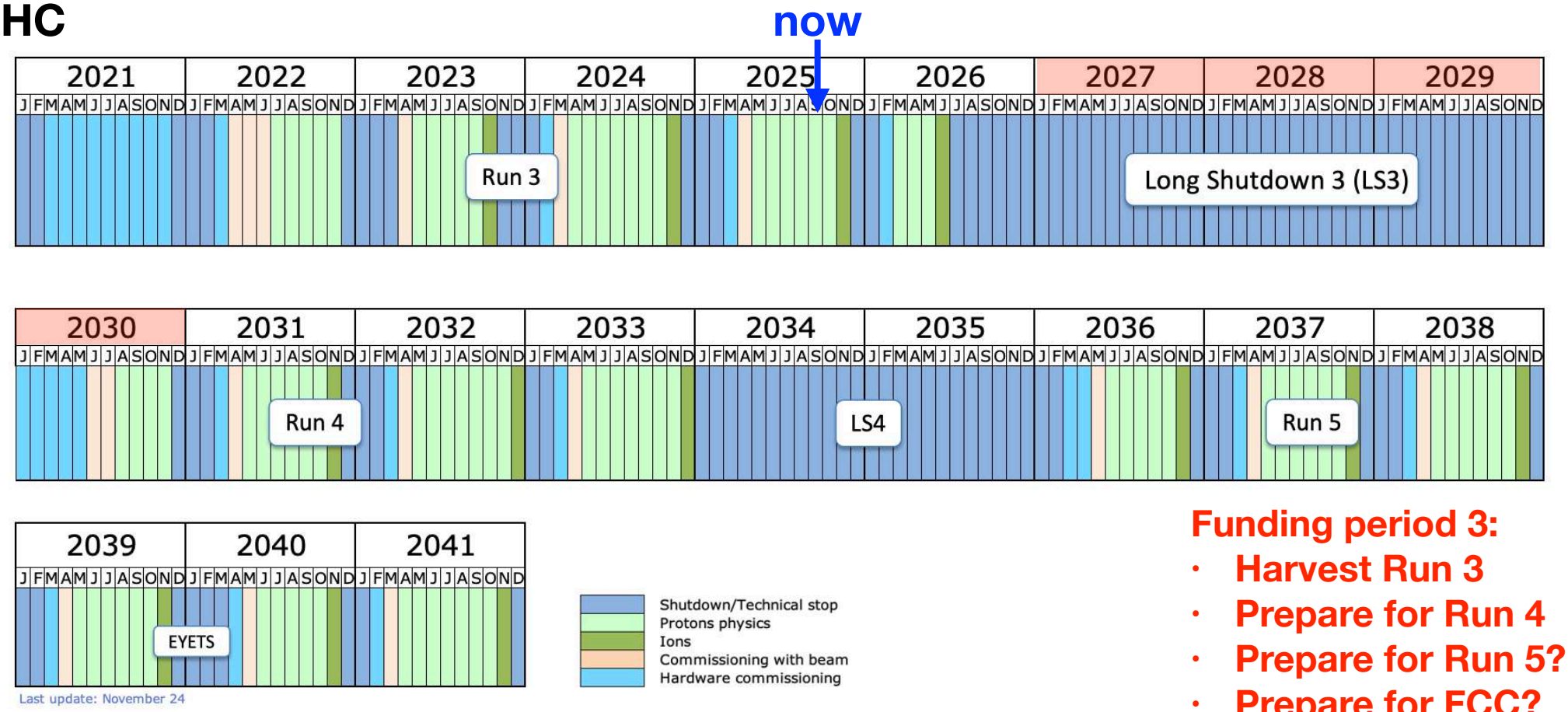
C2a: sehr gut
C2b: sehr gut bis exzellent

