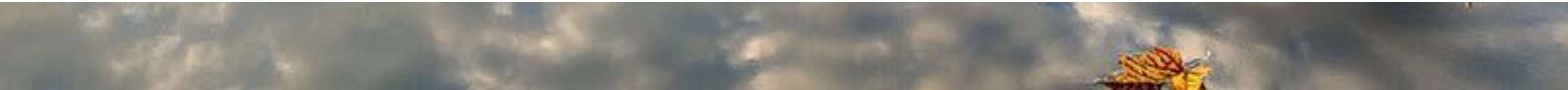
FLAVOUR PHYSICS IN THE LHC ERA

Alexander Lenz **Pheno 2017** 8.5.2017



INTRODUCTION

There are (at least) six kinds (=**flavours**) of quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \begin{pmatrix} q = +2/3 \\ q = -1/3 \end{pmatrix}$$

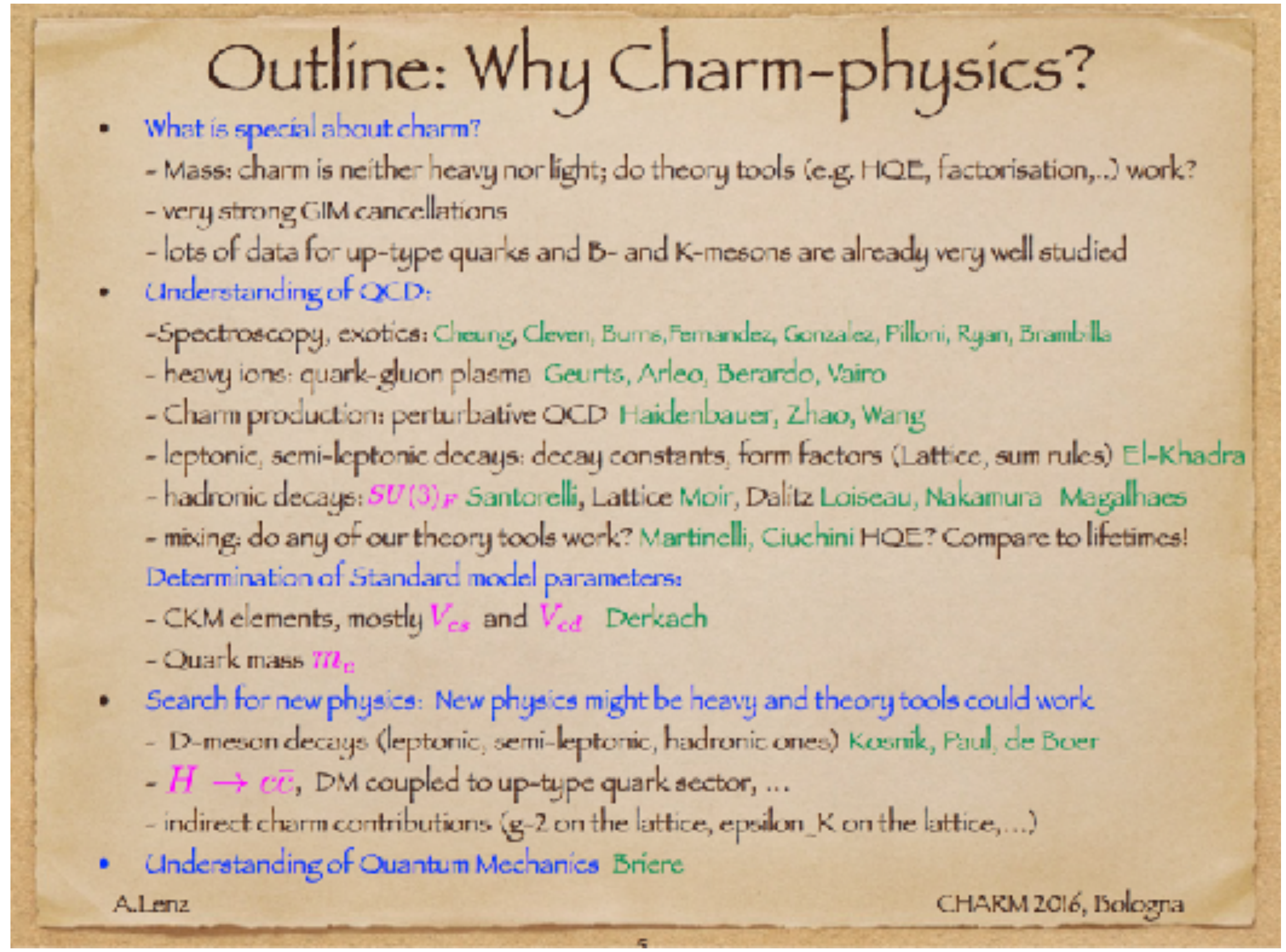
- Proton p = $|uud\rangle$
- **(Heavy) Flavour Physics** describes hadrons with a charm- or a bottom-quark

	$D^0 = (\bar{u}c)$	$D^+ = (\bar{d}c)$	$D_s^+ = (\bar{s}c)$	$\Lambda_c = (udc)$
Mass (GeV)	1.86486	1.86962	1.96850	2.28646
Lifetime (ps)	0.4101	1.040	0.500	0.200

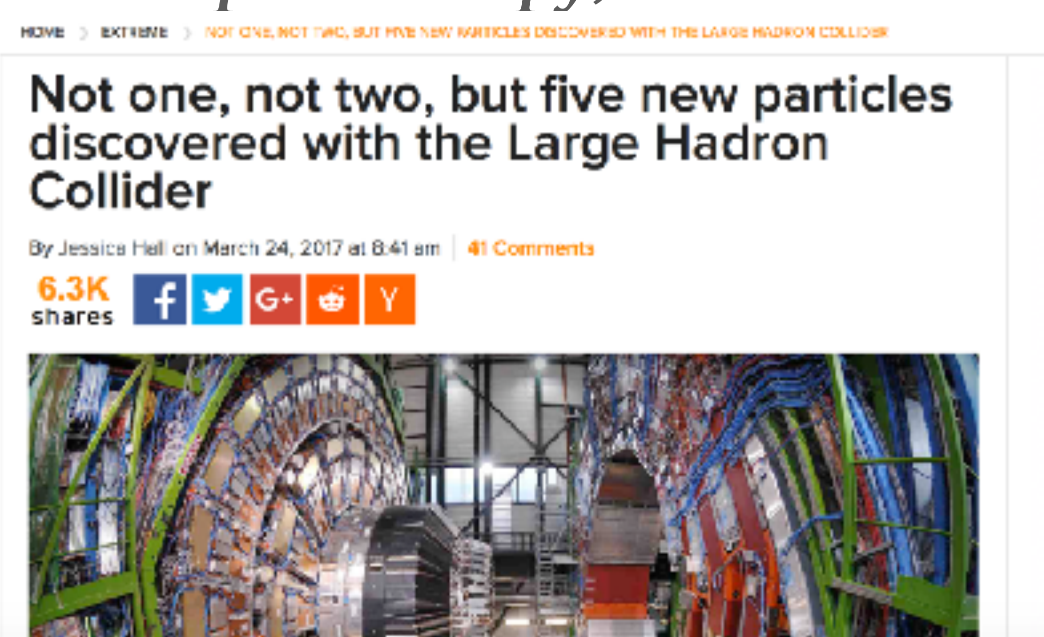
	$B_d = (\bar{b}d)$	$B^+ = (\bar{b}u)$	$B_s = (\bar{b}s)$	$B_c^+ = (\bar{b}c)$	$\Lambda_b = (udb)$
Mass (GeV)	5.27958	5.27926	5.3667	6.2745	5.6194
Lifetime(ps)	1.519	1.638	1.512	0.500	1.451

