CPV and mixing in the B and D system

1.6.2023
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Siegen

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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**

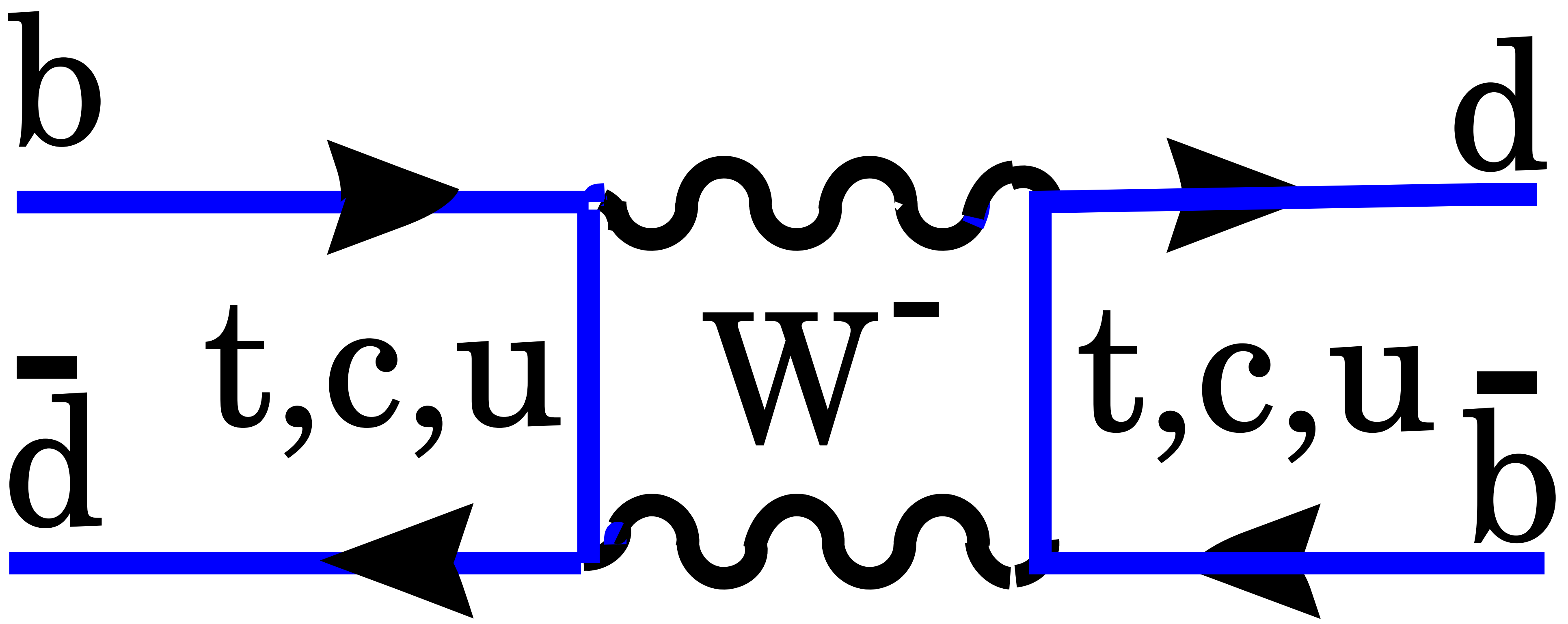
see e.g. Eleftheria Somonidi

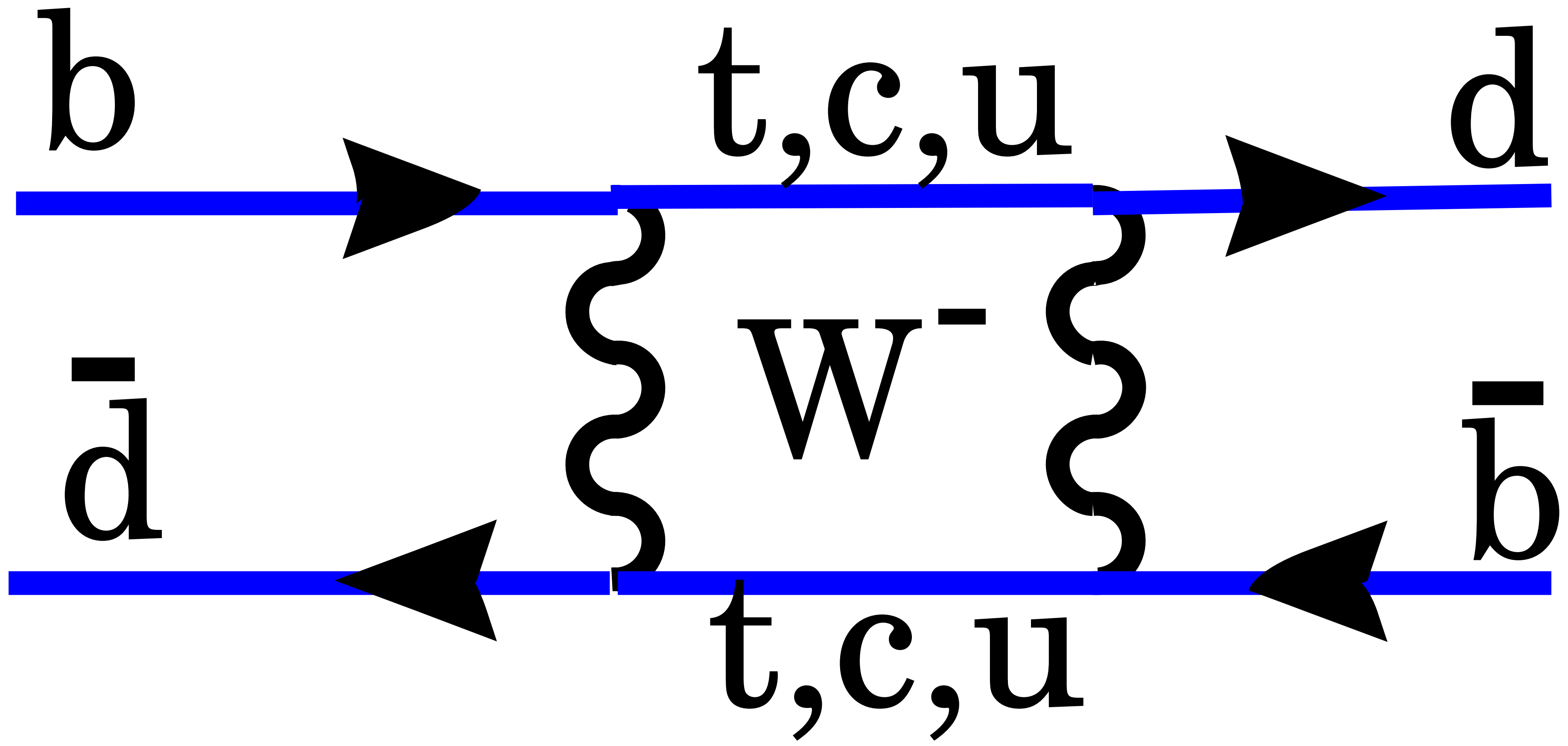
Experimental aspects:
Justin Skorupa
Valeria Lukashenko
Alexander Thaler
Ramon Angel Ruiz Fernandez
Jake Bennett
Serena Maccolini

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

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!!!

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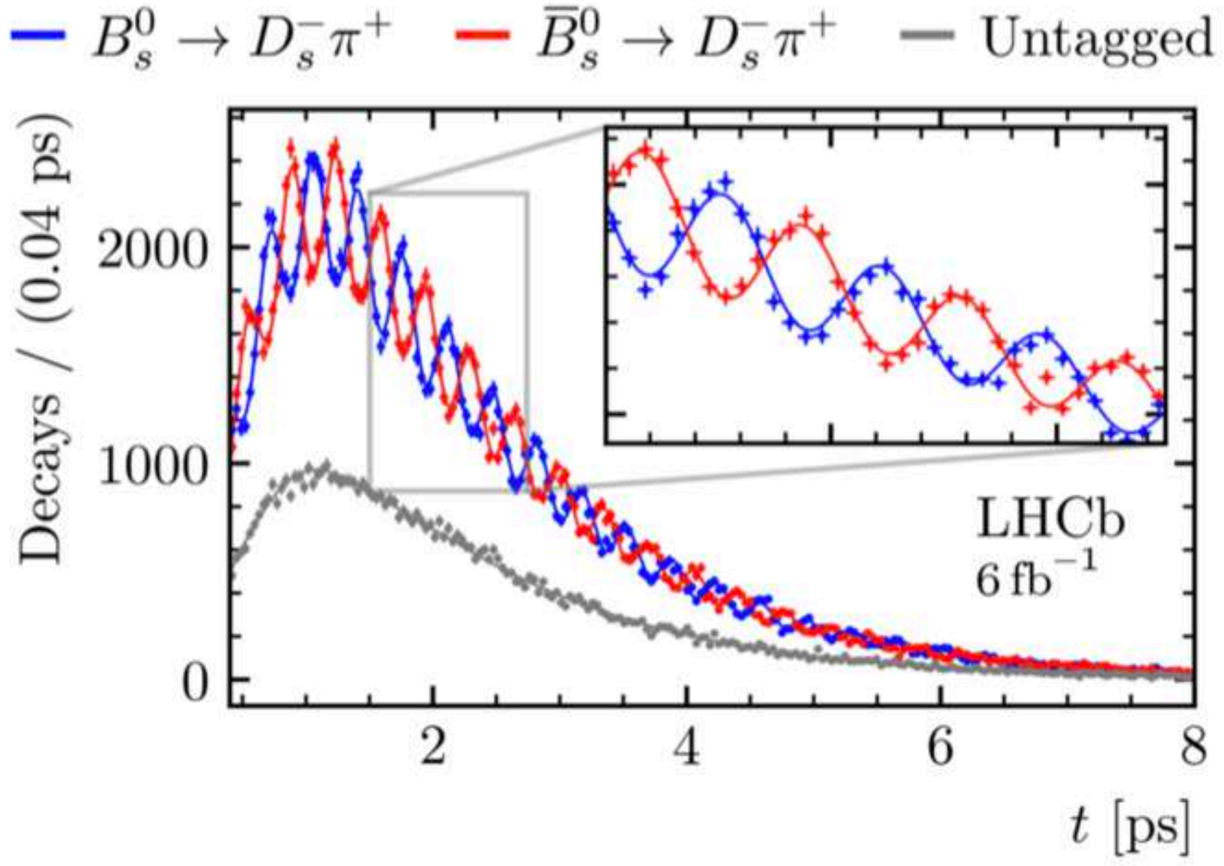
Mixing

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

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

With

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



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

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- Status Quo: CPV in interference
- Status Quo: Direct CPV

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CP Violation

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

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

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

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

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

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

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

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

See also 1511.09466, hep-ph/0201071

3. **CP violation in decay**

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

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

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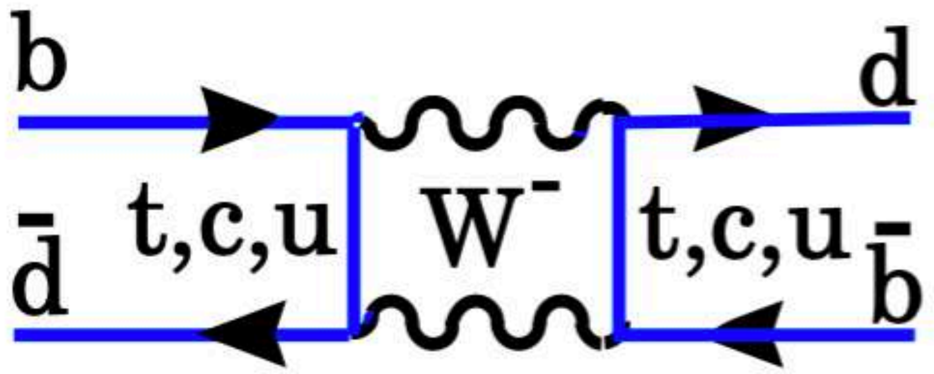
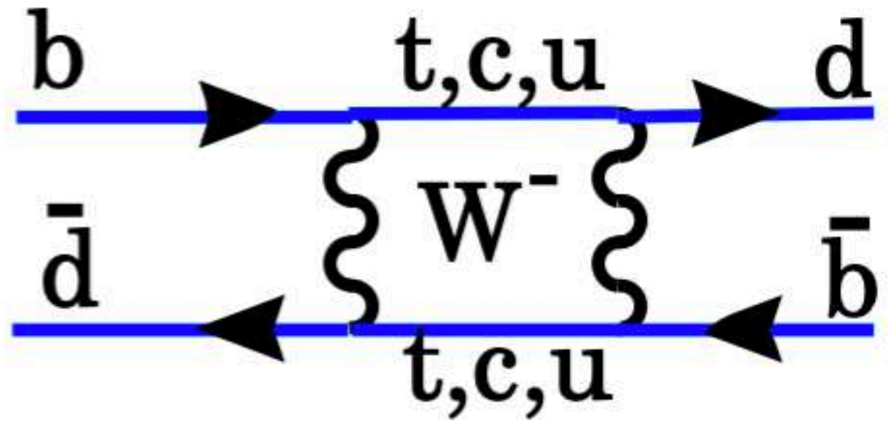
Status Quo: Mixing