C3a: sehr gut
C3b: gut

Flavour Physics

Setting the scene: future particle physics plans

LHC



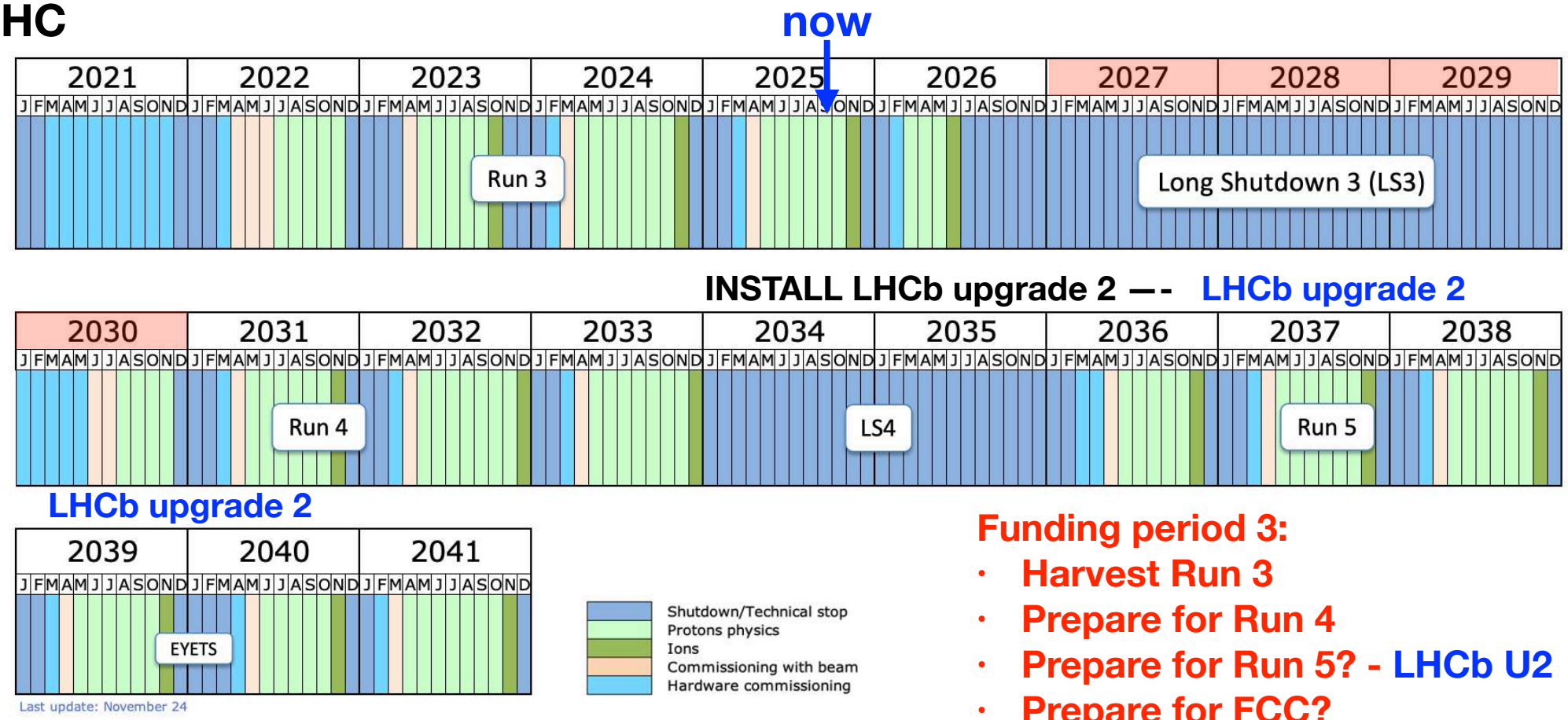
Funding period 3:

- **Harvest Run 3**
- **Prepare for Run 4**
- **Prepare for Run 5?**
- **Prepare for FCC?**

Flavour Physics

Setting the scene: future particle physics plans

LHC



Funding period 3:

