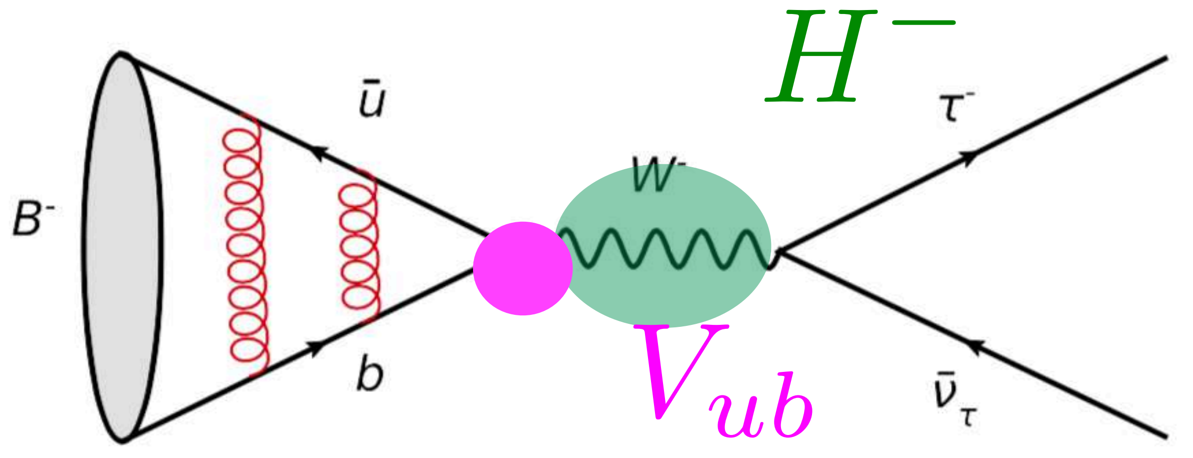
The Outlook for Hadronic Calculations

Beyond the Flavour Anomalies

28.4.2022
Alexander Lenz

Hadronic difficulty of Meson Decays

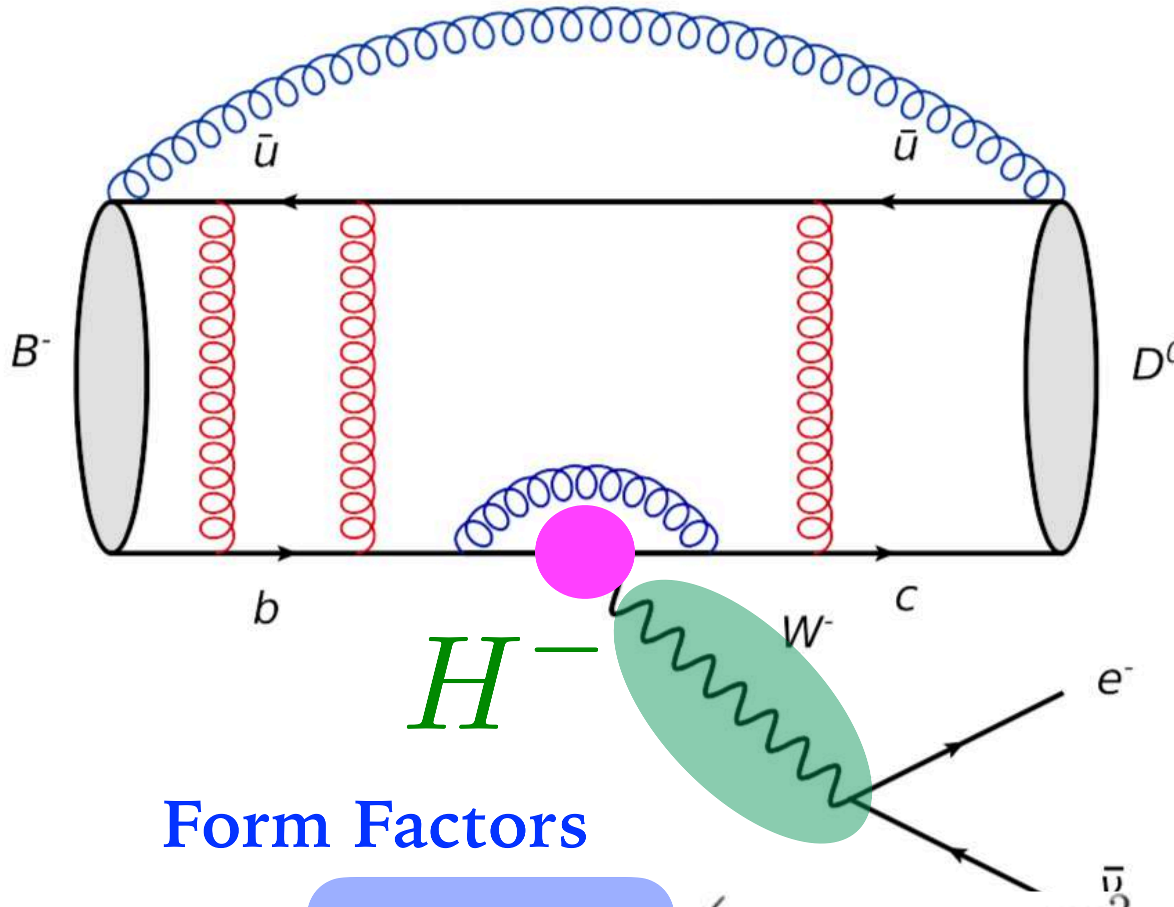
- Leptonic Decays



Decay constant

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

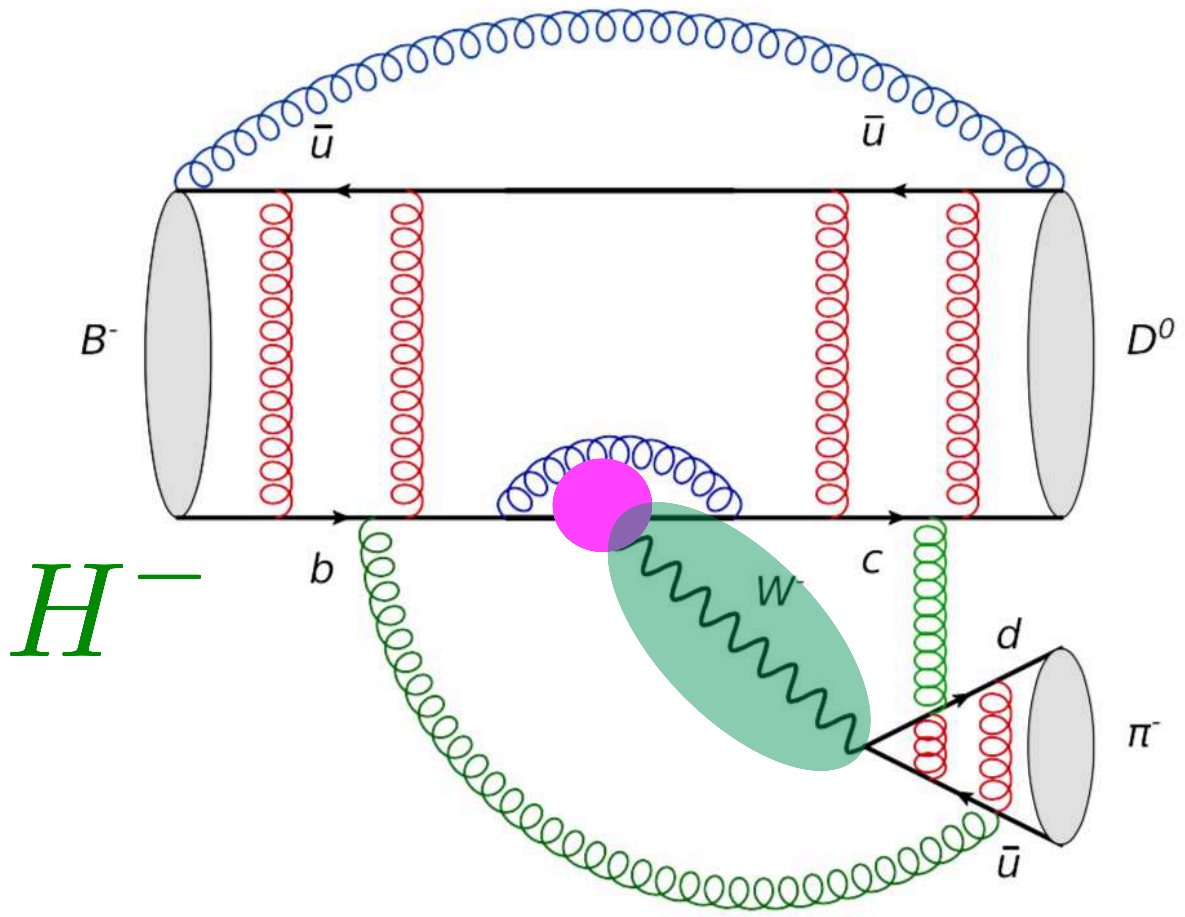
- Semileptonic Decays



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

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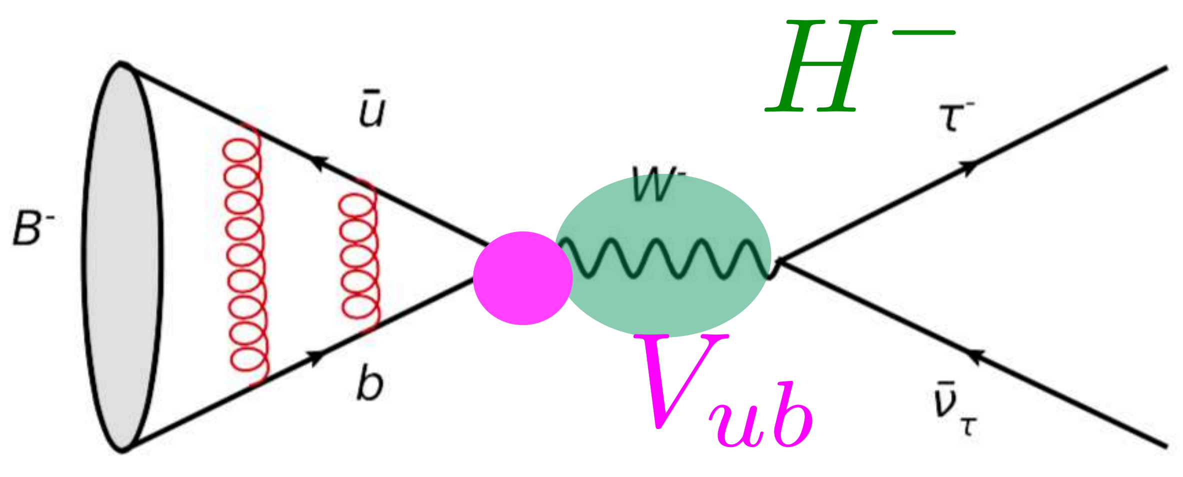

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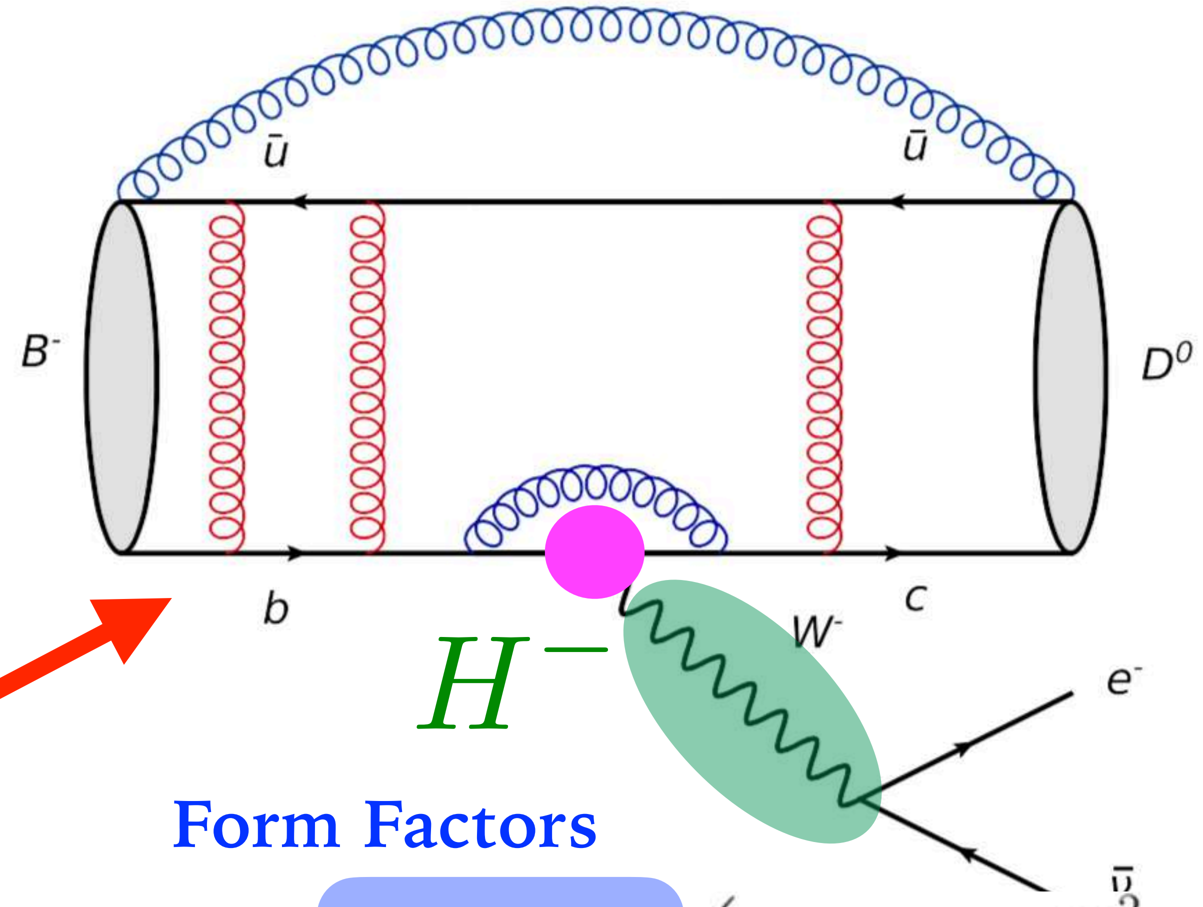

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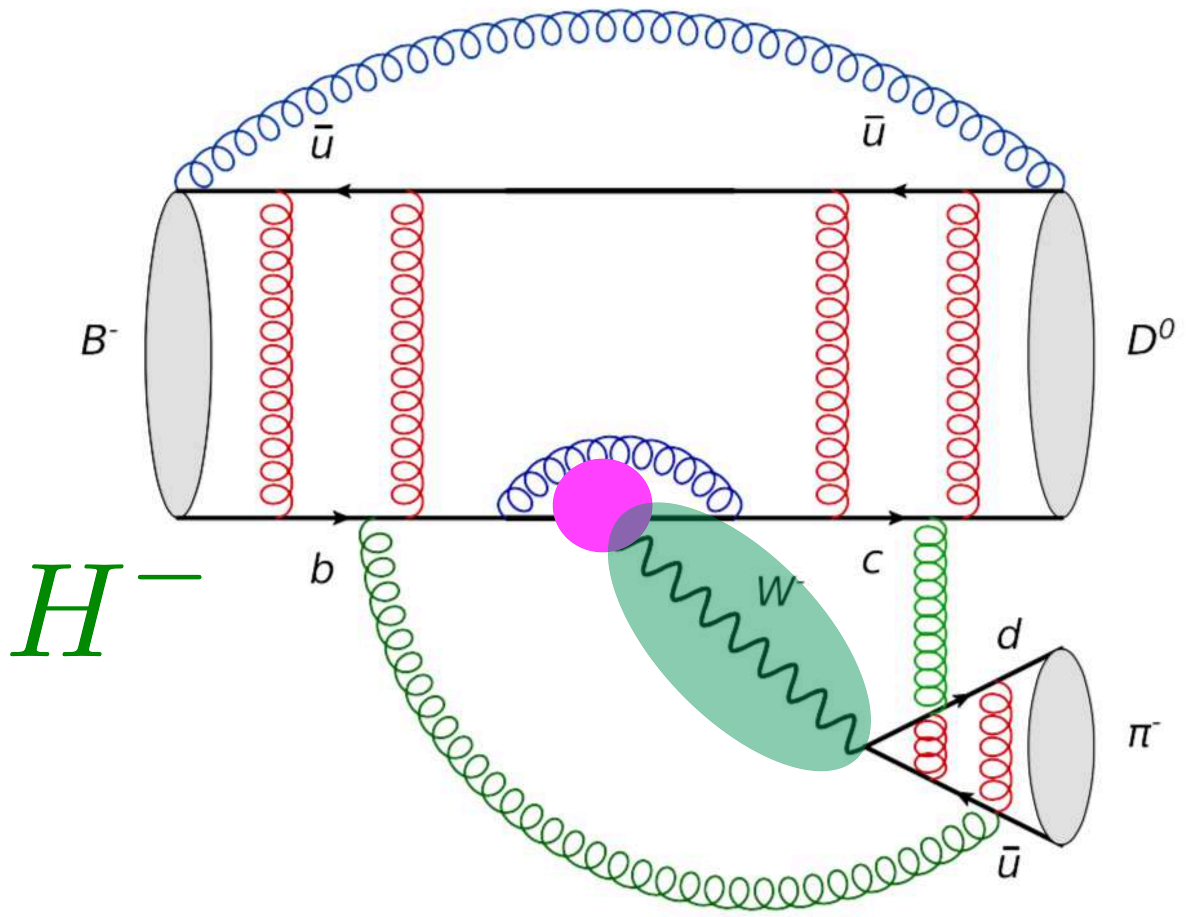

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Ancient B anomalies
Tree: V_{ub}, V_{cb}