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

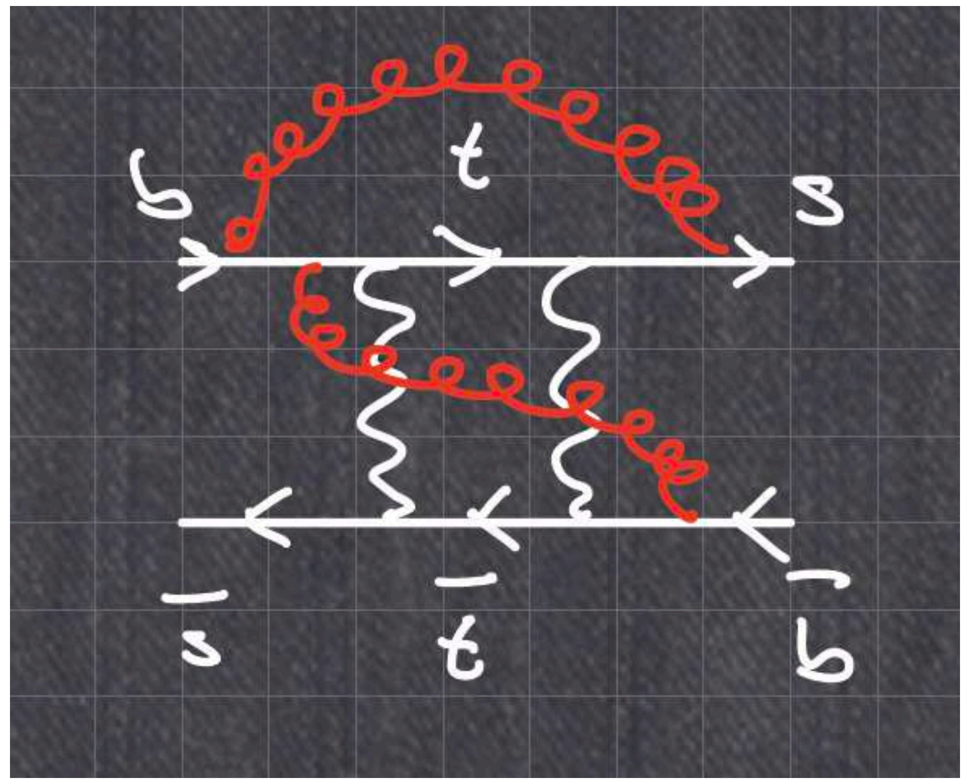




$$M_{12}^q = \frac{G_F^2}{12\pi^2} \lambda_t^2 M_W^2 S_0(x_t) B f_{B_q}^2 M_{B_q} \hat{\eta}_B \,,$$

Significant CKM dependence

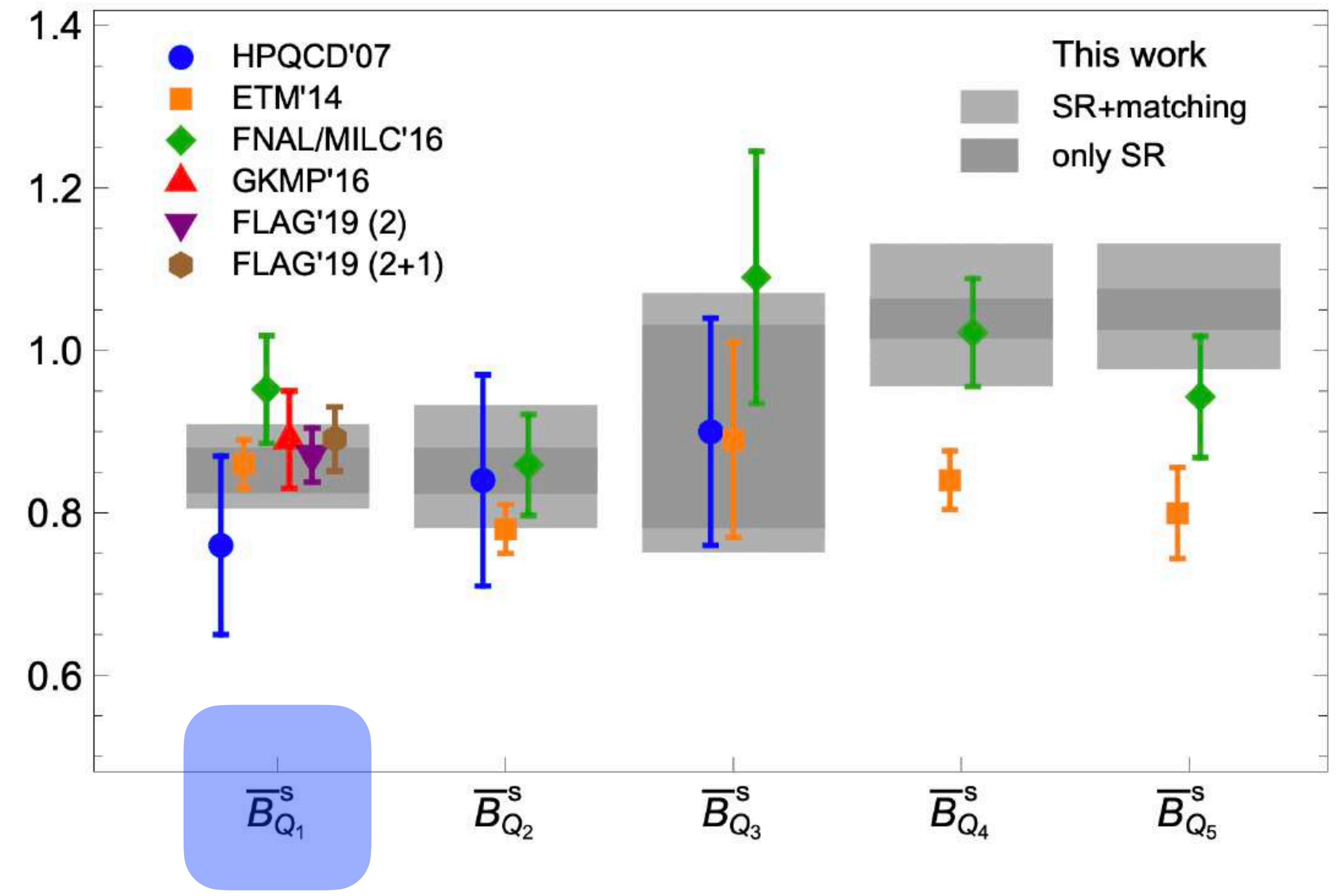
By far dominant uncertainty



2-loop: Buras, Jamin, Weisz
3-loop: Gorbahn, Stamou,……

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

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



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

See also talk by Stefan Meinel

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

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

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

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

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

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Status Quo: Mixing

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

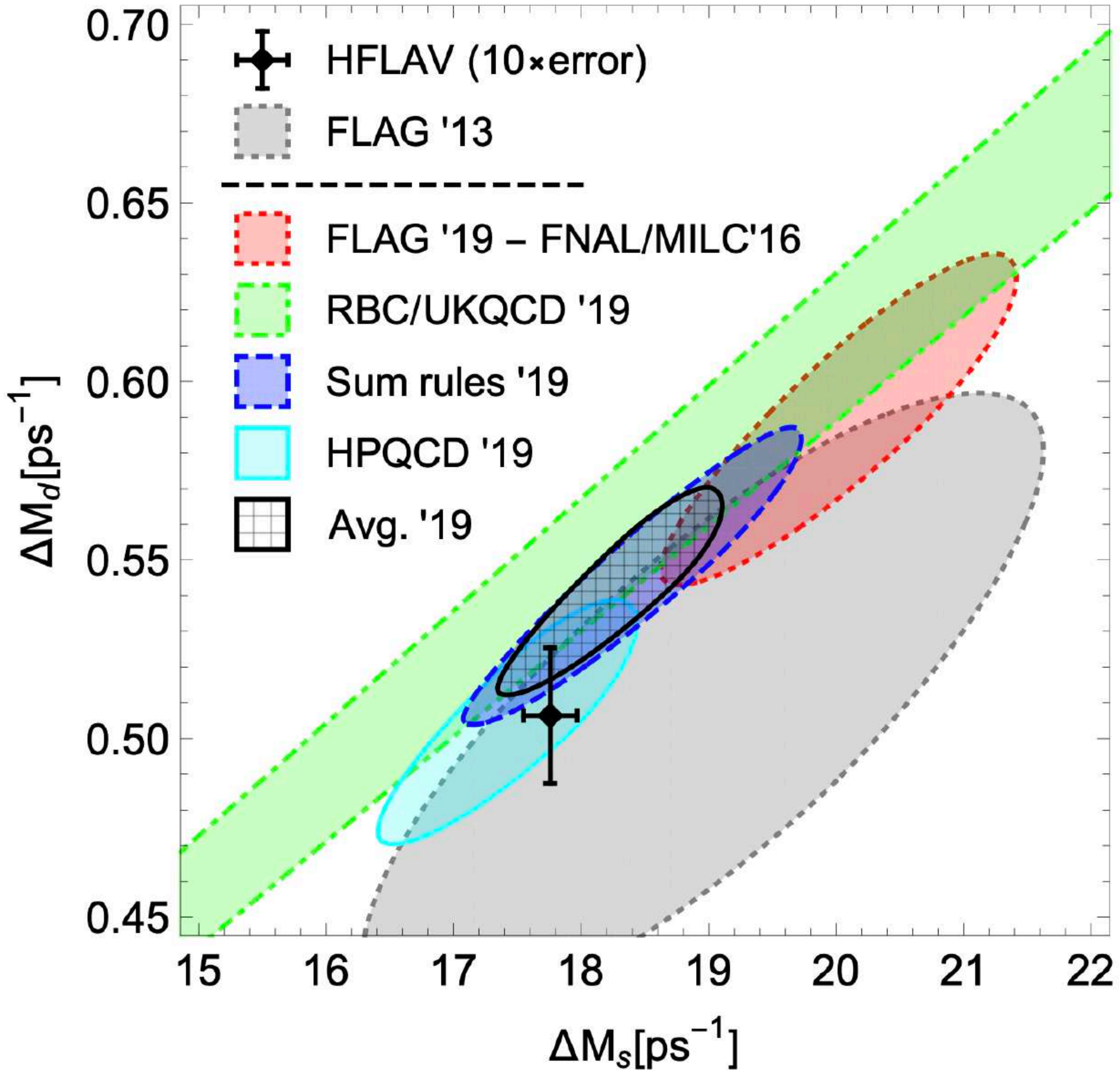
$\delta(\text{Theo.})/\delta(\text{Exp.}) \approx 140$

