Flavour-physics

Alexander Lenz

Siegen University

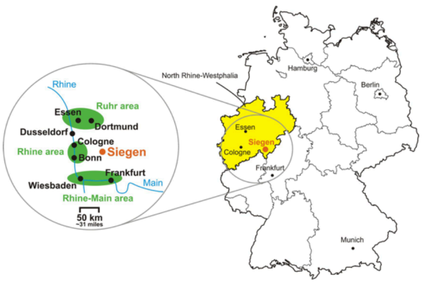
13./14./15. 9. 2023

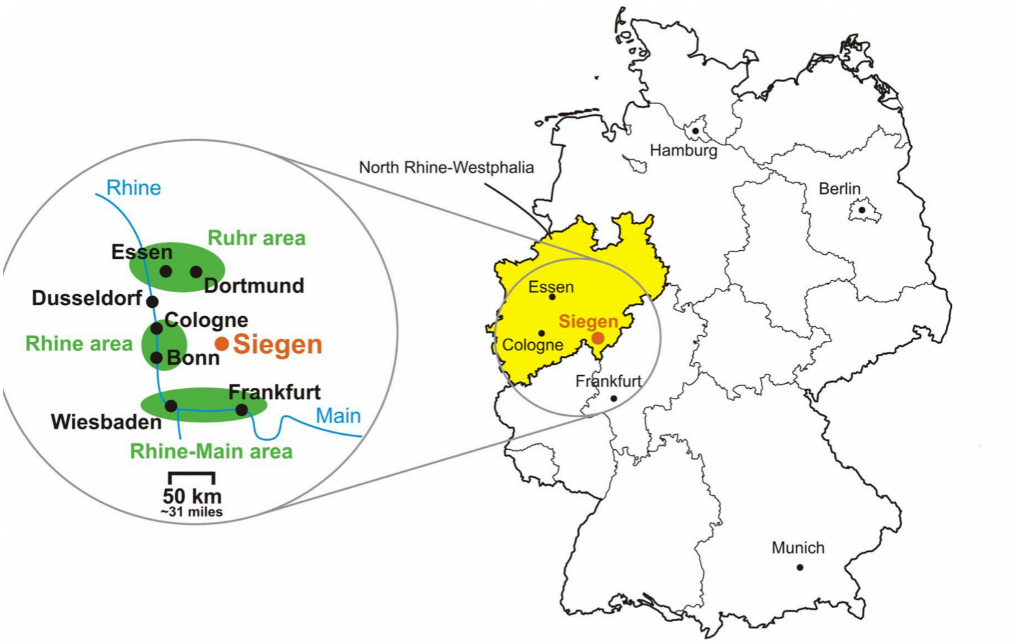
Siegen University

- 16 700 Students

Physics:

- 18 Professors
- approx. 65 post-docs
- Approx. 30 PhD students
- Each year around 30 first-year students




Hamburg
Berlin
North Rhine-Westphalia
Essen
Siegen
Cologne
Frankfurt
Munich
Rhine
Ruhr area
Essen
Dortmund
Dusseldorf
Cologne
Rhine area
Siegen
Bonn
Frankfurt
Wiesbaden
Main
Rhine-Main area
50 km
~31 miles

Lecture 1: SM, CKM, weak decay

Lecture 2: Theoretical Framework

Lecture 3: Mixing & $\not{CP}$

Lecture 1:

Unitarity triangle

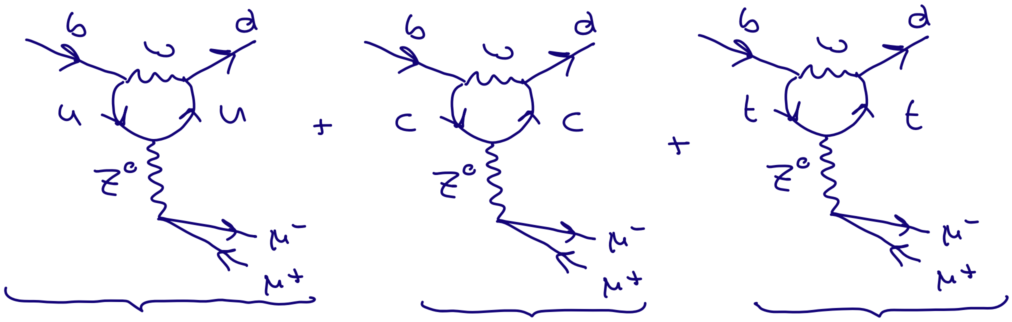
V_{CKM} is by construction unitary

$$V_{CKM}^{\dagger} V_{CKM} = \sum_{q_u = u,c,t} V_{q_u d_1}^{*} V_{q_u d_2} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V_{CKM} V_{CKM}^{\dagger} = \sum_{q_d = d,s,b} V_{u_1 q_d} V_{u_2 q_d}^{*} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

