HOT TOPICS IN FLAVOR PHYSICS

ALEXANDER LENZ SIEGEN UNIVERSITY 4TH MAY 2022

Outline:

- The usual suggestions for hot topics
- Not so well known
- Underdogs/Surprise

The usual Suspects:

flavour anomalies

- Independent experimental check of **anomalies**: ATLAS, CMS, Belle II plus higher precision, R_X,…

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See e.g. Fleischer et al. or Artuso, Borissov, AL 1511.09466

Peng $\approx \pm 1^\circ = \pm 17$ mrad

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- Baryonic decays $\Lambda_b \to \Lambda^{(*)}\ell\ell$,...

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- Baryonic decays $\Lambda_b \to \Lambda^{(*)}\ell\ell$,…
- CPV in charm
  - Direct CPV plus control measurements $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$
  - CPV in mixing
  - Baryonic analogue of $D \to \pi^+\pi^-, K^+K^-$: e.g. $\Lambda_c \to p\pi^0, \Sigma K$

LHCb 1903.08726

See e.g. Wilkinson, AL 2011.04443

All theorists agree:

ΔA_{CP} is clearly governed by NP!

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What is NP?

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P/T can currently not be calculated from first principles

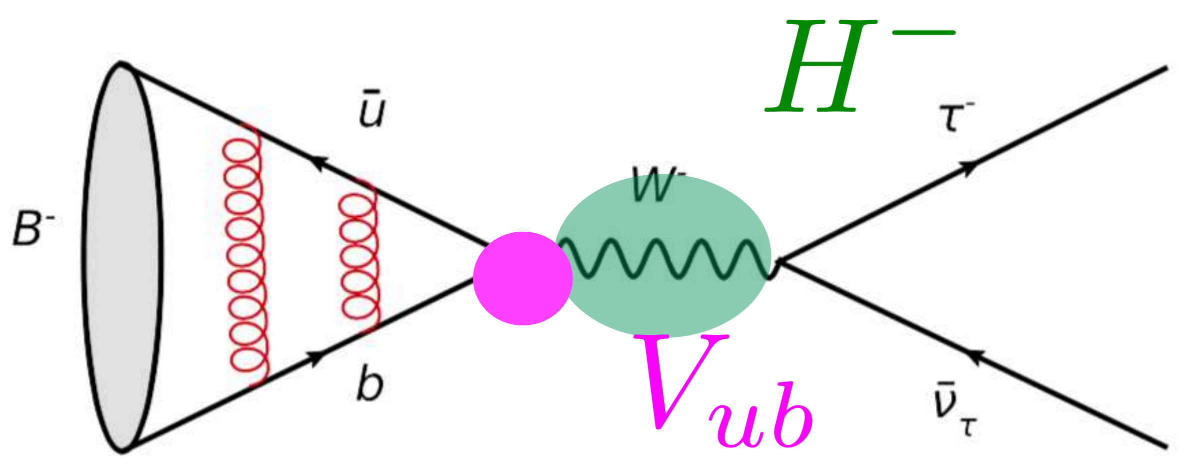
Additional assumptions (ideologies) needed - they might be wrong!

- **Ideology I:** NP = Non-perturbative physics
  - *"Non-perturbative effects are known to be huge"* Analogy to the $\Delta I = 1/2$ rule
  - Good starting point for arguing: $\sin\phi \approx 1 \Rightarrow P/T = 1.3$ sufficient for $\Delta a_{CP} = -0.00329$
- **Ideology II:** NP = New physics
  - *"Heavy quark expansion and factorisation are known to work well"* Analogy to the b-system
  - Good starting point for arguing: $\sin\phi \approx 1/10 \Rightarrow P/T = 13$ needed for $\Delta a_{CP} = -0.00329$

Control hadronic contributions in charm system

Hadronic Difficulty of Meson Decays

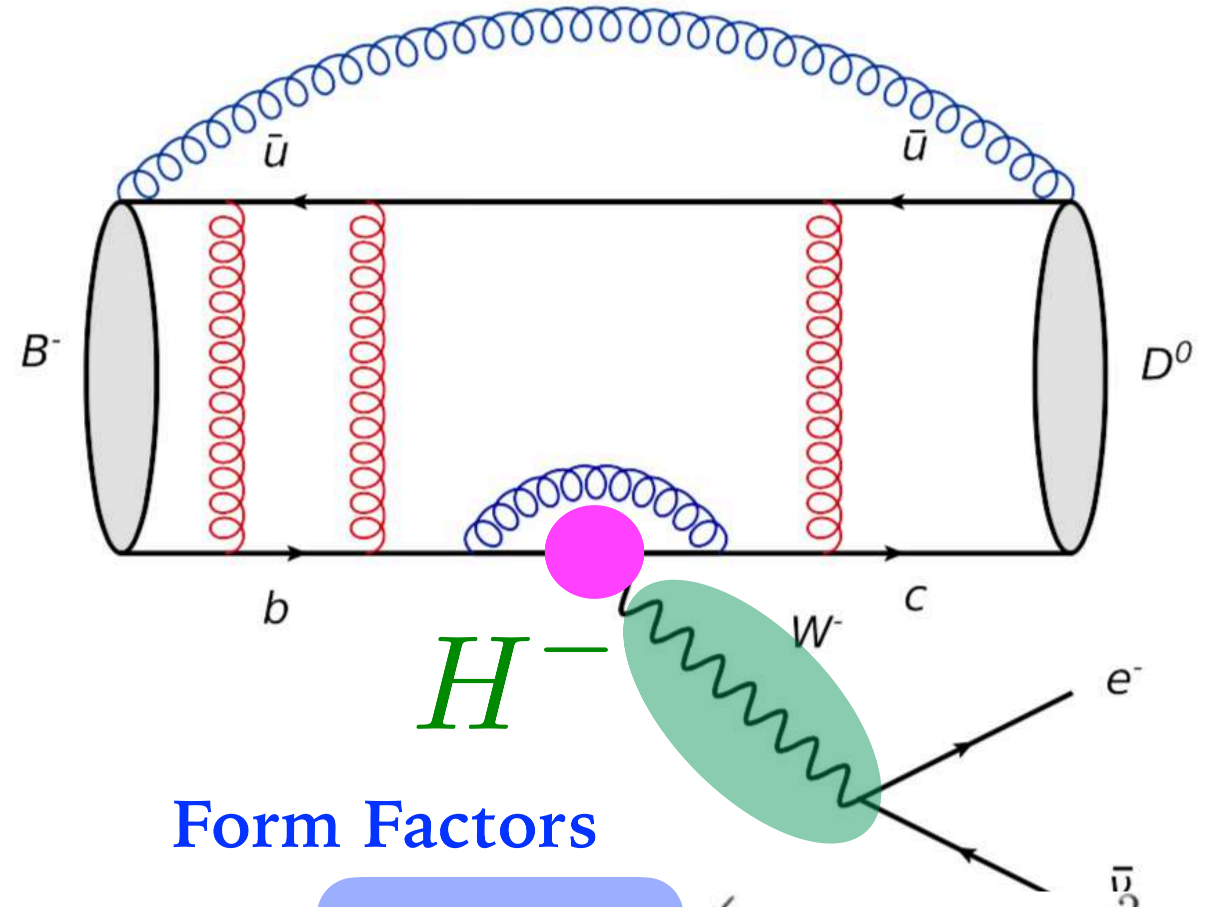
- Leptonic Decays



Decay constant

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

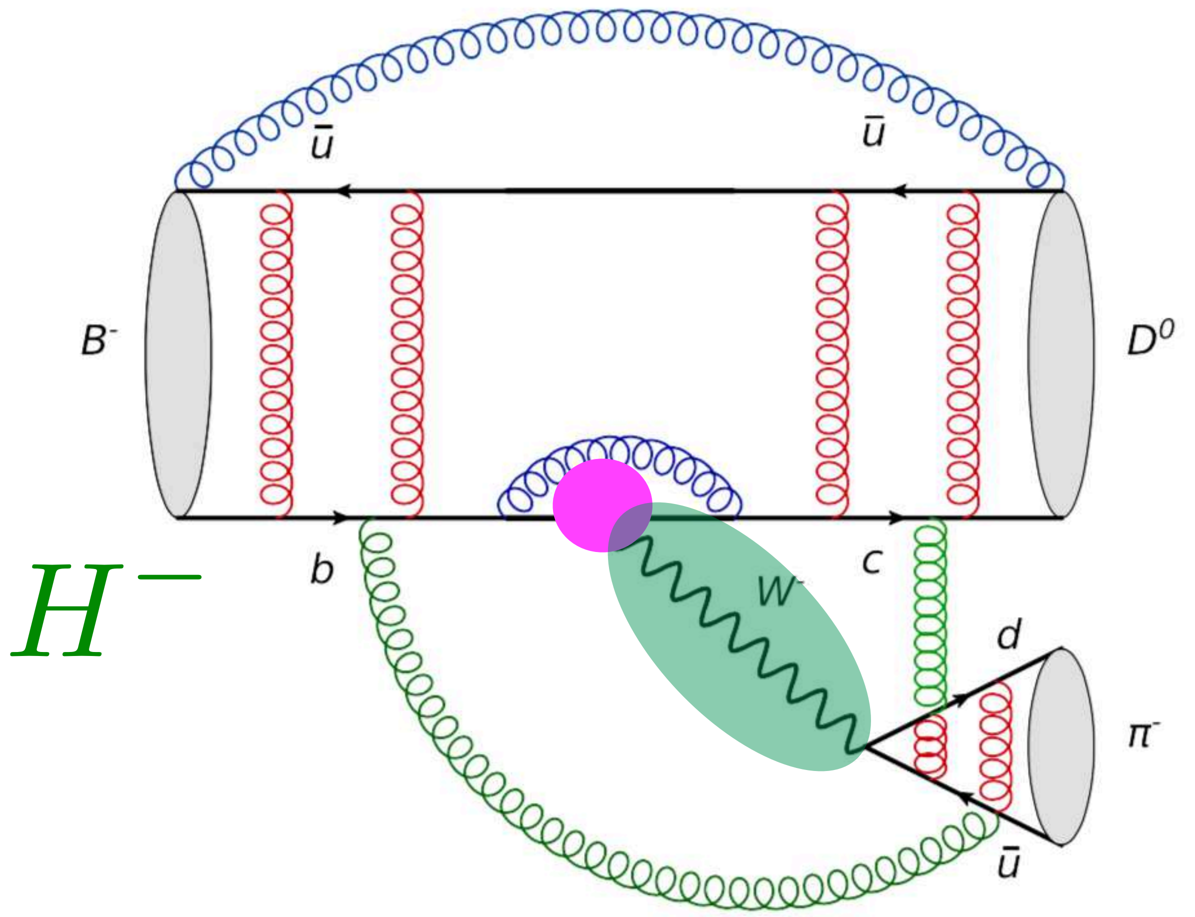
- Semileptonic Decays



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

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I) Imaginary part of CKM-elements = CP Violation

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

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Non-perturbative: decay constants, form factors, factorisation

IV) Determination of SM-Parameter

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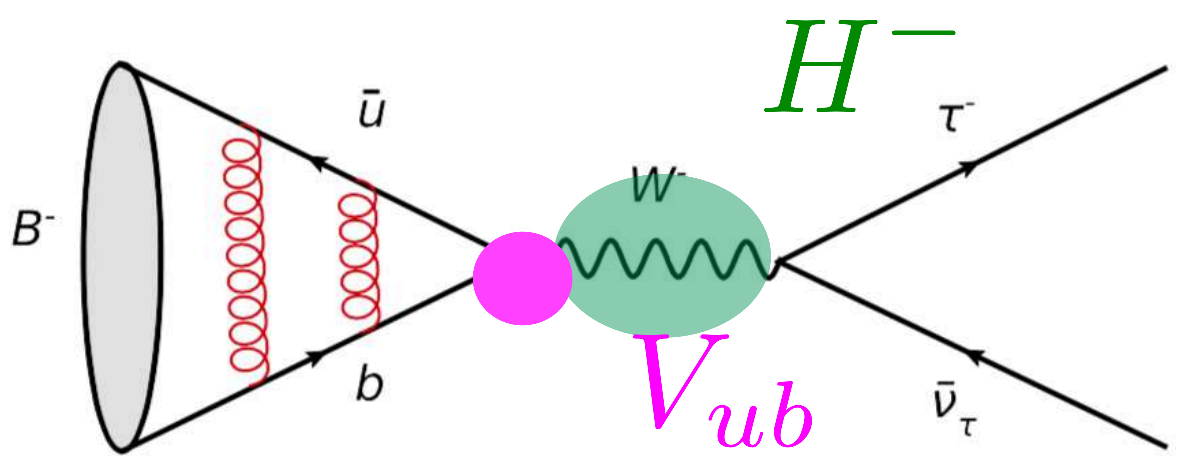

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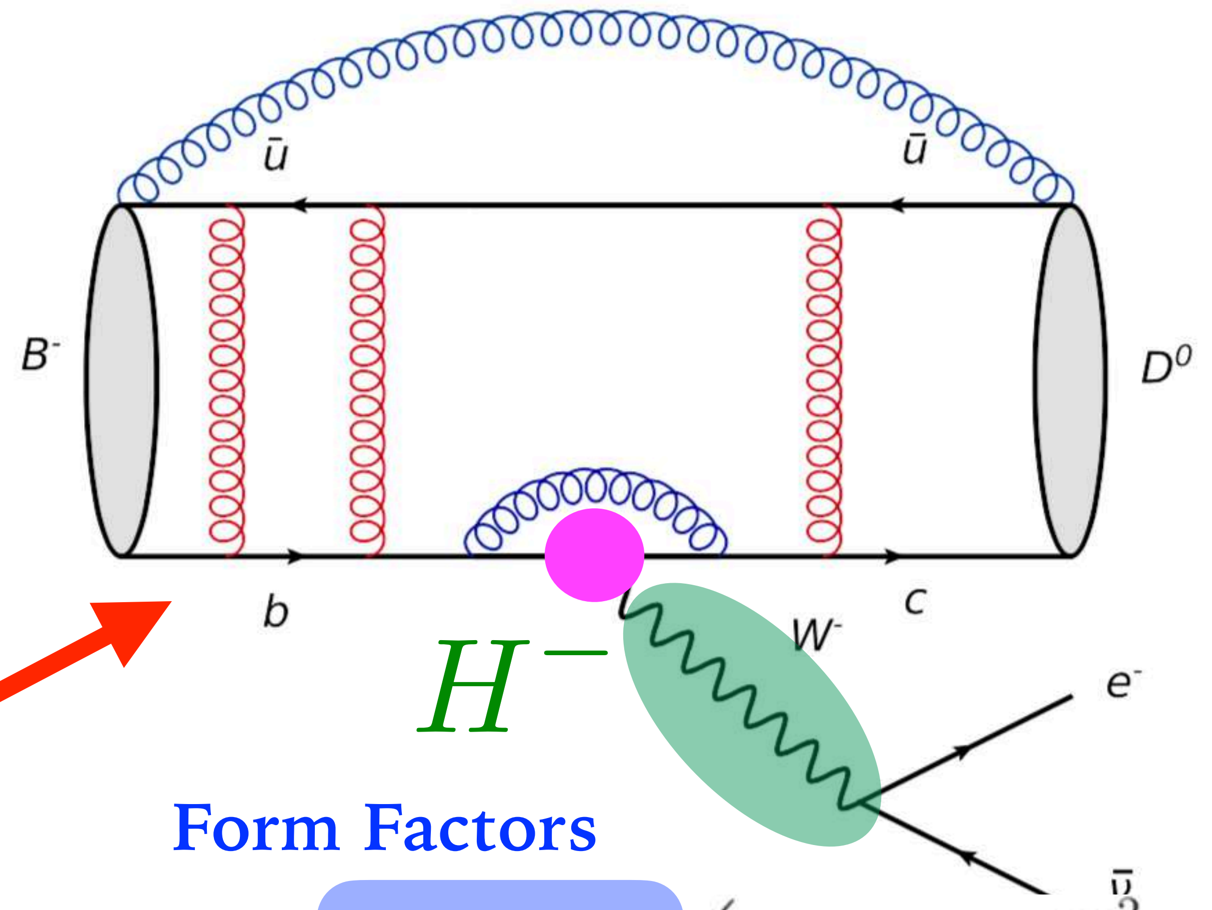

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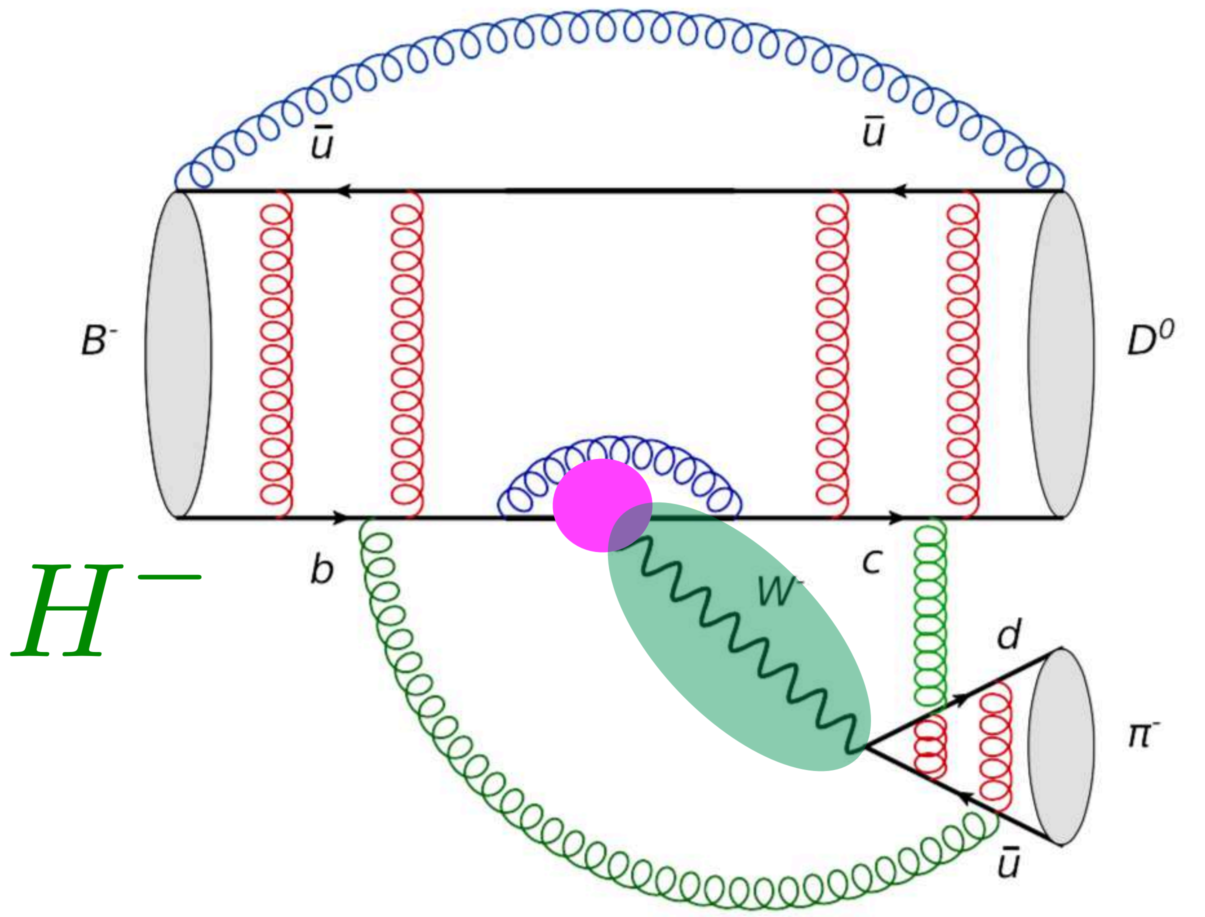

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Ancient B anomalies
Tree: V_{ub}, V_{cb}

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

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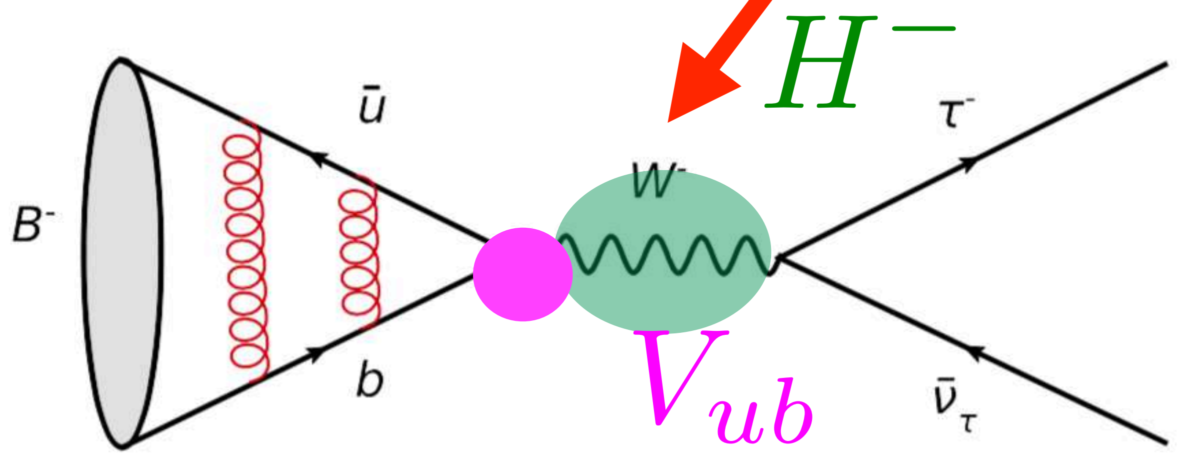

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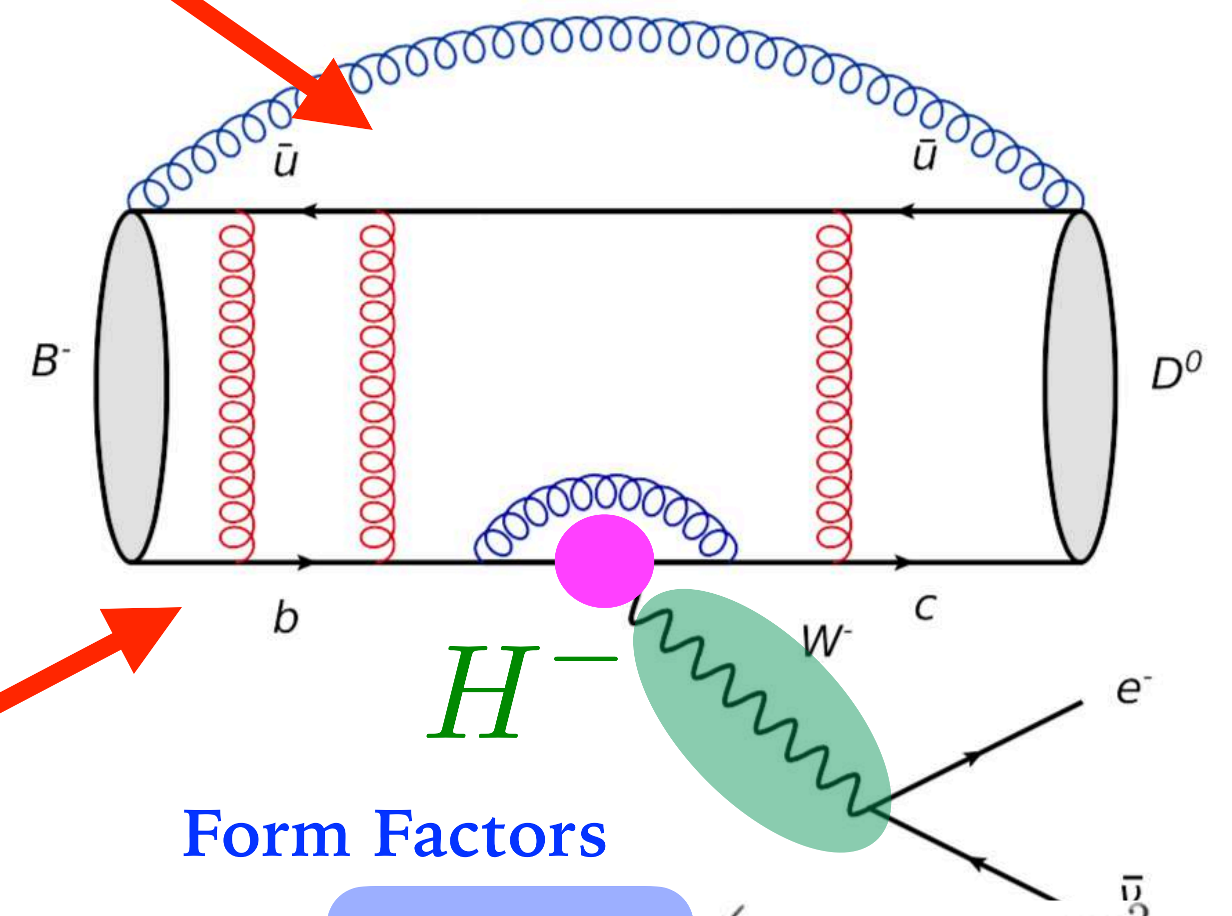
- **Semileptonic Decays**



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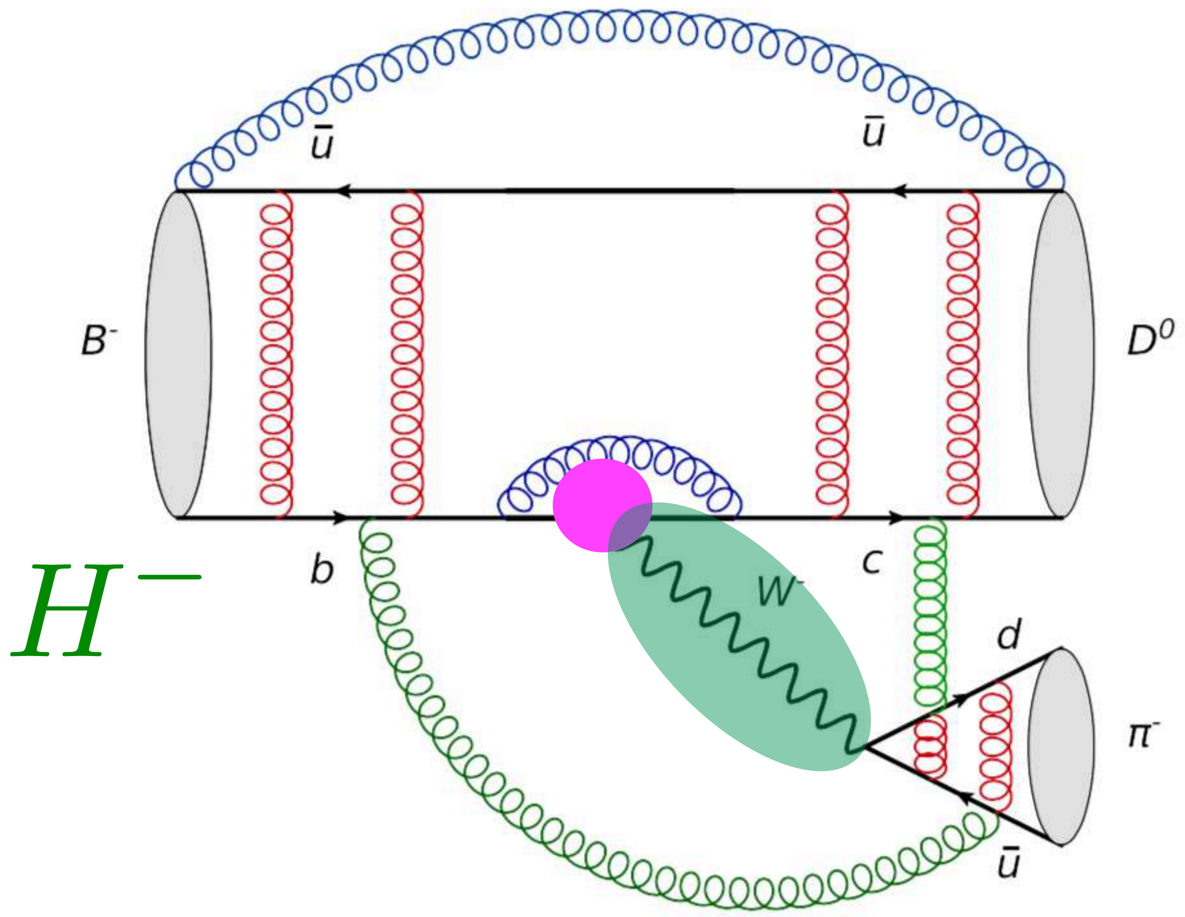