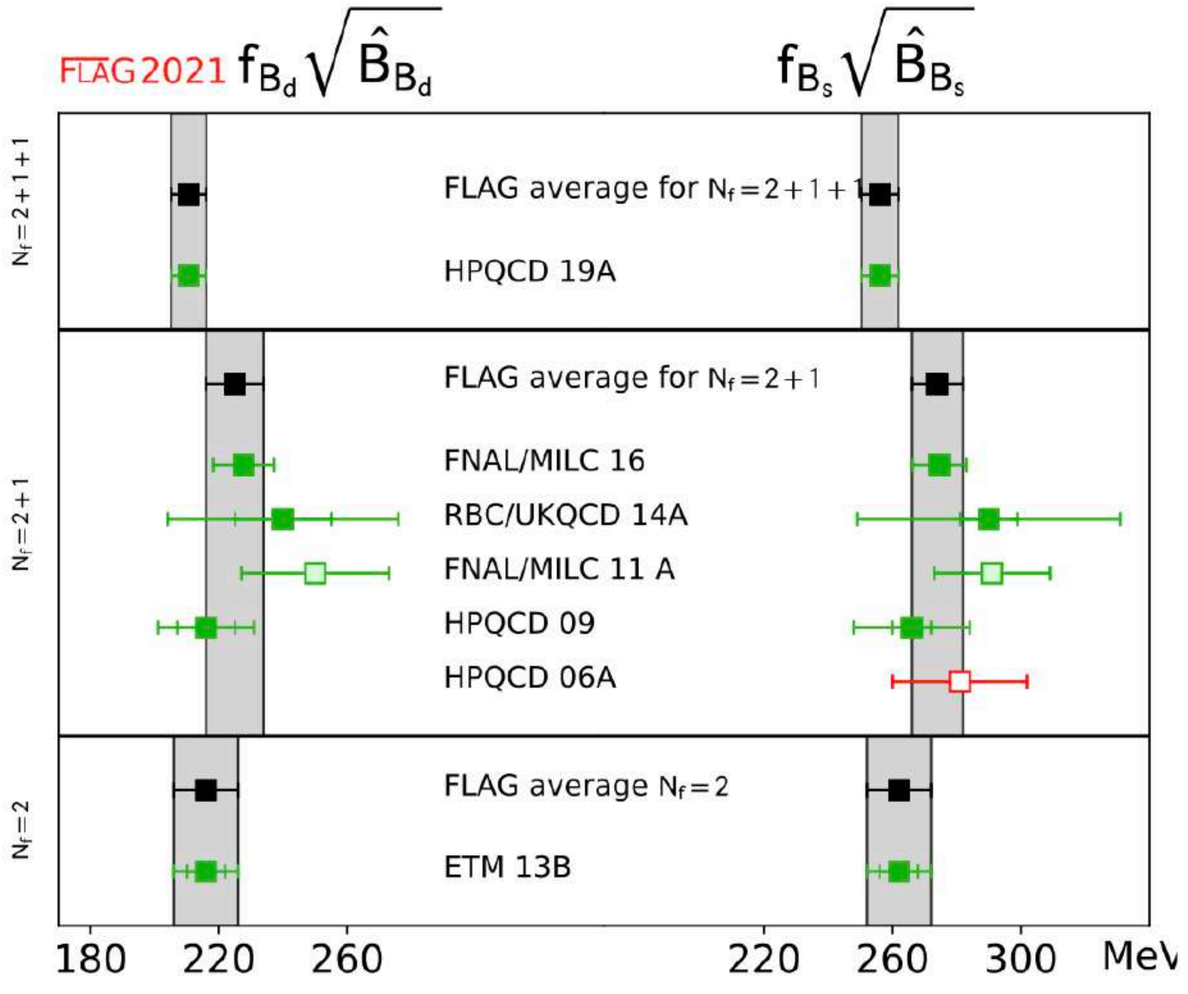
$$\Delta M_s = (17.765 \pm 0.006)\,\text{ps}^{-1} \qquad \Delta M_s = \left(18.4^{+0.7}_{-1.2}\right)\,\text{ps}^{-1}$$

$\delta(\text{Theo.})/\delta(\text{Exp.}) \approx 15$

HFLAV 2021

1909.11087, 2212.10497
Average lattice & sum rules





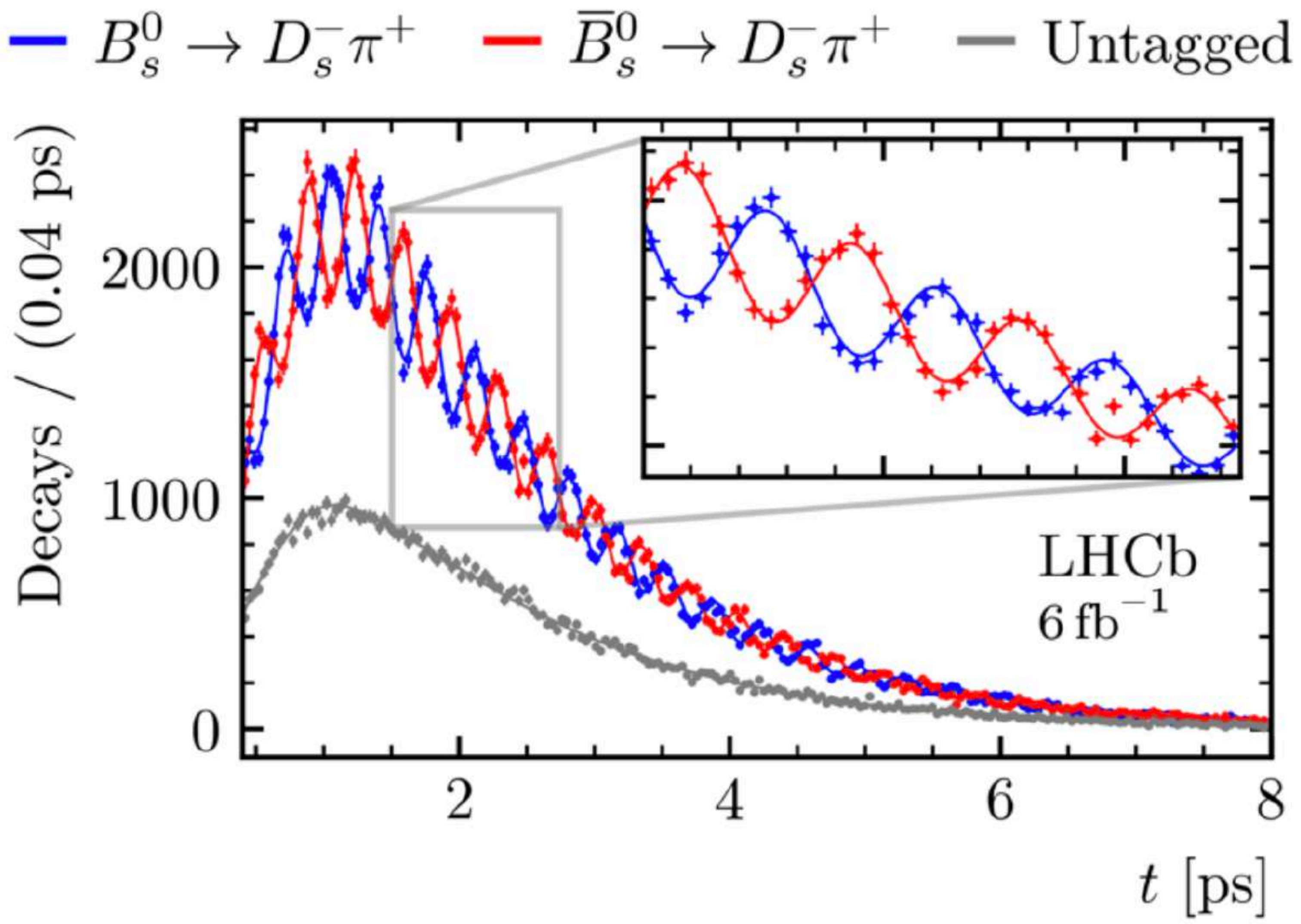
Work in progress by
RBC/UKQCD+JLQCD 2111.11287

12 April 2021: Fascinating quantum mechanics.

Precise determination of the $B_s^0-\overline{B}_s^0$ 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 $B_s^0-\overline{B}_s^0$ 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 $B_s^0-\overline{B}_s^0$ 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 $\overline{B}_s^0$ 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

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Status Quo: Mixing

2035:

- Lattice values for dim 6 matrix elements converge
- V_{cb} inclusive vs exclusive converges and direct measurement as FCC-ee
- 3-loop corrections known and confirmed

$$\Delta M_s^{\mathrm{SM},2035} = (19.20 \pm 0.29)\,\mathrm{ps}^{-1}$$

$$\Delta M_s^{\mathrm{EXP},2035} = (17.750 \pm 0.002)\,\mathrm{ps}^{-1}$$

Discovery of BSM with 5 standard deviations

For slides, see: https://indico.cern.ch/event/1186057/

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
- 2022 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
- ------------------------

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

This work

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

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

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

1912.07621

HFLAV, ATLAS 1605.07485

!FPCP2023: New LHCb

$$\Delta\Gamma_s^{LHCB} = (0.0846 \pm 0.0050)\,\mathrm{ps}^{-1}$$

$$\delta(\text{Theo.})/\delta(\text{Exp.}) \approx 2.6$$

xing

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

r ΔM, $B_{2,3,4,5}$ new

Klein, Mannel, Pivovarov B_d

uh B_d

uh B_s

07.01025

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

This work

m insertion approximation

0.00970

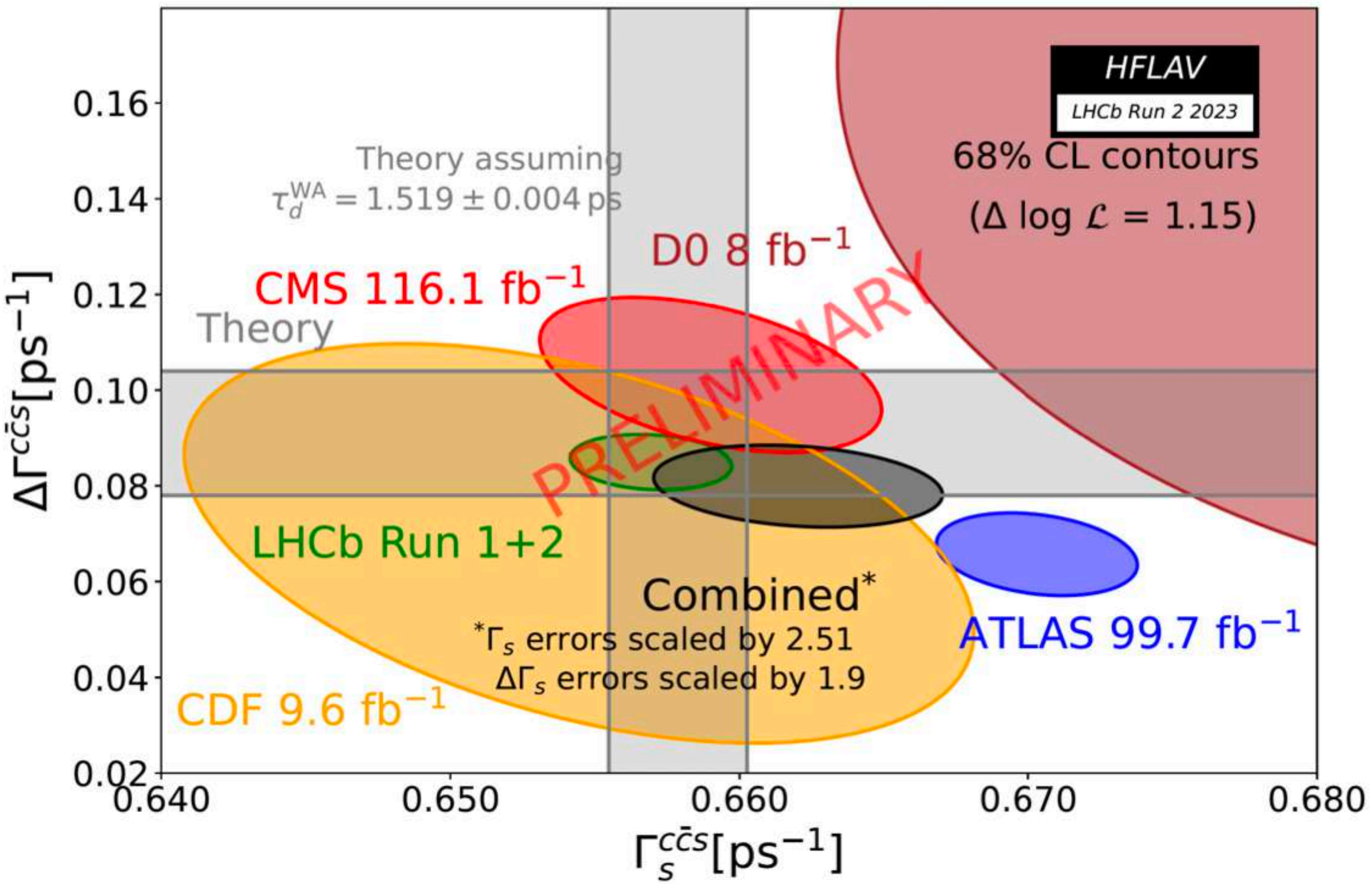
$$\Delta\Gamma_s^{\text{HQE, LYON2023}} = (0.0895 \pm 0.0131)\,\text{ps}^{-1}$$