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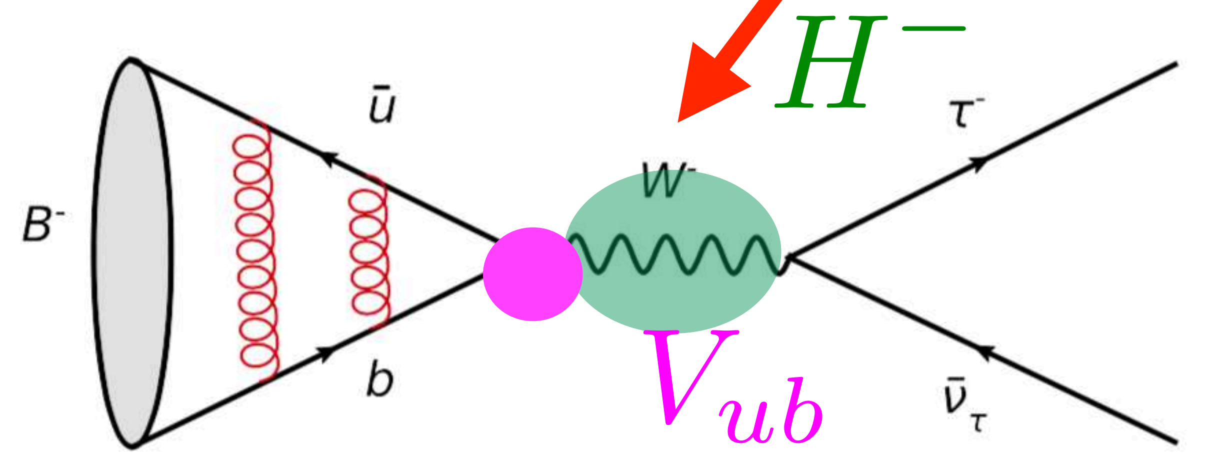
Hadronic difficulty of Meson Decays

$b \to sll$ **anomalies**
Loop

- Leptonic Decays
- Semileptonic Decays
- Non-leptonic Decays



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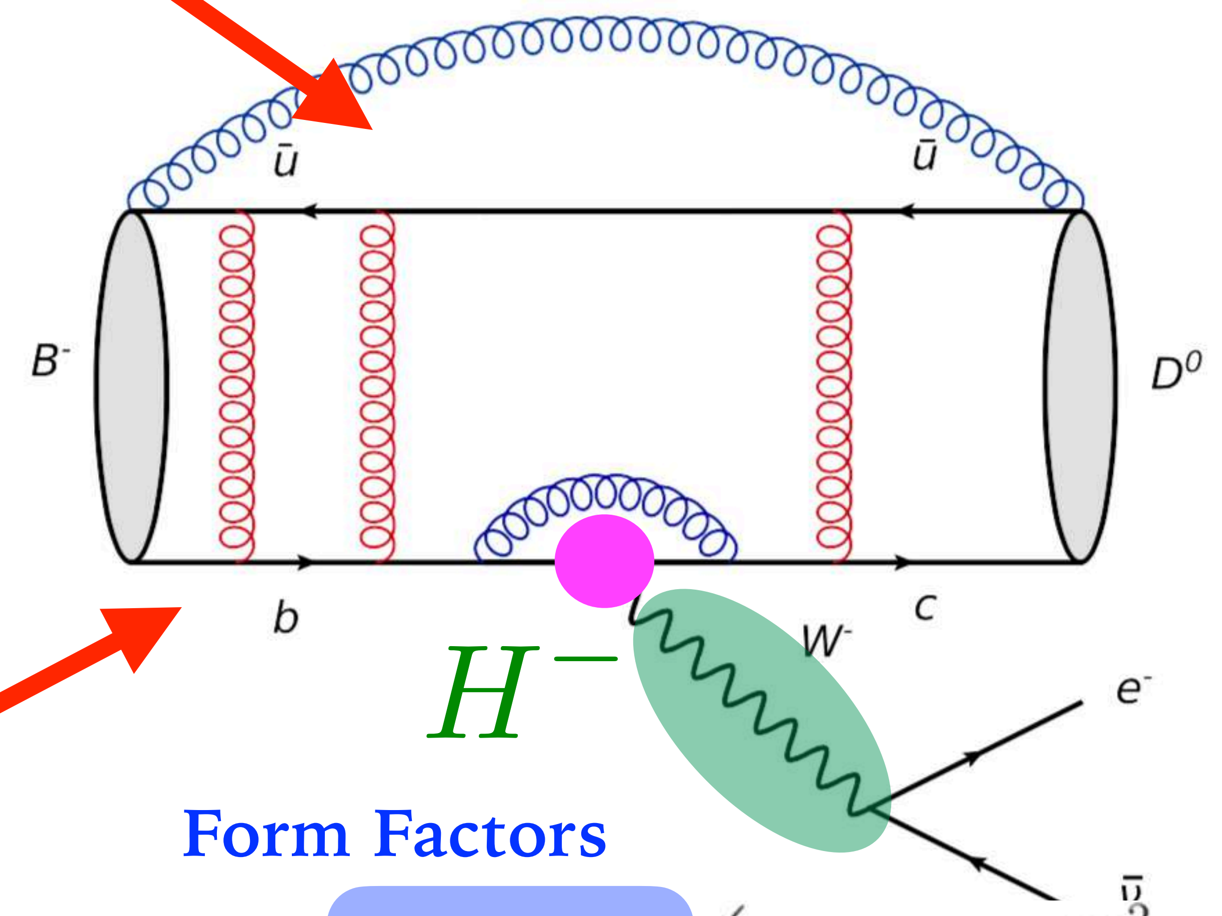

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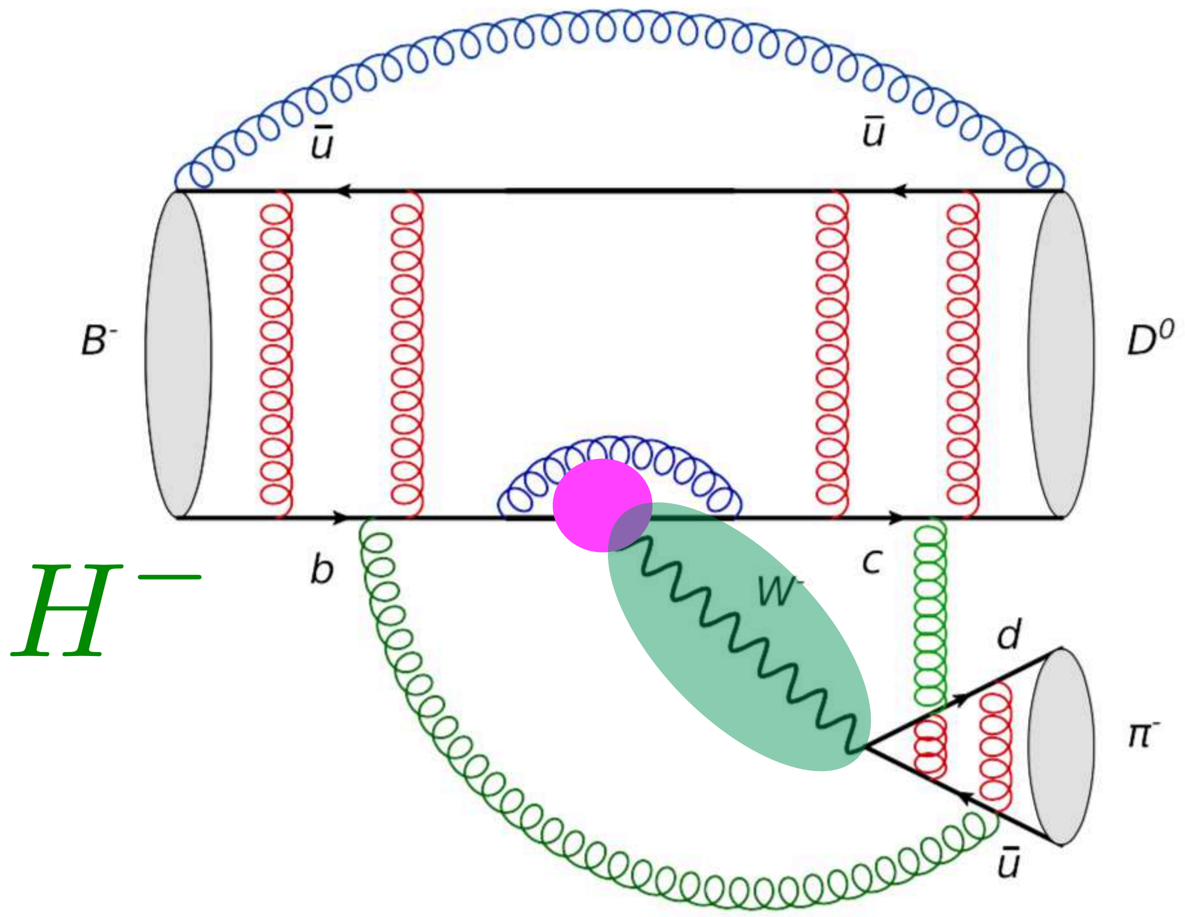

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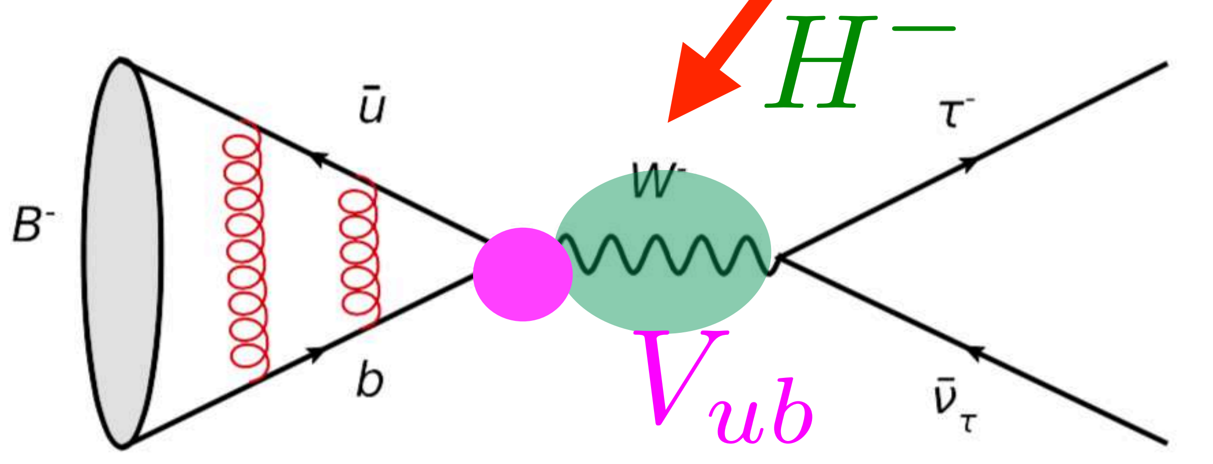

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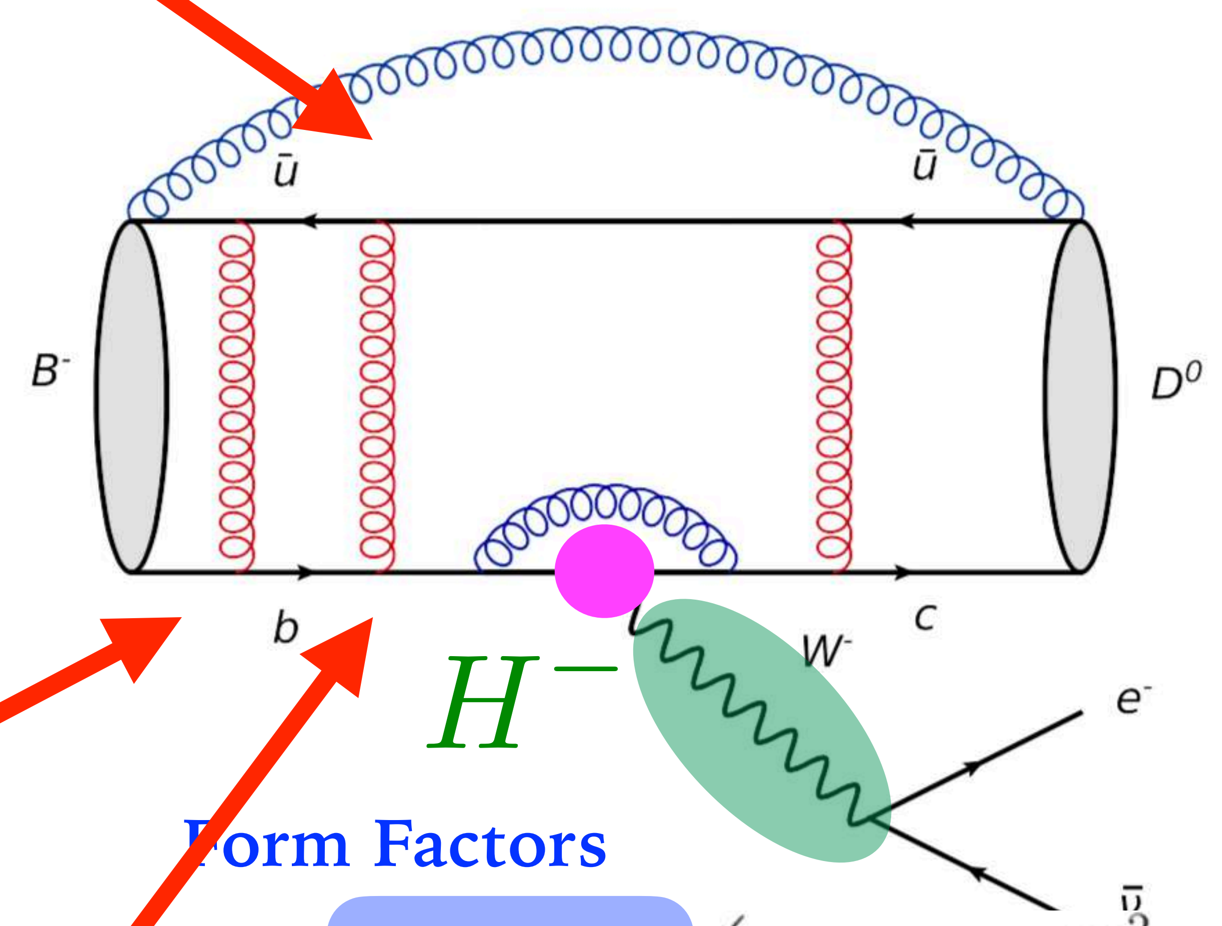

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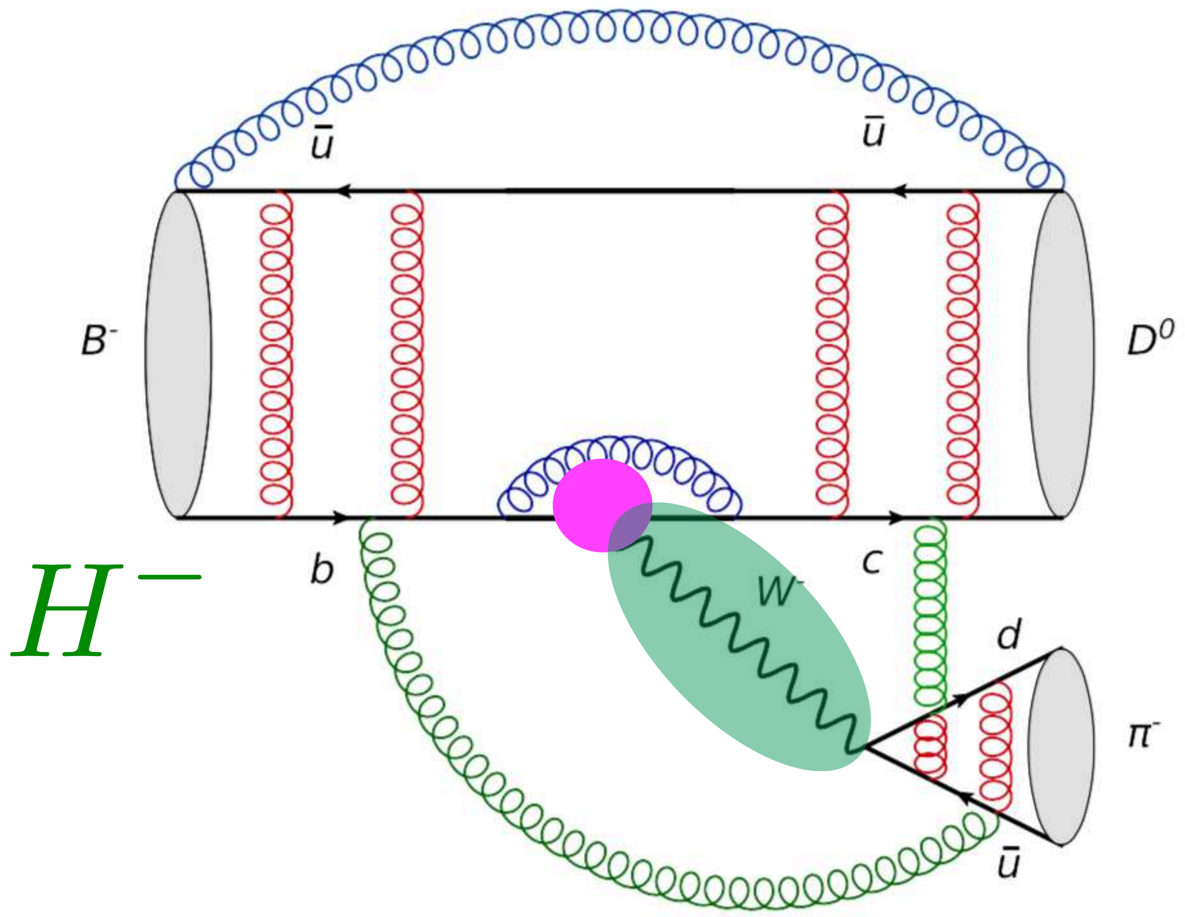

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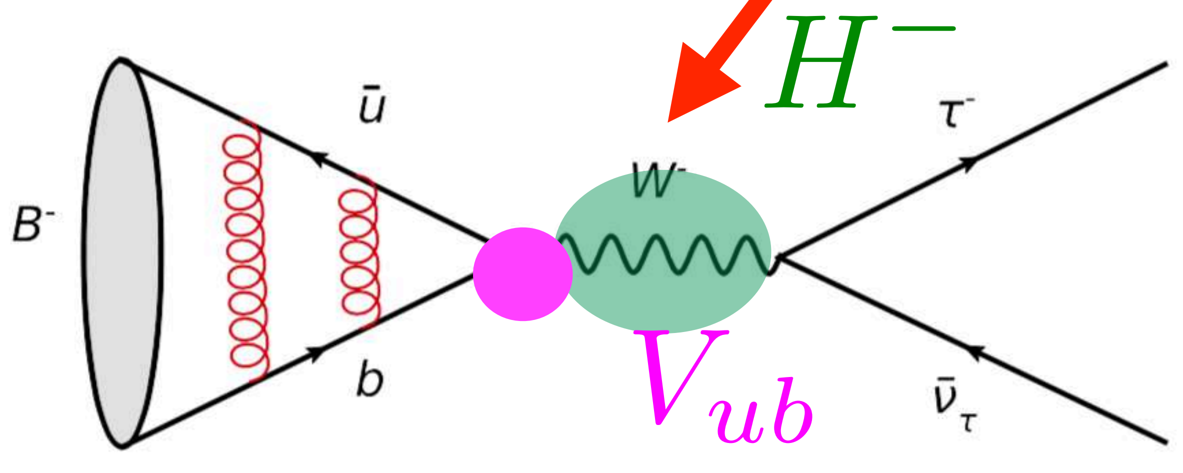

