Theoretical Aspects of CP Violation and Mixing in the Quark Sector

LEPTON PHOTON 2021 MAN

11.1.2022

Alexander Lenz

UNIVERSITÄT SIEGEN

Outline

Center for Particle Physics Siegen

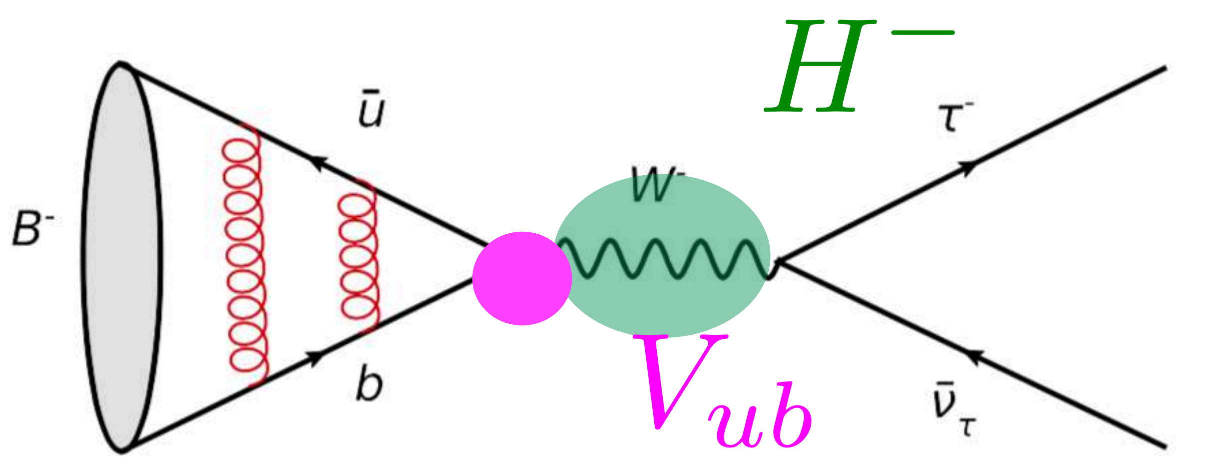
- **Intro: Meson decays and Mixing**
- **Intro: 3 Kinds of CPV violation**
- **Status Quo: Mixing & CPV in mixing**
  - Non-perturbative determination of bag parameter
  - Newest results for $\Delta\Gamma$, ΔM and a_{fs}
  - Peculiarities of Charm mixing
  - Alternative Renormalisation scale setting - changes for a_{fs}
- **Status Quo: CPV in interference**
  - Penguin pollution
  - Relation to CPV in mixing
- **Status Quo: Direct CPV**
  - ΔA_{CP}
  - QCD factorisation for non-leptonic B decays - a new anomaly?
  - **Flavour Specific CP asymmetries**

Experimental aspects
Malcolm John

For a comprehensive review
of CPV results
see e.g.
Gershon, Nir in PDG

Hadronic structure of Meson Decays

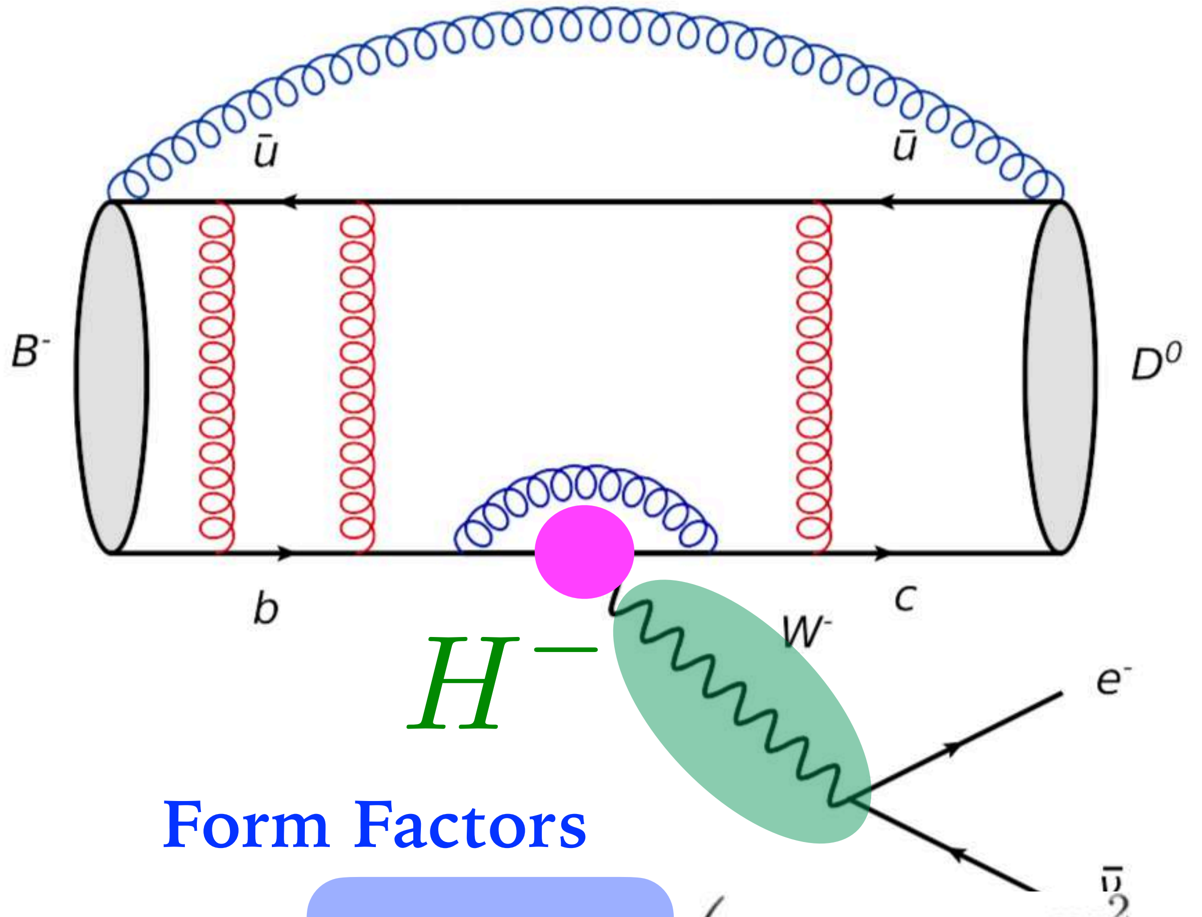
- Leptonic Decays



Decay constant

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

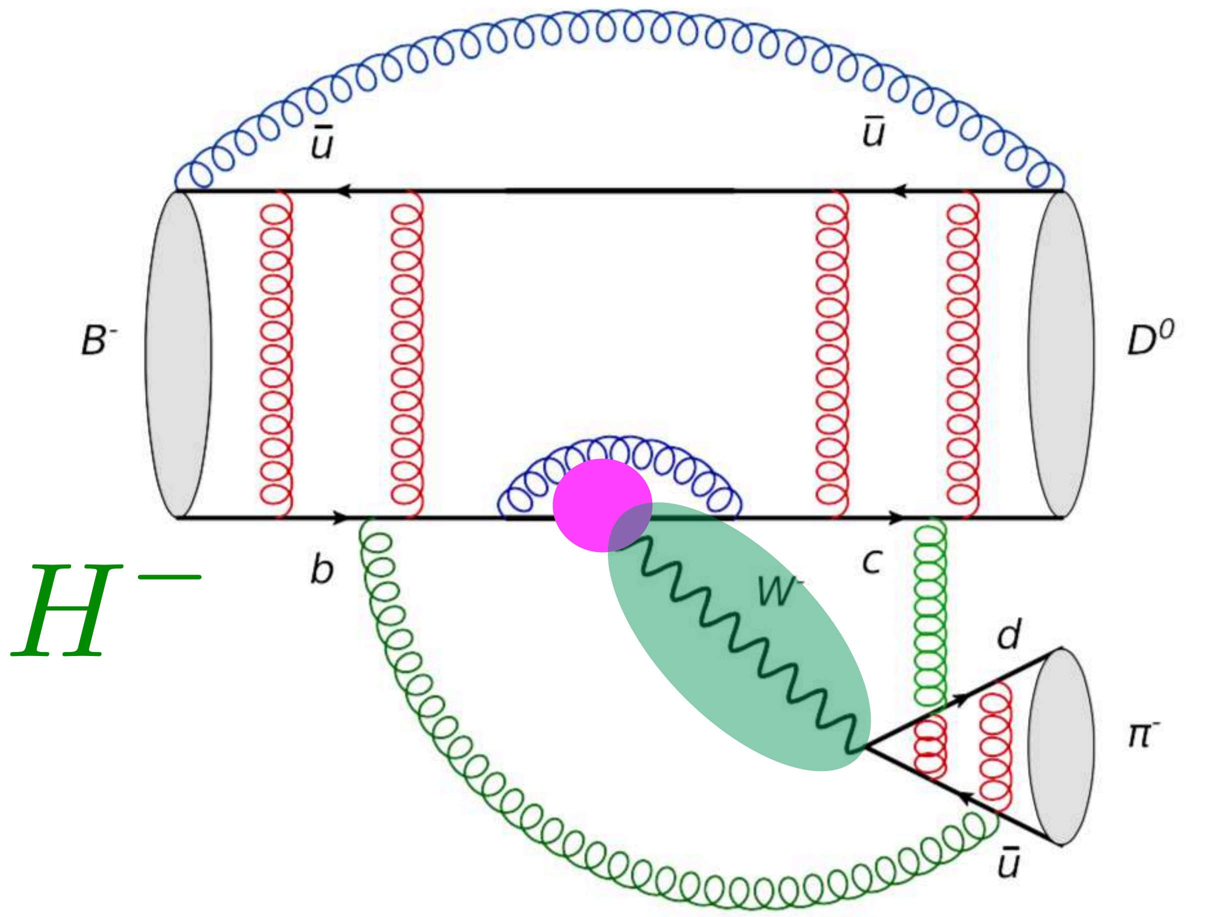
- Semileptonic Decays



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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Hadronic structure of Meson Decays

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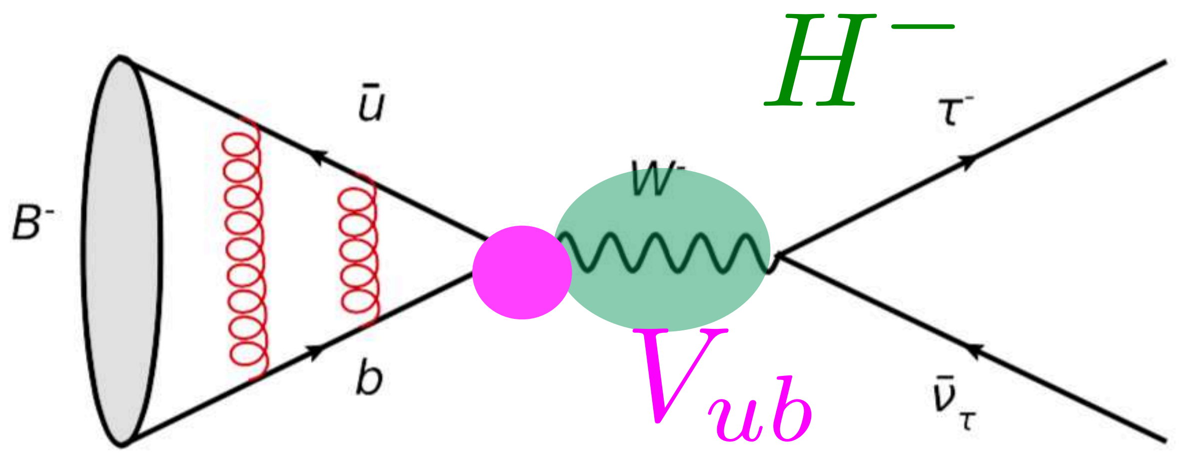
B anomalies e.g. Lucia Grillo, Danny van Dyk, Cristina Lazzeroni

- Leptonic Decays



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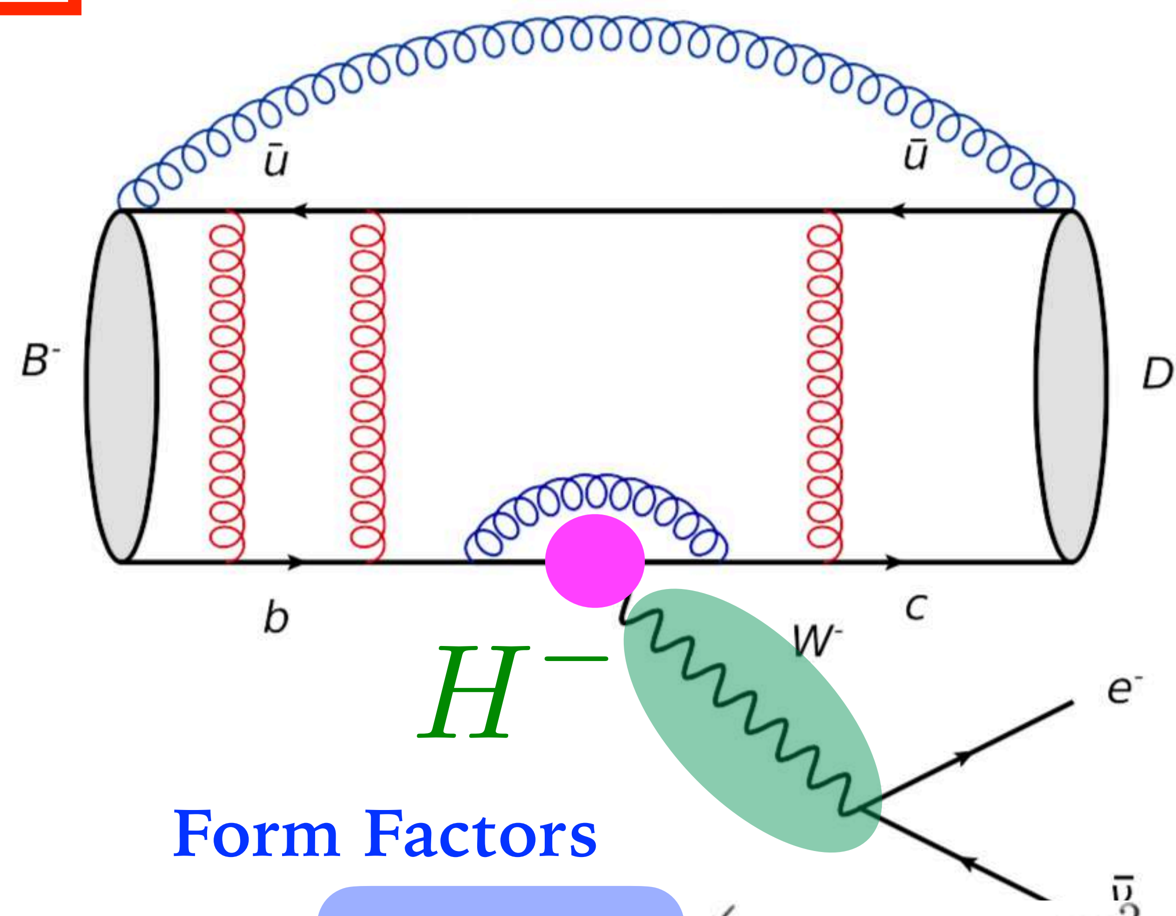

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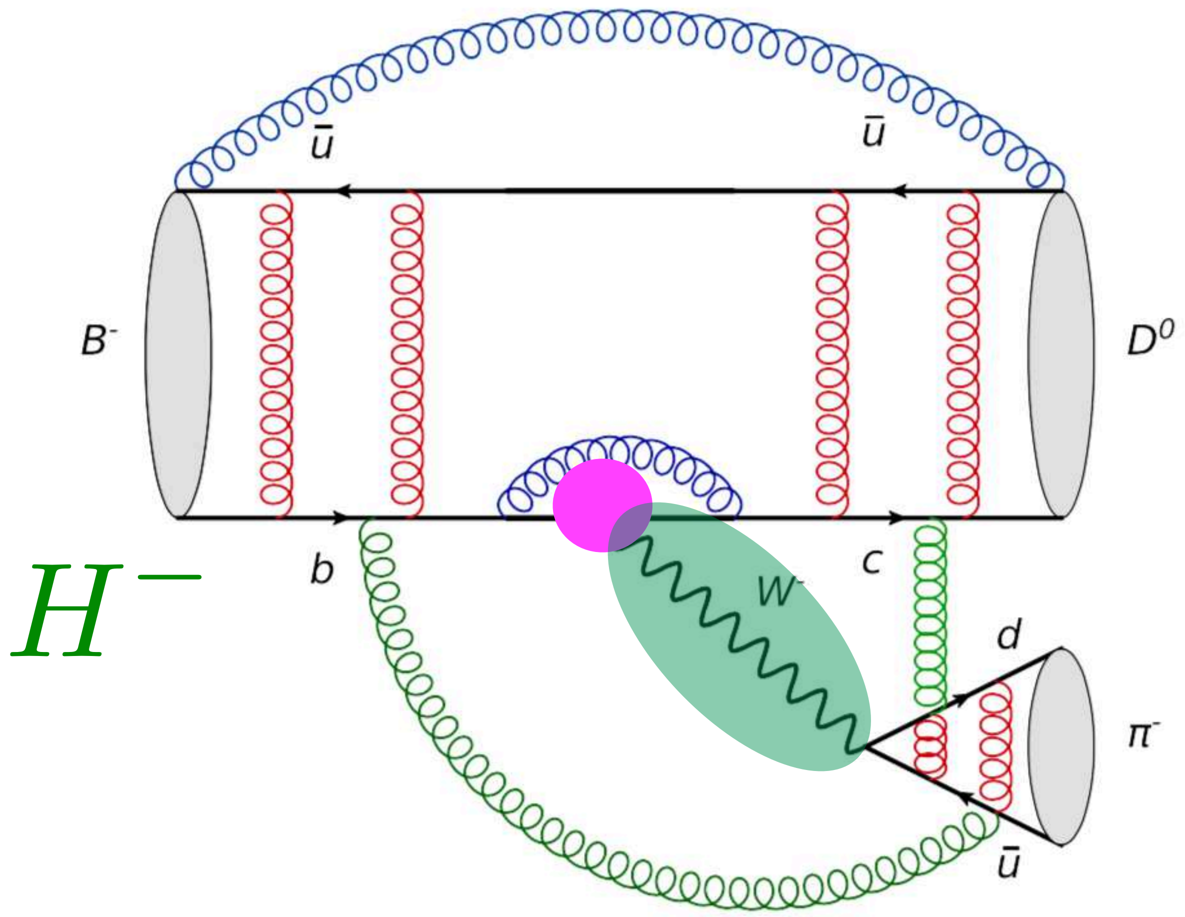
- Non-leptonic Decays



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I) Imaginary part of CKM-elements = CP Violation