B_d: $0 = V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*}$

* $b \to d\,\mu\mu$ - Penguin



$f(m_u) \quad + \quad f(m_c) \quad + \quad f(m_t)$

Ann 1: $m_u = m_c = m_t$

$$f(m_u)\left\{ V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} \right\} = 0$$

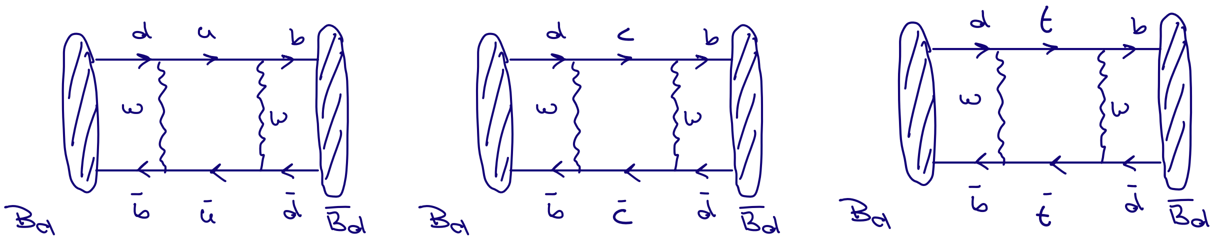
GIM Mechanismus

Glashow, Illiopoulos, Maiani

Ann 2: $f(m_q) = f_0 + \tilde{f}(m_q)$

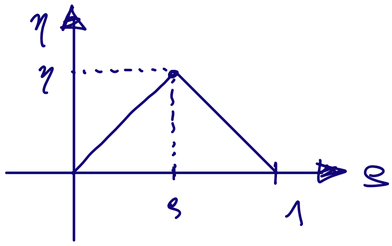
f_0: hebt sich weg

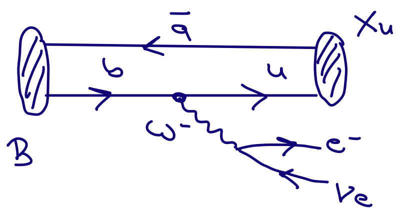
* B-Mischung: $B_d \leftrightarrow \bar{B}_d$

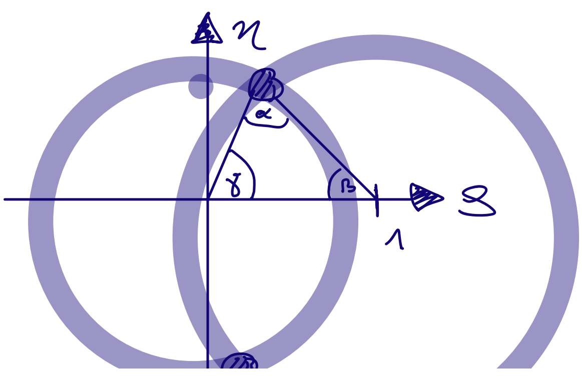


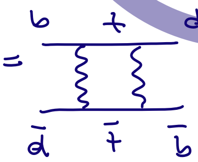
wieder $\left(V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} \right)^2$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$





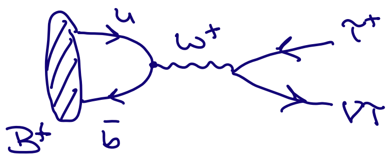


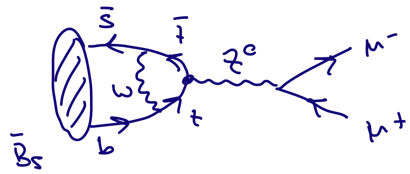
- $\Delta m_d = m_{B_H} - m_{B_L} =$ 

  ↓
  Exp:

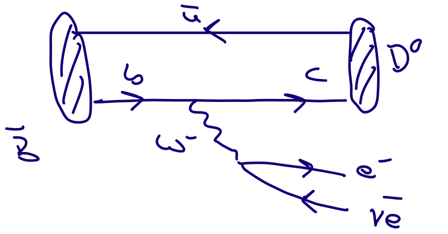
Classification of decays

	Tree-level	loop-level
leptonic:	$B^+ \to \tau^+ \nu_\tau$	$\bar{B}_s \to \mu^+ \mu^-$

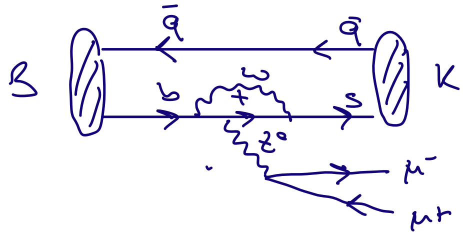




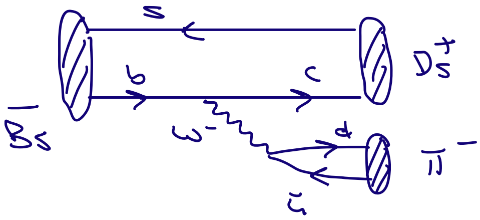
semi-leptonic: $\bar{B} \to D^0 e^- \bar{\nu}_e$