!FPCP2023: New LHCb

$$\Delta\Gamma_s^{LHCB} = (0.0846 \pm 0.0050)\,\text{ps}^{-1}$$

$$\delta(\text{Theo.})/\delta(\text{Exp.}) \approx 2.6$$

Status Quo: Mixing



Slide from
Ramon Angel Ruiz Fernandez

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Status Quo: Mixing

2035:
- Lattice and sum rule values for dim 7 matrix elements
- Better understanding of quark masses
- α_s/m_b corrections determined
- Lattice values for dim 6 matrix elements converge

$$\Delta\Gamma_s^{\mathrm{SM2035}} = (0.085 \pm 0.005)\,\mathrm{ps}^{-1}$$
$$\Delta\Gamma_s^{\mathrm{HFLAV2035}} = (0.080 \pm 0.002)\,\mathrm{ps}^{-1}$$

Amazing confirmation of HQE framework

For slides, see: https://indico.cern.ch/event/1186057/

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Status Quo: Charm Mixing

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

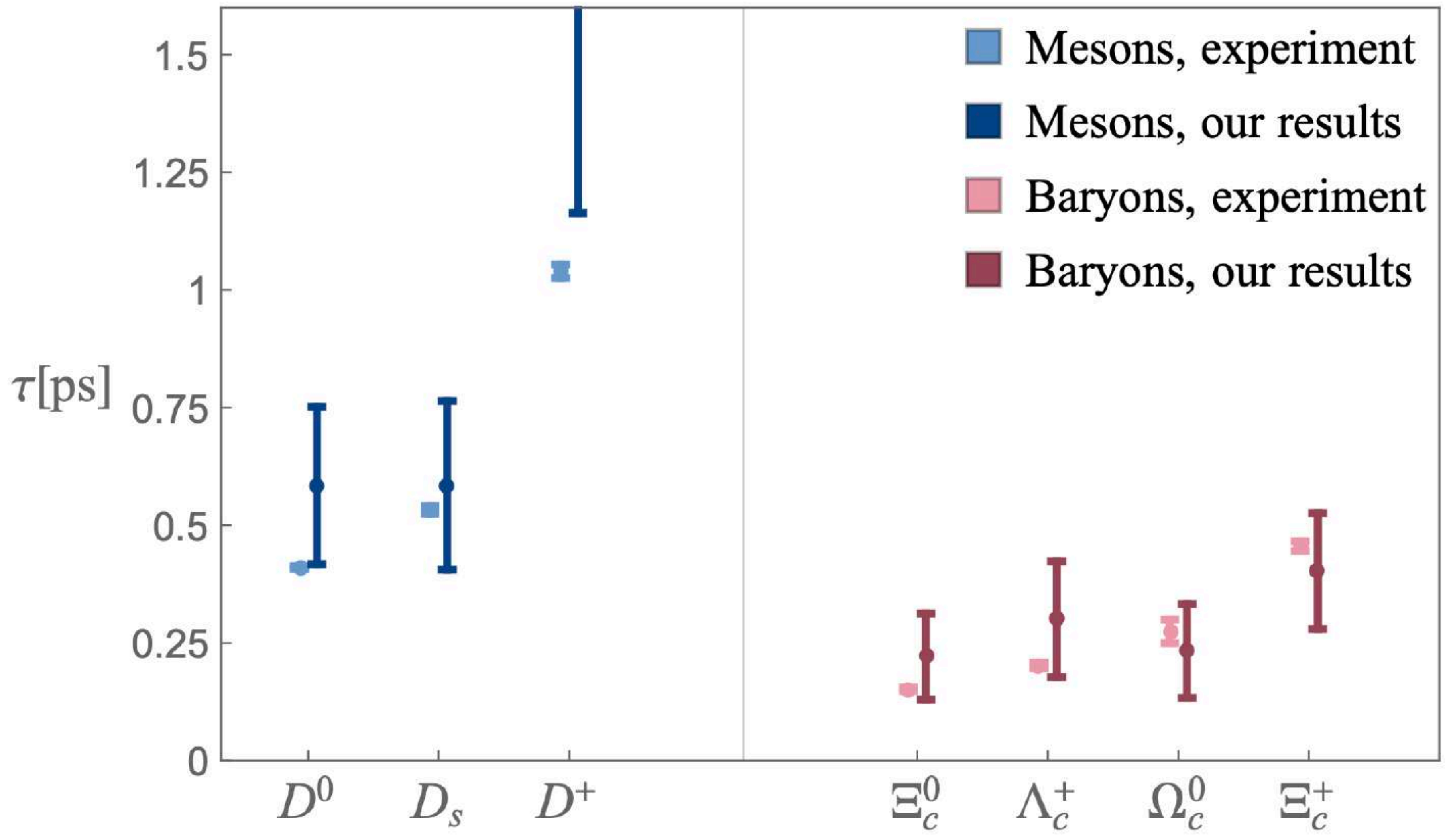
- $\alpha_s(m_c) \approx 0.34$
- $$\frac{\Lambda_{QCD}}{m_c} \approx 3\frac{\Lambda_{QCD}}{m_b}$$

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

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]

HQE seems to work for charm lifetimes

Revisiting inclusive decay widths of charmed mesons
Daniel King (Durham U., IPPP and Durham U.), Alexander Lenz (Siegen U.), Maria Laura Piscopo (Siegen U.), Thomas Rauh (U. Bern, AEC), Aleksey V. Rusov (Siegen U.) et al. (Sep 27, 2021)
Published in: *JHEP* 08 (2022) 241 • e-Print: 2109.13219 [hep-ph]



Lifetimes of singly charmed hadrons
James Gratrex (Boskovic Inst., Zagreb), Blaženka Melić (Boskovic Inst., Zagreb), Ivan Nišandžić (Boskovic Inst., Zagreb) (Apr 25, 2022)
Published in: *JHEP* 07 (2022) 058, *JHEP* 07 (2022) 058 • e-Print: 2204.11935 [hep-ph]

But for mixing it gets much worse

See talk by Jake Bennett

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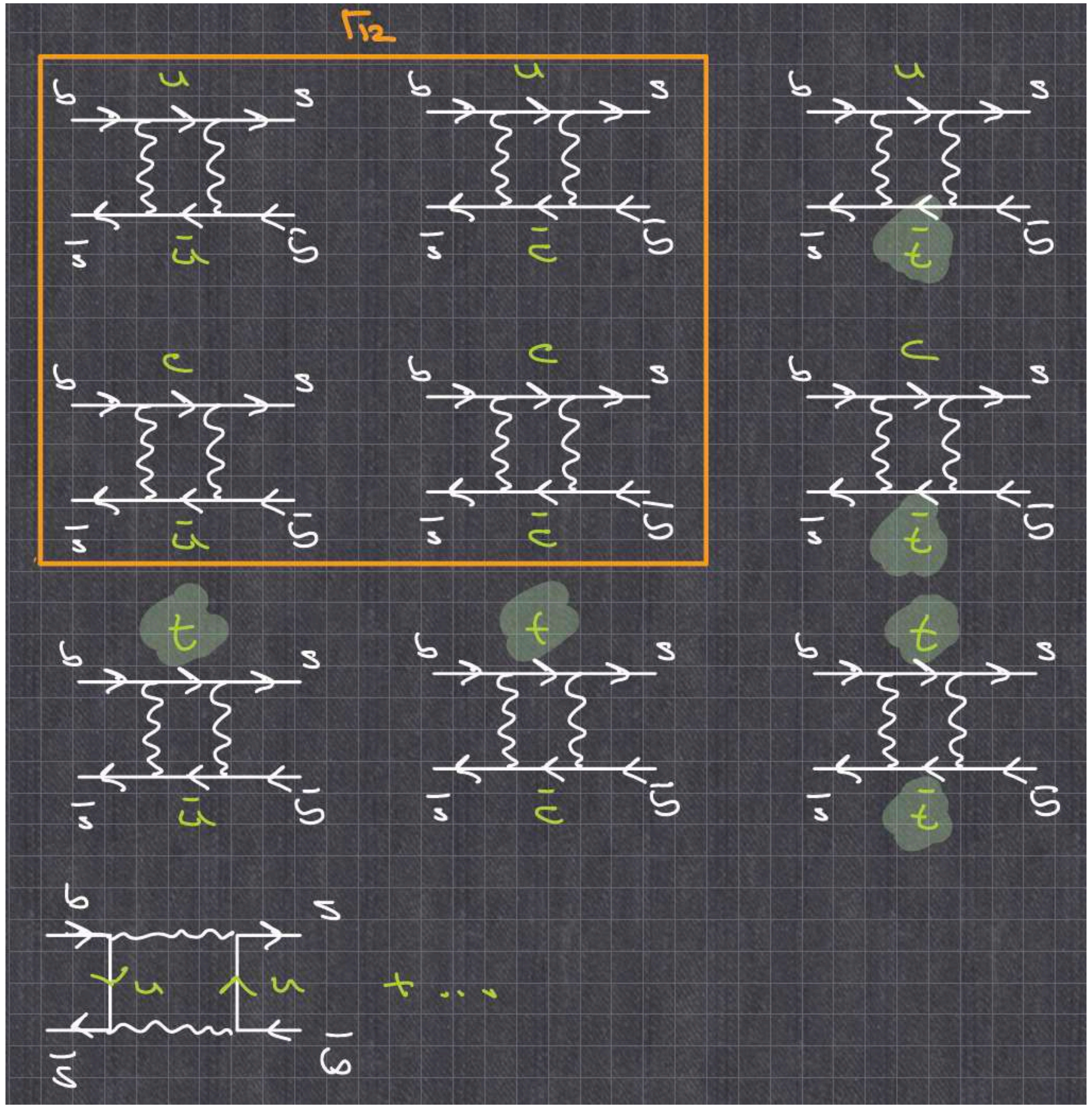
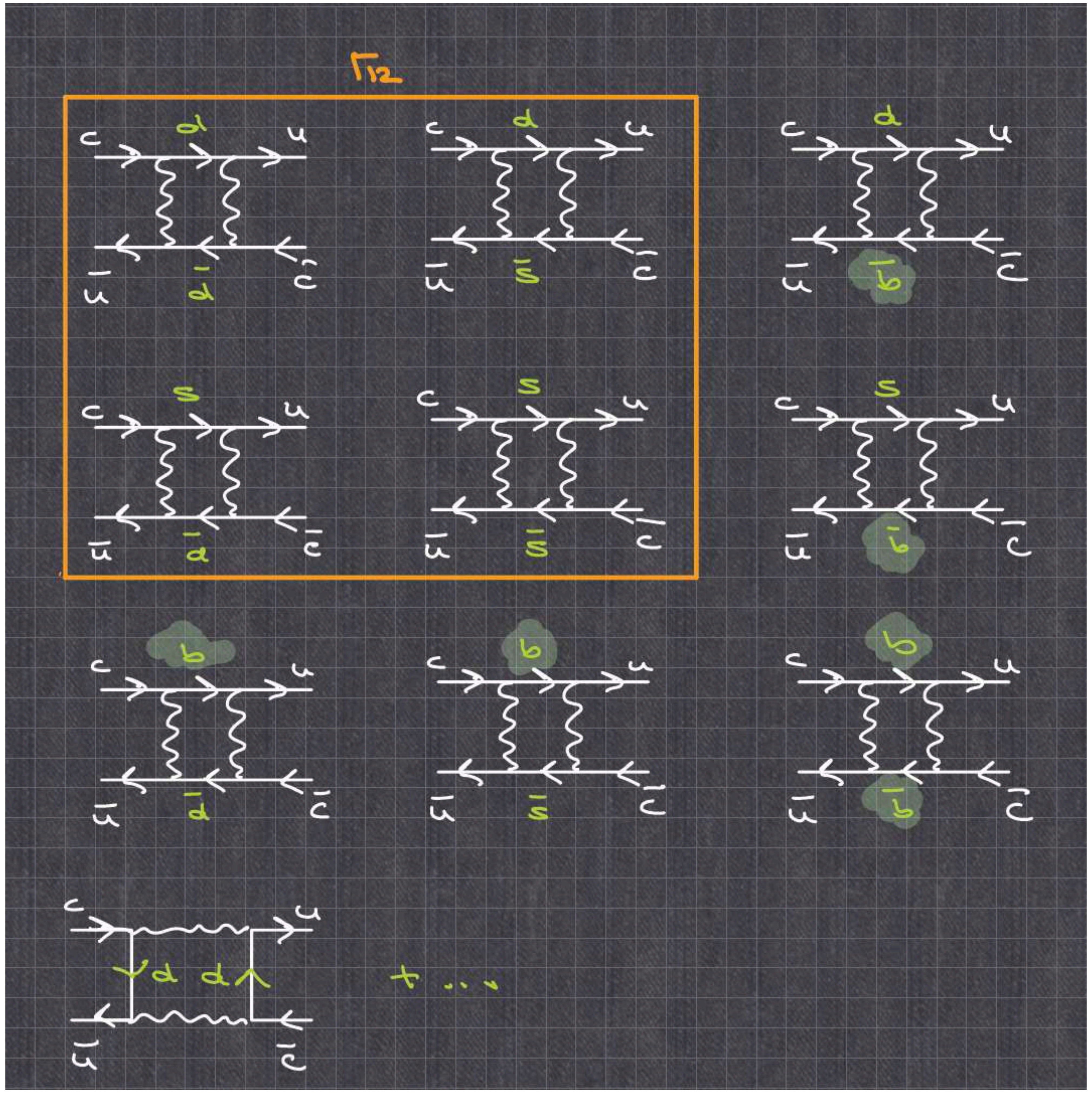
Status Quo: Charm Mixing

