Robert Harlander
Alexander Lenz
Ulrich Nierste

C1c | Non-perturbative matrix elements for B-mixing and lifetimes

TRR 257 P3H: Particle Physics Phenomenology after the Higgs discovery

Karlsruher Institut für Technologie
RWTH AACHEN UNIVERSITY
UNIVERSITÄT SIEGEN
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Project C1c - Overview:

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Summary: the main focus is **lifetimes and inclusive decays of B and D mesons.** Based on the **Heavy Quark Expansion** a systematic expansion of the physical quantities is obtained as an expansion in the inverse heavy quark mass.

$$\Gamma(H_Q) = \Gamma_3 + \sum_{i=2}^{\infty} \Gamma_{3+i} \frac{\langle \mathcal{O}_{3+i} \rangle}{m_Q^i} + 16\pi^2 \sum_{i=3}^{\infty} \tilde{\Gamma}_{3+i} \frac{\langle \tilde{\mathcal{O}}_{3+i} \rangle}{m_Q^i}$$

→ In case of only mixing

Non-perturbative matrix elements of four-quark operators of dimension six $\langle \tilde{\mathcal{O}}_6 \rangle$ and dimension seven $\langle \tilde{\mathcal{O}}_7 \rangle$ are computed with sum rules and lattice QCD and their phenomenological implications are studied.

Participating Scientists

Principal investigators

- R. Harlander Aachen
- A. Lenz Siegen
- U. Nierste Karlsruhe

Further Participating Scientists

- O. Witzel Siegen
- A. Pivovarov Siegen
- F. Lange Karlsruhe

Funded Positions

- Martin Lang, postdoctoral fellow Siegen
- Janosch Borgulat, PhD Aachen

Project C1c - Experimental Status:

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

***b*-hadron species**	**average lifetime**	**lifetime ratio**
B^0	**1.519 ± 0.004 ps**	
B^+	**1.638 ± 0.004 ps**	$B^+/B^0 = 1.076 \pm 0.004$
B_s^0	**1.520 ± 0.005 ps**	$B_s^0/B^0 = 1.001 \pm 0.004$
B_{sL}	**1.429 ± 0.007 ps**	
B_{sH}	**1.624 ± 0.009 ps**	
B_c^+	**0.510 ± 0.009 ps**	
Λ_b	**1.471 ± 0.009 ps**	$\Lambda_b/B^0 = 0.969 \pm 0.006$
Ξ_b^-	**1.572 ± 0.040 ps**	
Ξ_b^0	**1.480 ± 0.030 ps**	$\Xi_b^0/\Xi_b^- = 0.929 \pm 0.028$
Ω_b^-	**1.64 +0.18 −0.17 ps**	
b-hadron average (weighted by fractions in *Z* decays)	**1.5672 ± 0.0029 ps**	

HFLAV 2023

Project C1c - Experimental Status:

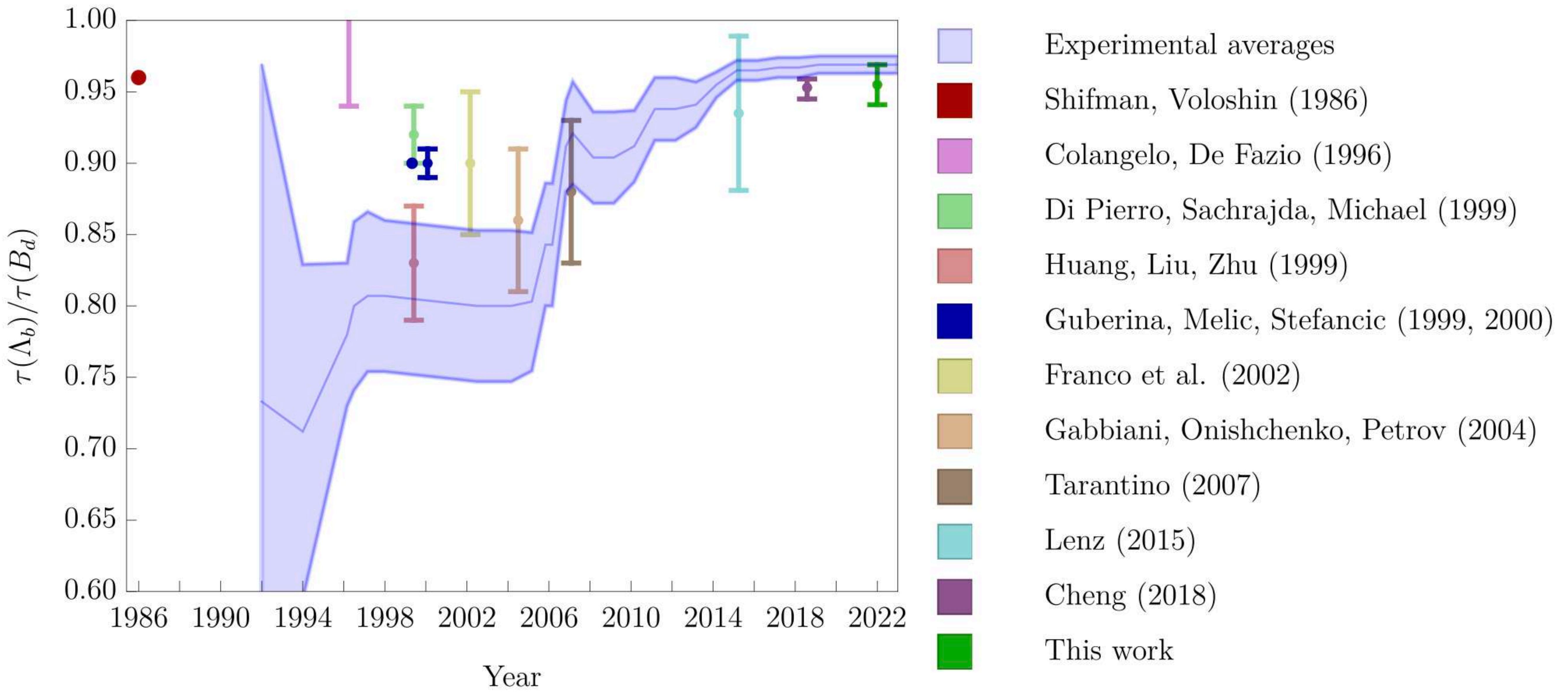
b-hadron species	average lifetime	lifetime ratio
B^0	1.519 ± 0.004 ps	
B^+	1.638 ± 0.004 ps	$B^+/B^0 = 1.076 \pm 0.004$
B_s^0	1.520 ± 0.005 ps	$B_s^0/B^0 = 1.001 \pm 0.004$
B_{sL}	1.429 ± 0.007 ps	
B_{sH}	1.624 ± 0.009 ps	
B_c^+	0.510 ± 0.009 ps	
Λ_b	1.471 ± 0.009 ps	$\Lambda_b/B^0 = 0.969 \pm 0.006$
Ξ_b^-	1.572 ± 0.040 ps	
Ξ_b^0	1.480 ± 0.030 ps	$\Xi_b^0/\Xi_b^- = 0.929 \pm 0.028$
Ω_b^-	1.64 +0.18 −0.17 ps	
b-hadron average (weighted by fractions in Z decays)	1.5672 ± 0.0029 ps	

HFLAV 2023

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)

e-Print: 2301.07698 [hep-ph]



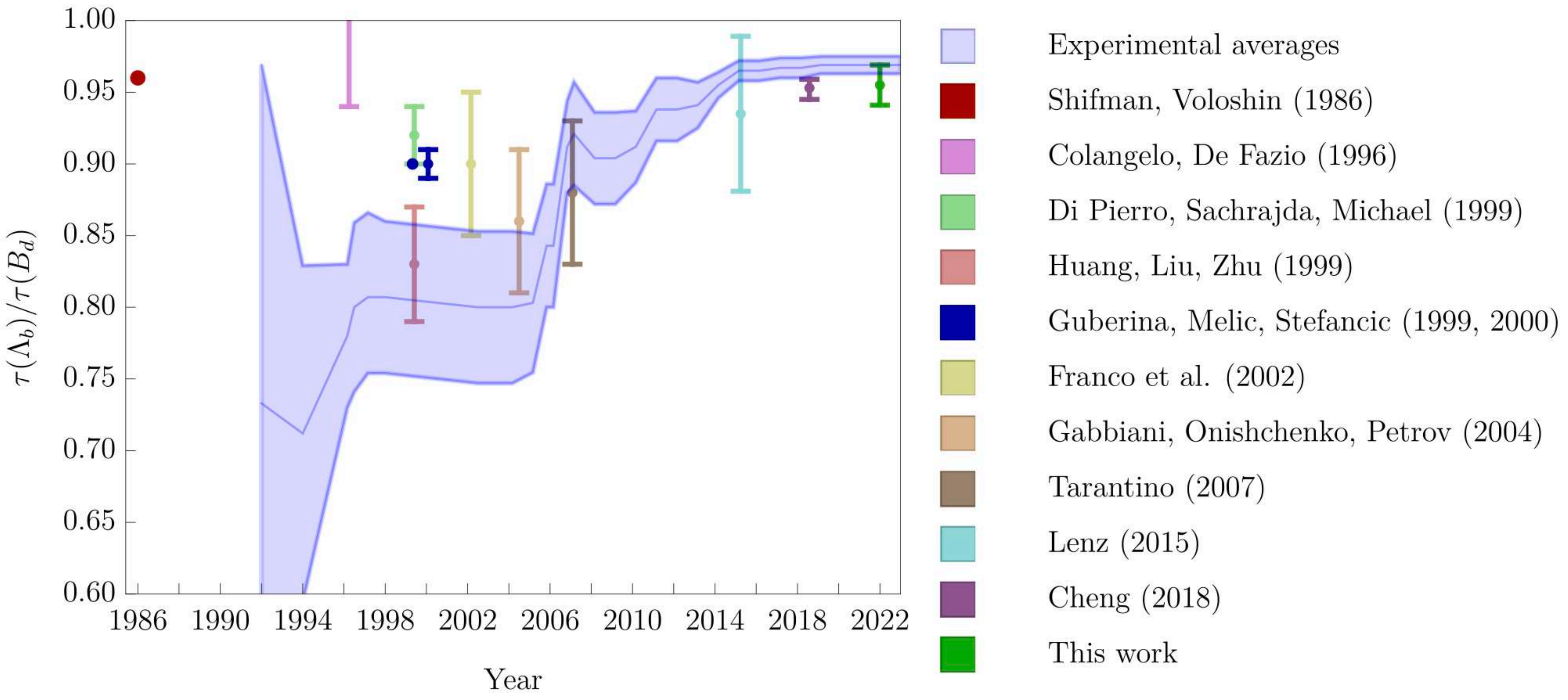
Project C1c - Experimental Status:

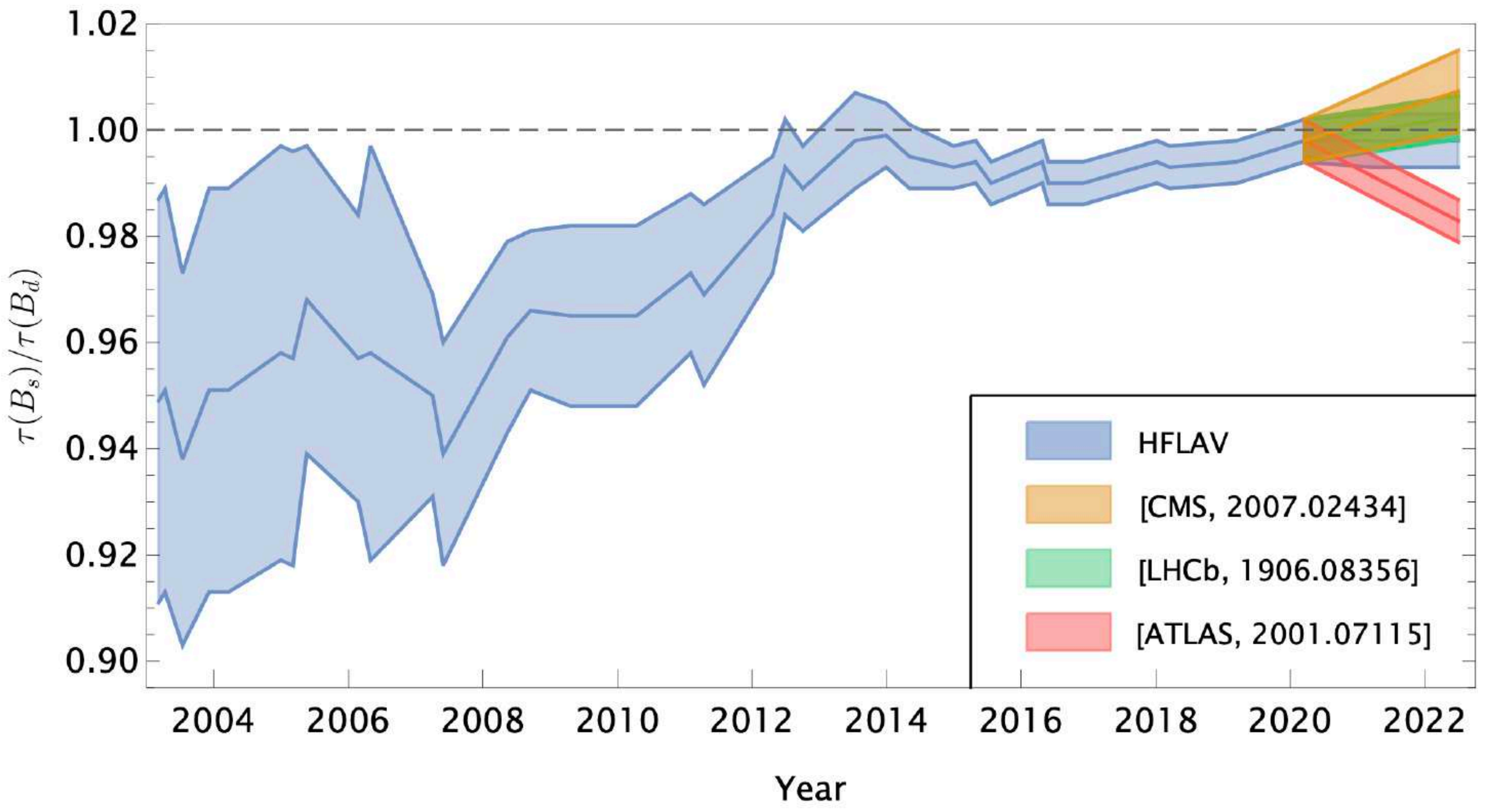
b-hadron species	average lifetime	lifetime ratio
B^0	1.519 ± 0.004 ps	
B^+	1.638 ± 0.004 ps	$B^+/B^0 = 1.076 \pm 0.004$
$B_s{}^0$	1.520 ± 0.005 ps	$B_s{}^0/B^0 = 1.001 \pm 0.004$
B_{sL}	1.429 ± 0.007 ps	
B_{sH}	1.624 ± 0.009 ps	
$B_c{}^+$	0.510 ± 0.009 ps	
Λ_b	1.471 ± 0.009 ps	$\Lambda_b/B^0 = 0.969 \pm 0.006$
$\Xi_b{}^-$	1.572 ± 0.040 ps	
$\Xi_b{}^0$	1.480 ± 0.030 ps	$\Xi_b{}^0/\Xi_b{}^- = 0.929 \pm 0.028$
$\Omega_b{}^-$	1.64 +0.18 −0.17 ps	
b-hadron average (weighted by fractions in Z decays)	1.5672 ± 0.0029 ps	