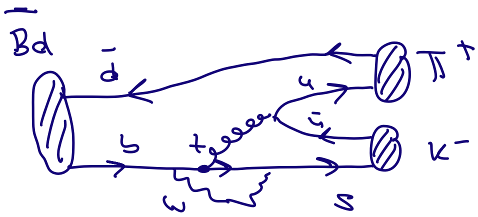
$B \to K \mu^+ \mu^-$



non-leptonic: $\bar{B}_s \to D_s^+ \pi^-$



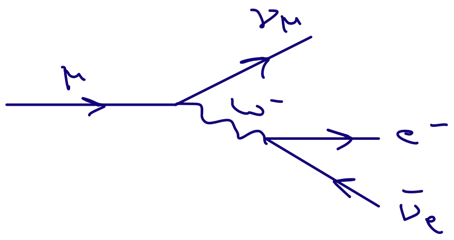
$\bar{B}_d \to \pi^+ K^-$

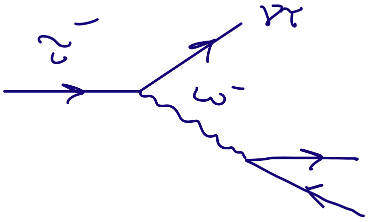


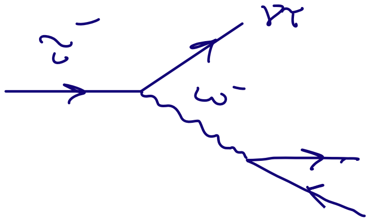
Lecture 2:

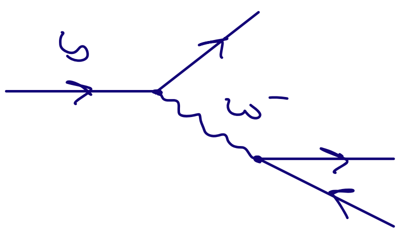
A. Buras

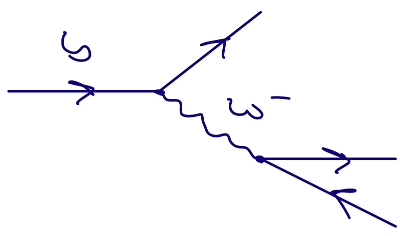
- hep-ph/9806471 Les Houches
- hep-ph/9512380 Review





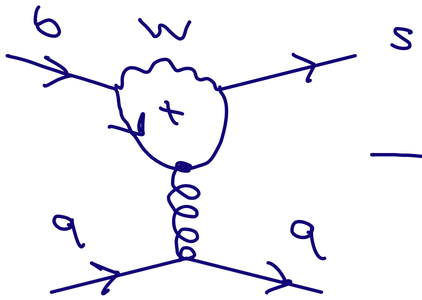






Penguin operators

QCD penguin operators



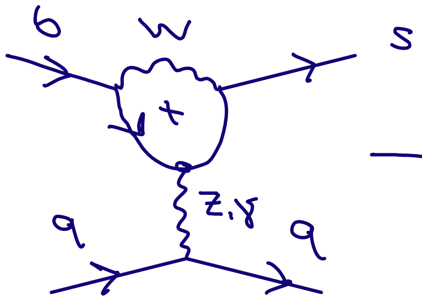
$$Q_3 = (\bar{s}\, b)_{V-A} \sum_{q=u,\dots,b} (\bar{q}\, q)_{V-A}$$

$$Q_4 = (\bar{s}^\alpha b^\beta)_{V-A} \sum_{q=u,\dots,b} (\bar{q}^\beta q^\alpha)_{V-A}$$

$$Q_5 = (\bar{s}\, b)_{V-A} \sum_{q=u,\dots,b} (\bar{q}\, q)_{V+A}$$

$$Q_6 = (\bar{s}^\alpha b^\beta)_{V-A} \sum_{q=u,\dots,b} (\bar{q}^\beta q^\alpha)_{V+A}$$