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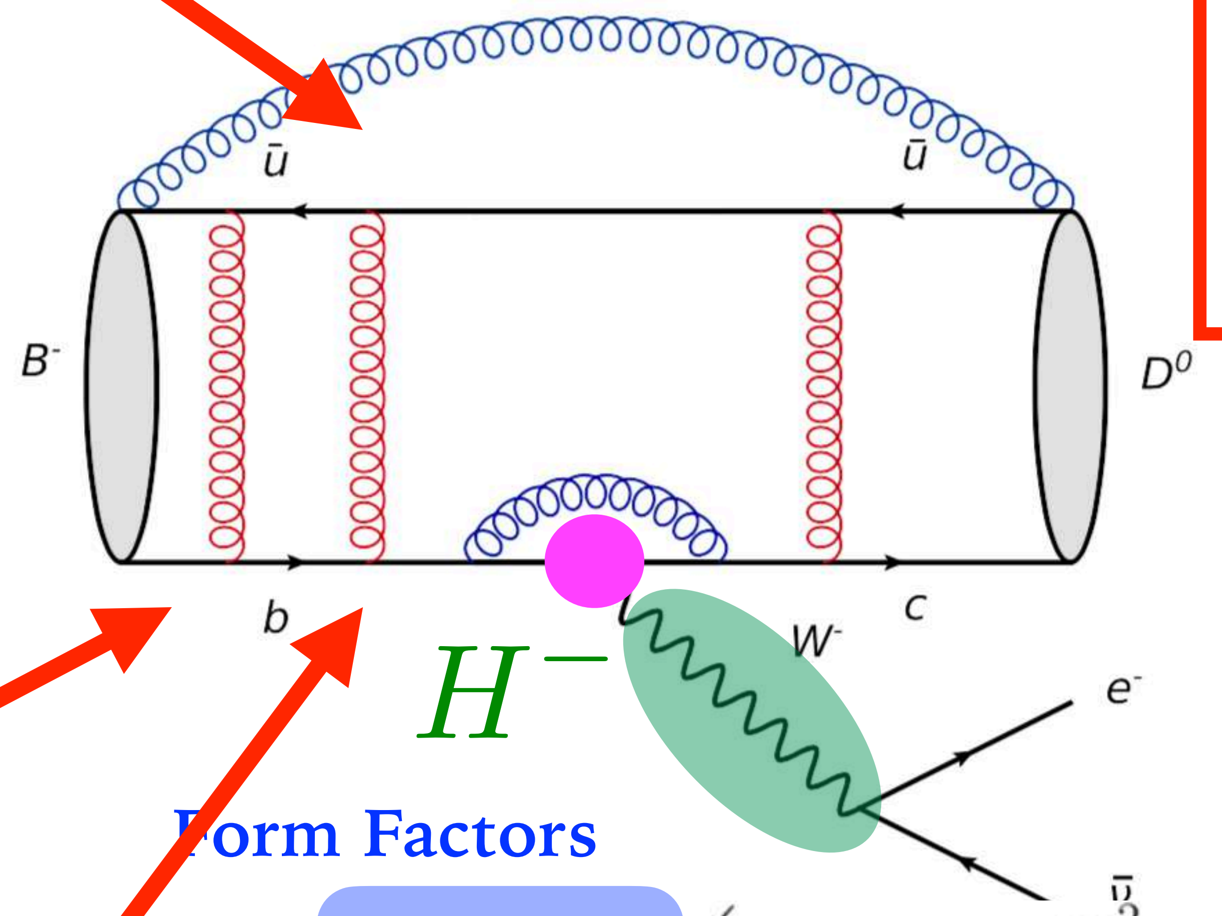

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New B anomalies?
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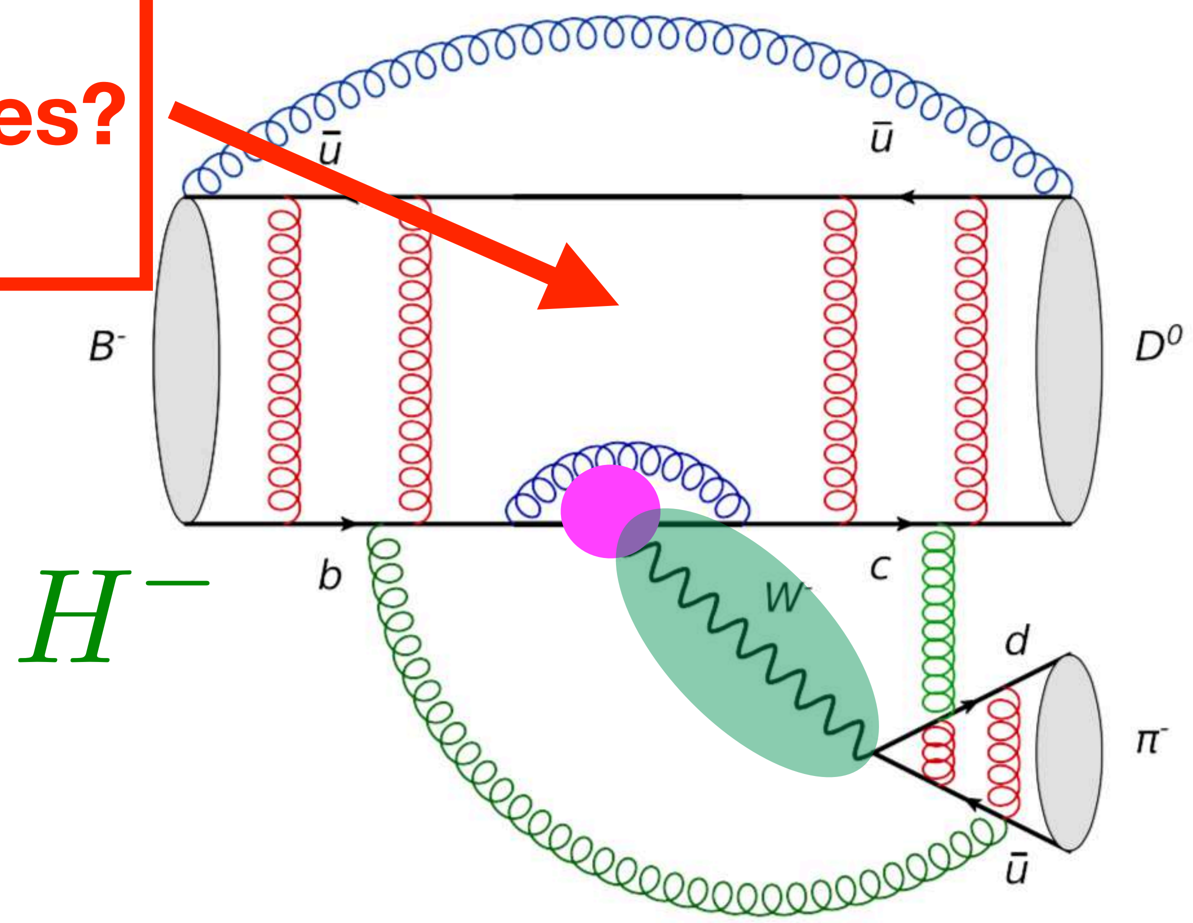

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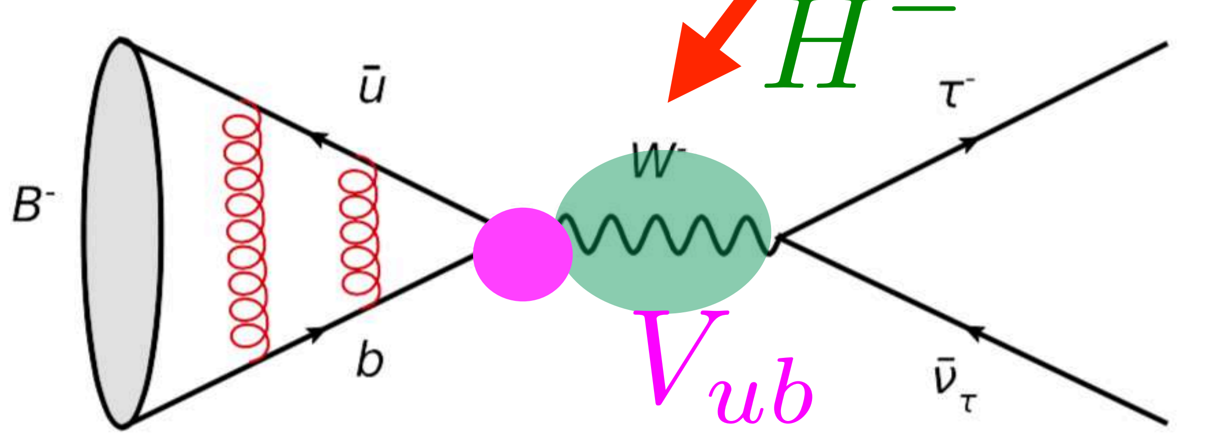

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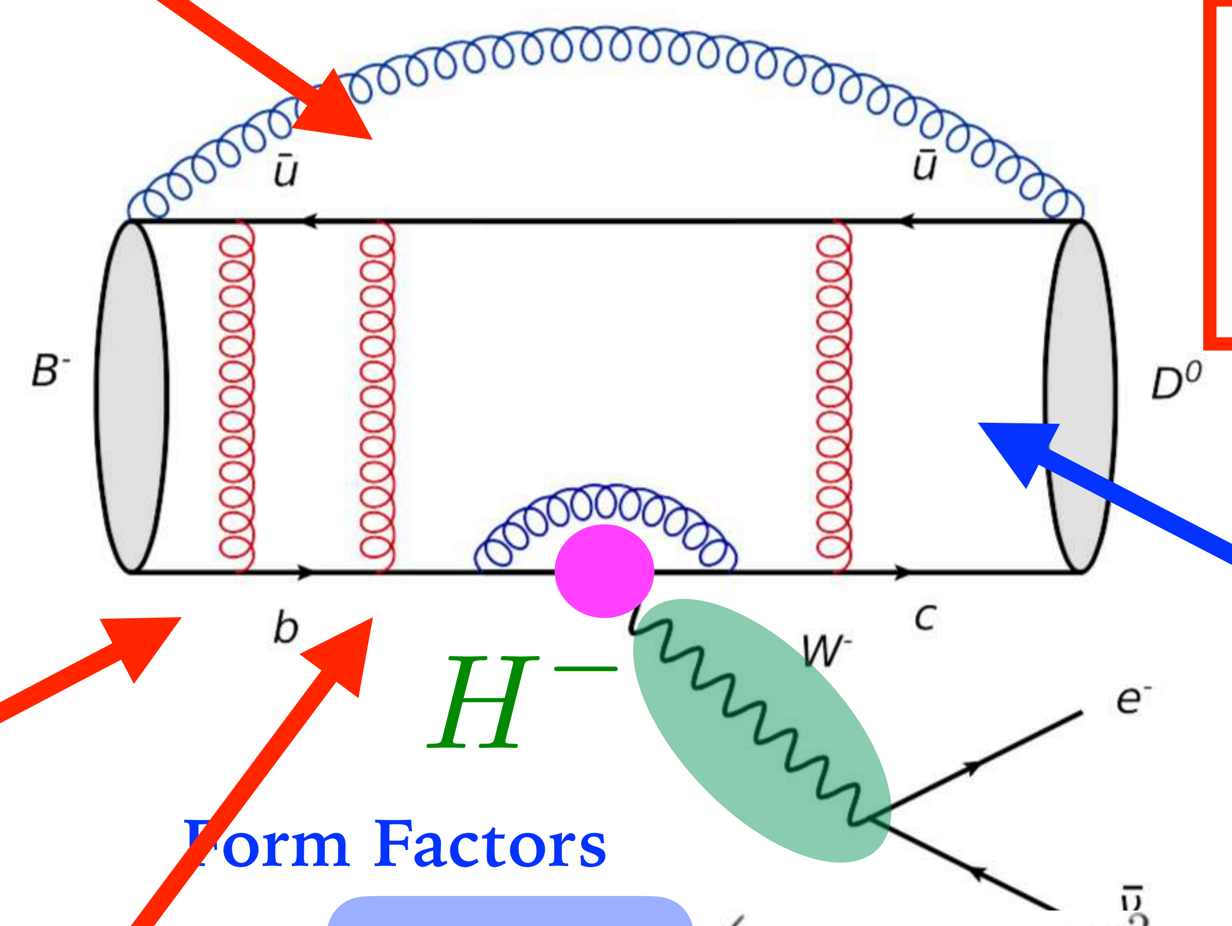

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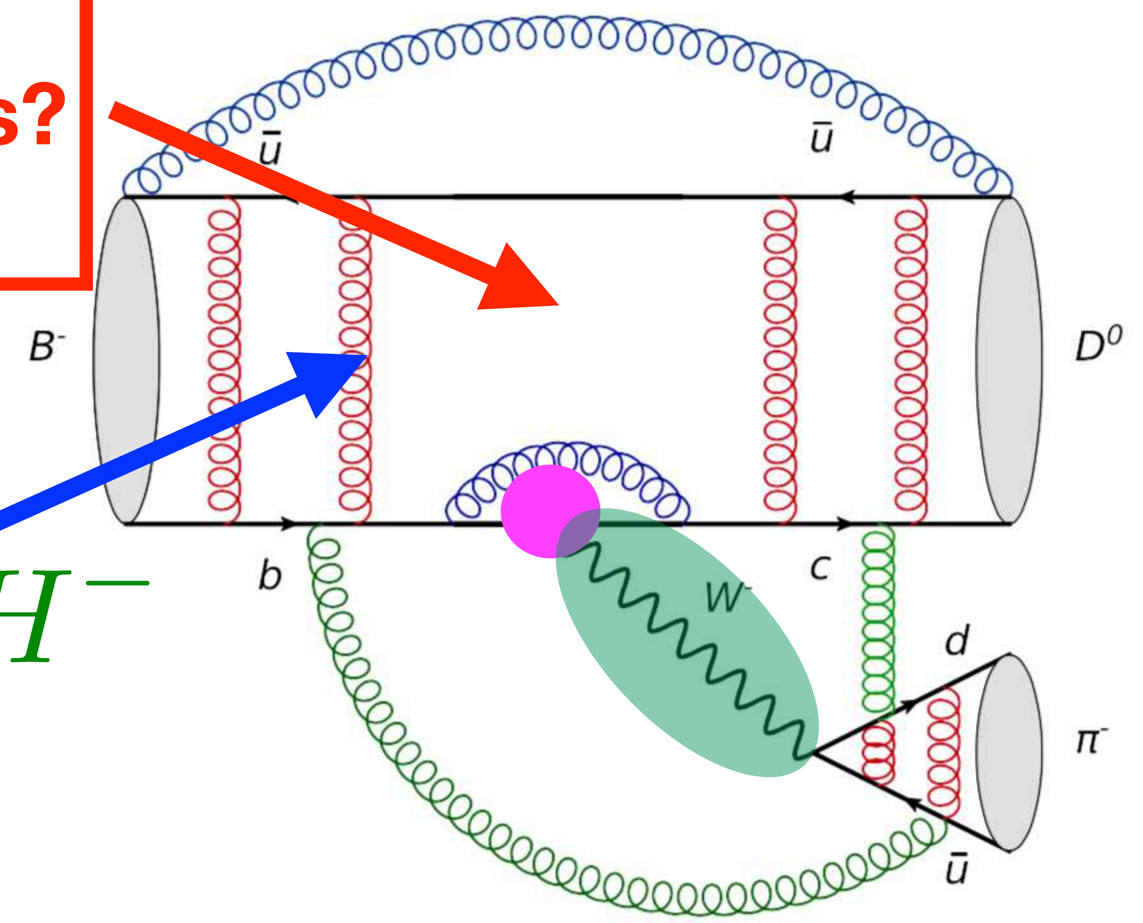

QCDf

Factorisation

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Ancient Anomalies

Beyond the Flavour Anomalies

V_{cb}: inclusive vs. exclusive

$$|V_{cb}|^{\text{incl.},2022} = (42.16 \pm 0.51) \cdot 10^{-3}$$

Bordone, Caddevilla, Gambino 2107.00604

Based on NNNLO-QCD!!!

Fael, Schönwald, Steinhauser 2011.13654

$$|V_{cb}|^{\text{excl.,PDG}} = (39.5 \pm 0.9) \cdot 10^{-3}\,.$$

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$$|V_{cb}|^{\text{excl.,PDG}} = (39.5 \pm 0.9) \cdot 10^{-3} \,.$$

$$|V_{cb}|^{\text{excl.}} = \begin{cases} (38.40 \pm 0.74) \cdot 10^{-3} & \text{FNAL/MILC} & B \to D^* \ell \nu \,, \\ (40.3 \pm 0.8) \cdot 10^{-3} & \text{LCSR2 and lattice} & B \to D^{(*)} \ell \nu \,, \\ (40.3 \pm 1.7) \cdot 10^{-3} & \text{LCSR1, BaBar} & B \to D \ell \nu \,, \\ (41.0 \pm 1.3) \cdot 10^{-3} & \text{LCSR1, Belle} & B \to D \ell \nu \,, \\ (41.0 \pm 1.2) \cdot 10^{-3} & \text{lattice + unitarity} & B \to D \ell \nu \,, \\ (42.2 \pm 2.3) \cdot 10^{-3} & \text{HPQCD} & B_s \to D_s^* \ell \nu \,. \end{cases}$$

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Study quark mass definitions

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Improved form factors

Ancient Anomalies

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Based on NNNLO-QCD!!!