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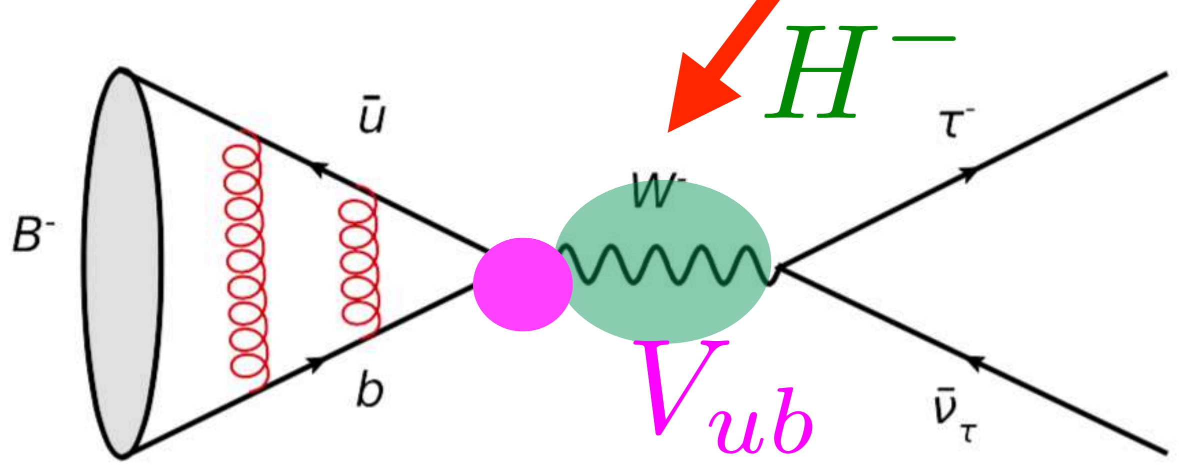
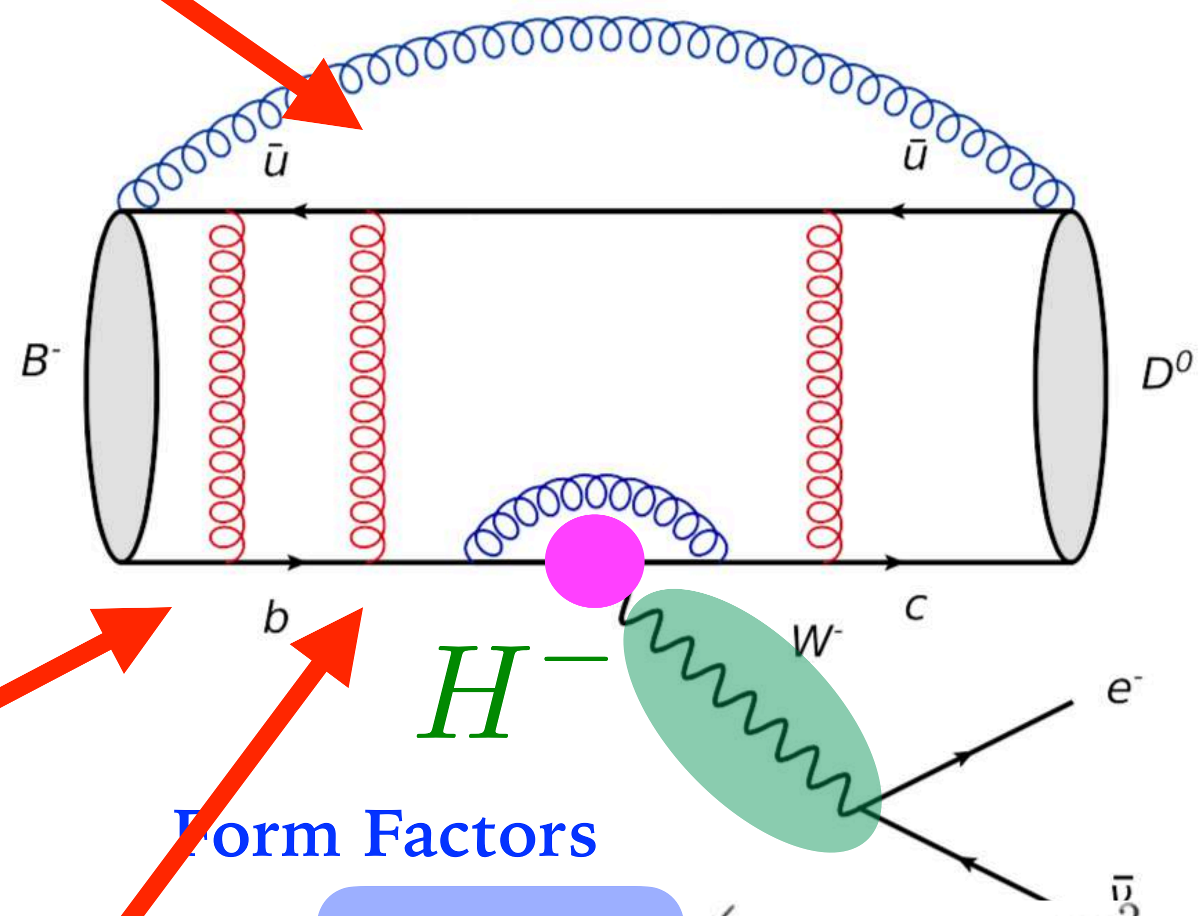
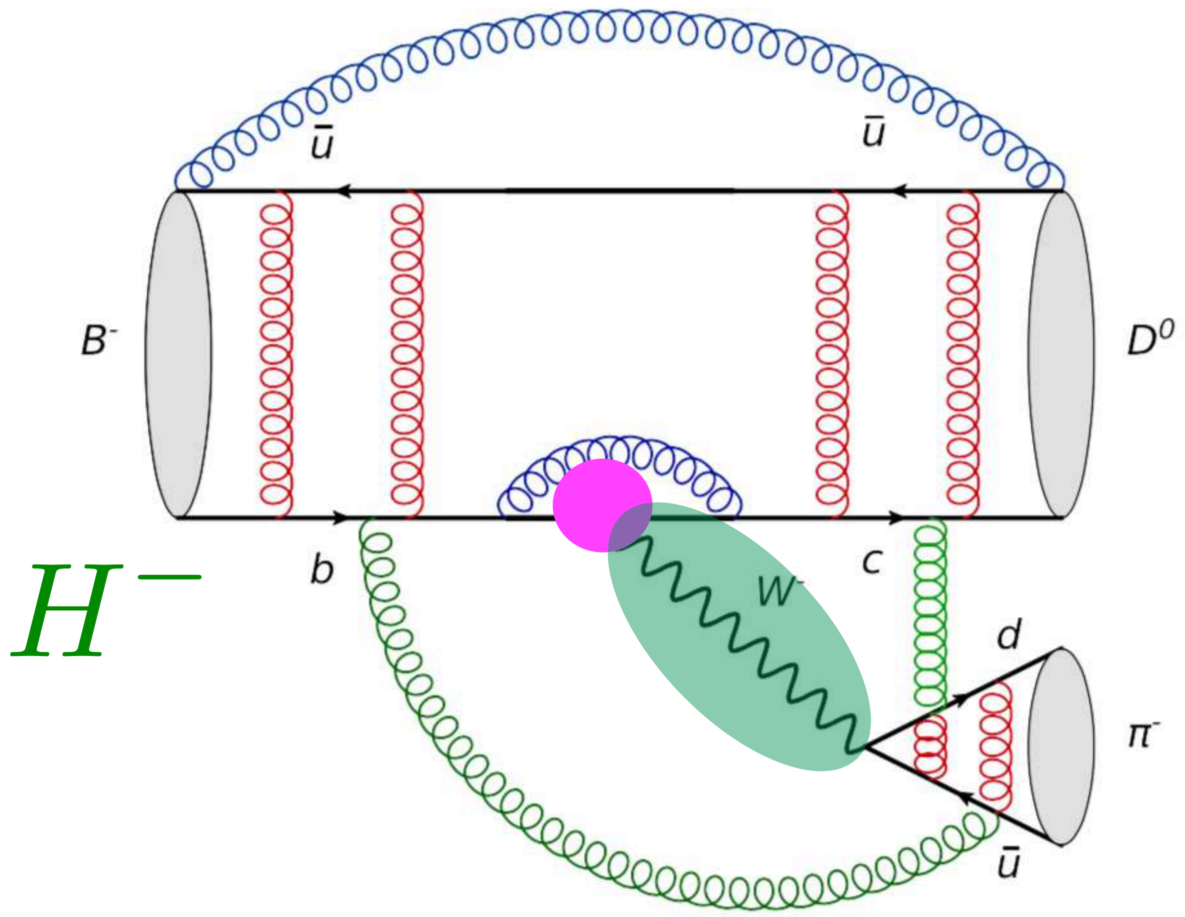
- Semileptonic Decays
- Non-leptonic Decays







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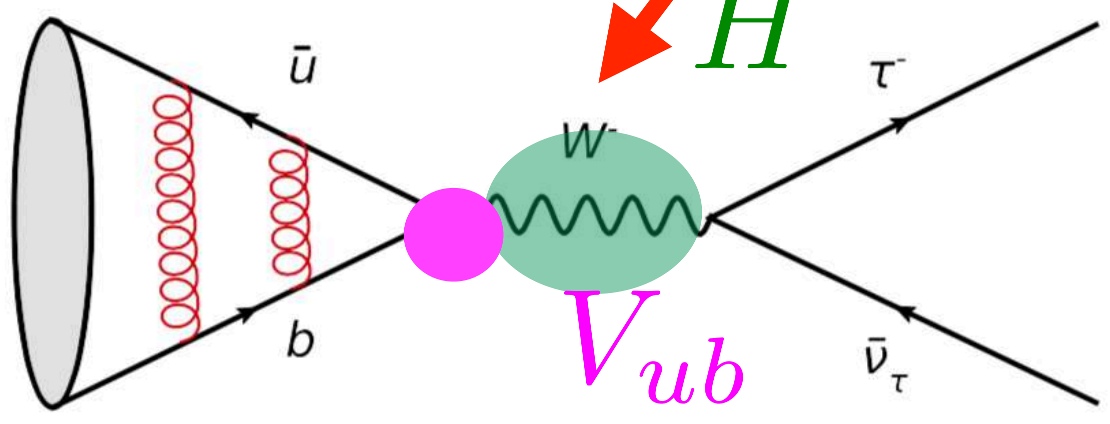

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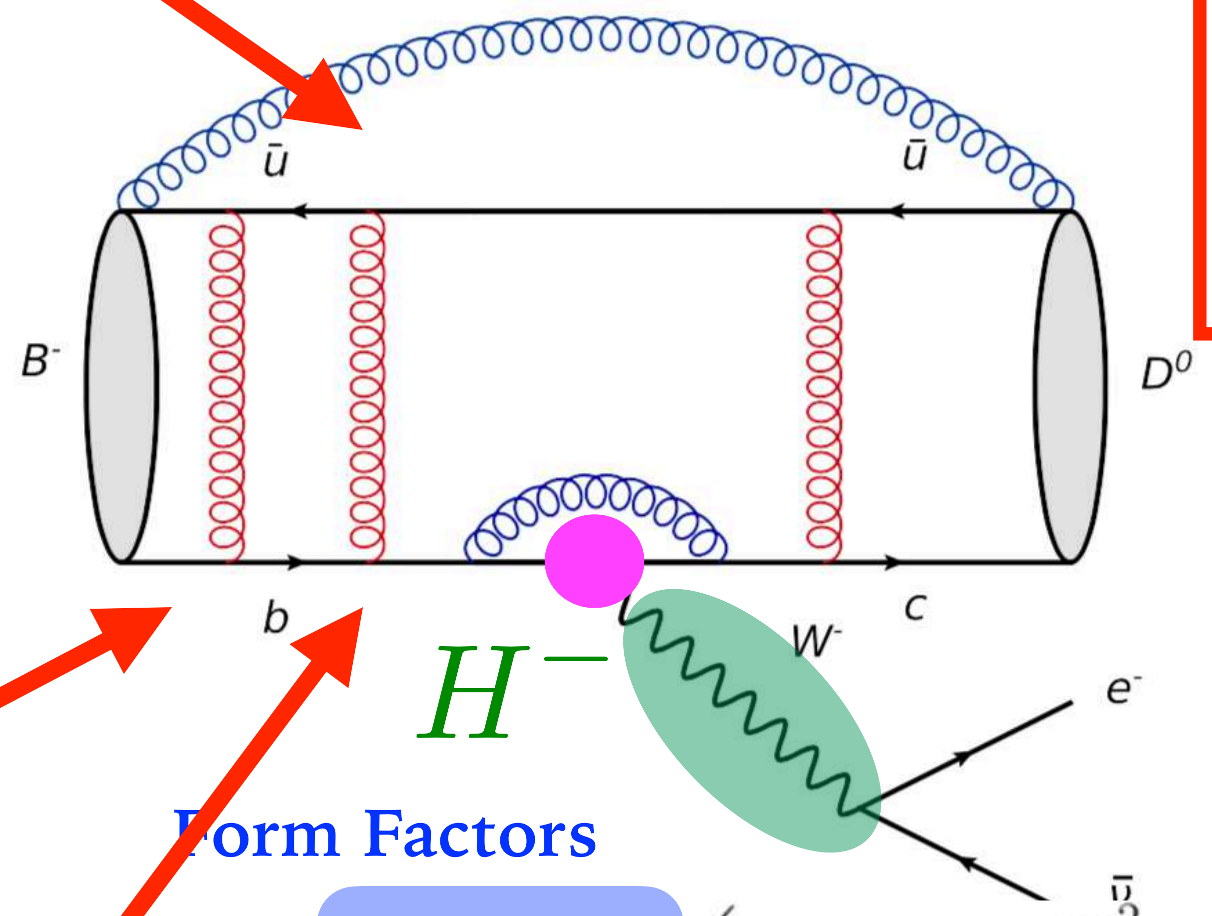

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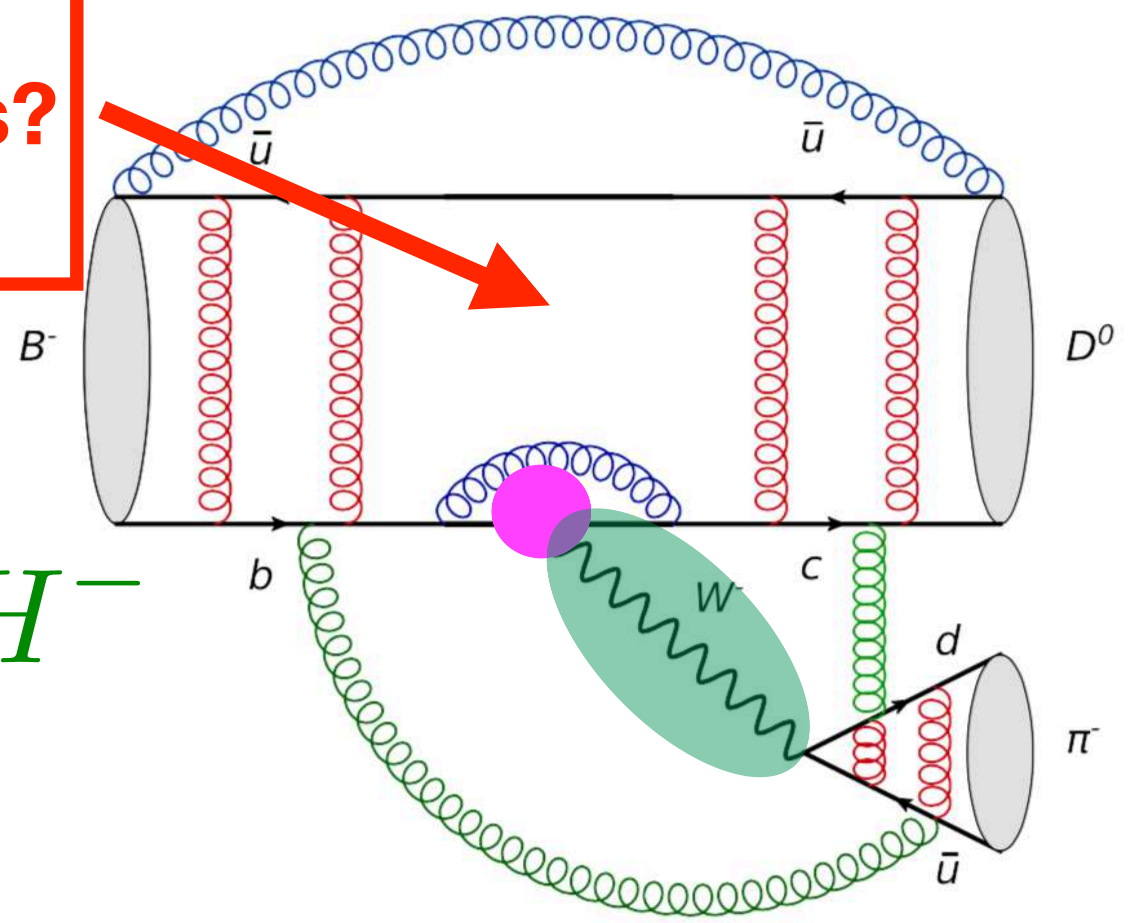

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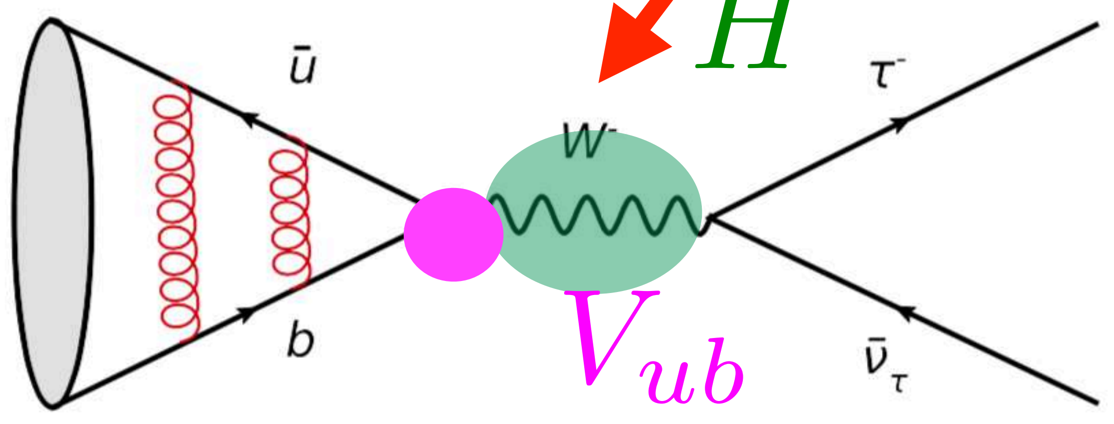

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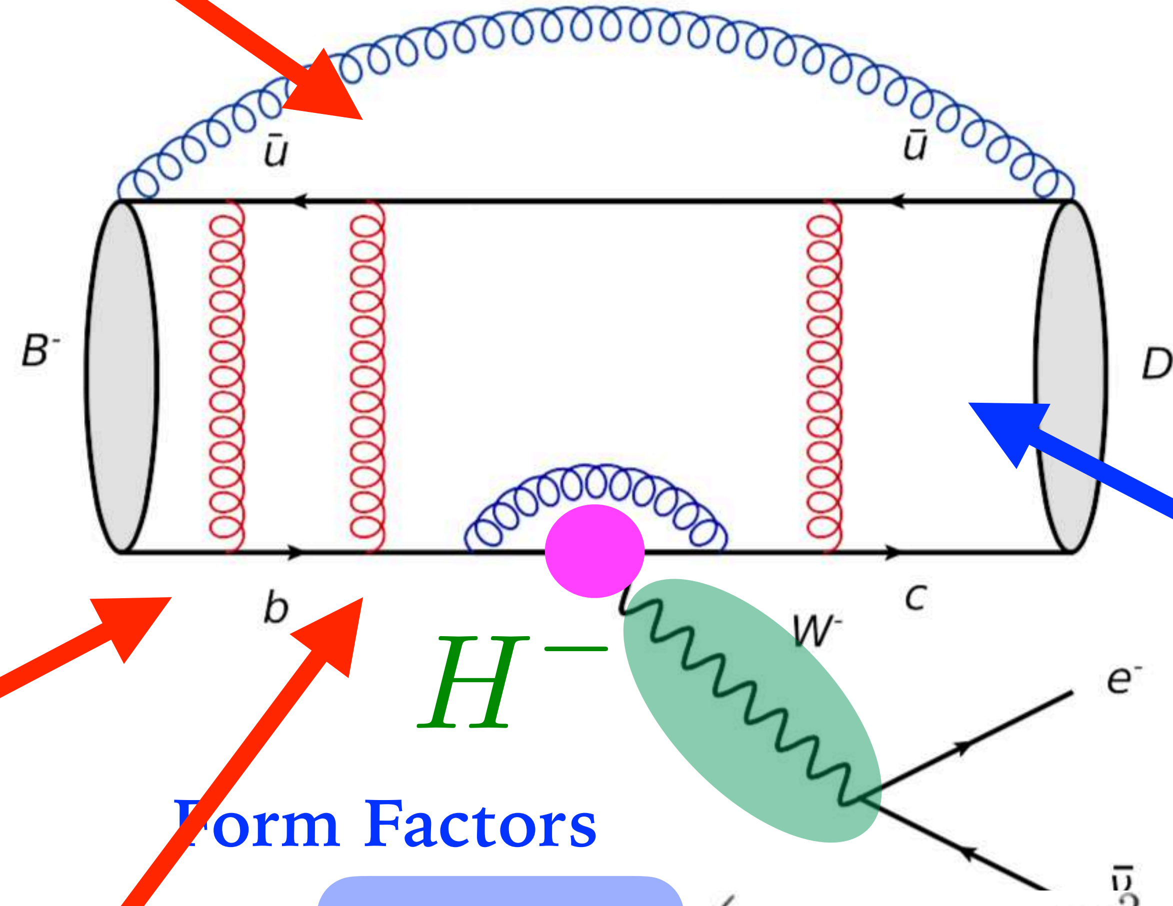

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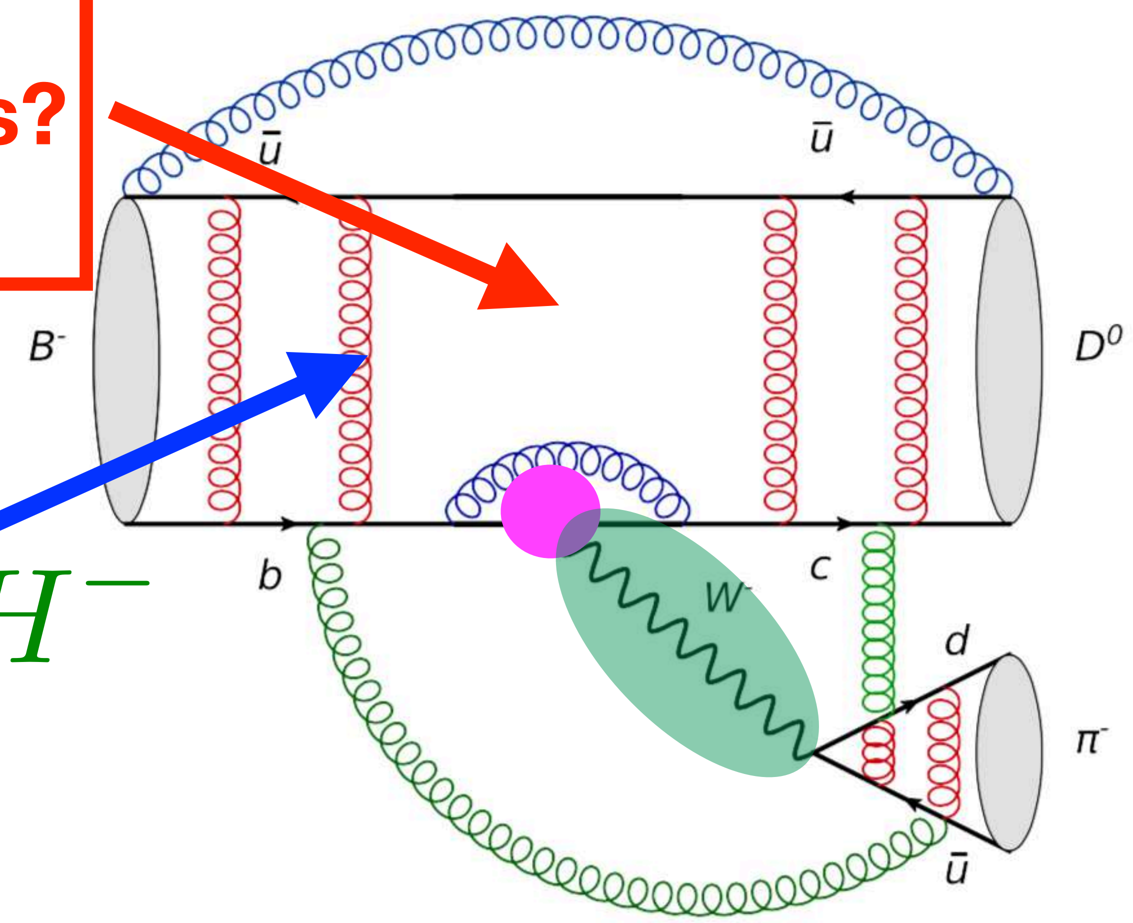
QCDf



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Ancient Anomalies

V_{cb}: inclusive vs. exclusive

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

Bordone, Caddevilla, Gambino 2107.00604

Based on NNNLO-QCD!!!