Electro-weak penguin operators



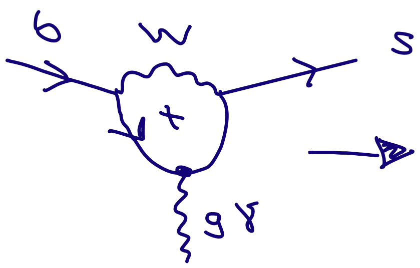
$$Q_7 = \frac{3}{2} (\bar{s}\, b)_{V-A} \sum_{q=u,\dots,b} e_q (\bar{q}\, q)_{V+A}$$

$$Q_8 = \frac{3}{2} (\bar{s}^\alpha b^\beta)_{V-A} \sum_{q=u,\dots,b} e_q (\bar{q}^\beta q^\alpha)_{V+A}$$

$$Q_9 = \frac{3}{2} (\bar{s}\, b)_{V-A} \sum_{q=u,\dots,b} e_q (\bar{q}\, q)_{V-A}$$

$$Q_{10} = \frac{3}{2} (\bar{s}^\alpha b^\beta)_{V-A} \sum_{q=u,\dots,b} e_q (\bar{q}^\beta q^\alpha)_{V-A}$$

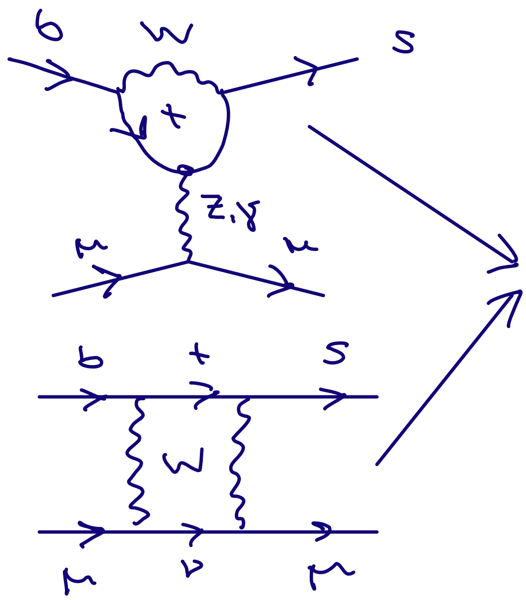
Magnetic penguin operators



$$Q_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} (1+\gamma_5)\, b_\alpha F_{\mu\nu}$$

$$Q_{8g} = \frac{g}{8\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} (1+\gamma_5) T^a_{\alpha\beta} b_\beta G^a_{\mu\nu}$$

Semileptonic penguin operators



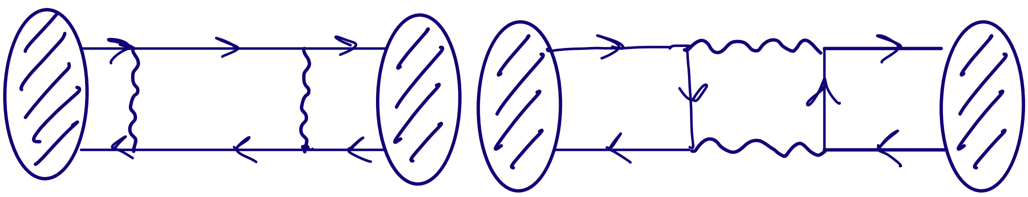
q^2

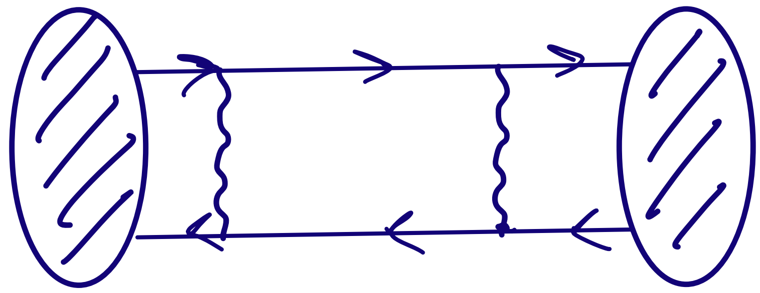
$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V$$

$$Q_{10A} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}}\left[\sum_{\substack{q=u,c\\ q'=u,c\\ q''=d,s}} V_c \left\{ C_1(\mu)Q_1^{qq'q''} + C_2(\mu)Q_2^{qq'q''} \right\} - V_p \sum_{j\geq 3} C_j(\mu)Q_j \right]$$

Lecture 3: Mixing & $\not{CP}$ in the B-system





$$B_{s,H} = p\, B_s + q\, \bar{B}_s$$
$$B_{s,L} = p\, B_s - q\, \bar{B}_s$$

$$\Delta M_s = 2\,|M_{12}^s| + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right)$$

$$\Delta \Gamma_s = 2\,|\Gamma_{12}^s| \cos(\phi_{12}^s) + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right)$$

$$\phi_{12}^s = \arg\left(-\frac{M_{12}^s}{\Gamma_{12}^s}\right)$$

$$\Rightarrow g_+(t) = e^{-iM_{B_s}t} \, e^{-\frac{\Gamma_{B_s}t}{2}} \Big[$$

$$\cosh\frac{\Delta\Gamma_s t}{4} \cdot \cos\frac{\Delta M_s t}{2}$$

$$- \sinh\frac{\Delta\Gamma_s t}{4} \cdot \sin\frac{\Delta M_s t}{2} \Big]$$

$g_-(t) \equiv$ see e.g. 1511.09466

$$\Gamma(\bar{B}_s(t) \to f) = N_f \, |A_f|^2 \, \frac{1 + |\lambda_f|^2}{2} \, e^{-\Gamma_s t}$$

$$\Big\{ \cosh\frac{\Delta\Gamma_s t}{2} \qquad - \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \cos\Delta M_s t$$