Fael, Schönwald, Steinhauser 2011.13654

$$\Delta M_s^{\text{SM}} = 18.3^{+0.7}_{-1.2}\,\text{ps}^{-1}$$

$$\Delta M_s^{\text{SM}} = 16.0^{+0.6}_{-1.0}\,\text{ps}^{-1}$$

Perfect match

around 3σ deviation

$$\Delta M_s^{\text{Exp}} = 17.741(20)\,\text{ps}^{-1}$$

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Ancient Anomalies

Beyond the Flavour Anomalies

The D0 dimuon anomaly is still not settled: 3.6σ

The New York Times

A New Clue to Explain Existence

By DENNIS OVERBYE MAY 17, 2010

Physicists at the Fermi National Accelerator Laboratory are reporting that they have discovered a new clue that could help unravel one of the biggest mysteries of cosmology: why the universe is composed of matter and not its evil-twin opposite, antimatter. If confirmed, the finding portends fundamental discoveries at the new Large Hadron Collider outside Geneva, as well as a possible explanation for our own existence.

$$A^{\mathrm{Di-muon}} = C_s a_{sl}^s + C_d a_{sl}^d + \frac{1}{2} C_\Delta \Delta\Gamma_d$$

Experiment disagrees with the Standard Model predictions by 4 σ

Evidence for an anomalous like-sign dimuon charge asymmetry
V.M.Abazov et al (D0 Collaboration)
Phys. Rev. Lett 105 (2010) 081801

Measurement of the anomalous like-sign dimuon charge asymmetry
V.M.Abazov et al (D0 Collaboration)
Phys. Rev. D 84 (2011) 052007

Study of CP violating charge asymmetry…
V.M.Abazov et al (D0 Collaboration)
Phys. Rev. D 89 (2014) 012002

Theoretical update of Bs mixing
Alexander Lenz, Uli Nierste
JHEP 0706(2007)072; hep-ph/0612167

Numerical update of lifetimes and mixing parameters
Alexander Lenz, Uli Nierste
hep-ph/1102.4274

CP violation in the Bs system
Marina Artuso, Guennadi Borissov, Alexander Lenz
Rev.Mod.Phys. 88 (2016) no.4,045002

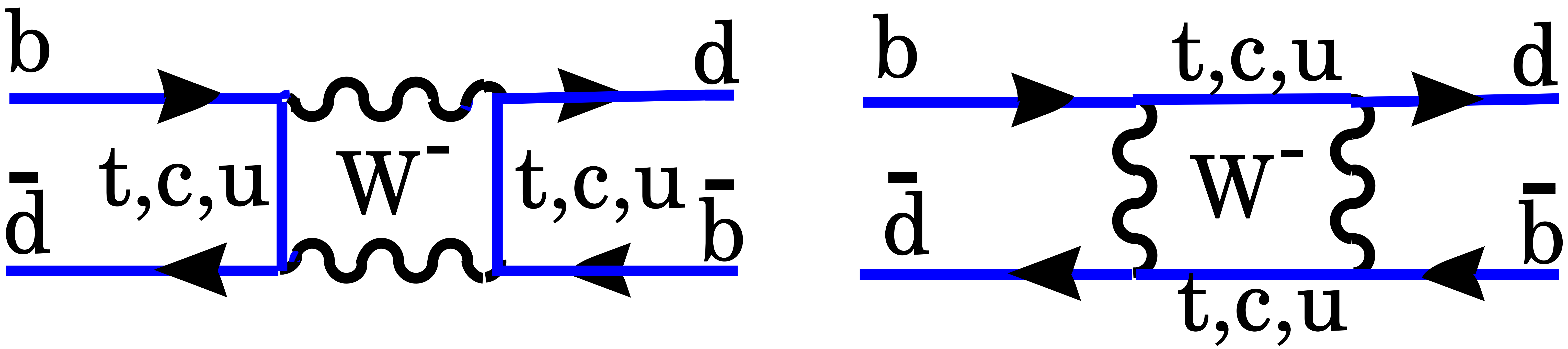
New interpretation of experimental measurement

Understanding the anomalous like-sign dimuon charge asymmetry
Guennadi Borissov, Boris Hoeneisen
Phys. Rev. D 87 (2013) 074020

Effect of Delta Gamma_d on the dimoun asymmetry
Uli Nierste
Talk at CKM 2014

Mixing

$$|B_{q,L}\rangle = p|B_q\rangle + q|\bar{B}_q\rangle$$
$$|B_{q,H}\rangle = p|B_q\rangle - q|\bar{B}_q\rangle$$



$|M_{12}|$, $|\Gamma_{12}|$ and $\phi = \arg(-M_{12}/\Gamma_{12})$ can be related to three observables:

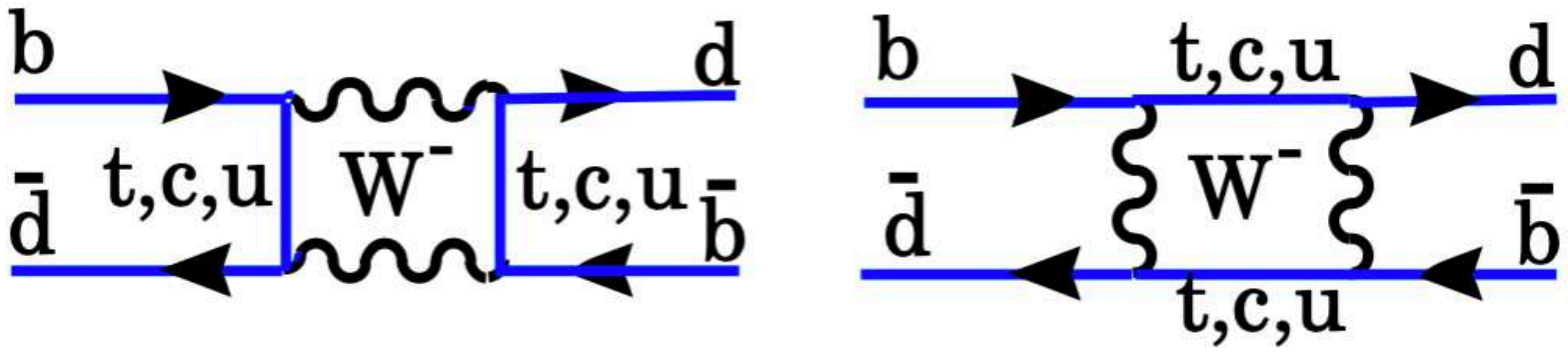
- **Mass difference:** $\Delta M := M_H - M_L \approx 2|M_{12}|$ **(off-shell)**
  $|M_{12}|$: heavy internal particles: t, SUSY, ...
- **Decay rate difference:** $\Delta\Gamma := \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi$ **(on-shell)**
  $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!
- **Flavor specific/semi-leptonic CP asymmetries:** e.g. $B_q \to X l \nu$ (*semi-leptonic*)

$$a_{sl} \equiv a_{fs} = \frac{\Gamma(\overline{B}_q(t) \to f) - \Gamma(B_q(t) \to \overline{f})}{\Gamma(\overline{B}_q(t) \to f) + \Gamma(B_q(t) \to \overline{f})} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi$$

Status Quo: Mixing

Beyond the Flavour Anomalies

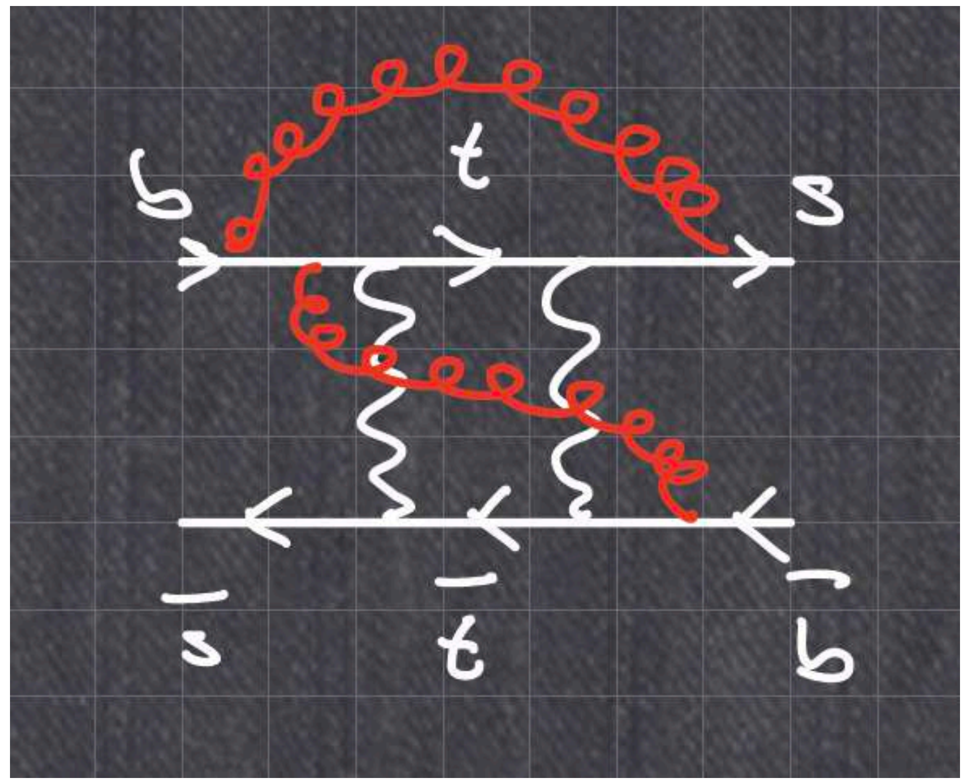
$$\Delta M_s = 2\,|M_{12}^s|$$



$$M_{12}^q = \frac{G_F^2}{12\pi^2}\lambda_t^2 M_W^2 S_0(x_t) B f_{B_q}^2 M_{B_q} \hat{\eta}_B\,,$$

Significant CKM dependence

By far dominant uncertainty

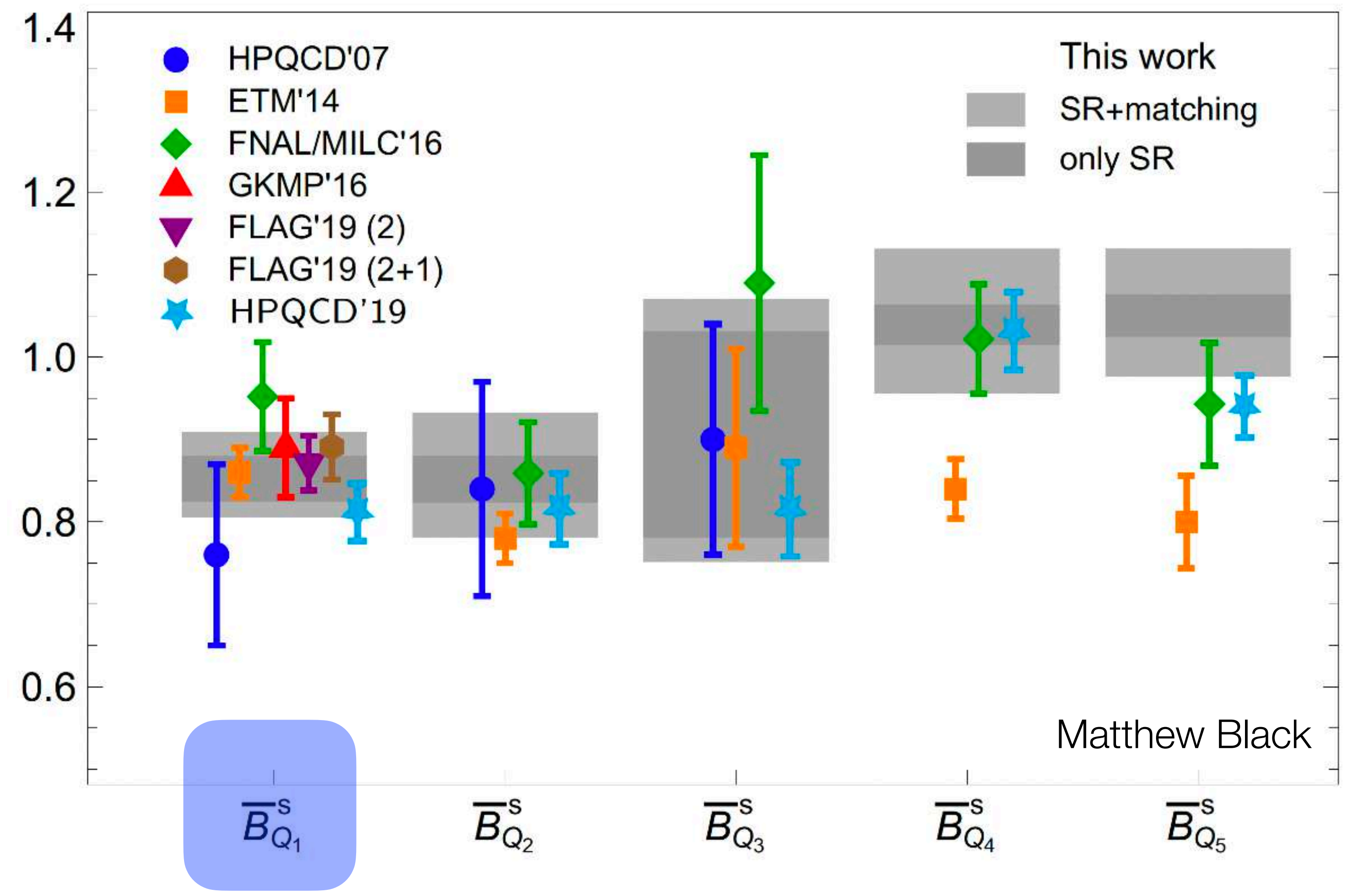


2-loop: Buras, Jamin, Weisz

3-loop: Gorbahn,...

$$Q = \bar{s}^\alpha \gamma_\mu (1-\gamma_5) b^\alpha \times \bar{s}^\beta \gamma^\mu (1-\gamma_5) b^\beta$$

$$\langle Q \rangle \equiv \langle B_s^0 | Q | \bar{B}_s^0 \rangle = \frac{8}{3} M_{B_s}^2 f_{B_s}^2 B(\mu)$$



Lattice

- B_s, B_d and D mixing: FNAL/MILC 1602.03560
- Ratio of B_s and B_d mixing: RBC/UK QCD 1812.08791
- B_s and B_d mixing: HQPCD 19007.01025

HQET-sum rules: 3-loop + part of NNLO matching:

*B_d mixing:
Siegen: Grozin, Klein, Mannel, Pivovarov 1606.06054, 1706.05910, 1806.00253

*B_d and D mixing, D^0, D^+, B_d and B^+ lifetimes
Durham: Kirk (Rome), AL, Rauh (Bern) 1711.02100