HFLAV 2023

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)
e-Print: 2301.07698 [hep-ph]

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery





Disintegration of beauty: a precision study
Alexander Lenz (Siegen U.), Maria Laura Piscopo (Siegen U.), Aleksey V. Rusov (Siegen U.) (Aug 4, 2022)
Published in: *JHEP* 01 (2023) 004 • e-Print: 2208.02643 [hep-ph]

Project C1c - Experimental Status (Charm):

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

	D^0	D^+	D_s^+
τ [ps]	0.4101(15)	1.040(7)	0.504(4)
Γ [ps^{-1}]	2.44(1)	0.96(1)	1.98(2)
$\tau(D_q)/\tau(D^0)$	1	2.54(2)	1.20(1)
$\mathrm{Br}(D_q \to X e^+ \nu_e)[\%]$	6.49(11)	16.07(30)	6.30(16)
$\frac{\Gamma(D_q \to X e^+ \nu_e)}{\Gamma(D^0 \to X e^+ \nu_e)}$	1	0.977(26)	0.790(26)

PDG 2023

Project C1c - Experimental Status (Charm):

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

	D^0	D^+	D_s^+
τ [ps]	$0.4101(15)$	$1.040(7)$	$0.504(4)$
Γ [ps^{-1}]	$2.44(1)$	$0.96(1)$	$1.98(2)$
$\tau(D_q)/\tau(D^0)$	1	$2.54(2)$	$1.20(1)$
$\mathrm{Br}(D_q \to X e^+ \nu_e)[\%]$	$6.49(11)$	$16.07(30)$	$6.30(16)$
$\frac{\Gamma(D_q \to X e^+ \nu_e)}{\Gamma(D^0 \to X e^+ \nu_e)}$	1	$0.977(26)$	$0.790(26)$

Collaboration	$\tau(\Lambda_c^+)/\mathrm{fs}$	$\tau(\Xi_c^+)/\mathrm{fs}$	$\tau(\Xi_c^0)/\mathrm{fs}$	$\tau(\Omega_c^0)/\mathrm{fs}$
CLEO [5, 7]	179.6 ± 8.2	503 ± 50	N/A	N/A
FOCUS [6, 8, 9, 11]	203.5 ± 4.2	439 ± 24	118^{+15}_{-13}	72 ± 16
SELEX [4, 12]	198.1 ± 9.0	N/A	N/A	65 ± 16 [2]
LHCb [1, 2]	203.5 ± 2.2	457 ± 6	154.5 ± 2.6	268 ± 26
LHCb 2021 [3]	N/A	N/A	148.0 ± 3.2	276.5 ± 14.1
PDG 2018 [10]	200 ± 6	442 ± 26	112^{+13}_{-10}	69 ± 12
PDG 2020 [21]	202.4 ± 3.1	456 ± 5	153 ± 6	$268 \pm 24 \pm 10$
Reference values	202.4 ± 3.1 [21]	456 ± 5 [21]	152.0 ± 2.0 [3]	274.5 ± 12.4 [3]

PDG 2023

Project C1c - Experimental Status (Charm):

	D^0	D^+	D_s^+
τ [ps]	0.4101(15)	1.040(7)	0.504(4)
Γ [ps^{-1}]	2.44(1)	0.96(1)	1.98(2)
$\tau(D_q)/\tau(D^0)$	1	2.54(2)	1.20(1)
$\mathrm{Br}(D_q \to X e^+ \nu_e)[\%]$	6.49(11)	16.07(30)	6.30(16)
$\frac{\Gamma(D_q \to X e^+ \nu_e)}{\Gamma(D^0 \to X e^+ \nu_e)}$	1	0.977(26)	0.790(26)

Collaboration	$\tau(\Lambda_c^+)$/fs	$\tau(\Xi_c^+)$/fs	$\tau(\Xi_c^0)$/fs	$\tau(\Omega_c^0)$/fs
CLEO [5, 7]	179.6 ± 8.2	503 ± 50	N/A	N/A
FOCUS [6, 8, 9, 11]	203.5 ± 4.2	439 ± 24	118^{+15}_{-13}	72 ± 16
SELEX [4, 12]	198.1 ± 9.0	N/A	N/A	65 ± 16 [2]
LHCb [1, 2]	203.5 ± 2.2	457 ± 6	154.5 ± 2.6	268 ± 26
LHCb 2021 [3]	N/A	N/A	148.0 ± 3.2	276.5 ± 14.1
PDG 2018 [10]	200 ± 6	442 ± 26	112^{+13}_{-10}	69 ± 12
PDG 2020 [21]	202.4 ± 3.1	456 ± 5	153 ± 6	$268 \pm 24 \pm 10$
Reference values	202.4 ± 3.1 [21]	456 ± 5 [21]	152.0 ± 2.0 [3]	274.5 ± 12.4 [3]

PDG 2023

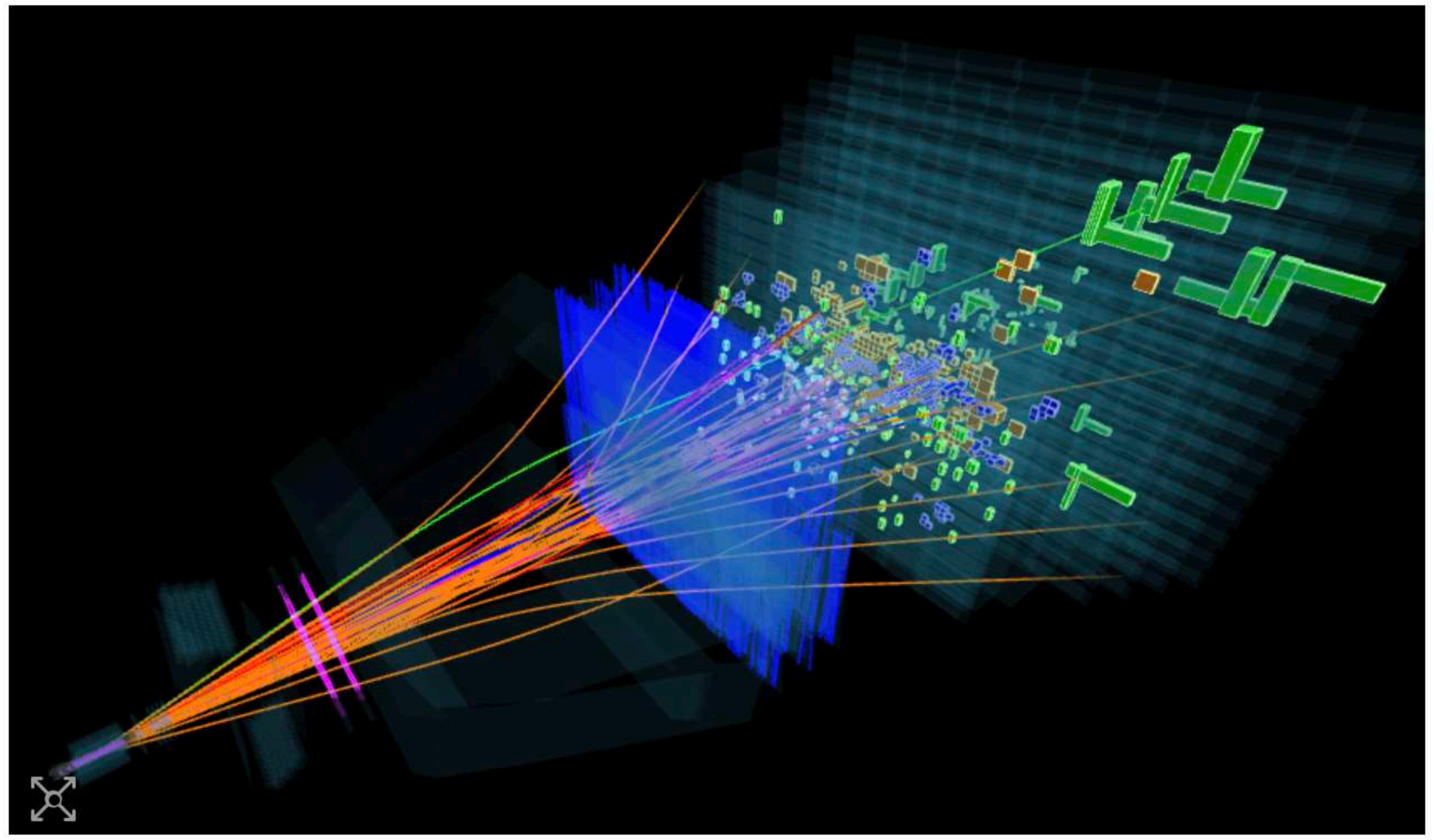
physicsworld | Magazine | Latest | People | Impa

particles and interactions

PARTICLES AND INTERACTIONS | RESEARCH UPDATE

Charmed baryon puzzles particle physicists by living longer

14 Aug 2018



Colliding protons: a collision captured by LHCb. (Courtesy: LHCb/CERN)

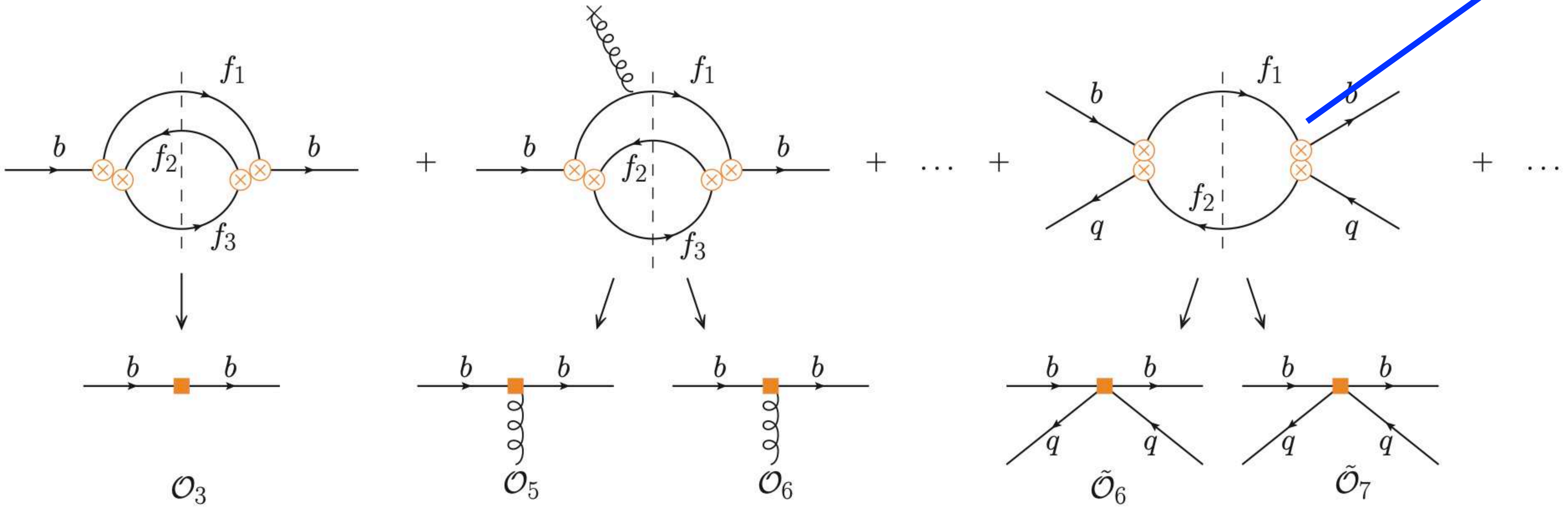
The most precise measurement of the lifetime of the Ω_c^0 particle has been made by physicists working on the LHCb experiment at CERN. The charmed baryon decays within femtoseconds after being produced in proton-proton collisions at the Large Hadron Collider