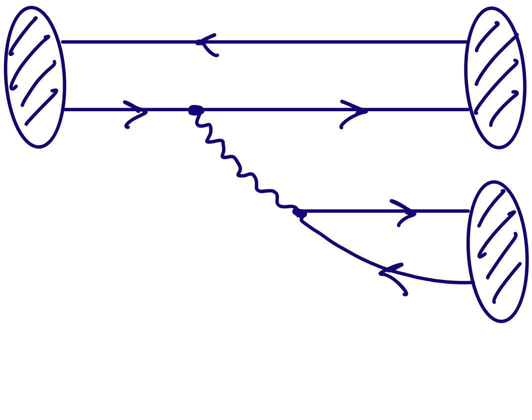
$$- \sinh\frac{\Delta\Gamma_s t}{2} \frac{2\mathrm{Re}(\lambda_f)}{1 + |\lambda_f|^2} + \frac{2\mathrm{Im}(\lambda_f)}{1 + |\lambda_f|^2} \sin\Delta M_s t \Big\}$$

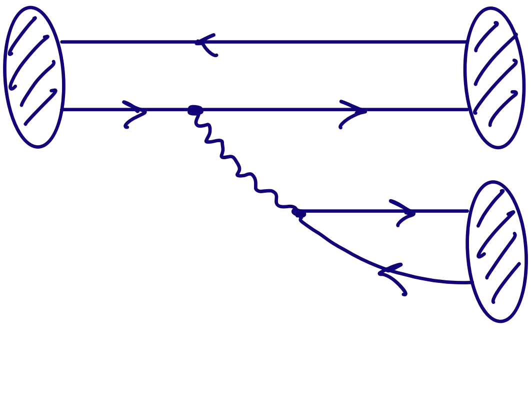
$$(1 + a_{fs}^s)$$

$$\mathcal{A}_f = \langle f | \mathcal{H}_{eff} | B_s \rangle$$

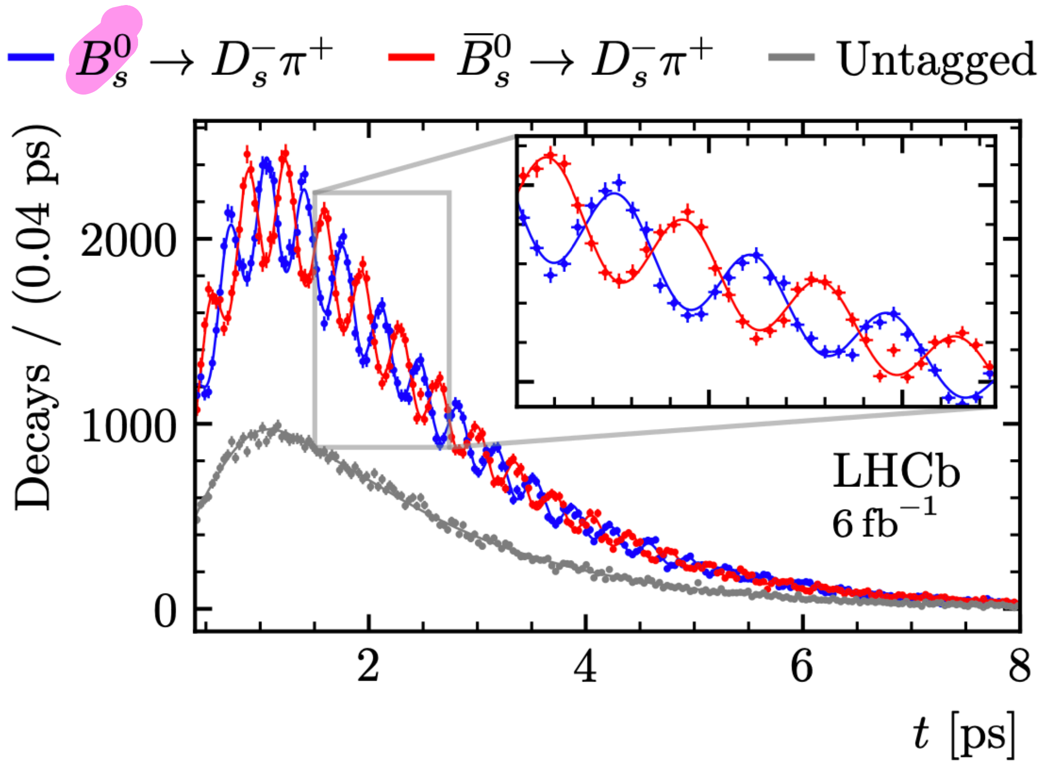
$$\bar{\mathcal{A}}_f = \langle f | \mathcal{H}_{eff} | \bar{B}_s \rangle \qquad \bar{\mathcal{A}}_f = \langle f | \mathcal{H}_{eff} | \bar{B}_q \rangle$$

$$\lambda_f = \frac{q}{p} \frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$$