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

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

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

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

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

2012: $\Delta\Gamma_s$ by LHCb

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

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

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 $x \approx y$

Exp. data Cheng, Chiang 1005.1106 $x \propto \mathcal{O}(0.1\%)$ $y \propto \mathcal{O}(few\ 0.1\%)$

U-Spin sum rule Gronau, Rosner 2012

Factorisation-assisted topological amplitude approach

Jiang et al. 1705.07335 $y \approx 0.2\%$

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Status Quo: Charm Mixing

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

=> apply it for D-mixing

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

How can this be?

Look only at a single diagram:

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

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**

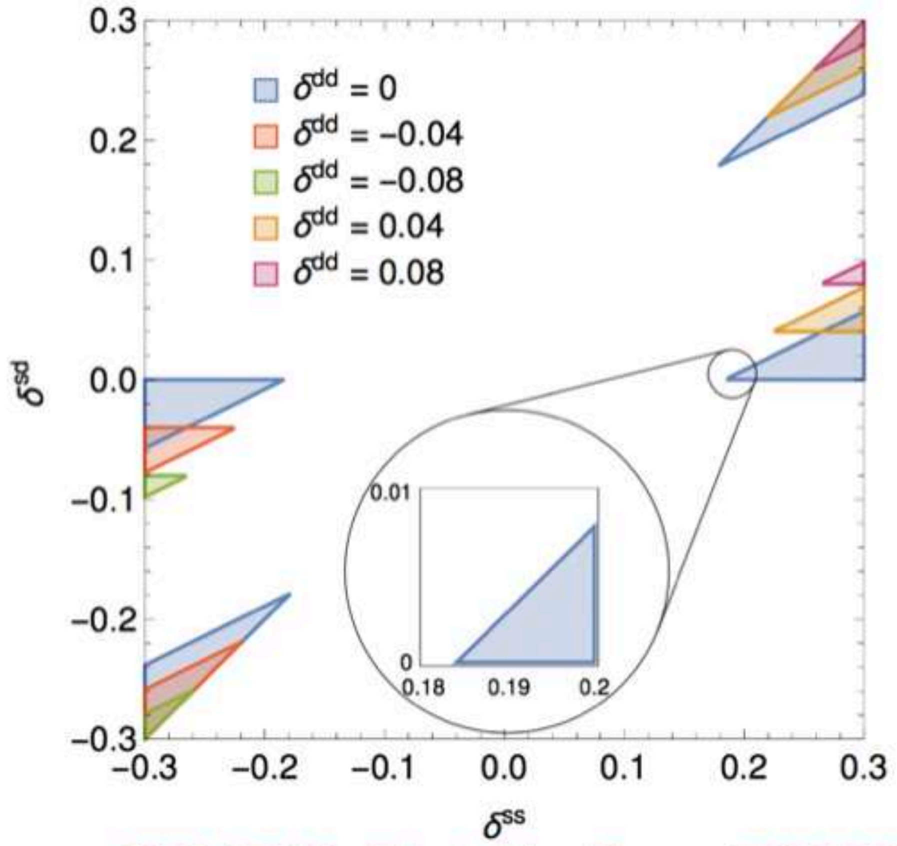
$$\Gamma_{12}^{ss} \to \Gamma_{12}^{ss}(1+\delta^{ss})\,,$$

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

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

20% of duality violation is sufficient to explain experiment

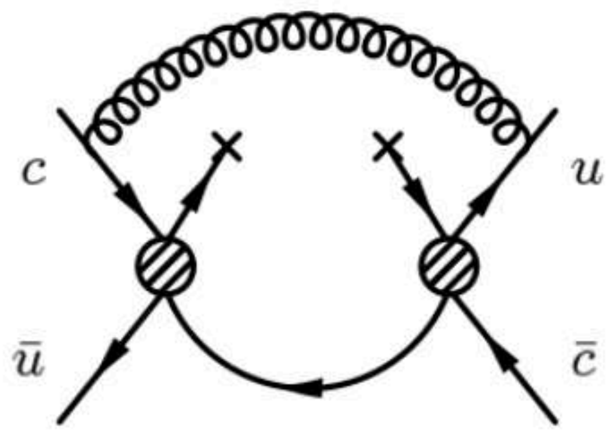
Jubb, Kirk, AL, Tetlalmatzi-Xolocotzi 2016

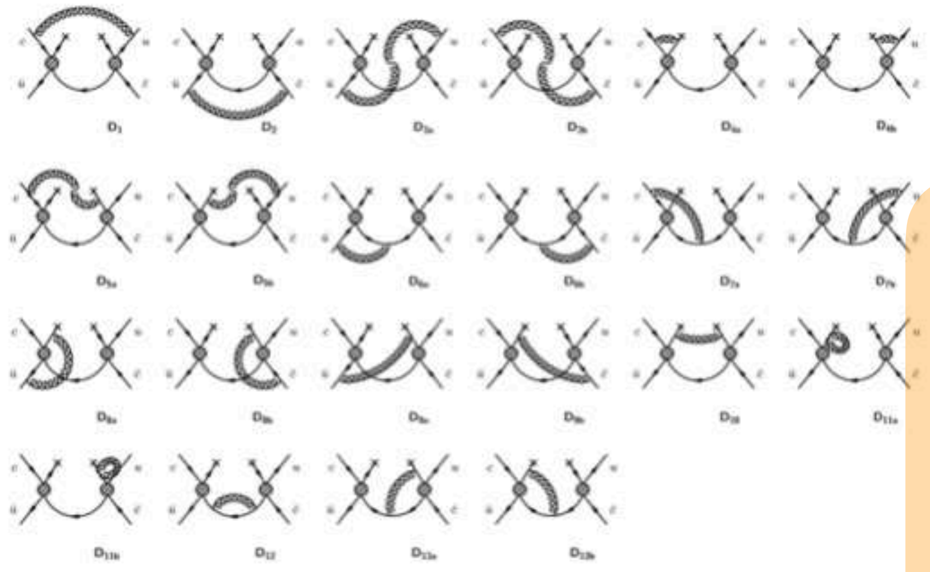


2. **Higher dimensions** Georgi 9209291; Ohl, Ricciardi,Simmons 9301212; Bigi, Uraltsev 0005089

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
   $\Rightarrow$ uncertainty increases and exp. value is covered
2) Choose scales somehow phase space inspired as

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

$\Rightarrow$ exp. value is covered

Exclusive and inclusive approaches can over the experimental regions

No precision determination possible

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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

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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

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Status Quo: CPV in Interference

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

$$A_{\rm CP}^{\rm dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\,,$$

$$A_{\rm CP}^{\rm mix} = -\frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}\,,$$

$$A_{\Delta\Gamma} = -\frac{2\Re(\lambda_f)}{1+|\lambda_f|^2}\,.$$

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

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

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

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

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

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

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

All hadronic uncertainties are cancelling exactly in the CP asymmetry!

Gold-plated modes

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Status Quo: CPV in Interference

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

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

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

Could also be BSM if there is only one SM amplitude

Then the CP asymmetry depends on

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

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)

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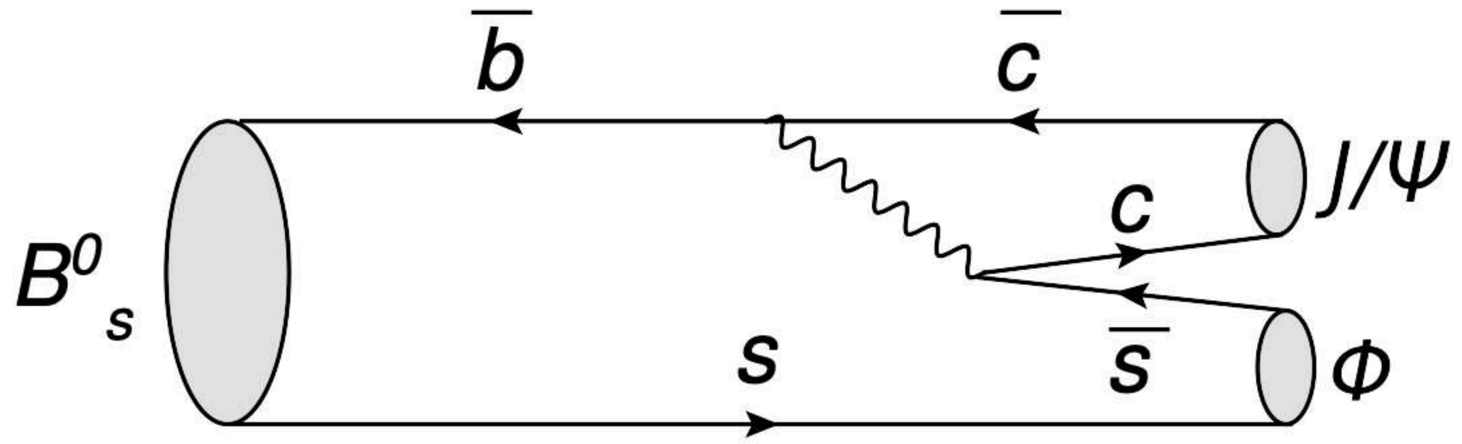
If penguins are small compared to tree-level, the hadronic corrections are cancelling to leading order and there is a correction proportional to r

Penguin pollution

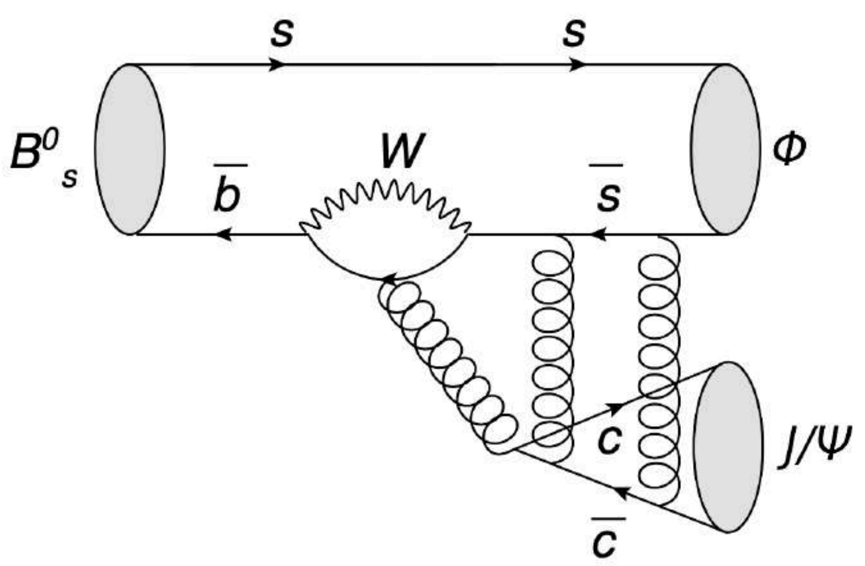
Status Quo: CPV in Interference

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

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



$+$



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!