*B_s mixing
Durham: King, AL, Rauh (Bern) 1904.00940

*B_s and D_s^+ lifetimes
Siegen: King (Durham), AL, Rauh (Bern) 2112.03691

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Status Quo: Mixing

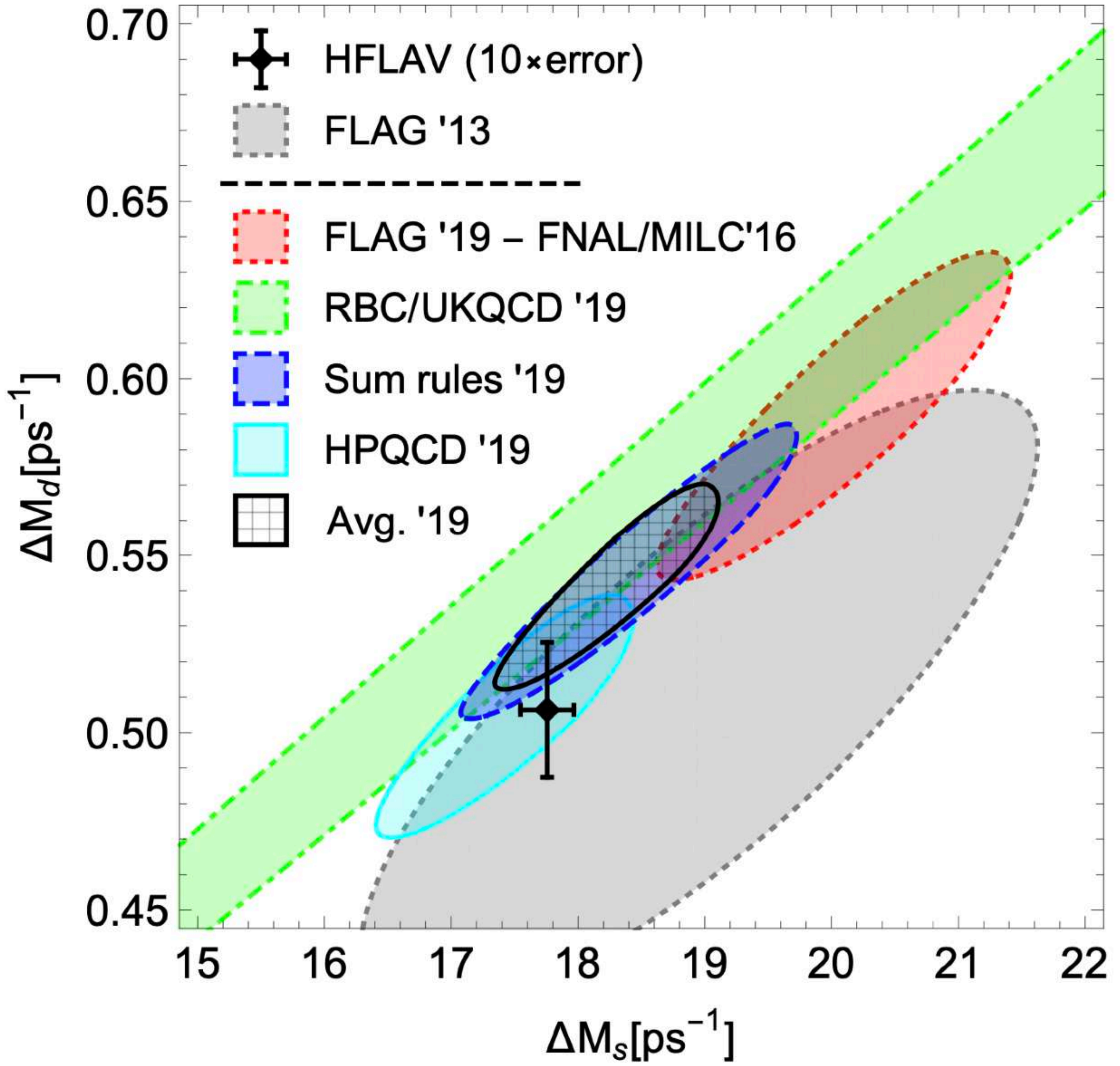
Beyond the Flavour Anomalies

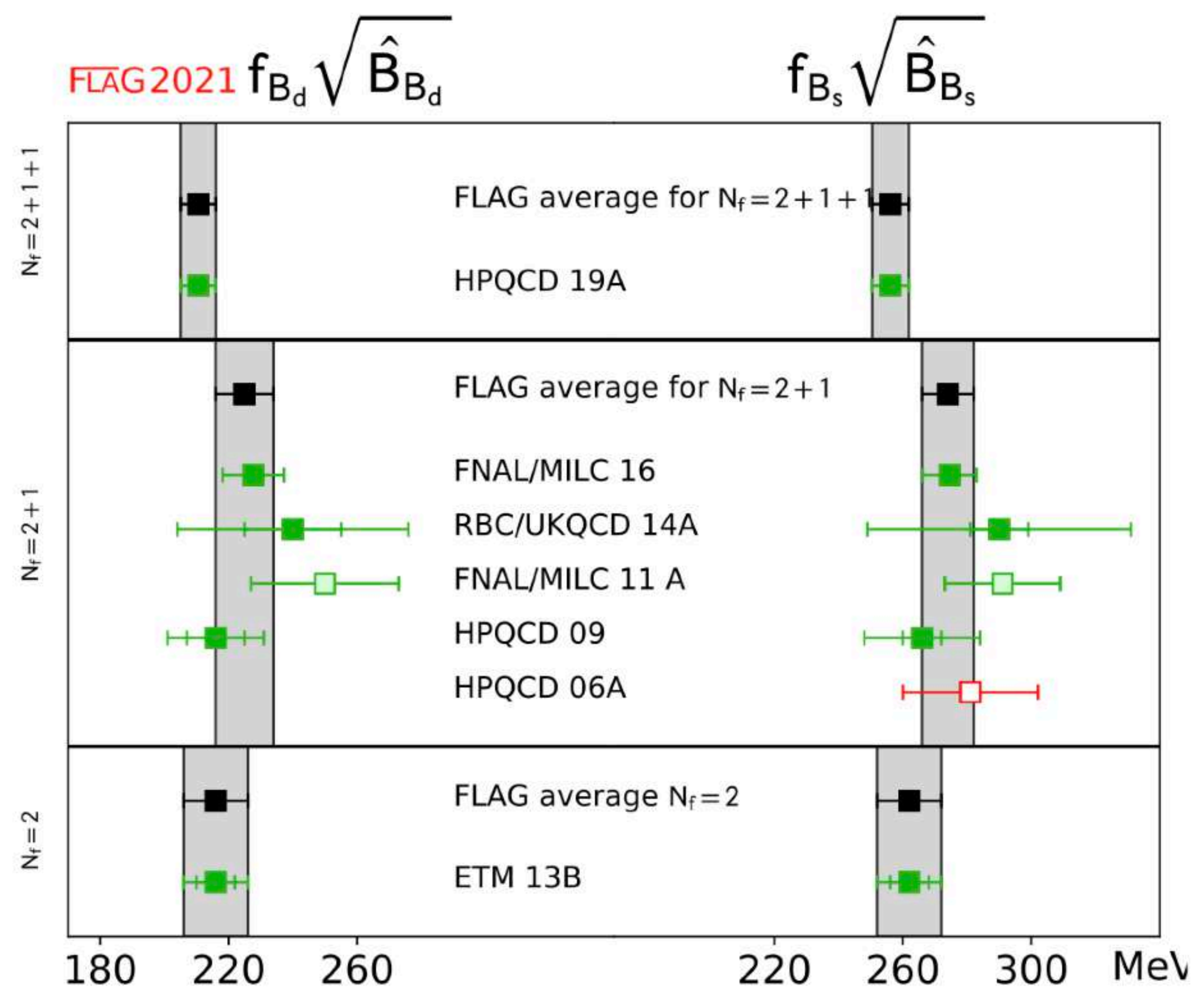
$$\Delta M_d = (0.5065 \pm 0.0019)\,\mathrm{ps}^{-1} \qquad \Delta M_d = \left(0.533^{+0.022}_{-0.036}\right)\,\mathrm{ps}^{-1}$$

$$\Delta M_s = (17.741 \pm 0.020)\,\mathrm{ps}^{-1} \qquad \Delta M_s = \left(18.4^{+0.7}_{-1.2}\right)\,\mathrm{ps}^{-1}$$

HFLAV 2021

1909.11087
Average lattice & sum rules





Work in progress by
RBC/UKQCD+JLQCD 2111.11287

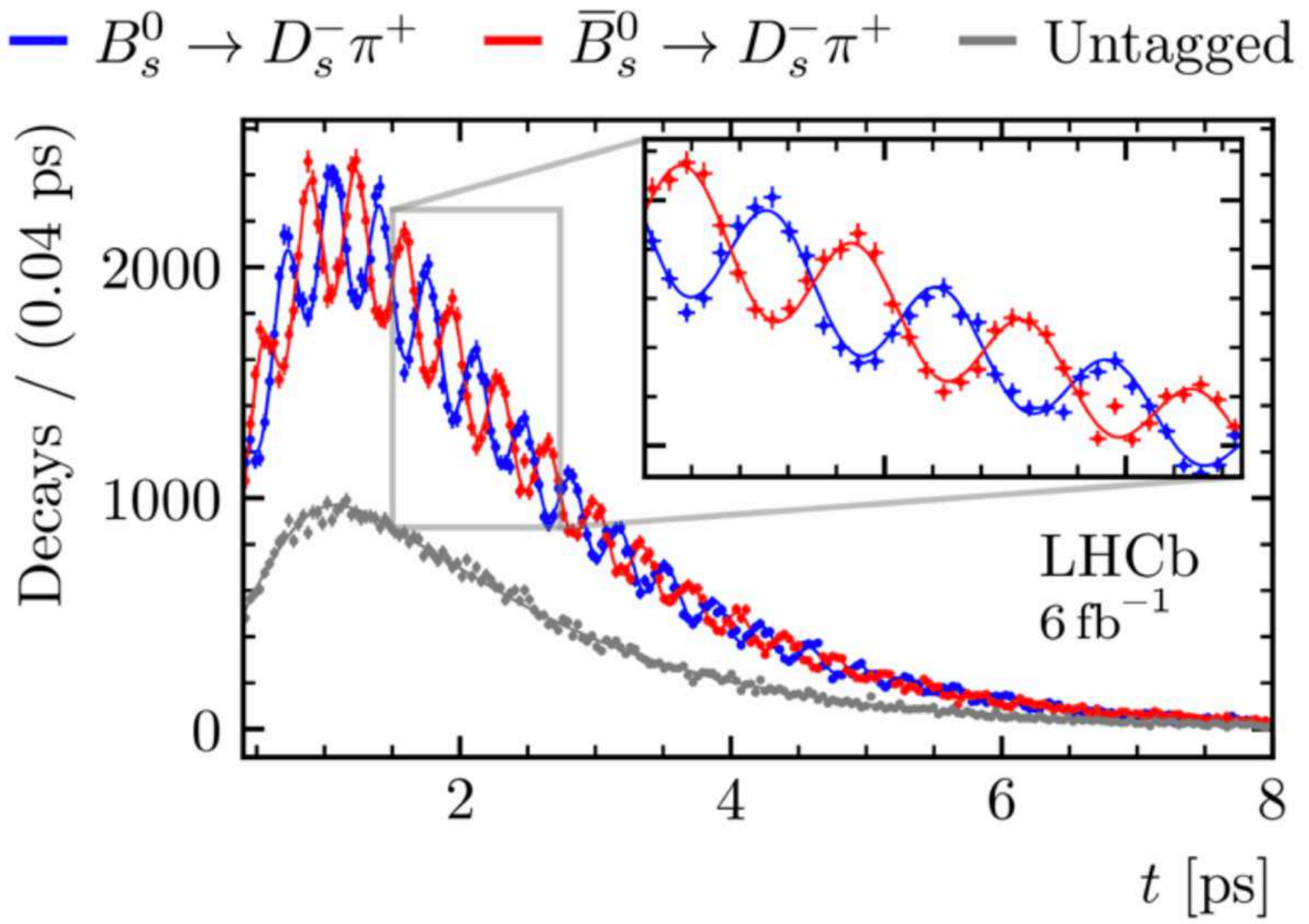
http://lhcb-public.web.cern.ch

12 April 2021: Fascinating quantum mechanics.

Precise determination of the $B_s^0-\bar{B}_s^0$ oscillation frequency.

"A phenomenon in which quantum mechanics gives a most remarkable prediction" - Richard Feynman

Today, the LHCb Collaboration submitted a paper for publication that reports a precise determination of the $B_s^0-\bar{B}_s^0$ oscillation frequency. This result is presented also today at the joint annual conference of the UK Institute of Physics (IOP), organized by the University of Edinburgh. The $B_s^0-\bar{B}_s^0$ oscillation is a spectacular and fascinating feature of quantum mechanics. The strange beauty particle B^0_s composed of a beauty antiquark ($\bar{b}$) bound with a strange quark s turns into its antiparticle partner $\bar{B}_s^0$ composed of a b quark and an s antiquark ($\bar{s}$) about 3 million million times per second ($3*10^{12}$) as seen in the image below.



Higher precision for Bag

Status Quo: Mixing

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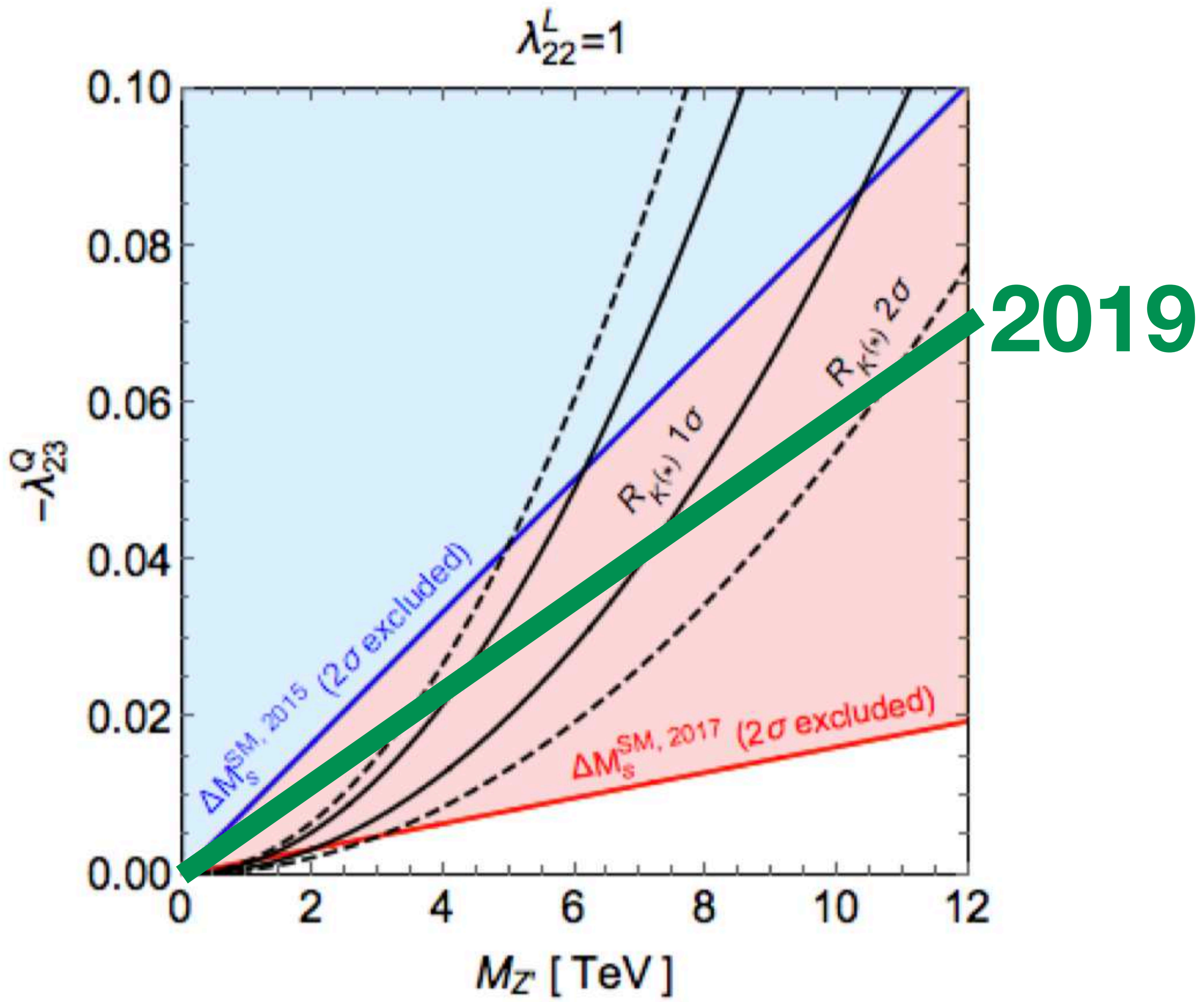
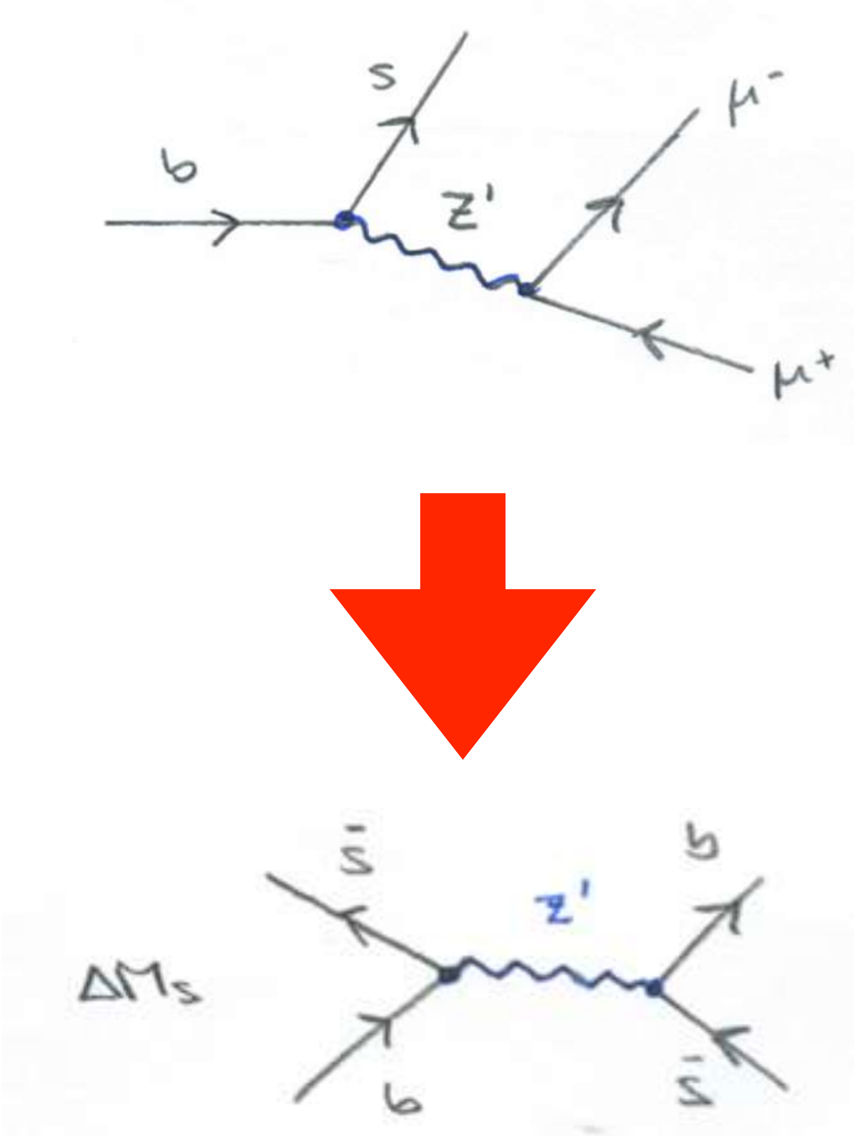
The 2016 theory value for B-mixing has dramatic consequences for BSM models explaining the B anomalies





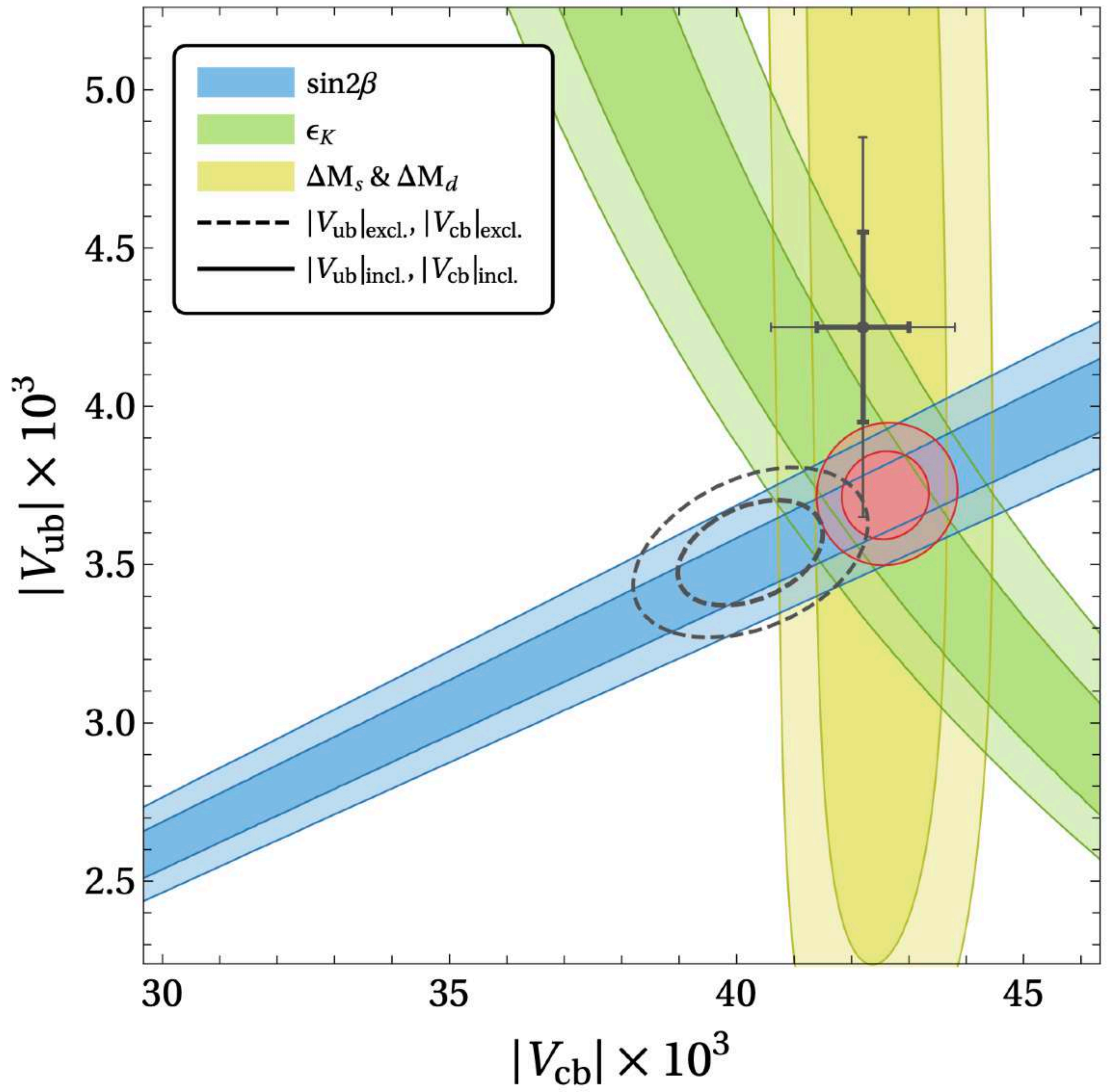
One constraint to kill them all?