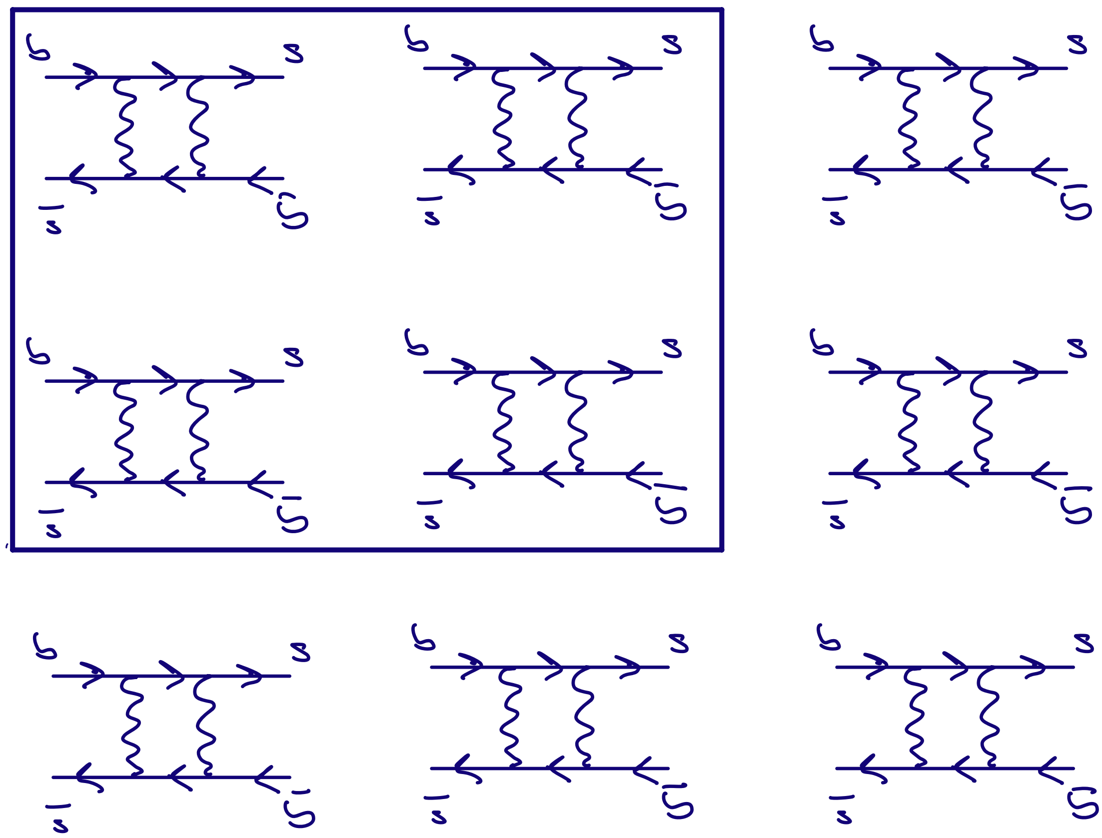


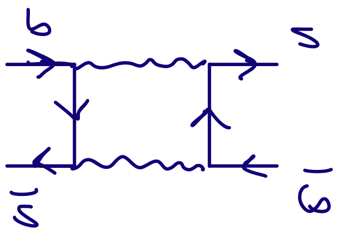


How to measure ΔM?



How to calculate ΔM?





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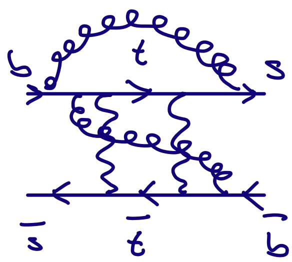


$$M_{12} = \lambda_u^2 F(u,u) + \lambda_u \lambda_c F(u,c) + \lambda_u \lambda_t F(u,t)$$
$$+ \lambda_c \lambda_u F(c,u) + \lambda_c^2 F(c,c) + \lambda_c \lambda_t F(c,t)$$
$$+ \lambda_t \lambda_u F(\ ,u) + \lambda_t \lambda_c F(t,c) + \lambda_t^2 F(t,t)$$