NOT COVERED

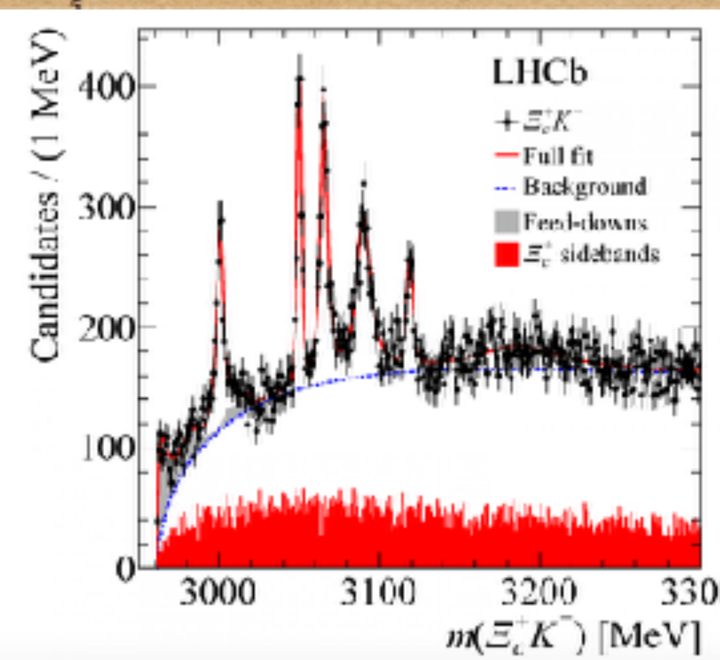
- *Charm Physics*



- *Spectroscopy, Production*



talks by Grimmer and Hiller Blin



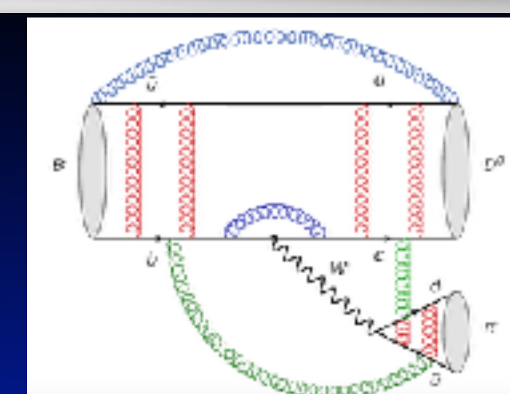
MOTIVATION FOR FLAVOUR PHYSICS

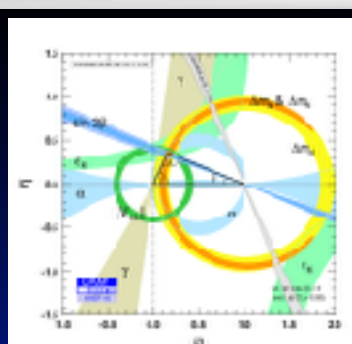
Baryon Asymmetry in the Universe:
A violation of the CP symmetry - which causes matter and anti-matter to evolve differently with time - seems to be necessary to explain the existence of matter in the Universe.
CP violation has so far only been found in hadron decays, which are experimentally investigated at LHCb and NA62 (CERN), SuperBelle (Japan),…

Indirect Search for BSM Physics:
To find hints for Physics beyond the Standard Model we can either use brute force (= higher energies) or more subtle strategies like high precision measurements.
New contributions to an observable f are identified via:

$$f^{\mathrm{SM}} + f^{\mathrm{NP}} = f^{\mathrm{Exp}}$$

Understanding QCD:
Hadron decays are strongly affected by QCD (strong interactions) effects, which tend to overshadow the interesting fundamental decay dynamics. Theory tools like effective theories, Heavy Quark Expansion, HQET, SCET ,…enable a control over QCD-effects and they are used in other fields like Collider Physics, Higgs Physics, DM searches…

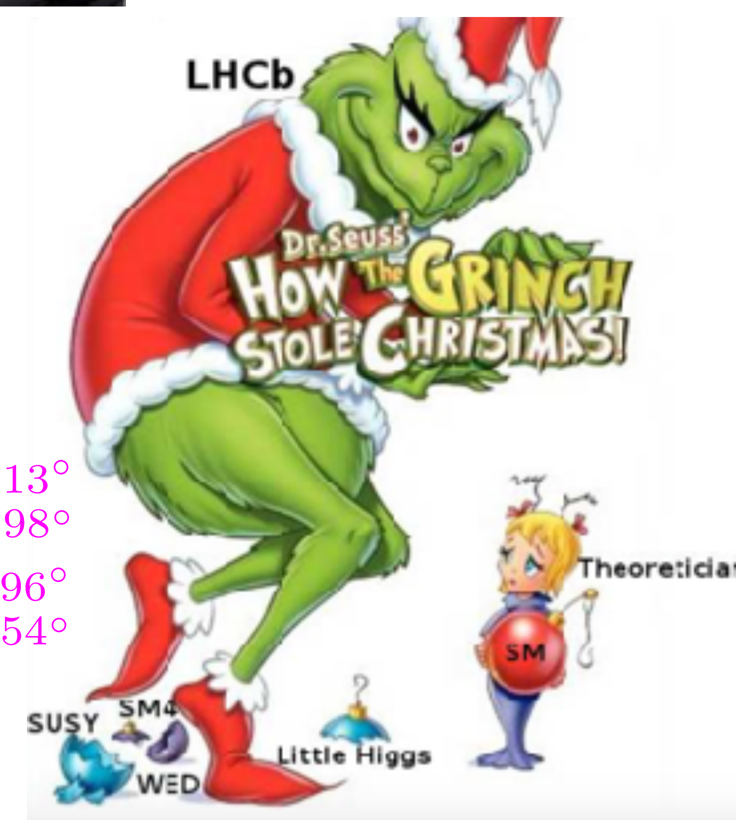




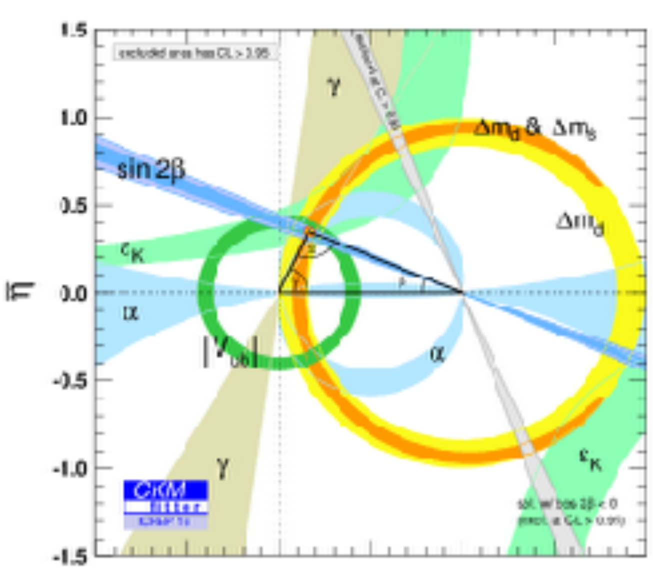
Standard Model parameters:
Hadron decays depend strongly on Standard Model parameters like quark masses and CKM couplings (which are the only known source of CP violation in the SM). A precise knowledge of these parameters is needed for all branches of particle physics.