Project C1c - Theoretical Status:

The total decay rate of a B_q meson can be expressed as

$\Delta B = 1$ **effective Hamiltonian**

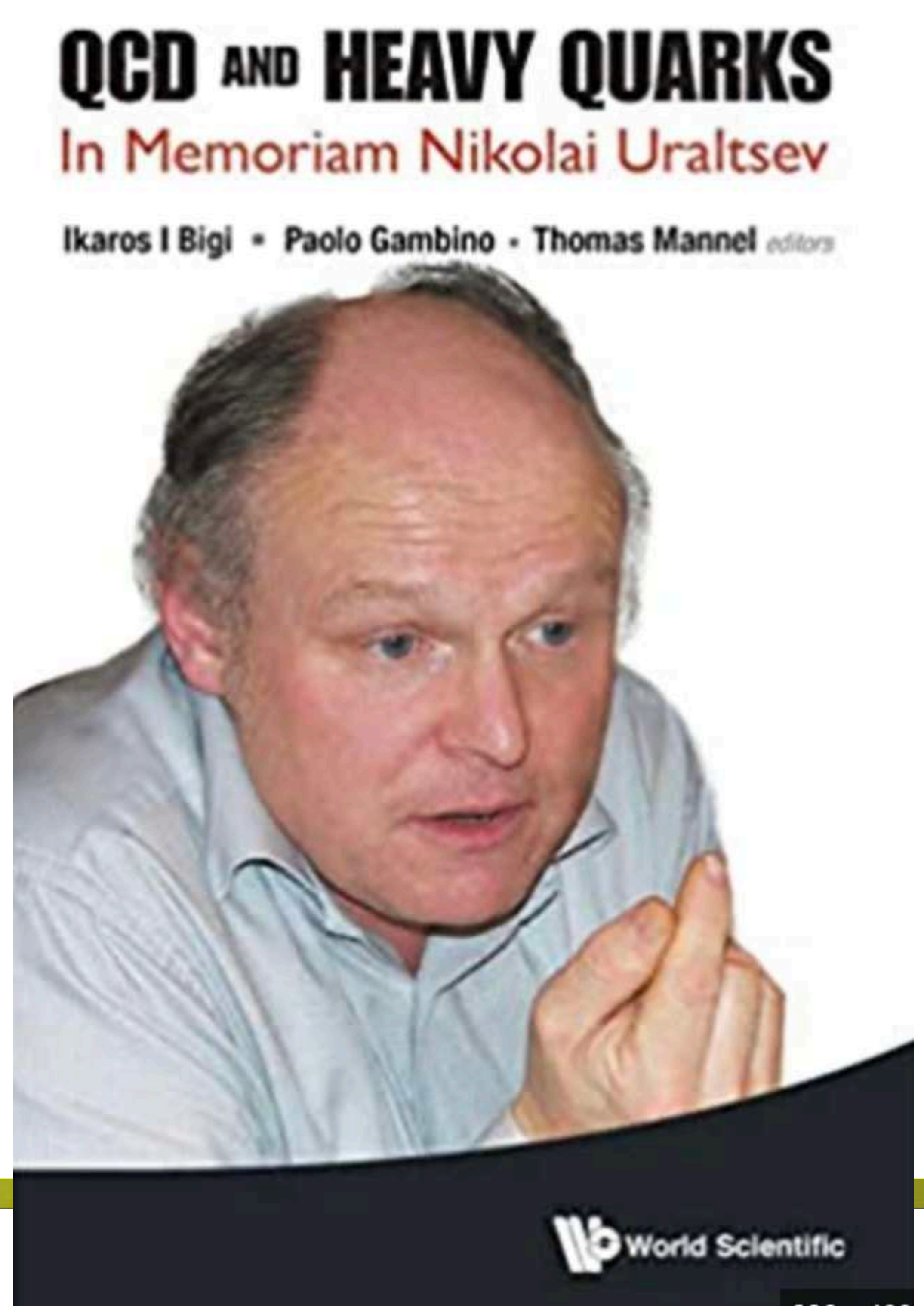
$$\Gamma(B_q) = \frac{1}{2m_{B_q}} \sum_X \int_{PS} (2\pi)^4 \delta^{(4)}(p_B - p_X) \, |\langle X(p_X)|\mathcal{H}_{\text{eff}}|B_q(p_B)\rangle|^2 ,$$



Heavy Quark Expansion:

Shifman, Voloshin 1983,…

For history see: AL 1405.3601



Using the optical theorem this can be rewritten as

$$\Gamma(B_q) = \frac{1}{2m_{B_q}} \text{Im}\langle B_q|\mathcal{T}|B_q\rangle , \qquad \mathcal{T} = i \int d^4x \, T\left\{\mathcal{H}_{\text{eff}}(x) \, , \mathcal{H}_{\text{eff}}(0)\right\} .$$

Project C1c - Theoretical Status:

The total decay rate of a B_q meson can be expressed as

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

- **Perturbative Wilson coefficients** $\Gamma_i = \Gamma_i^{(0)} + \frac{\alpha_s}{4\pi} \Gamma_i^{(1)} + \left(\frac{\alpha_s}{4\pi}\right)^2 \Gamma_i^{(2)} + \ldots,$

  Project C1b
  Lenz, Nierste, Steinhauser

- **Non-perturbative matrix elements of 2 quark operators** $\langle \mathcal{O}_i \rangle$

- **Non-perturbative matrix elements of 4 quark operators** $\langle \tilde{\mathcal{O}}_i \rangle$

  Project C1c
  Harlander, Lenz, Nierste

Project C1c - Theoretical Status:

The total decay rate of a B_q meson can be expressed as

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

- Perturbative Wilson coefficients

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

Project C1b
Lenz, Nierste, Steinhauser

Γ_i independent of B meson

- Non-perturbative matrix elements of 2 quark operators $\langle \mathcal{O}_i \rangle$

- Non-perturbative matrix elements of 4 quark operators $\langle \tilde{\mathcal{O}}_i \rangle$

Project C1c
Harlander, Lenz, Nierste

Project C1c - Theoretical Status:

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

The total decay rate of a B_q meson can be expressed as

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

- **Perturbative Wilson coefficients**

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

Project C1b
Lenz, Nierste, Steinhauser

Γ_i independent of B meson - $\tilde{\Gamma}_i$ dependent of B meson

- **Non-perturbative matrix elements of 2 quark operators** $\langle \mathcal{O}_i \rangle$: dependent of B meson

- **Non-perturbative matrix elements of 4 quark operators** $\langle \tilde{\mathcal{O}}_i \rangle$: dependent of B meson

Project C1c
Harlander, Lenz, Nierste

Project C1c - Theoretical Status Quo

Perturbative semi-leptonic

$\Gamma_3^{(1)}$	1983	HoKim, Pham
$\Gamma_3^{(2)}$	1997 – 2013	Czarnecki, Melnikov, vanRitbergen, Pak, Dowling, Bonciani, Ferroglia, Biswas, Brucherseifer, Caola
$\Gamma_3^{(3)}$	2020 2021	Fael, Schoenwald, Steinhauser Czakon, Czarnecki, Dowling
$\Gamma_5^{(0)}$	1992	Bigi, Uraltsev, Vainshtein, Blok, Shifman
$\Gamma_5^{(1)}$	2013 – 2015	Alberti, Gambino, Nandi, Mannel, Pivovarov, Rosenthal
$\Gamma_6^{(0)}$	1996	Gremm, Kapustin
$\Gamma_6^{(1)}$	2019	Mannel, Pivovarov
$\Gamma_7^{(0)}$	2006	Dassinger, Mannel, Turczyk
$\Gamma_8^{(0)}$	2010	Mannel, Turczyk, Uraltsev

Perturbative non-leptonic

$\Gamma_3^{(1)}$	1983 – 2013	HoKim, Pham, Altarelli, Petrarca, Voloshin, Bagan, Ball, Braun, Goszinsky, Fiol, Lenz, Nierste, Ostermaier, Krinner, Rauh, Greub, Liniger
$\Gamma_3^{(2)}$	2005	partly by : Czarnecki, Slusarczyk
$\Gamma_5^{(0)}$	1992	Bigi, Uraltsev, Vainshtein, Blok, Shifman
$\Gamma_6^{(0)}$	2020	Lenz, Piscopo, Rusov, Mannel, Moreno, Pivovarov
$\tilde{\Gamma}_6^{(0)}$	1979 – 1996	Guberina, Nussinov, Peccei, Ruckl, Shifman, Voloshin, Uraltsev, Neubert, Sachrajda
$\tilde{\Gamma}_6^{(1)}$	2002	Beneke, Buchalla, Greub, Lenz, Nierste Franco, Lubicz, Mescia, Tarantino, Rauh
$\tilde{\Gamma}_7^{(0)}$	2004	*Lenz*, *Nierste*, Gabbiani, Onishchenko, Petrov

Non-perturbative matrix elements

Piscopo 2302.14590

	B_d, B^+	B_s	Λ_b	$\Xi_b^-, \Xi_b^0, \Omega_b^-$
$\langle \mathcal{O}_5 \rangle$	*Fits to SL data [26–29]* *HQET sum rules [30, 31]* *Lattice QCD [32, 33]*	*Spectroscopy [35]*	*Spectroscopy [37]*	*Spectroscopy [41]*
$\langle \mathcal{O}_6 \rangle$	*Fits to SL data [26–29]* *EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$*	*Sum rules estimates [35]* *EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$*	*EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$*	*EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$*
$\langle \tilde{\mathcal{O}}_6 \rangle$	*HQET sum rules [34]*	*HQET sum rules [36]*	*HQET SR [38]; NRCQM + spectroscopy [39, 40]*	*NRCQM + spectroscopy [39, 40]*
$\langle \tilde{\mathcal{O}}_7 \rangle$	*Vacuum insertion approximation*		——	—-

Project C1c - Theoretical Status Quo

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Perturbative semi-leptonic

$\Gamma_3^{(1)}$	1983	HoKim, Pham
$\Gamma_3^{(2)}$	1997 – 2013	Czarnecki, Melnikov, vanRitbergen, Pak, Dowling, Bonciani, Ferroglia, Biswas, Brucherseifer, Caola
$\Gamma_3^{(3)}$	2020 2021	Fael, Schoenwald, Steinhauser Czakon, Czarnecki, Dowling
$\Gamma_5^{(0)}$	1992	Bigi, Uraltsev, Vainshtein, Blok, Shifman
$\Gamma_5^{(1)}$	2013 – 2015	Alberti, Gambino, Nandi, Mannel, Pivovarov, Rosenthal
$\Gamma_6^{(0)}$	1996	Gremm, Kapustin
$\Gamma_6^{(1)}$	2019	Mannel, Pivovarov
$\Gamma_7^{(0)}$	2006	Dassinger, Mannel, Turczyk
$\Gamma_8^{(0)}$	2010	Mannel, Turczyk, Uraltsev

Perturbative non-leptonic

$\Gamma_3^{(1)}$	1983 – 2013	HoKim, Pham, Altarelli, Petrarca, Voloshin, Bagan, Ball, Braun, Goszinsky, Fiol, Lenz, Nierste, Ostermaier, Krinner, Rauh, Greub, Liniger
$\Gamma_3^{(2)}$	2005	partly by : Czarnecki, Slusarczyk
$\Gamma_5^{(0)}$	1992	Bigi, Uraltsev, Vainshtein, Blok, Shifman
$\Gamma_6^{(0)}$	2020	Lenz, Piscopo, Rusov, Mannel, Moreno, Pivovarov
$\tilde{\Gamma}_6^{(0)}$	1979 – 1996	Guberina, Nussinov, Peccei, Ruckl, Shifman, Voloshin, Uraltsev, Neubert, Sachrajda
$\tilde{\Gamma}_6^{(1)}$	2002	Beneke, Buchalla, Greub, Lenz, Nierste Franco, Lubicz, Mescia, Tarantino, Rauh
$\tilde{\Gamma}_7^{(0)}$	2004	*Lenz, Nierste*, Gabbiani, Onishchenko, Petrov

Non-perturbative matrix elements

Piscopo 2302.14590

	B_d, B^+	B_s	Λ_b	$\Xi_b^-, \Xi_b^0, \Omega_b^-$
$\langle \mathcal{O}_5 \rangle$	*Fits to SL data [26–29]* *HQET sum rules [30, 31]* *Lattice QCD [32, 33]*	*Spectroscopy [35]*	*Spectroscopy [37]*	*Spectroscopy [41]*
$\langle \mathcal{O}_6 \rangle$	*Fits to SL data [26–29]* *EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$*	*Sum rules estimates [35]* *EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$*	*EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$*	*EOM relation to $\langle \tilde{\mathcal{O}}_6 \rangle$*
$\langle \tilde{\mathcal{O}}_6 \rangle$	*HQET sum rules [34]*	*HQET sum rules [36]*	*HQET SR [38]; NRCQM + spectroscopy [39, 40]*	*NRCQM + spectroscopy [39, 40]*
$\langle \tilde{\mathcal{O}}_7 \rangle$	*Vacuum insertion approximation*		—	—