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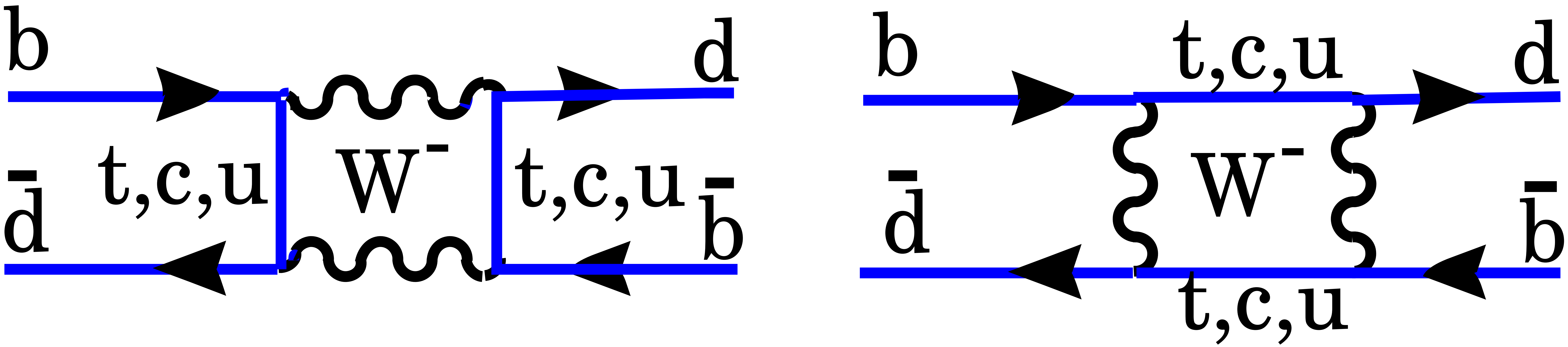
Mixing

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



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

Mixing

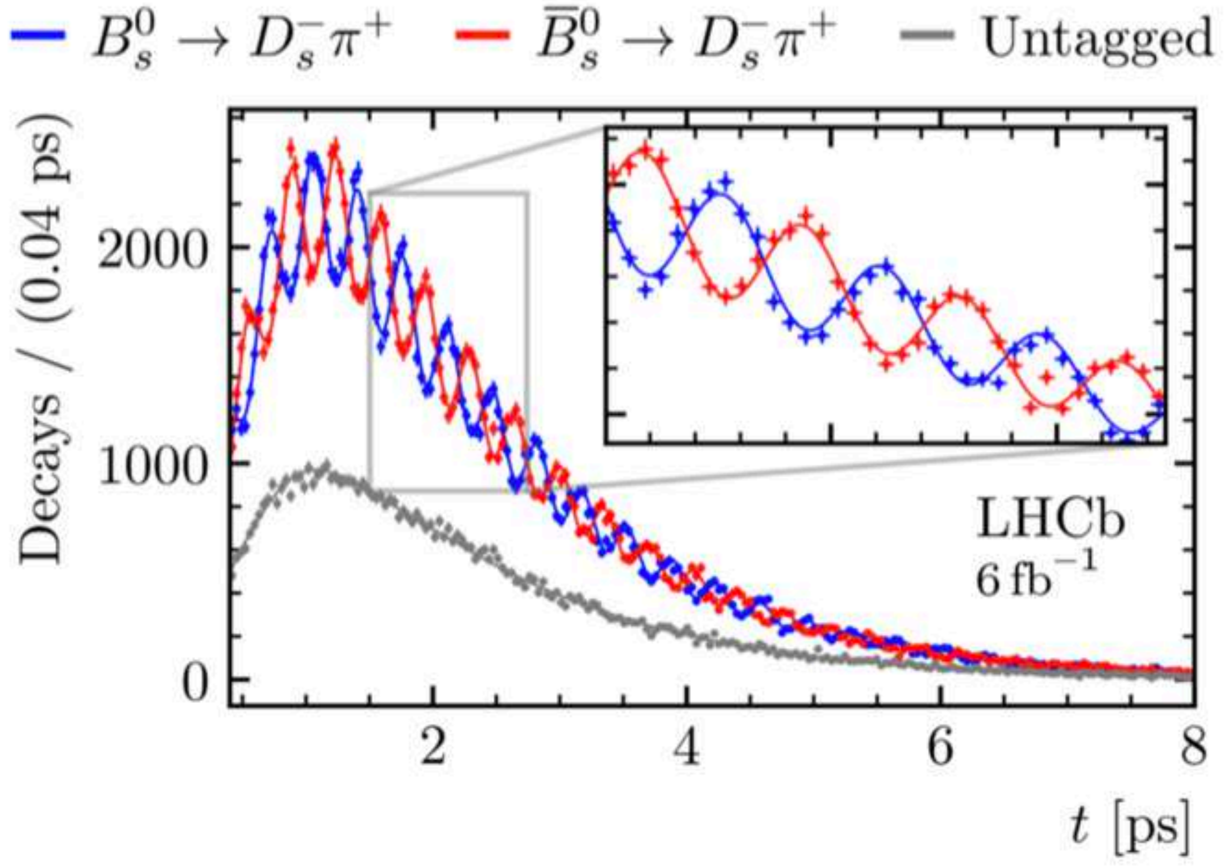
Time evolution of neutral B mesons (quantum mechanics on a macroscopic scale)

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

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^q_{fs} to be defined below



Outline

- **Intro: Meson decays and Mixing**
- **Intro: 3 Kinds of CPV violation**
- **Status Quo: Mixing & CPV in mixing**
- **Status Quo: CPV in interference**
- **Status Quo: Direct CPV**

CP Violation

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

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

$\boxed{\bar A_{\bar f} = A_f}$

=

No direct CP violation

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

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

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

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

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 $D^0 \to \pi^-\pi^+, K^-K^+$

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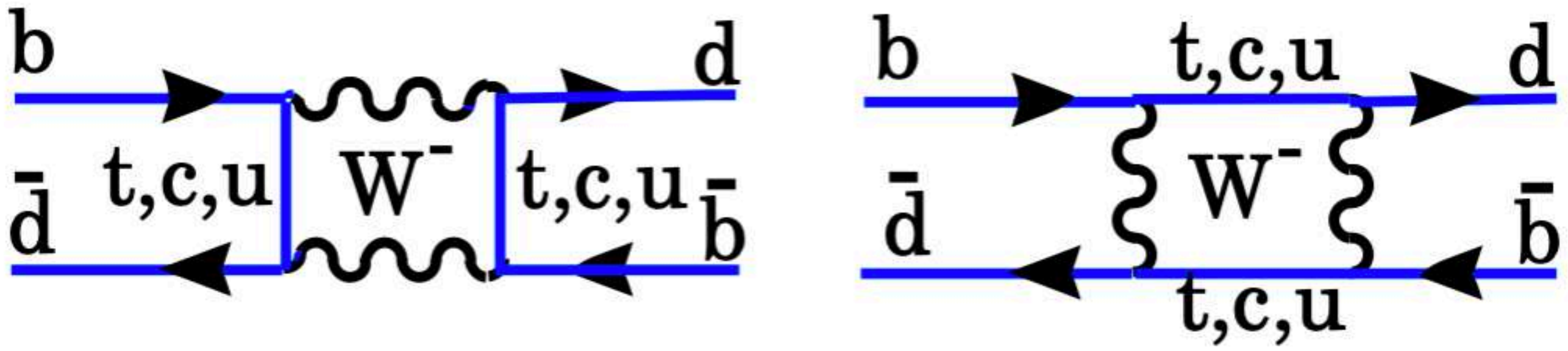
Status Quo: Mixing

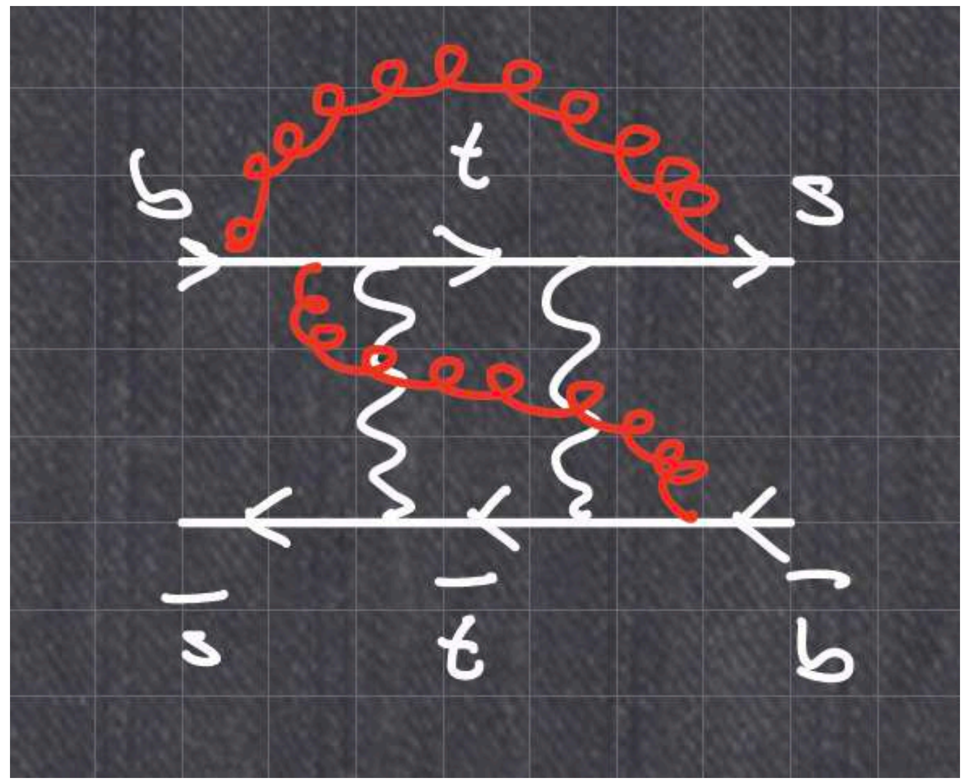
$$\Delta M_s = 2\,|M_{12}^s|$$



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

Significant CKM dependence

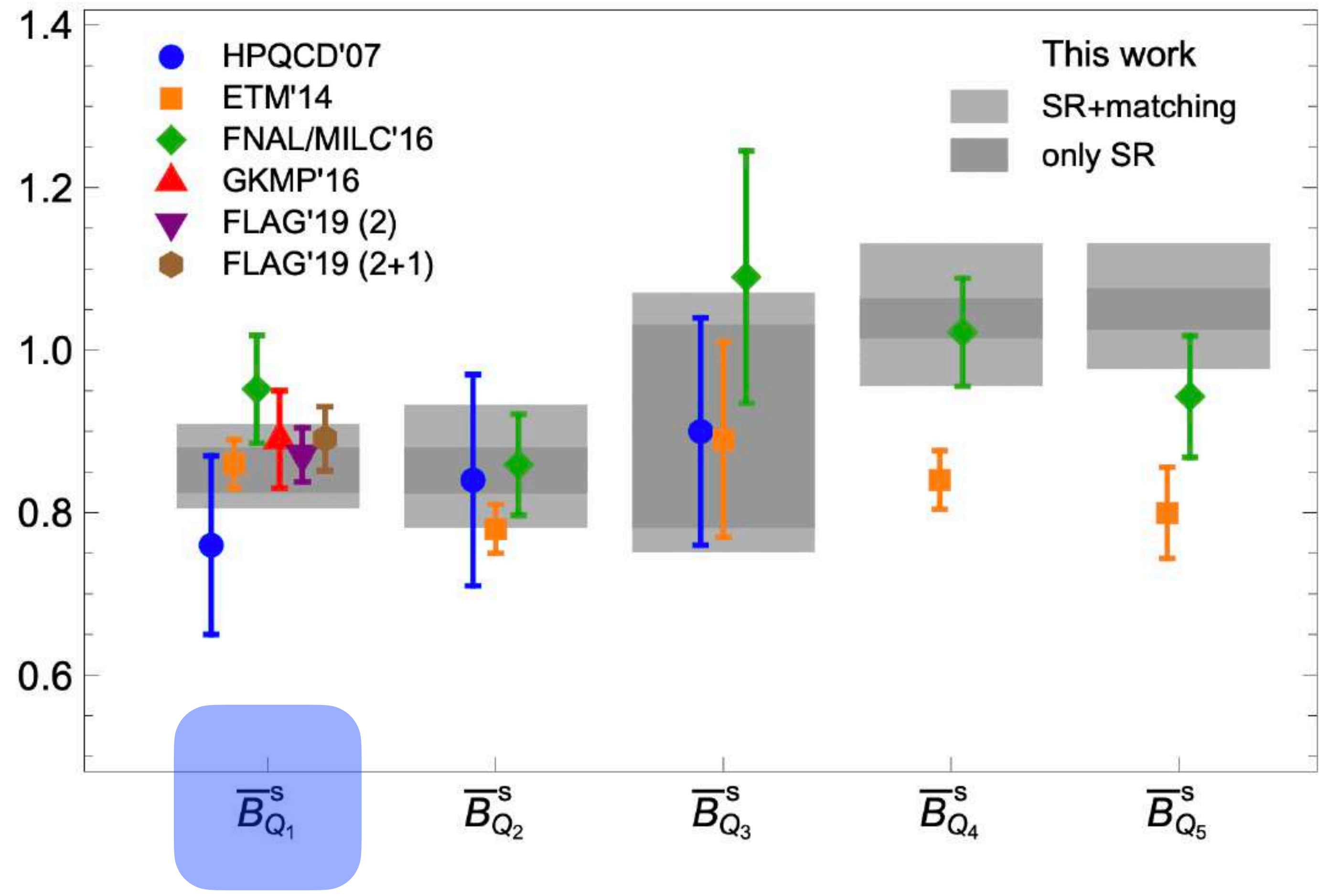
By far dominant uncertainty



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

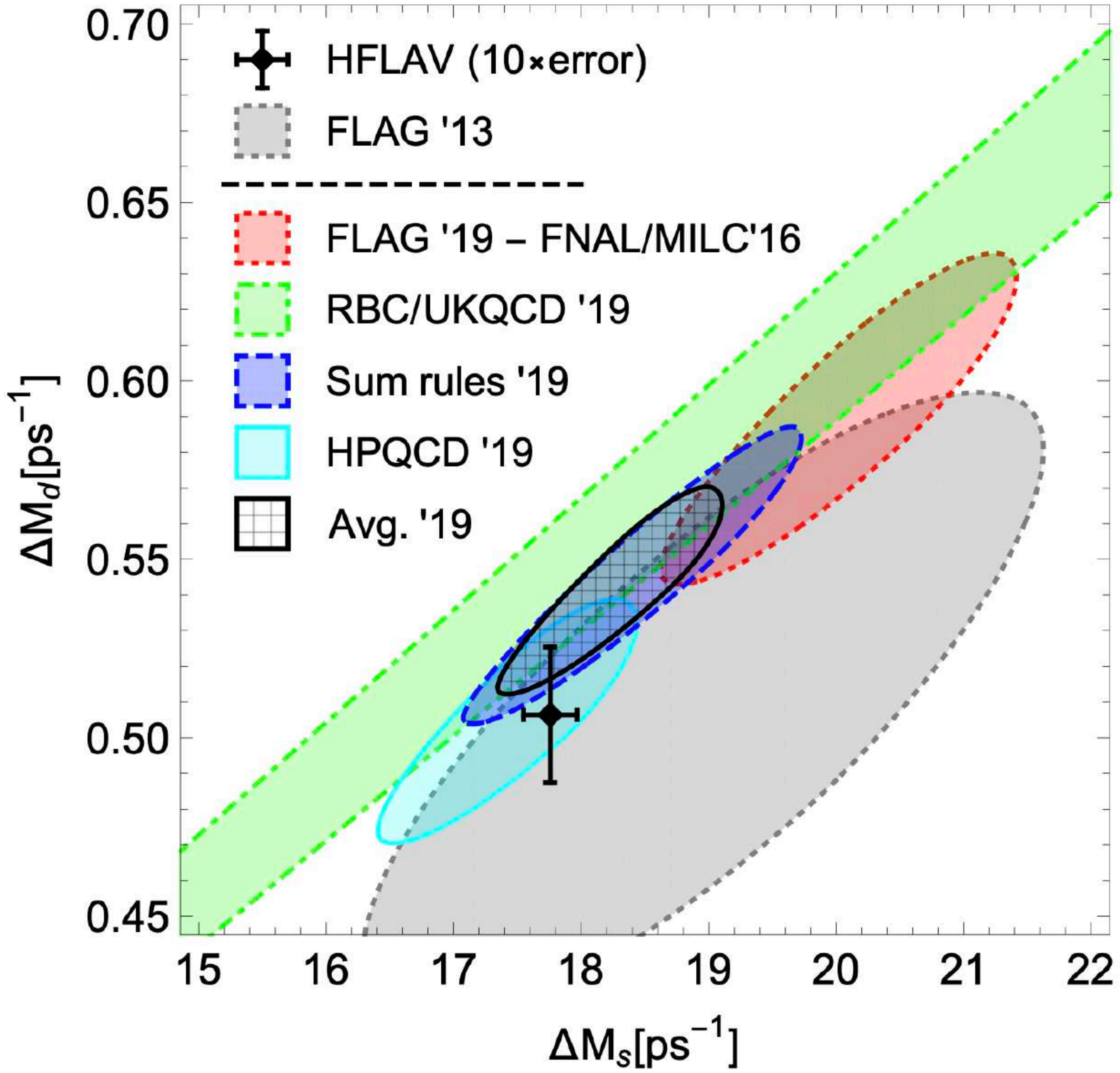
Status Quo: Mixing

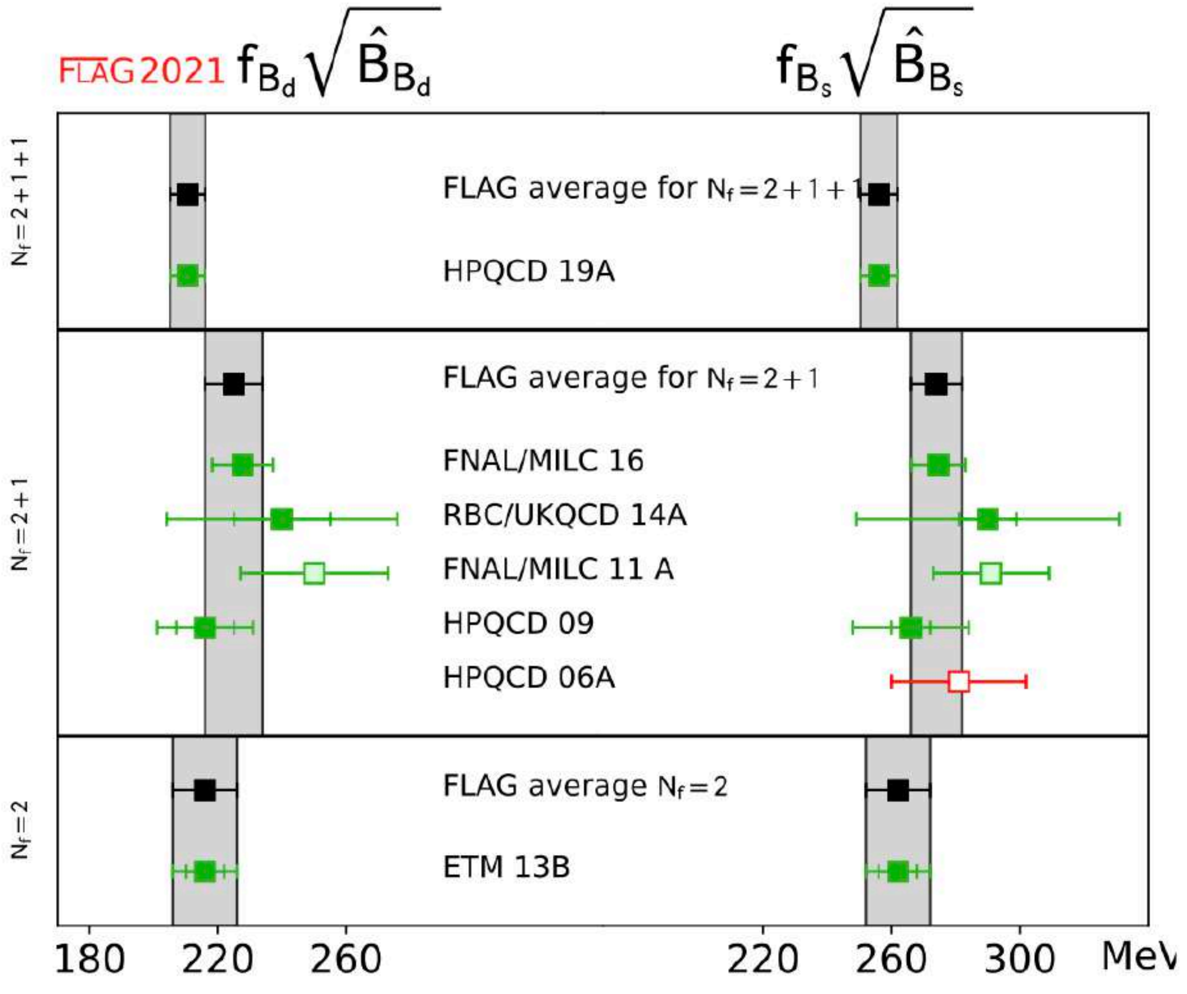
$$\Delta M_d = (0.5065 \pm 0.0019)\,\mathrm{ps}^{-1} \qquad \Delta M_d = \left(0.533^{+0.022}_{-0.036}\right)\,\mathrm{ps}^{-1}$$