Fael, Schönwald, Steinhauser 2011.13654

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

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

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Study quark mass definitions

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Improved form factors

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

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

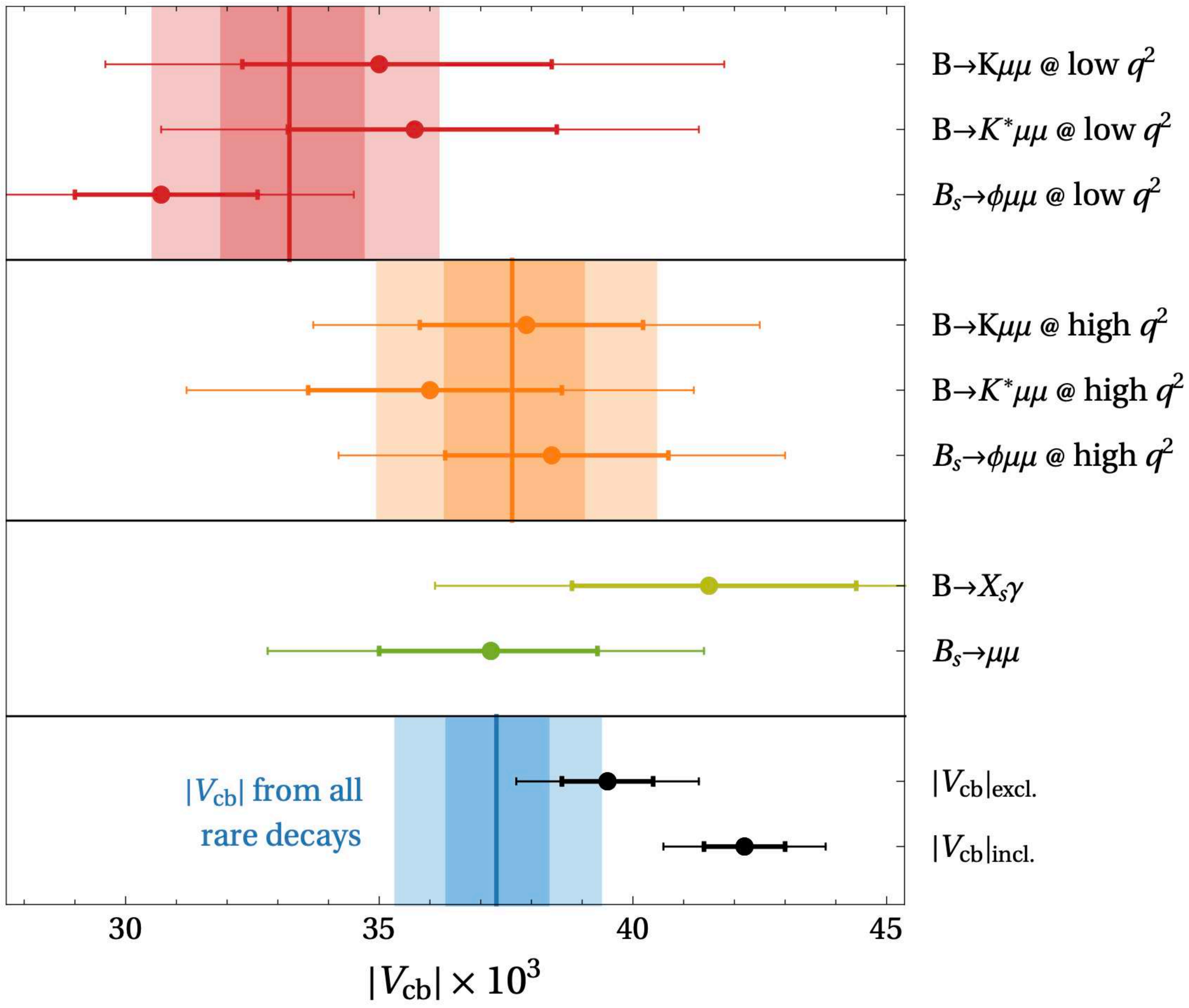
Perfect match

around 3σ deviation

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

B Anomalies

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



Altmannshofer, Lewis 2112.03437

B 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.

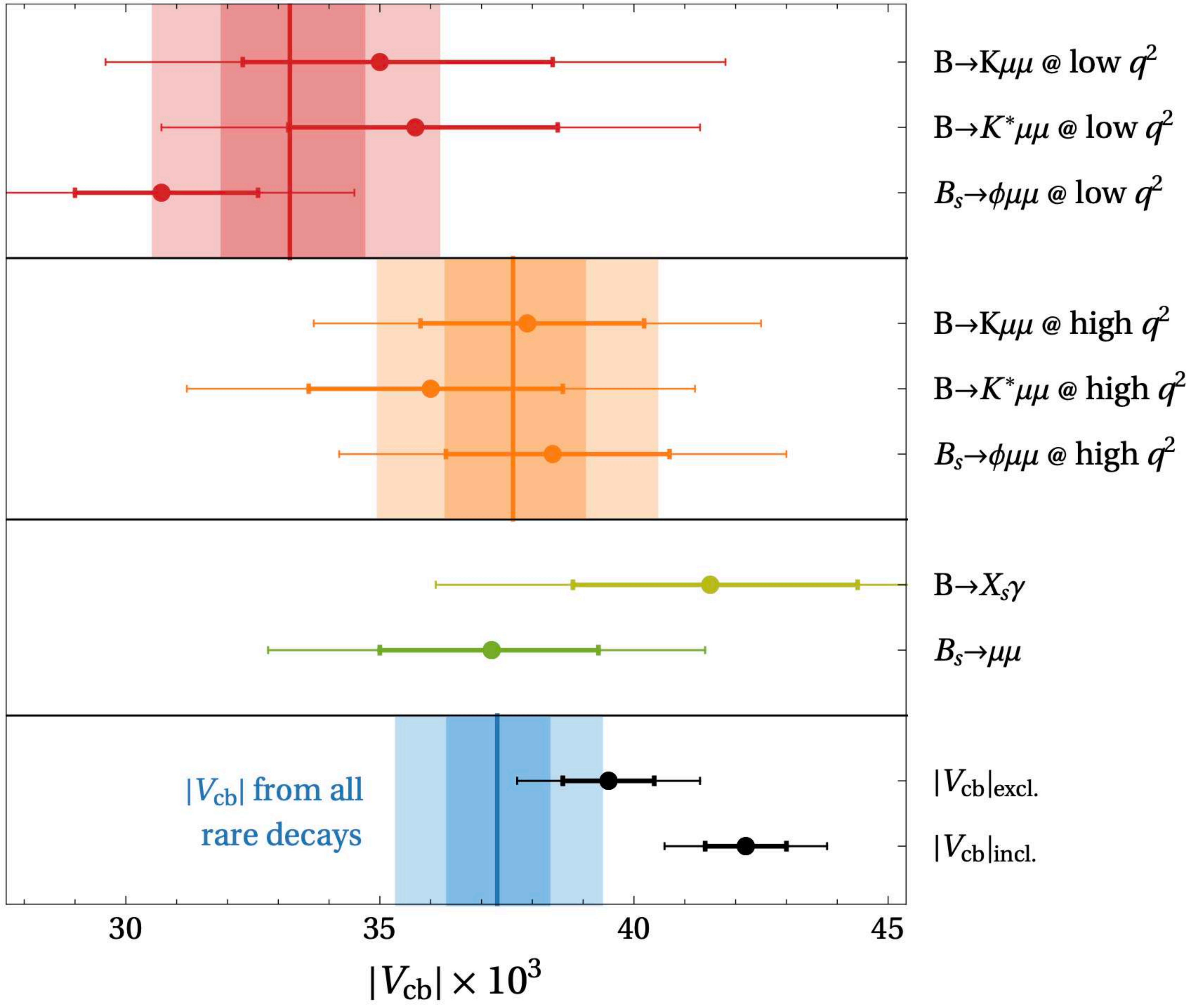
[43] M. Hansen, A. Lupo, and N. Tantalo, *Extraction of spectral densities from lattice correlators*, Phys. Rev. D **99** (2019) 094508, arXiv:1903.06476.

[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.



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The usual Suspects:

- High precision in γ^{CKM}

within the SM

LHCb

$$\gamma = \left(65.4^{+3.8}_{-4.2}\right)^\circ$$

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

Joachim Brod and Jure Zupan

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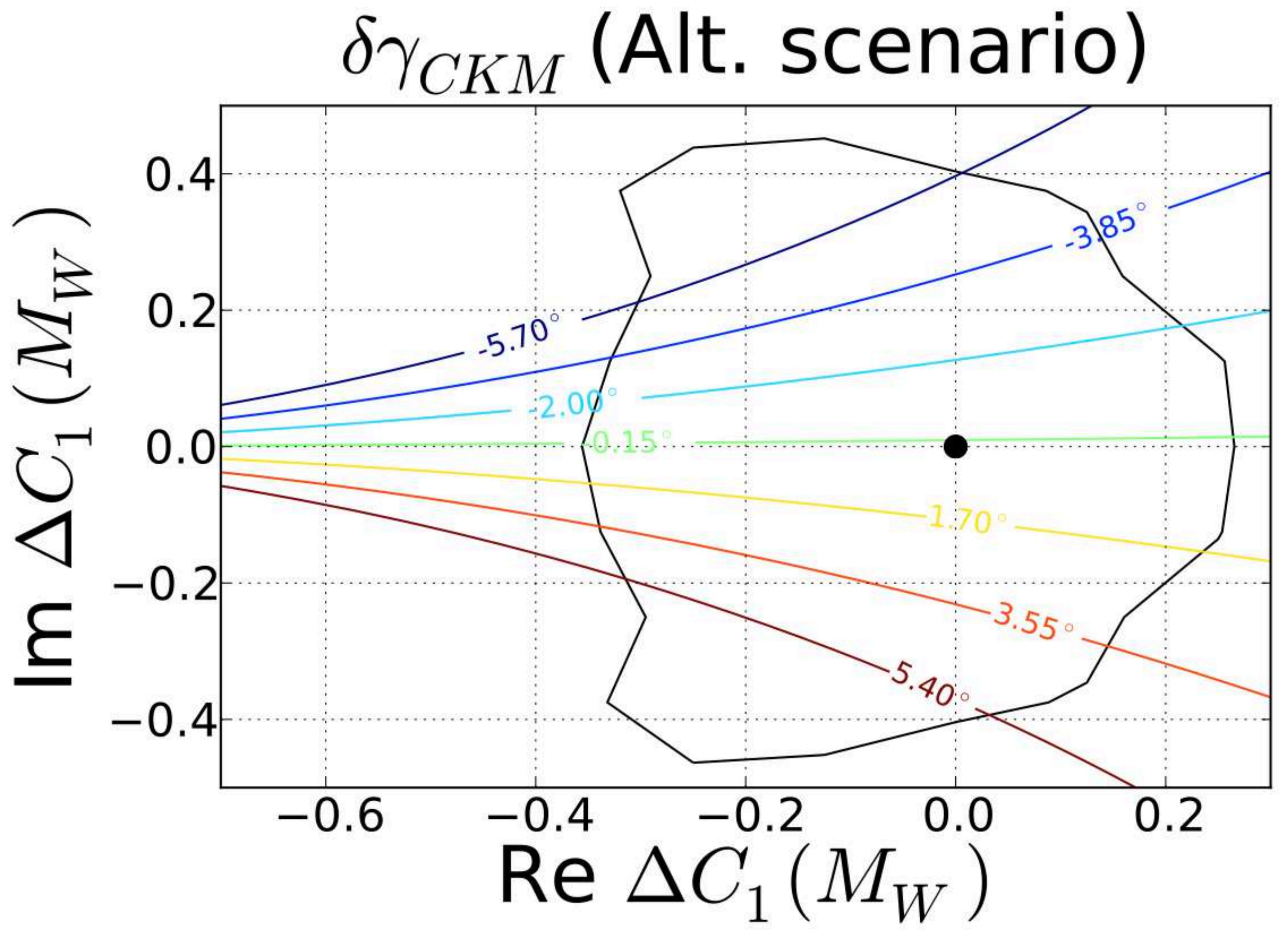
ABSTRACT: The angle γ of the standard CKM unitarity triangle can be determined from $B \to DK$ decays with a very small irreducible theoretical error, which is only due to second-order electroweak corrections. We study these contributions and estimate that their impact on the γ determination is to introduce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

Allow BSM effects in tree-level

$$C_1(M_W) := C_1^{\text{SM}}(M_W) + \Delta C_1(M_W),$$
$$C_2(M_W) := C_2^{\text{SM}}(M_W) + \Delta C_2(M_W),$$



Brod, AL, Tetlamatzi-Xolocotzi 1412.1446

AL, Tetlamatzi-Xolocotzi 1912.07621

Ancient 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

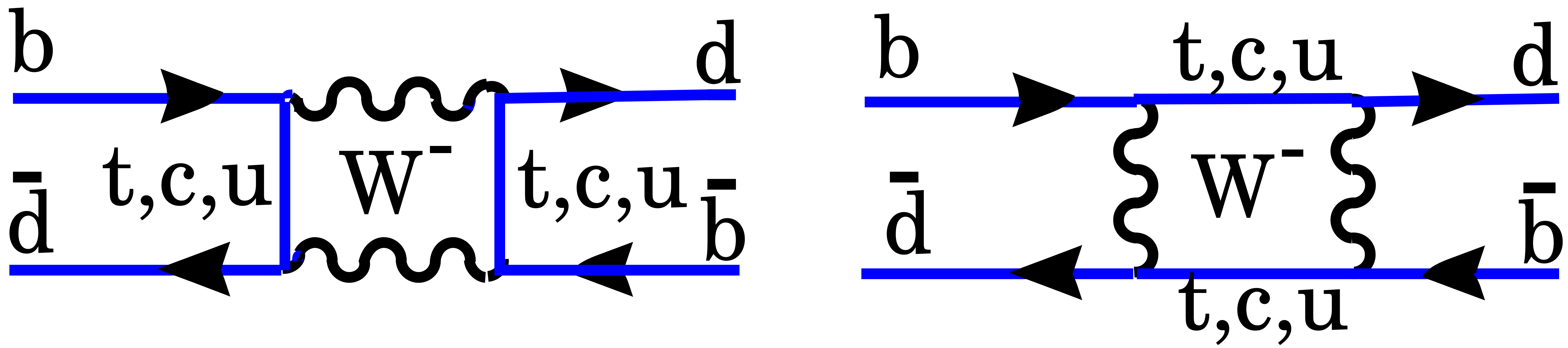
New interpretation of experimental measurement

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

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



$|M_{12}|$, $|\Gamma_{12}|$ and $\phi = \text{arg}(-M_{12}/\Gamma_{12})$ 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, ...

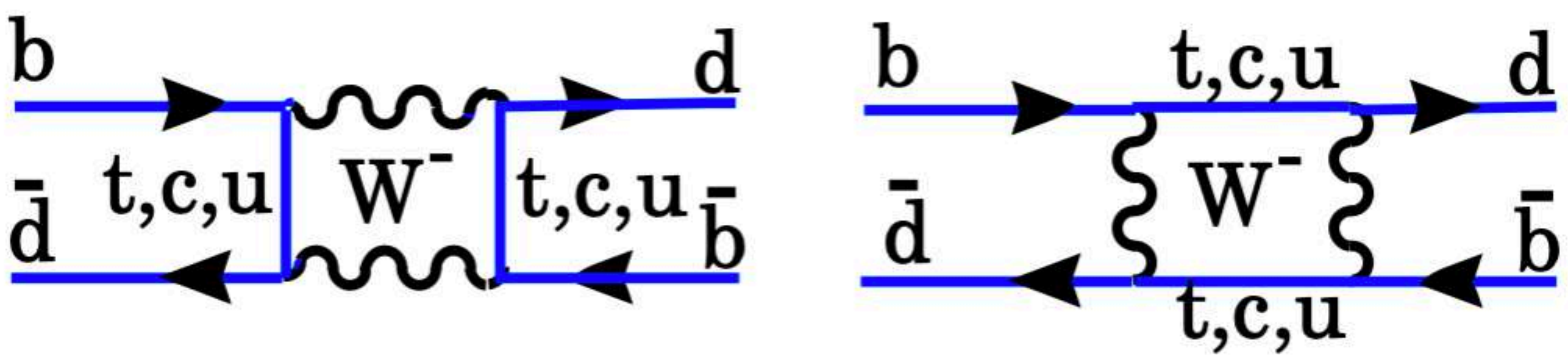
- **Decay rate difference:** $\Delta\Gamma := \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi$ **(on-shell)**
  $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!

- **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

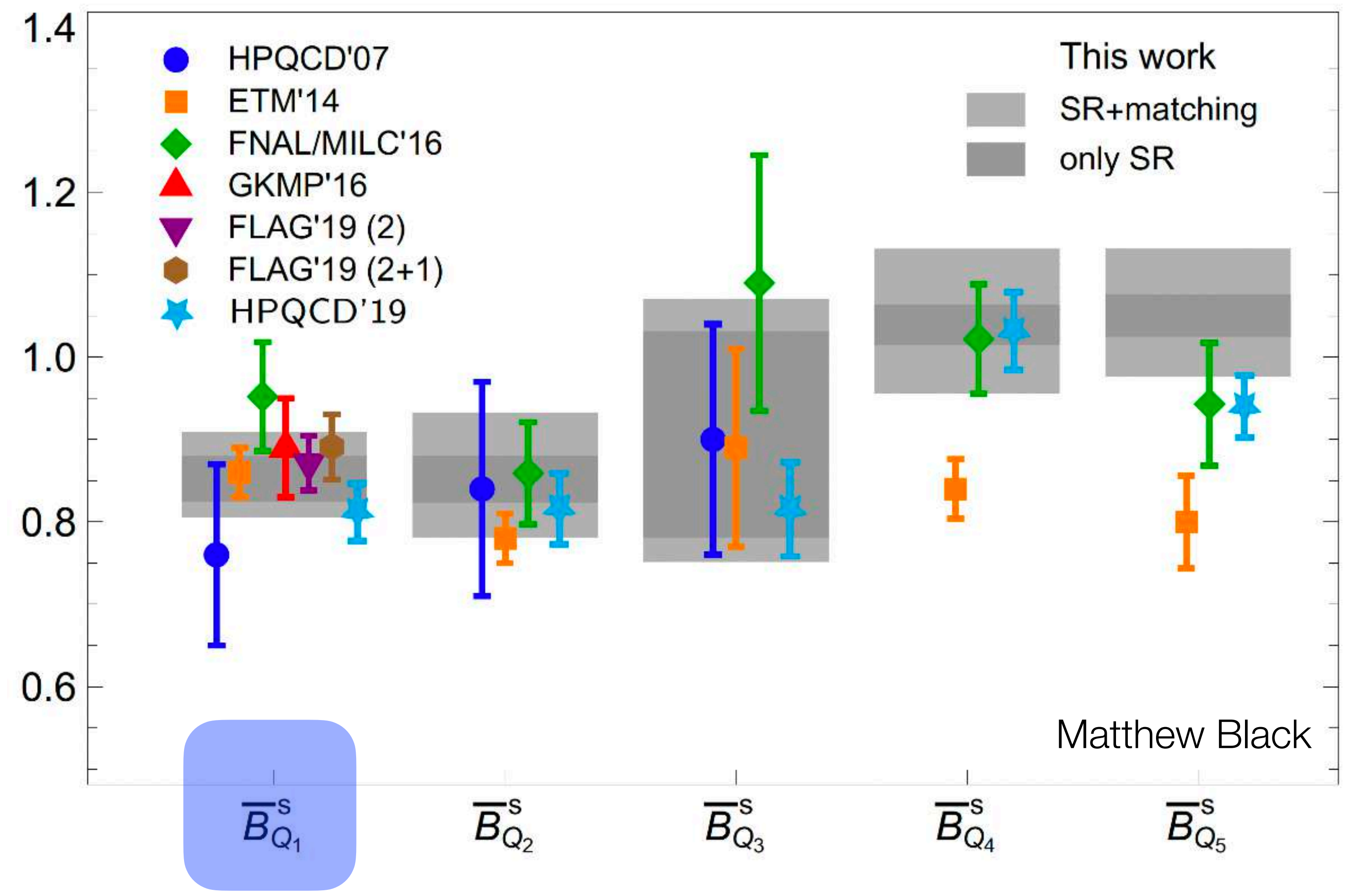
$$\Delta M_s = 2|M_{12}^s|$$



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

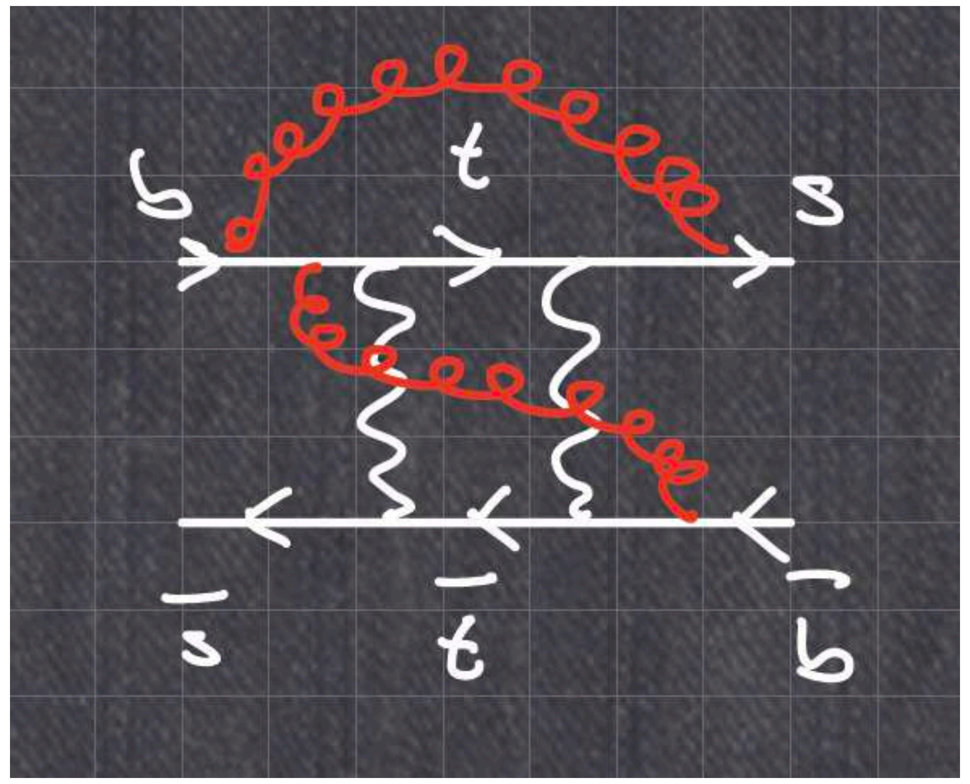
Significant CKM dependence

By far dominant uncertainty



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



2-loop: Buras, Jamin, Weisz

3-loop: Gorbahn,...

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

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

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

Status Quo: Mixing

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

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

HFLAV 2021

1909.11087
Average lattice & sum rules

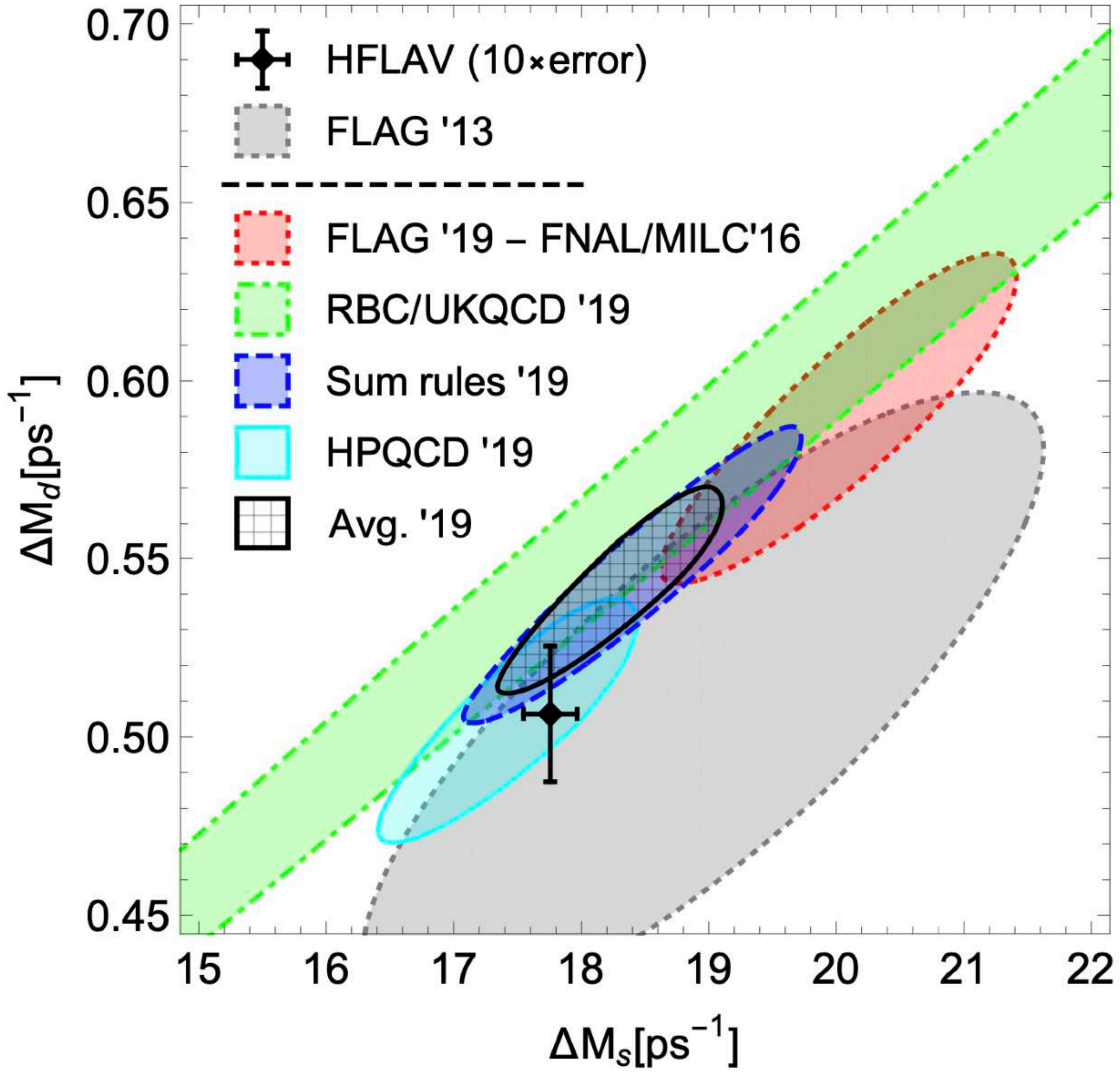
http://lhcb-public.web.cern.ch

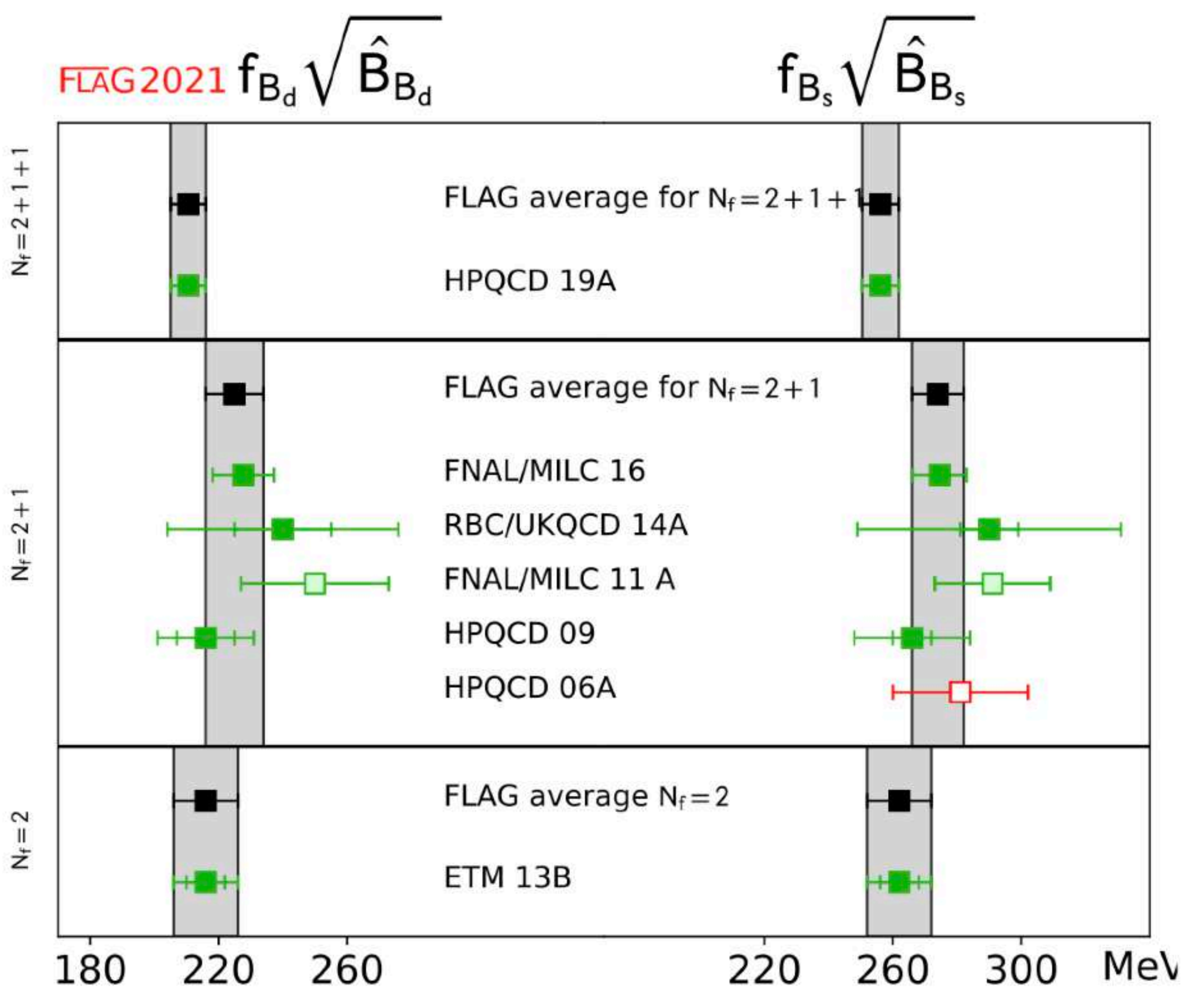
12 April 2021: Fascinating quantum mechanics.