CP violation in the B_s^0 system
Marina Artuso (Syracuse U.), Guennadi Borissov (Lancaster U.), Alexander Lenz (Durham U., IPPP) (Nov 30, 2015)
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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,…

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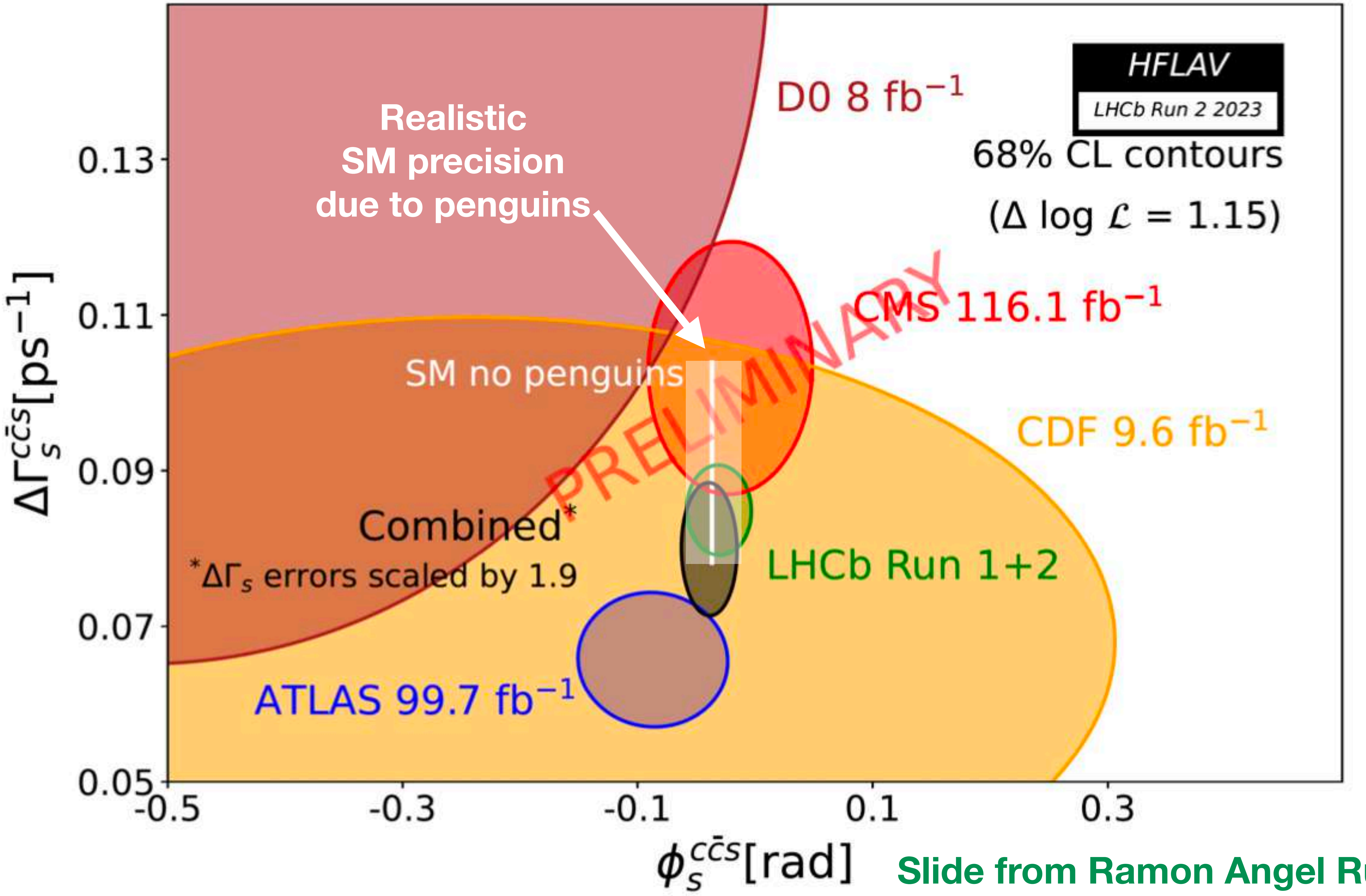
Status Quo: CPV in Interference

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

HFLAV Preliminary

$\phi_{s,Prelim.}^{c\bar{c}s}$ = -0.039 ± 0.016 mrad

$\approx \pm 0.9^\circ$



Modification due to **New Physics**

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

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

See 1106.3200

$B_s \to J/\Psi\phi$

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

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

a_{fs}^s

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

Slide from Ramon Angel Ruiz Fernandez

LHCb-PAPER-2023-013 $\sin(2\beta) = 0.716(15) \;\approx \pm 0.6^\circ$

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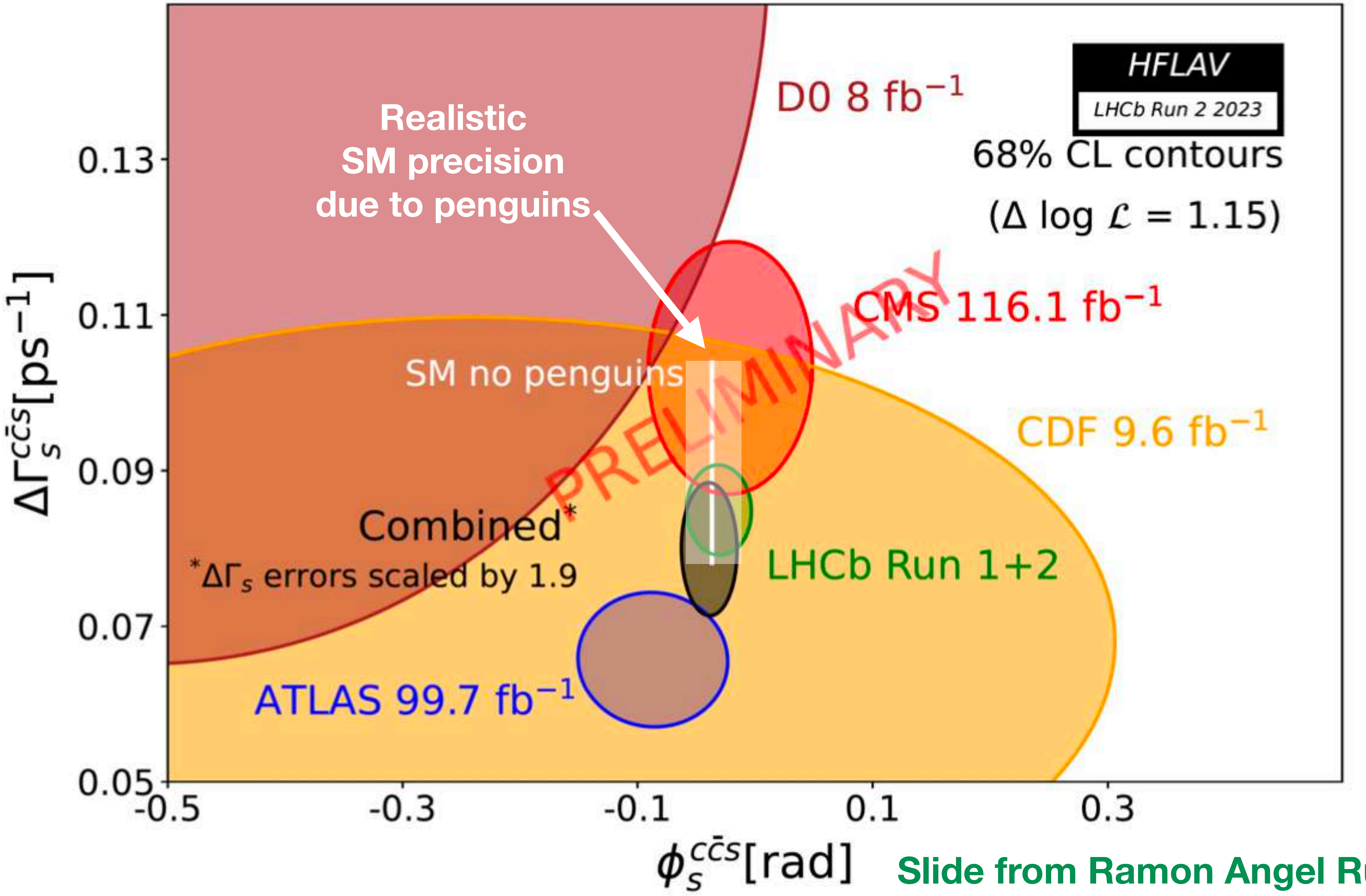
Valeria Lukashenko, e+e-:Justin Skorupa

Status Quo: CPV in Interference

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

HFLAV Preliminary

$\phi^{c\bar{c}s}_{s,Prelim.} = -0.039 \pm 0.016$ mrad $\approx \pm 0.9^\circ$



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See 1106.3200

$B_s \to J/\Psi\phi$

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

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

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Status Quo: CPV in Decay

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

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

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

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

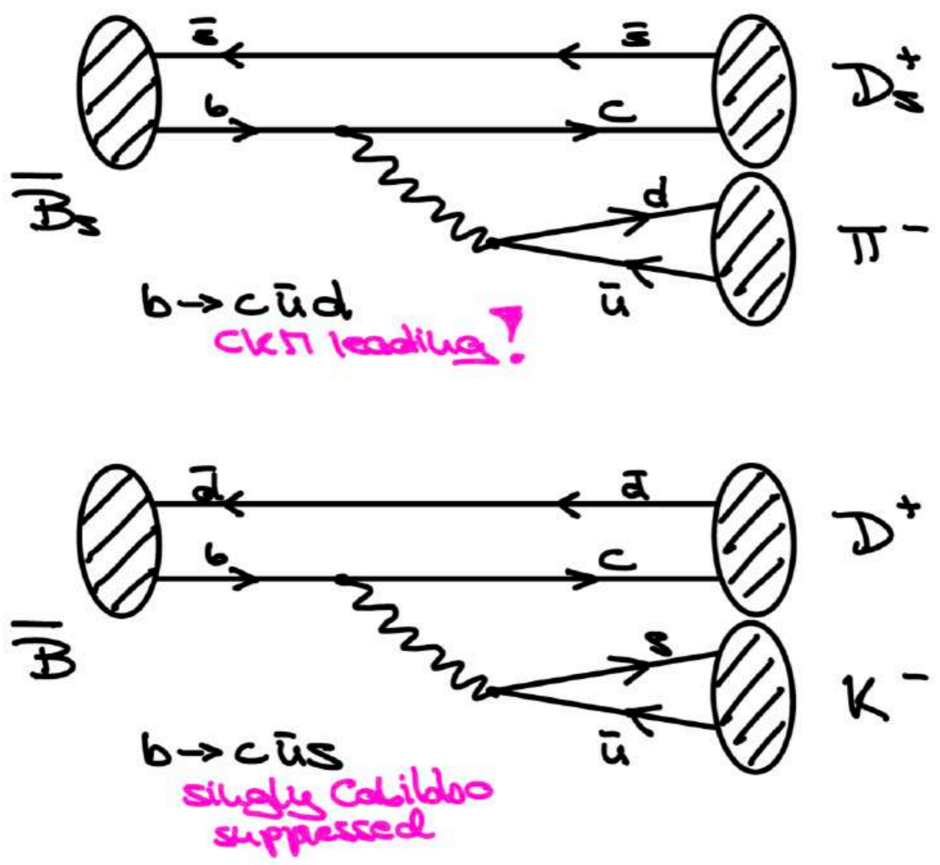
Extremely hard to predict!