People in Aachen, Karlsruhe, Siegen

Project C1c - Theoretical Status Quo

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Perturbative semi-leptonic

$\Gamma_3^{(1)}$	1983	HoKim, Pham
$\Gamma_3^{(2)}$	1997 – 2013	Czarnecki, Melnikov, vanRitbergen, Pak, Dowling, Bonciani, Ferroglia, Biswas, Brucherseifer, Caola
$\Gamma_3^{(3)}$	2020 2021	Fael, Schoenwald, Steinhauser Czakon, Czarnecki, Dowling
$\Gamma_5^{(0)}$	1992	Bigi, Uraltsev, Vainshtein, Blok, Shifman
$\Gamma_5^{(1)}$	2013 – 2015	Alberti, Gambino, Nandi, Mannel, Pivovarov, Rosenthal
$\Gamma_6^{(0)}$	1996	Gremm, Kapustin
$\Gamma_6^{(1)}$	2019	Mannel, Pivovarov
$\Gamma_7^{(0)}$	2006	Dassinger, Mannel, Turczyk
$\Gamma_8^{(0)}$	2010	Mannel, Turczyk, Uraltsev

Perturbative non-leptonic

$\Gamma_3^{(1)}$	1983 – 2013	HoKim, Pham, Altarelli, Petrarca, Voloshin, Bagan, Ball, Braun, Goszinsky, Fiol, Lenz, Nierste, Ostermaier, Krinner, Rauh, Greub, Liniger
$\Gamma_3^{(2)}$	2005	partly by : Czarnecki, Slusarczyk
$\Gamma_5^{(0)}$	1992	Bigi, Uraltsev, Vainshtein, Blok, Shifman
$\Gamma_6^{(0)}$	2020	Lenz, Piscopo, Rusov, Mannel, Moreno, Pivovarov
$\tilde{\Gamma}_6^{(0)}$	1979 – 1996	Guberina, Nussinov, Peccei, Ruckl, Shifman, Voloshin, Uraltsev, Neubert, Sachrajda
$\tilde{\Gamma}_6^{(1)}$	2002	Beneke, Buchalla, Greub, Lenz, Nierste Franco, Lubicz, Mescia, Tarantino, Rauh
$\tilde{\Gamma}_7^{(0)}$	2004	*Lenz, Nierste*, Gabbiani, Onishchenko, Petrov

Non-perturbative matrix elements

Piscopo 2302.14590

	B_d, B^+	B_s	Λ_b	$\Xi_b^-, \Xi_b^0, \Omega_b^-$
$\langle \mathcal{O}_5 \rangle$	*Fits to SL data [26–29]* *HQET sum rules [30, 31]* *Lattice QCD [32, 33]*	*Spectroscopy [35]*	*Spectroscopy [37]*	*Spectroscopy [41]*
$\langle \mathcal{O}_6 \rangle$	*Fits to SL data [26–29]* *EOM relation to* $\langle \tilde{\mathcal{O}}_6 \rangle$	*Sum rules estimates [35]* *EOM relation to* $\langle \tilde{\mathcal{O}}_6 \rangle$	*EOM relation to* $\langle \tilde{\mathcal{O}}_6 \rangle$	*EOM relation to* $\langle \tilde{\mathcal{O}}_6 \rangle$
$\langle \tilde{\mathcal{O}}_6 \rangle$	*HQET sum rules [34]*	*HQET sum rules [36]*	*HQET SR [38]; NRCQM + spectroscopy [39, 40]*	*NRCQM + spectroscopy [39, 40]*
$\langle \tilde{\mathcal{O}}_7 \rangle$	*Vacuum insertion approximation*		—–	—–

People in Aachen, Karlsruhe, Siegen

No lattice values

Project C1c - Theoretical Status: Ratios

Lifetime ratios

$$\frac{\tau(B^+)}{\tau(B_d)} = 1 + \left[\Gamma(B_d) - \Gamma(B^+)\right] \cdot \tau(B^+)$$

$$= 1 + \left[\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_d} - \langle \mathcal{O}_5 \rangle_{B^+}}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_d} - \langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} + \ldots + 16\pi^2 \left\{ \tilde{\Gamma}_{6B_d} \frac{\langle \mathcal{O}_6 \rangle_{B_d}}{m_b^3} - \tilde{\Gamma}_{6B^+} \frac{\langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} + \tilde{\Gamma}_{7B_d} \frac{\langle \mathcal{O}_7 \rangle_{B_d}}{m_b^4} - \tilde{\Gamma}_{7B^+} \frac{\langle \mathcal{O}_7 \rangle_{B^+}}{m_b^4} + \ldots \right\}\right] \cdot \tau(B^+)$$

Project C1c - Theoretical Status: Ratios

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Lifetime ratios

$$\frac{\tau(B^+)}{\tau(B_d)} = 1 + \left[\Gamma(B_d) - \Gamma(B^+)\right] \cdot \tau(B^+)$$

$$= 1 + \left[\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_d} - \langle \mathcal{O}_5 \rangle_{B^+}}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_d} - \langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} + \ldots + 16\pi^2 \left\{ \tilde{\Gamma}_{6B_d} \frac{\langle \mathcal{O}_6 \rangle_{B_d}}{m_b^3} - \tilde{\Gamma}_{6B^+} \frac{\langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} + \tilde{\Gamma}_{7B_d} \frac{\langle \mathcal{O}_7 \rangle_{B_d}}{m_b^4} - \tilde{\Gamma}_{7B^+} \frac{\langle \mathcal{O}_7 \rangle_{B^+}}{m_b^4} + \ldots \right\} \right] \cdot \tau(B^+)$$

- **Free quark decay Γ_3 cancels exactly**

Project C1c - Theoretical Status: Ratios

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Lifetime ratios

$$\frac{\tau(B^+)}{\tau(B_d)} = 1 + \left[\Gamma(B_d) - \Gamma(B^+)\right] \cdot \tau(B^+)$$

$$= 1 + \left[\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_d} - \langle \mathcal{O}_5 \rangle_{B^+}}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_d} - \langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} + \ldots + 16\pi^2 \left\{ \tilde{\Gamma}_{6B_d} \frac{\langle \mathcal{O}_6 \rangle_{B_d}}{m_b^3} - \tilde{\Gamma}_{6B^+} \frac{\langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} + \tilde{\Gamma}_{7B_d} \frac{\langle \mathcal{O}_7 \rangle_{B_d}}{m_b^4} - \tilde{\Gamma}_{7B^+} \frac{\langle \mathcal{O}_7 \rangle_{B^+}}{m_b^4} + \ldots \right\}\right] \cdot \tau(B^+)$$

- **Free quark decay Γ_3 cancels exactly**
- **Kinetic, chromo-magnetic, Darwin term proportional to isospin violating effects**

Project C1c - Theoretical Status: Ratios

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Lifetime ratios

$$\frac{\tau(B^+)}{\tau(B_d)} = 1 + \left[\Gamma(B_d) - \Gamma(B^+)\right] \cdot \tau(B^+)$$

$$= 1 + \left[\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_d} - \langle \mathcal{O}_5 \rangle_{B^+}}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_d} - \langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} + \ldots + 16\pi^2 \left\{ \tilde{\Gamma}_{6B_d} \frac{\langle \mathcal{O}_6 \rangle_{B_d}}{m_b^3} - \tilde{\Gamma}_{6B^+} \frac{\langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} + \tilde{\Gamma}_{7B_d} \frac{\langle \mathcal{O}_7 \rangle_{B_d}}{m_b^4} - \tilde{\Gamma}_{7B^+} \frac{\langle \mathcal{O}_7 \rangle_{B^+}}{m_b^4} + \ldots \right\}\right] \cdot \tau(B^+)$$

- **Free quark decay Γ_3 cancels exactly**
- **Kinetic, chromo-magnetic, Darwin term proportional to isospin violating effects**
- **Sizable effects expected due to spectator effects: Pauli interference**

Project C1c - Theoretical Status: Ratios

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Lifetime ratios

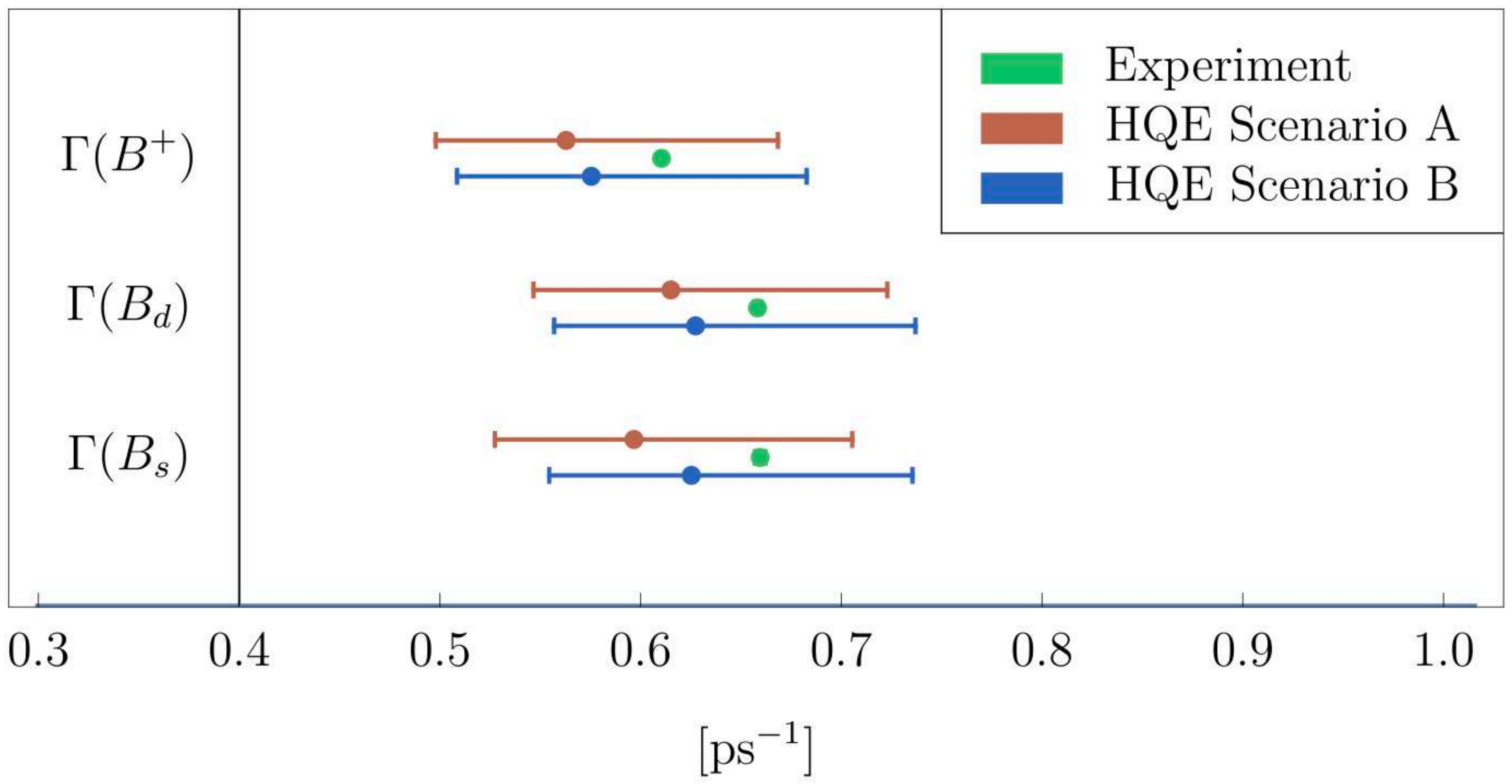
Could be dominant for $\frac{\tau(B_s)}{\tau(B_d)}$