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

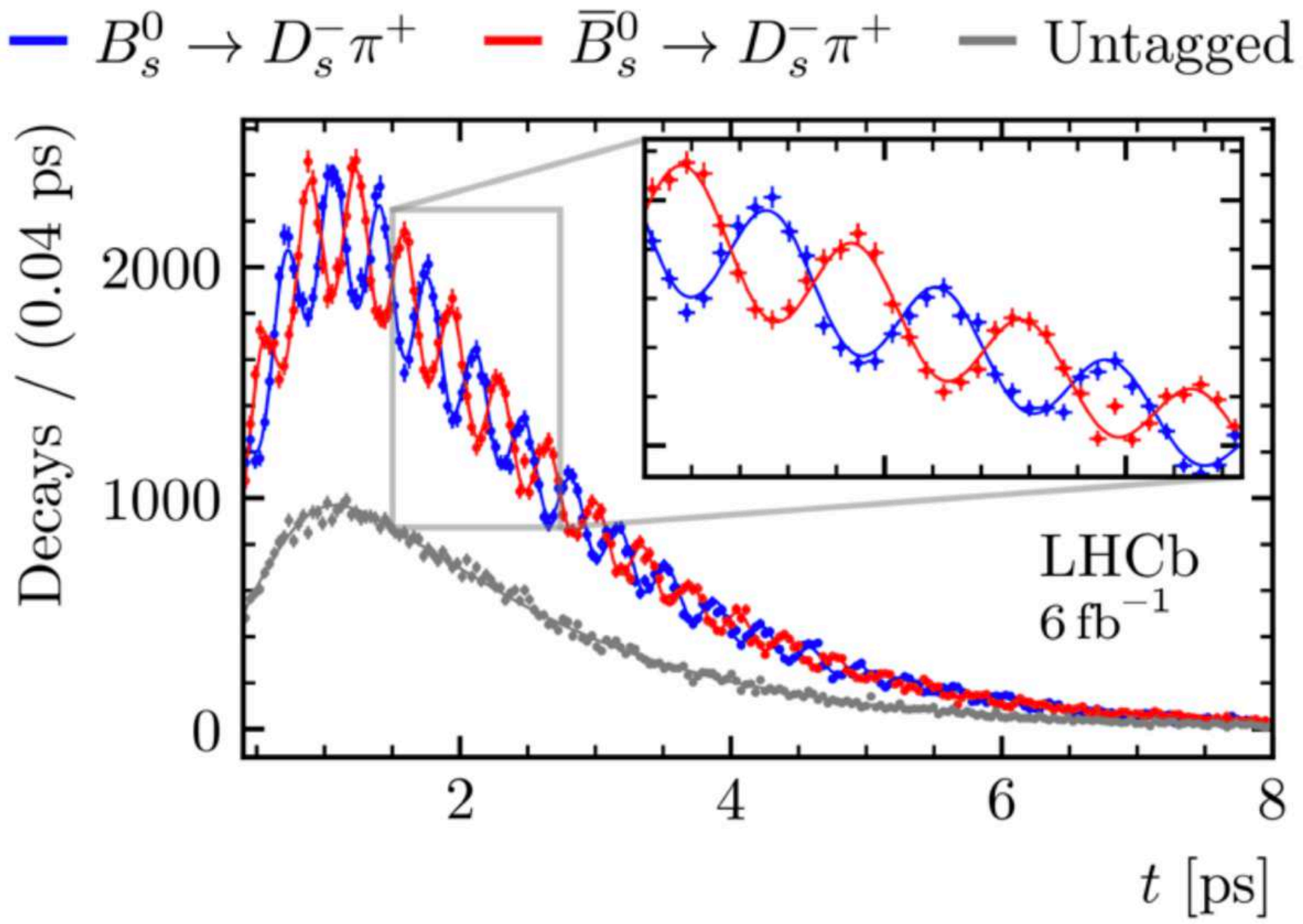
"A phenomenon in which quantum mechanics gives a most remarkable prediction" - Richard Feynman

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 ($3 \cdot 10^{12}$) as seen in the image below.





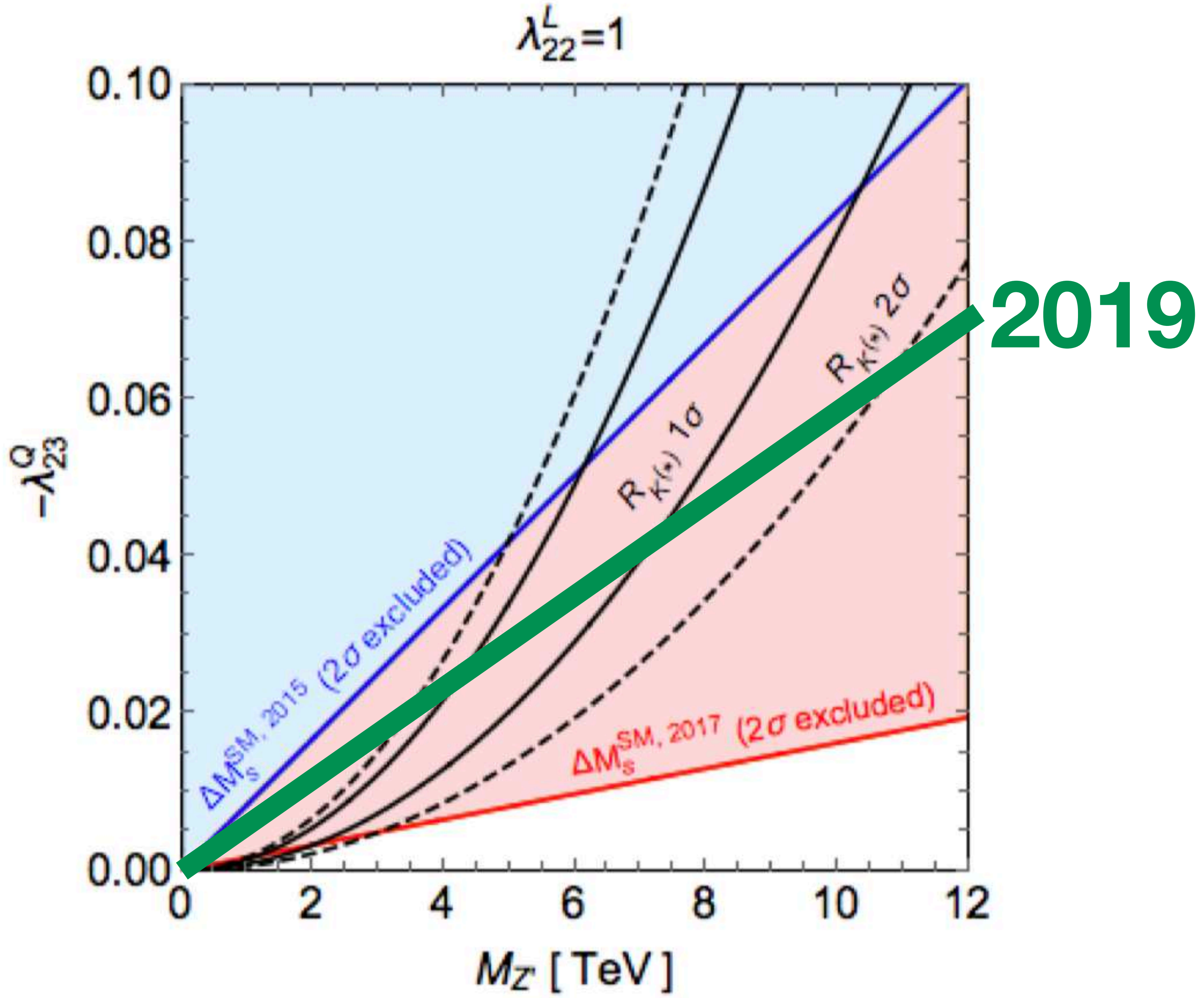
Work in progress by
RBC/UKQCD+JLQCD 2111.11287

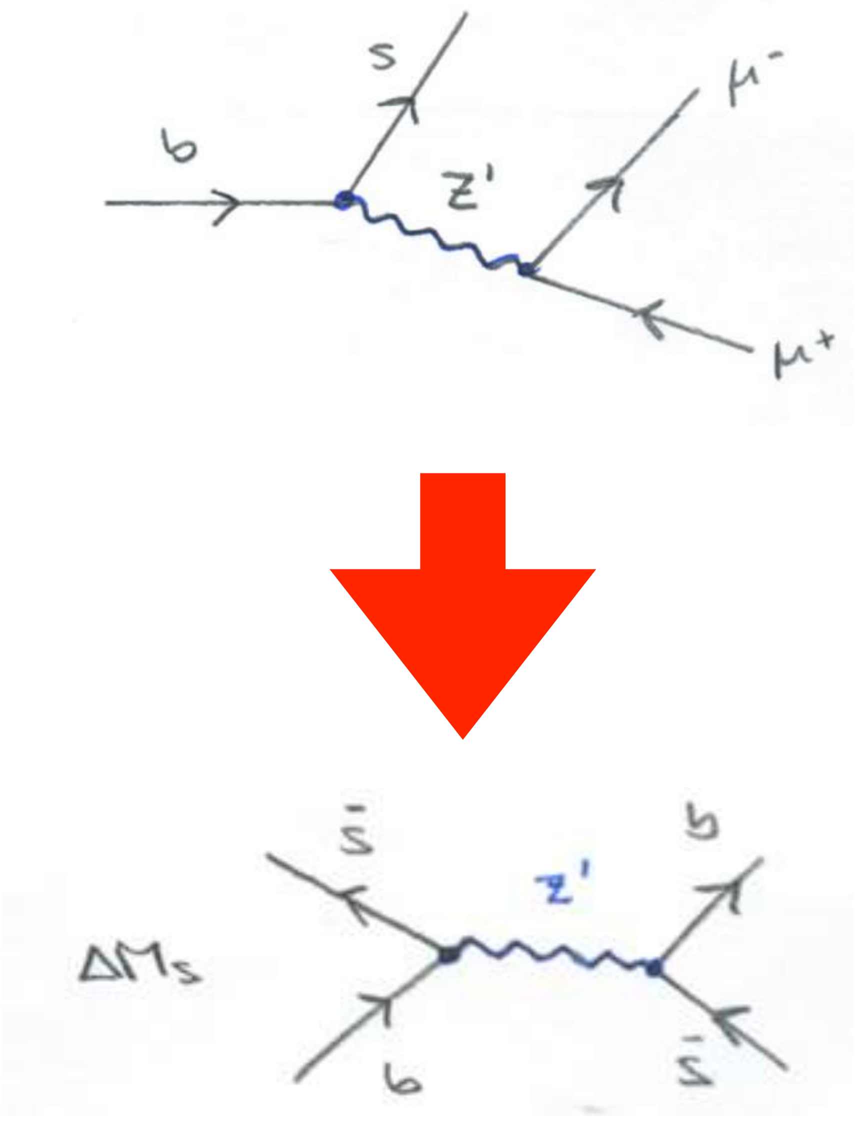


Higher precision for Bag

Status Quo: Mixing

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





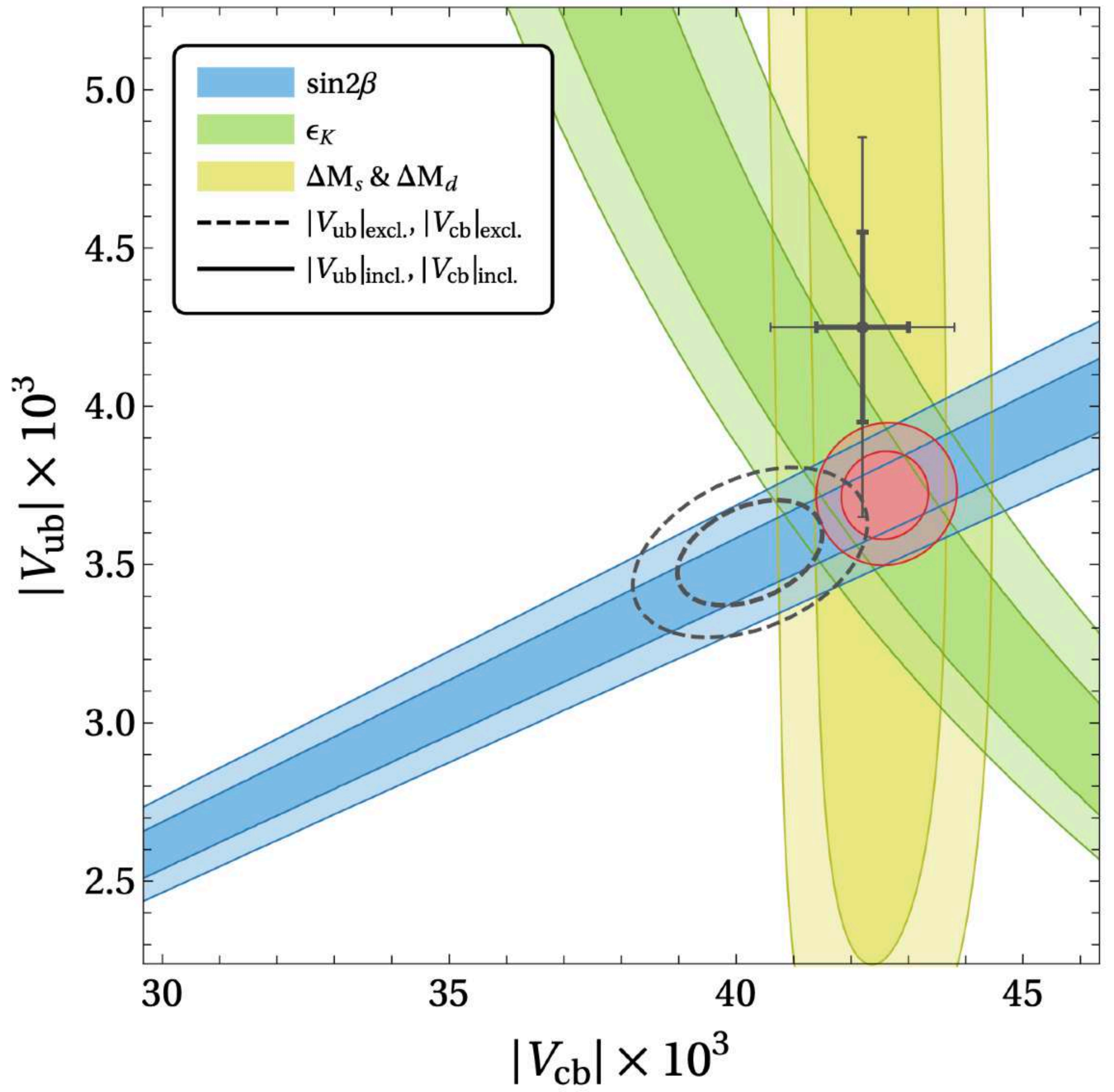
One constraint to kill them all?

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

The usual Suspects:

PHYSICAL REVIEW D **104,** 035028 (2021)

Editors' Suggestion

Collider signals of baryogenesis and dark matter from B mesons: A roadmap to discovery

Gonzalo Alonso-Álvarez,[1,2,*] Gilly Elor,[3,†] and Miguel Escudero[4,‡]

- Semileptonic CP asymmetries a^d_{sl}, a^s_{sl} - Could explain Baryon asymmetry...

Semi-leptonic CP asymmetries

Relation to experiment

$$\Re\left(\frac{\Gamma^q_{12}}{M^q_{12}}\right) = -\frac{\Delta\Gamma_s}{\Delta M_q}$$

CP violating!

$$\Im\left(\frac{\Gamma^q_{12}}{M^q_{12}}\right) = a^q_{sl}$$

- **Decay constants cancel completely**
- **Bag parameter cancel largely**

Status Quo: Mixing

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

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 $\tilde{\Gamma}_i = \tilde{\Gamma}_i^{(0)} + \frac{\alpha}{4\pi}\tilde{\Gamma}_i^{(1)} + \ldots$

$\tilde{\Gamma}_6^{(1)}$
- 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

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

CP Violation

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

$$A_{\rm fs}^q = \frac{\Gamma\left(\bar{B}_q(t) \to f\right) - \Gamma\left(B_q(t) \to \bar{f}\right)}{\Gamma\left(\bar{B}_q(t) \to f\right) + \Gamma\left(B_q(t) \to \bar{f}\right)}$$

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

$$a_{\rm fs}^q \approx \frac{|\Gamma_{12}^q|}{|M_{12}^q|} \sin \phi_{12}^q$$

e.g. $B \to Xl\nu$
or $\bar{B}_s \to D_s^+ \pi^-$
or $\bar{B}_d \to D^+ K^-$

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

$$A_{\rm ind}^q = \frac{\Gamma\left(\bar{B}_q(t) \to f\right) - \Gamma\left(B_q(t) \to f\right)}{\Gamma\left(\bar{B}_q(t) \to f\right) + \Gamma\left(B_q(t) \to f\right)}$$

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**

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

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

Time evolution

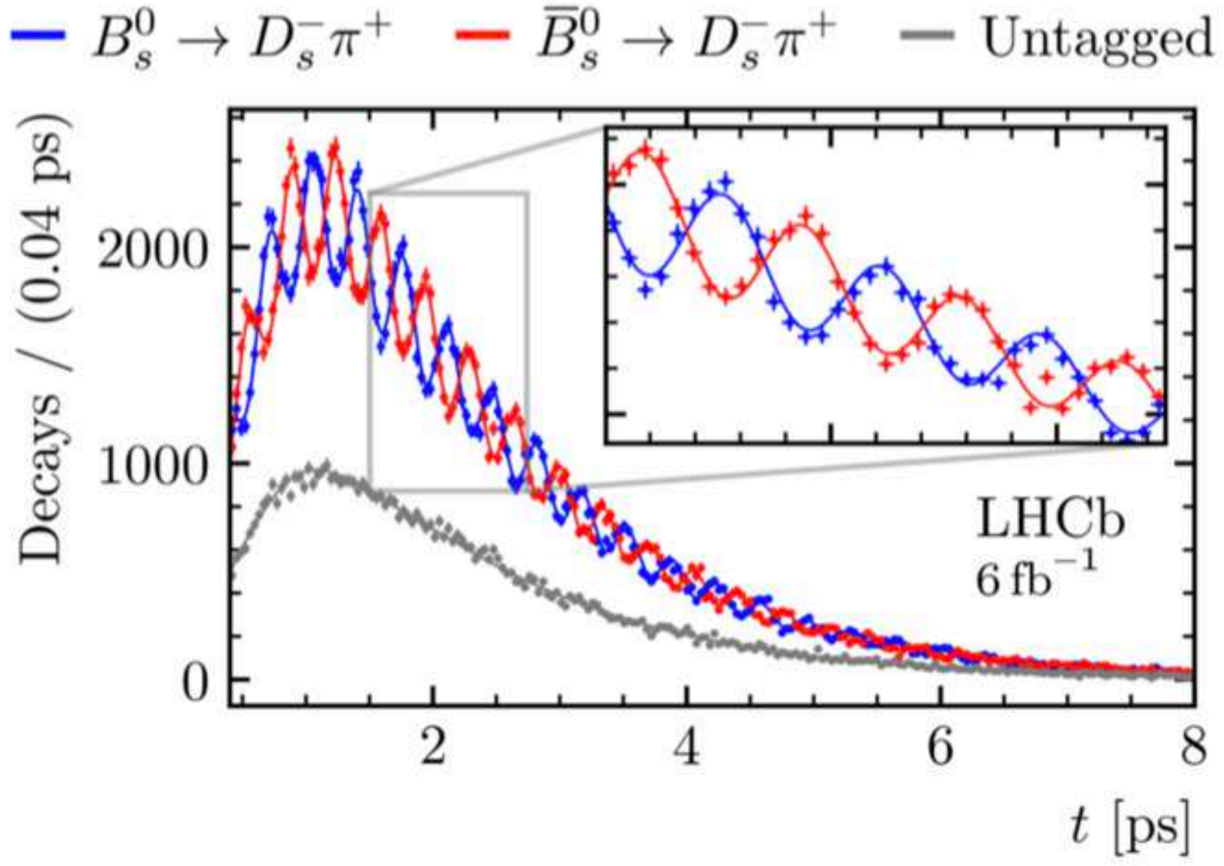
Time evolution of neutral B mesons (quantum mechanics on a macroscopic scale)

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

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



Status Quo: CPV in Interference

$$A_{CP,f}(t) = \frac{\Gamma\left(\bar{B}_s^0(t) \to f\right) - \Gamma\left(B_s^0(t) \to f\right)}{\Gamma\left(\bar{B}_s^0(t) \to f\right) + \Gamma\left(B_s^0(t) \to f\right)} = -\frac{A_{\rm CP}^{\rm dir}\cos(\Delta M_s t) + A_{\rm CP}^{\rm mix}\sin(\Delta M_s t)}{\cosh(\frac{\Delta\Gamma_s t}{2}) + A_{\Delta\Gamma}\sinh(\frac{\Delta\Gamma_s t}{2})}$$

$$A_{\rm CP}^{\rm dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad A_{\rm CP}^{\rm mix} = -\frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}, \quad A_{\Delta\Gamma} = -\frac{2\Re(\lambda_f)}{1+|\lambda_f|^2}.$$

$$\lambda_f \approx -\frac{V_{ts}V_{tb}^*}{V_{ts}^*V_{tb}}\frac{\bar{A}_f}{A_f}\left[1 - \frac{a_{\rm fs}^s}{2}\right]$$

$$\mathcal{A}_f = \langle f|\mathcal{H}_{eff}|B_s^0\rangle$$
$$\bar{\mathcal{A}}_f = \langle f|\mathcal{H}_{eff}|\bar{B}_s^0\rangle$$

CP violation in the B_s^0 system

Marina Artuso (Syracuse U.), Guennadi Borissov (Lancaster U.), Alexander Lenz (Durham U., IPPP) (Nov 30, 2015)

Published in: *Rev.Mod.Phys.* 88 (2016) 4, 045002, *Rev.Mod.Phys.* 91 (2019) 4, 049901 (addendum) • e-Print: 1511.09466 [hep-ph]

If there is **only one decay topology** contributing to the decay

$$\mathcal{A}_f = |\mathcal{A}_f^{\rm Tree}|\, e^{i\left[\phi_{\rm Tree}^{\rm QCD} + \arg(\lambda_c)\right]}$$

$$\bar{\mathcal{A}}_{\bar{f}} = |\mathcal{A}_f^{\rm Tree}|\, e^{i\left[\phi_{\rm Tree}^{\rm QCD} - \arg(\lambda_c)\right]}$$

$$\frac{\bar{\mathcal{A}}_{f_{\rm CP}}}{\mathcal{A}_{f_{\rm CP}}} = -\eta_{\rm CP}e^{-2i\phi_j^{\rm CKM}}$$

All hadronic uncertainties are cancelling exactly in the CP asymmetry!