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

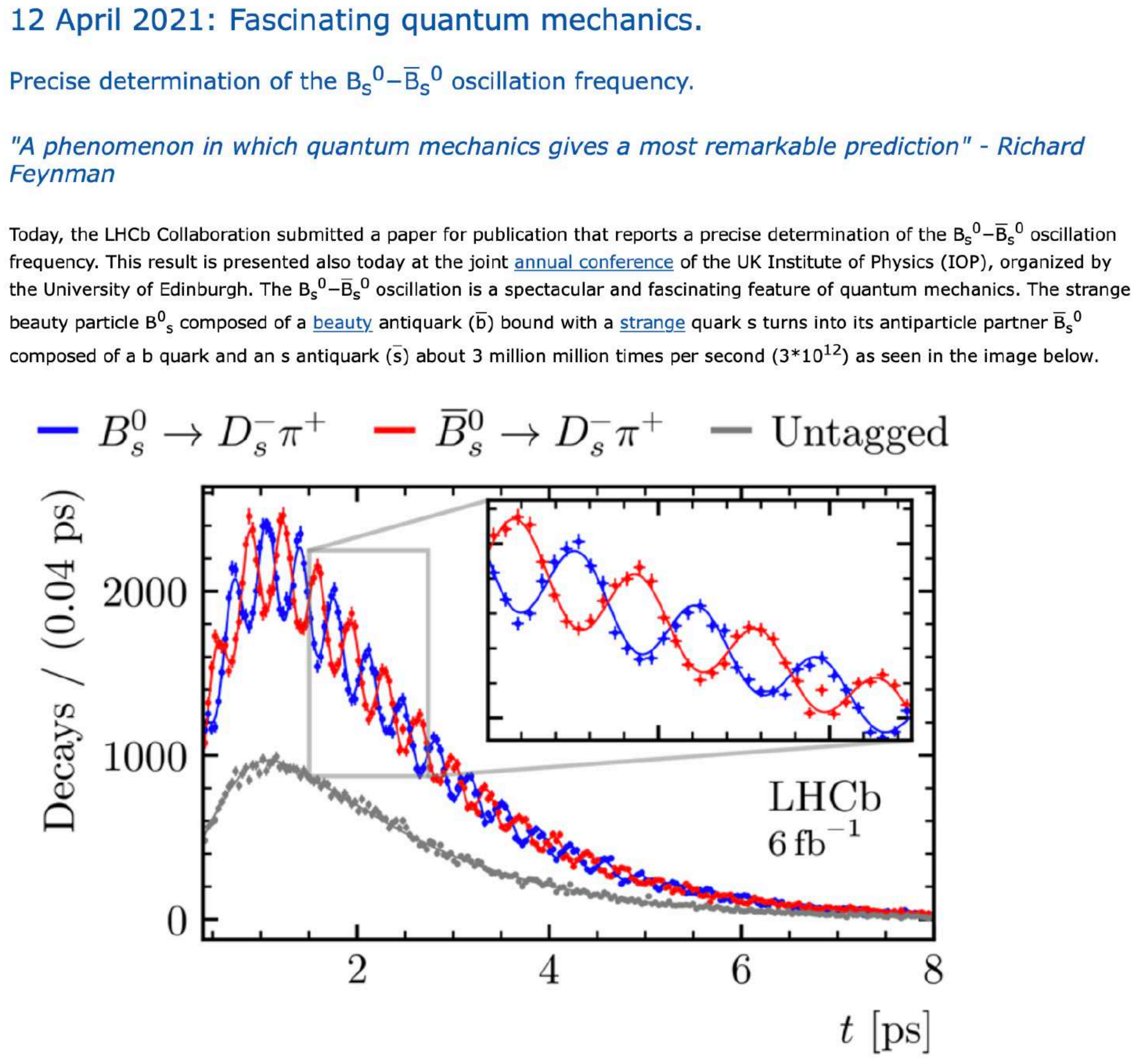
HFLAV 2021

1909.11087
Average lattice & sum rules





Work in progress by
RBC/UKQCD+JLQCD 2111.11287



12 April 2021: Fascinating quantum mechanics.

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

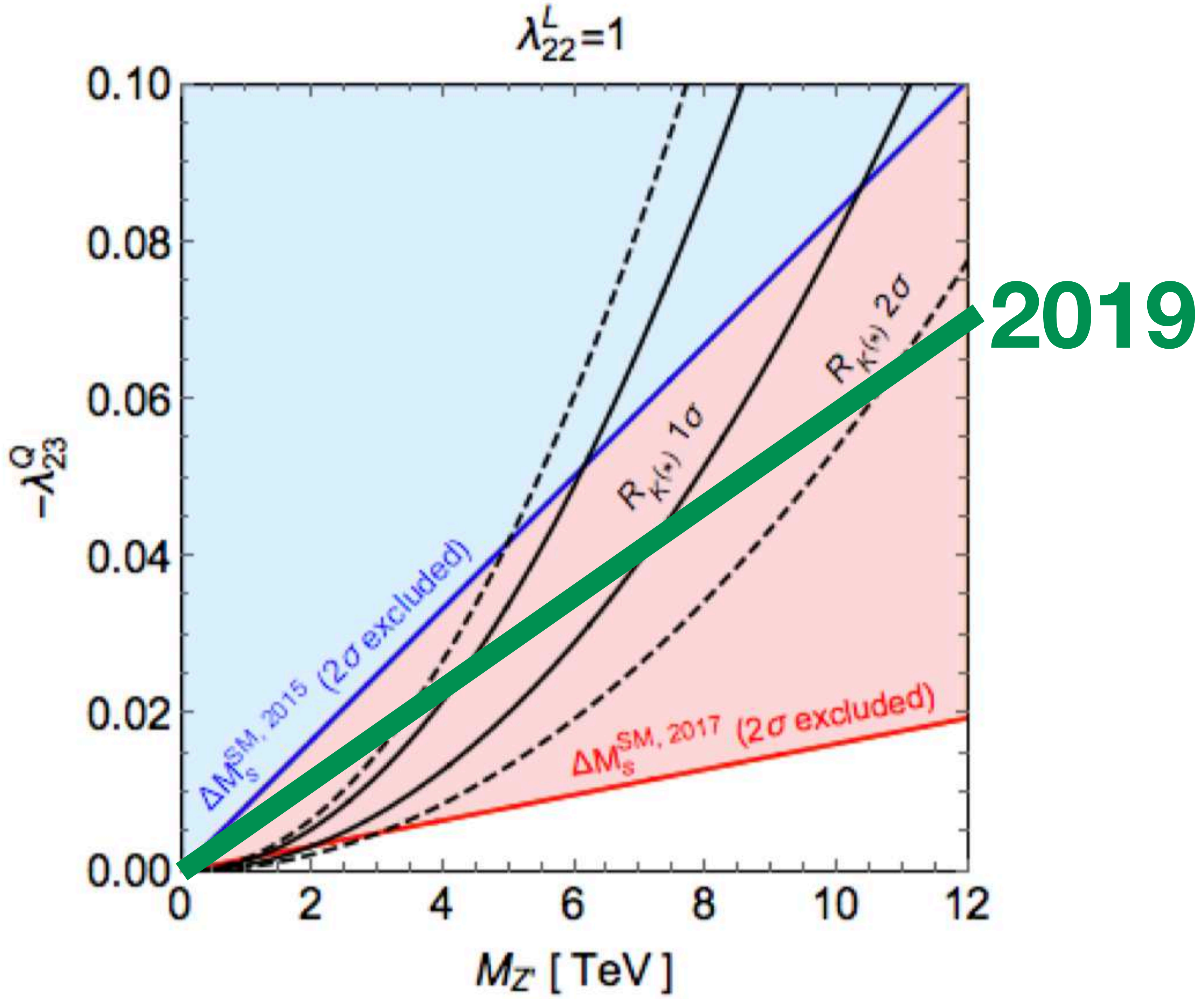
"A phenomenon in which quantum mechanics gives a most remarkable prediction" - Richard Feynman

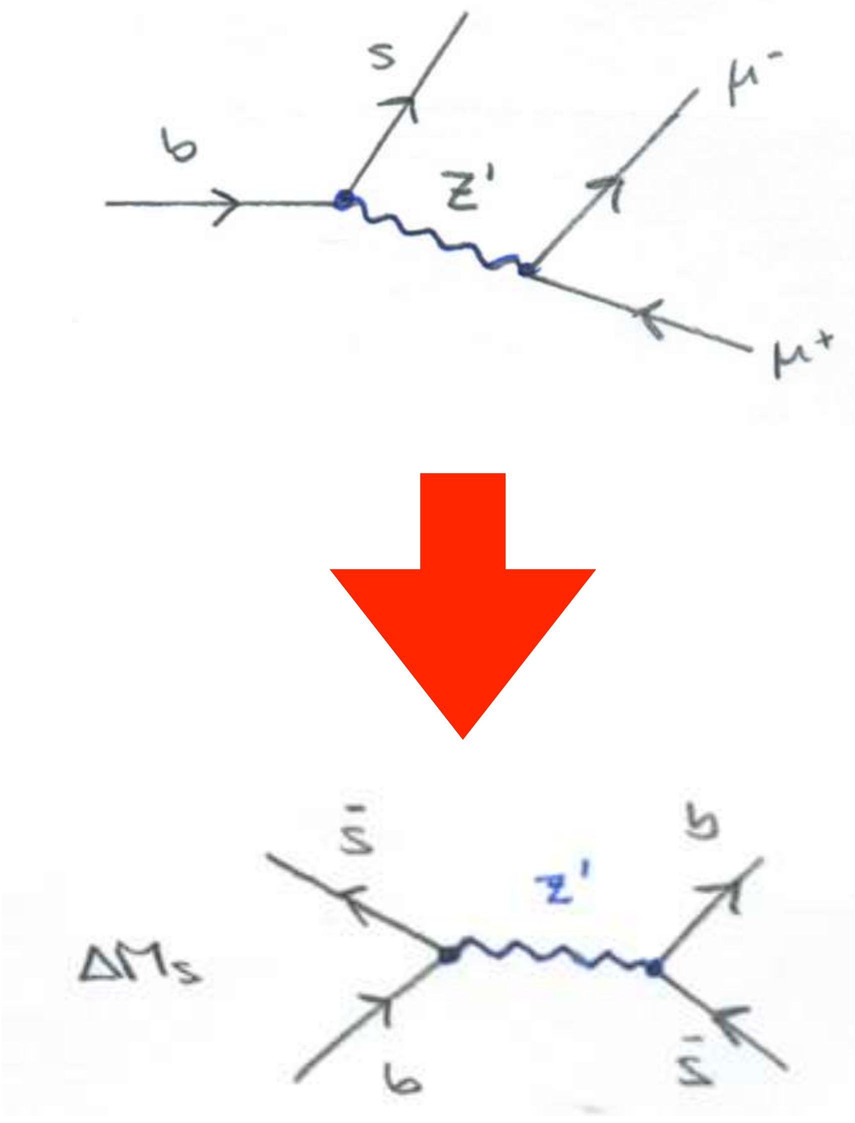
Today, the LHCb Collaboration submitted a paper for publication that reports a precise determination of the $B_s^0-\bar{B}_s^0$ oscillation frequency. This result is presented also today at the joint annual conference of the UK Institute of Physics (IOP), organized by the University of Edinburgh. The $B_s^0-\bar{B}_s^0$ 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.

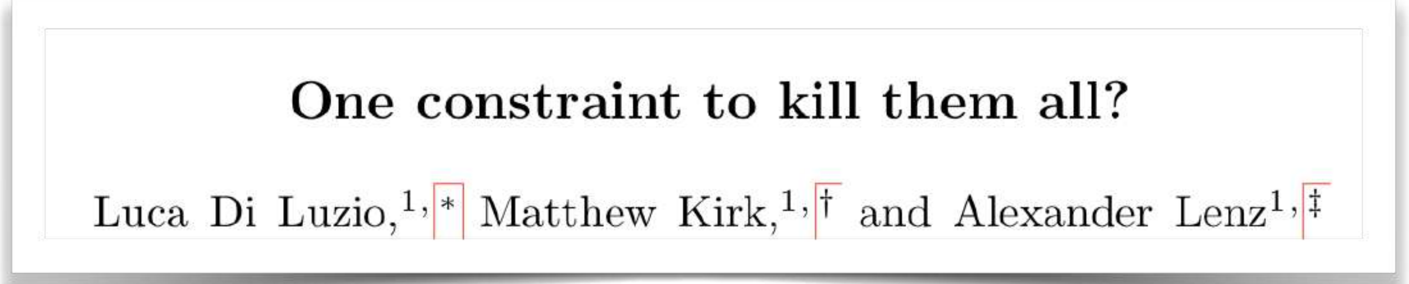
http://lhcb-public.web.cern.ch

Status Quo: Mixing

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





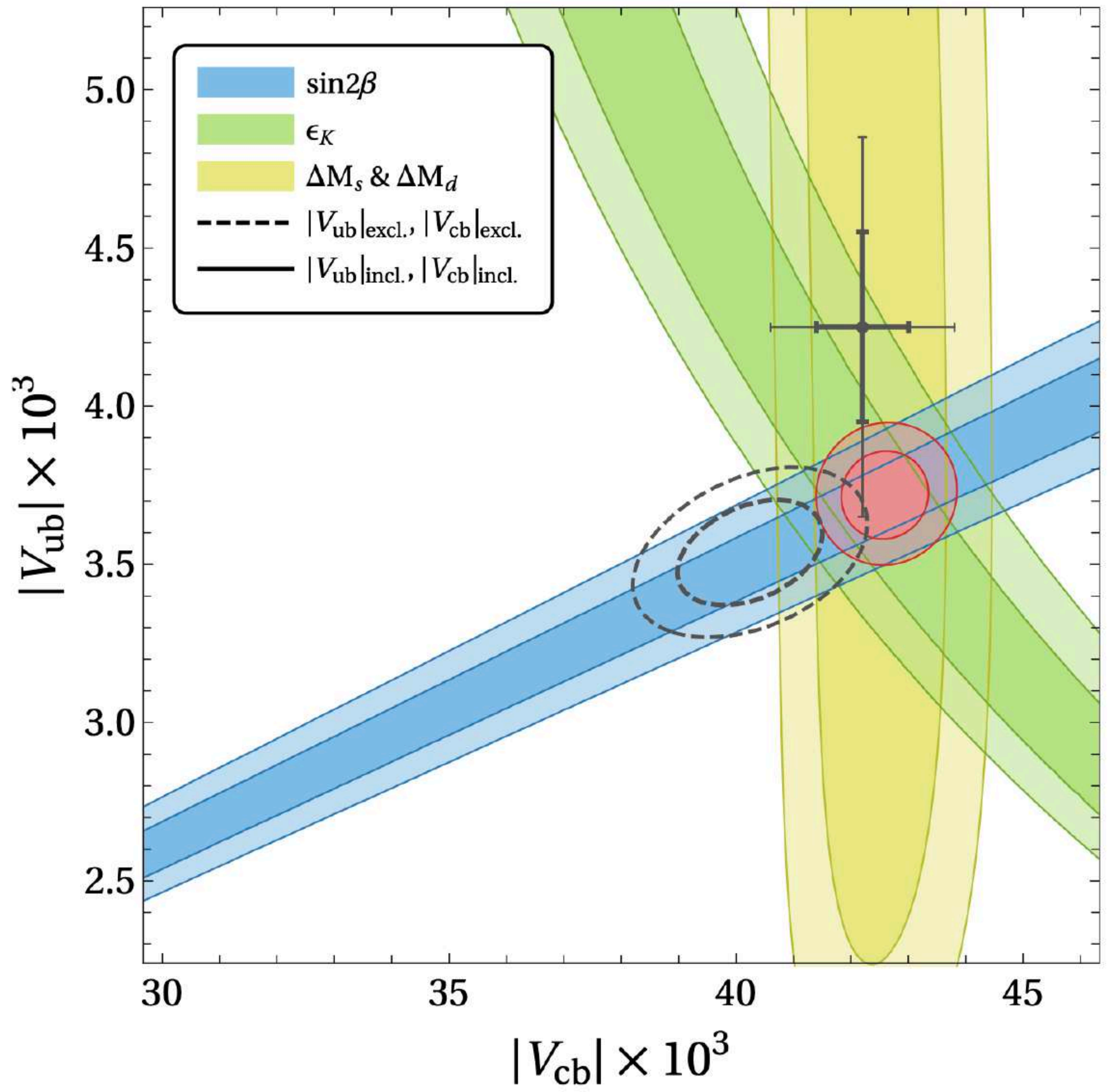

One constraint to kill them all?