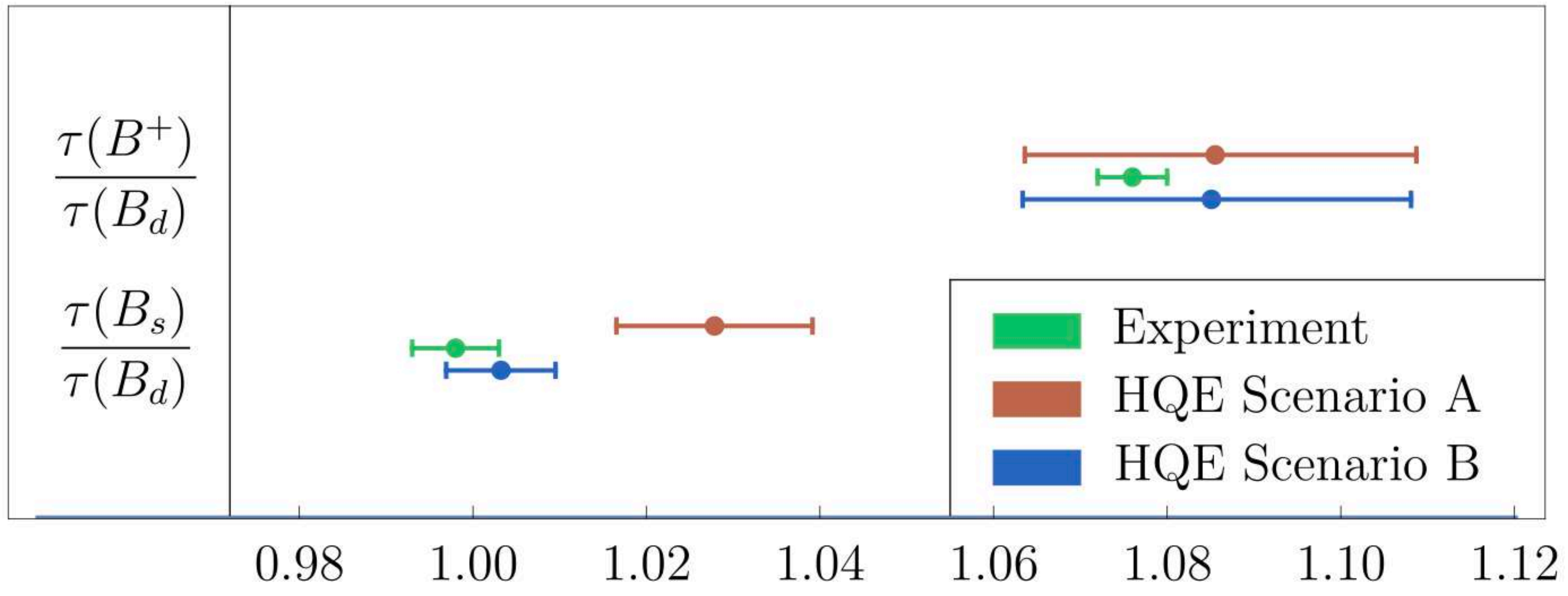
$$\frac{\tau(B^+)}{\tau(B_d)} = 1 + \left[\Gamma(B_d) - \Gamma(B^+)\right] \cdot \tau(B^+)$$

$$= 1 + \left[\Gamma_5 \frac{\langle \mathcal{O}_5 \rangle_{B_d} - \langle \mathcal{O}_5 \rangle_{B^+}}{m_b^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle_{B_d} - \langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} + \ldots + 16\pi^2 \left\{ \tilde{\Gamma}_{6B_d} \frac{\langle \mathcal{O}_6 \rangle_{B_d}}{m_b^3} - \tilde{\Gamma}_{6B^+} \frac{\langle \mathcal{O}_6 \rangle_{B^+}}{m_b^3} + \tilde{\Gamma}_{7B_d} \frac{\langle \mathcal{O}_7 \rangle_{B_d}}{m_b^4} - \tilde{\Gamma}_{7B^+} \frac{\langle \mathcal{O}_7 \rangle_{B^+}}{m_b^4} + \ldots \right\}\right] \cdot \tau(B^+)$$

- **Free quark decay Γ_3 cancels exactly**
- **Kinetic, chromo-magnetic, Darwin term proportional to isospin violating effects**
- **Sizable effects expected due to spectator effects: Pauli interference**
- **For B_s: large contribution due to Darwin term, $\langle \mathcal{O}_6 \rangle_{B_s}$ unknown! , $\langle \mathcal{O}_6 \rangle_{B_d}$ extracted from inclusive V_{cb} fits - 2 different results! Gambino et al. vs Vos et al.**

Project C1c - Theoretical Status: Results for bottom Hadrons

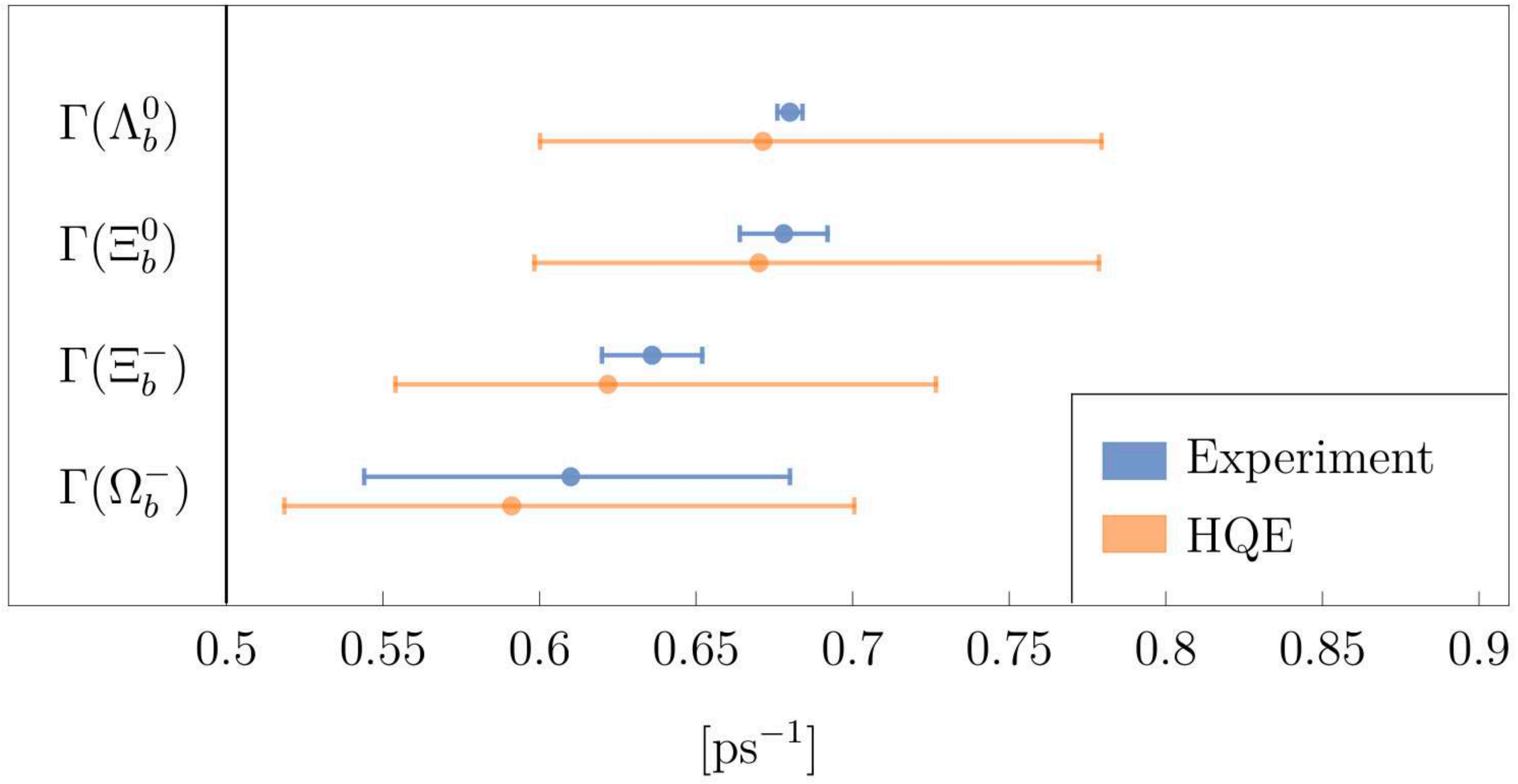


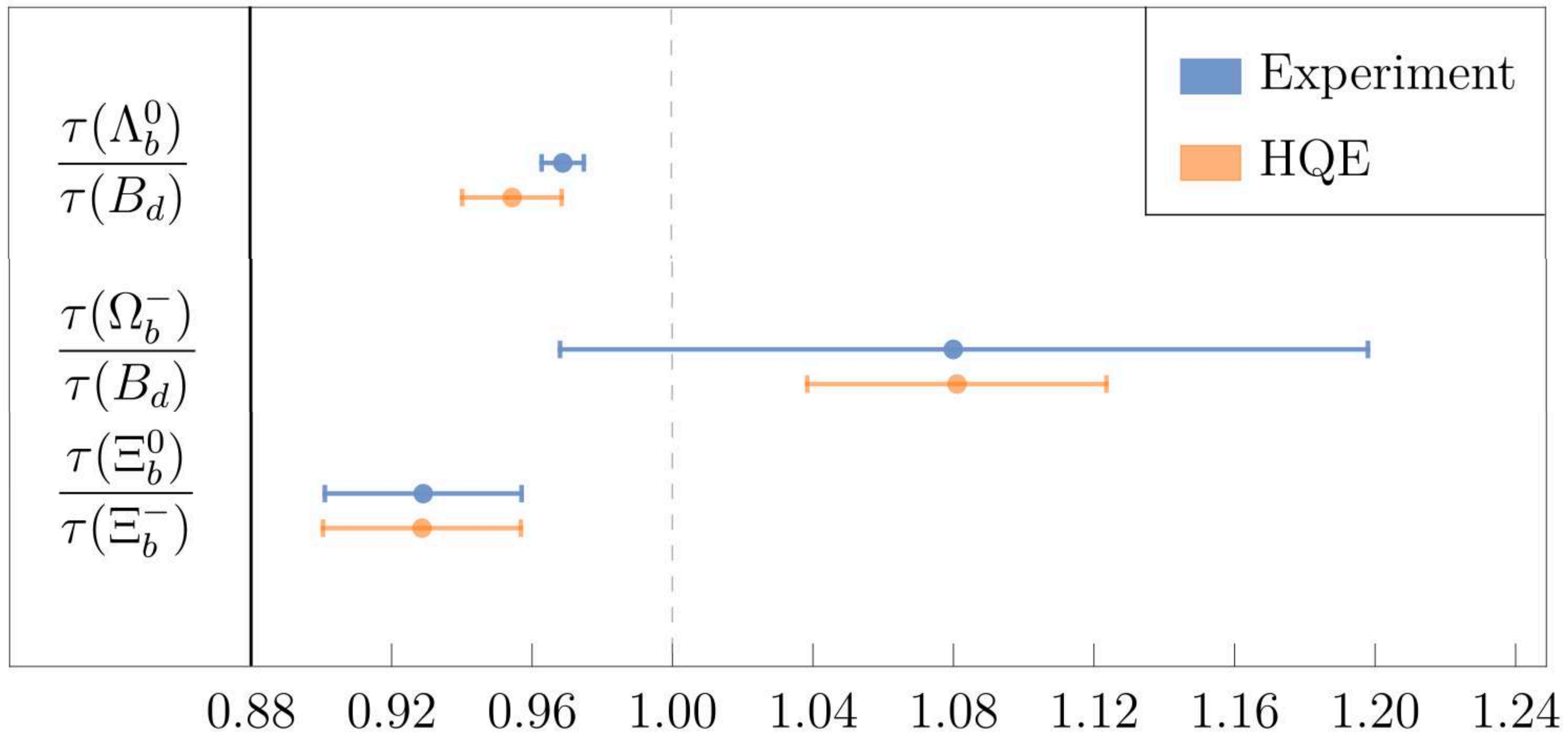


Disintegration of beauty: a precision study

Alexander Lenz (Siegen U.), Maria Laura Piscopo (Siegen U.), Aleksey V. Rusov (Siegen U.) (Aug 4, 2022)

Published in: *JHEP* 01 (2023) 004 • e-Print: 2208.02643 [hep-ph]





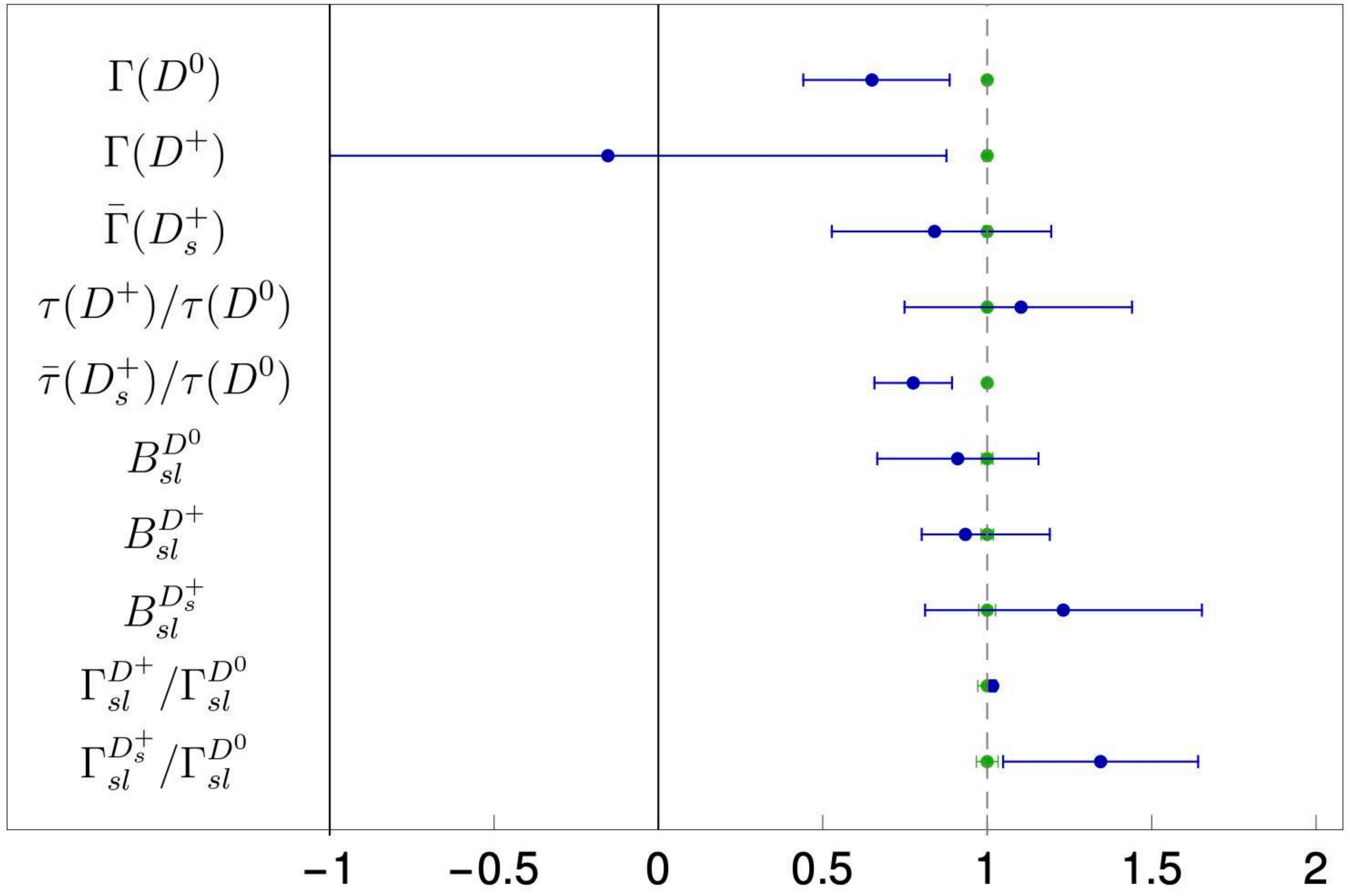
Quark-hadron duality at work: lifetimes of bottom baryons