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

Flavour Physics

Setting the scene: future particle physics plans

LHC

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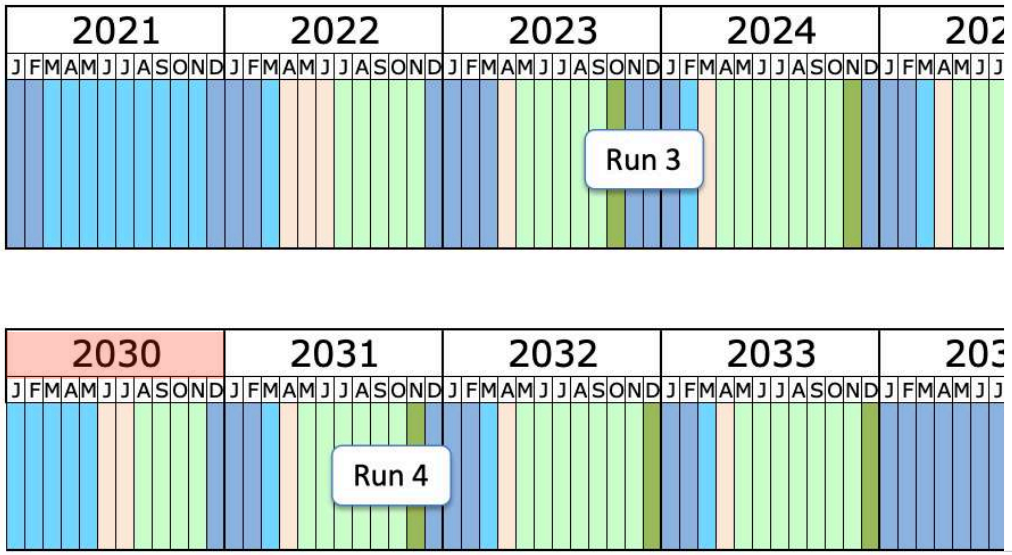
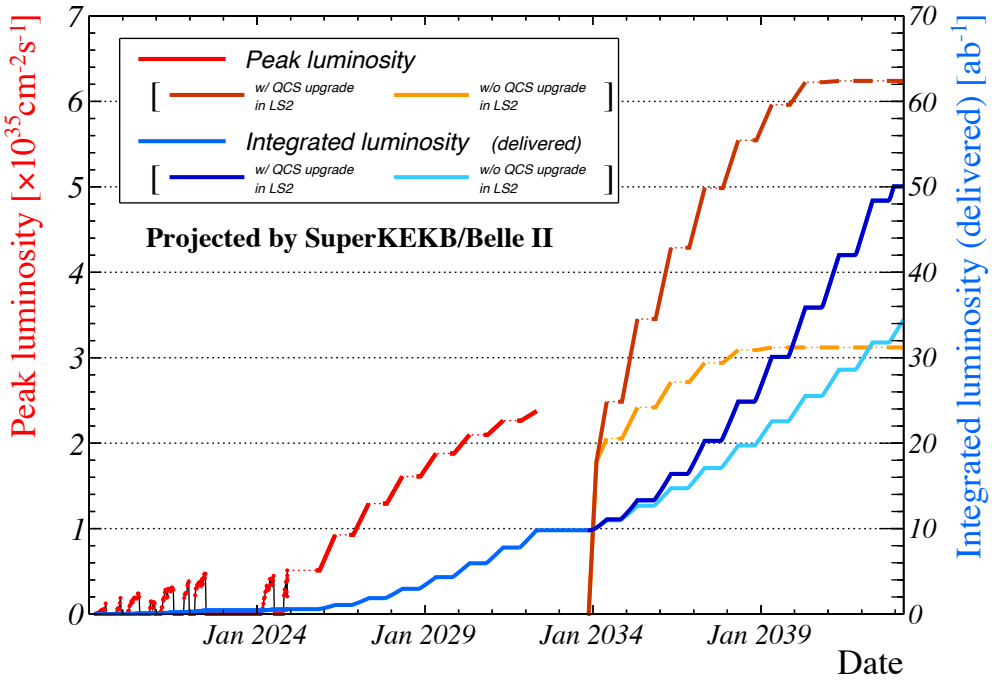


Belle II

- Harvest/prepare for 30 ab-1
- Prepare for 60 ab-^



Flavour Physics

Setting the scene: future particle physics plans

LHC

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

Belle II

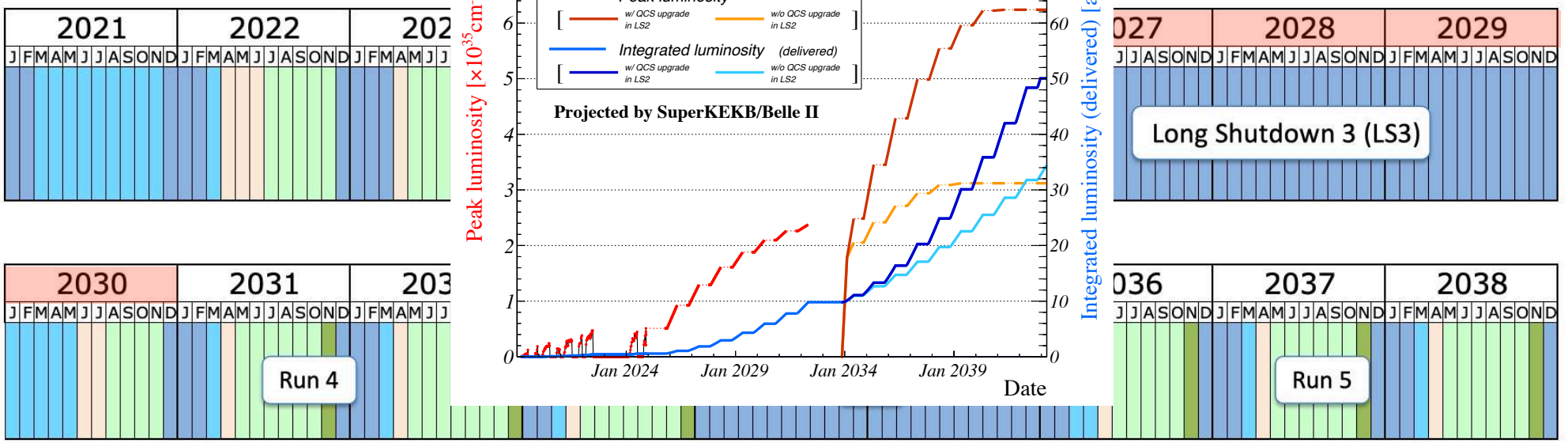
- Harvest/prepare for 30 ab-1
- Prepare for 60 ab-^