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

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

$\Delta\Gamma_s^{HQE} = (0.091 \pm 0.013)\,\mathrm{ps}^{-1}$ $\quad$ $\Delta\Gamma_s^{HFLAV} = (0.082 \pm 0.005)\,\mathrm{ps}^{-1}$

$\Delta\Gamma_d^{HQE} = (2.6 \pm 0.4)\cdot 10^{-3}\,\mathrm{ps}^{-1}$ $\quad$ $\Delta\Gamma_d^{HFLAV} = (-1.3 \pm 6.6)\cdot 10^{-3}\,\mathrm{ps}^{-1}$

1912.07621

HFLAV, ATLAS 1605.07485

Status Quo: Mixing

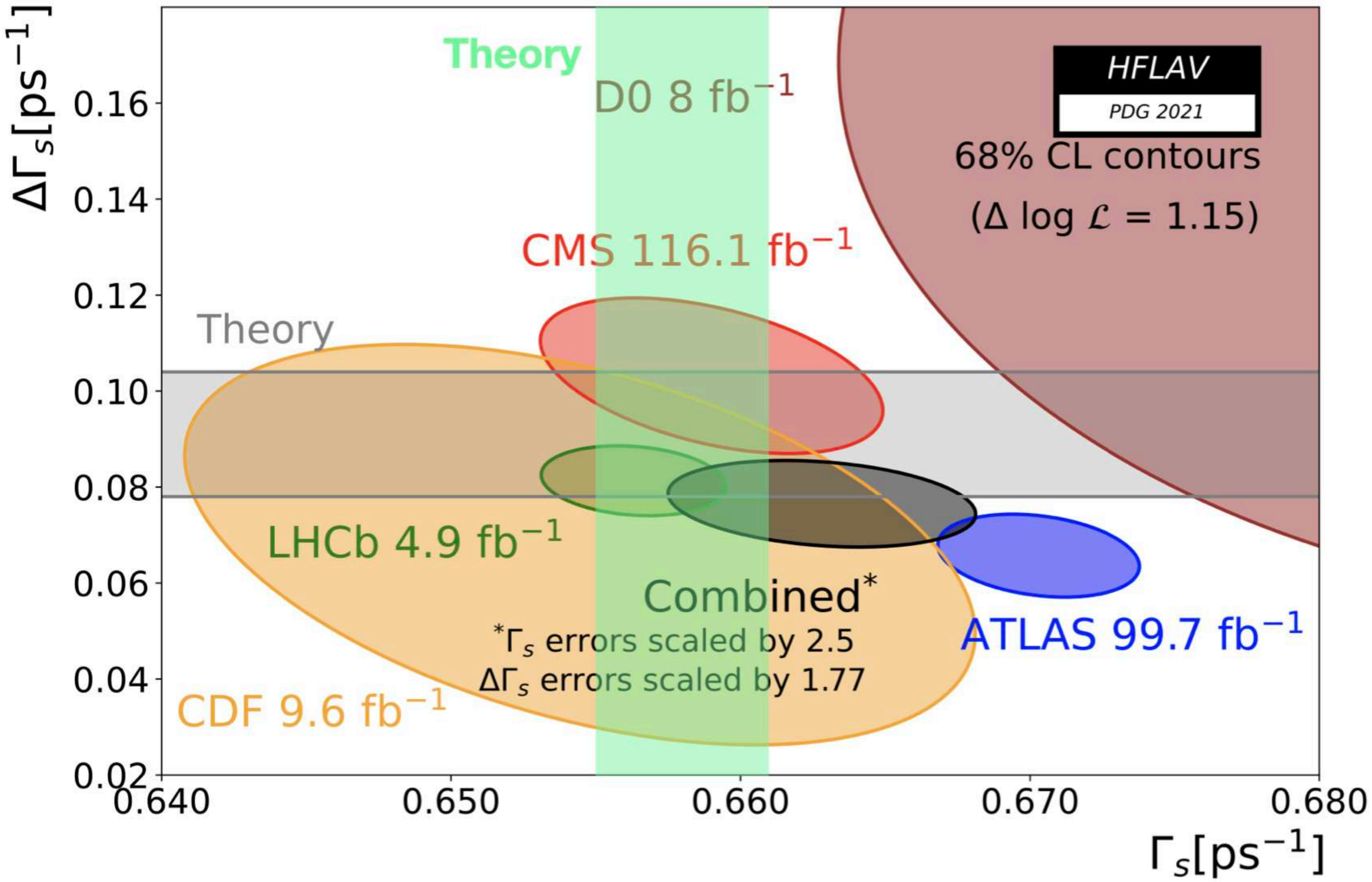


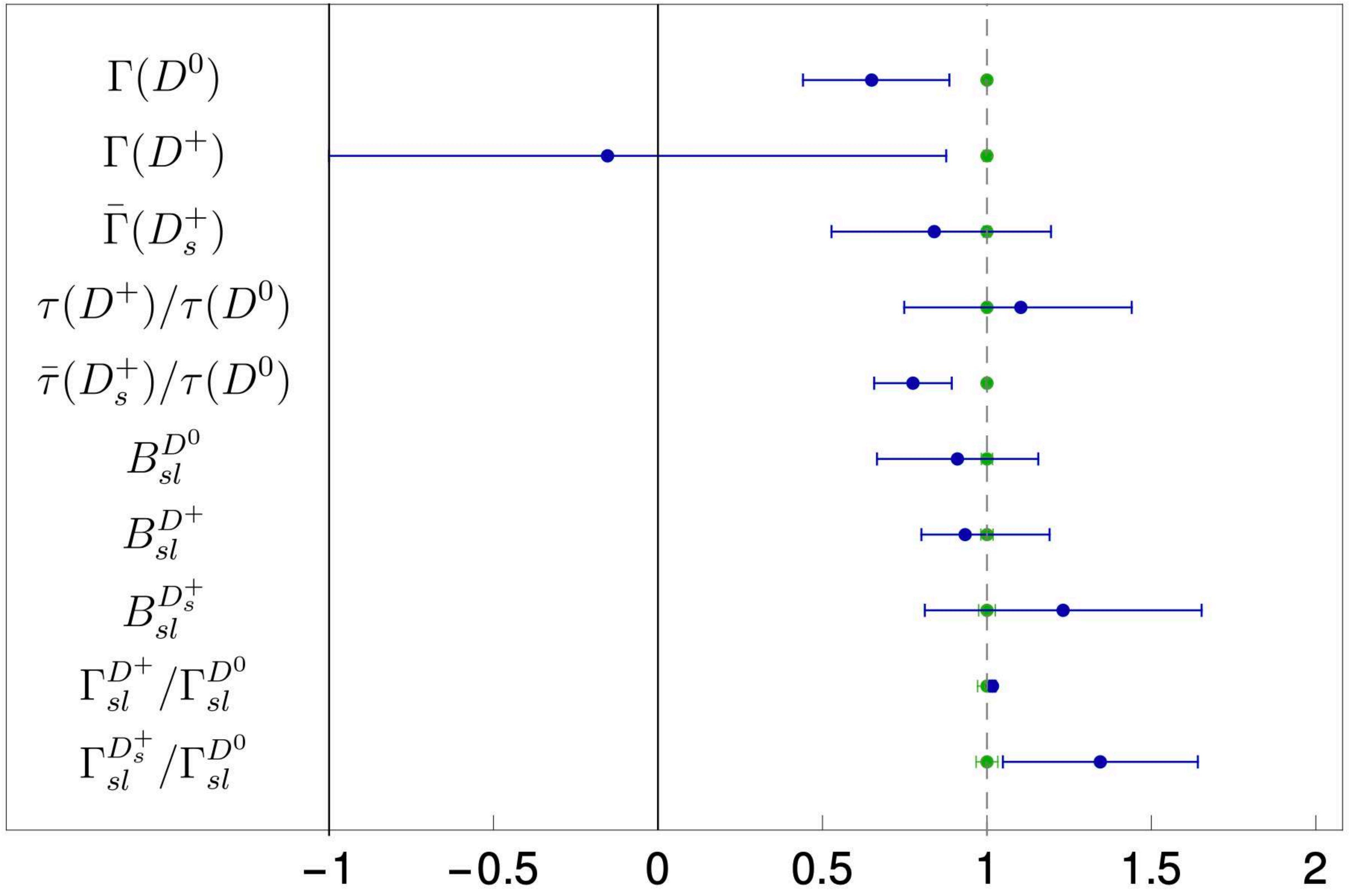
Figure 1: Experimental combination of results for $\Delta\Gamma_s$ and Γ_s by HFLAV. We have drawn by hand the SM prediction for Γ_s from Eq.(17) in the colour *sea foam*.

Status Quo: Charm Mixing

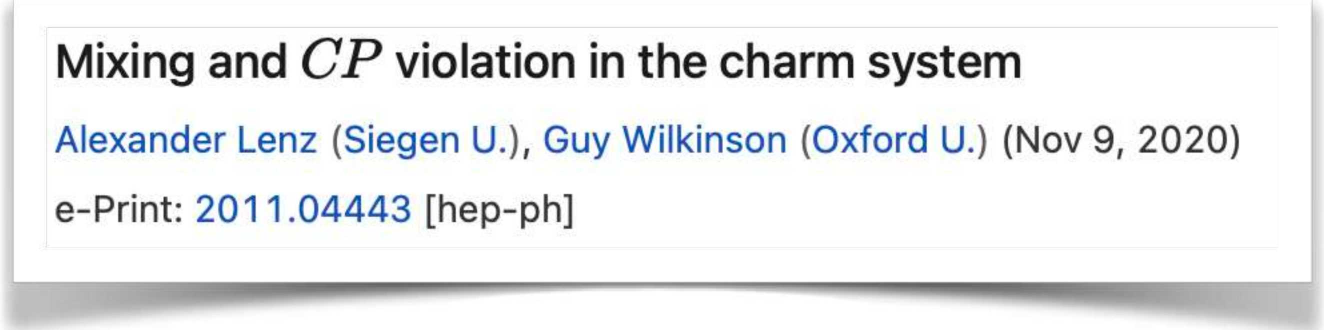
The charm system is theoretically more difficult than the b system since

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

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

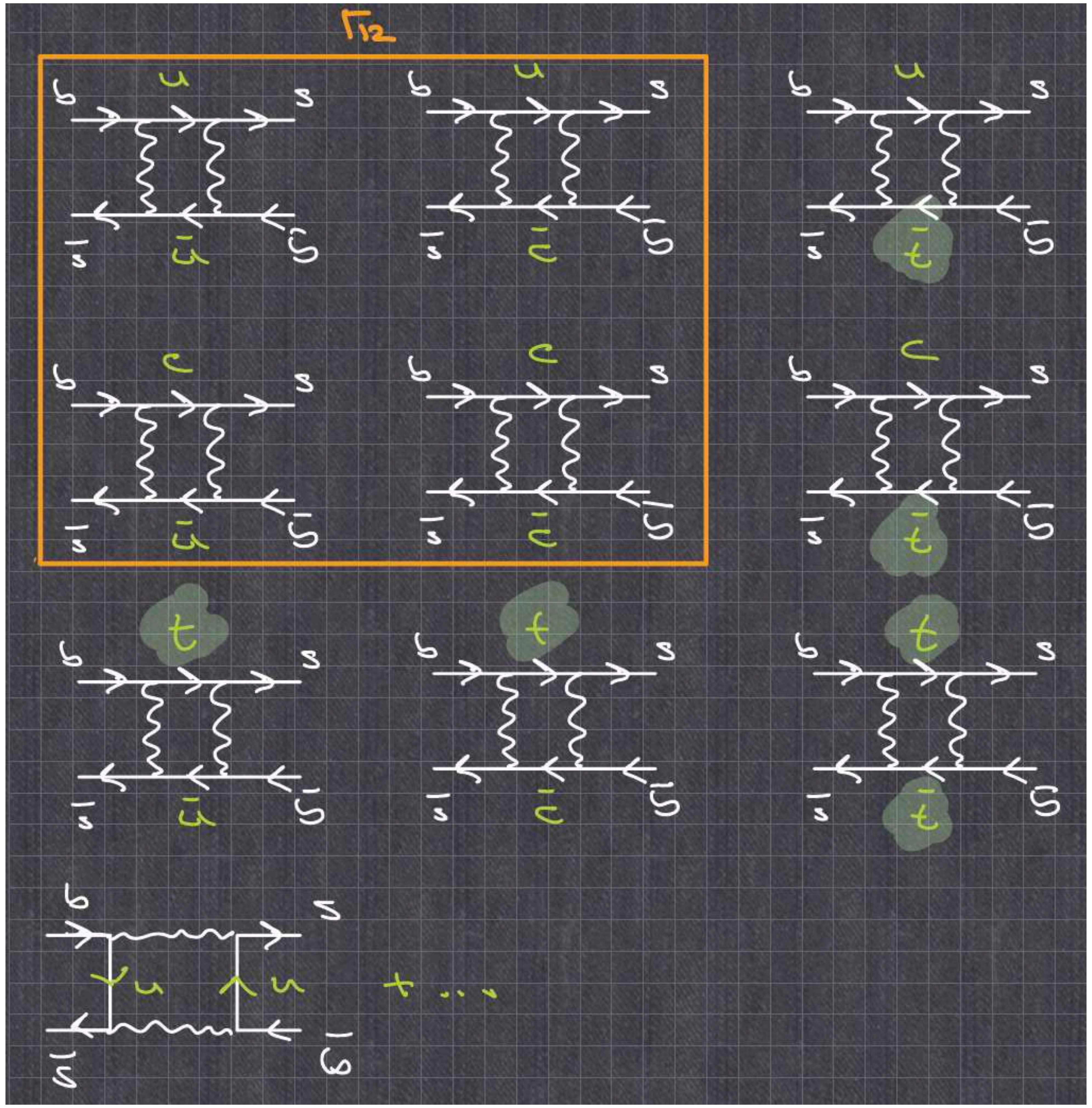
Alexander Lenz (Siegen U.), Guy Wilkinson (Oxford U.) (Nov 9, 2020)

e-Print: 2011.04443 [hep-ph]