STATUS OF QUO I: THE SM RULES

- **Huge** experimental progress: B-factories, Tevatron and LHC
- **LHCb**: 462 papers
  20689 citations
  till 2016 5fb-1
  see/saw **Uli Uwer**
  Soeren Prell



- **Message 1:** SM and CKM work perfectly



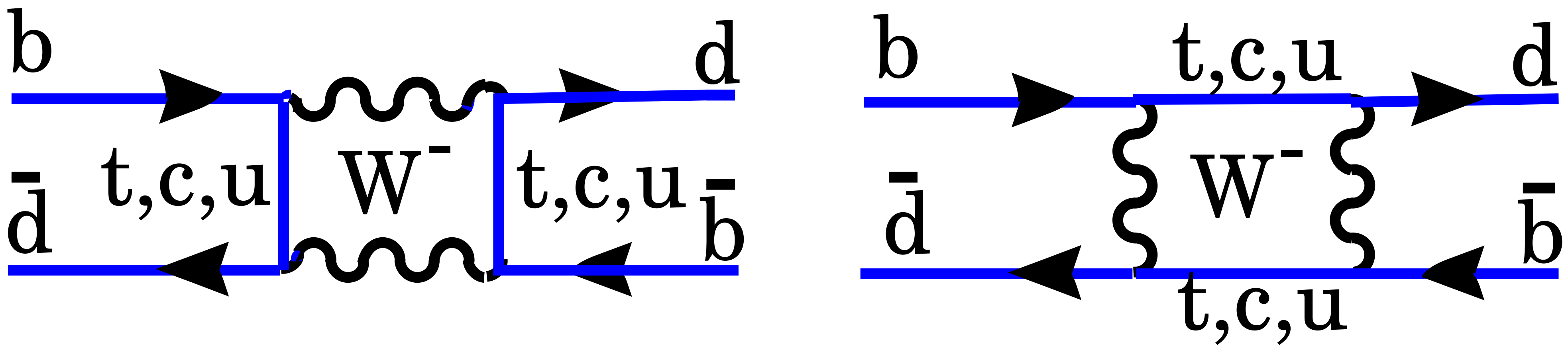
$$\beta^{\mathrm{HFAG}} = 21.9^\circ \pm 0.7^\circ \quad \text{vs.} \quad \beta^{\mathrm{CKMfitter}} = 23.74^\circ{}^{+1.13^\circ}_{-0.98^\circ}$$

$$\gamma^{\mathrm{HFAG}} = 71.3^\circ{}^{+5.7^\circ}_{-6.1^\circ} \quad \text{vs.} \quad \gamma^{\mathrm{CKMfitter}} = 65.33^\circ{}^{+0.96^\circ}_{-2.54^\circ}$$

similar results from UTfit; Eigen et al.; Laiho et al

STATUS OF QUO I: THE SM RULES

➤ **Message 2:** Many times: $\delta^{\text{Exp.}} < \delta^{\text{Theory}}$ e.g. B-mixing



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

- **Mass difference:** $\Delta M := M_H - M_L \approx 2|M_{12}|$ **(off-shell)**
  $|M_{12}|$: heavy internal particles: t, SUSY, ...

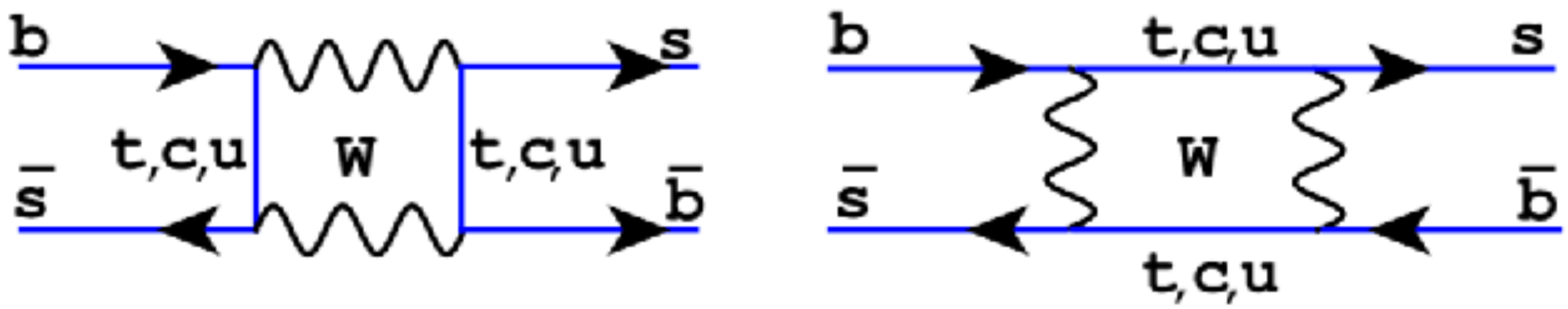
- **Decay rate difference:** $\Delta\Gamma := \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi$ **(on-shell)**
  $|\Gamma_{12}|$: light internal particles: u, c, ... (almost) no NP!!!

- **Flavor specific/semi-leptonic CP asymmetries:** e.g. $B_q \to Xl\nu$ (*semi-leptonic*)

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

STATUS OF QUO I: THE SM RULES

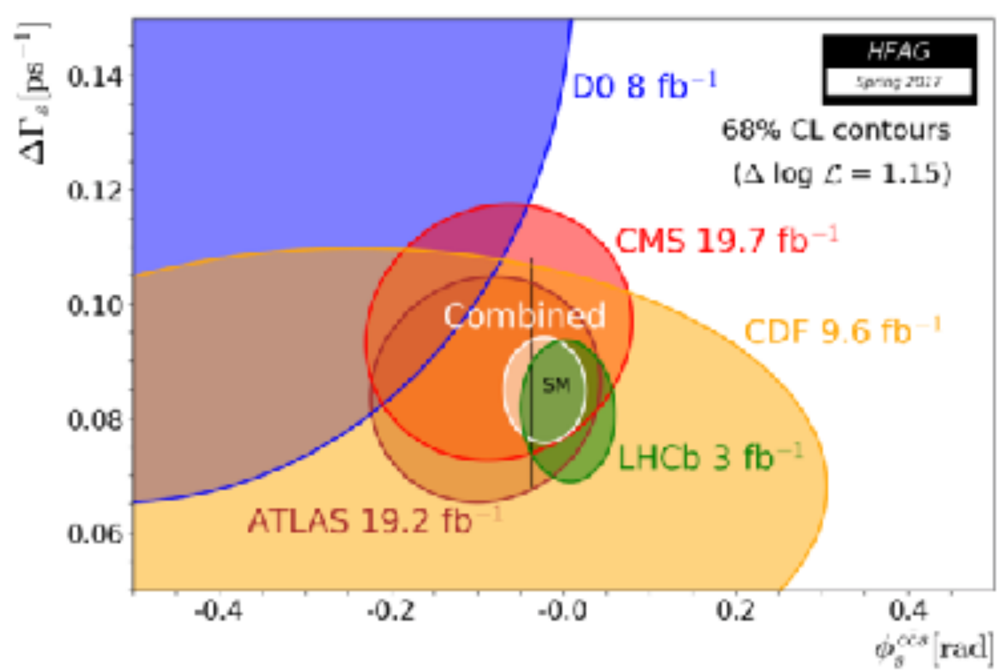
➤ **Message 2:** Many times: $\delta^{\text{Exp.}} < \delta^{\text{Theory}}$ e.g. B-mixing



$$\Delta M_s = 2|M_{12}^s|\,, \qquad \Delta\Gamma_s = 2|\Gamma_{12}^s|\cos\phi_{12}^s\,, \qquad a_{sl}^s = \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right|\sin\phi_{12}^s$$