Luca Di Luzio,[1,*] Matthew Kirk,[1,†] and Alexander Lenz[1,‡]

1712.06572

Direct determination of $V_{td}V_{tb}$, $V_{ts}V_{tb}$ and V_{ts}/V_{td}

Loopy determination of V_{cb} and V_{ub}

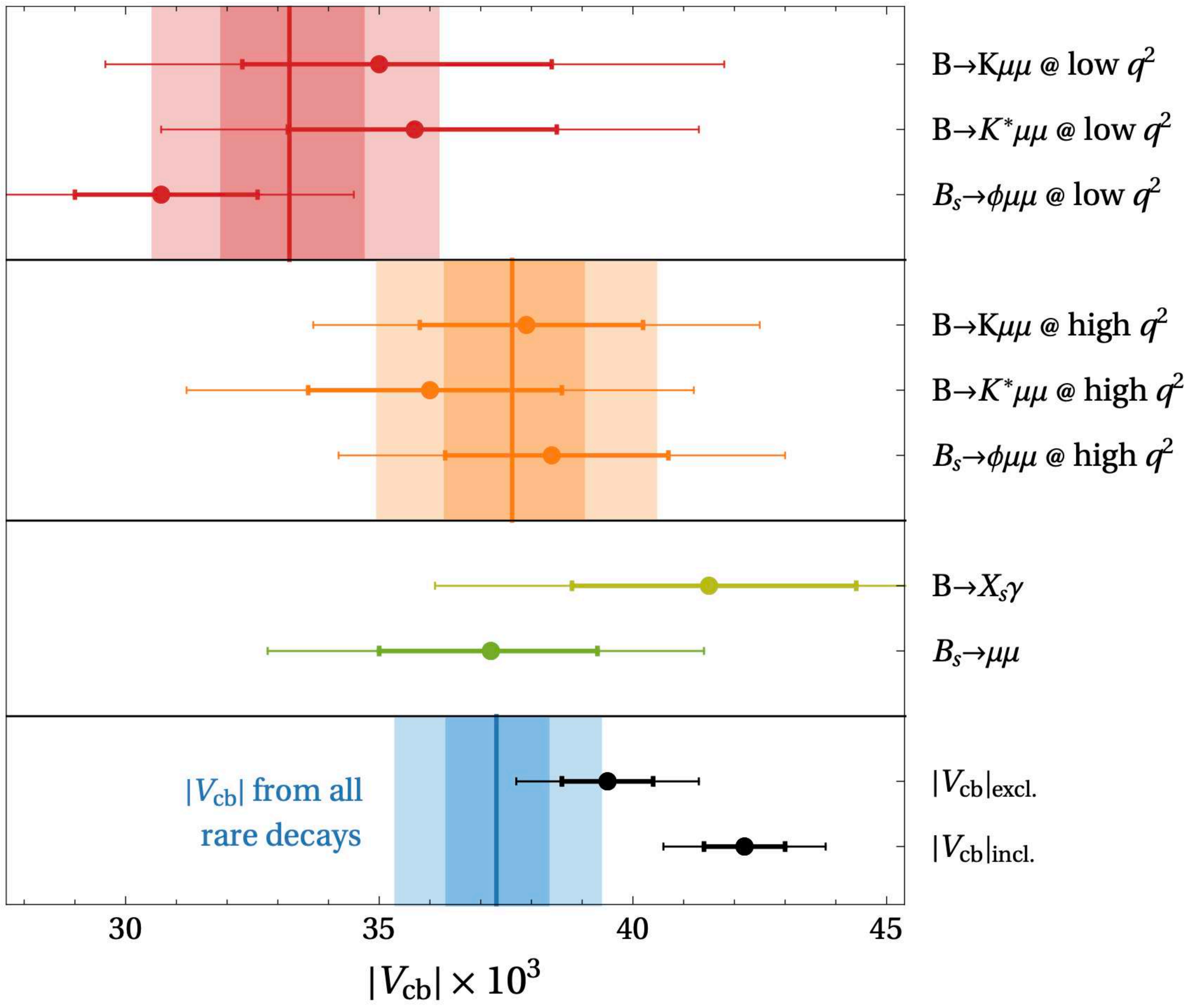


Altmannshofer, Lewis 2112.03437

King, Kirk, AL, Rauh 1911.07856

Old anomalies

V_{cb}: inclusive vs. exclusive affects also the $b \to sll$ anomalies



Altmannshofer, Lewis 2112.03437

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Old anomalies

Beyond the Flavour Anomalies

V_{cb}: inclusive vs. exclusive affects also some of the $b \to sll$ anomalies

Interesting suggestion to determine inclusive B decays directly with Lattice-QCD

[42] S. Hashimoto, *Inclusive semi-leptonic B meson decay structure functions from lattice QCD*, PTEP **2017** (2017) 053B03, arXiv:1703.01881.

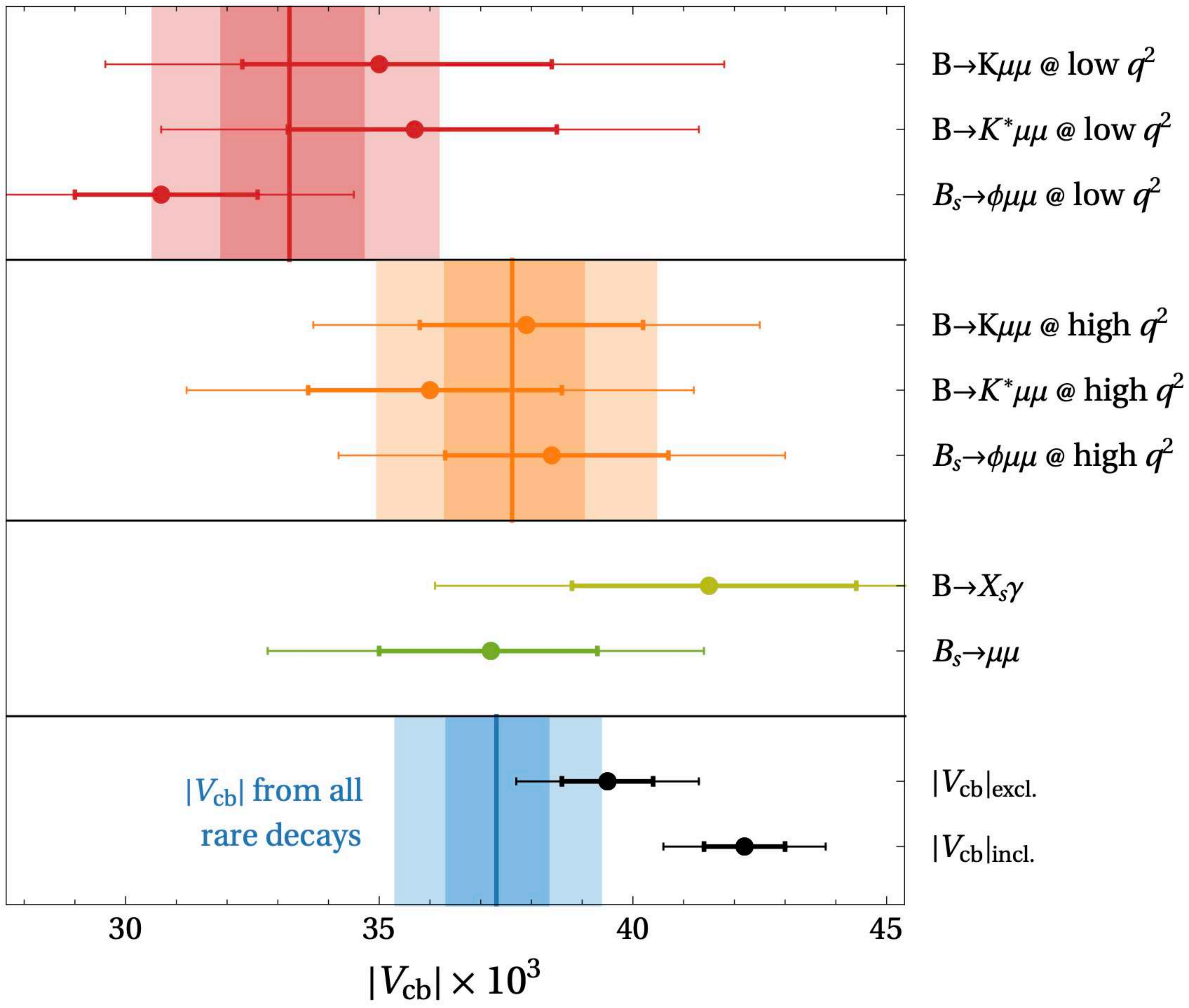
[43] M. Hansen, A. Lupo, and N. Tantalo, *Extraction of spectral densities from lattice correlators*, Phys. Rev. D **99** (2019) 094508, arXiv:1903.06476.

[44] J. Bulava and M. T. Hansen, *Scattering amplitudes from finite-volume spectral functions*, Phys. Rev. D **100** (2019) 034521, arXiv:1903.11735.

[45] P. Gambino and S. Hashimoto, *Inclusive Semileptonic Decays from Lattice QCD*, Phys. Rev. Lett. **125** (2020) 032001, arXiv:2005.13730.

[46] J. Bulava *et al.*, *Inclusive rates from smeared spectral densities in the two-dimensional O(3) non-linear σ-model*, arXiv:2111.12774.

[47] P. Gambino *et al.*, *Lattice QCD study of inclusive semileptonic decays of heavy mesons*, arXiv:2203.11762.



Altmannshofer, Lewis 2112.03437

CP Violation

1. **CP violation in Mixing**: Consider a **flavour specific (** $\mathcal{A}_{\bar f} = 0 = \bar{\mathcal{A}}_f$**) decay** $B \to f$

$$A^q_{\rm fs} = \frac{\Gamma\left(\bar B_q(t) \to f\right) - \Gamma\left(B_q(t) \to \bar f\right)}{\Gamma\left(\bar B_q(t) \to f\right) + \Gamma\left(B_q(t) \to \bar f\right)}$$

$\boxed{\bar{\mathcal{A}}_{\bar f} = \mathcal{A}_f}$ = **No direct CP violation**

$$a^q_{\rm fs} \approx \frac{|\Gamma^q_{12}|}{|M^q_{12}|} \sin \phi^q_{12}$$

e.g. $B \to X l \nu$
or $\bar B_s \to D_s^+ \pi^-$
or $\bar B_d \to D^+ K^-$

2. **CP violation in interference of mixing and decay**

$$A^q_{\rm ind} = \frac{\Gamma\left(\bar B_q(t) \to f\right) - \Gamma\left(B_q(t) \to f\right)}{\Gamma\left(\bar B_q(t) \to f\right) + \Gamma\left(B_q(t) \to f\right)}$$

e.g. $B_s \to J/\Psi \phi$
or $B_d \to J/\Psi K_s$

See also 1511.09466, hep-ph/0201071

3. **CP violation in decay**

$$A^q_{\rm dir} = \frac{\Gamma\left(\bar B_q(t) \to \bar f\right) - \Gamma\left(B_q(t) \to f\right)}{\Gamma\left(\bar B_q(t) \to \bar f\right) + \Gamma\left(B_q(t) \to f\right)} = \frac{|\bar{\mathcal{A}}_{\bar f}|^2 - |\mathcal{A}_f|^2}{|\bar{\mathcal{A}}_{\bar f}|^2 + |\mathcal{A}_f|^2}$$

e.g. ΔA_{CP}
or $D^0 \to \pi^- \pi^+, K^- K^+$

Beyond the Flavour Anomalies

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Time evolution

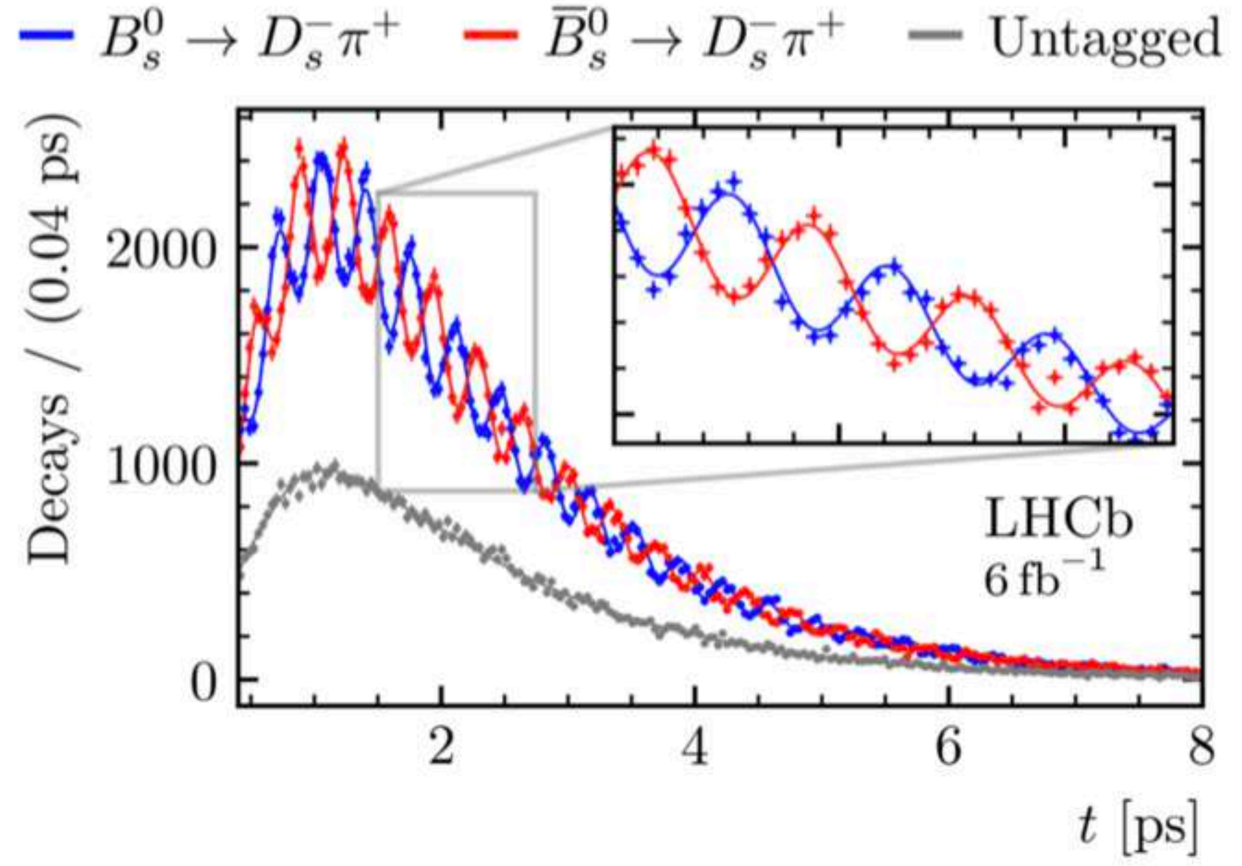
Time evolution of neutral B mesons (quantum mechanics on a macroscopic scale)

$$\Gamma\left[\bar{B}_q(t)\to f\right] = N_f\,|\mathcal{A}_f|^2\,\frac{(1+|\lambda_f|^2)}{2}(1+a_{\rm fs}^q)\,e^{-\Gamma_q t}\left\{\cosh\left(\frac{\Delta\Gamma_q t}{2}\right)-\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos\left(\Delta M_q t\right)\right.$$
$$\left.-\frac{2\,{\rm Re}(\lambda_f)}{1+|\lambda_f|^2}\sinh\left(\frac{\Delta\Gamma_q t}{2}\right)+\frac{2\,{\rm Im}(\lambda_f)}{1+|\lambda_f|^2}\sin\left(\Delta M_q t\right)\right\},$$

With

$$\mathcal{A}_f = \langle f|\mathcal{H}_{\rm eff}|B_q\rangle\,,\qquad \bar{\mathcal{A}}_f = \langle f|\mathcal{H}_{\rm eff}|\bar{B}_q\rangle\,,\qquad \lambda_f = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$$

and the tiny quantity a_{fs}^q to be defined below



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Status Quo: Mixing

Beyond the Flavour Anomalies

$$\Gamma_{12} = \frac{\Lambda^3}{m_b^3}\tilde{\Gamma}_6\langle\tilde{Q}_6\rangle + \frac{\Lambda^4}{m_b^4}\tilde{\Gamma}_7\langle\tilde{Q}_7\rangle + \dots$$

with $\langle\tilde{Q}_6\rangle \propto f_B^2 B_{1,2,3}$ and $\langle\tilde{Q}_7\rangle \propto f_B^2 R_{0,2,3}, m_s/m_b f_B^2 B_{4,5}$ and $\tilde{\Gamma}_i = \tilde{\Gamma}_i^{(0)} + \frac{\alpha}{4\pi}\tilde{\Gamma}_i^{(1)} + \dots$

$\tilde{\Gamma}_6^{(1)}$
- 1998 Beneke, Buchalla, Greub, AL, Nierste
- 2003 Franco, Lubicz, Mescia, Tarantino
- 2003 Beneke, Buchalla, AL, Nierste
- 2006 AL, Nierste
- ––––––––––––––––––––––––––––––––

$\tilde{\Gamma}_6^{(2)}$
- 2017 partly: Asatrian, Hovhannisyan, Nierste, Yeghiazaryan
- 2020 partly: Asatrian, Asatryan, Hovhannisyan, Nierste, Tumasyan
- 2021 partly: Gerlach, Nierste, Shtabovenko, Steinhauser
- ––––––––––––––––––––––––––––––––

$\tilde{\Gamma}_7^{(0)}$
- 1996 Beneke, Buchalla, Dunietz
- 2001 Dighe, Hurth, Kim
- ––––––––––––––––––––––––––––––––