Gold-plated modes

Status Quo: CPV in Interference

If there are **two decay topologies** contributing to the decay

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

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

Could also be BSM if there is only one SM amplitude

Then the CP asymmetry depends on

$$\frac{\bar{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_f} = -e^{-2i\arg(\lambda_c)} \left[\frac{1 + re^{-i\arg\left(\frac{\lambda_u}{\lambda_c}\right)}}{1 + re^{+i\arg\left(\frac{\lambda_u}{\lambda_c}\right)}}\right]$$

with $r = |\mathscr{A}_f^{\text{Peng}}|/|\mathscr{A}_f^{\text{Tree}}|$

CP violation in the B_s^0 system

Marina Artuso (Syracuse U.), Guennadi Borissov (Lancaster U.), Alexander Lenz (Durham U., IPPP) (Nov 30, 2015)

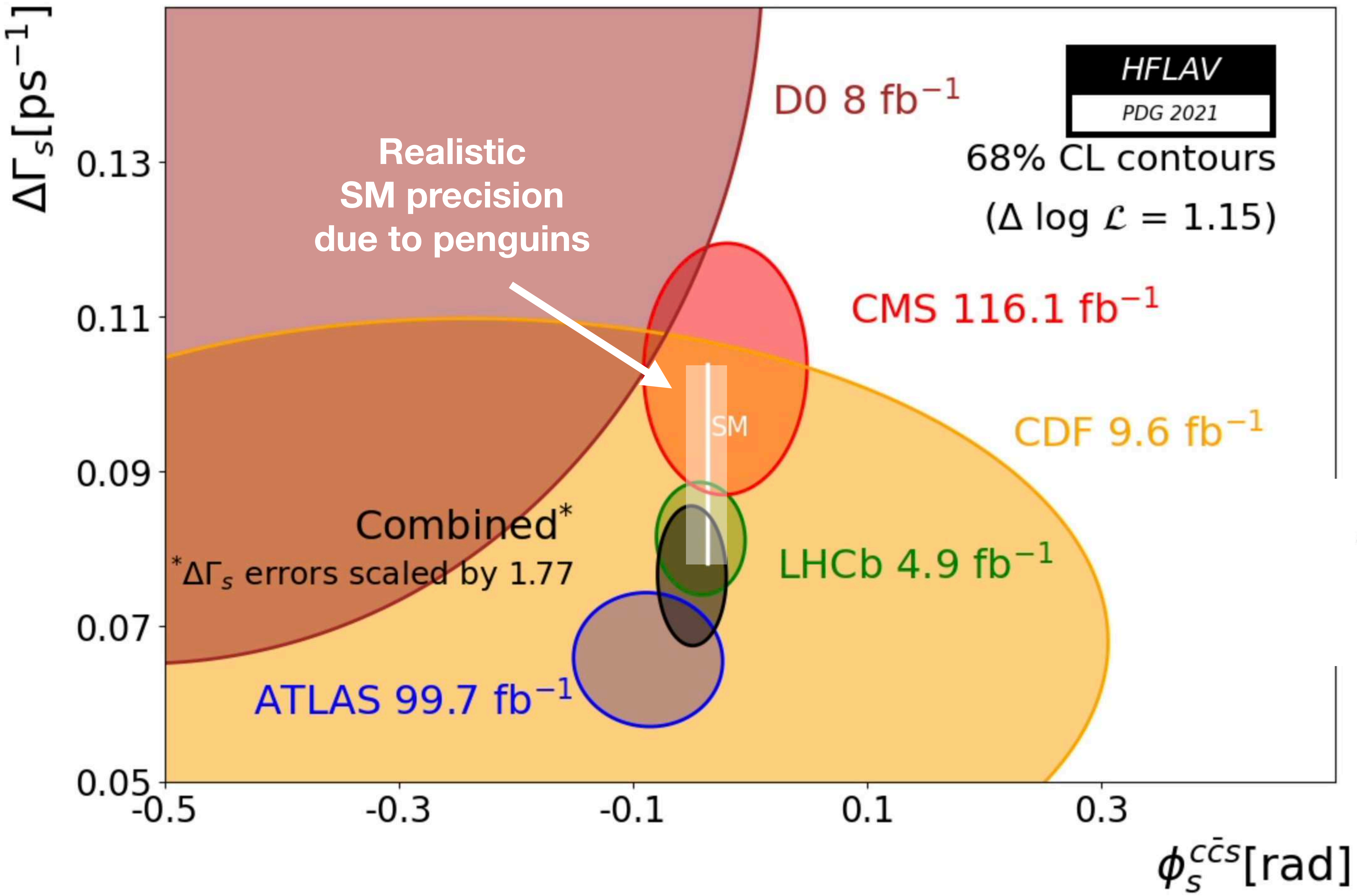
Published in: *Rev.Mod.Phys.* 88 (2016) 4, 045002, *Rev.Mod.Phys.* 91 (2019) 4, 049901 (addendum) • e-Print: 1511.09466 [hep-ph]

If penguins are small compared to tree-level, the hadronic corrections are cancelling to leading order and there is a correction proportional to r

Penguin pollution

Status Quo: CPV in Interference

Golden plated modes: $B_s \to J/\Psi\phi$



Modification due to **New Physics**

$$M_{12}^s = M_{12}^{s,\mathrm{SM}} |\Delta_s| e^{i\phi_s^\Delta}$$

$$\Gamma_{12}^s = \Gamma_{12}^{s,\mathrm{SM}} \left|\tilde{\Delta}\right| e^{-i\phi_s^{\tilde{\Delta}}}$$

$B_s \to J/\Psi\phi$

$$-2\beta_s^{\mathrm{Exp}} = -2\beta_{s,\mathrm{Tree}}^{\mathrm{SM}} + \phi_s^\Delta + \beta_{s,\mathrm{Peng}}^{\mathrm{SM}} + \beta_{s,\mathrm{Peng}}^{\mathrm{BSM}},$$

$$\phi_{12}^{s,\mathrm{Exp}} = \phi_{12}^{s,\mathrm{SM}} + \phi_s^\Delta + \tilde{\phi}_s^\Delta,$$

a_{fs}^s

not really constrained by $\phi_s^{c\bar{c}s}$

Status Quo: CPV in Decay

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

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

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

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

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)

Direct CP asymmetries

- $B \to K\pi$ puzzle still present, see. e.g. 1507.03700

  Updates: **2002.03262** complete 2-loop penguins
  2107.03819 QED corrections
  2104.14871 $A_{CP}(B^0 \to \pi^0 \bar{K}^0)$ Belle II
  SU(3) symmetry e.g. **1806.08783, 2111.06418,…**
  comprehensive phenomenological study missing

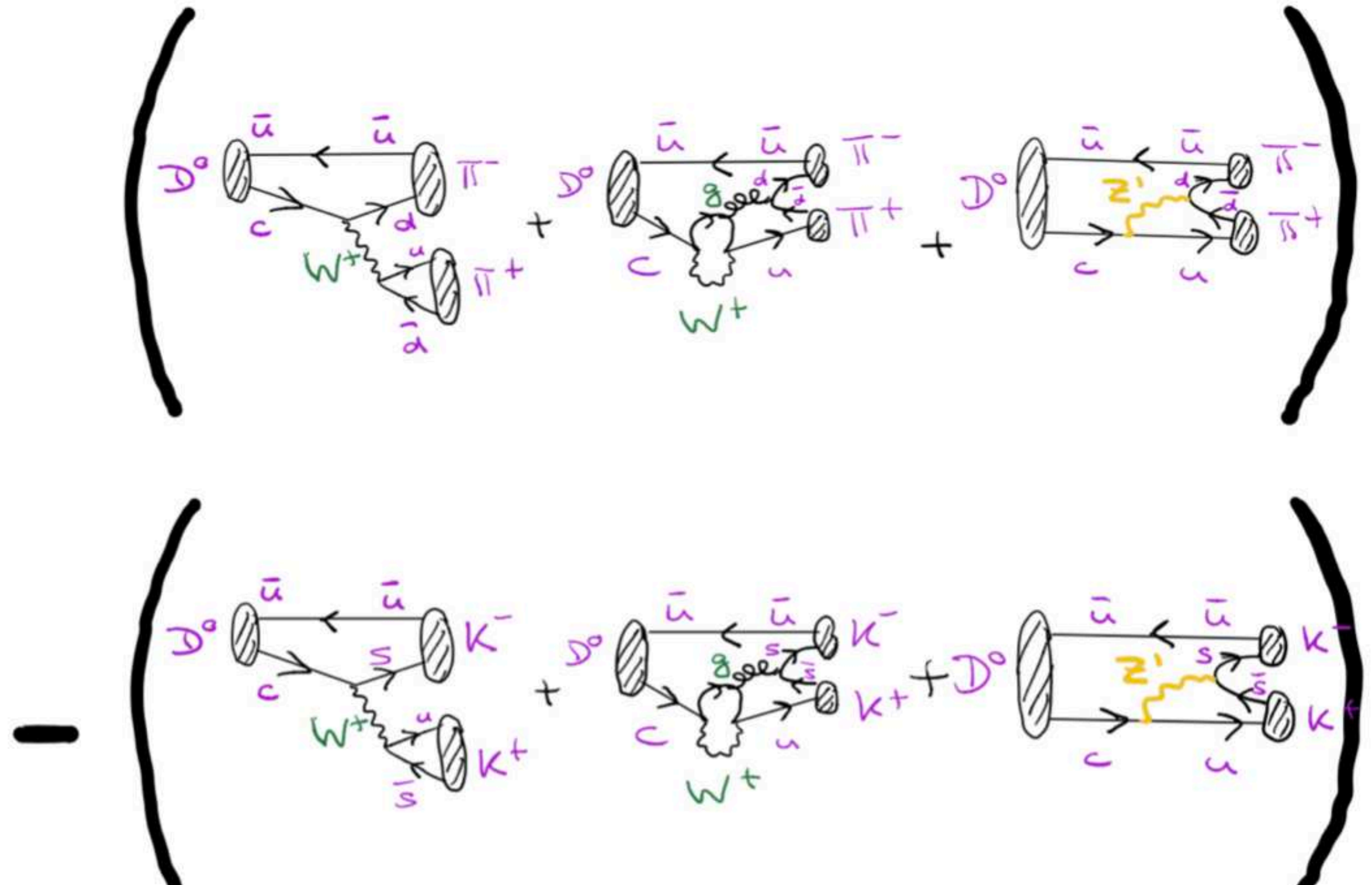
We need $r = |\mathscr{A}_f^{\text{Peng}}|/|\mathscr{A}_f^{\text{Tree}}|$

- ΔA_{CP}: direct CP violation in the charm system $D^0 \to K^+K^-$ vs. $D^0 \to \pi^+\pi^-$

  Experiment: LHCb 03/2019

  Theory: SM or not SM?
  E.g. 1903.10952,1909.03063 vs. 1903.10490, 1909.11242

We need $r = |\mathscr{A}_f^{\text{Peng}}|/|\mathscr{A}_f^{\text{Tree}}|$



Not so well-known:

Not so well-known:

Measurement of the relative width difference of the B^0-$\bar{B}^0$ system with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

Abstract: This paper presents the measurement of the relative width difference $\Delta\Gamma_d/\Gamma_d$ of the B^0-$\bar{B}^0$ system using the data collected by the ATLAS experiment at the LHC in pp collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of 25.2 fb^{-1}. The value of $\Delta\Gamma_d/\Gamma_d$ is obtained by comparing the decay-time distributions of $B^0 \to J/\psi K_S$ and $B^0 \to J/\psi K^{*0}(892)$ decays. The result is $\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1\ \text{(stat.)} \pm 0.9\ \text{(syst.)}) \times 10^{-2}$. Currently, this is the most precise single measurement of $\Delta\Gamma_d/\Gamma_d$. It agrees with the Standard Model prediction and the measurements by other experiments.

JHEP06(2016)081

$\Delta\Gamma_d$: A Forgotten Null Test of the Standard Model

Tim Gershon[1]

- $\tau(B_s)/\tau(B_d)$ and $\Delta\Gamma_d$

Remember: D0 di muon asymmetry….

- $b \to d\ell\ell$, e.g. differential q^2 distr. & CP asym. in $B \to \pi\ell\ell$, see e.g. **Rusov 1911.12819**, R_π
- $b \to s\tau\tau$ transitions, e.g. **Cornella, Isidori, König, Liechti, Owen 2001.04470**
- Inclusive $B \to X_s\ell\ell$, e.g. **Huber, Hurth, Jenkins, Lunghi, Qin, Vos 2007.04191**
- $B \to D^*\mu\nu$- angular distribution, or even better $B \to D^*\tau\nu$ distribution q^2 distribution not enough, as effects of some NP operators can only be seen in particular angular observables

Rusa Mandal, Clara Murgui, Ana Peñuelas, Antonio Pich 2004.06726

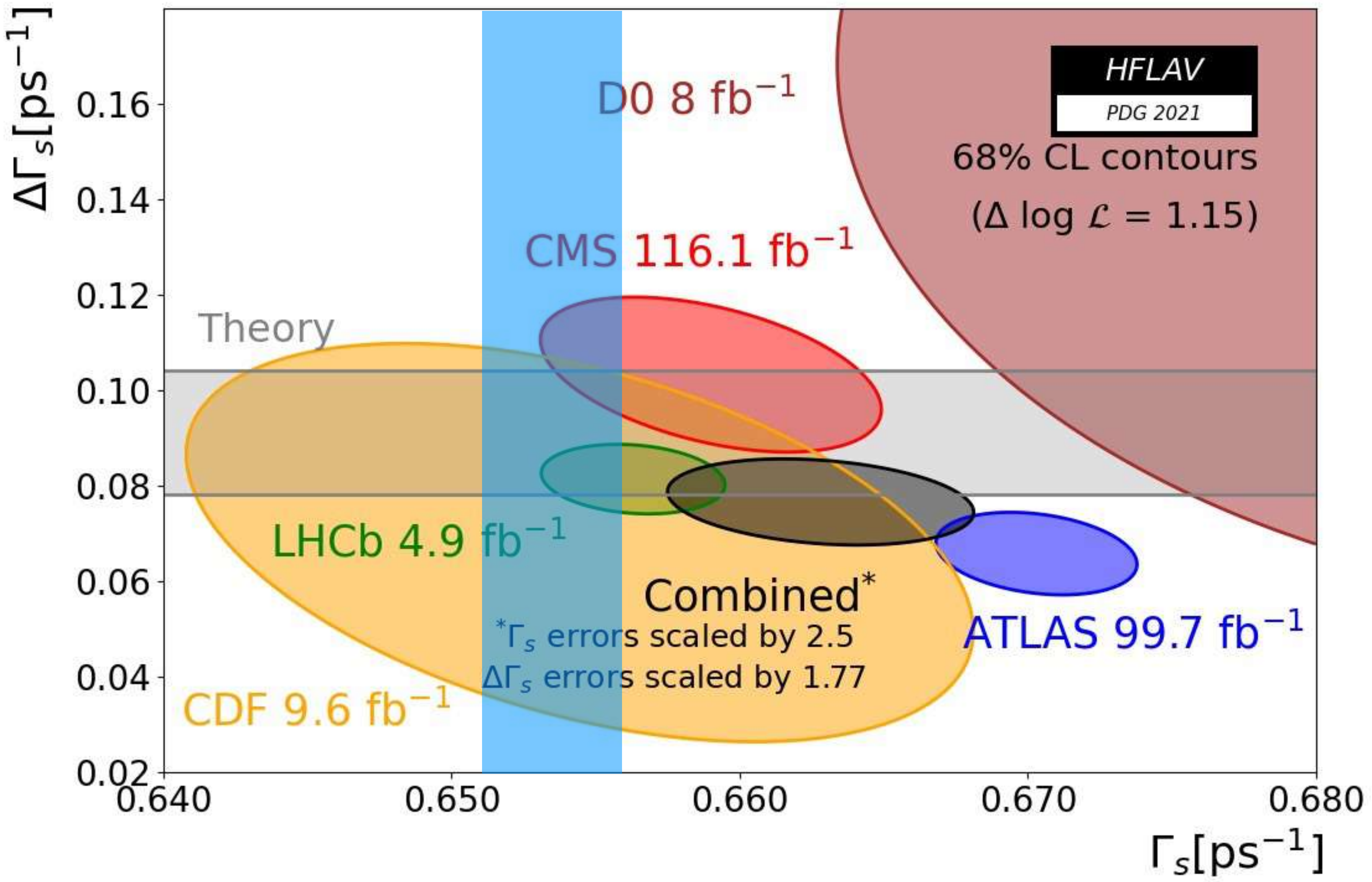
- **for a complete LCSR analysis of nonlocal effects (charm loop etc.) in** $B_s \to \phi\ell\ell$, accurate data on BR and amplitude decomposition are needed on hadronic B_s-decays such as $B_s \to \psi\phi$ where ψ are charmonia $J/\psi, \psi(2S)$ and above, also $B_s \to D^{(*)}\bar{D}\phi$ (for $B \to K$ and $B \to K^*$ channels this type of data is available)

The BR and angular distributions of hadronic decays are needed as inputs (pole residues) in the dispersion relation for the $B_s \to \phi\ell\ell$ nonlocal amplitude to be matched to the LCSR calculation

A. Khodjamirian

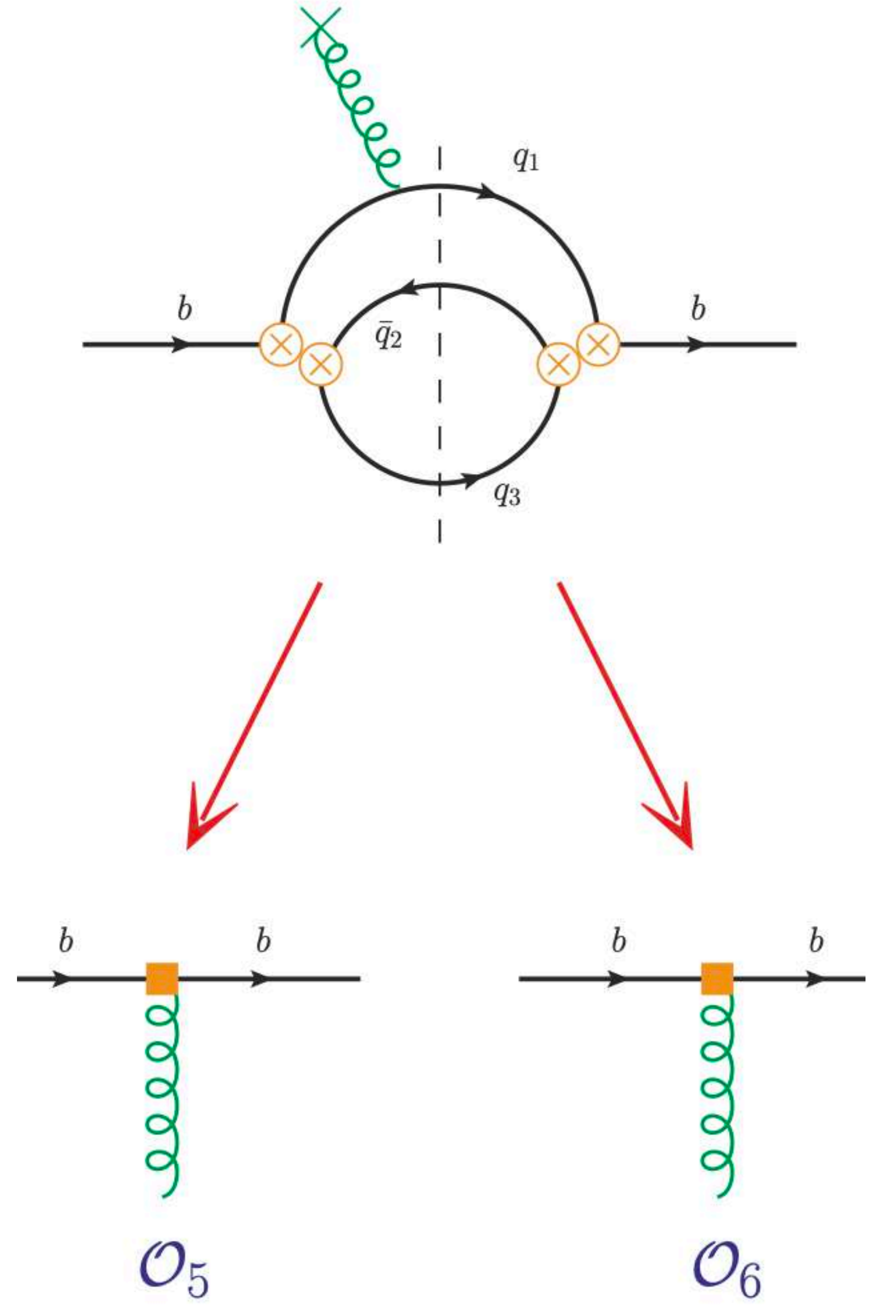
$\tau(B_s)/\tau(B_d)$

A less well known 4 sigma anomaly :-)



But be aware:

so far large Darwin term has not been included



AL, Piscopo, Rusov 2004.09527

Mannel, Moreno, Pivovarov 2004.09485

Dominant uncertainty

$$\rho_D^3(B_s) - \rho_D^3(B_d)$$

unknown **Known from inclusive V_{cb} determination**

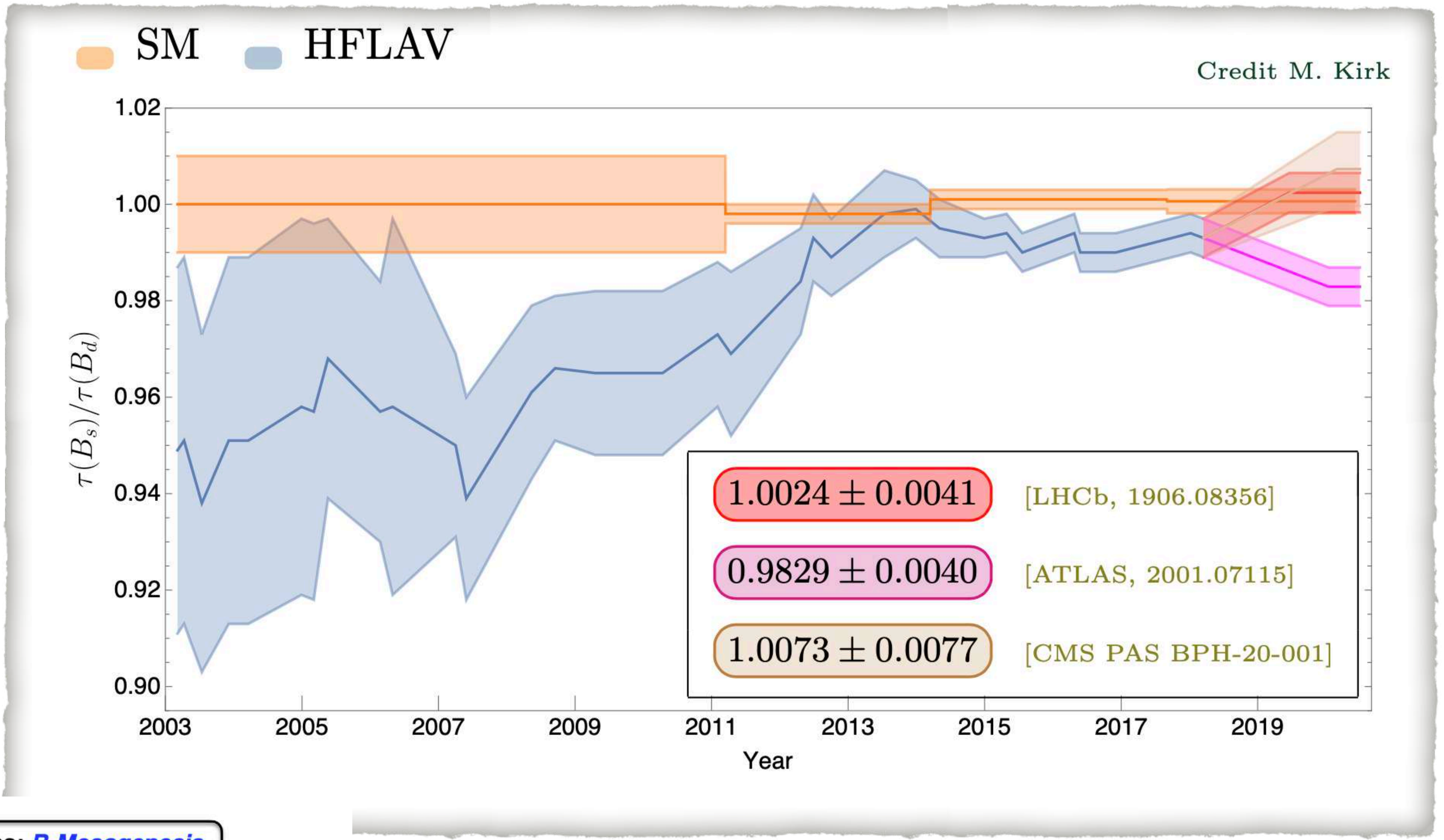
SM based on 1711.02100,
based on hep-ph/0202106
and hep-ph/0203089 - obtained via $\Gamma_s = 1/[\tau(B_s)/\tau(B_d)]^{HQE} * 1/\tau(B_d)^{EXP}$

$\tau(B_s)/\tau(B_d)$

Precise lifetime ratio in Exp. and Theory can be used to constrain BSM effects

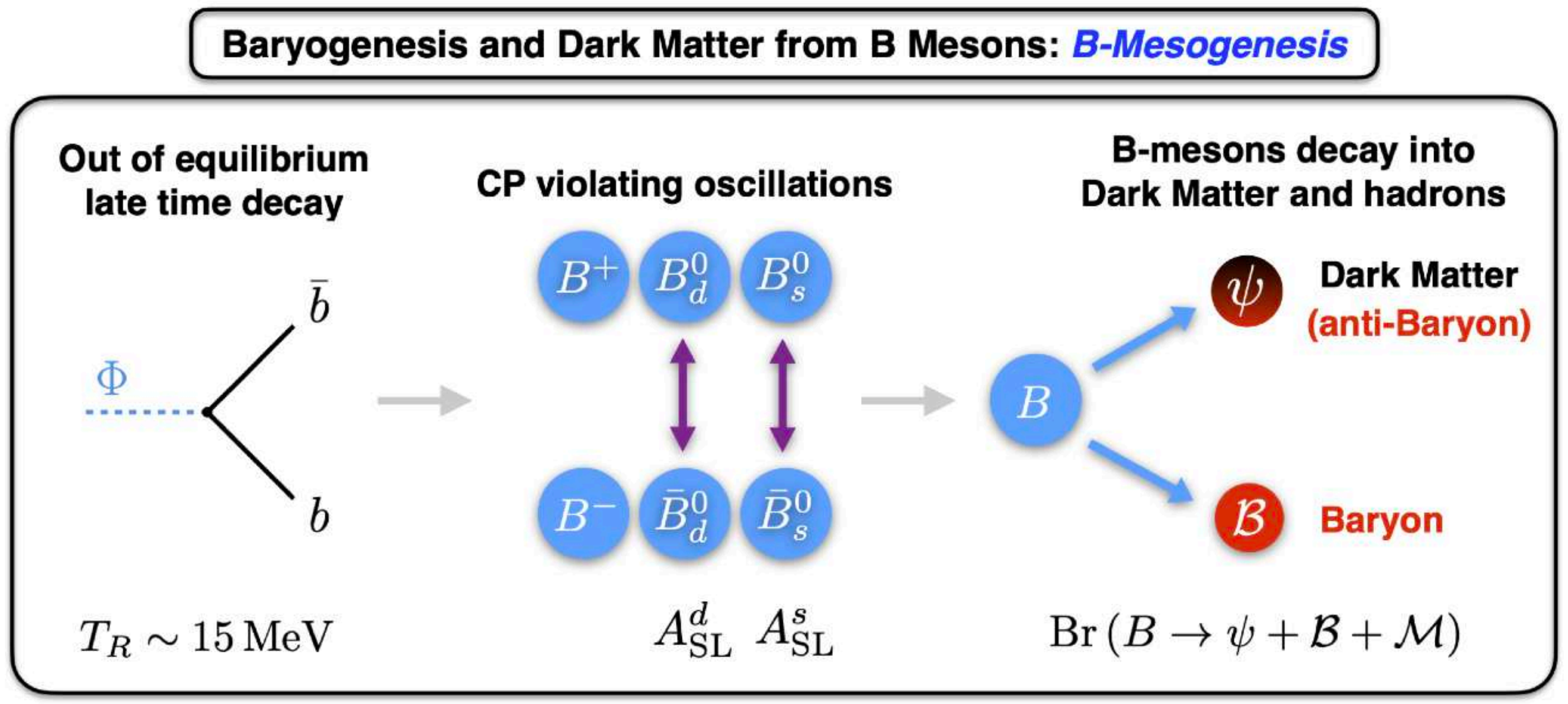
$$\underbrace{\frac{\tau(B_s)}{\tau(B_d)}}_{\text{exp.}} \approx 1 + \underbrace{\tau(B_s)\left(\delta\Gamma^{\rm SM}_{B_d} - \delta\Gamma^{\rm SM}_{B_s}\right)}_{\text{theory}} + \underbrace{\left[\mathrm{BR}(B_d \to X)^{\rm BSM} - \mathrm{BR}(B_s \to X)^{\rm BSM}\right]}_{\text{indirectly constrained}}$$

Still higher experimental precision needed



Examples:

- $b \to s\tau\tau$, see **Bobeth, Haisch 1109.1826**
- New non-leptonic tree-level operators
- B meson baryogengesis
- ….