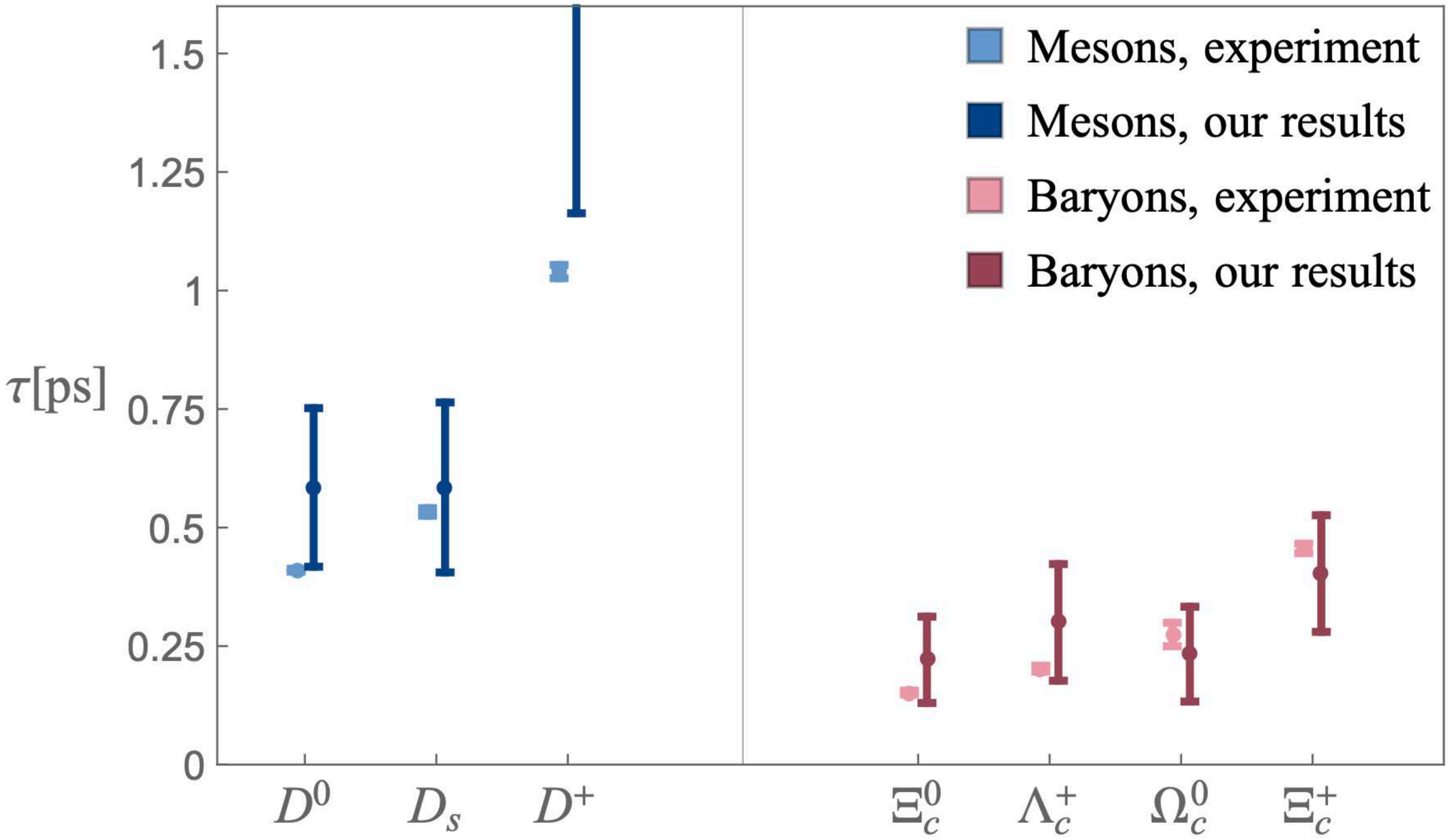
James Gratrex (Boskovic Inst., Zagreb), Alexander Lenz (Siegen U.), Blaženka Melić (Boskovic Inst., Zagreb), Ivan Nišandžić (Boskovic Inst., Zagreb), Maria Laura Piscopo (Siegen U.) et al. (Jan 18, 2023)

e-Print: 2301.07698 [hep-ph]

Project C1c - Theoretical Status: Results for charm hadrons

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery





Revisiting inclusive decay widths of charmed mesons

Daniel King (Durham U., IPPP and Durham U.), Alexander Lenz (Siegen U.), Maria Laura Piscopo (Siegen U.), Thomas Rauh (U. Bern, AEC), Aleksey V. Rusov (Siegen U.) et al. (Sep 27, 2021)

Published in: *JHEP* 08 (2022) 241 • e-Print: 2109.13219 [hep-ph]

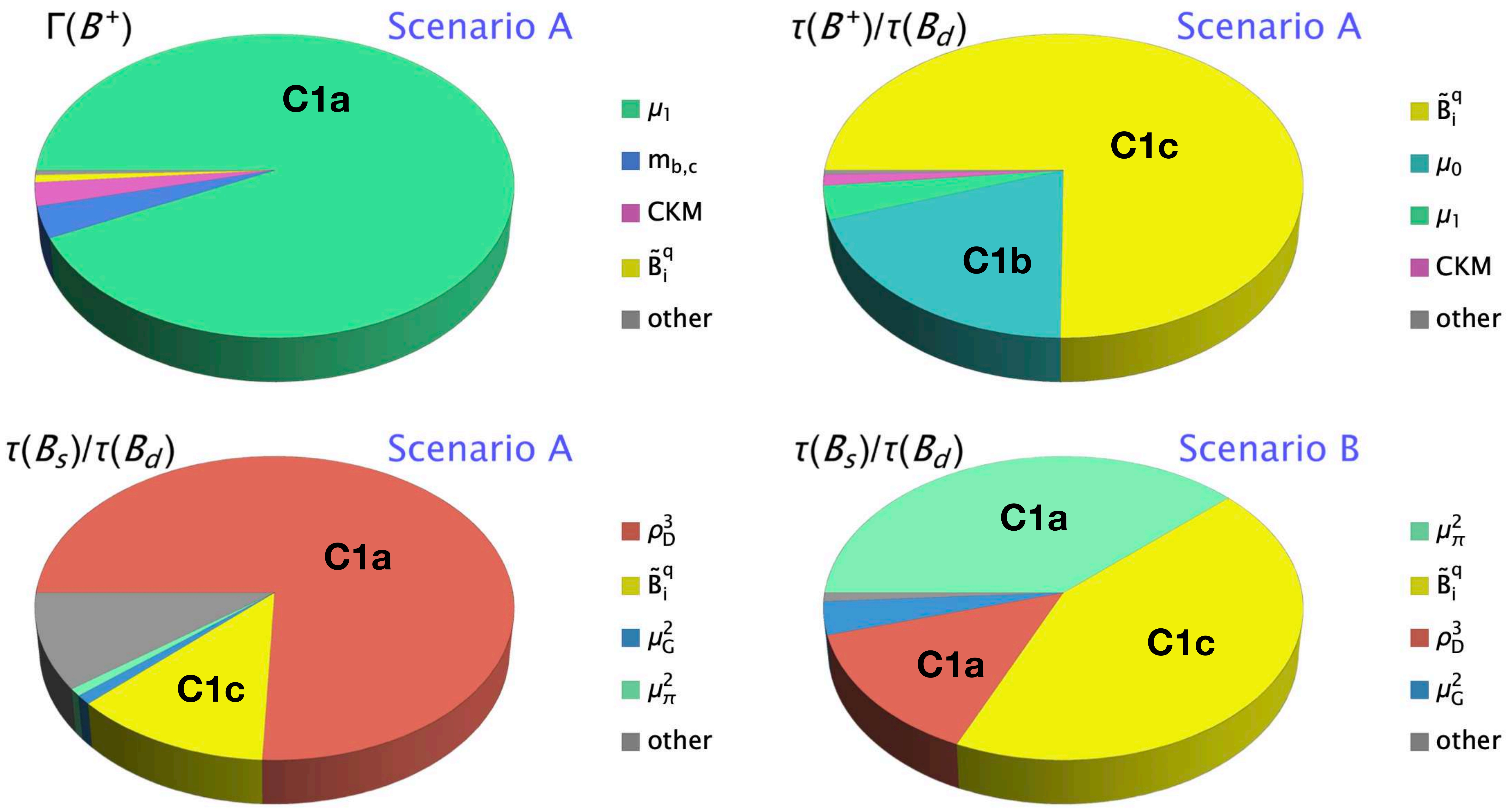
Lifetimes of singly charmed hadrons

James Gratrex (Boskovic Inst., Zagreb), Blaženka Melić (Boskovic Inst., Zagreb), Ivan Nišandžić (Boskovic Inst., Zagreb) (Apr 25, 2022)

Published in: *JHEP* 07 (2022) 058, *JHEP* 07 (2022) 058 • e-Print: 2204.11935 [hep-ph]

Project C1c: Current theory uncertainties

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery



Lenz, Piscopo, Rusov; 2208.02643

Project C1c - Project plans:

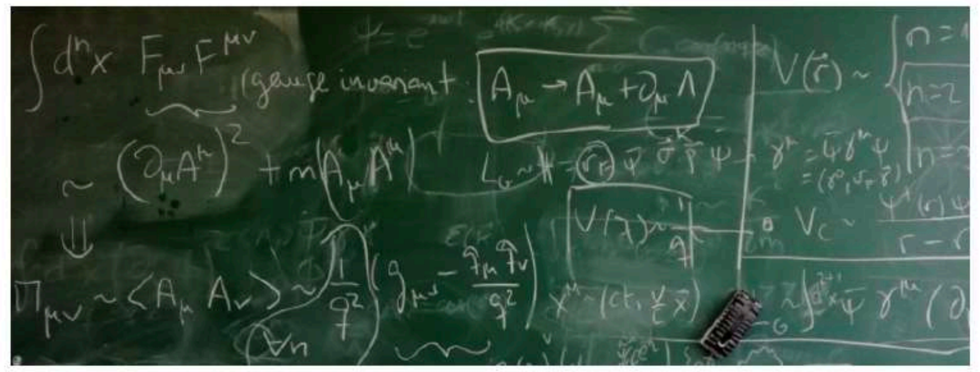
TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

1. Calculation of sum rules for $\langle \tilde{\mathcal{O}}_7 \rangle$ for mixing
2. Calculation of sum rules for $\langle \tilde{\mathcal{O}}_7 \rangle$ for lifetimes
3. Perturbative calculation of flowed matching matrix $\zeta_{nm}(t)$ through NNLO
4. Lattice calculation of flowed matrix elements $\langle \tilde{O}_n(t) \rangle$
5. Extrapolation to zero flow time
6. Phenomenological studies

Currently Matthew Black, Soon Martin Lang (items 1, 2)

Matthew Black, Robert Harlander, Fabian Lange, Oliver Witzel (items 3, 4, 5)

THE GRADIENT FLOW IN QCD AND OTHER STRONGLY COUPLED FIELD THEORIES



20 March 2023 — 24 March 2023

ECT* - Villa Tambosi

Strada delle Tabarelle, 286
Trento - Italy

Show map Get directions

The gradient flow field transformation is a continuous smoothing transformation that removes ultraviolet fluctuations. It can serve as a tool to renormalize quantum field theories, allowing numerical studies of strongly coupled systems. The flow has been used extensively in lattice gauge theory calculations, both in QCD and in beyond the standard model settings for applications including scale setting, the determination of the running coupling constant and the corresponding renormalization group beta function, and the topological structure of the vacuum. Many of the newly emerging applications of the gradient flow depend on the perturbative connection of the gradient flow and continuum renormalization schemes, requiring difficult perturbative calculations that match the non-perturbative lattice methods. This workshop will bring together experts in lattice and perturbative QCD to discuss recent progress in the application of the gradient flow, develop common ideas, identify needs and possibilities for the gradient flow and to spark collaborative efforts.