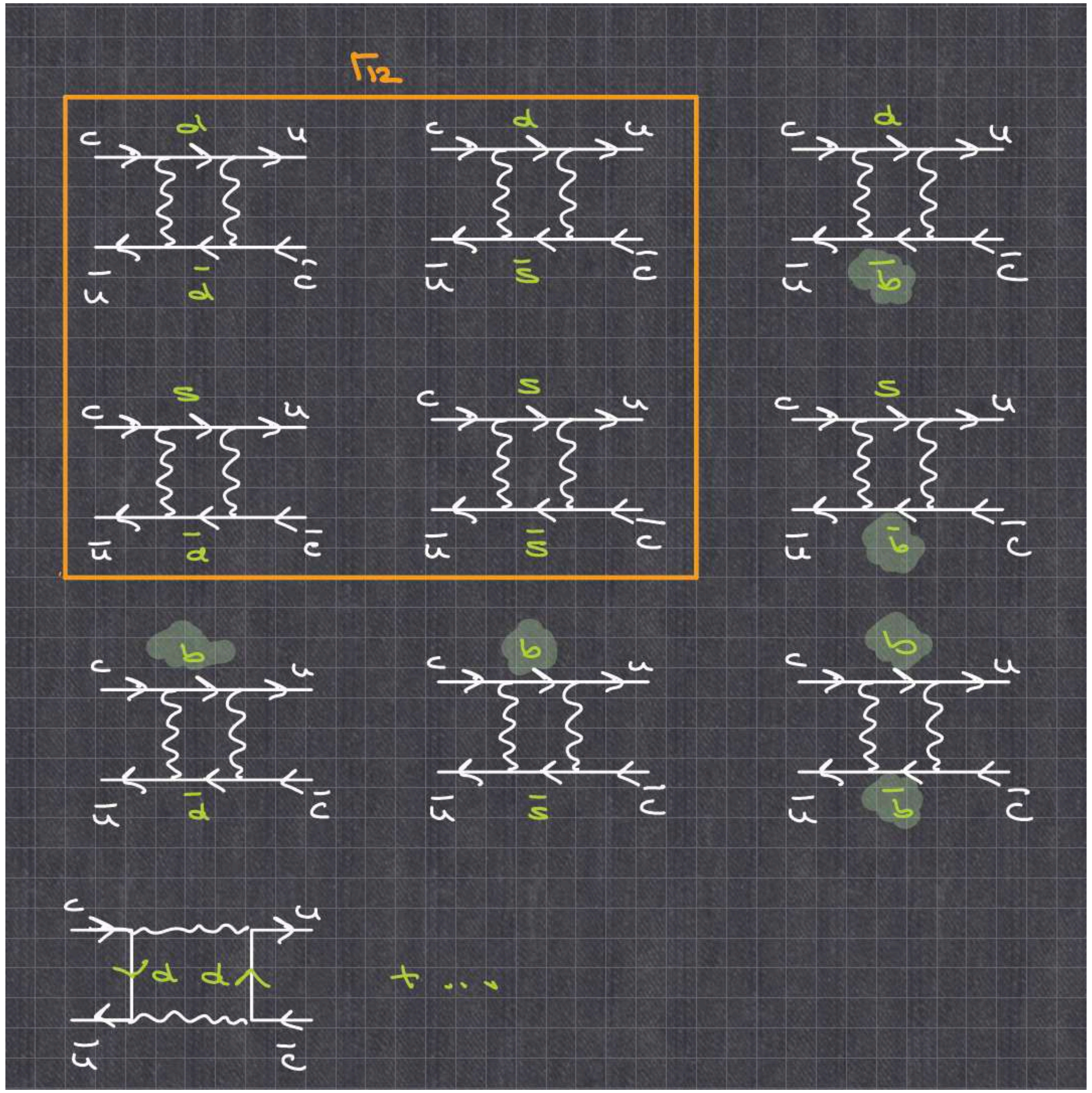
But for mixing it gets much worse

Status Quo: Charm Mixing

B-mixing

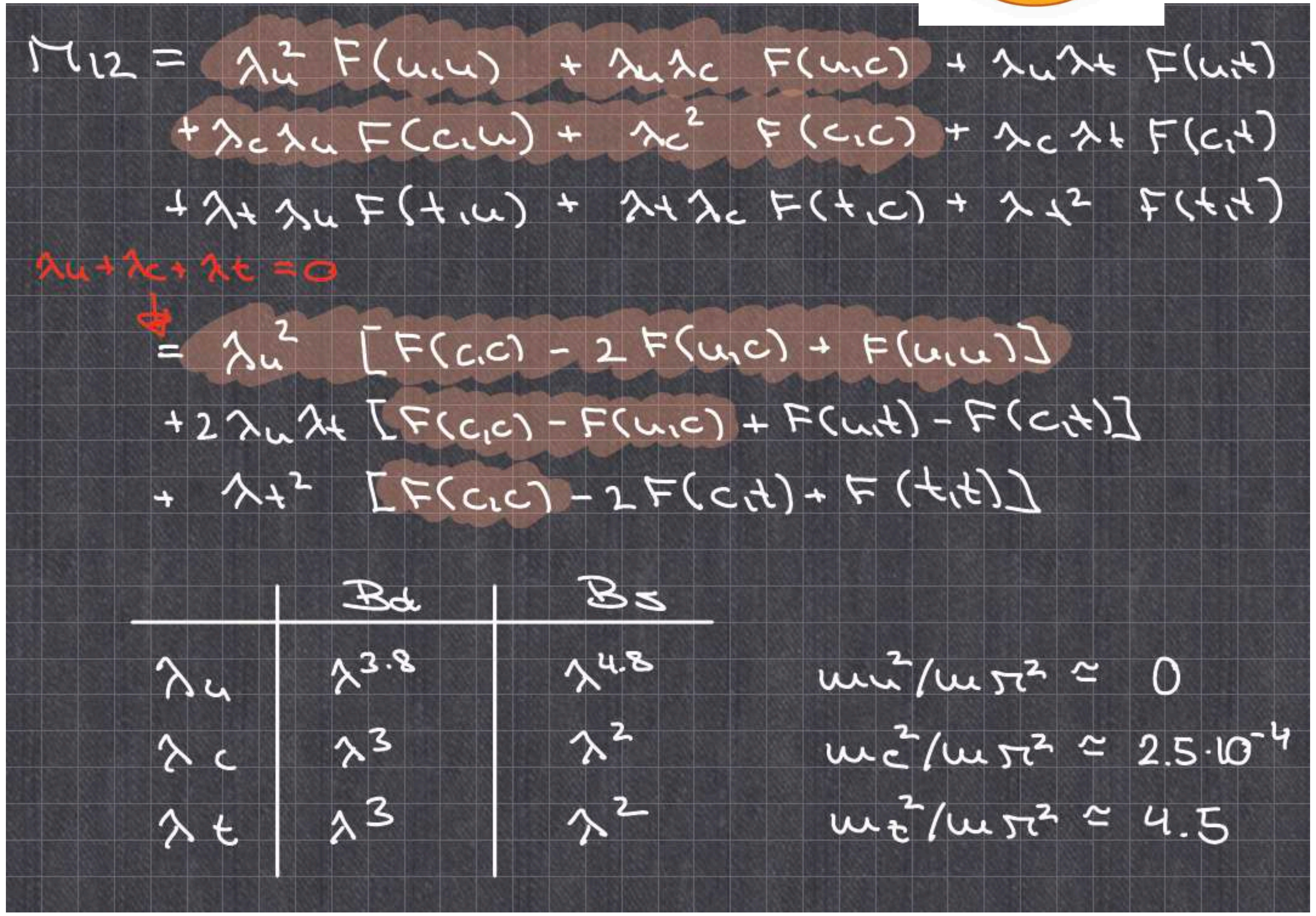


D-mixing



Status Quo: Charm Mixing

B-mixing



$$\Gamma_{12} = \lambda_u^2 F(u,u) + \lambda_u \lambda_c F(u,c) + \lambda_u \lambda_t F(u,t)$$
$$+ \lambda_c \lambda_u F(c,u) + \lambda_c^2 F(c,c) + \lambda_c \lambda_t F(c,t)$$
$$+ \lambda_t \lambda_u F(t,u) + \lambda_t \lambda_c F(t,c) + \lambda_t^2 F(t,t)$$

$\lambda_u + \lambda_c + \lambda_t = 0$

$$= \lambda_u^2 \left[F(c,c) - 2F(u,c) + F(u,u)\right]$$
$$+ 2\lambda_u \lambda_t \left[F(c,c) - F(u,c) + F(u,t) - F(c,t)\right]$$
$$+ \lambda_t^2 \left[F(c,c) - 2F(c,t) + F(t,t)\right]$$

	B_d	B_s
λ_u	$\lambda^{3.8}$	$\lambda^{4.8}$
λ_c	λ^3	λ^2
λ_t	λ^3	λ^2

$m_u^2/m_W^2 \simeq 0$

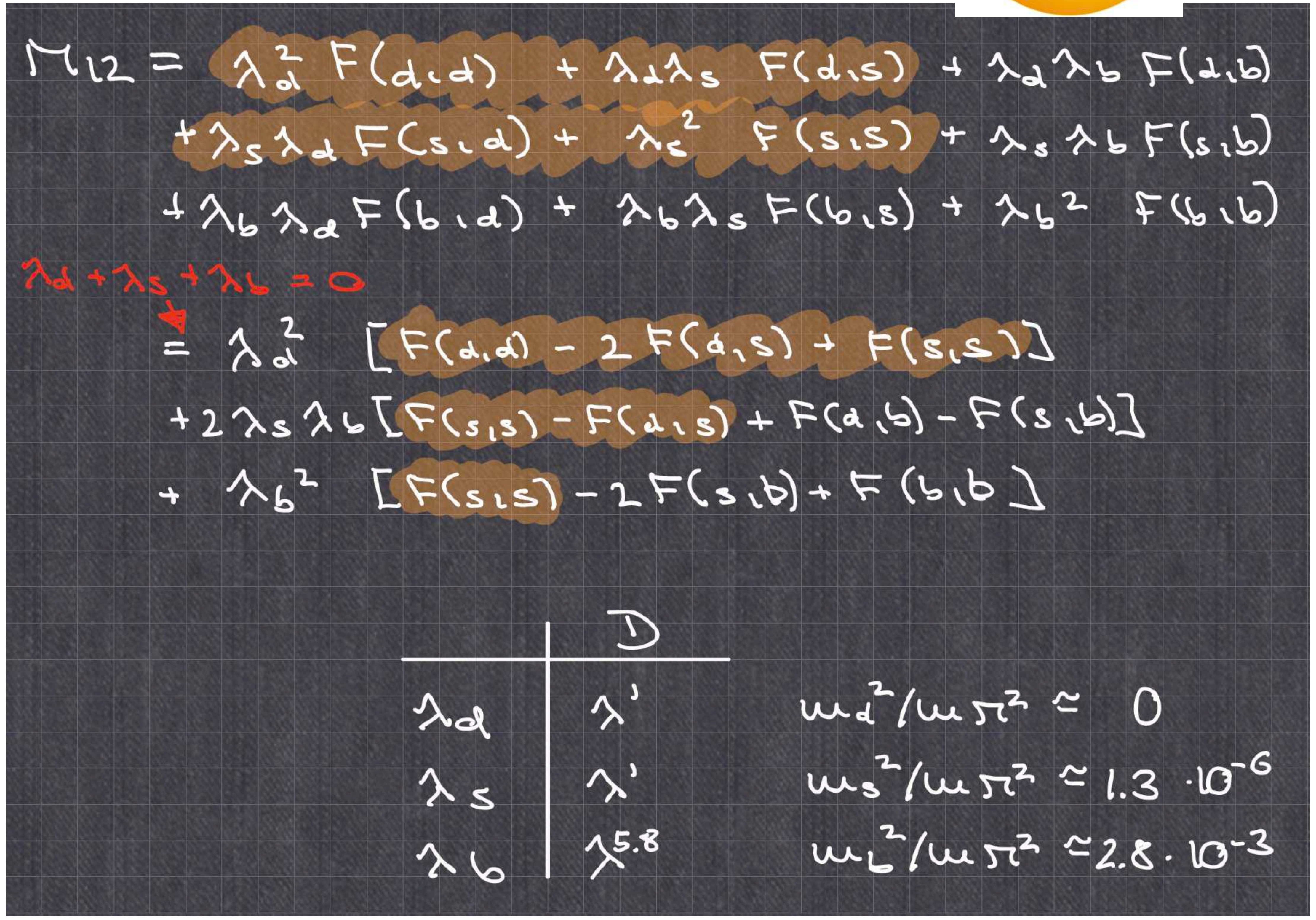
$m_c^2/m_W^2 \simeq 2.5 \cdot 10^{-4}$

$m_t^2/m_W^2 \simeq 4.5$

CKM dominant ≡ GIM dominant

CKM suppressed ≡ GIM suppressed

D-mixing



$$\Gamma_{12} = \lambda_d^2 F(d,d) + \lambda_d \lambda_s F(d,s) + \lambda_d \lambda_b F(d,b)$$
$$+ \lambda_s \lambda_d F(s,d) + \lambda_s^2 F(s,s) + \lambda_s \lambda_b F(s,b)$$
$$+ \lambda_b \lambda_d F(b,d) + \lambda_b \lambda_s F(b,s) + \lambda_b^2 F(b,b)$$

$\lambda_d + \lambda_s + \lambda_b = 0$

$$= \lambda_d^2 \left[F(d,d) - 2F(d,s) + F(s,s)\right]$$
$$+ 2\lambda_s \lambda_b \left[F(s,s) - F(d,s) + F(d,b) - F(s,b)\right]$$
$$+ \lambda_b^2 \left[F(s,s) - 2F(s,b) + F(b,b)\right]$$

	D
λ_d	λ^1
λ_s	λ^1
λ_b	$\lambda^{5.8}$

$m_d^2/m_W^2 \simeq 0$

$m_s^2/m_W^2 \simeq 1.3 \cdot 10^{-6}$

$m_b^2/m_W^2 \simeq 2.8 \cdot 10^{-3}$

CKM suppressed ≡ GIM dominant

CKM dominant ≡ GIM suppressed

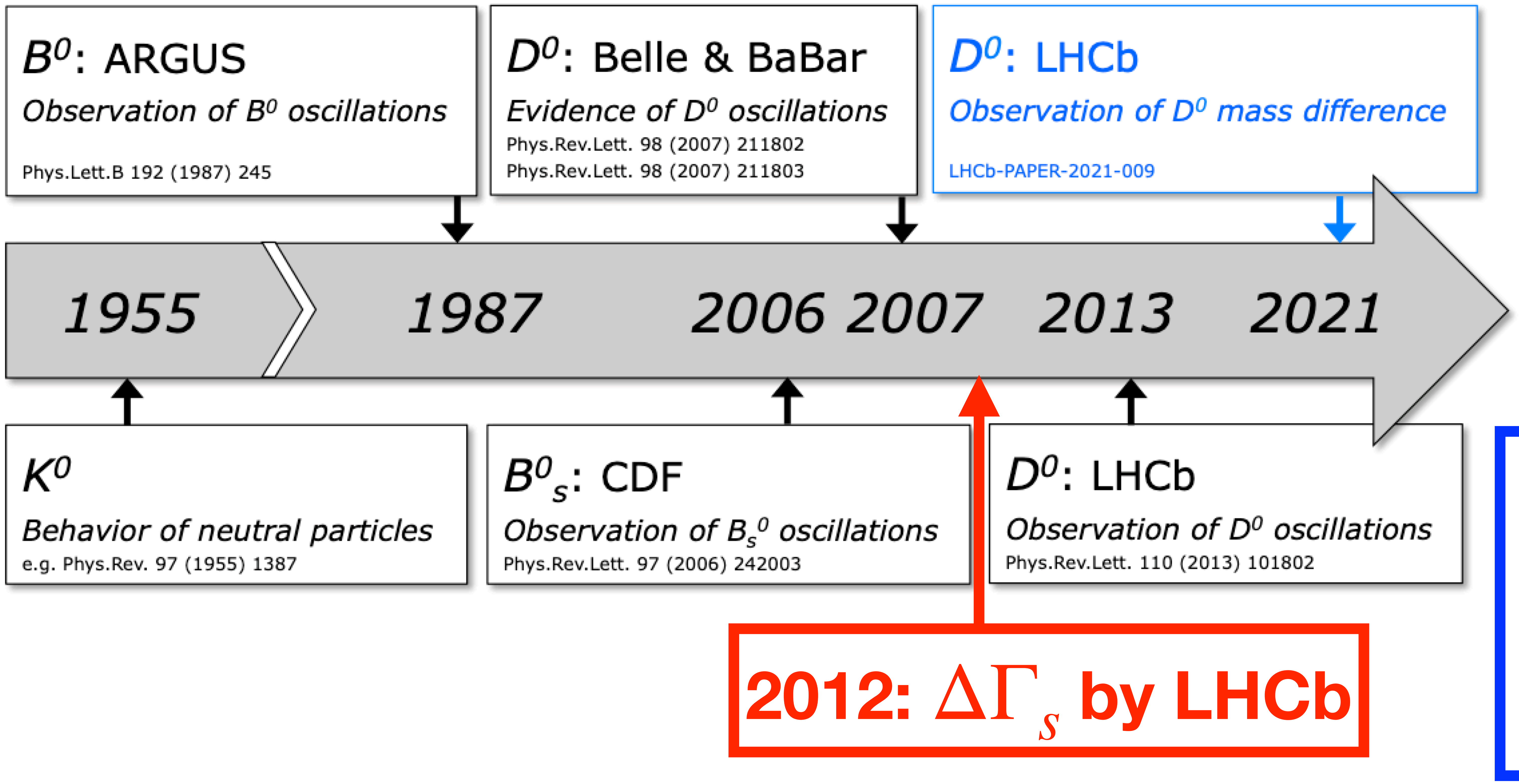
Status Quo: Charm Mixing

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

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

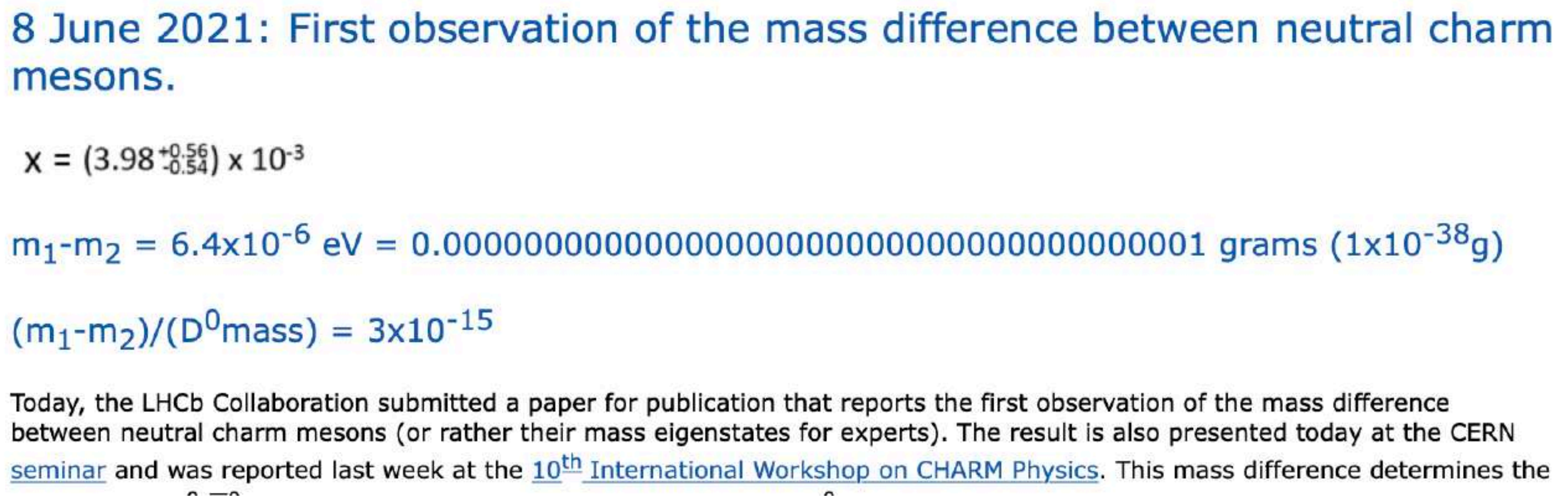
D^0: LHCb
Observation of D^0 mass difference
LHCb-PAPER-2021-009

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

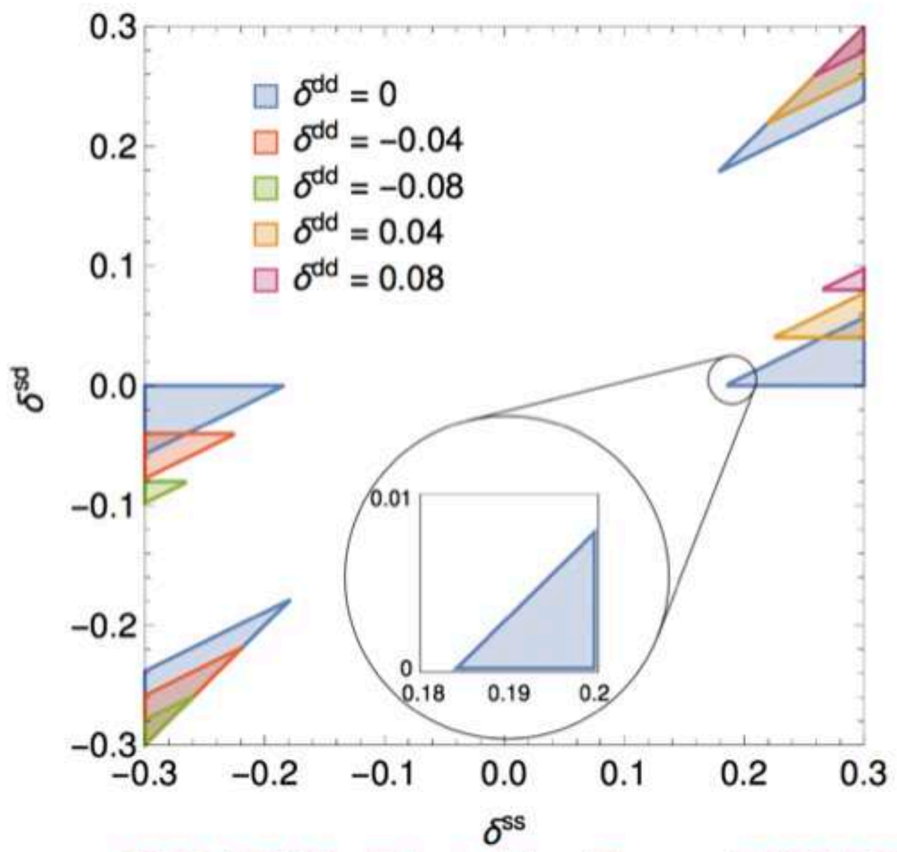
$$\Gamma_{12}^{ss} \to \Gamma_{12}^{ss}(1+\delta^{ss})\,,$$