Observable	SM	Experiment
ΔM_s	$(18.3 \pm 2.7)\ \text{ps}^{-1}$	$(17.757 \pm 0.021)\ \text{ps}^{-1}$
$\Delta\Gamma_s$	$(0.088 \pm 0.020)\ \text{ps}^{-1}$	$(0.082 \pm 0.006)\ \text{ps}^{-1}$
a_{sl}^s	$(2.22 \pm 0.27) \cdot 10^{-5}$	$(-750 \pm 410) \cdot 10^{-5}$
$\Delta\Gamma_s/\Delta M_s$	$48.1\,(1 \pm 0.173) \cdot 10^{-4}$	$46.2\,(1 \pm 0.073) \cdot 10^{-4}$

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



Preliminary - Moriond 2017
Tim Gershon

STATUS OF QUO I: THE SM RULES

➤ Message 3: Higher precision in theory needed

$\Delta\Gamma_s^{SM}$	This work
Central value	0.088 ps^{-1}
$\delta(B_{\tilde{R}_2})$	14.8%
$\delta(f_{B_s}\sqrt{B})$	13.9%
$\delta(\mu)$	8.4%
$\delta(V_{cb})$	4.9%
$\delta(\tilde{B}_S)$	2.1%
$\delta(B_{R_0})$	2.1%
$\delta(\bar{z})$	1.1%
$\delta(m_b)$	0.8%
$\delta(B_{\tilde{R}_1})$	0.7%
$\delta(B_{\tilde{R}_3})$	0.6%
$\delta(B_{R_1})$	0.5%
$\delta(B_{R_3})$	0.2%
$\delta(m_s)$	0.1%
$\delta(\gamma)$	0.1%
$\delta(\alpha_s)$	0.1%
$\delta(\|V_{ub}/V_{cb}\|)$	0.1%
$\delta(\bar{m}_t(\bar{m}_t))$	0.0%
$\sum\delta$	22.8%

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

- **Dim 7 has never been done**

  -**Wingate** works on lattice

  -**Rauh, Kirk, AL** with QCD sum rules

$$\langle R_2\rangle = -\frac{2}{3}\left[\frac{M_{B_s}^2}{m_b^{\text{pow}2}} - 1\right] M_{B_s}^2 f_{B_s}^2 B_{R_2}, \qquad R_2 = \frac{1}{m_b^2}\, \bar{s}_\alpha \overleftarrow{D}_\rho \gamma^\mu (1-\gamma_5) D^\rho b_\alpha\, \bar{s}_\beta \gamma_\mu (1-\gamma_5) b_\beta$$

- **Dim 6 is done on the lattice** - newest result:

  B(s)-mixing matrix elements from lattice QCD for the Standard Model and beyond
  Fermilab Lattice and MILC Collaborations
  Phys.Rev. D93 (2016) no.11, 113016, arXiv:1602.03560 [hep-lat]

$$\langle Q\rangle \equiv \langle \bar{B}_s^0|Q|B_s^0\rangle = \tfrac{8}{3} M_{B_s^0}^2 f_{B_s}^2 B(\mu) \qquad Q = \bar{s}^\alpha \gamma_\mu (1-\gamma_5) b^\alpha \times \bar{s}^\beta \gamma^\mu (1-\gamma_5) b^\beta$$

  Also QCD sum rules: **B-mixing at NLO**
  Grozin, Klein, Mannel, Pivovarov
  Phys.Rev. D94 (2016) no.3, 034024, arXiv:1606.06054 [hep-ph]

  indicates a small tension with experiment

- **First steps in NNLO-QCD**

  The phase space analysis for 3 and 4 massive particles in final states
  Asatrian, Hovhannisyan, Yeghiazaryan
  Phys.Rev. D86 (2012) 114023, arXiv:1210.7939 [hep-ph]

STATUS OF QUO I: THE SM RULES

High experimental precision requires to think again:

- **Message 4: Standard assumptions/textbook wisdom might have to be re-considered**
  - How large are penguins?   How well does SU(3)_F work?
    e.g. Frings, Nierste, Wiebusch 2016,...
  - How large can quark hadron duality violation be?
  - How well does QCD-factorisation work?
    e.g. Bobeth, Gorbahn, Vickers 2014; Bell 2015;...
  - How large can BSM effects be in tree-level decays?
  - ...

- **Message 5: SM/CKM dominance gives bounds on BSM models**

Meson mixing:

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti} V_{tj}^*\rvert$	tree level	17	19
(CKM-like)	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$	tree level	2×10^3	5×10^2
(no hierarchy)	one loop	2×10^2	40

e.g.Charles,Descotes-Genon,Ligeti,Monteil,Papucciand,Trabelsi

Phys.Rev.D89,no. 3, 033016 (2014) [arXiv:1309.2293].

TEST OF UNDERLYING THEORY ASSUMPTIONS: DUALITY

Basic idea: Sum overall hadrons = quark level

Our definition: duality violation is deviation from HQE

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \frac{\Lambda^4}{m_b^4}\Gamma_4 + \dots$$