CKM: $\lambda_u = V_{us}^* V_{ub}$

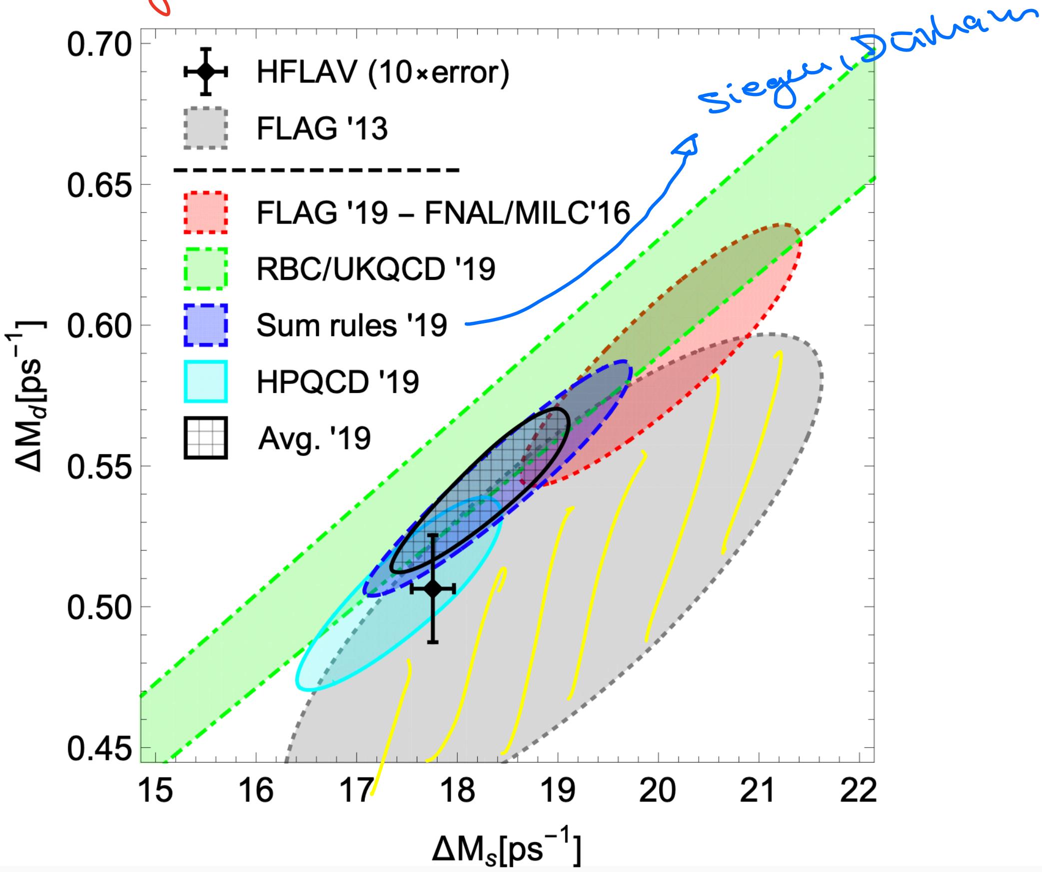
$\lambda_c = V_{cs}^* V_{cb}$

$\lambda_t = V_{ts}^* V_{tb}$

$$\Rightarrow M_{12} = \lambda_u^2 \left[F(c,c) - 2F(u,c) + F(u,u)\right]_1$$
$$+ 2\lambda_u \lambda_t \left[F(c,c) - F(u,c) + F(u,t) - F(c,t)\right]_2$$
$$+ \lambda_t^2 \left[F(c,c) - 2F(c,t) + F(t,t)\right]_3$$

$$S(x) = \frac{4x - 11x^2 + x^3}{4(1-x)^2} - \frac{3x\ln x}{2(1-x)^2}$$

Average lattice & sum rules: 1909.11087



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

1909.11087

High Energy Physics – Phenomenology

[Submitted on 18 Dec 2017 (v1), last revised 15 May 2018 (this version, v2)]

One constraint to kill them all?

Luca Di Luzio, Matthew Kirk, Alexander Lenz

Many new physics models that explain the intriguing anomalies in the b-quark flavour sector are severely constrained by B_s-mixing, for which the Standard Model prediction and experiment agreed well until recently. The most recent FLAG average of lattice results for the non-perturbative matrix elements points, however, in the direction of a small discrepancy in this observable. Using up-to-date inputs from standard sources such as PDG, FLAG and one of the two leading CKM fitting groups to determine $\Delta M_s^{\rm SM}$, we find a severe reduction of the allowed parameter space of Z' and leptoquark models explaining the B-anomalies. Remarkably, in the former case the upper bound on the Z' mass approaches dangerously close to the energy scales already probed by the LHC. We finally identify some model building directions in order to alleviate the tension with B_s-mixing.