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

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

20% of duality violation is sufficient to explain experiment

Jubb, Kirk, AL, Tetlalmatzi-Xolocotzi 2016



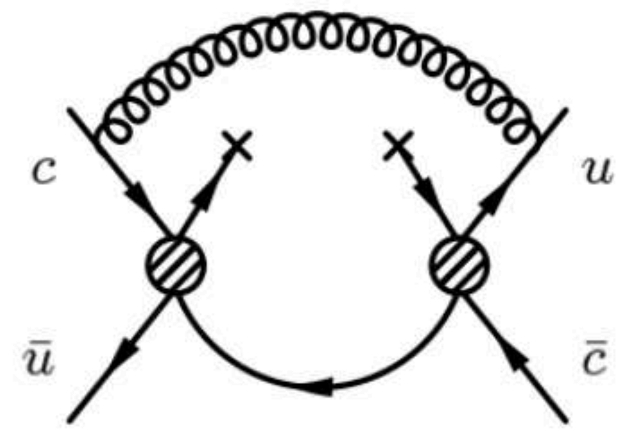
2. Higher dimensions

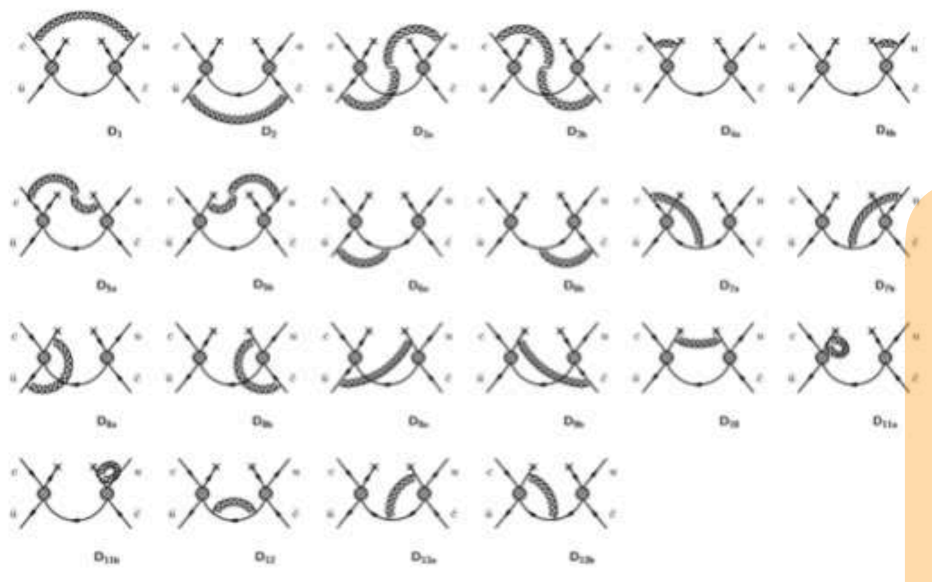
Georgi 9209291; Ohl, Ricciardi, Simmons 9301212; Bigi, Uraltsev 0005089

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

$$\boxed{\begin{aligned}\mu^{ss} &= m_c - 2\epsilon\\ \mu^{sd} &= m_c - \epsilon\\ \mu^{dd} &= m_c\end{aligned}}$$

⇒ exp. value is covered

Exclusive and inclusive approaches can over the experimental regions

No precision determination possible

Outline

- Intro: Meson decays and Mixing
- Intro: 3 Kinds of CPV violation
- Status Quo: Mixing & CPV in mixing
- Status Quo: CPV in interference
- Status Quo: Direct CPV

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 $\Delta\Gamma$

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

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

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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Status Quo: CPV in Interference

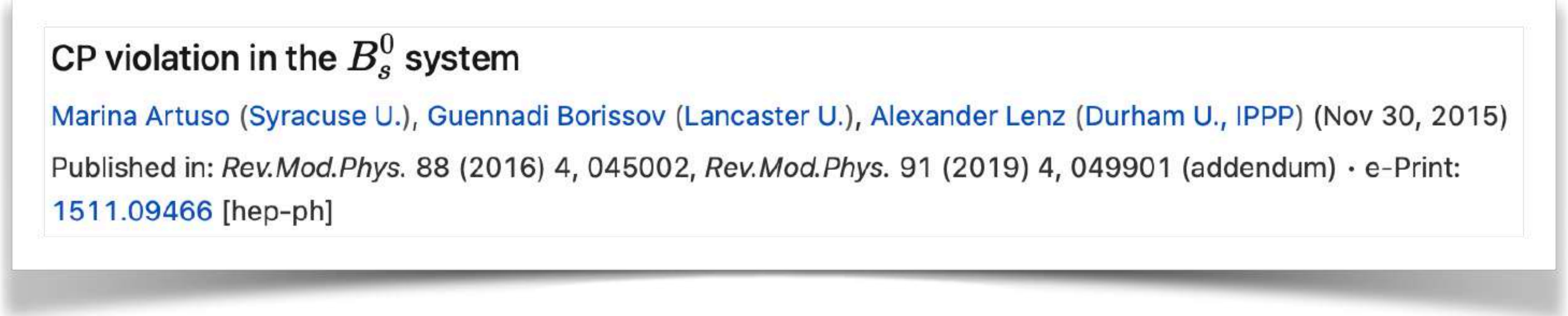
$$A_{CP,f}(t) = \frac{\Gamma\left(\bar{B}_s^0(t) \to f\right) - \Gamma\left(B_s^0(t) \to f\right)}{\Gamma\left(\bar{B}_s^0(t) \to f\right) + \Gamma\left(B_s^0(t) \to f\right)} = -\frac{A_{\mathrm{CP}}^{\mathrm{dir}} \cos(\Delta M_s t) + A_{\mathrm{CP}}^{\mathrm{mix}} \sin(\Delta M_s t)}{\cosh(\frac{\Delta\Gamma_s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

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

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

$$A_f = \langle f | \mathcal{H}_{eff} | B_s^0 \rangle$$

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



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

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

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

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

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

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

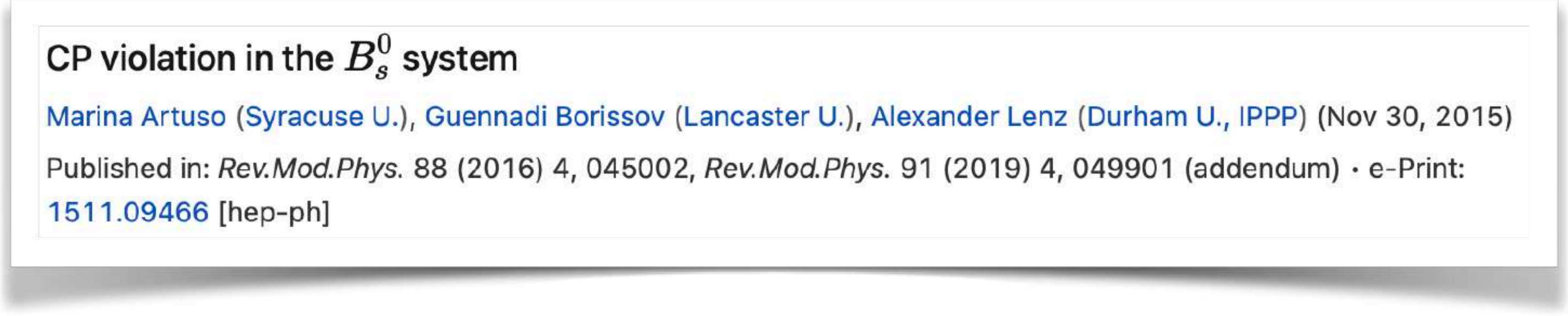
$$\bar{\mathcal{A}}_{\bar f} = \left|\mathcal{A}_f^{\mathrm{Tree}}\right| e^{i\left[\phi^{\mathrm{QCD}}_{\mathrm{Tree}}-\arg(\lambda_c)\right]} + \left|\mathcal{A}_f^{\mathrm{Peng}}\right| e^{i\left[\phi^{\mathrm{QCD}}_{\mathrm{Peng}}-\arg(\lambda_u)\right]}$$

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



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

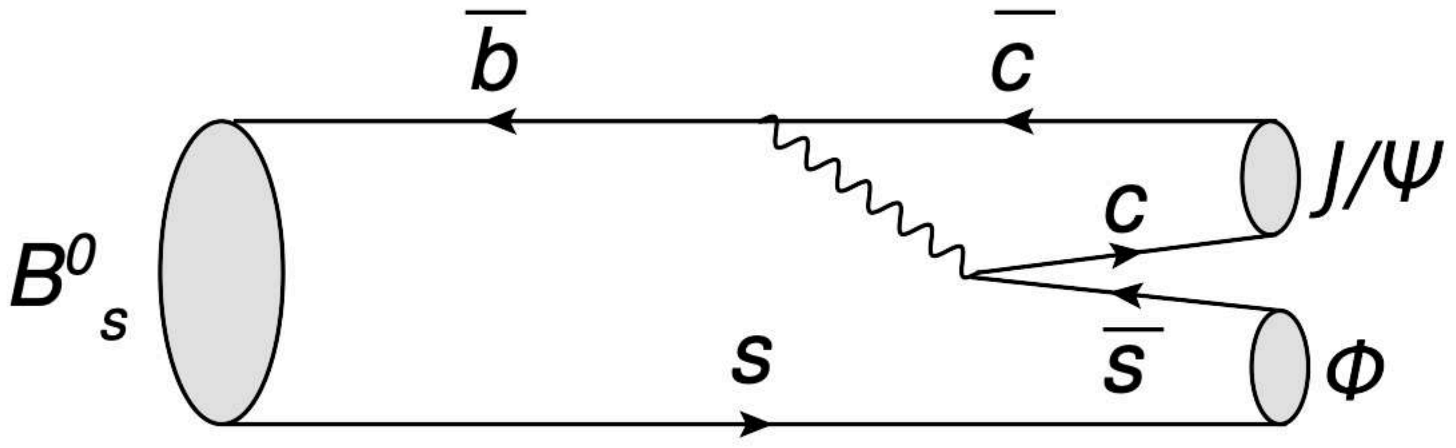
Penguin pollution

Status Quo: CPV in Interference

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

$$\mathcal{A}_f = \sum_j \mathcal{A}_j e^{i(\phi_j^{\text{strong}} + \phi_j^{\text{CKM}})}$$

=



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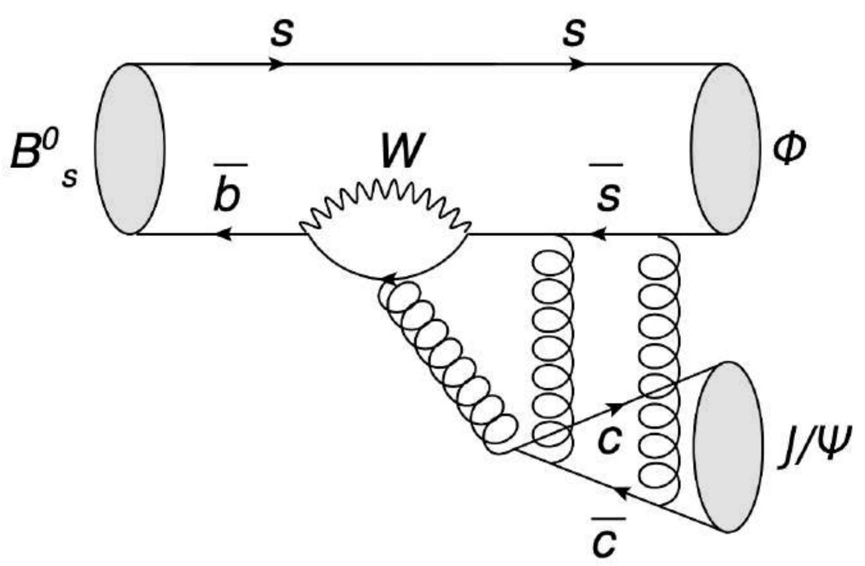


This is not the SM prediction for ϕ_s!

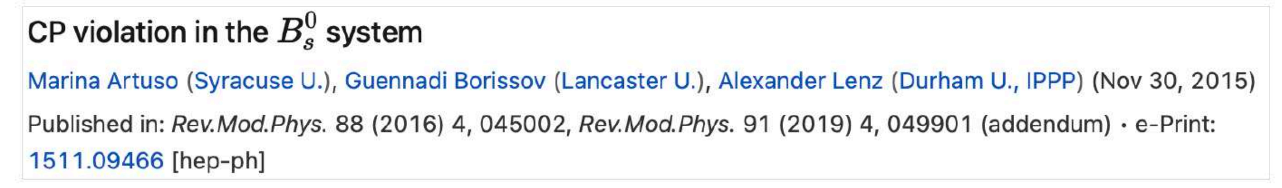
Neglect penguins:

CP asymmetry in $B_s \to J/\Psi\phi$ is directly proportional to sin $(2\beta_s)$ with $\phi_s = -2\beta_s^{\text{CKMFitter}} = -0.0370^{+0.0007}_{-0.0008}$

CP asymmetry in $B_d \to J/\Psi K_s$ is directly proportional to sin (2β)

Bigi, Sanda 1981,…

Since there is only one amplitude, all hadronic effects cancel exactly!



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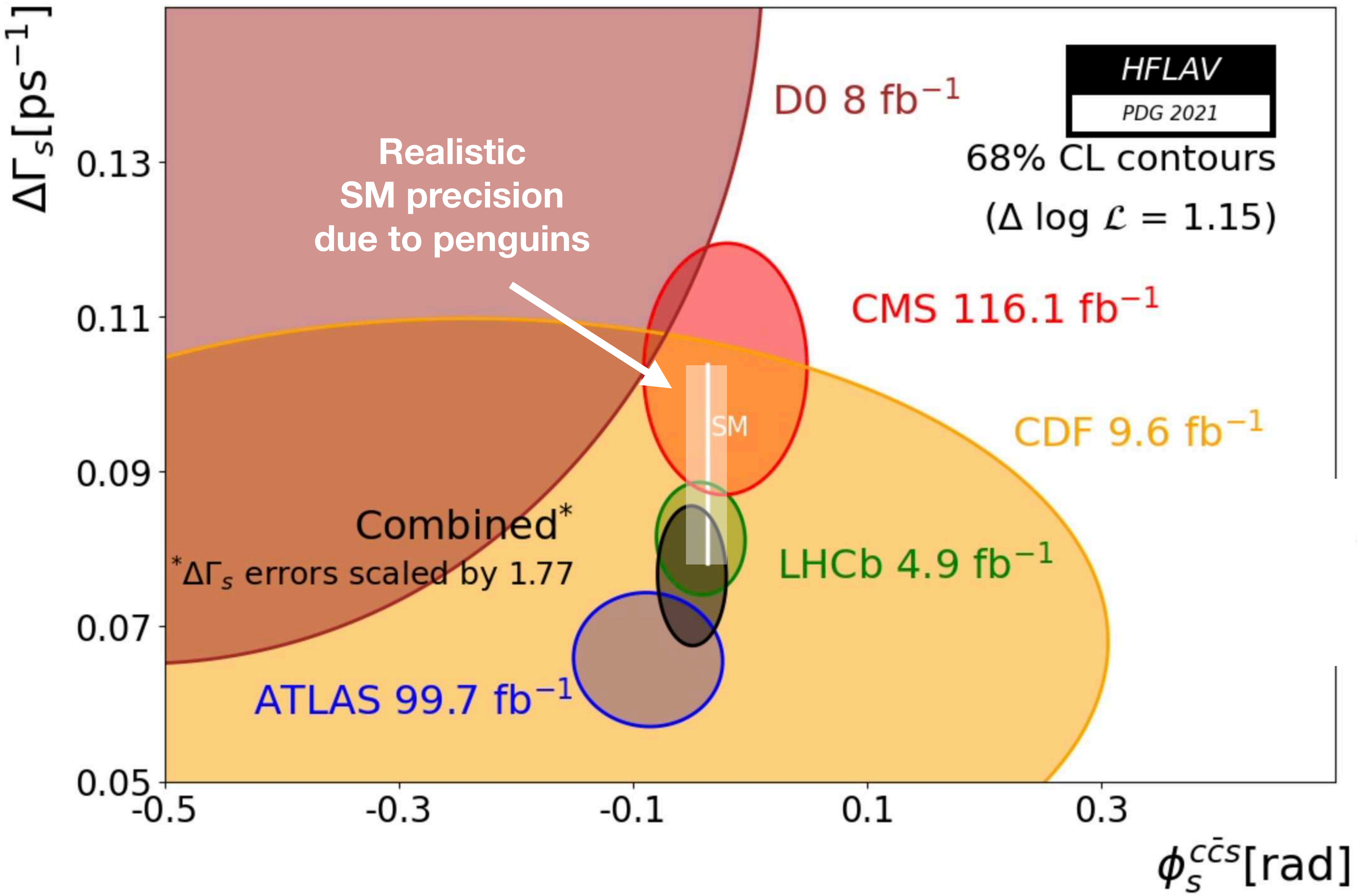
Within the SM penguins are expected to give contributions of the order of $\pm 1^\circ \approx \pm 0.017$

Now the hadronic ratio of penguin/tree has to be known - extremely challenging

Fleischer,… (2010.14423), Ciuchini et al, Faller et al, Jung, Ligeti et al, Frings, Nierste and Wiebusch,…

Status Quo: CPV in Interference

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



Realistic SM precision due to penguins

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 $\phi_s^{c\bar{c}s}$

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Status Quo: CPV in Decay

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

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

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

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

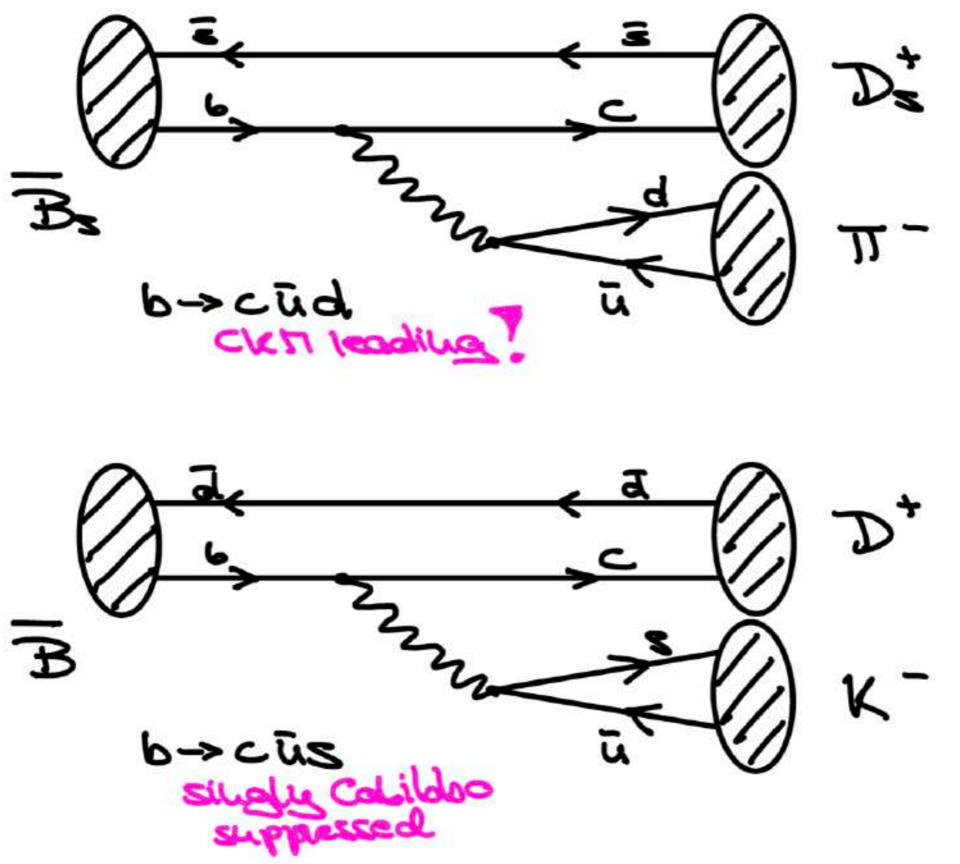
Extremely hard to predict!