(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

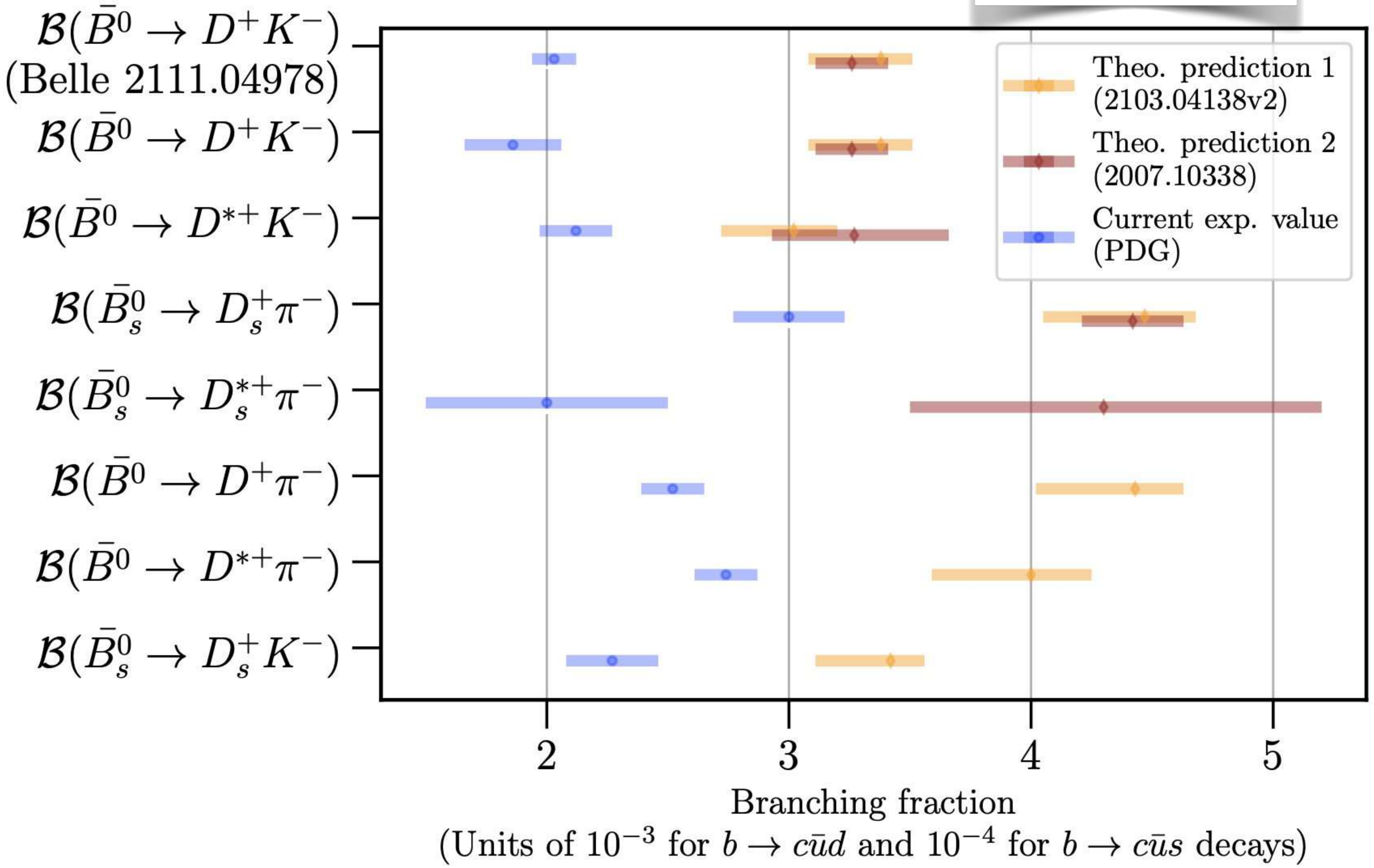


- CKM leading decays
- The are no annihilation, penguins,…
- QCDf should work at its best!

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



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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

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Status Quo: 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 $B_s \to D_s^{\mp} K^{\pm}$
- **Fleischer, Malami** 2110.04240, 2109.04950

In progress: Piscopo, Rusov

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

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Direct CP asymmetries

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

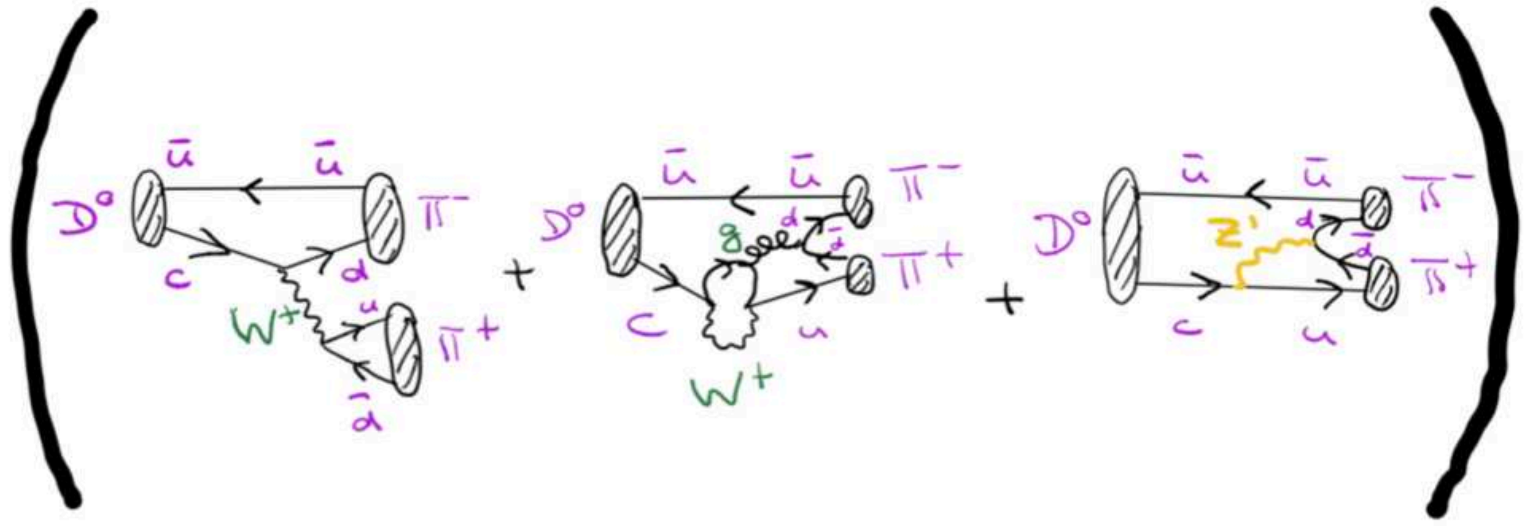
Updates: **2002.03262** complete 2-loop penguins
2107.03819 QED corrections
2104.14871 $A_{CP}(B^0 \to \pi^0 \bar{K}^0)$ Belle II
SU(3) symmetry e.g. **1806.08783, 2111.06418,…**
comprehensive phenomenological study missing

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. $D^0 \to \pi^+\pi^-$

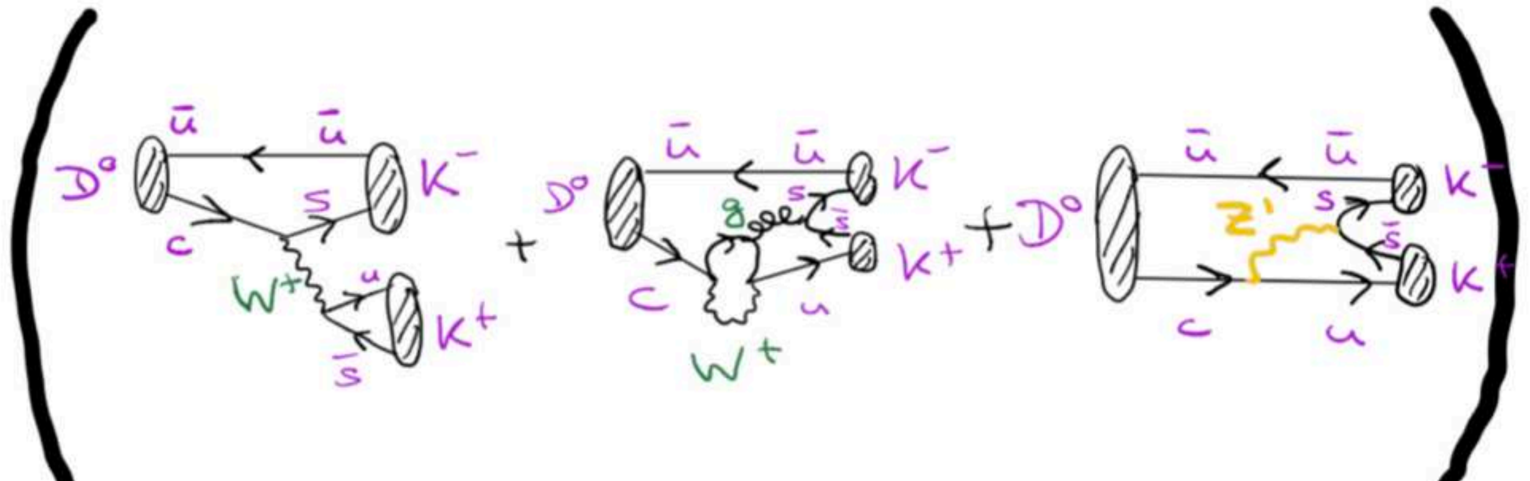
Experiment: LHCb 03/2019

Theory: SM or not SM? **See talk by Eleftheria Solomonidi**
E.g. 1903.10952,1909.03063 vs. 1903.10490, 1909.11242