$\tilde{\Gamma}_7^{(1)}$
- 202x Nierste and friends
- ––––––––––––––––––––––––––––––––

$\tilde{\Gamma}_8^{(0)}$
- 2007 Badin, Gabbiani, Petrov

$\langle\tilde{Q}_6\rangle$
- B_1 the same as for ΔM, $B_{2,3,4,5}$ new
- 2016 FNAL/MILC
- 2016-18 Grozin, Klein, Mannel, Pivovarov B_d
- 2017 Kirk, AL, Rauh B_d
- 2019 King, AL, Rauh B_s
- 2019 HPQCD 19007.01025
- ––––––––––––––––

$\langle\tilde{Q}_7\rangle$
- So far only Vacuum insertion approximation
- 2019 HPQCD 1910.00970

$$R_2 = \frac{1}{m_b^2}(\bar{b}^\alpha \overleftarrow{D}_\rho \gamma^\mu (1-\gamma^5) D^\rho s^\alpha)(\bar{b}^\beta \gamma_\mu (1-\gamma^5) s^\beta)$$
$$R_3 = \frac{1}{m_b^2}(\bar{b}^\alpha \overleftarrow{D}_\rho (1-\gamma^5) D^\rho s^\alpha)(\bar{b}^\beta (1-\gamma^5) s^\beta)$$

This work

$$\Delta\Gamma_s^{HQE} = (0.091 \pm 0.013)\,\mathrm{ps}^{-1} \qquad \Delta\Gamma_s^{HFLAV} = (0.082 \pm 0.005)\,\mathrm{ps}^{-1}$$
$$\Delta\Gamma_d^{HQE} = (2.6 \pm 0.4)\cdot 10^{-3}\,\mathrm{ps}^{-1} \qquad \Delta\Gamma_d^{HFLAV} = (-1.3 \pm 6.6)\cdot 10^{-3}\,\mathrm{ps}^{-1}$$

1912.07621

HFLAV, ATLAS 1605.07485

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Status Quo: Mixing

Beyond the Flavour Anomalies

$$\Gamma_{12} = \frac{\Lambda^3}{m_b^3}\tilde{\Gamma}_6\langle\tilde{Q}_6\rangle + \frac{\Lambda^4}{m_b^4}\tilde{\Gamma}_7\langle\tilde{Q}_7\rangle + \ldots$$

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$$R_3 = \frac{1}{m_b^2}(\bar{b}^\alpha \overleftarrow{D}_\rho (1-\gamma^5) D^\rho s^\alpha)(\bar{b}^\beta (1-\gamma^5) s^\beta)$$

This work

Higher perturbative orders and determinations of dim. 7 Bag

Status Quo: CPV in Mixing

In the ratio Γ_{12}/M_{12} theory uncertainties are cancelling

$$\mathrm{Re}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right) = -\frac{\Delta\Gamma_s}{\Delta M_s}\,, \qquad \mathrm{Im}\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right) = a_{fs}^s\,.$$

$$-\frac{\Gamma_{12}^s}{M_{12}^s} = \frac{\lambda_c^2\Gamma_{12}^{s,cc} + 2\lambda_c\lambda_u\Gamma_{12}^{s,uc} + \lambda_u^2\Gamma_{12}^{s,uu}}{\lambda_t^2\tilde{M}_{12}^s} = \frac{\Gamma_{12}^{s,cc}}{\tilde{M}_{12}^s} + 2\frac{\lambda_u}{\lambda_t}\frac{\Gamma_{12}^{s,cc}-\Gamma_{12}^{s,uc}}{\tilde{M}_{12}^s} + \left(\frac{\lambda_u}{\lambda_t}\right)^2\frac{\Gamma_{12}^{s,cc}-2\Gamma_{12}^{s,uc}+\Gamma_{12}^{s,uu}}{\tilde{M}_{12}^s}$$

- No CKM dependence!
- No GIM suppression!
- No imaginary part!
- Small $\approx \mathcal{O}(5\cdot 10^{-3})$
- Leading contribution to $\Delta\Gamma$

- CKM suppression
- GIM suppression
- Imaginary part via CKM
- Leading contribution to a_{fs}
- Tiny contribution to $\Delta\Gamma$

$$\frac{V_{ub}V_{ud}}{V_{tb}V_{td}} = \lambda^{0.8}$$

$$\frac{V_{ub}V_{us}}{V_{tb}V_{ts}} = \lambda^{2.8}$$

- Stronger CKM suppression
- Very strong GIM suppression
- Imaginary part via CKM
- Subleading contribution to a_{fs} and $\Delta\Gamma$

$$a_{sl}^{s,\mathrm{Exp}} = \left(60 \pm 280\right)\cdot 10^{-5}, \qquad a_{sl}^{s,\mathrm{SM}} = \left(2.06 \pm 0.18\right)\cdot 10^{-5},$$

$$a_{sl}^{d,\mathrm{Exp}} = \left(-21 \pm 17\right)\cdot 10^{-4}. \qquad a_{sl}^{d,\mathrm{SM}} = \left(-4.73 \pm 0.42\right)\cdot 10^{-4}.$$

HFLAV 1970?

1912.07621

Alternative Scale Setting

ϵ (GeV)	Γ_{12}^s/M_{12}^s	Γ_{12}^d/M_{12}^d
0.	$-0.00499 + 0.000022I$	$-0.00497 - 0.00050I$
0.2.	$-0.00494 + 0.000023I$	$-0.00492 - 0.00053I$
0.5.	$-0.00484 + 0.000026I$	$-0.00482 - 0.00059I$
1.0	$-0.00447 + 0.000037I$	$-0.00448 - 0.00084I$
1.5.	$-0.00287 + 0.000091I$	$-0.00309 - 0.0021I$

Theory uncertainties might be larger, but this will only become relevant if the exp. precision reaches around $2\,a_{fs}^{\mathrm{SM}}$

AL, Piscopo, Vlahos 2007.03022

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Beyond the Flavour Anomalies

CPV in Decay

$$A_{\text{dir.CP},f}(t) = \frac{\Gamma\left(\bar{B}^0_s(t) \to \bar{f}\right) - \Gamma\left(B^0_s(t) \to f\right)}{\Gamma\left(\bar{B}^0_s(t) \to \bar{f}\right) + \Gamma\left(B^0_s(t) \to f\right)} = \frac{\left|\bar{\mathcal{A}}_{\bar{f}}\right|^2 - \left|\mathcal{A}_f\right|^2}{\left|\bar{\mathcal{A}}_{\bar{f}}\right|^2 + \left|\mathcal{A}_f\right|^2} = \frac{2|r| \sin\left(\phi^{\text{QCD}}_{\text{Peng}} - \phi^{\text{QCD}}_{\text{Tree}}\right) \sin\left[\arg(\lambda_u) - \arg(\lambda_c)\right]}{1 + |r|^2 + 2|r| \cos\left(\phi^{\text{QCD}}_{\text{Peng}} - \phi^{\text{QCD}}_{\text{Tree}}\right) \cos\left[\arg(\lambda_u) - \arg(\lambda_c)\right]}$$

$$\mathcal{A}_f = \left|\mathcal{A}^{\text{Tree}}_f\right| e^{i\left[\phi^{\text{QCD}}_{\text{Tree}} + \arg(\lambda_c)\right]} + \left|\mathcal{A}^{\text{Peng}}_f\right| e^{i\left[\phi^{\text{QCD}}_{\text{Peng}} + \arg(\lambda_u)\right]}$$

$$\bar{\mathcal{A}}_{\bar{f}} = \left|\mathcal{A}^{\text{Tree}}_f\right| e^{i\left[\phi^{\text{QCD}}_{\text{Tree}} - \arg(\lambda_c)\right]} + \left|\mathcal{A}^{\text{Peng}}_f\right| e^{i\left[\phi^{\text{QCD}}_{\text{Peng}} - \arg(\lambda_u)\right]}$$

The **leading contribution to the CP asymmetry is proportional to** $r = |\mathscr{A}^{\text{Peng}}_f| / |\mathscr{A}^{\text{Tree}}_f|$

Extremely hard to predict!

(In the case of CPV in interference the leading term was free of hadronic uncertainties and only the penguin corrections depended on r)

Non-leptonic decays

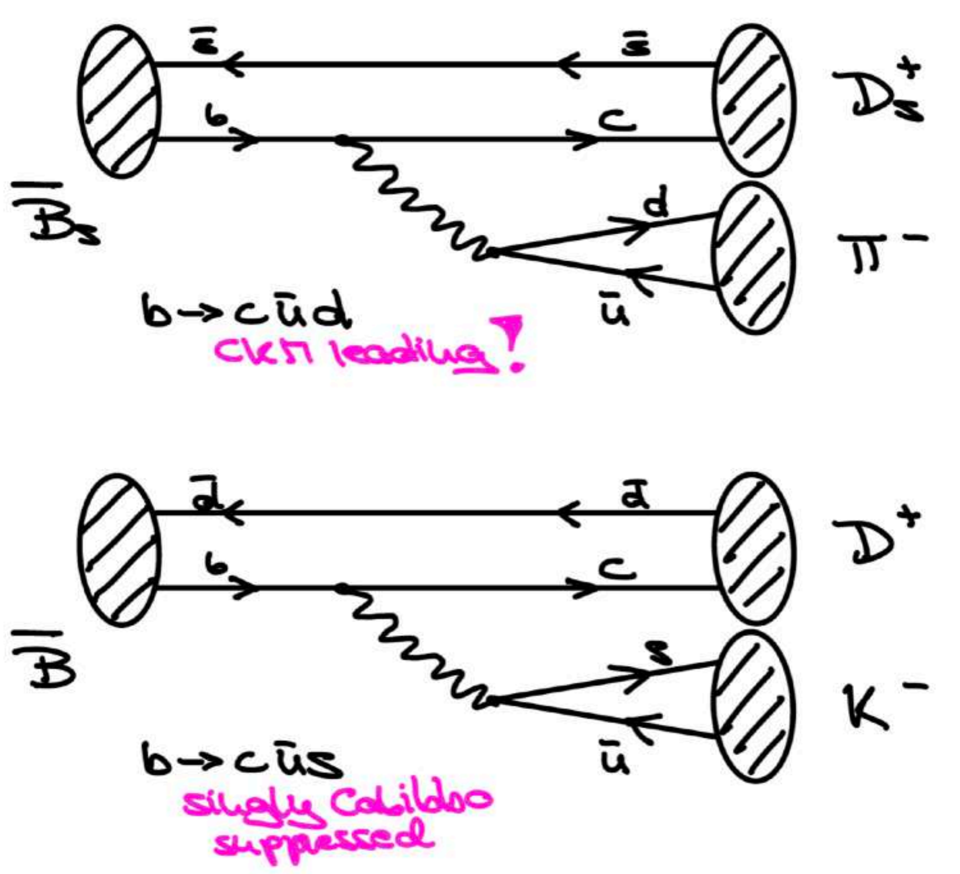
Beyond the Flavour Anomalies

3 σ to 9 σ deviation of experiment from QCDf predictions with standard error estimates

Talk by Daniel Ferlewicz, Nico Gubernari

N. Skidmore

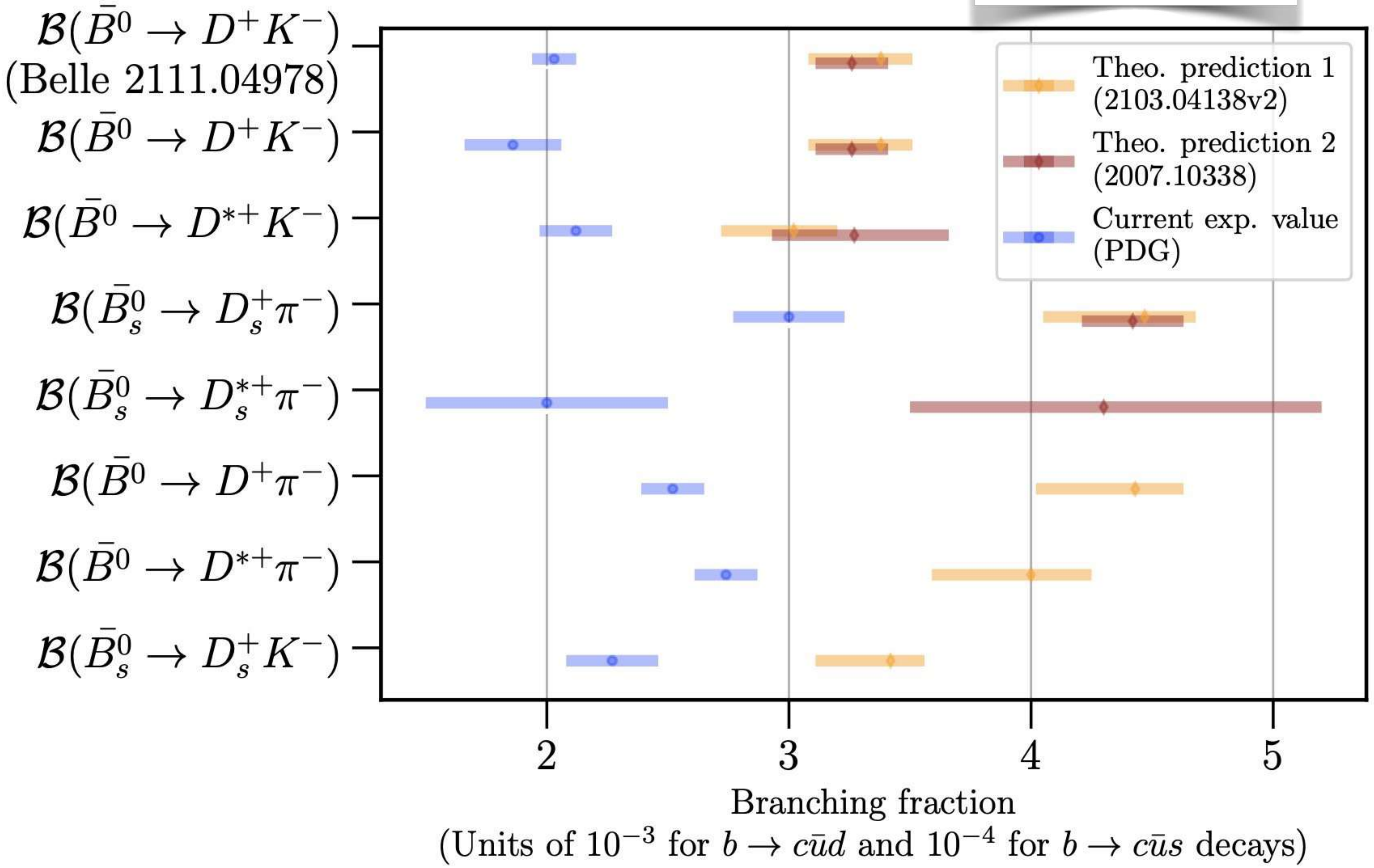
Colour-allowed Tree-level Decays



- CKM leading decays
- The are no annihilation, penguins,…
- QCDf should work at its best!

Beneke, Buchalla, Neubert, Sachrajda 1999…

$$\langle D_q^{(*)+} L^- | \mathcal{Q}_i | \bar{B}_q^0 \rangle = \sum_j F_j^{\bar{B}_q \to D_q^{(*)}}(M_L^2) \times \int_0^1 du\, T_{ij}(u) \phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$



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Non-leptonic decays

Beyond the Flavour Anomalies

3 σ to 9 σ deviation of experiment from QCDf predictions with standard error estimates

Non-leptonic decays

What could go wrong?

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Non-leptonic decays

Beyond the Flavour Anomalies

What could go wrong?

Alexander Lenz
@alexlenz42

According to the new Belle measurement in 2111.04978, the decay barB_d to D+ K- is around 7 sigma of the QCD factorisation prediction in 2007.10338. Where is this discrepancy rooted?

QCD factorisation	**90.9%**
New Physics	9.1%
Experiment	0%

33 votes · Final results

9:47 AM · Nov 10, 2021 · Twitter Web App

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Non-leptonic decays

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- **Huber, Kränkl** 1606.02888
- **Bordone, Gubernari, Huber, Jung, vanDyk** 2007.10338
- **Iguro, Kitahara** 2008.01086
- **Cai, Deng, Li, Yang** 2103.04138
- **Bordone, Greljo,Maryocca** 2103.10332
- **Beneke, Böer, Finauro, Vos** 2107.03819

Similar for $B_s \to D_s^{\mp} K^{\pm}$

- **Fleischer, Malami** 2110.04240, 2109.04950

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Non-leptonic decays

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Similar for $B_s \to D_s^{\mp} K^{\pm}$

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In the SM the determination of γ is super precise

The ultimate theoretical error on γ from $B \to DK$ decays

Joachim Brod[1,*] and Jure Zupan[1,†]

[1]Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221,USA

Abstract

The angle γ of the standard CKM unitarity triangle can be determined from $B \to DK$ decays with a very small irreducible theoretical error, which is only due to second-order electroweak corrections. We study these contributions and estimate that their impact on the γ determination is to introduce a shift $|\delta\gamma| \lesssim \mathcal{O}(10^{-7})$, well below any present or planned future experiment.