Actual expansion parameter is momentum release $\frac{\Lambda}{M_i^2 - M_f^2}$

Taylor expansion of exp[-1/x] in x does give zero

Best candidate: $b \to c\bar{c}s$

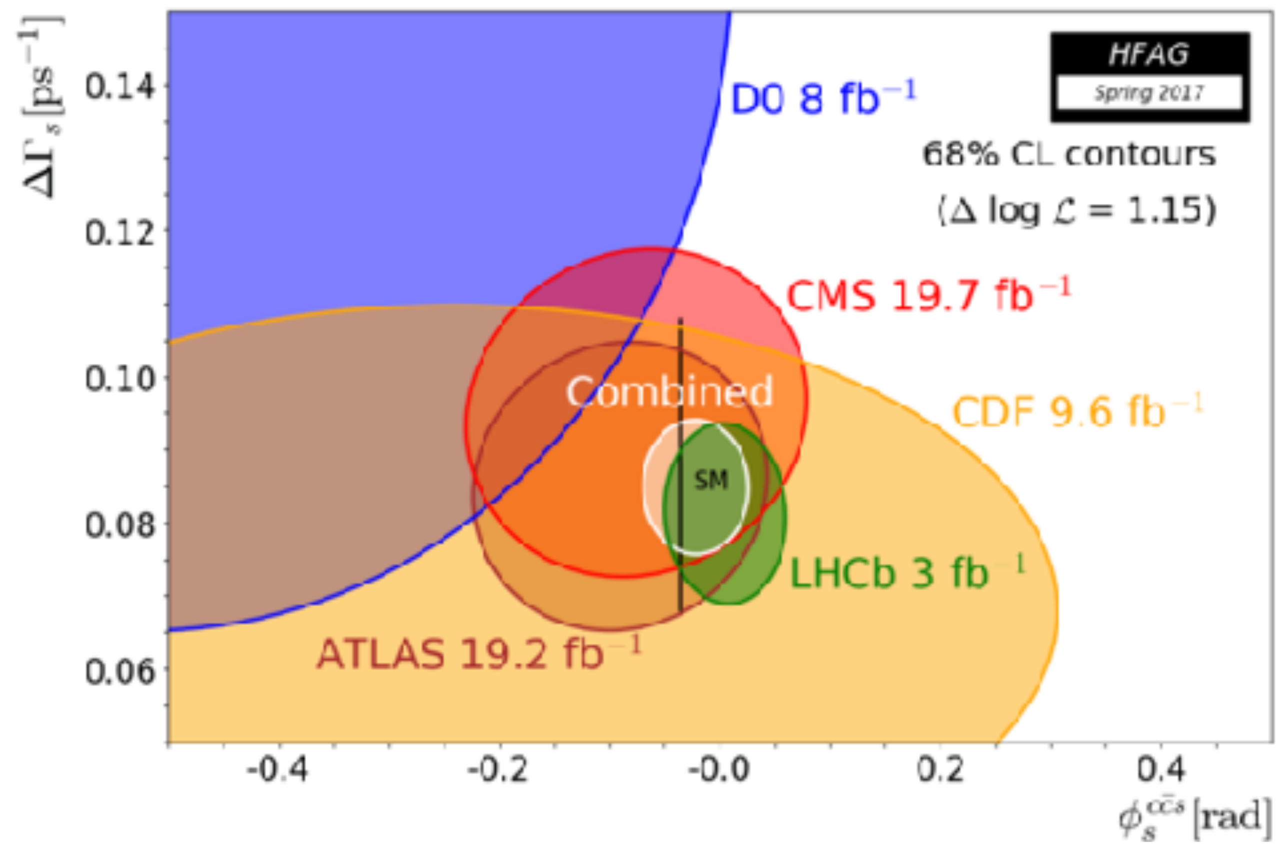
- Many historic hints for possible duality violation: **missing charm puzzle, Λ_b-lifetime, dimuon asymmetry,…**

QUARK HADRON DUALITY VIOLATION

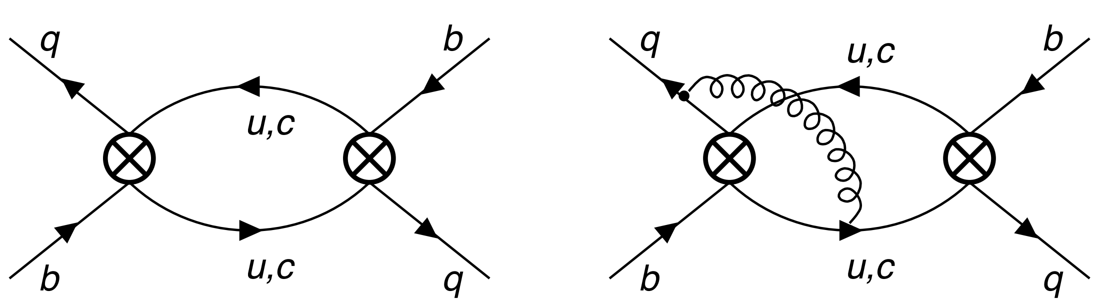
- Since Moriond 2012:

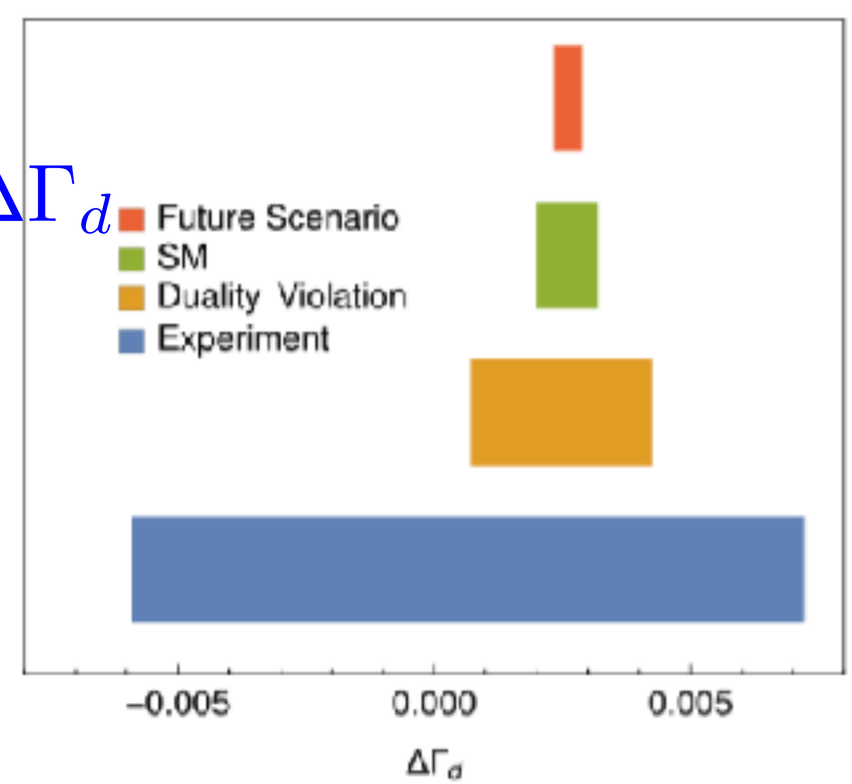
size of duality violations is severely constrained by perfect agreement of experiment and theory for

$$\frac{\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\mathrm{SM}}}{\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\mathrm{Exp}}} = 0.99 \pm 0.20$$