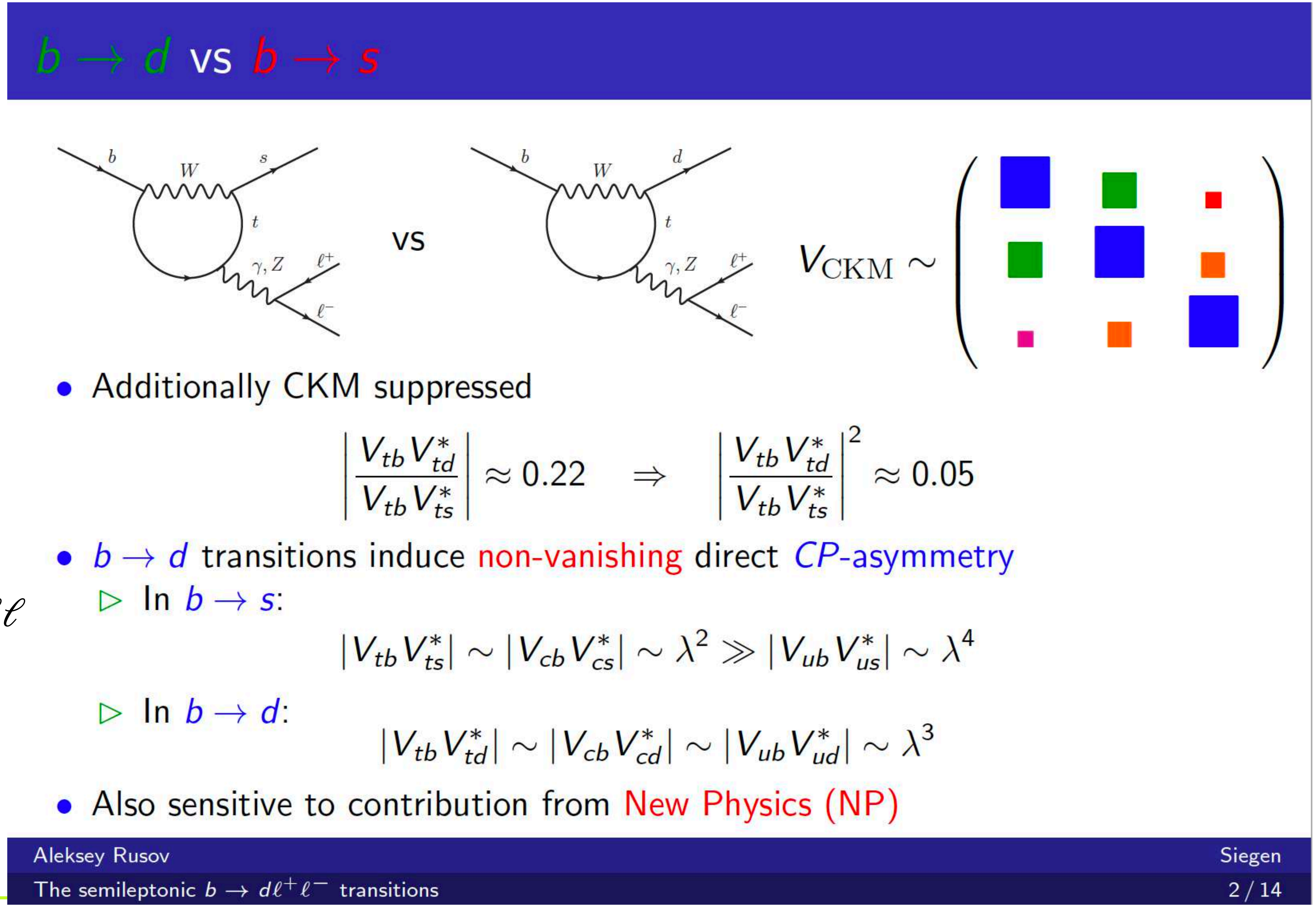


Ann Nelson,….
Gonzalo-Alvarez, Elor, Escudero

$b \to d\ell\ell$

Study also decays like

$B \to (\pi, \rho, \omega)\ell\ell$ and $B_s \to (\eta, K^*)\ell\ell$



$b \to d$ vs $b \to s$

$V_{\text{CKM}} \sim$

- Additionally CKM suppressed

$$\left|\frac{V_{tb}V_{td}^*}{V_{tb}V_{ts}^*}\right| \approx 0.22 \quad \Rightarrow \quad \left|\frac{V_{tb}V_{td}^*}{V_{tb}V_{ts}^*}\right|^2 \approx 0.05$$

- $b \to d$ transitions induce non-vanishing direct CP-asymmetry
  - ▷ In $b \to s$:

$$|V_{tb}V_{ts}^*| \sim |V_{cb}V_{cs}^*| \sim \lambda^2 \gg |V_{ub}V_{us}^*| \sim \lambda^4$$

  - ▷ In $b \to d$:

$$|V_{tb}V_{td}^*| \sim |V_{cb}V_{cd}^*| \sim |V_{ub}V_{ud}^*| \sim \lambda^3$$

- Also sensitive to contribution from New Physics (NP)

Surprise and/or Underdogs

Surprise and/or underdogs...:

- Inclusive semi-leptonic fit of moments in B_s decays at LHCb? Belle II?
  Determine also non-perturbative matrix elements $\mu_G^2(B_s), \mu_\pi^2(B_s), \rho_D^3(B_s), \ldots$
- Inclusive semi-leptonic fit of moments of charm decays BESIII, Belle II?
  Determine also non-perturbative matrix elements $\mu_G^2(D), \mu_\pi^2(D), \rho_D^3(D), \ldots$
- Non-leptonic tree-level decays: BSM in leading tree-level? $B \to K\pi$ puzzle
- $B_c \to \tau\nu$: determination of V_{cb} depending only on decay constant f_{B_c}
- Very rare to impossible decays: $B_{(s)} \to \tau\mu, B \to K\tau\mu$,.... and also D decays
  $\tau \to \mu\mu\mu$ and friends
- measurement of V_{us} from τ decays with reasonable precision, Belle II?
  Test Cabibbo anomaly, without any lattice input

Surprise and/or underdogs…:

Test of our theory tools:

Results

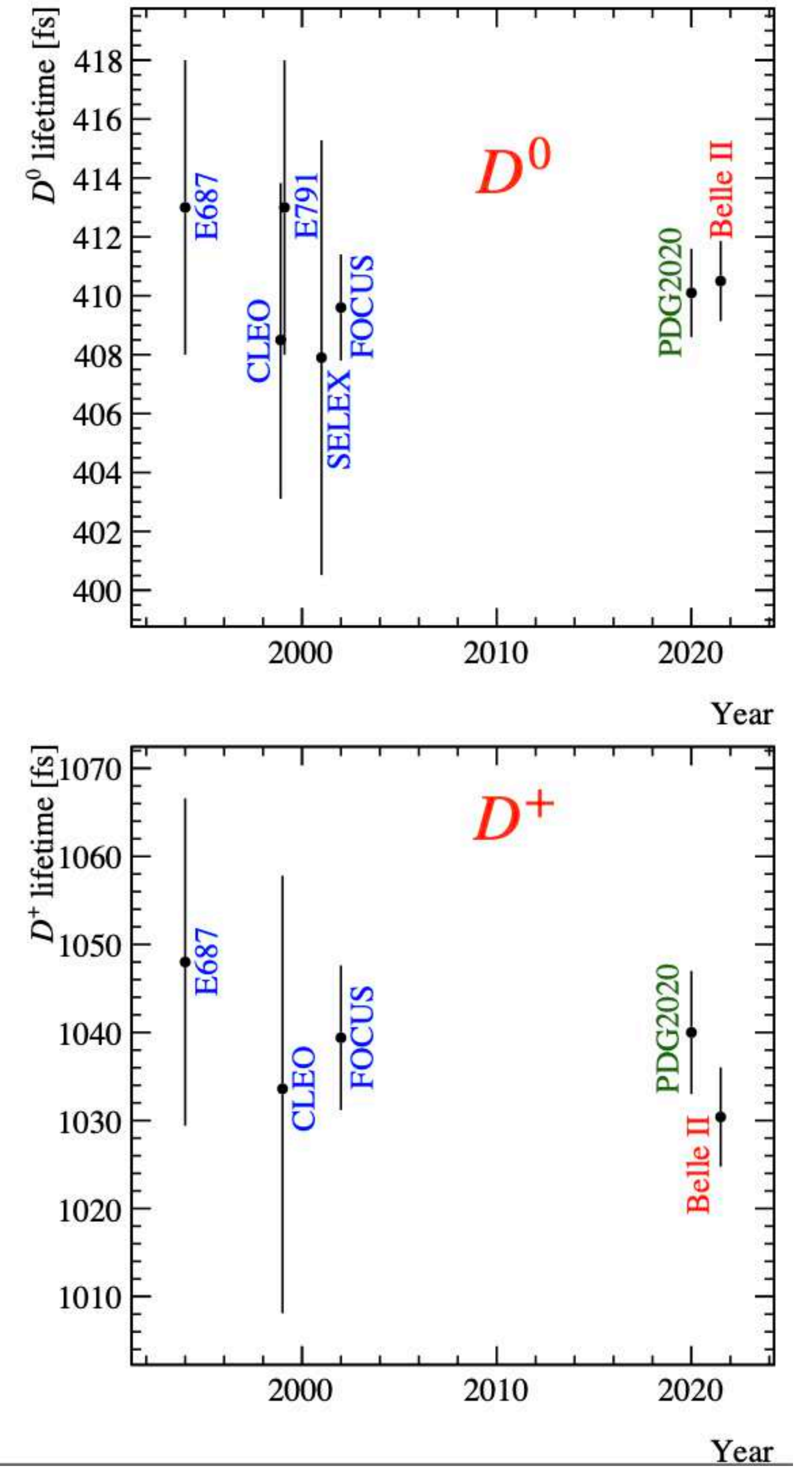
$$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8\,\text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1\,\text{fs}$$

$$\tau(D^+)/\tau(D^0) = 2.510 \pm 0.015$$

determined considering correlations between (systematic) uncertainties

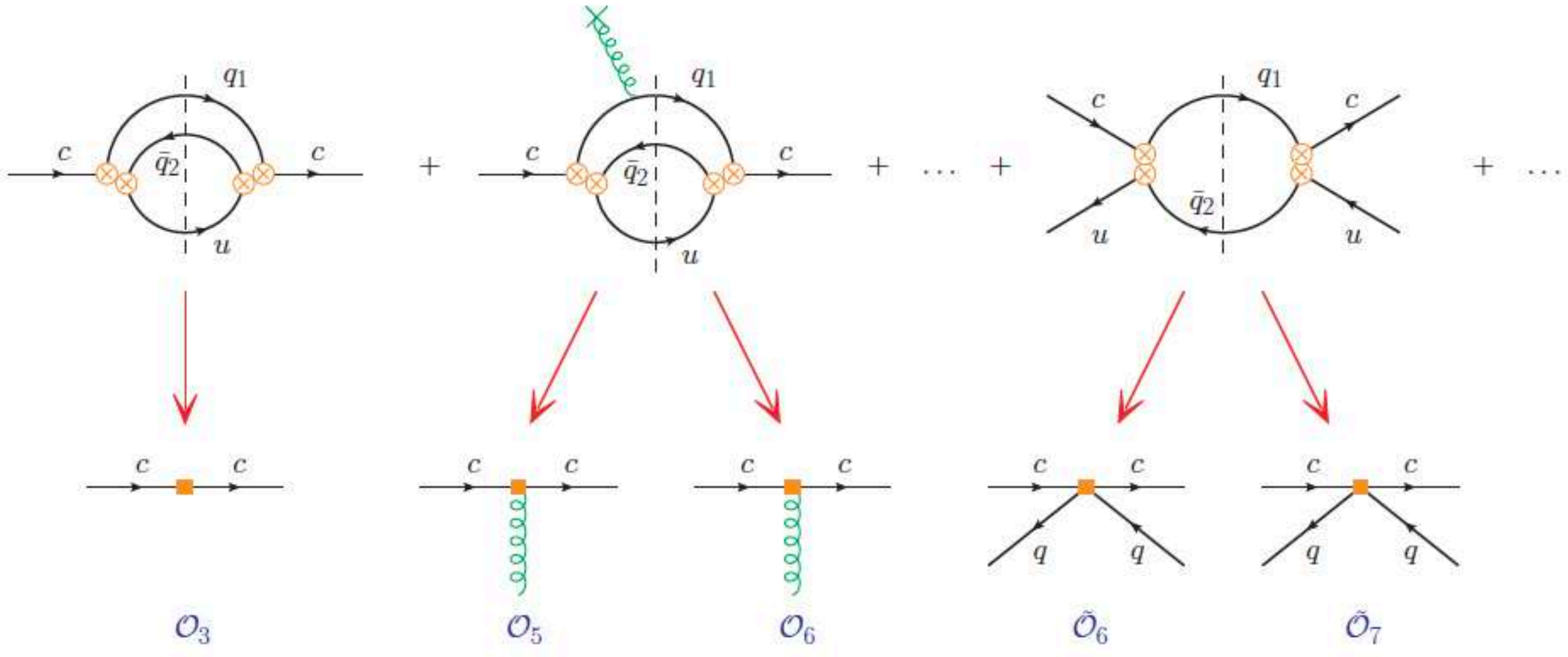
- Consistent with current world averages 410.1±1.5 fs (D^0) and 1040±7 fs (D^+).
- World's most precise measurements of the D^0 and D^+ lifetimes
- Few ‰ accuracy (3.5‰ for the D^0 and 5.4‰ for the D^+) establishes excellent performance of our detector!
- submitted to PRL, https://arxiv.org/abs/2108.03216

D lifetimes HQL2021



Total inclusive quantities, like lifetimes or inclusive semi-leptonic branching ratios: Theoretically well-behaved compared to crazy GIM cancellations in D- mixing

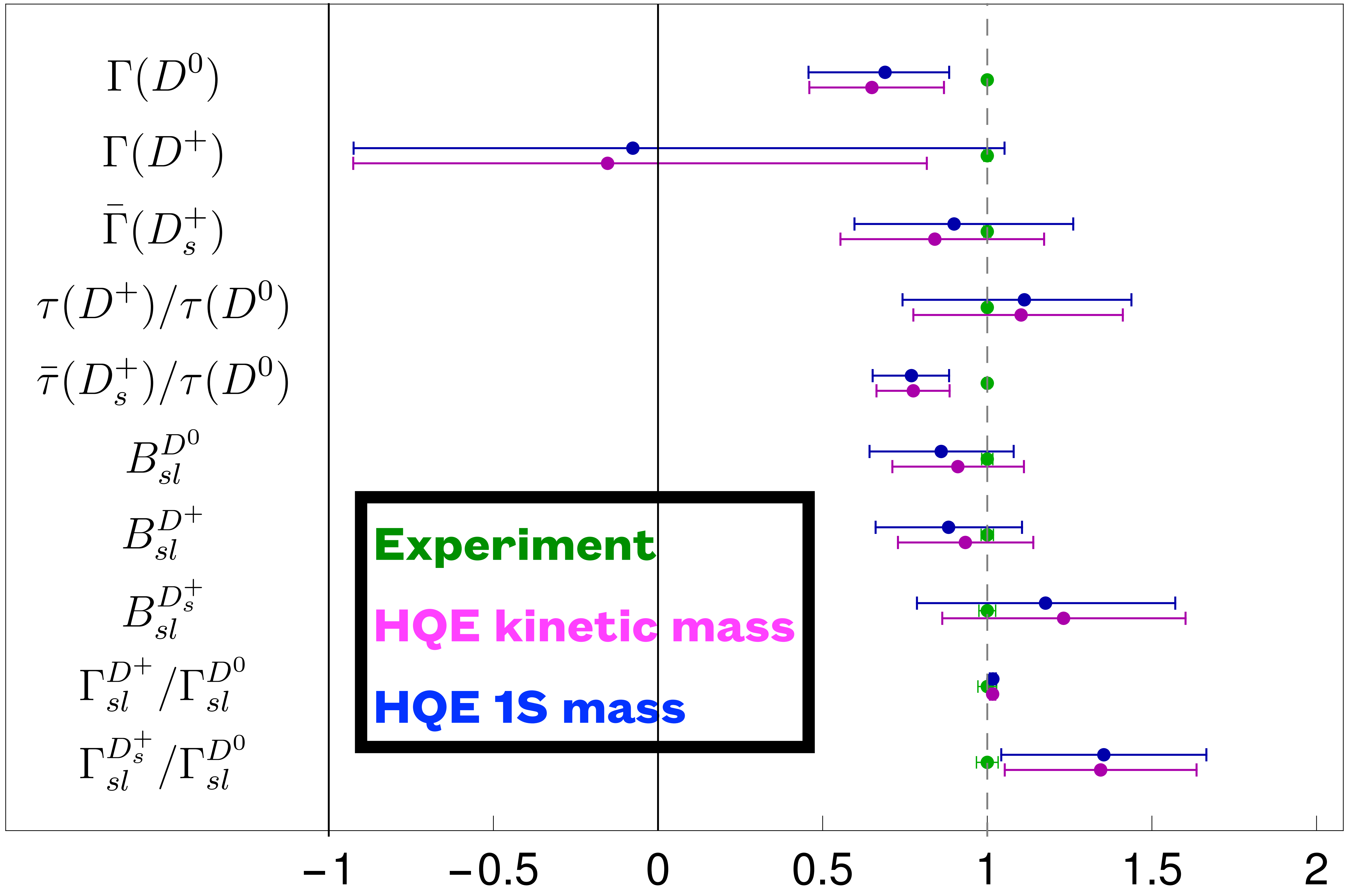
$$\Gamma(D) = \Gamma_3 + \Gamma_5 \frac{\langle \mathcal{O}_5 \rangle}{m_c^2} + \Gamma_6 \frac{\langle \mathcal{O}_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left(\tilde{\Gamma}_6 \frac{\langle \tilde{\mathcal{O}}_6 \rangle}{m_c^3} + \tilde{\Gamma}_7 \frac{\langle \tilde{\mathcal{O}}_7 \rangle}{m_c^4} + \ldots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

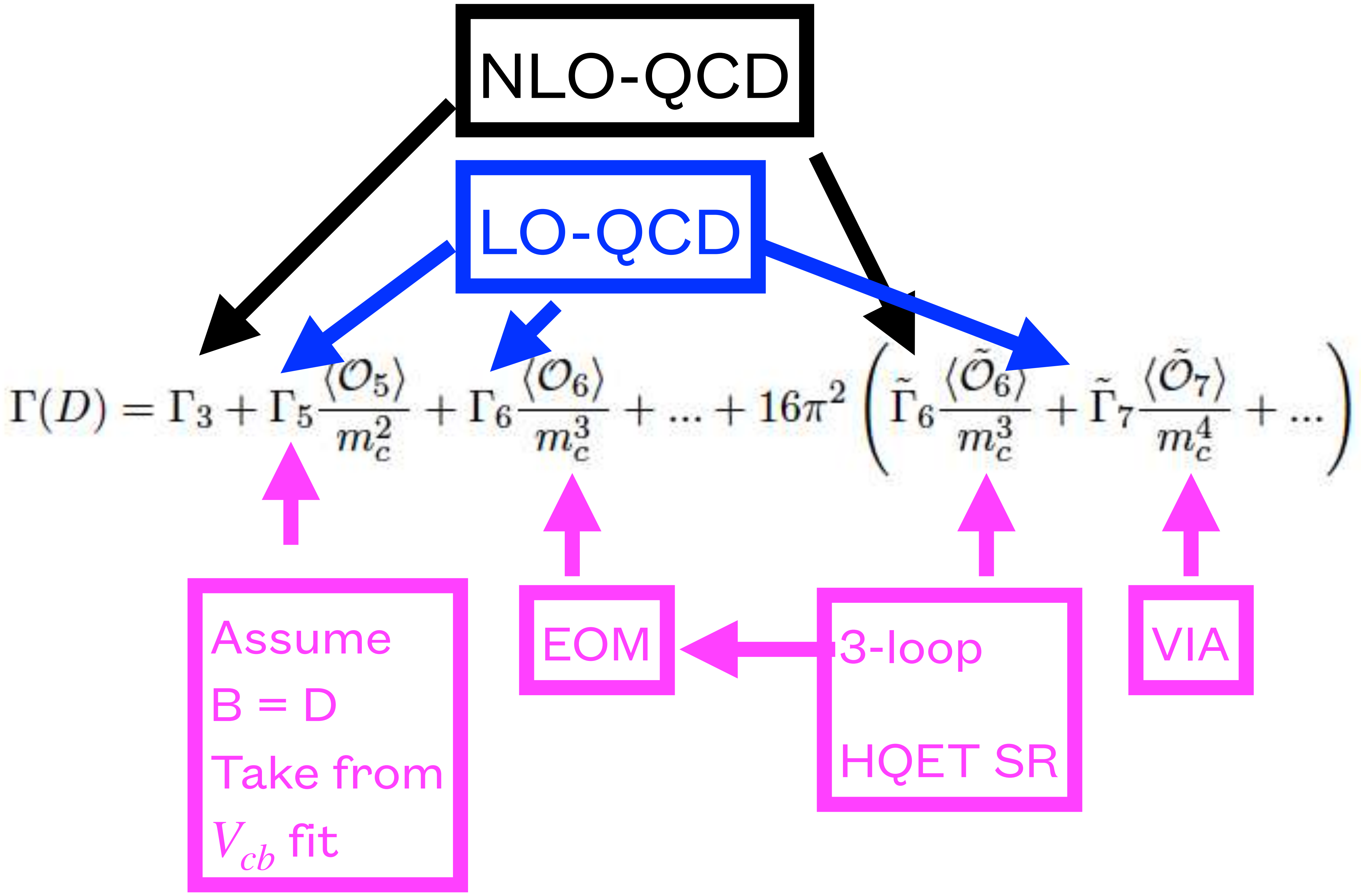


See also: charmed baryons **Gratrex, Melic, Nisandzic 2204.11935**

Surprise and/or underdogs...:

Convergence of HQE in the charm system?





- **Huge uncertainties**
- **HQE covers experiment**
- $< 1\sigma$ **deviation for SU(3)F breaking in sl**

D. King, AL, M.L. Piscopo, T. Rauh, A. Rusov, C. Vlahos 2109.13219

Surprise and/or underdogs...:

How to improve the precision of the HQE in the charm system?

$$\frac{\Gamma_{sl}^{D_s^+}}{\Gamma_{sl}^{D^0}} = 1 - 0.40\,[\mu_\pi^2(D_s) - \mu_\pi^2(D)] - 1.21\,[\mu_G^2(D_s) - \mu_G^2(D)] + 3.13\,[\rho_D^3(D_s) - \rho_D^3(D)]$$

$$-8.84\,\tilde{B}_1^s + 8.84\,\tilde{B}_2^s - 3.02\,\tilde{\epsilon}_1^s + 2.79\,\tilde{\epsilon}_2^s \underbrace{+0.00}_{\mathrm{dim-7,VIA}}$$

$$+0.35\,\tilde{\delta}_1^{qq} - 0.35\,\tilde{\delta}_2^{qq} + 6.60\,\tilde{\delta}_1^{qs} - 6.60\,\tilde{\delta}_2^{qs} - 0.52\,\tilde{\delta}_1^{sq} + 0.52\,\tilde{\delta}_2^{sq} + 9.68\,\tilde{\delta}_1^{ss} - 9.68\,\tilde{\delta}_2^{ss}$$

$$= 1 - 0.04\,\frac{\mu_\pi^2(D_s) - \mu_\pi^2(D)}{0.1\,\mathrm{GeV}^2} - 0.02\,\frac{\mu_G^2(D_s) - \mu_G^2(D)}{0.02\,\mathrm{GeV}^2} + 0.11\,\frac{\rho_D^3(D_s) - \rho_D^3(D)}{0.035\,\mathrm{GeV}^2}$$

$$\underbrace{+0.00}_{\mathrm{dim-6,7,VIA}} - 0.09\,\delta\tilde{B}_1^s + 0.09\,\delta\tilde{B}_2^s + 0.06\,\frac{\tilde{\epsilon}_1^s}{-0.02} - 0.06\,\frac{\tilde{\epsilon}_2^s}{-0.02}$$

$$+0.0009\,r_1^{qq} + 0.0006\,r_2^{qq} + 0.0112\,r_1^{qs} + 0.0079\,r_2^{qs}$$

$$-0.0013\,r_1^{sq} - 0.0009\,r_2^{sq} + 0.0223\,r_1^{ss} + 0.0165\,r_2^{ss}$$

Could probably be extracted from momentum analysis of inclusive semileptonic D meson decays by BESIII, Belle II,...