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

Status Quo: Non-leptonic decays

3 σ to 7 σ deviation of experiment from QCDf predictions with standard error estimates

Colour-allowed Tree-level Decays

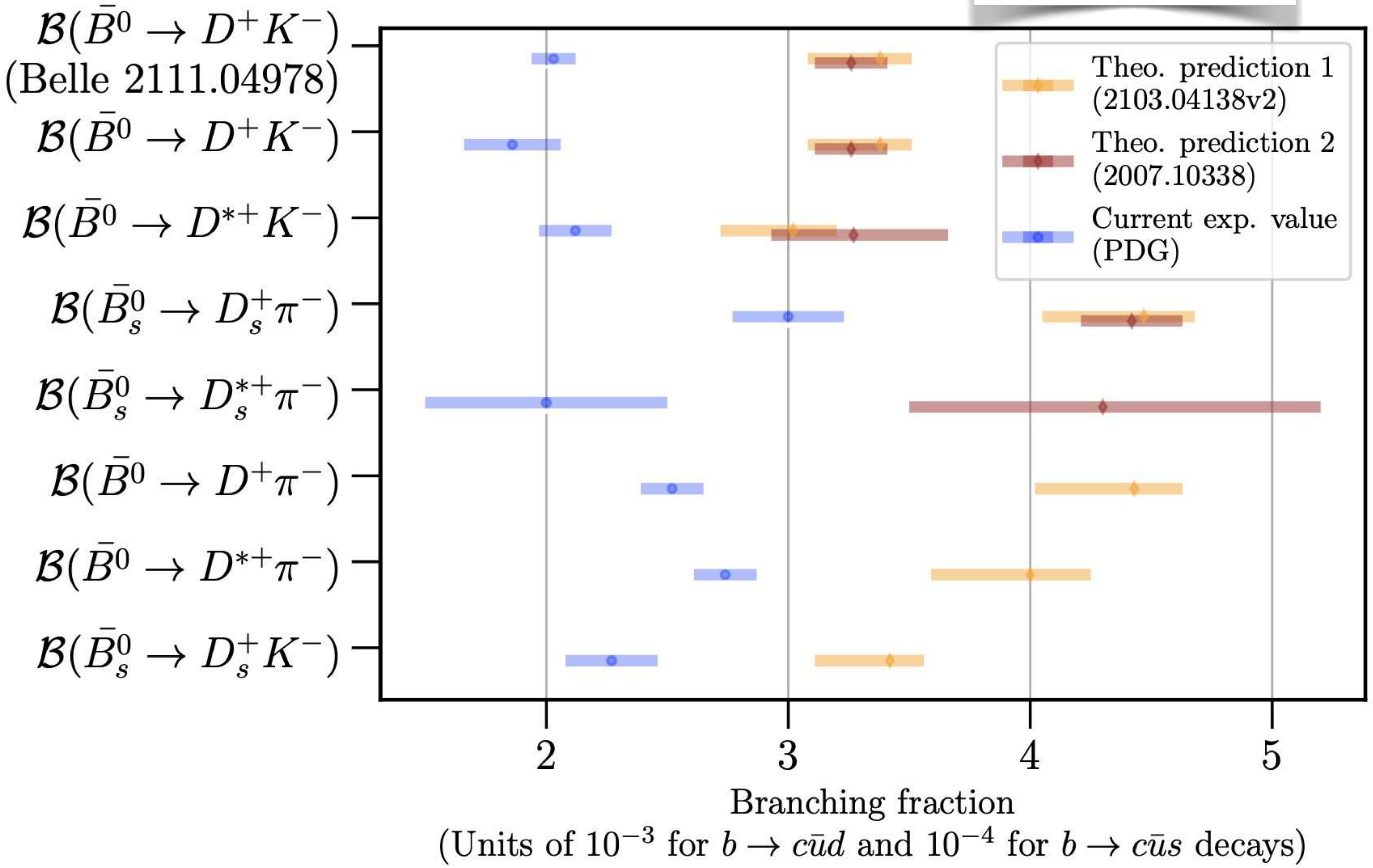


- CKM leading decays
- The are no annihilation, penguins,…
- QCDf should work at its best!

Beneke, Buchalla, Neubert, Sachrajda 1999…

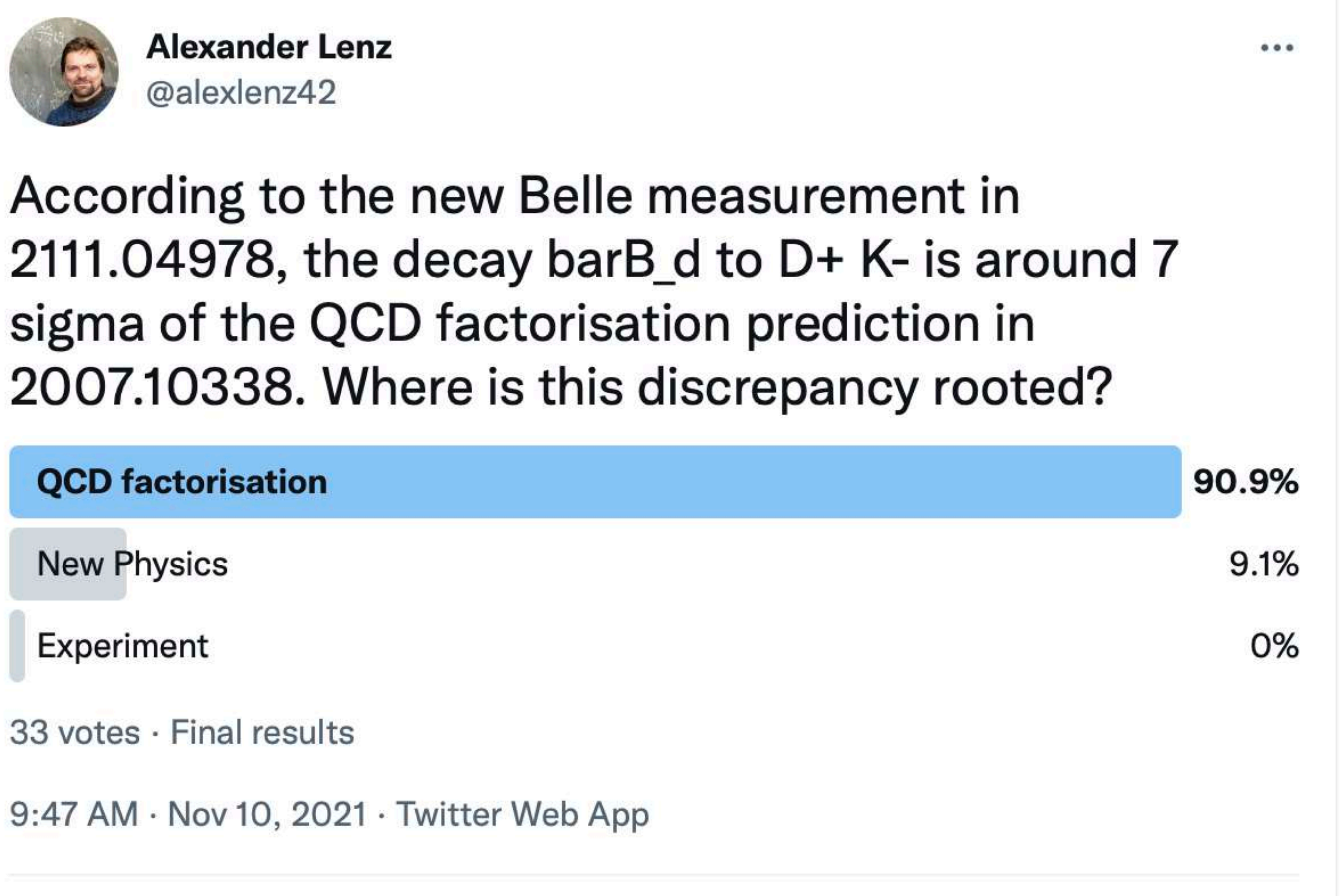
$$\langle D_q^{(*)+} L^- |\, \mathcal{Q}_i \,| \bar{B}_q^0 \rangle = \sum_j F_j^{\bar{B}_q \to D_q^{(*)}}(M_L^2) \times \int_0^1 du\, T_{ij}(u) \phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

N. Skidmore



Status Quo: 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

Status Quo: Non-leptonic decays

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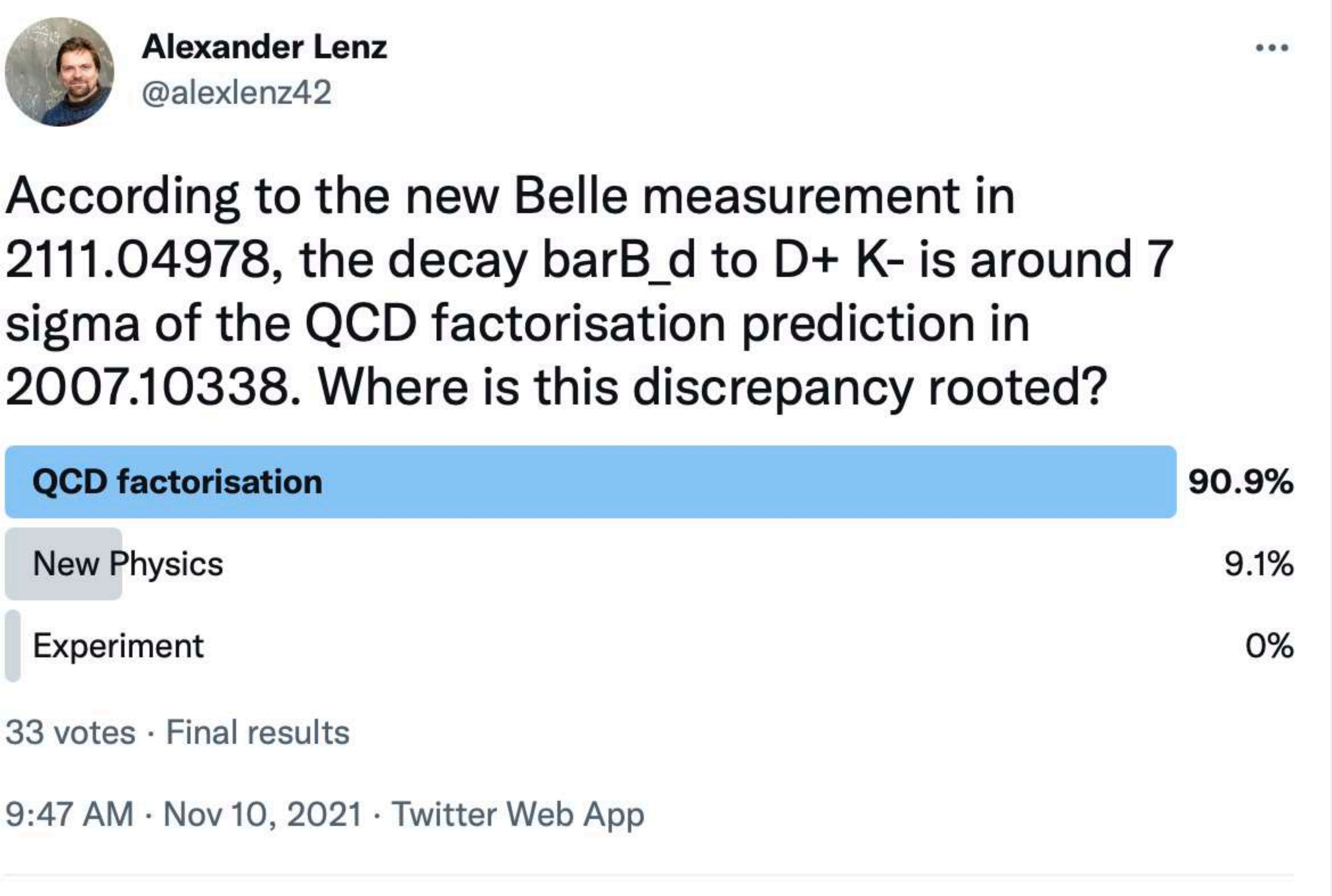

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- **Huber, Kränkl** 1606.02888
- **Bordone, Gubernari, Huber, Jung, vanDyk** 2007.10338
- **Iguro, Kitahara** 2008.01086
- **Cai, Deng, Li, Yang** 2103.04138
- **Bordone, Greljo,Maryocca** 2103.10332
- **Beneke, Böer, Finauro, Vos** 2107.03819

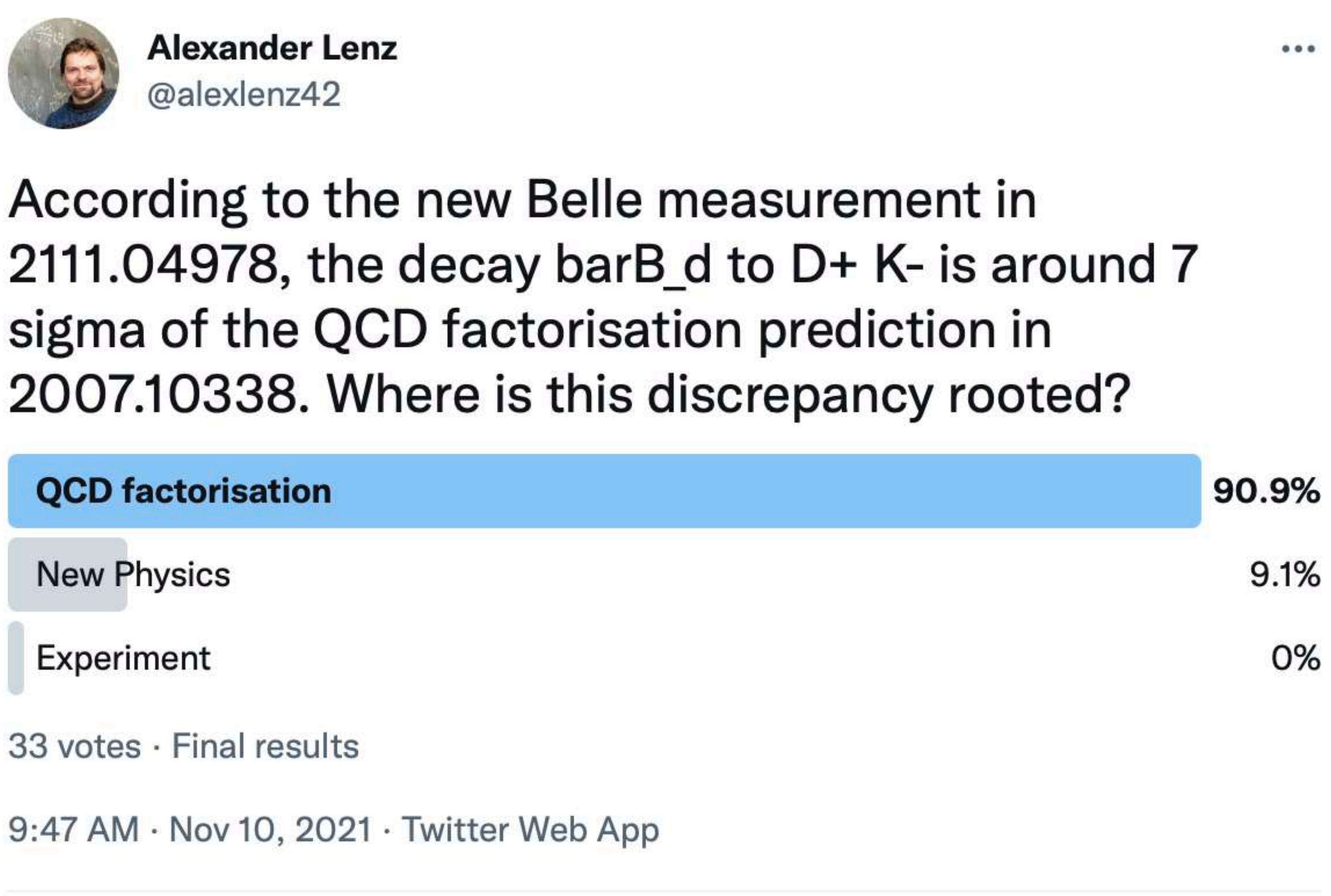
Similar for $B_s \to D_s^\mp K^\pm$
- **Fleischer, Malami** 2110.04240, 2109.04950

UNIVERSITÄT SIEGEN

Status Quo: Non-leptonic decays

LEPTON PHOTON 2021 MAN

What could go wrong?