- The same diagrams contribute also to a_{sl}^q and $\Delta\Gamma_d$



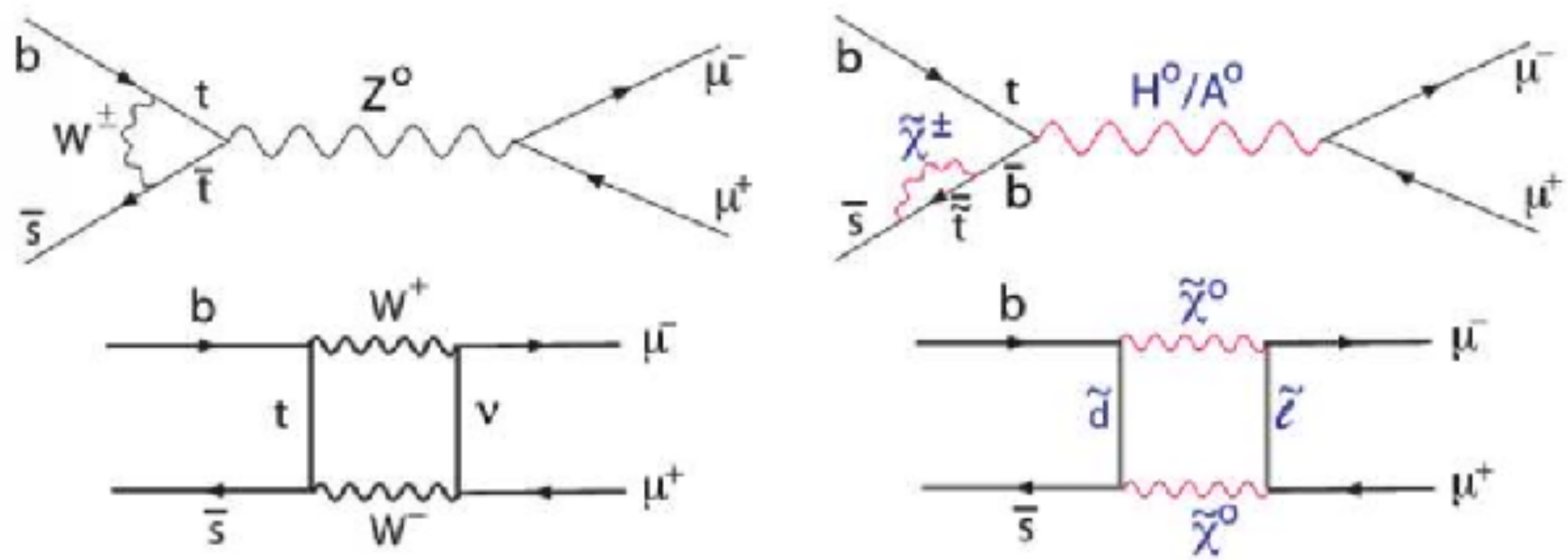


On the ultimate precision of meson mixing observables
Thomas Jubb, Matthew Kirk, Alexander Lenz, Gilberto Tetlalmatzi-Xolocotzi
Published in Nucl.Phys. B915 (2017) 431-453

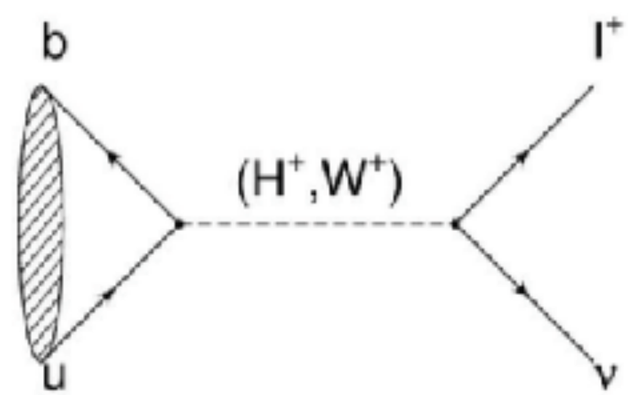
STATUS QUO II: ANOMALIES $2\sigma - 7\sigma$

MOTIVATION FOR BSM SEARCHES WITH FLAVOUR PHYSICS

- **CP violation** till now only found in quark flavour physics
- **Theoretically clean:** $\alpha_s(m_b) \approx 0.2 \approx \Lambda/m_b$
- many processes strongly suppressed in the SM due to quantum cor
  - $B_s \to \mu\mu$ or $b \to s\gamma$: **F**lavour **C**hanging **N**eutral **C**urrents



  - But also: $B \to \tau\nu$,...



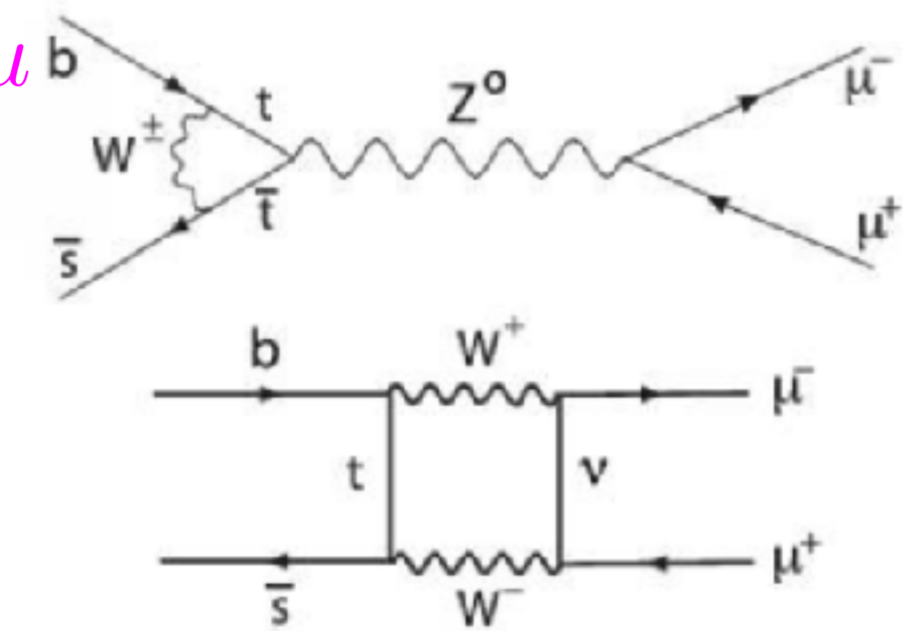
STATUS QUO II: ANOMALIES $2\sigma - 7\sigma$

➤ **Message 6:** There are interesting anomalies

	b	τ	μ
• 5-7: Proton Radius Puzzle — talk by Gil Paz	-	-	x
• 3-6: Semi-leptonic loop-level decays — talk by Prell	x	-	x
• 3.9: Semi-leptonic tree-level decays — talks by Soni, Umasankar, Westhoff	x	x	-
• 3.6: B-Meson mixing	x	-	-
• 3.5: Muon g-2 — Talk by Chris Polly, Christoph Lehner	-	-	x
• 2.8: K-mixing (huge lattice progress) — Talk by Christoph Lehner	-	-	-
• 2.6: 30 GeV resonance (ALEPH)	x	-	x
• 2.6: Zbb coupling (LEP FB asym)	x	-	-
• 2.x: Bs lifetime compare to Bd	x	-	-
• 2.x: K-pi puzzle	x	-	-

STATUS QUO II: ANOMALIES $2\sigma - 7\sigma$

Loop-level (semi) leptonic decays: $b \to s\mu\mu$



very simple hadronic structure

$B_{d,s} \to \mu\mu$: decay constant

$H_b \to H_q \mu\mu$: form factor

Can be determined with lattice, sum rules,…

Talk by Christoph Lehner

Observables:

- Branching ratios $Br(B_s \to \phi\mu\mu), Br(B \to K^*\mu\mu),$
- Angular observables, e.g. P_5' hadronic uncertainties cancel partially
- Ratios $R_K = \frac{Br(B^+ \to K^+\mu^-\mu^+)}{Br(B^+ \to K^+e^-e^+)}$ hadronic uncertainties cancel completely

STATUS QUO II: ANOMALIES $2\sigma - 7\sigma$

Loop-level (semi) leptonic decays: Pessimistic view

- Hadronic contributions might be larger than expected: entertaining fights in the community - **this does not hold for R_K**