Bag parameter determined with 3-loop HQET sum rules:1711.02100
New: ms corrections King, AL, Rauh, to appear

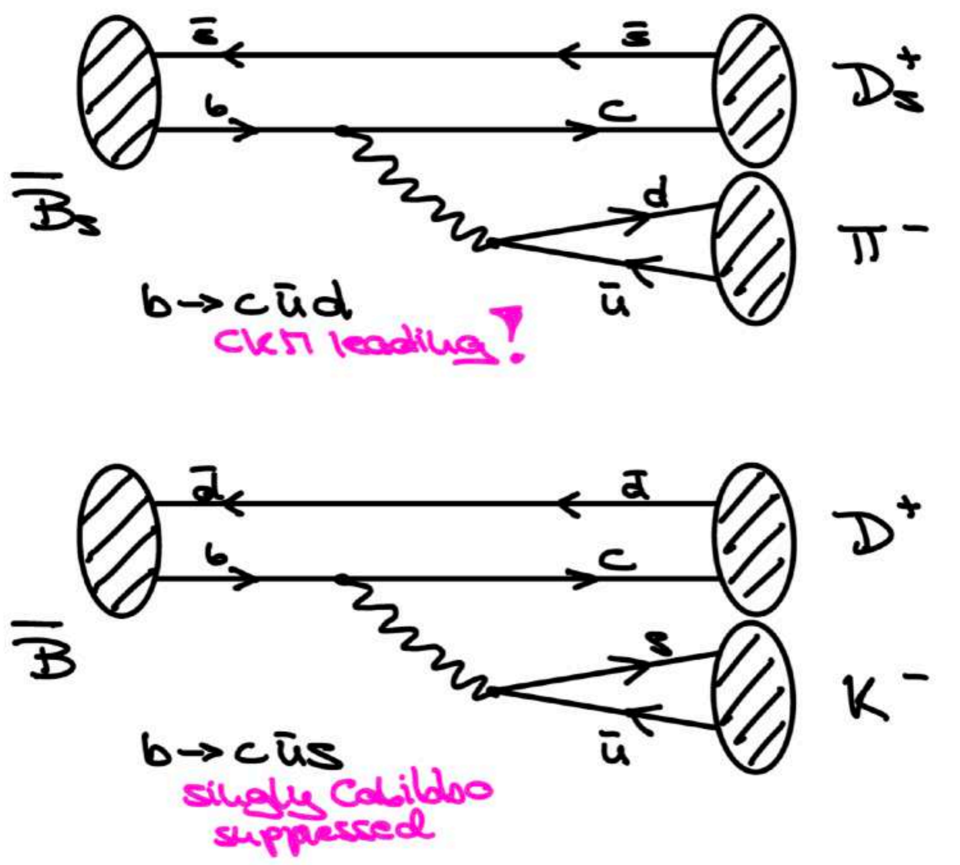
New: first ever determination of eye-contractions King, AL, Rauh, to appear

Lattice cross-check of HQET sum rules: Oliver Witzel, Matthew Black

Non-leptonic decays

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

Colour-allowed Tree-level Decays

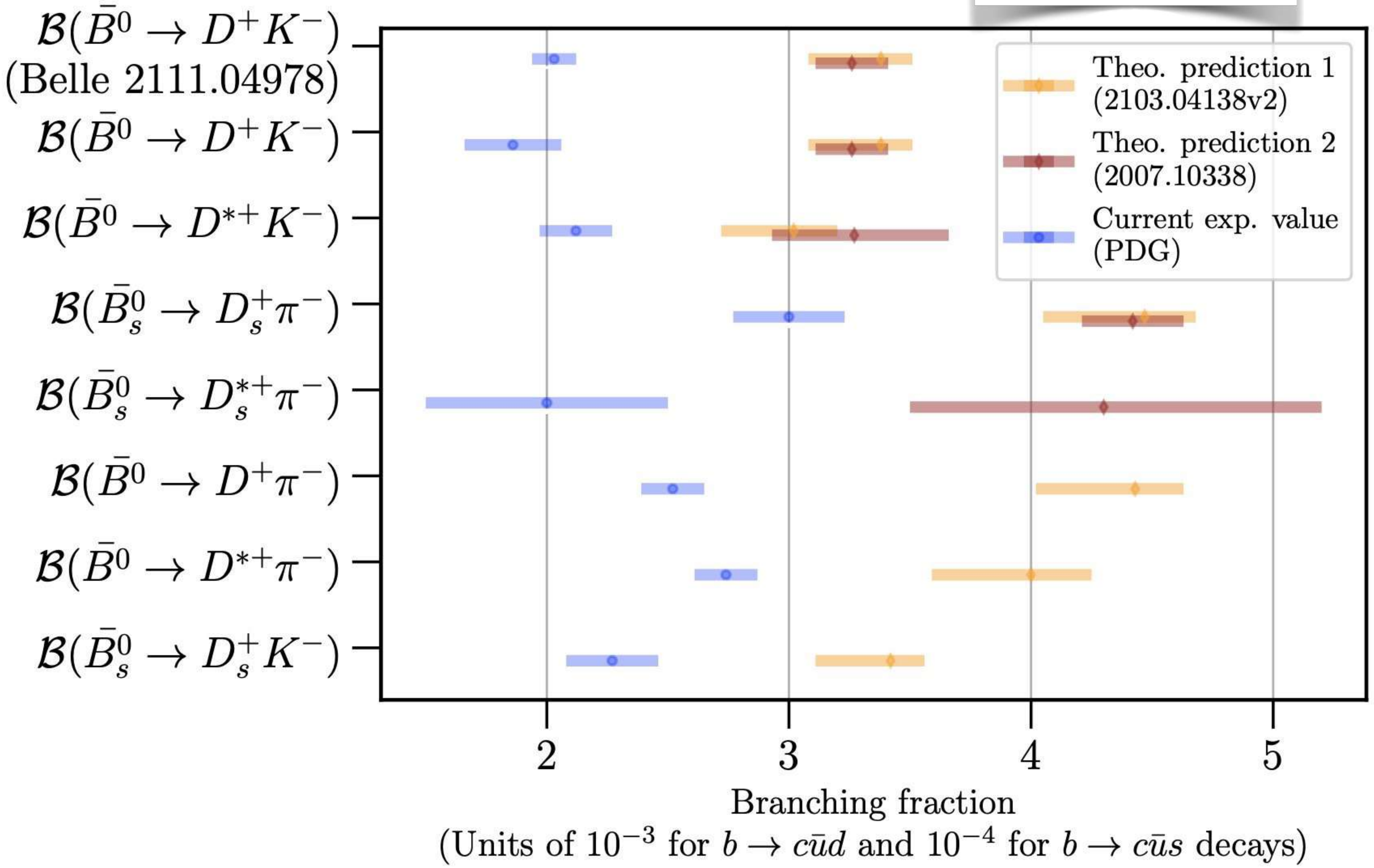


- CKM leading decays
- The are no annihilation, penguins,…
- QCDf should work at its best!

Beneke, Buchalla, Neubert, Sachrajda 1999…

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

N. Skidmore



Non-leptonic decays

What could go wrong?

Non-leptonic decays

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?

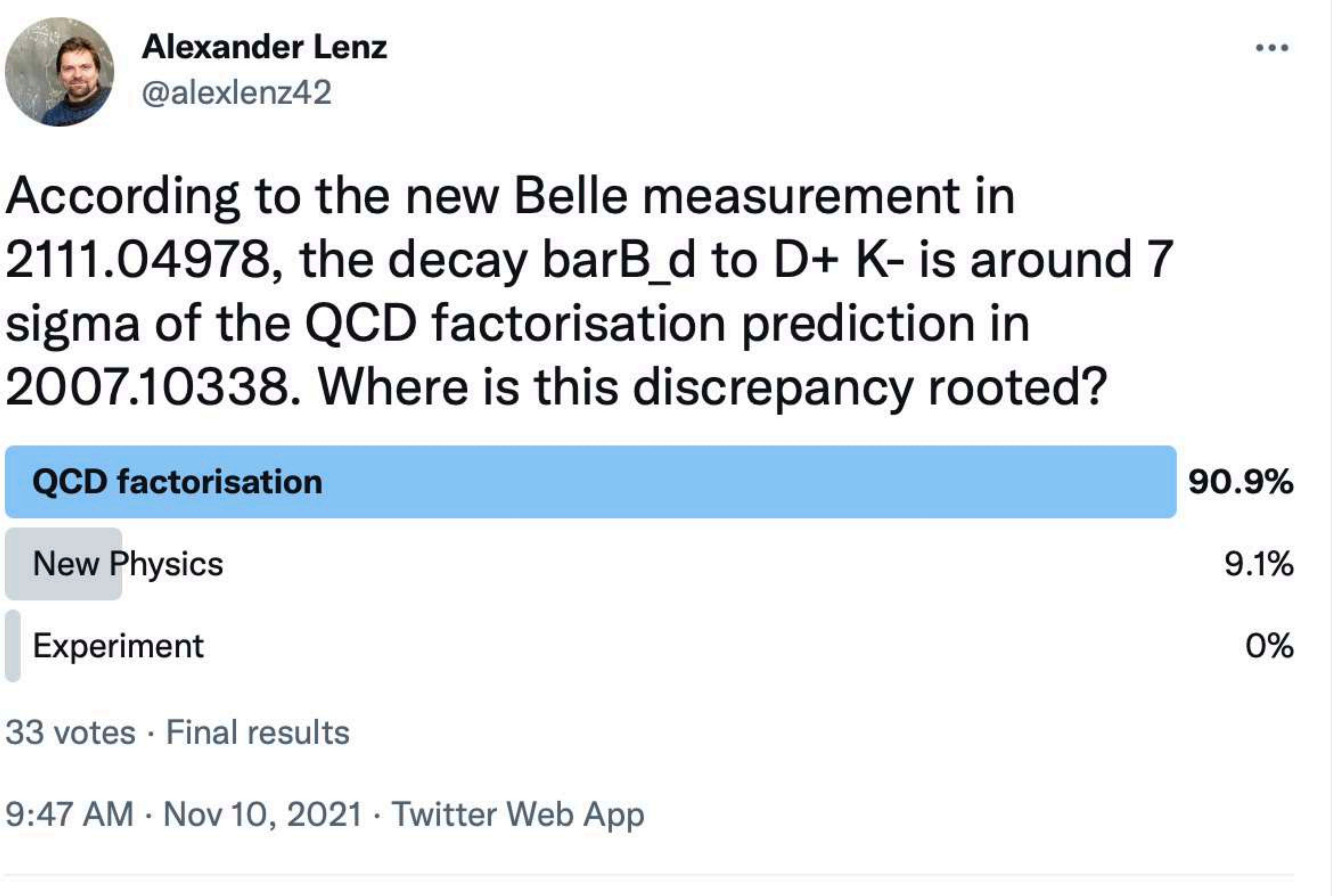
QCD factorisation	**90.9%**
New Physics	9.1%
Experiment	0%

33 votes · Final results

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

Non-leptonic decays

What could go wrong?



- **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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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

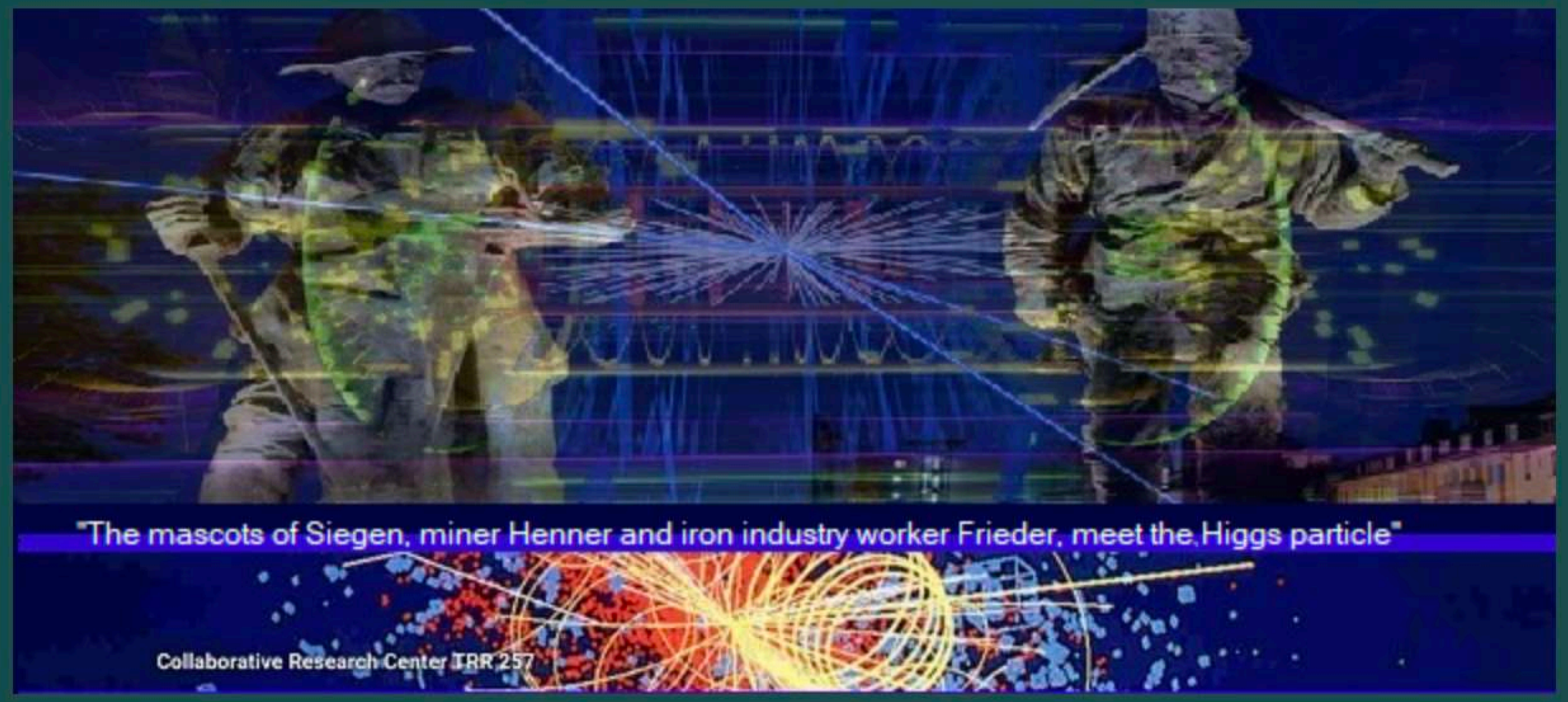
Non-leptonic decays

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



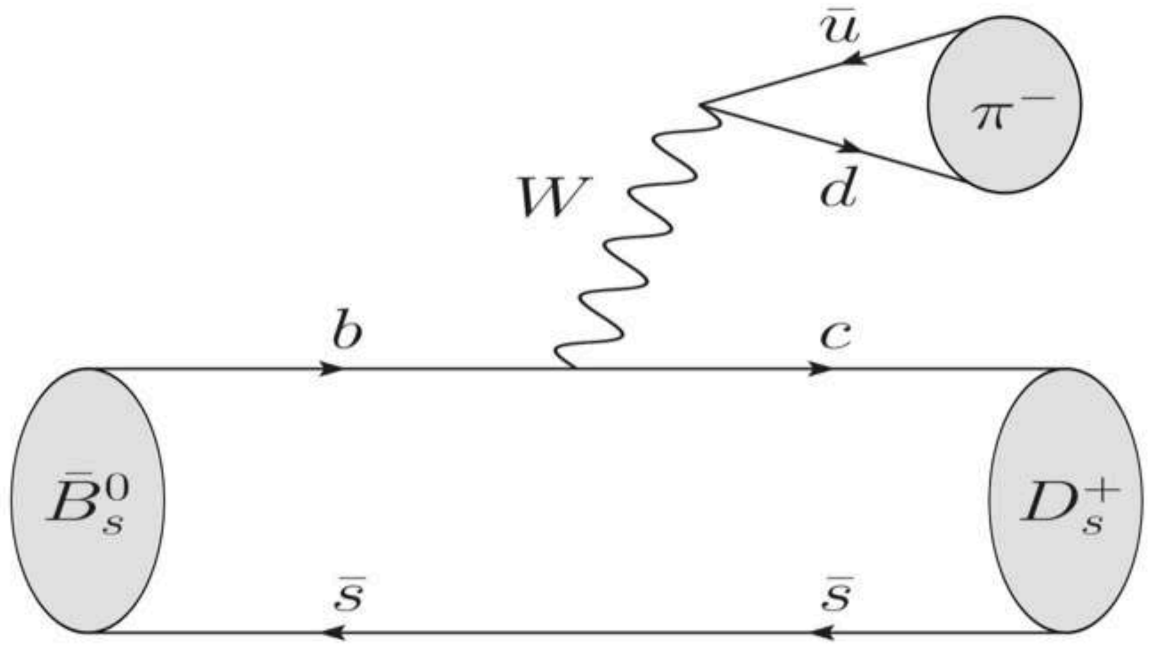
Status and prospects of Non-leptonic B meson decays

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/

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

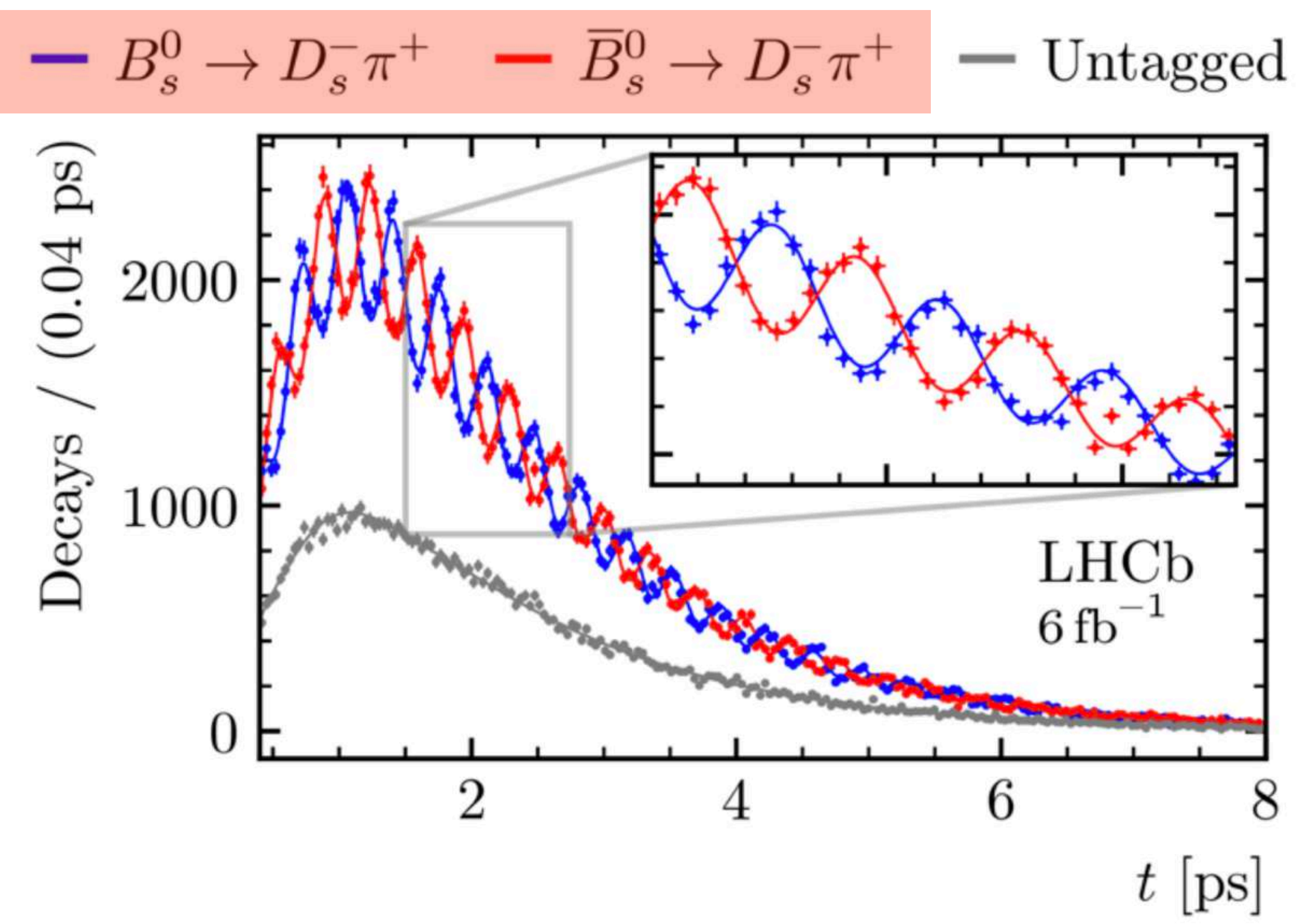
- a_{fs}^q is typically measured with semi-leptonic B_q decays
- One could also use the flavour specific $\bar{B}_s \to D_s^+ \pi^-$ decay

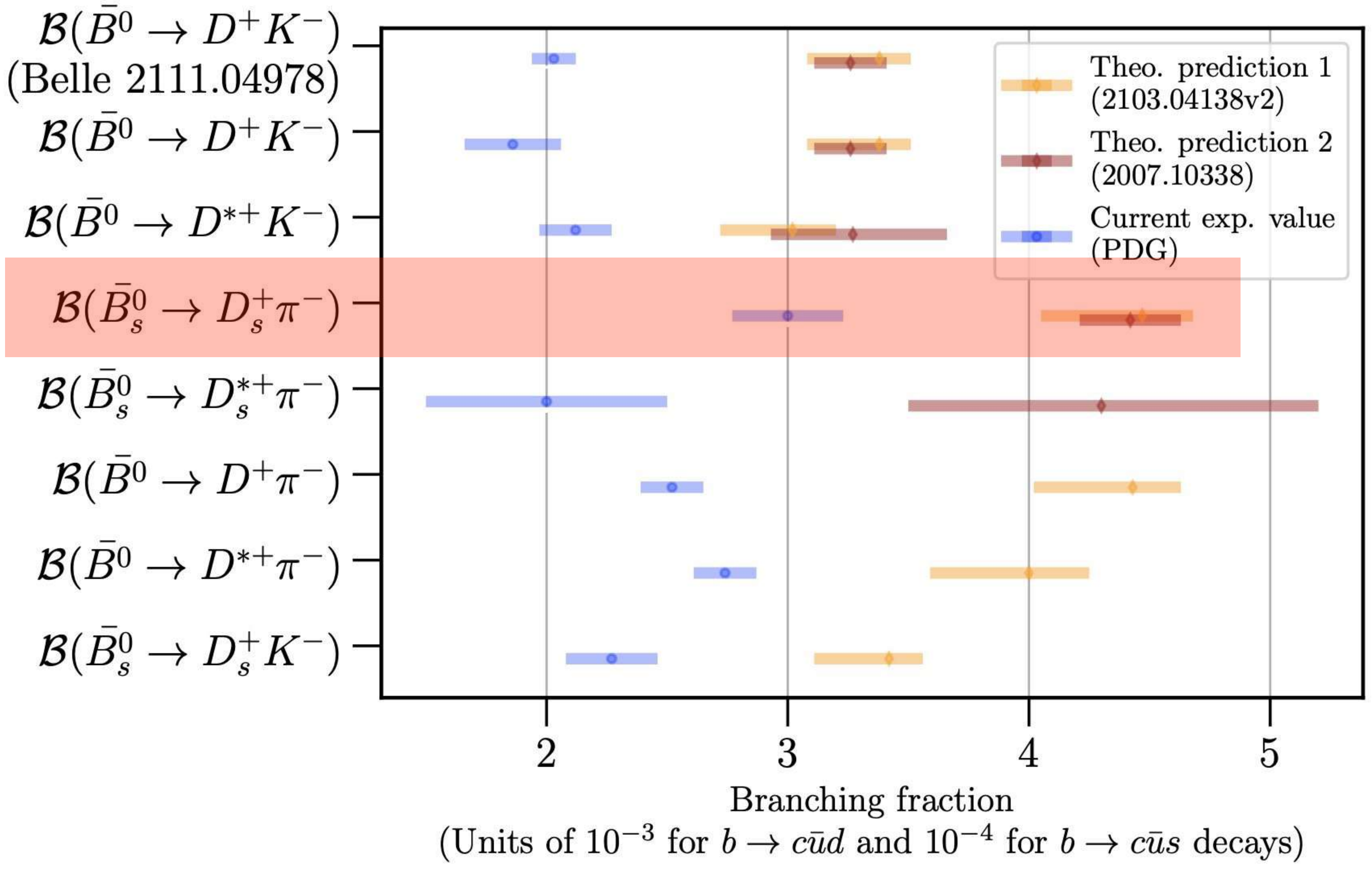
12 April 2021: Fascinating quantum mechanics.

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.





Flavour specific decays

- 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

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

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

Flavour specific decays

- a_{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
- Derive CP asymmetry

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

$$A_{\rm fs}^{q} = \frac{a_{\rm fs}^{q} - 2r\sin\phi\sin\varphi + 2a_{\rm fs}^{q} r\cos\phi\cos\varphi + a_{\rm fs}^{q} r^2}{1 + 2r\cos\phi\cos\varphi + r^2 - 2a_{\rm fs}^{q} r\sin\phi\sin\varphi} \approx a_{\rm fs}^{q} - A_{\rm dir}^{q}$$

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?

Flavour specific decays

Gershon, AL, Rusov, Skidmore
2111.04478

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- Assume: there is new physics in these decays, potentially CP violating
- Derive CP asymmetry

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

$$A_{\rm fs}^{q} = \frac{a_{\rm fs}^{q} - 2r\sin\phi\sin\varphi + 2a_{\rm fs}^{q} r\cos\phi\cos\varphi + a_{\rm fs}^{q} r^2}{1 + 2r\cos\phi\cos\varphi + r^2 - 2a_{\rm fs}^{q} r\sin\phi\sin\varphi} \approx a_{\rm fs}^{q} - A_{\rm dir}^{q}$$

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?