Comments: 12 pages, 5 figures. To appear in PRD, matches the published version up to the title

Subjects: **High Energy Physics – Phenomenology (hep-ph)**

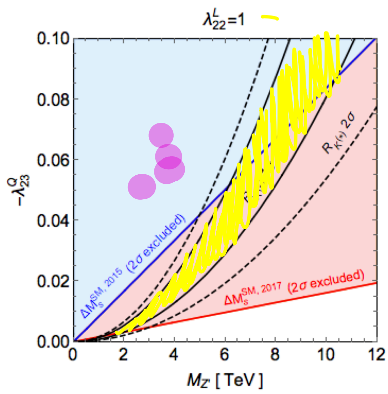
From: <prd@aps.org>
Subject: DP11848 Di Luzio
Date: 8 February 2018 at 17:08:14 GMT
To: <luca.di-luzio@durham.ac.uk>
Reply-To: <prd@aps.org>

Re: DP11848
One constraint to kill them all?
by Luca Di Luzio, Matthew Kirk, and Alexander Lenz

Dear Dr. Di Luzio,

Please suggest another title for the above paper that reflects more accurately the content of your manuscript and which facilitates information retrieval. We ask for a physically more informative title without reference to violence.

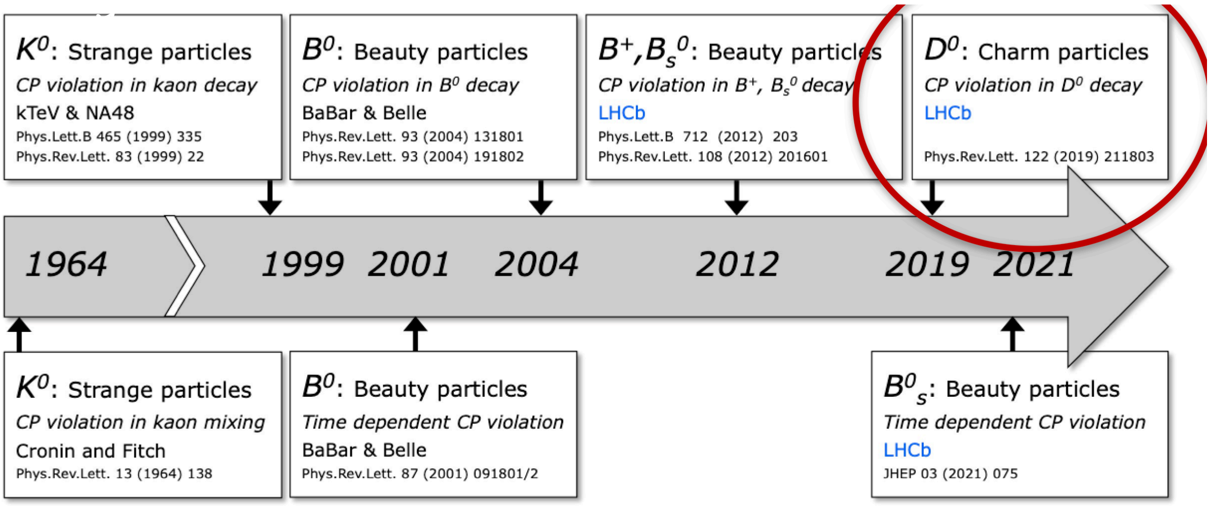
Yours sincerely,



Updated B_s-mixing constraints on new physics models for $b \to s\ell^+\ell^-$ anomalies #5

Luca Di Luzio (Durham U., IPPP), Matthew Kirk (Durham U., IPPP), Alexander Lenz (Durham U., IPPP) (Dec 18, 2017)

Published in: *Phys.Rev.D* 97 (2018) 9, 095035 • e-Print: 1712.06572 [hep-ph]



K0: Strange particles
CP violation in kaon decay
kTeV & NA48
Phys.Lett.B 465 (1999) 335
Phys.Rev.Lett. 83 (1999) 22
B0: Beauty particles
CP violation in B0 decay
BaBar & Belle
Phys.Rev.Lett. 93 (2004) 131801
Phys.Rev.Lett. 93 (2004) 191802
B+,Bs0: Beauty particles
CP violation in B+, Bs0 decay
LHCb
Phys.Lett.B 712 (2012) 203
Phys.Rev.Lett. 108 (2012) 201601
D0: Charm particles
CP violation in D0 decay
LHCb
Phys.Rev.Lett. 122 (2019) 211803
1964
1999
2001
2004
2012
2019
2021
K0: Strange particles
CP violation in kaon mixing
Cronin and Fitch
Phys.Rev.Lett. 13 (1964) 138
B0: Beauty particles
Time dependent CP violation
BaBar & Belle
Phys.Rev.Lett. 87 (2001) 091801/2
B0s: Beauty particles
Time dependent CP violation
LHCb
JHEP 03 (2021) 075