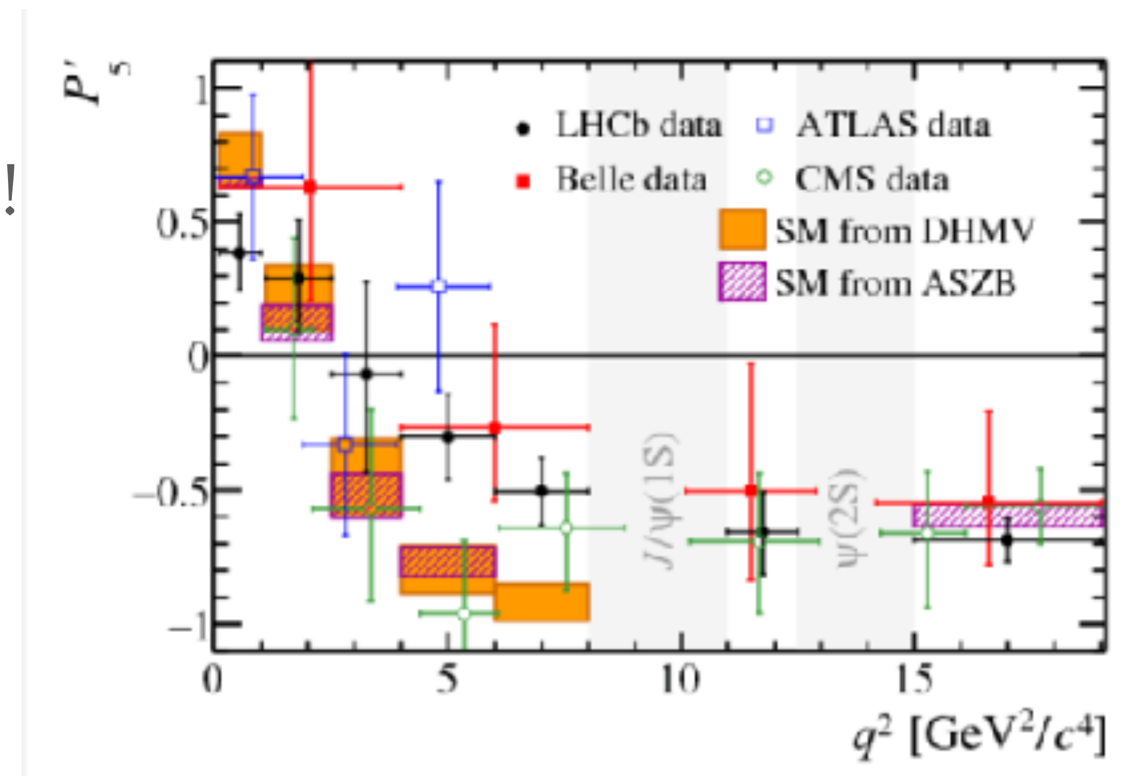
  see e.g. **Jaeger, Camalich; Rome group; Zwicky,…**

  e.g. Bordone, Isidori, Pattori 1605.07633

- New ATLAS and CMS results are closer to the SM but are consistent with LHCb **talk by Prell**

- Individual observables do not exceed 3 sigma!

2.9	P_5'	[4,6]
2.9	P_5'	[6,8]
2.6	R_K	
2.6	R_{K^*}	[1.1,6]
2.3	R_{K^*}	[0.045,1.1]
2.2	$Br(B_s \to \phi\mu\mu)$	[2,5]
2.2	$Br(B_s \to \phi\mu\mu)$	[5,8]



Patterns of NP in b->sll transitions in the light of recent data
Capdevilla, Crivellin, Descotes-Genon, Matias, Virto
1704.05340

STATUS QUO II: ANOMALIES $2\sigma - 7\sigma$

Loop-level (semi) leptonic decays: Optimistic view

all can be fitted in very simple scenario

$$Q_{9V} = \frac{\alpha_e}{4\pi}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{l}\gamma^\mu l\right)$$
$$Q_{10A} = \frac{\alpha_e}{4\pi}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{l}\gamma^\mu\gamma^5 l\right)$$

e.g. just modify the Wilson coefficient C9!

$3\,\sigma$ 1704.05447

Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli

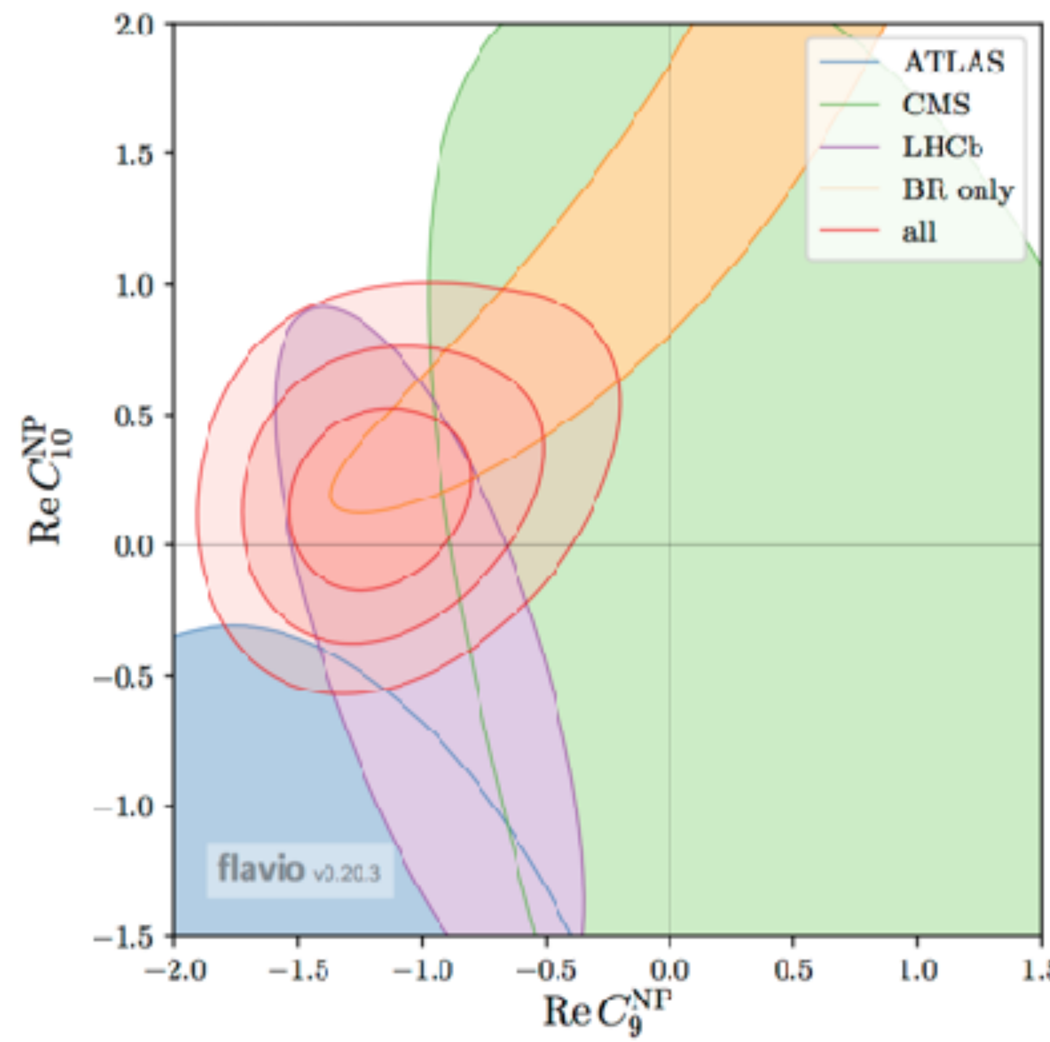
On Flavourful Easter eggs for NP hunger and LFU violation

.... (see next page)

5.7σ 1704.05340

Capdevilla, Cvrivellin, Descotes-Genon, Matias, Virto

Patterns of NP in b to all transitions in the light of recent data



arXiv:1703.09189 [pdf, other]