Significant exp. deviation of A_{fs}^{q} from a_{sl}^{q}
= unambiguous and theory independent signal for BSM

Conclusion

Many, many interesting topics ahead of us

also besides the very important and interesting B anomalies

Quirks in Quark Flavour Physics

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

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

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/

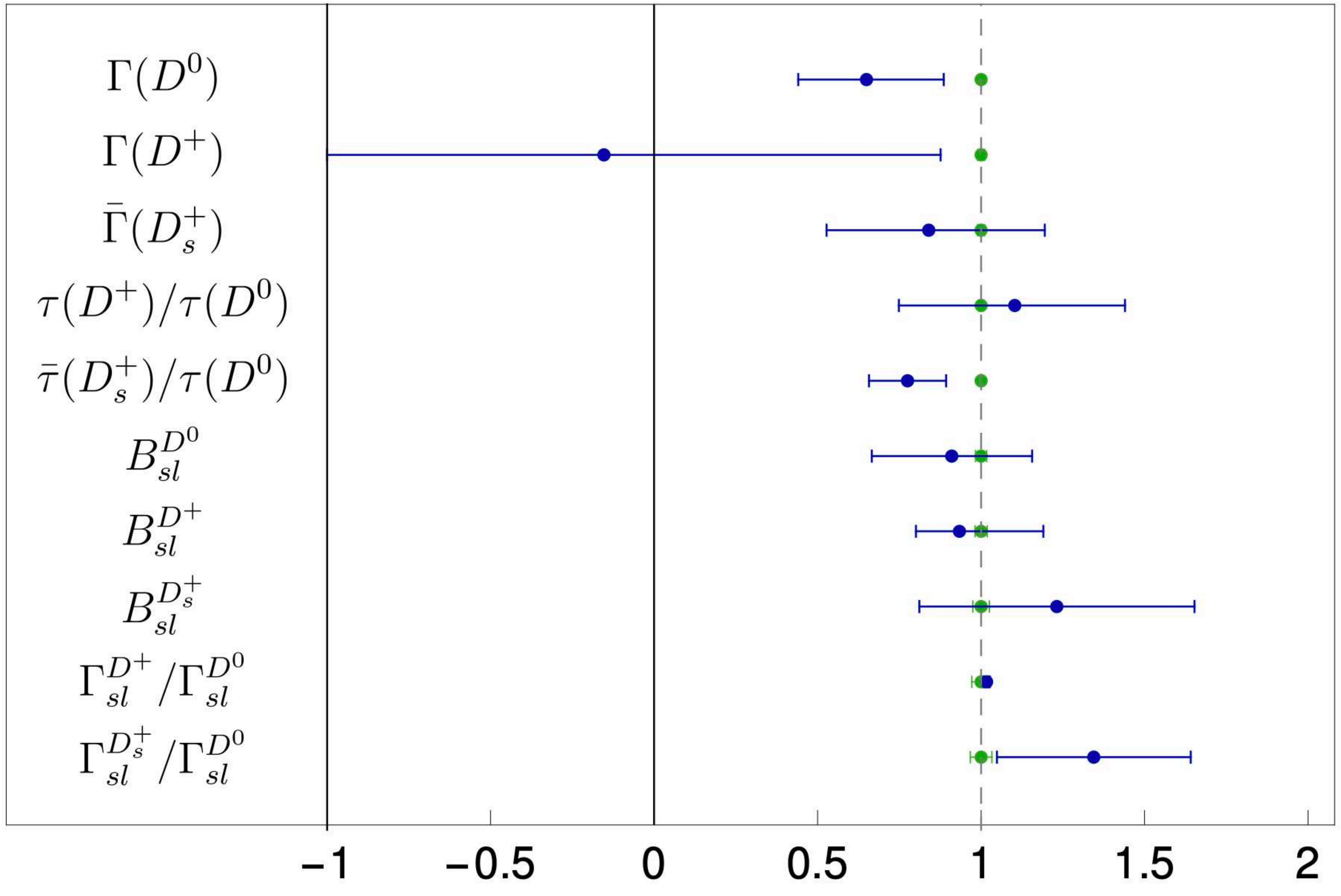
Additional Material

Status Quo: Charm Mixing

The charm system is theoretically more difficult than the b system since

- $\alpha_s(m_c) \approx 0.34$
- $\frac{\Lambda_{QCD}}{m_c} \approx 3 \frac{\Lambda_{QCD}}{m_b}$

Nevertheless the Heavy Quark Expansion might still converge in the charm system



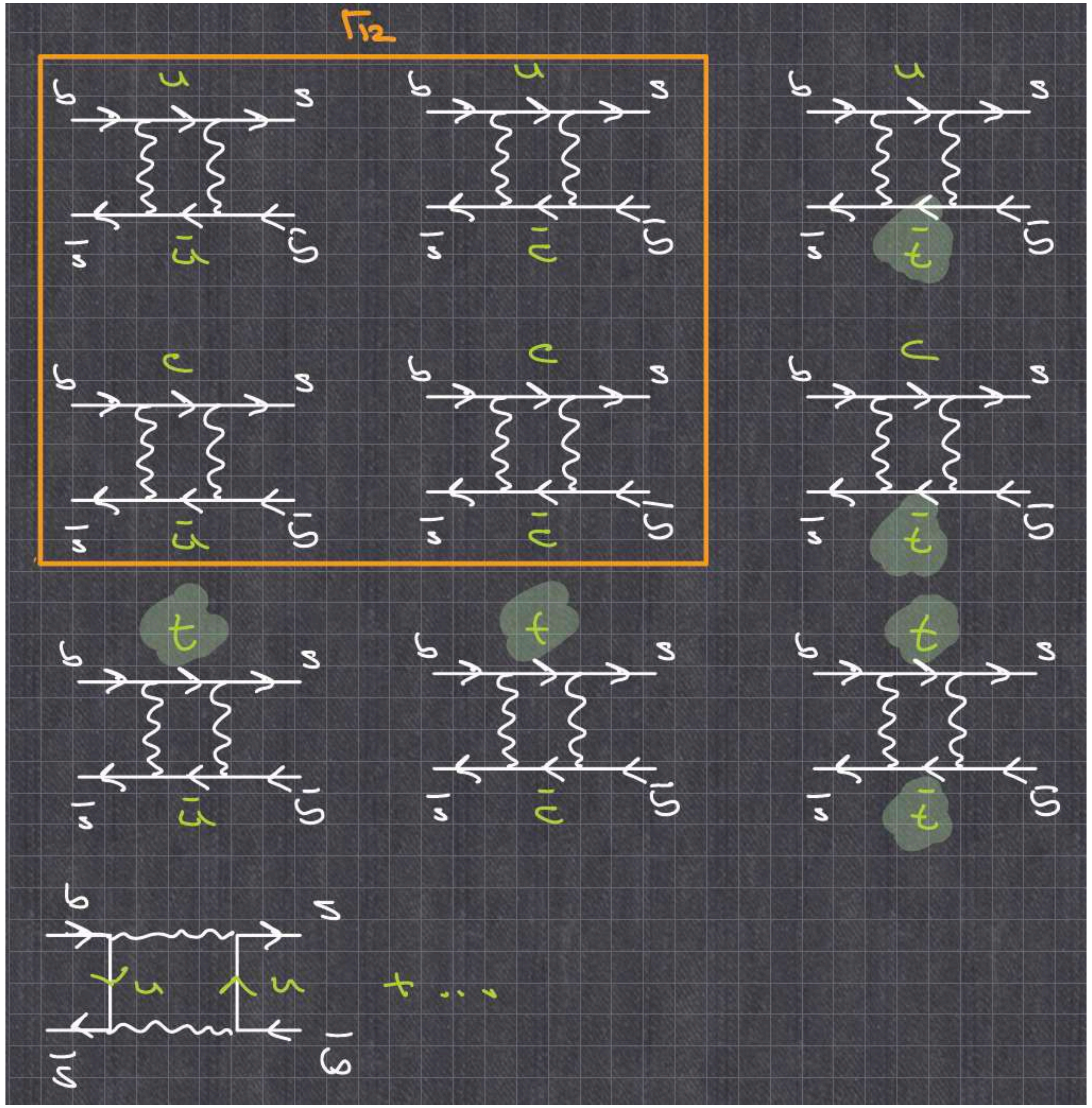
King, AL, Piscopo, Rauh, Rusov, Vlahos
2109.13219

Mixing and CP violation in the charm system
Alexander Lenz (Siegen U.), Guy Wilkinson (Oxford U.) (Nov 9, 2020)
e-Print: 2011.04443 [hep-ph]

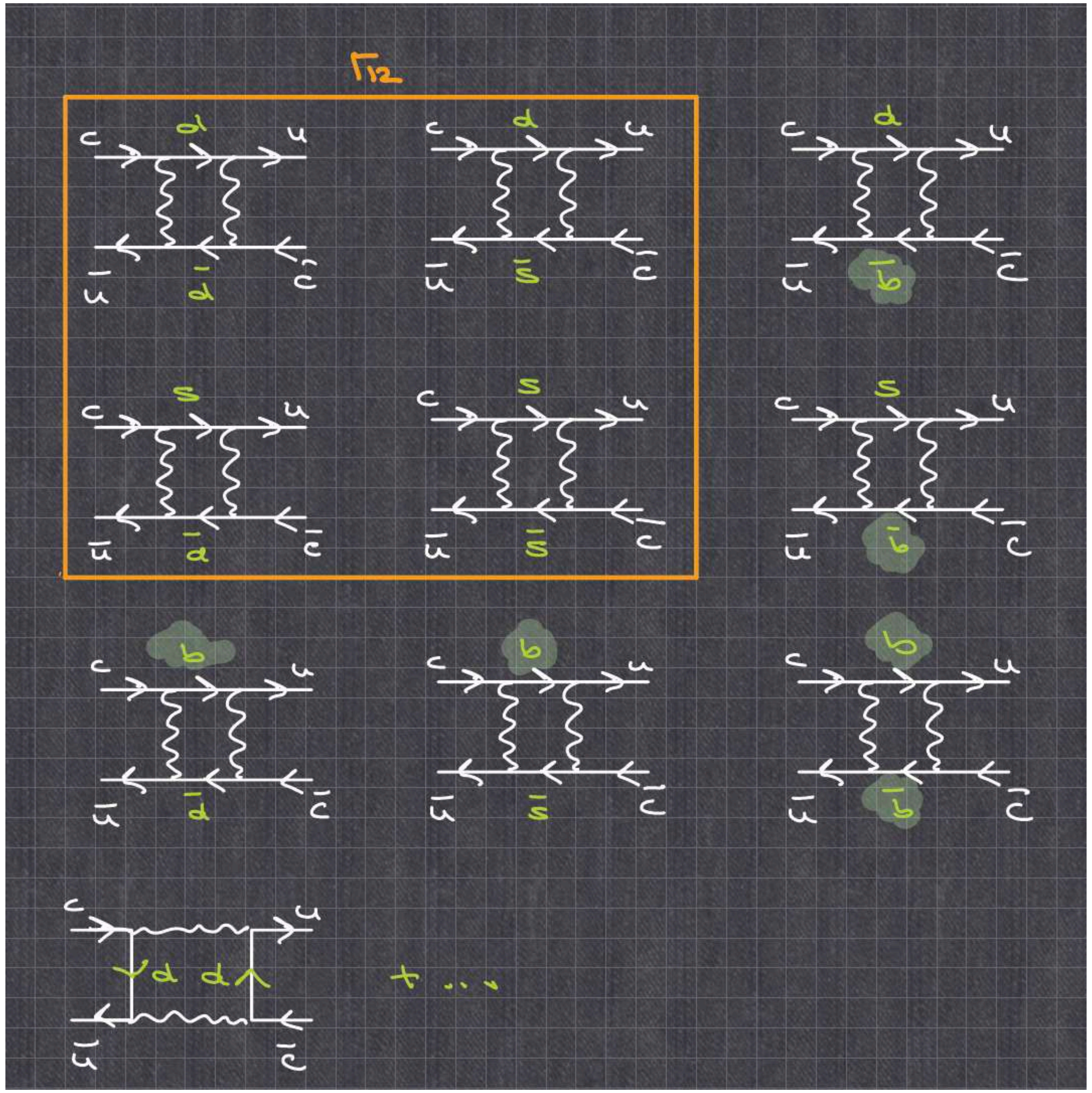
But for mixing it gets much worse

Status Quo: Charm Mixing

B-mixing

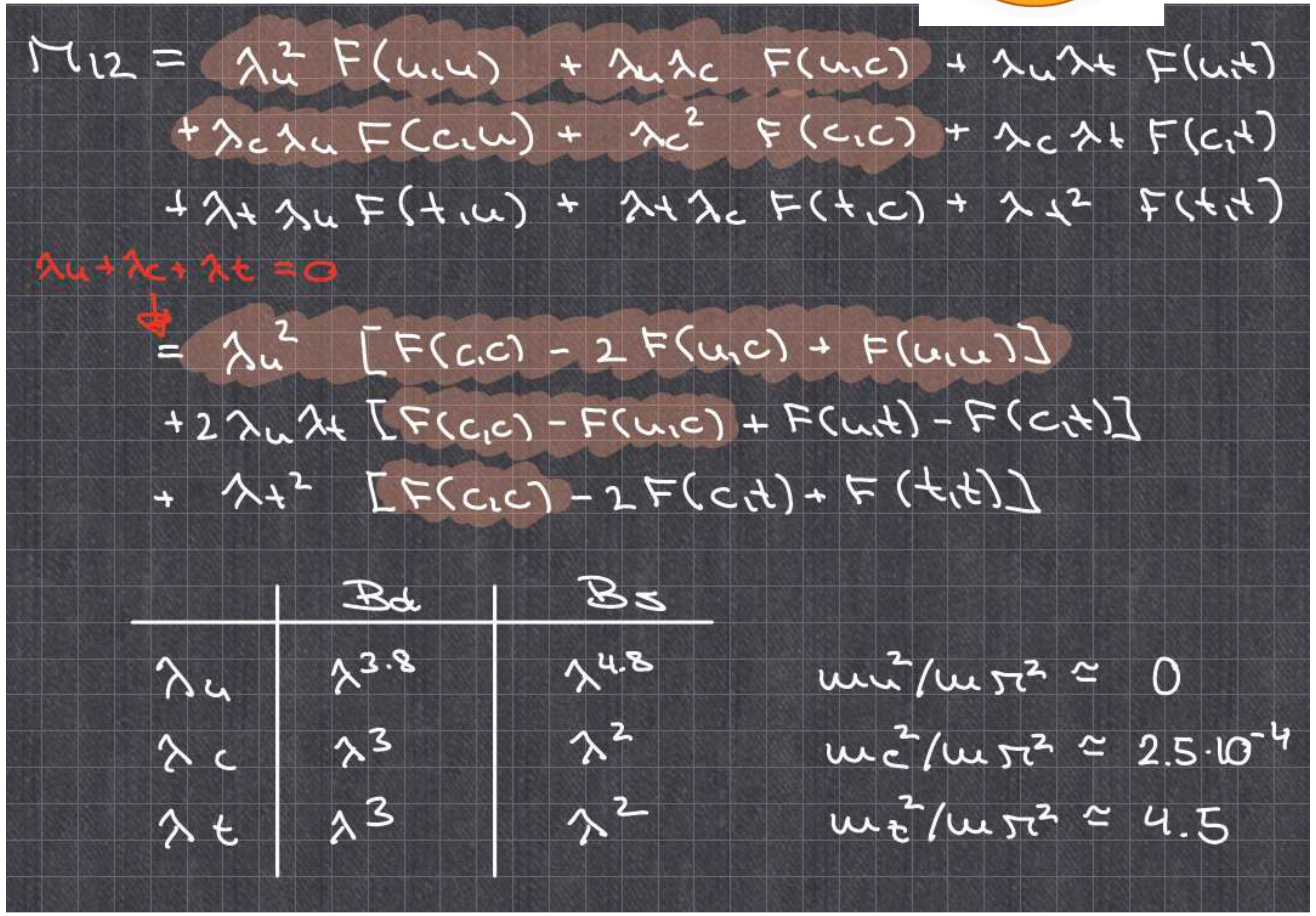


D-mixing



Status Quo: Charm Mixing

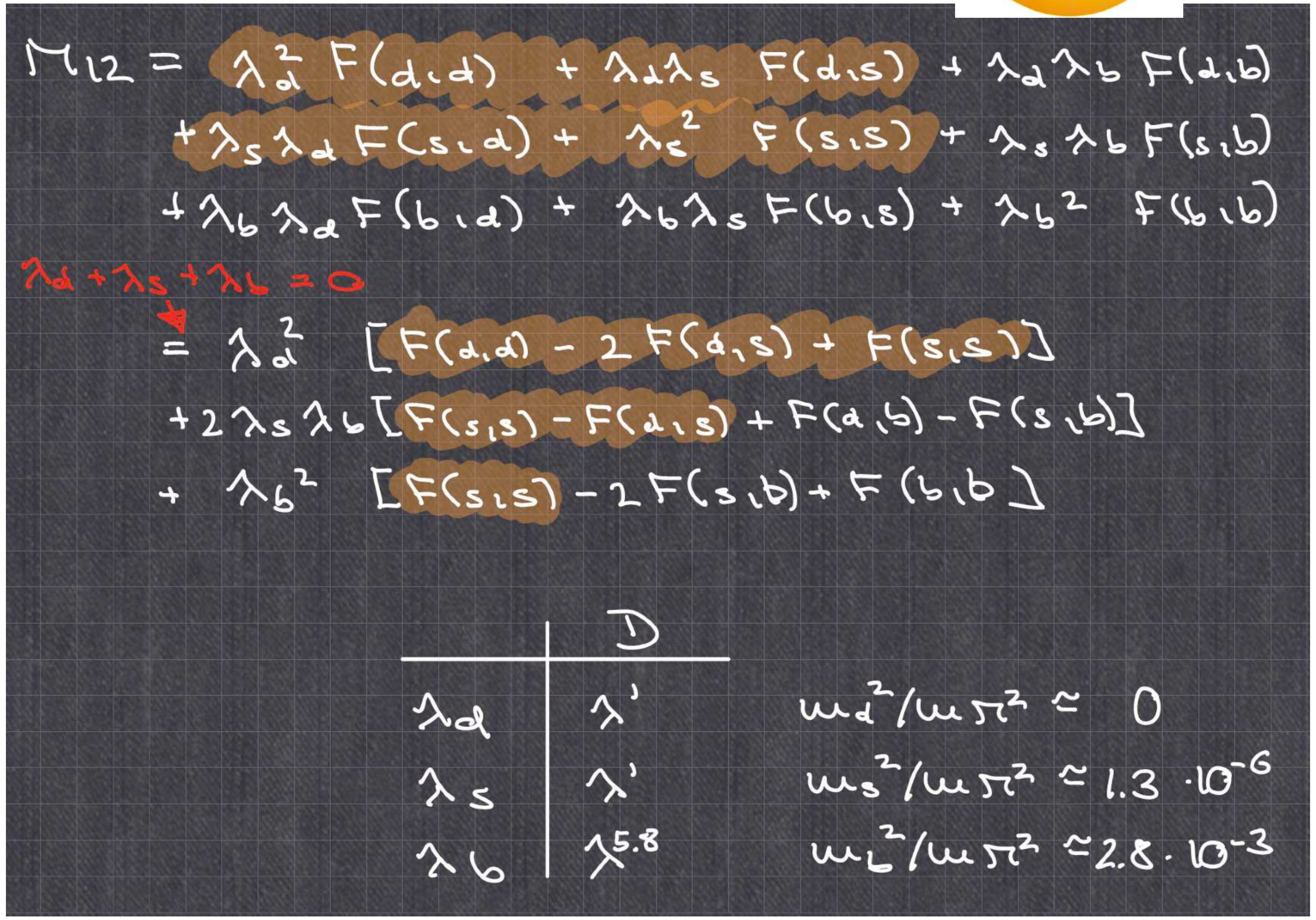
B-mixing



CKM dominant ≡ GIM dominant

CKM suppressed ≡ GIM suppressed

D-mixing



CKM suppressed ≡ GIM dominant

CKM dominant ≡ GIM suppressed

Status Quo: Charm Mixing

$$x \equiv \frac{\Delta M_D}{\Gamma_D} = 4.09^{+0.48}_{-0.49} \cdot 10^{-3}$$

HFLAV

$$\frac{\Delta \Gamma_D}{2\Gamma_D} = 6.15^{+0.56}_{-0.55} \cdot 10^{-3} \qquad \frac{\Delta\Gamma_D^{\text{naive HQE}}}{\Delta\Gamma_D^{\text{EXp.}}} \approx 10^{-5} \ldots 10^{-4}$$

AL, Piscopo, Vlahos
2007.03022

B^0: ARGUS
Observation of B^0 oscillations
Phys.Lett.B 192 (1987) 245

D^0: Belle & BaBar
Evidence of D^0 oscillations
Phys.Rev.Lett. 98 (2007) 211802
Phys.Rev.Lett. 98 (2007) 211803

D^0: LHCb
Observation of D^0 mass difference
LHCb-PAPER-2021-009

1955 | 1987 | 2006 2007 | 2013 | 2021

K^0
Behavior of neutral particles
e.g. Phys.Rev. 97 (1955) 1387

B^0_s: CDF
Observation of B_s^0 oscillations
Phys.Rev.Lett. 97 (2006) 242003

D^0: LHCb
Observation of D^0 oscillations
Phys.Rev.Lett. 110 (2013) 101802

2012: $\Delta\Gamma_s$ by LHCb

8 June 2021: First observation of the mass difference between neutral charm mesons.

$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3}$

$m_1 - m_2 = 6.4 \times 10^{-6}$ eV = 0.00000000000000000000000000000000000001 grams (1×10^{-38}g)

$(m_1 - m_2)/(D^0 \text{mass}) = 3 \times 10^{-15}$

Today, the LHCb Collaboration submitted a paper for publication that reports the first observation of the mass difference between neutral charm mesons (or rather their mass eigenstates for experts). The result is also presented today at the CERN seminar and was reported last week at the 10th International Workshop on CHARM Physics. This mass difference determines the

Exclusive approaches

Estimate phase space effects for y: Falk et al. 0110317
- assume pert. SU(3)F breaking
- neglect 3rd family
- neglect SU(3)F breaking in matrix elements - no QCD calculation

$y \approx 1\%$

Mass difference from a dispersion relation Falk et al. 0402204
Exp. data Cheng, Chiang 1005.1106
U-Spin sum rule Gronau, Rosner 2012
Factorisation-assisted topological amplitude approach
Jiang et al. 1705.07335

$x \approx y$

$x \propto \mathcal{O}(0.1\%)$ $\quad y \propto \mathcal{O}(few\ 0.1\%)$

$y \approx 0.2\%$

Status Quo: Charm Mixing

The HQE is successful in the B system and for D meson lifetimes

=> apply it for D-mixing

$$y_D^{\rm HQE} \approx \lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd}\right) \approx 10^{-5} y_D^{\rm Exp.}$$

How can this be?

Look only at a single diagram:

$$y_D^{\rm HQE} \neq \lambda_s^2 \Gamma_{12}^{ss} \tau_D = 3.7 \cdot 10^{-2} \approx 5.6 y_D^{\rm Exp.}$$

pert. calculation: Bobrowski et al 1002.4794
lattice input: ETM 1403.7302; 1505.06639; FNAL/MILC 1706.04622
HQET sum rules: Kirk, AL, Rauh 1711.02100

The problem seems to originate in the extreme GIM cancellations

Status Quo: Charm Mixing

1. Duality violations - break down of HQE

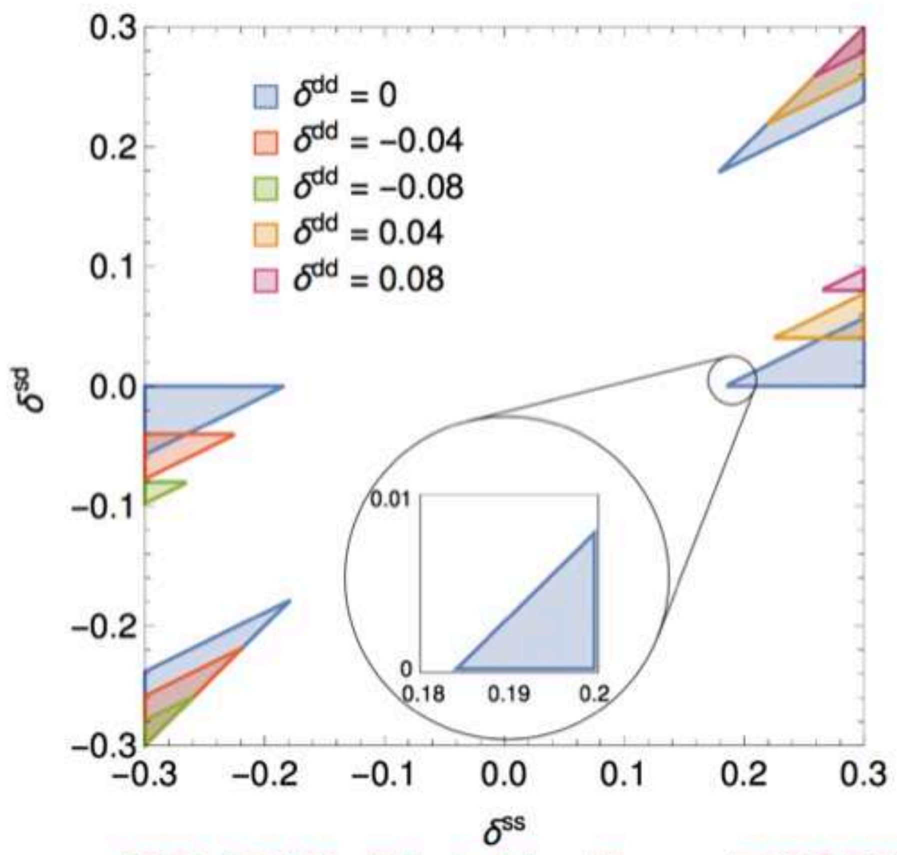
$$\Gamma_{12}^{ss} \to \Gamma_{12}^{ss}(1+\delta^{ss}) \, ,$$

$$\Gamma_{12}^{sd} \to \Gamma_{12}^{sd}(1+\delta^{sd}) \, ,$$

$$\Gamma_{12}^{dd} \to \Gamma_{12}^{dd}(1+\delta^{dd}) \, ,$$

20% of duality violation is sufficient to explain experiment

Jubb, Kirk, AL, Tetlalmatzi-Xolocotzi 2016

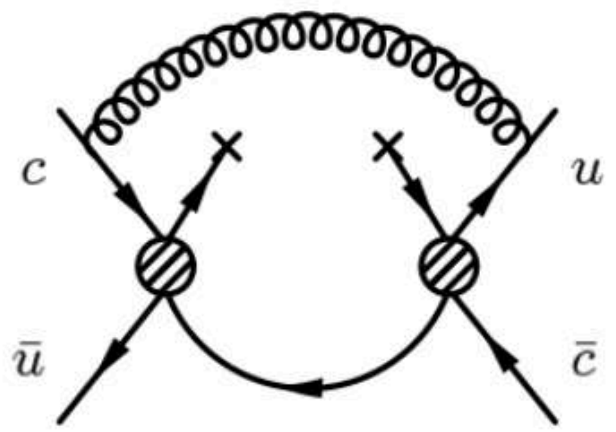


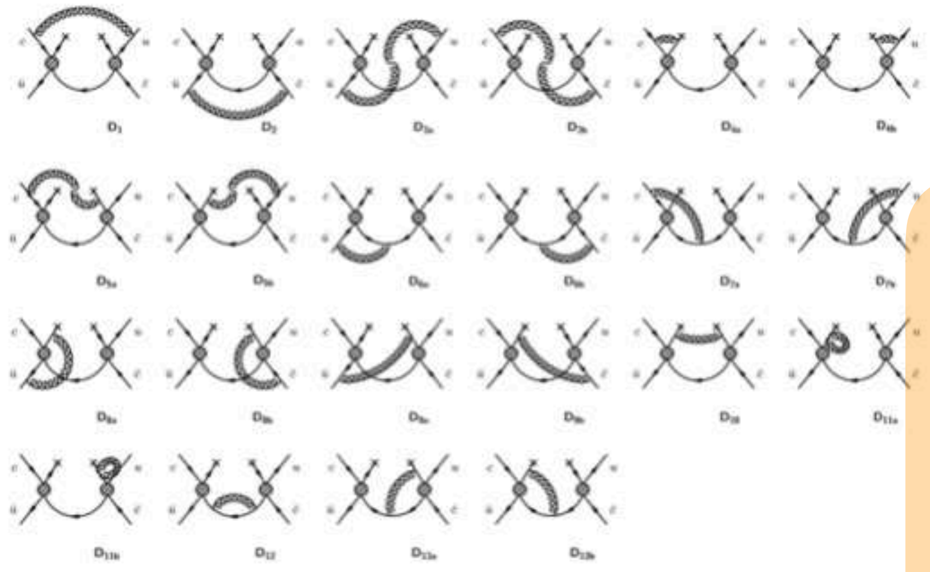
2. Higher dimensions

Georgi 9209291; Ohl, Ricciardi,Simmons 9301212; Bigi, Uraltsev 0005089

Idea: GIM cancellation is lifted by higher orders in the HQE - overcompensating the 1/mc suppression.

Partial calculation of D=9 yields an enhancement - but not to the experimental value Bobrowski, AL, Rauh 2012





3. Renormalisation scale setting:

AL, Piscopo, Vlahos 2020

$$\mu_x^{ss} = \mu_x^{sd} = \mu_x^{dd}$$

Implicitly assumes a precision of 10^-5!

4. New Physics is present and we cannot prove it yet:-)

1) Vary $\mu^{ss,dd}$ and μ^{ds} independently between 1 GeV and 2 m_c

   ⇒ uncertainty increases and exp. value is covered

2) Choose scales somehow phase space inspired as

$$\mu^{ss} = m_c - 2\epsilon$$
$$\mu^{sd} = m_c - \epsilon$$
$$\mu^{dd} = m_c$$

⇒ exp. value is covered

Exclusive and inclusive approaches can over the experimental regions

No precision determination possible