If there are BSM effects in non-leptonic decays, the determination of γ can be modified by $\mathcal{O}(5^\circ)$

PHYSICAL REVIEW D **92,** 033002 (2015)

New physics effects in tree-level decays and the precision in the determination of the quark mixing angle γ

Joachim Brod
PRISMA Cluster of Excellence and Mainz Institute for Theoretical Physics, Johannes Gutenberg University, 55099 Mainz, Germany

Alexander Lenz, Gilberto Tetlalmatzi-Xolocotzi, and Martin Wiebusch
Institute for Particle Physics Phenomenology, Department of Physics, Durham University, South Road, Durham DH1 3LE, United Kingdom

update
AL, Tetlalmatzi-Xolocotzi 1912.07621

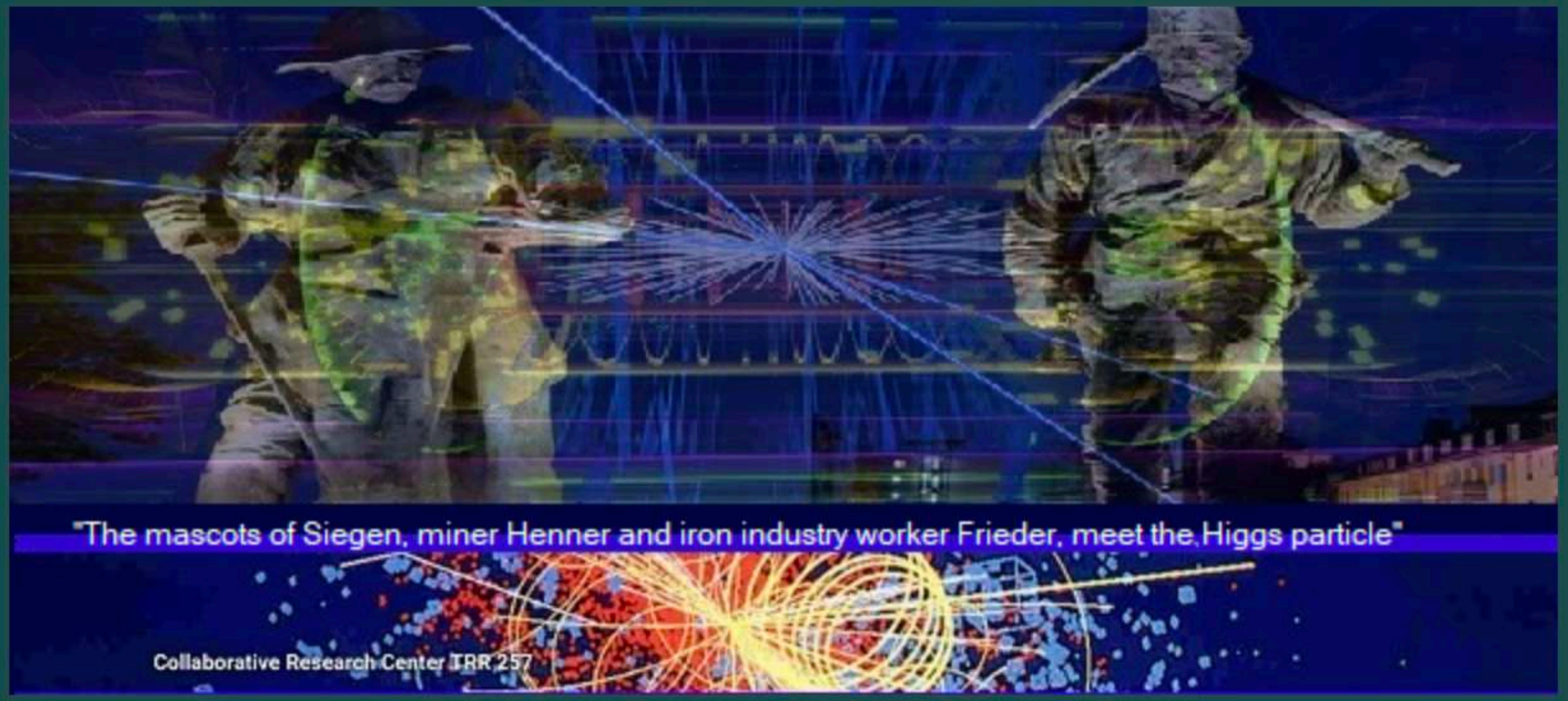
Non-leptonic decays

Things to check

- **Reconsidering QCDf uncertainty estimates: Khodjamirian, Piscopo, Rusov**
  if new effects will be found, then this
  might also affect the estimate of charm loops

- **BSM in $b \to c\bar{u}d$ would also affect $\tau(B^+)/\tau(B_d)$ AL, Müller, Piscopo, Rusov**

- **Consider CP asymmetries in colour allowed tree-level decays**
  there is only one amplitude in the SM

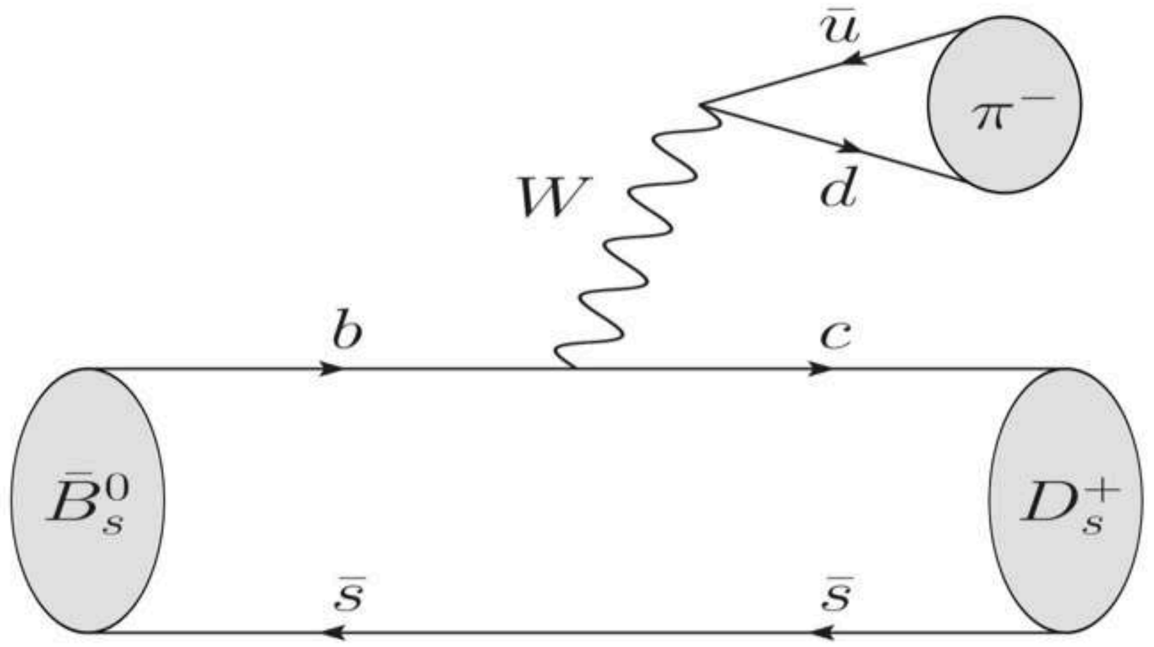


Status and prospects of Non-leptonic B meson decays

31 May 2022 to 2 June 2022

Europe/Berlin timezone

The aim of this event is to discuss the current status in theory and experiment of non-leptonic B meson decays. This entails talks on calculation techniques, including QCD factorization and perturbative QCD with special emphasis on the current status of estimating power corrections. Moreover, this workshop will include sessions devoted to the discussion of different puzzles, old and new, arising within the context of purely hadronic B meson processes. Here, discrepancies between the theoretical and the experimental determinations may indicate either potential physics beyond the SM or a critical reassessment of our theory tools. Finally, future experimental prospects on the expected precision and the measurement of different non-leptonic channels will also be addressed.



The University of Siegen has around 18.000 students and it has a large theoretical flavour physics group with around 40 members. Downtown Siegen offers many pubs, restaurants and cafes, but als theaters, cinemas and concert halls.

https://indico.scc.kit.edu/event/2641/

Non-leptonic decays

If you are fed up with our (=theorists) estimates of hadronic effects

Flavour specific decays

- a_{fs}^{q} is typically measured with semi-leptonic B_q decays

$$a_{sl}^{s,\mathrm{Exp}} = \left(60 \pm 280\right) \cdot 10^{-5},$$
$$a_{sl}^{d,\mathrm{Exp}} = \left(-21 \pm 17\right) \cdot 10^{-4}.$$

HFLAV 1970?

Flavour specific decays

Beyond the Flavour Anomalies

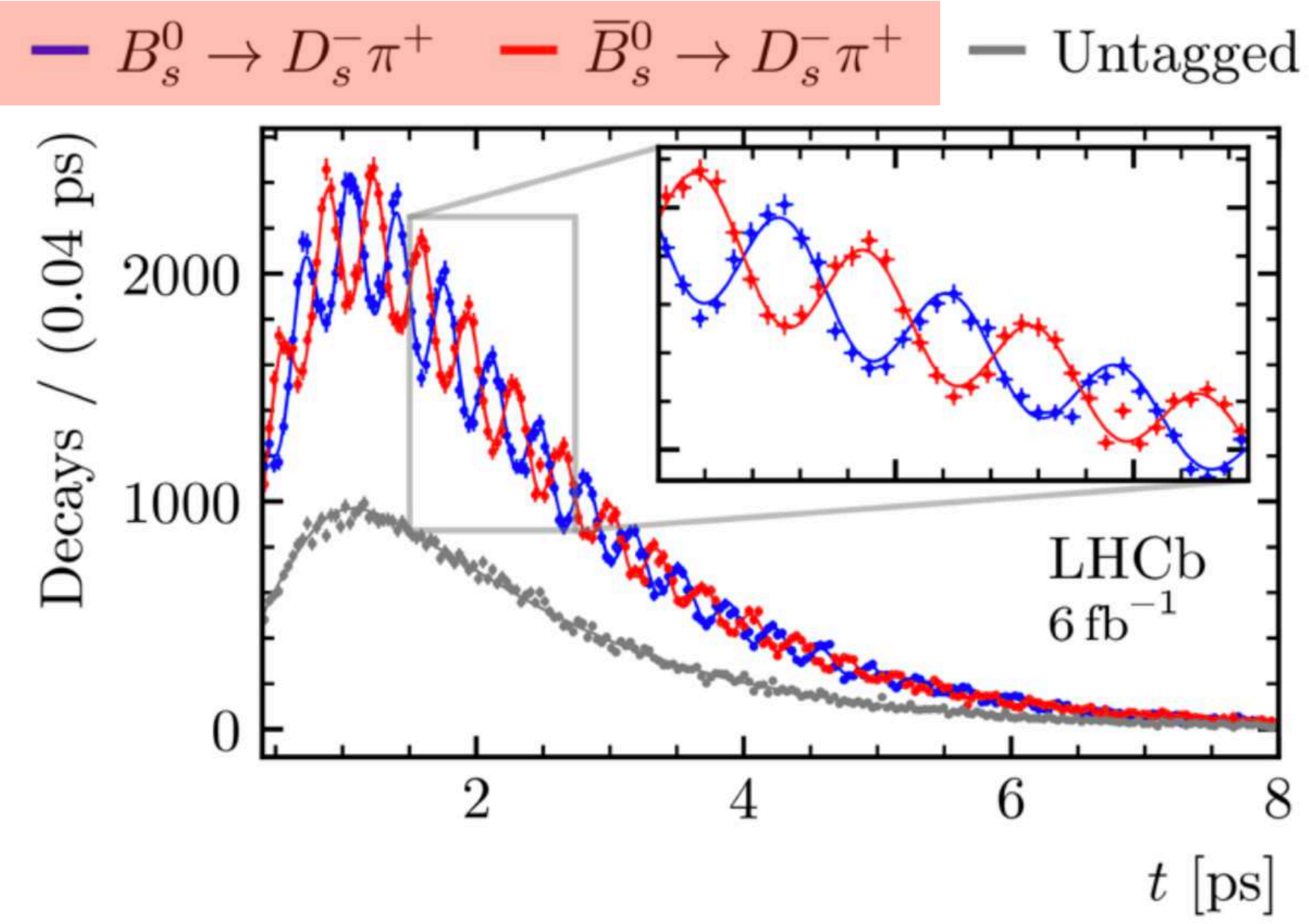
- a_{fs}^q is typically measured with semi-leptonic B_q decays
- One could also use the flavour specific $\bar{B}_s \to D_s^+ \pi^-$ decay

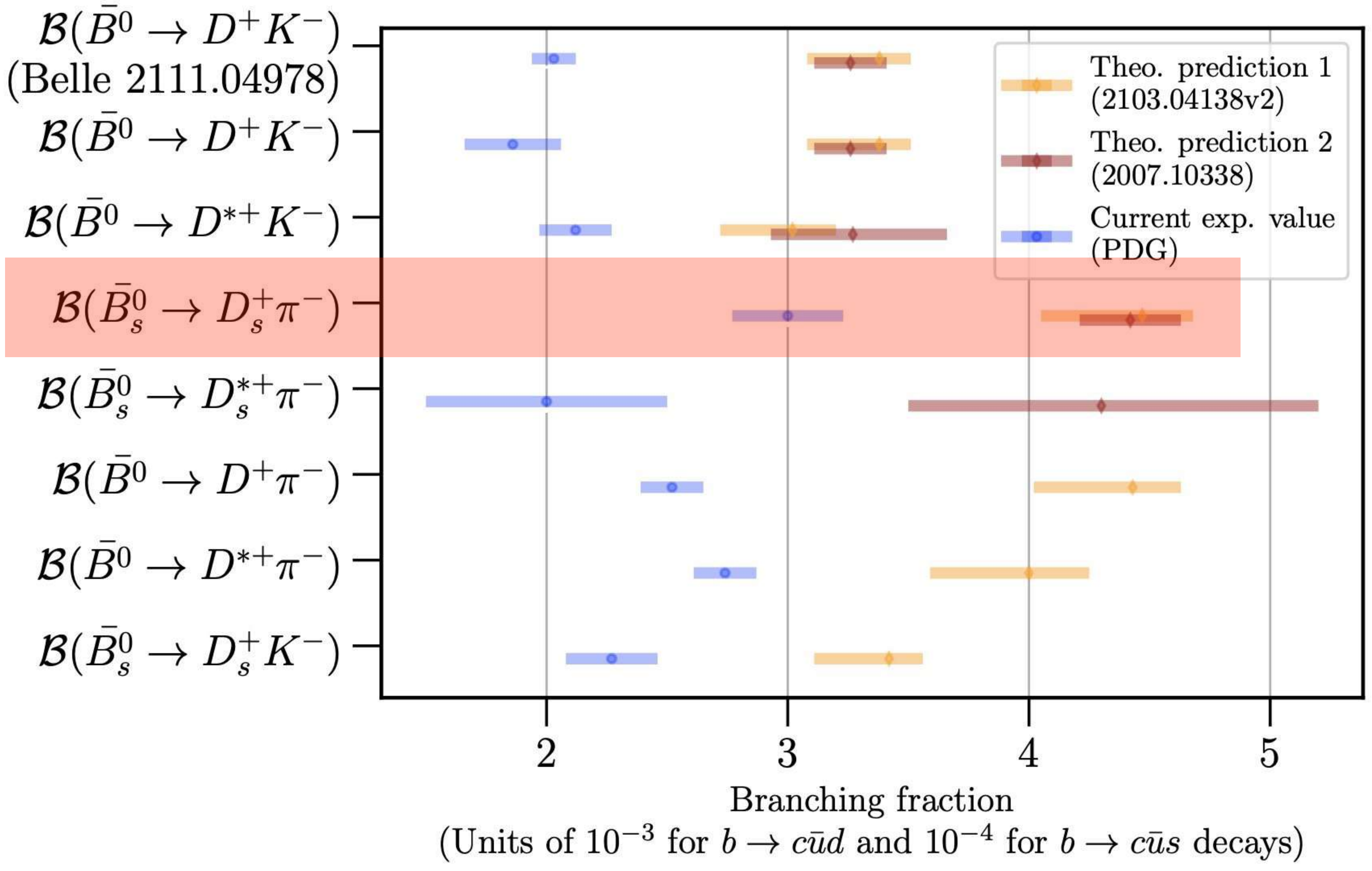
12 April 2021: Fascinating quantum mechanics.

Precise determination of the $B_s^0 - \bar{B}_s^0$ oscillation frequency.

"A phenomenon in which quantum mechanics gives a most remarkable prediction" - Richard Feynman

Today, the LHCb Collaboration submitted a paper for publication that reports a precise determination of the $B_s^0 - \bar{B}_s^0$ oscillation frequency. This result is presented also today at the joint annual conference of the UK Institute of Physics (IOP), organized by the University of Edinburgh. The $B_s^0 - \bar{B}_s^0$ oscillation is a spectacular and fascinating feature of quantum mechanics. The strange beauty particle B^0_s composed of a beauty antiquark ($\bar{b}$) bound with a strange quark s turns into its antiparticle partner $\bar{B}_s^0$ composed of a b quark and an s antiquark ($\bar{s}$) about 3 million million times per second ($3*10^{12}$) as seen in the image below.





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Flavour specific decays

Beyond the Flavour Anomalies

- a_{fs}^{q} is typically measured with semi-leptonic B_q decays
- One could also use the flavour specific $\bar{B}_s \to D_s^+ \pi^-$ decay
- Assume: there is new physics in these decays, potentially CP violating

$$\begin{aligned} \mathcal{A}_f &= \left|\mathcal{A}_f^{\mathrm{SM}}\right| e^{i\phi^{\mathrm{SM}}} e^{i\varphi^{\mathrm{SM}}} + \left|\mathcal{A}_f^{\mathrm{BSM}}\right| e^{i\phi^{\mathrm{BSM}}} e^{i\varphi^{\mathrm{BSM}}} \\ &=: \left|\mathcal{A}_f^{\mathrm{SM}}\right| e^{i\phi^{\mathrm{SM}}} e^{i\varphi^{\mathrm{SM}}} \left(1 + r e^{i\phi} e^{i\varphi}\right) , \end{aligned}$$

Discrepancy QCDf vs Exp. suggests $r \approx 0.1 - 0.2$

Flavour specific decays

- a^q_{fs} is typically measured with semi-leptonic B_q decays
- One could also use the flavour specific $\bar{B}_s \to D_s^+\pi^-$ decay
- Assume: there is new physics in these decays, potentially CP violating
- Derive CP asymmetry

$\approx 2r\sin\phi\sin\varphi < 0.40$

$$A^q_{\rm fs} = \frac{a^q_{\rm fs} - 2r\sin\phi\sin\varphi + 2a^q_{\rm fs}r\cos\phi\cos\varphi + a^q_{\rm fs}r^2}{1 + 2r\cos\phi\cos\varphi + r^2 - 2a^q_{\rm fs}r\sin\phi\sin\varphi} \approx a^q_{\rm fs} - A^q_{\rm dir}$$

Constrained by semi-leptonic Measurements

$$a_{sl}^{s,\rm Exp} = \left(60 \pm 280\right)\cdot 10^{-5},$$
$$a_{sl}^{d,\rm Exp} = \left(-21 \pm 17\right)\cdot 10^{-4}.$$

HFLAV 1970?

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Flavour specific decays

Beyond the Flavour Anomalies

Gershon, AL, Rusov, Skidmore 2111.04478

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Significant exp. deviation of A^q_{fs} from a^q_{sl}

= unambiguous and theory independent signal for BSM

Jun 14 – 17, 2022
Zadar, Croatia
Europe/Berlin timezone

Quirks in Quark Flavour Physics

The workshop will take place in the beautiful coastal city of Zadar, Croatia.

We will discuss the state of the current anomalies, puzzles, and quirks in quark flavour physics. Participants will contribute in the fields of experimental physics, phenomenology, and lattice field theory.

https://indico.ph.tum.de/event/6994/