Organizers

Christopher Monahan (William & Mary, United States)
cjmonahan@wm.edu
Robert Harlander (Aachen University, Germany)
harlander@physik.rwth-aachen.de
Anna Hasenfratz (University of Colorado, Boulder, United States)
anna.hasenfratz@colorado.edu
Oliver Witzel (Siegen University, Germany)
oliver.witzel@uni-siegen.de

Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation
INFN
Particle Physics Phenomenology after the Higgs Discovery

Project C1c - Work package 6:

Lifetimes and mixing parameter to test the SM and extensions of it

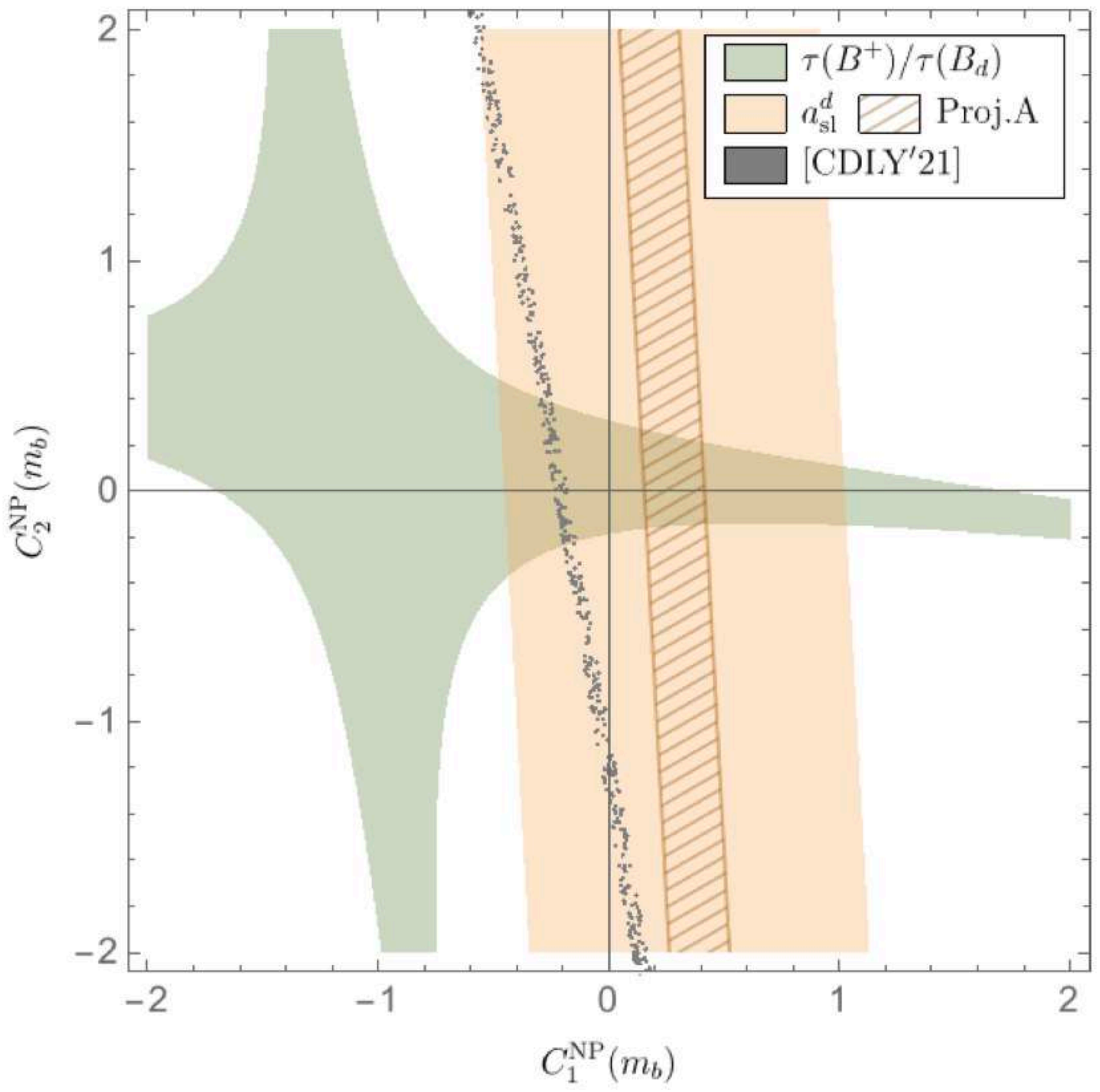
Improved knowledge of the values of the matrix elements of dimension-6 and -7 four-quark operators will considerably increase the precision of the SM predictions for B meson lifetimes and B mixing parameter, providing crucial tests of the SM. Within the SM such an increased precision can further be used to directly determine CKM parameters involving the top quark, or V_{cb} indirectly. Extensions of the SM can significantly modify the theory predictions for lifetimes and mixing, and we will investigate the impact of our results on different BSM approaches, which are studied within the CRC.

$$\frac{\tau(B^+)}{\tau(B_d)}^{\mathrm{HQE}} = 1 + \left[\Gamma^{\mathrm{SM}}(B_d) - \Gamma^{\mathrm{SM}}(B^+)\right] \tau^{\mathrm{Exp.}}(B^+) + \left[\Gamma^{\mathrm{BSM}}(B_d) - \Gamma^{\mathrm{BSM}}(B^+)\right] \tau^{\mathrm{Exp.}}(B^+)$$

Taming New Physics in $b \to c\bar{u}d(s)$ with $\tau(B^+)/\tau(B_d)$ and a_{sl}^d #

Alexander Lenz (Siegen U.), Jakob Müller (Siegen U.), Maria Laura Piscopo (Siegen U.), Aleksey V. Rusov (Siegen U.) (Nov 4, 2022)

e-Print: 2211.02724 [hep-ph]



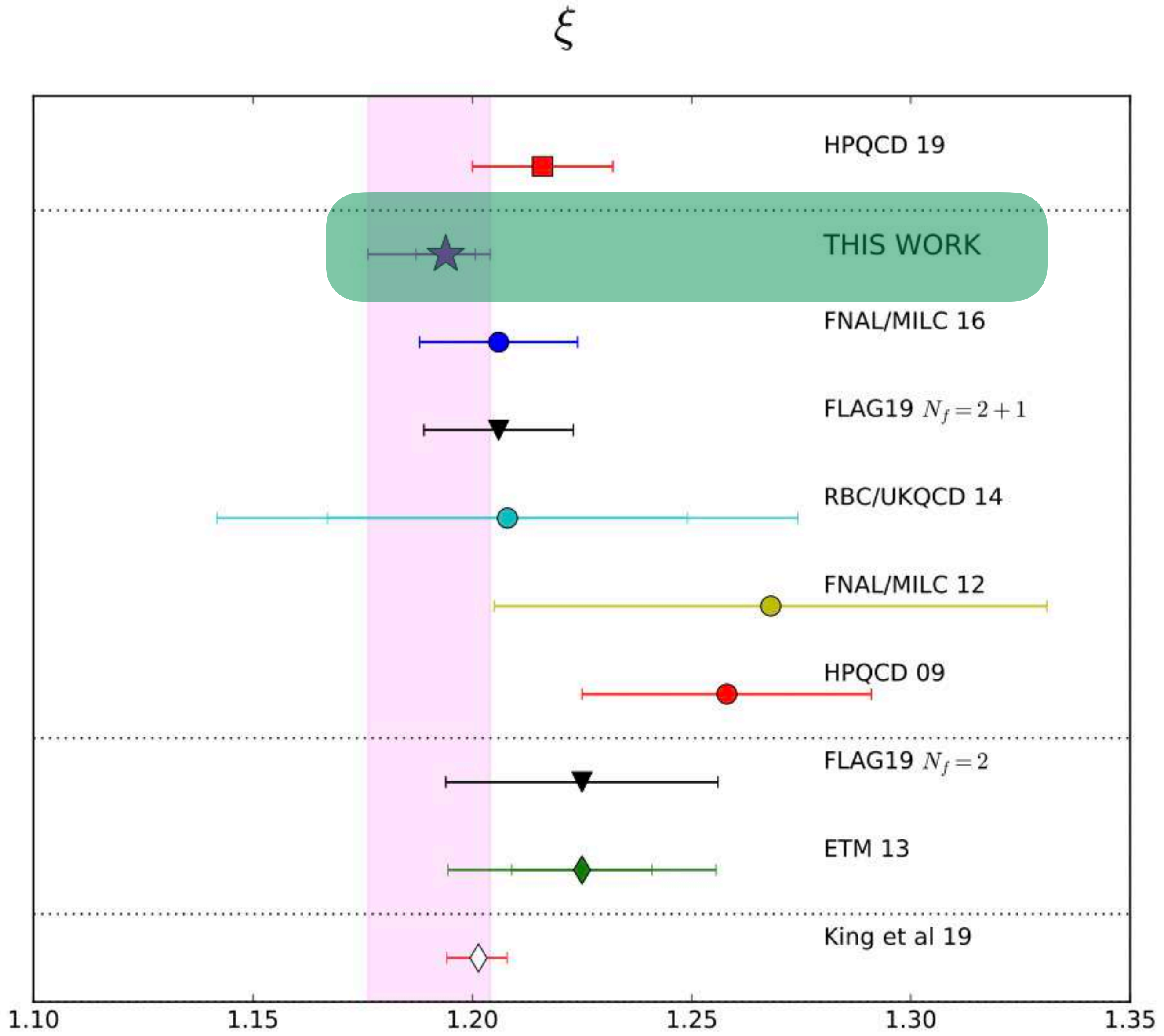
Spare slides

Project C1c - Overview 2:

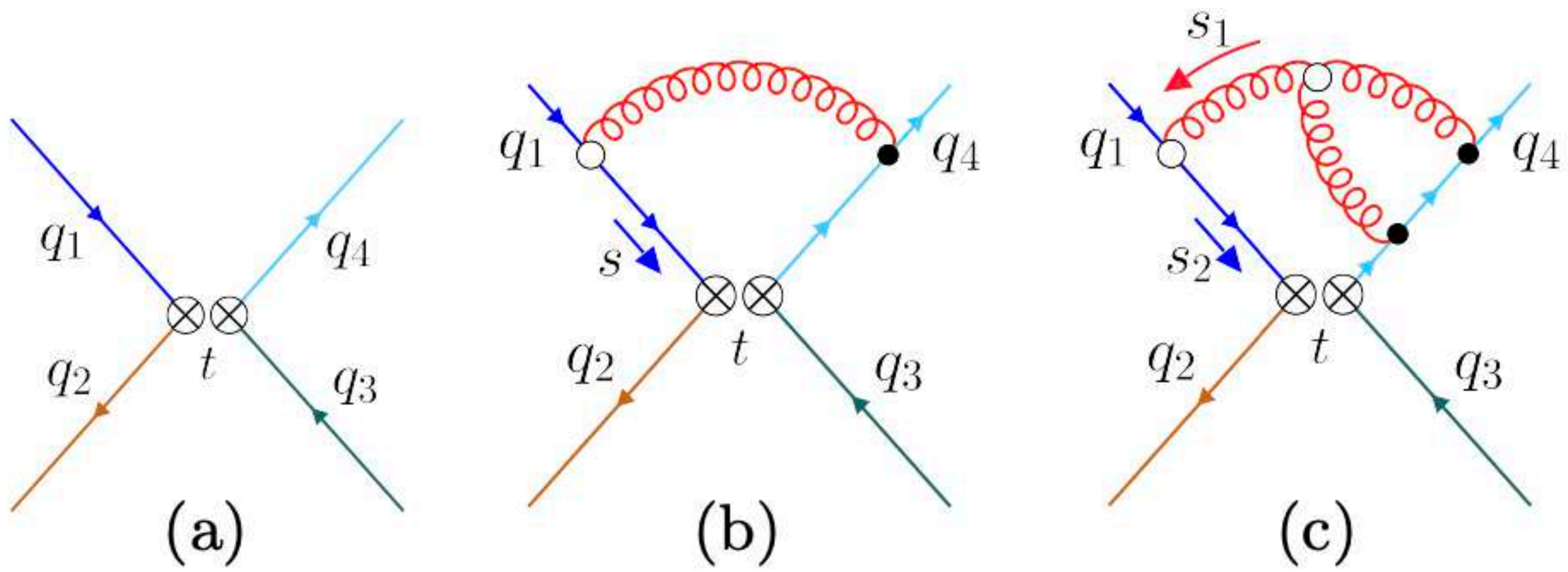
Previous work of the participating scientists:

- HQET sum rule: calculation of dimension six matrix elements $\langle \tilde{\mathcal{O}}_6 \rangle$ for B_d and D mixing and for lifetimes of B_d, B^+, D^0 and D^+mesons and of m_s corrections to describe B_s mixing and lifetimes and D_s^+ lifetimes

- Lattice: calculation of dimension six matrix elements $\langle \tilde{\mathcal{O}}_6 \rangle$ for B_s mixing within RBC-UKQCD



- Gradient flow: software framework for perturbative calculations in the gradient flow formalism / various applications / flowed coefficients of dimension-6 current-current operators