BESS III

- data taking till 2030/32

Super tau charm

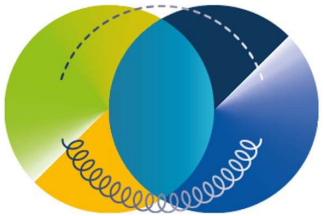
- Operation from 2033 onwards



Flavour Physics

Setting the scene: structural developments at sites

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



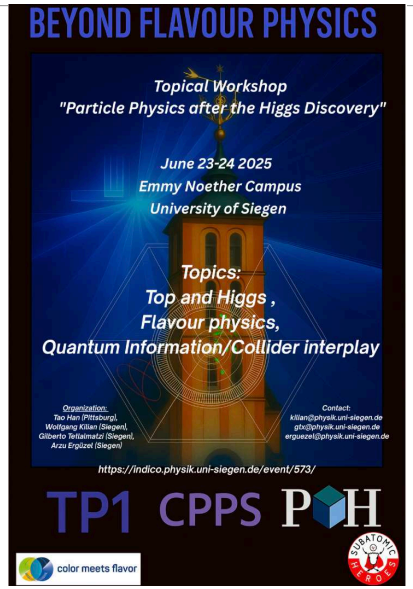
color meets flavor

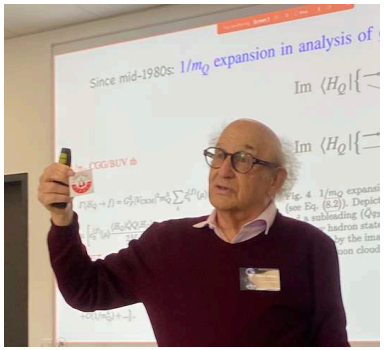
- **1.1.2026 New W3 Computational Physics in Siegen**
- **New W3 Theoretical Physics Karlsruhe in Karlsruhe**
- **1.1.2026 New W1 Cosmology? In Karlsruhe**
- **Oliver Witzel permanent in Siegen**

- What else?

Flavour Physics

Setting the scene: hot topics in flavour communities





Flavour Physics

Setting the scene: hot topics in flavour communities

Start of a new series:

2023: Trento (Harlander, Witzel)

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

2026: Edinburgh (Matthew Black -> PhD Siegen)

Universität Siegen

Flavour Physics

PH

Setting the scene: hot topics in flavour communities

- **Origin of anomalies:**
  - Hadronic contributions to $b \to s\ell\ell$
  - $V_{cb} - V_{ub}$ puzzle
  - Precision of QCD factorisation in B decays/LCSR
- **Match experimental precision:**
  - Mixing: ΔM_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?** $\Delta A_{CP} : D^0 \to \pi^+\pi^-, K^+K^-$, **D-mixing**
- **What else?**

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	2.8°	[20, 21]	1.3°	0.8°	0.3°
ϕ_s ($B_s^0 \to J/\psi\phi$)	20 mrad	[24]	12 mrad	8 mrad	3 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[56, 57]	3%	2%	1%
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[27]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[31]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K^0_S\pi^+\pi^-$)	18×10^{-5}	[58]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[32, 33]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_T^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[59]	0.060	0.043	0.016
$S_{\phi\gamma}$($B_s^0 \to \phi\gamma$)	0.32	[60]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[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.