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

$-$

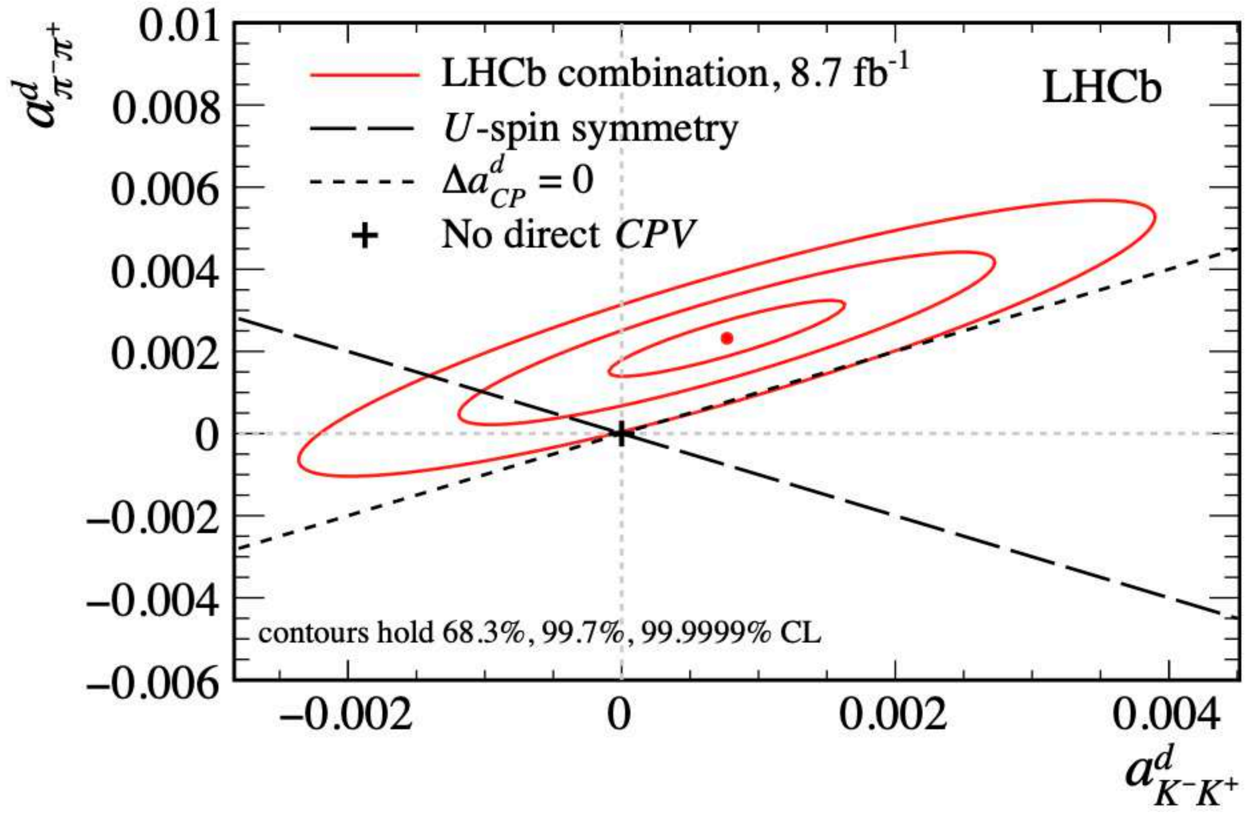


ΔA_{CP}: $D^0 \to K^+K^-$ vs. $D^0 \to \pi^+\pi^-$

- **Experimental news:**

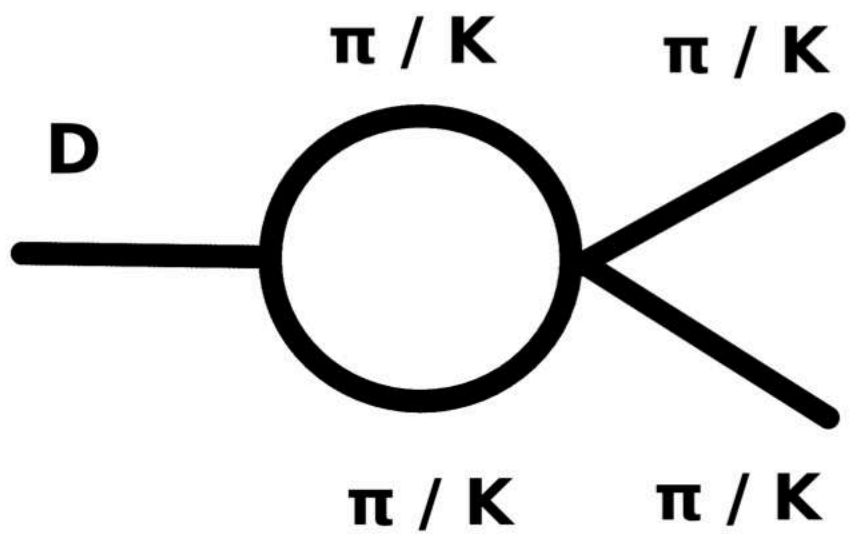
See talk by Serena Maccolini

$$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4}$$
with $\rho(a^d_{KK}, a^d_{\pi\pi}) = 88\%$



- **Theoretical news:**

See talk by Eleftheria Solomonidi



- Confirms small SM value, as LCSR a la Khodjamirian, Petrov
- Contains nearby resonances
- Found inconsistencies in predictions obtaining large SM values

hep-ph/2305.11951

Shedding light into the dark

Flavour specific decays

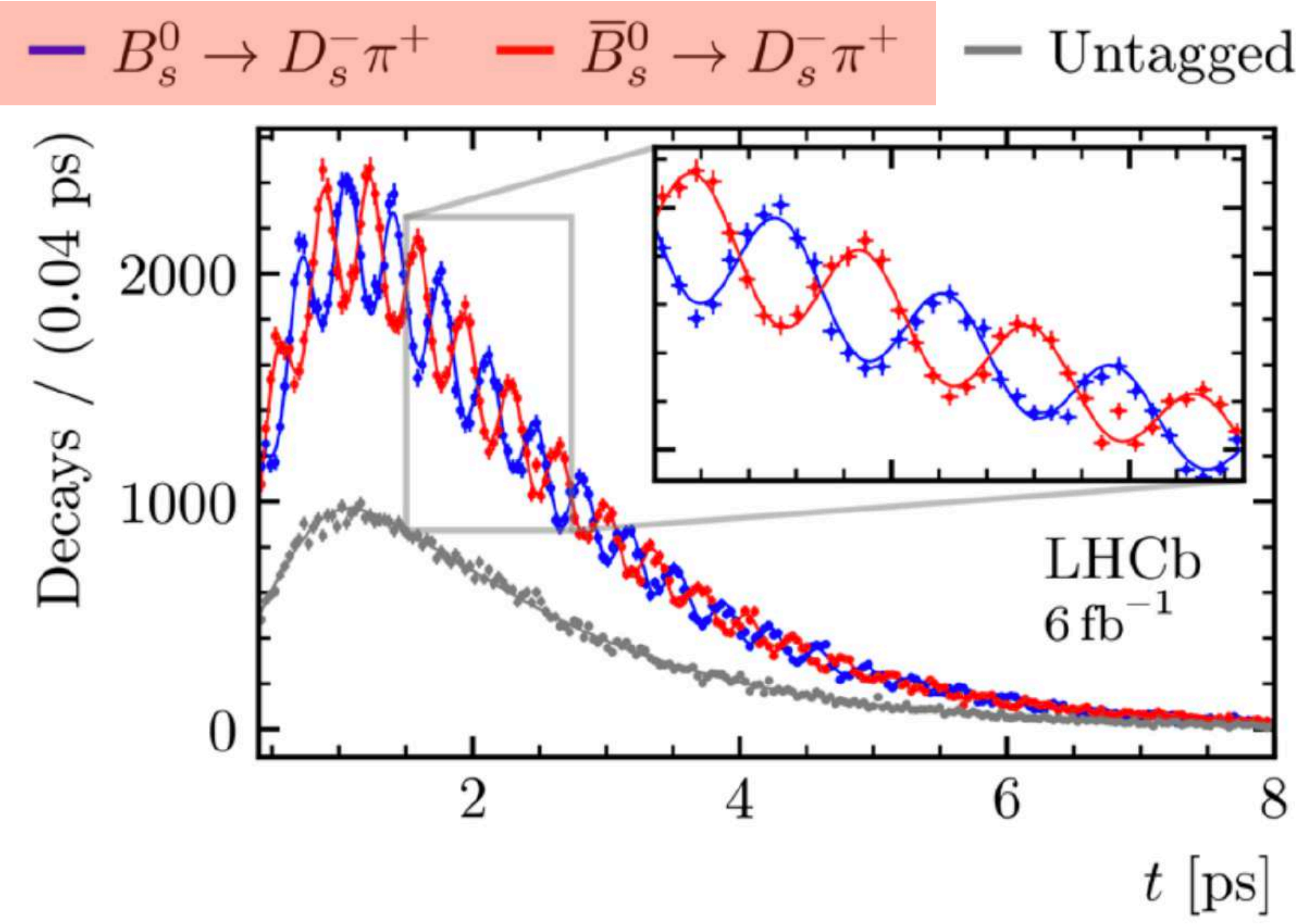
- a_{fs}^{q} is typically measured with semi-leptonic B_q decays
- One could also use the flavour specific $\bar{B}_s \to D_s^+ \pi^-$ decay

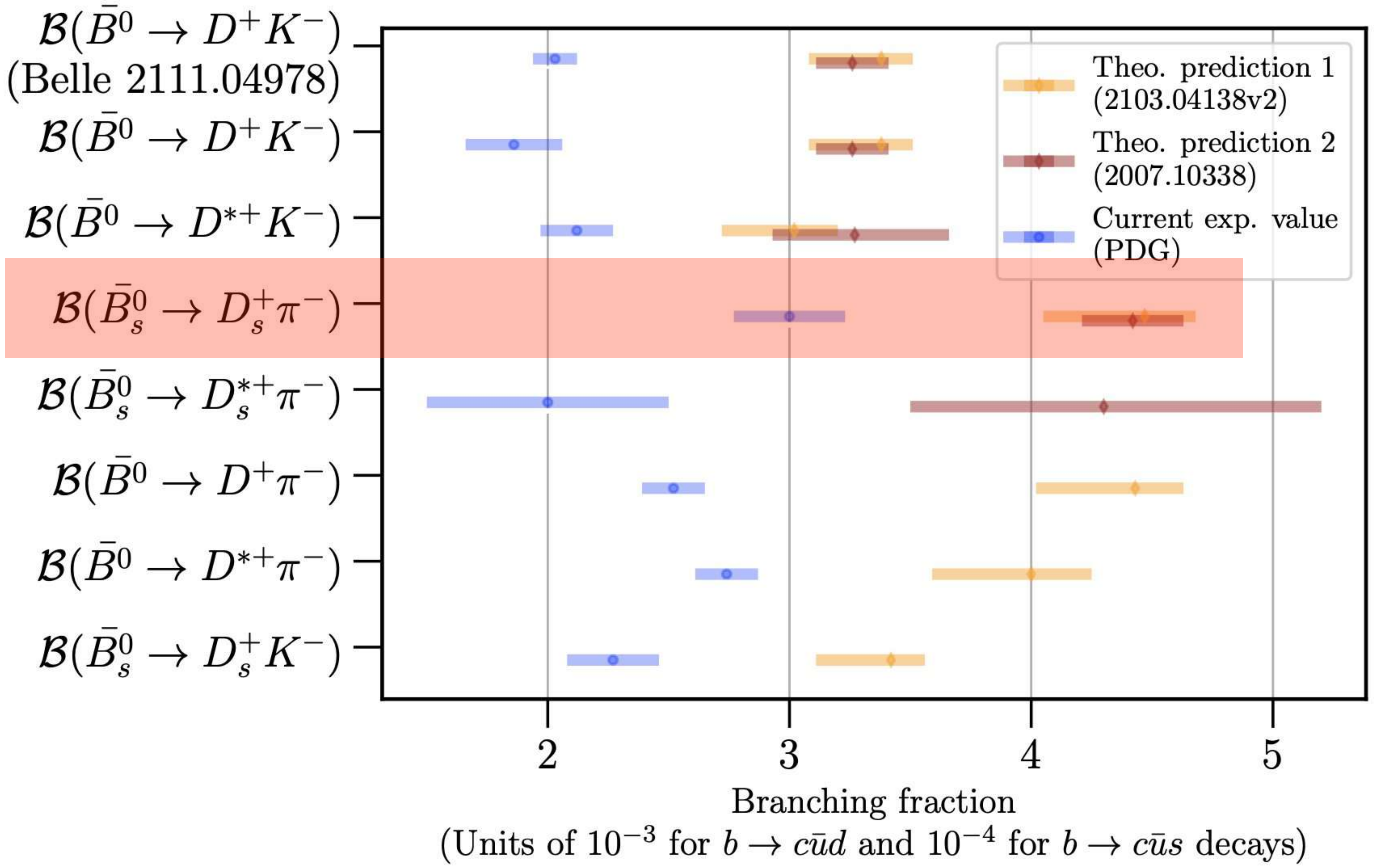
12 April 2021: Fascinating quantum mechanics.

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

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

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

Flavour specific decays

- a_{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?

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Flavour specific decays

Gershon, AL, Rusov, Skidmore
2111.04478

- 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

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HFLAV 1970?

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

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Conclusions

- Continuous progress in experiment and theory for mixing observables
- SM model and theory tools seem to work very well

- SM Penguin pollution is crucial now
- Interesting developments in hadronic decays $\bar{B}_s \to D_s^+\pi^-$, $\Delta A_{CP}, \ldots$
- QCD independent strategies to identify BSM effects!

- We want a_{fs}^q!!!

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