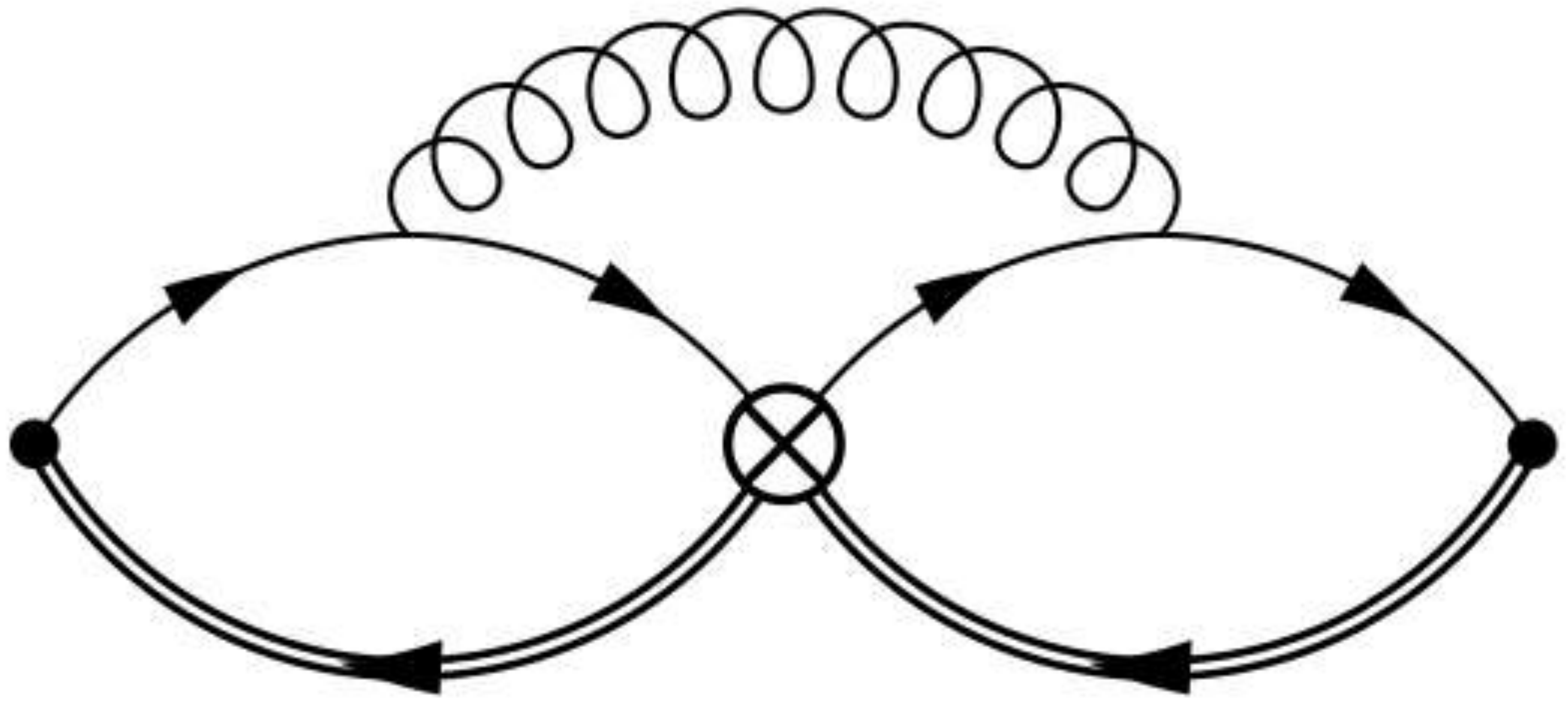
Project C1c - Work package 1:

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Sum rule determination of matrix elements of dimension-7 operators for mixing

We will calculate the perturbative three-loop correction to the three-point sum rules with an insertion of the dimension-7 four-quark $\Delta B = 2$ operators. This work proceeds analogously to the calculations performed in (Kirk, Lenz, Rauh, 2017) for dimension-6 operators. First the case of massless spectator quarks will be considered and then extended to massive spectator quarks by expanding in light quark masses, as done in (King, Lenz, Rauh, 2019).

$$
\begin{aligned}
R_1 &= \frac{m_s}{m_b}\, \bar{s}_\alpha (1+\gamma_5) b_\alpha \, \bar{s}_\beta (1-\gamma_5) b_\beta \\
R_2 &= \frac{1}{m_b^2}\, \bar{s}_\alpha \overleftarrow{D}_\rho \gamma^\mu (1-\gamma_5) D^\rho b_\alpha \, \bar{s}_\beta \gamma_\mu (1-\gamma_5) b_\beta \\
R_3 &= \frac{1}{m_b^2}\, \bar{s}_\alpha \overleftarrow{D}_\rho (1+\gamma_5) D^\rho b_\alpha \, \bar{s}_\beta (1+\gamma_5) b_\beta
\end{aligned}
$$



Project C1c - Work package 2:

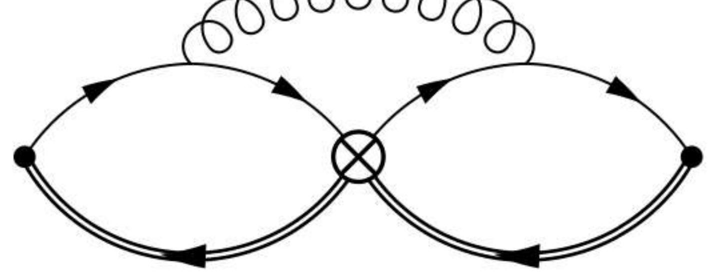
Sum rule determination of matrix elements of dimension-7 operators for lifetimes

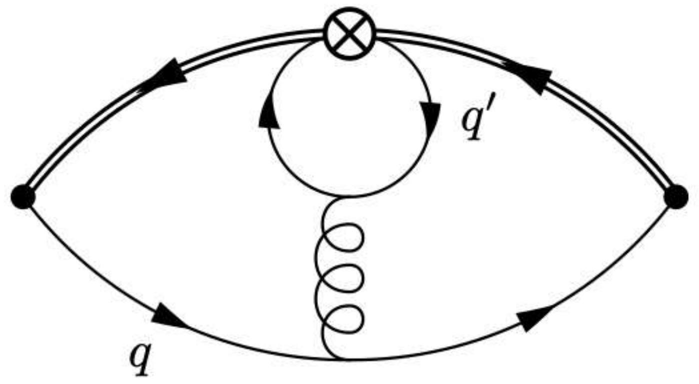
For the lifetimes we plan to calculate non-perturbative and perturbative three-loop corrections to the three-point sum rules with an insertion of the dimension-7 four-quark operators. Again, we will start with the massless spectator quark case and later also expand in light spectator quark masses, following the calculations performed for dimension-6 operators (Kirk, Lenz, Rauh, 2017) (King, Lenz, Rauh, 2022). In addition we will study the size of eye-contractions at dimension seven.

$$P_1^q = m_q\,(\bar{c}(1-\gamma_5)q)(\bar{q}(1-\gamma_5)c)\,,$$

$$P_2^q = \frac{1}{m_c}(\bar{c}\overleftarrow{D}_\nu\gamma_\mu(1-\gamma_5)D^\nu q)(\bar{q}\gamma^\mu(1-\gamma_5)c)\,,$$

$$P_3^q = \frac{1}{m_c}(\bar{c}\overleftarrow{D}_\nu(1-\gamma_5)D^\nu q)(\bar{q}(1+\gamma_5)c)\,,$$



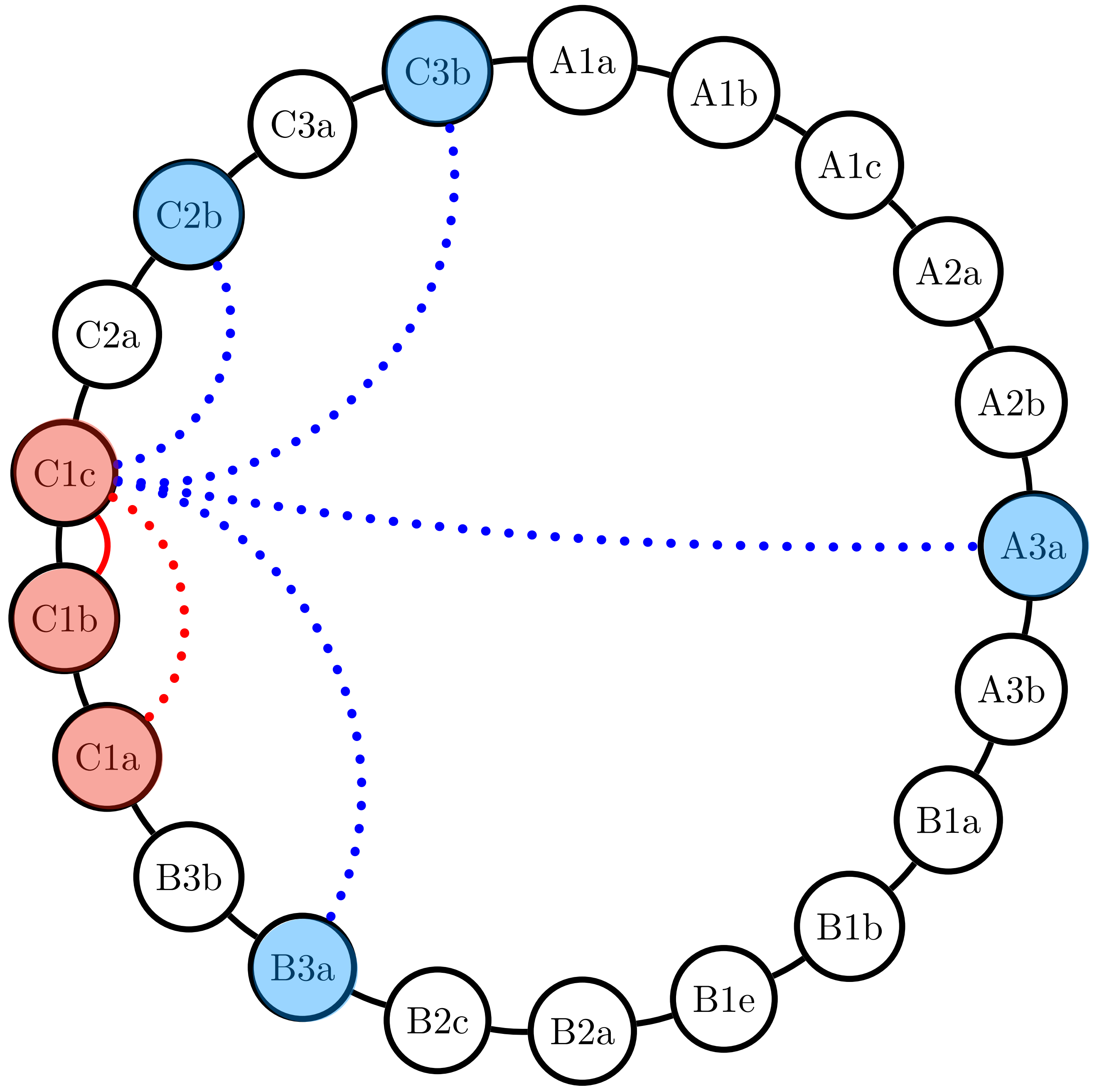


Project C1c - Overview 3:

References

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Role within the CRC



- C1b: perturbative Wilson coefficients
- C1a: Parameter of HQE
- A3a, B3a, C3b: BSM models
- C2b: constraints on BSM in non-leptonic decays

1. M. Beneke, G. Buchalla, C. Greub, **A. Lenz**, and **U. Nierste**
   Next-to-leading order QCD corrections to the lifetime difference of B_s mesons
   Phys. Lett. B, 459:631–640, 1999
2. L. Di Luzio, M. Kirk, **A. Lenz**, and T. Rauh
   ΔM_s theory precision confronts flavour anomalies
   JHEP, 12:009, 2019
3. **R. Harlander**, Y. Kluth, and **F. Lange**
   The two-loop energy–momentum tensor within the gradient-flow formalism
   Eur. Phys. J. C, 78(11):944, 2018
4. **R. Harlander** and **F. Lange**
   Effective electroweak Hamiltonian in the gradient-flow formalism
   Phys. Rev. D, 105(7):L071504, 2022
5. **R. Harlander**, **F. Lange**, and T. Neumann
   Hadronic vacuum polarization using gradient flow
   JHEP, 08:109, 2020
6. D. King, **A. Lenz**, and T. Rauh
   B_s mixing observables and $|V_{td}/V_{ts}|$ from sum rules
   JHEP, 05:034, 2019
7. D. King, **A. Lenz**, and T. Rauh
   $SU(3)$ breaking effects in B and D meson lifetimes
   JHEP, 06:134, 2022
8. M. Kirk, **A. Lenz**, and T. Rauh
   Dimension-six matrix elements for meson mixing and lifetimes from sum rules
   JHEP, 12:068, 2017
9. A. Hasenfratz, C.J. Monahan, M.D. Rizik, A. Shindler, and **O. Witzel**
   A novel nonperturbative renormalisation scheme for local operators
   Proceedings of the 38th International Symposium on Lattice Field Theory,
   arXiv:2201.09740
10. P.A. Boyle, L. Del Debbio, N. Garron, A. Juttner, A. Soni, J.T. Tsang, and **O. Witzel**
    $SU(3)$-breaking ratios for $D_{(s)}$ and $B_{(s)}$ mesons
    arXiv:1812.08791