Flavour Physics

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Universität Siegen

Flavour Physics

PH

Overall impact

C1a: Inclusive semileptonic, rare and radiative decays of B mesons
C1b: $\mathbf{B} - \overline{\mathbf{B}}$ 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 Γ_{12}

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

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

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

Flavour Physics

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

for non-leptonic decays:

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

Already on the arxive/published

Should be done by the end of 2026

Flavour Physics

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- $\Gamma_3^{(2)}$ — KIT
- $\Gamma_5^{(0)}$ — penguins+ BSM — Siegen
- $\Gamma_5^{(1)}$ — SM - tree-level op — Siegen
- $\Gamma_6^{(0)}$ — penguins+ BSM — Siegen
- $\tilde{\Gamma}_6^{(2)}$ — KIT
- $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$ — HQET - SM/BSM — Siegen
- $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$ — GF-matching — **Aachen/ Siegen**
- $\langle \tilde{\mathcal{O}}_6 \rangle_{B_q}$ — GF-lattice — **Aachen/ Siegen**

Flavour Physics

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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

Flavour Physics

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for semi-leptonic decays:

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

$\Gamma_3^{(2)}$ KIT — Arbitrary m_q

$\Gamma_8^{(0)}$ Siegen

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for rare decays:

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

$\Gamma_3^{(2)}$ KIT

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

$\Gamma_3^{(1)}$ Siegen

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

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

Phenomenology

Inclusive $\overline{B} \to X_s \ell^+ \ell^-$ 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]

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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

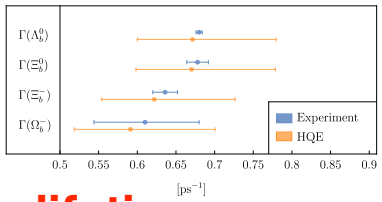
world-leading precision in lifetimes&ratios

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

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

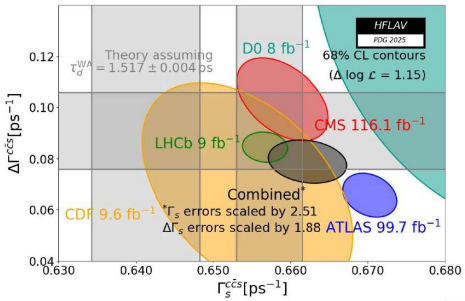
Marvin Gerlach (KIT, Karlsruhe, TTP), Ulrich Nierste (KIT, Karlsruhe, TTP), Pascal Reeck (KIT, Karlsruhe, TTP), Vladyslav Shtabovenko (Siegen U.), Matthias Steinhauser (KIT, Karlsruhe, TTP) (May 28, 2025)

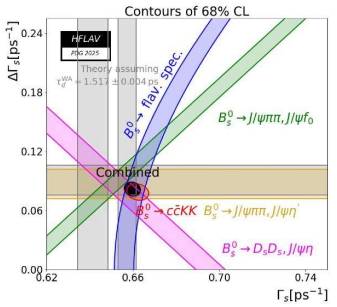
KIT/ Siegen

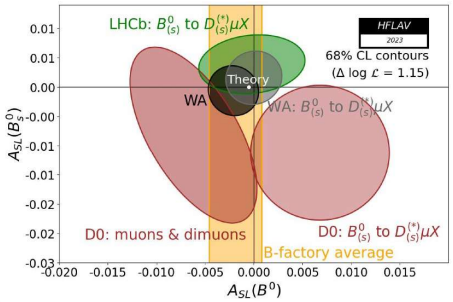
world-leading precision in mixing

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

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.J.ST* 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 [hep-ph]

KIT/ Siegen

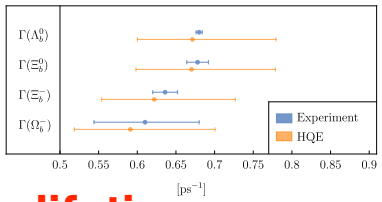
world-leading precision in lifetimes&ratios

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

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 Reeck (KIT, Karlsruhe, TTP), Vladyslav Shtabovenko (Siegen U.), Matthias Steinhauser (KIT, Karlsruhe, TTP) (May 28, 2025)

KIT/ Siegen

world-leading precision in mixing

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

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

Flavour Physics

Overall impact

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

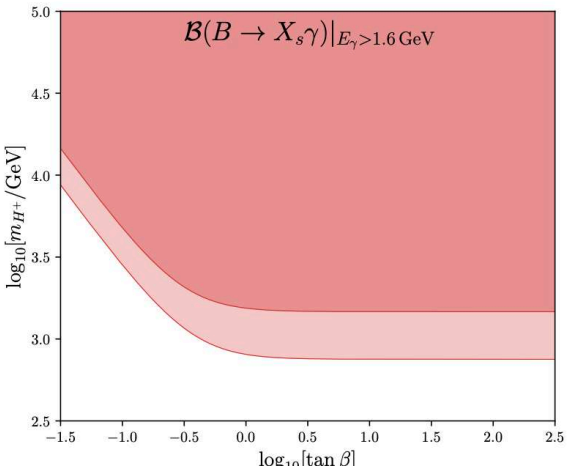
HQE: state of the art dominated by CRC-TRR 257 contributions

Phenomenology:

Combined semi-leptonic & Lifetime fit

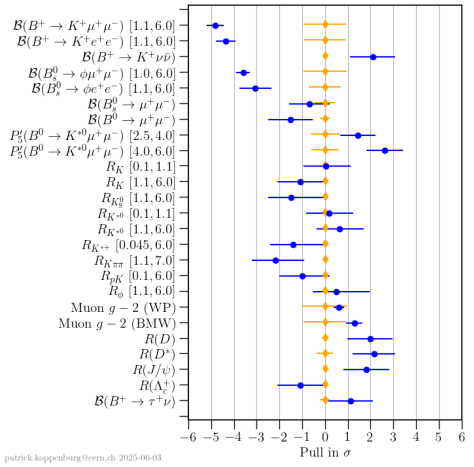
$b \to s\gamma$

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



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

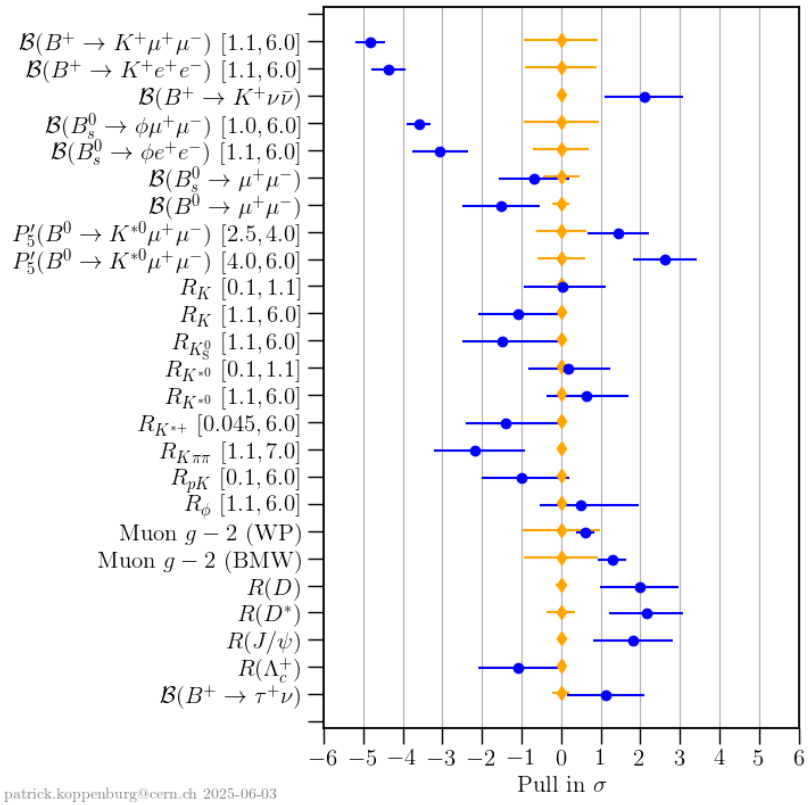
Independent cross-check of anomalies in exclusive decays