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

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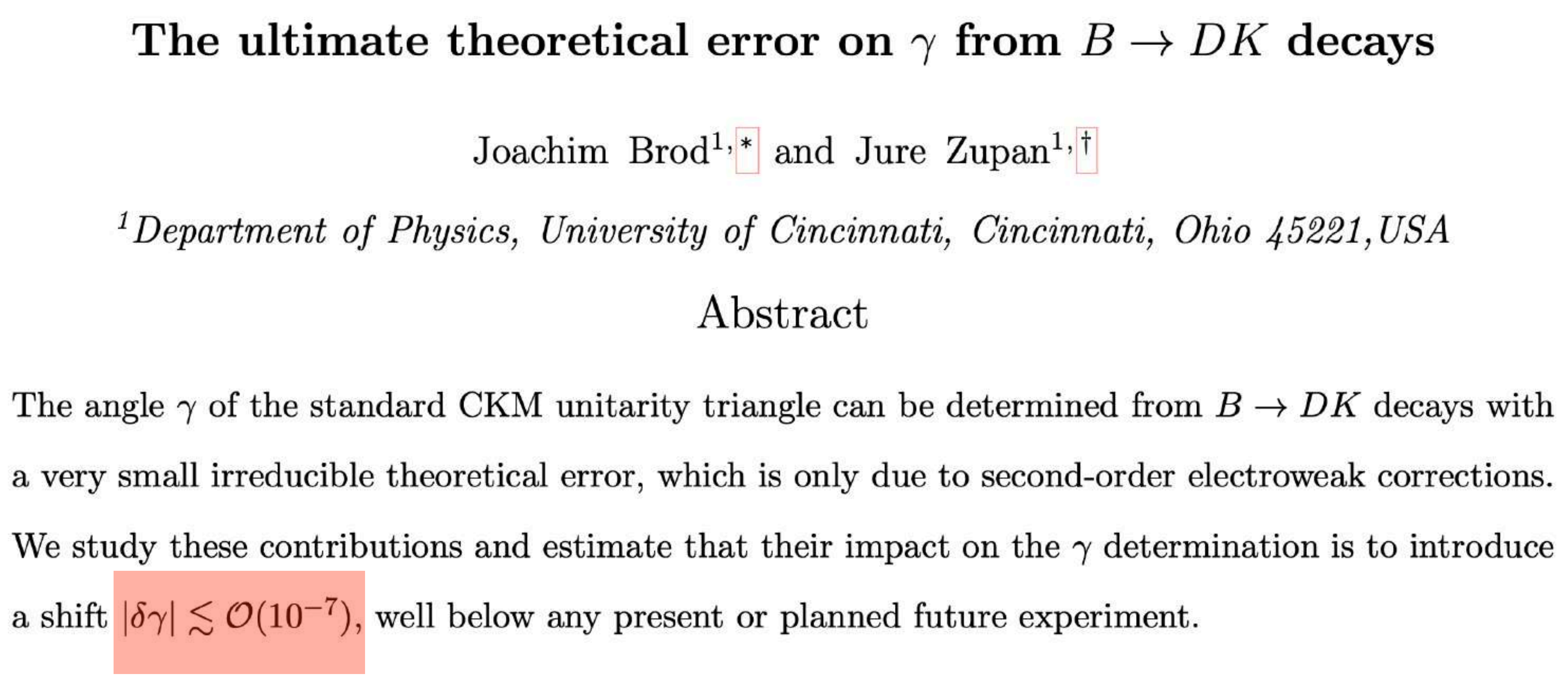
In the SM the determination of γ is super precise



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

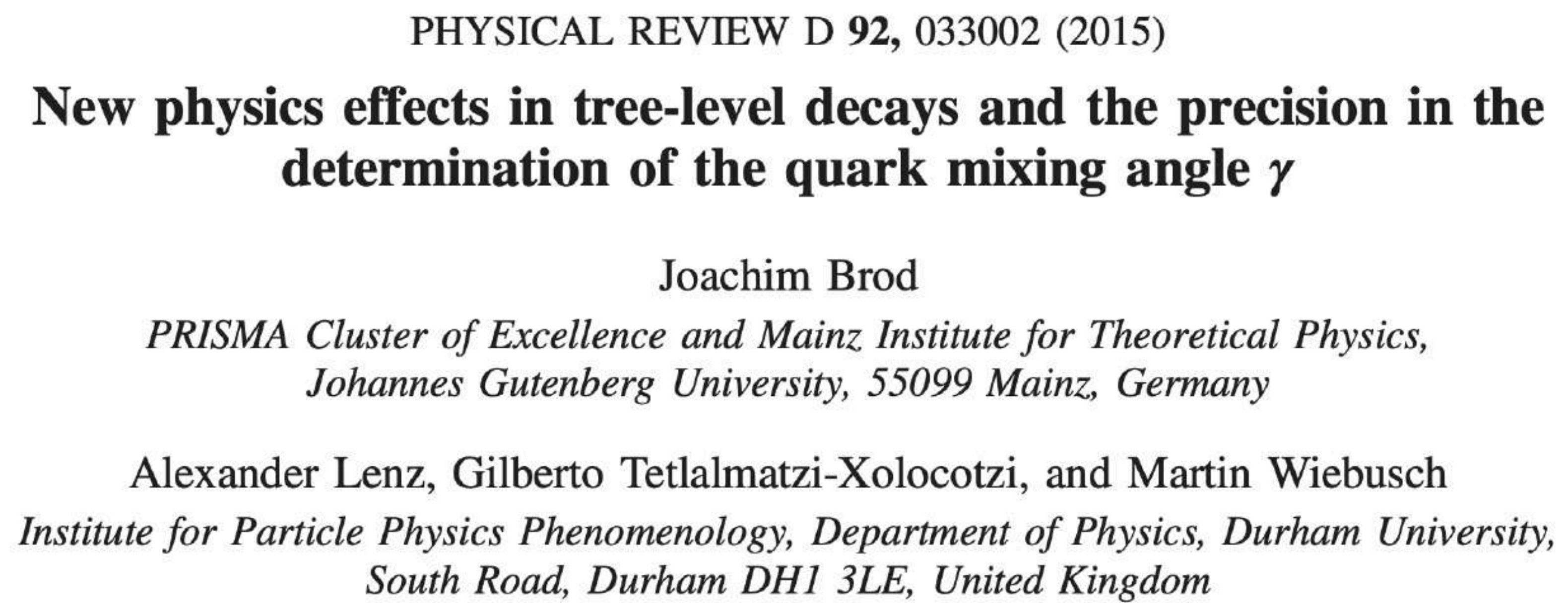
Joachim Brod[1,*] and Jure Zupan[1,†]

[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

Direct CP asymmetries

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

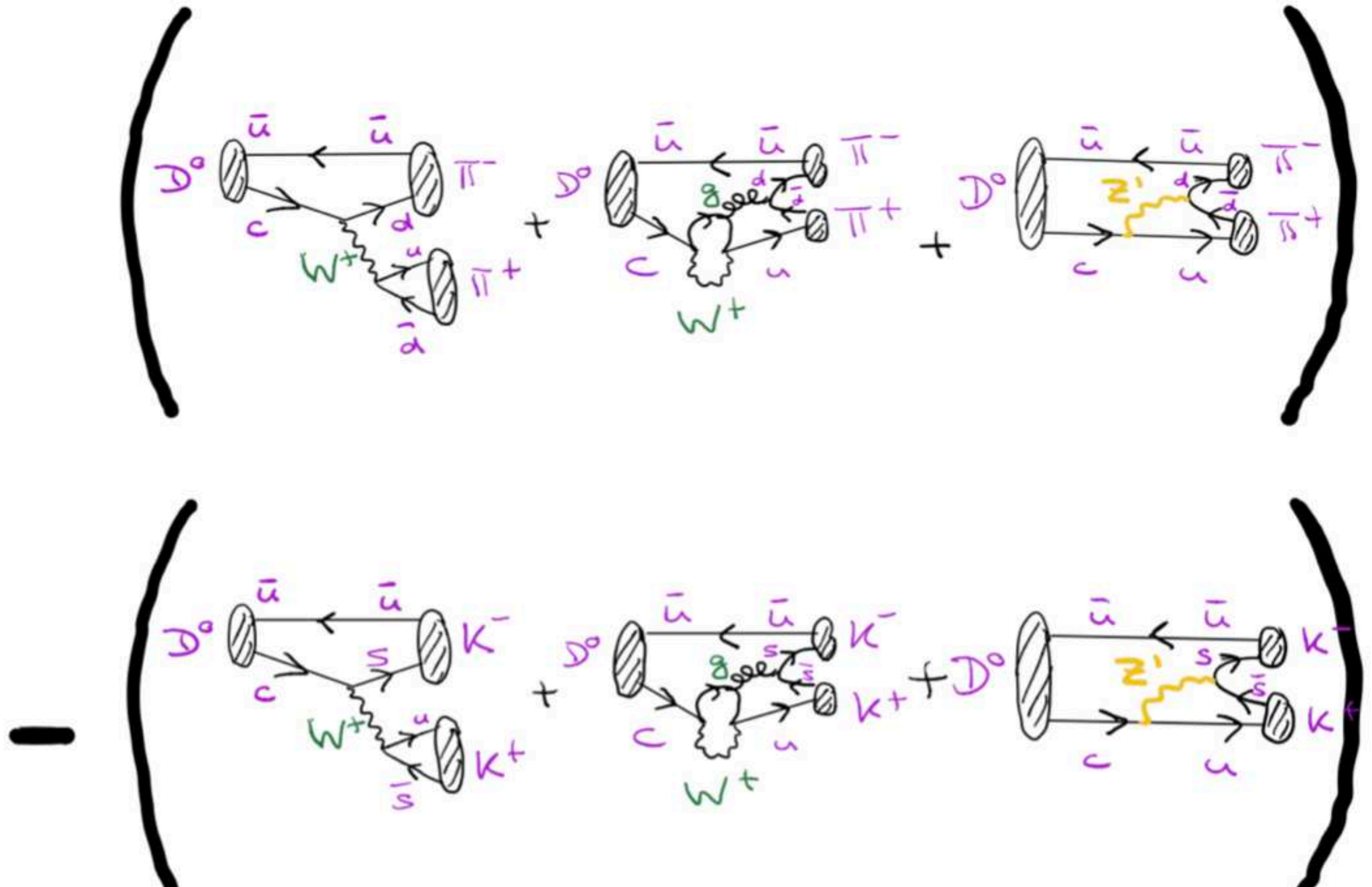
Updates: **2002.03262** complete 2-loop penguins
2107.03819 QED corrections
2104.14871 $A_{CP}(B^0 \to \pi^0 \bar{K}^0)$ Belle II
SU(3) symmetry e.g. **1806.08783, 2111.06418,…**
comprehensive phenomenological study missing

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

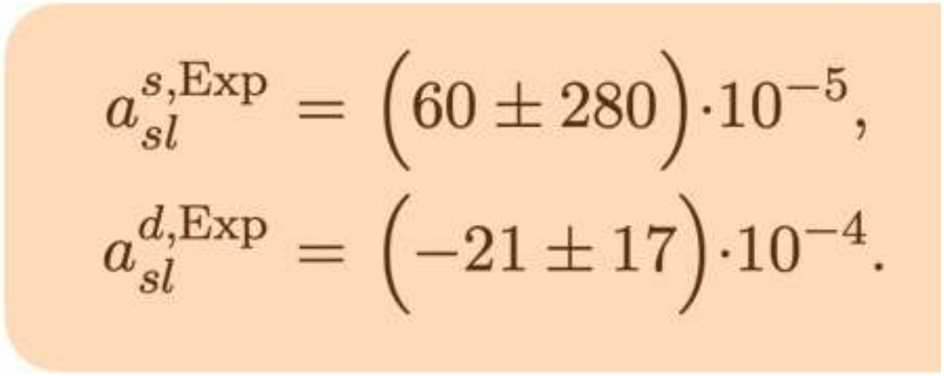


We need $r = |\mathscr{A}_f^{\text{Peng}}| / |\mathscr{A}_f^{\text{Tree}}|$

Shedding light into the dark

Flavour specific decays

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

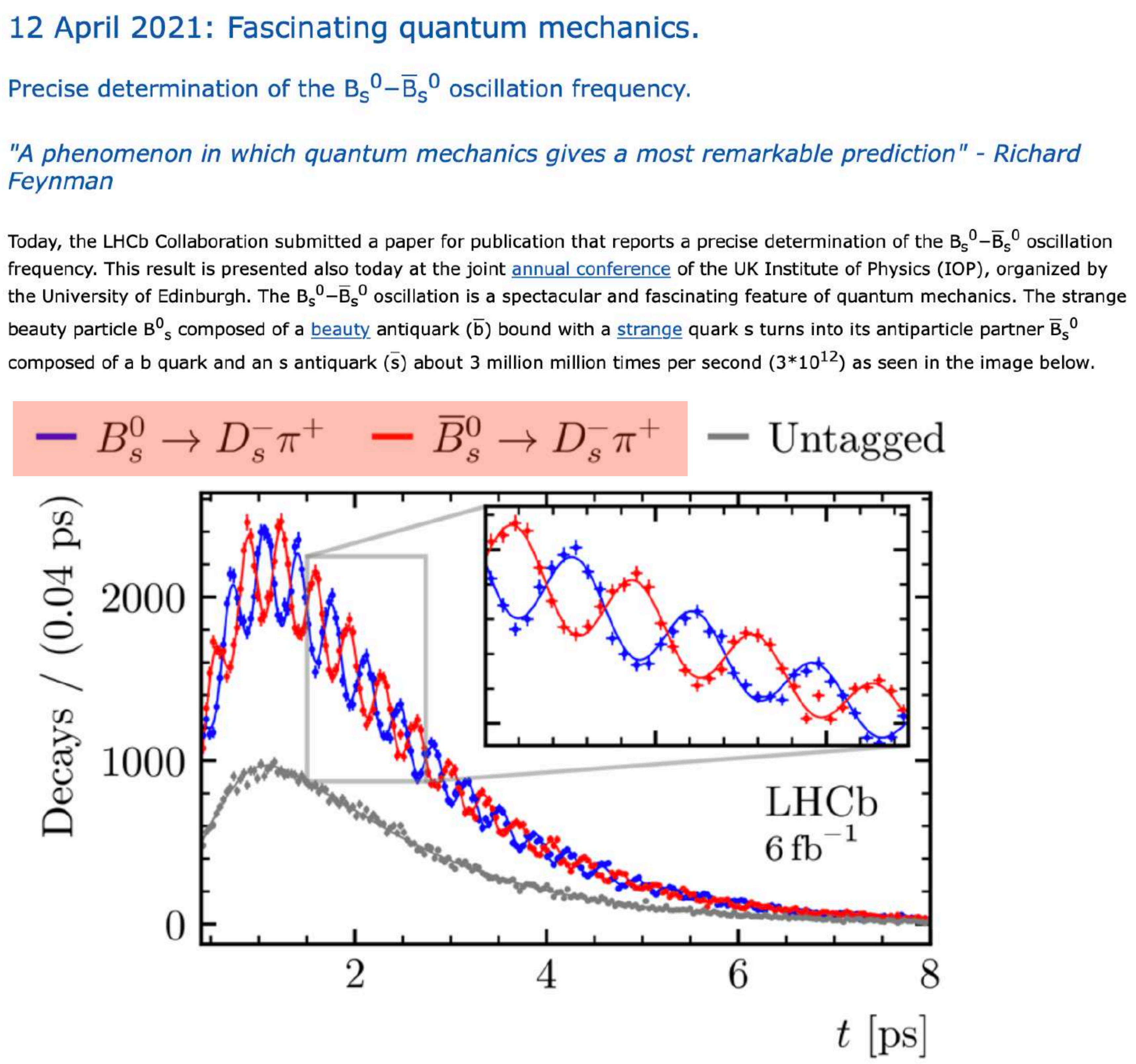


$$a_{sl}^{s,\mathrm{Exp}} = \left(60 \pm 280\right) \cdot 10^{-5},$$
$$a_{sl}^{d,\mathrm{Exp}} = \left(-21 \pm 17\right) \cdot 10^{-4}.$$

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

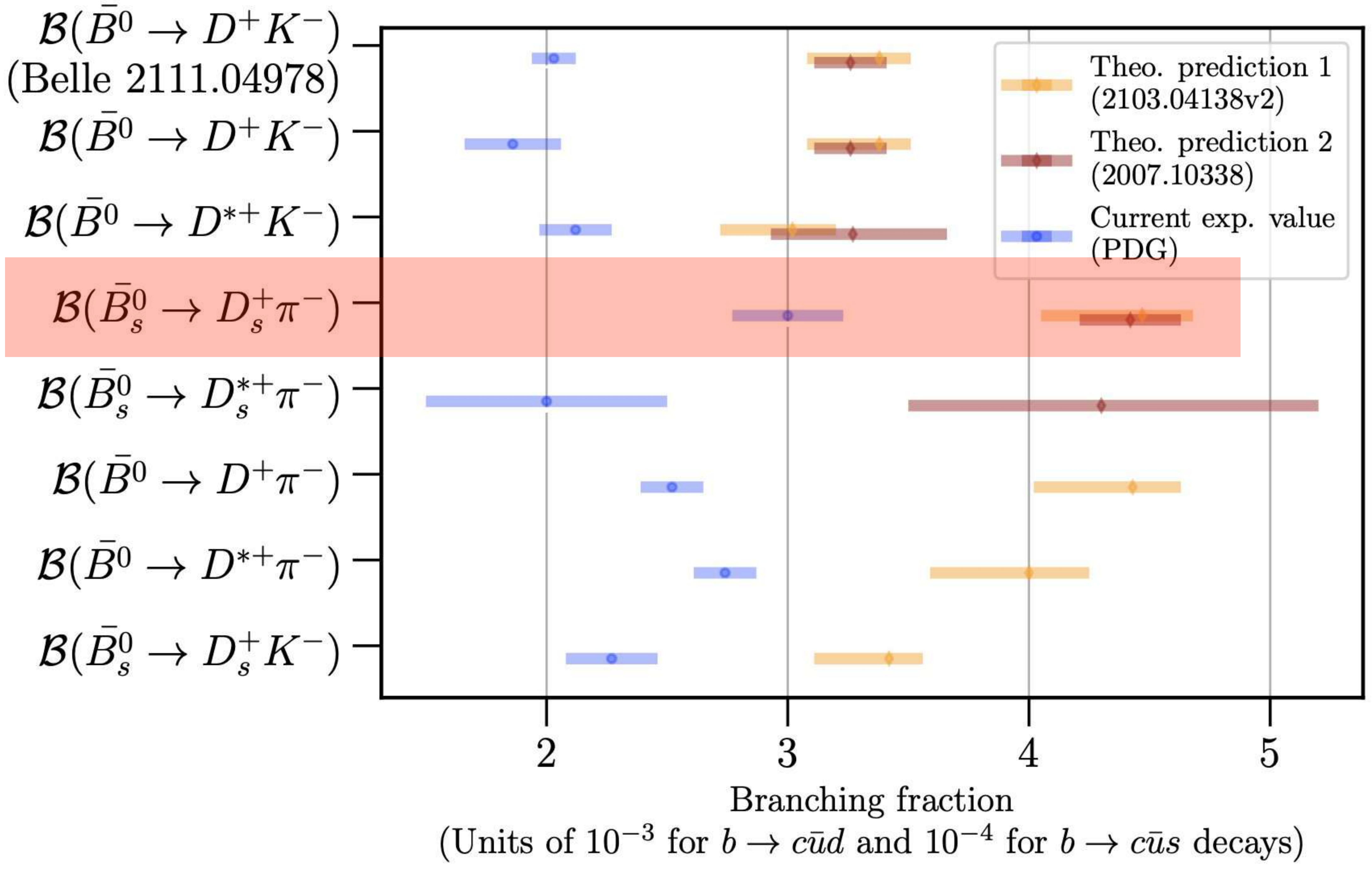


12 April 2021: Fascinating quantum mechanics.

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

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

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

Flavour specific decays

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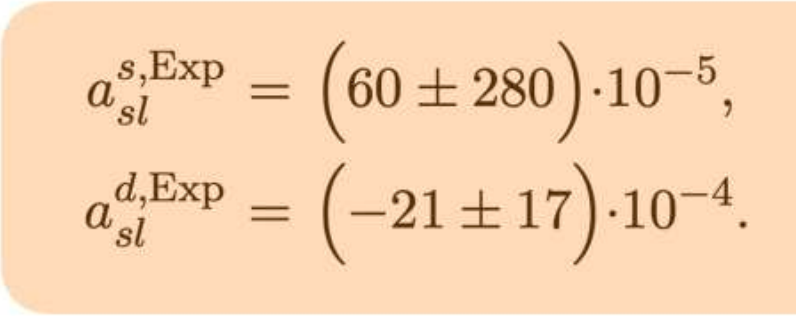
- Assume: there is new physics in these decays, potentially CP violating
- Derive CP asymmetry

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

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

Constrained by semi-leptonic Measurements



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HFLAV 1970?

Flavour specific decays

Gershon, AL, Rusov, Skidmore
2111.04478

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