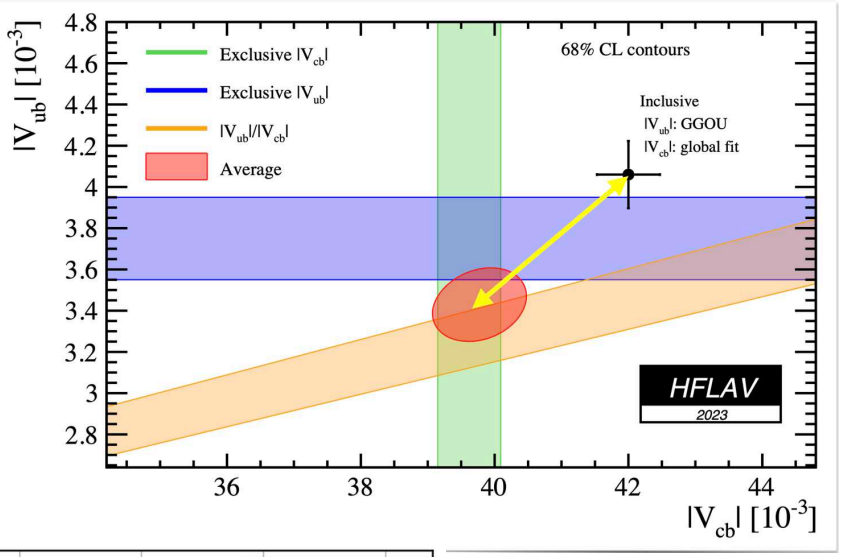


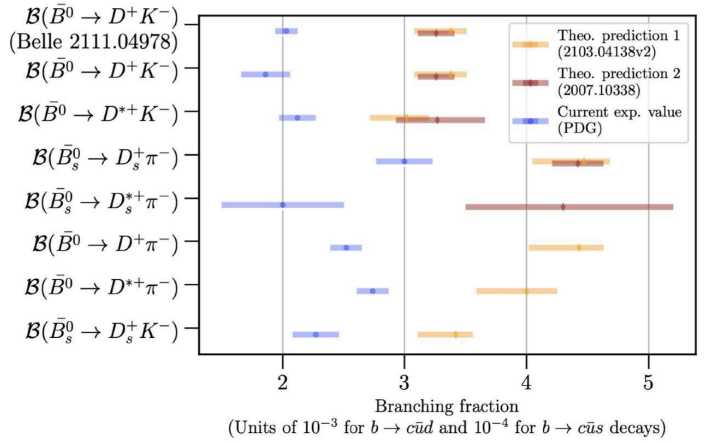
Flavour Physics

Motivation:

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





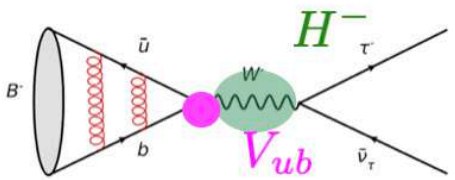


Flavour Physics

Motivation:

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

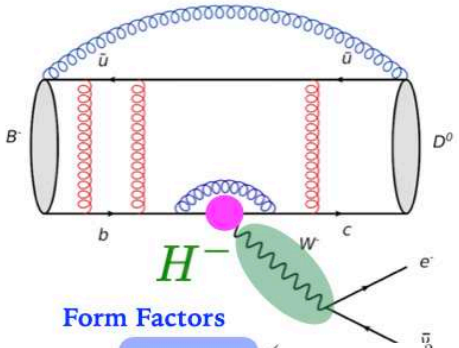
- **Leptonic Decays**



Decay constant

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

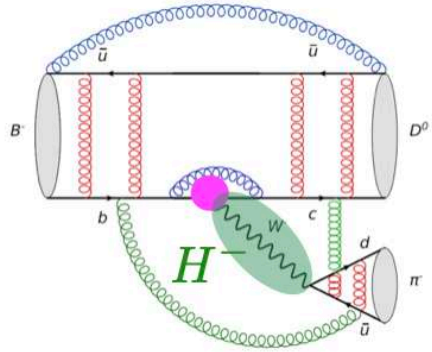
- **Semileptonic Decays**



Form Factors

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

- **Non-leptonic Decays**



Factorisation

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

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

Flavour Physics

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

Universität Siegen

Flavour Physics

P H

Overall impact

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

1. Overall impact of the CRC research in this area?

- 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

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

WA1:

- perturbative tail for Λ_b LCDA √
- strange-quark mass effects in B_s LCDA √
- 2-loop-improved parametrization of B-meson LCDA [in progress]

WA2:

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

WA3:

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

WA4:

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

Flavour Physics

Overall impact

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

3. Synergies

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

5. Modification of cover story?

- Less emphasis on sum rules - more emphasis on latte

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 $B \to \gamma\ell\nu$.
- 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

Flavour Physics

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 $B \to K^* \ell\ell$; hadronic operators in $B \to K^* \ell\ell$ 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 $B \to \pi$ form factor; extension to non-leptonic and rare decays
4. Phenomenology of non-leptonic Decays:
   comprehensive NNLO analysis of $B \to PP, VP, VV$ 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 $B \to K^* \ell\ell$ at large hadronic recoil realistic parametrization of hadronic resonances beyond factorization, rare radiative decays of B_s, B_c and Λ_b.

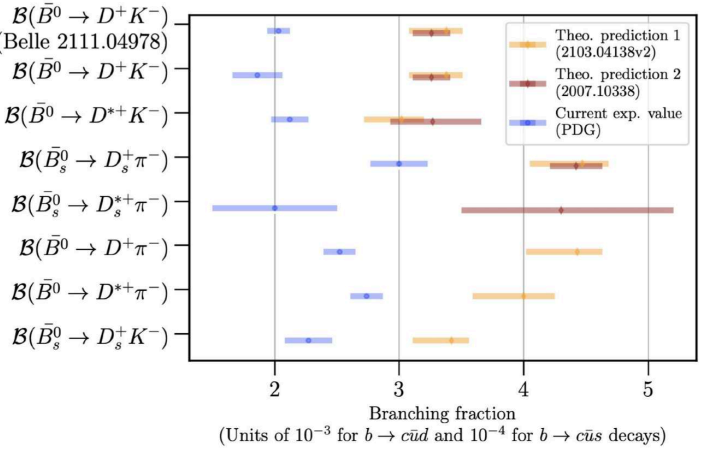
Flavour Physics

Overall impact

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

1. Overall impact

- New insights in flavour anomalies
- Improved estimates of the non-factorising QCD & QED effects
- Pheno studies on potential BSM effects in non-leptonic and rare decays



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

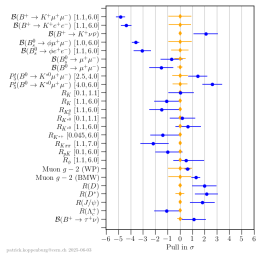
WA1:

- computation of Wilson coefficient a_6 in QCDF [start in Oct'25]

WA2:

- detailed investigations on $B \to D\pi$ 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]

WA3:



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

Flavour Physics

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?

Flavour Physics

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

Flavour Physics

Overall impact: conceptual developments in C1 & C2

Perturbation theory:

- Expand and match — **KIT**
- four-loop massless form factors — **KIT**
- $2 \to 2$ processes with massive internal particles
  application to $H \to b\bar{b}$ — **KIT/ Siegen**
- Massive three-loop form factors: Anomaly contribution
  Heavy to light — **KIT**

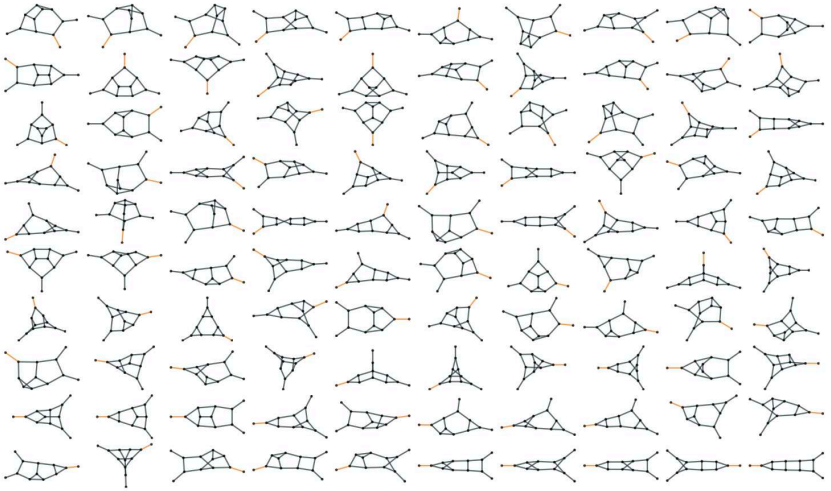
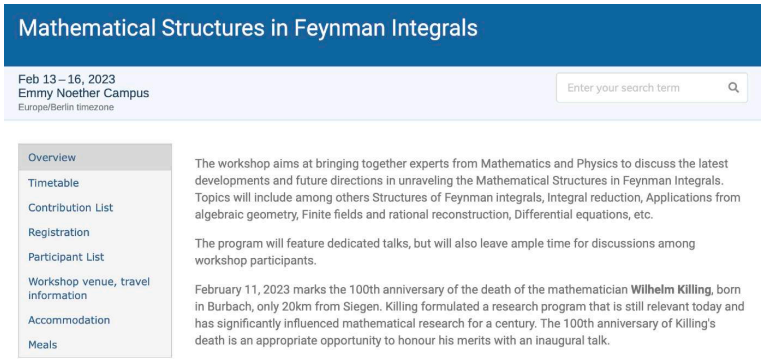


Figure 1. Reducible and irreducible top-level topologies for four-loop form factor integrals with one off-shell leg.



Flavour Physics

Outline

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

Flavour Physics

New ideas

A. **Increase SM precision** - continue to to provide world-leading precision develop new concepts like Gradient Flow

- C1 obvious
- $b \to s\ell\ell$: revisit form factors and non-local contributions/charm-loops
  Include more lattice? - how? In what collaborations?
- Λ_b decays - polarisation for FCC and V_{ub} determination from $\Lambda_b \to p\ell\nu$ (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
- ΔA_{CP}. — Connection with multi body CPV $B \to K\pi\pi$ (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- $t \to bW, cZ, uZ, \ldots$ and $B_s \to \mu\mu$
- Uli: 3b more general and bottom-up; additional PI from Aachen and/or Siegen

D. **Multi-body hadronic decays/CPV/Dalitz**

$B \to K\pi\pi$ methods by Kubis

Flavour Physics

New ideas

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….