Status of the $B \to K^*\mu^+\mu^-$ anomaly after Moriond 2017

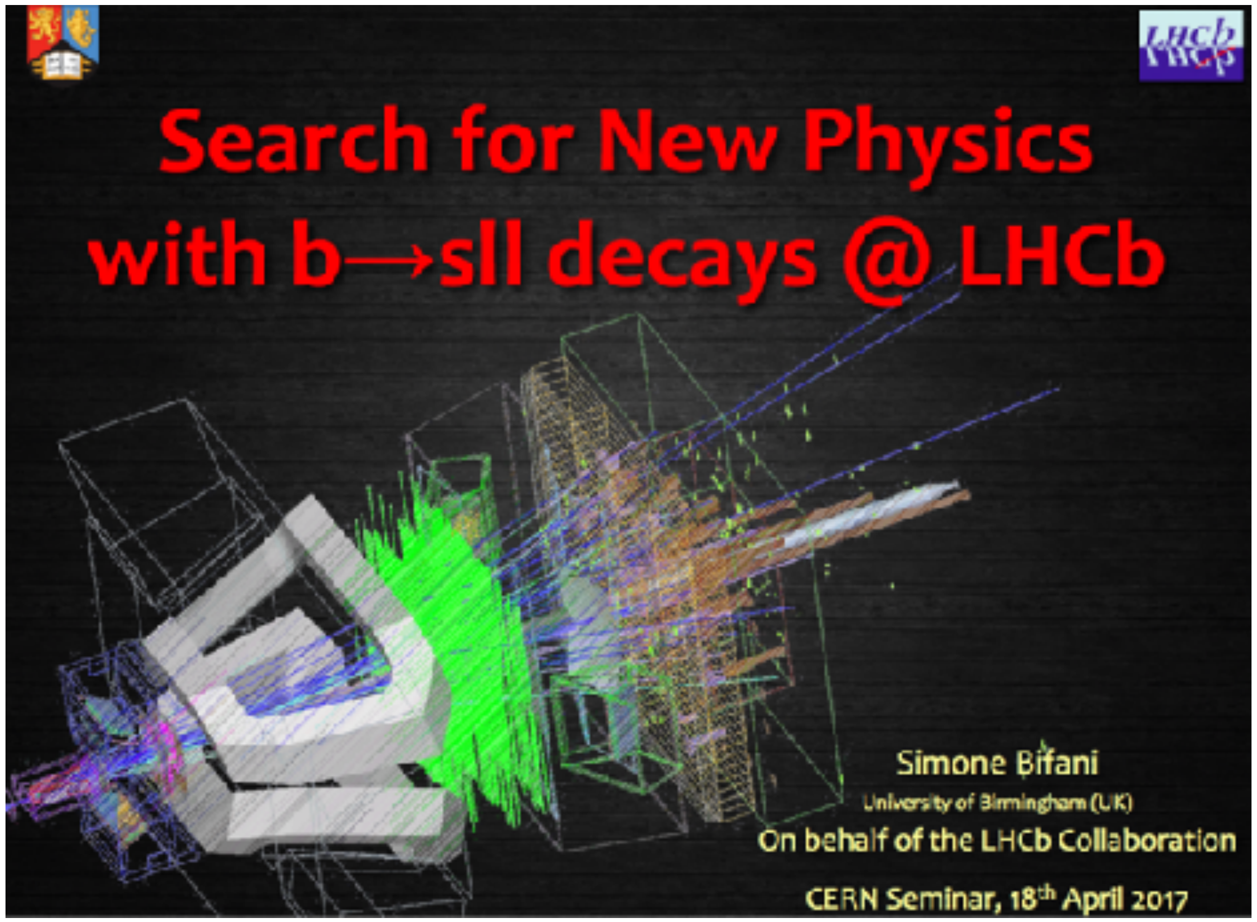
Wolfgang Altmannshofer, Christoph Niehoff, Peter Stangl, David M. Straub

Instant workshop on B meson anomalies

17 May 2017, 09:00 → 19 May 2017, 15:30 Europe/Zurich

4-3-006 - TH Conference Room (CERN)

Description In light of recent anomalies in B physics there is an increased interest in the theory community on its implications. As a quick response we are organizing an 'Instant workshop on B meson anomalies' at CERN from May 17-May 19 2017.



10:00 → 11:45 R_K(*): Experimental status and SM predictions

- 10:00 **Experimental status of R_K* and siblings** — Speaker: Marie Helene Schune (Universite de Paris-Sud 11 (FR))
- 10:30 **R_K: Quo vadis?** — Speaker: Mitesh Patel (Imperial College (GB))
- 10:55 **Overview of SM predictions** — Speaker: Sebastian Jager
- 11:25 **The role of EM corrections** — Speaker: Marzia Bordone (University of Zurich)

14:00 → 15:45 R_K(*): Fits and model building

- 14:00 **Angular analysis** — Speaker: Konstantinos Petridis (University of Bristol (GB))
- 14:30 **Global Fits and Global New Physics Patterns** — Speaker: Javier Virto
- 14:50 **What do we learn from fits**

10:00 → 12:00 R_K(*)

- 10:20 **RS and composites** — Speaker: Giuliano Panico
- 10:30 **Further thoughts on RS and composites** — Speaker: Mariano Quiros Carcelen
- 10:45 **Flavor models** — Speaker: Gino Isidori
- 11:15 **LightNP** — Speaker: Diptimoy Ghosh
- 11:45 **LFV and neutrinos** — Speaker: John Gargalionis

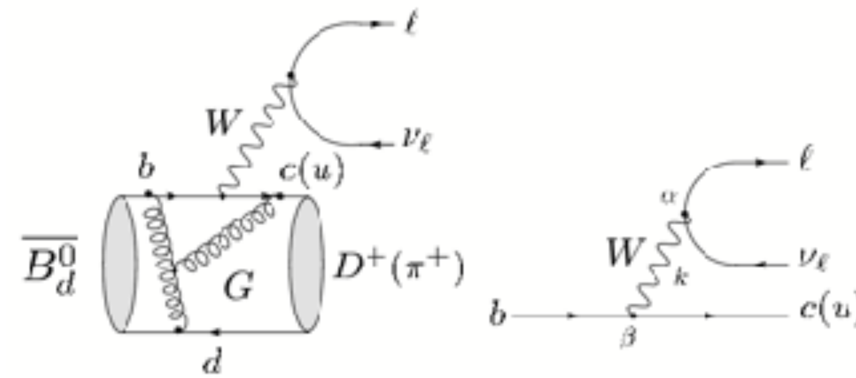
13:30 → 15:00 R_K(*)

- 13:30 **Theory prospects** — Speaker: Gudrun Hiller
- 14:20 **LHCb prospects** — Speaker: Ulrik Egede (Imperial College (GB))
- 14:30 **Belle2 prospects** — Speaker: Bostjan Golob

- *1704.05340 Capdevilla, Cvrivellin, Descotes-Genon, Matias, VirtoPatterns of NP in b to all transit*
- *1704.05435 Altmannshoher, Stange, Straub Interpreting hints for LEtpon Universality Violation*
- *1704.05438 D'Amico, Nardecchia, Panci, Sannino, Stremai, Torre, Urbano Flavour anomalies aft*
- *1704.05444 Hiller, Nisandzic RK and RK* beyond the SM*
- *1704.05446 Geng, Grinstein, Jaeger, Camalich, Ren, Shi Towards the discovery of new physics wit*
- *1704.05447 Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli On Flavourful Easter eggs f*
- *1704.05672 Celis, Fuentes-Martin, Vicente, Virto Gauge-invariant implications of the LHCb measu*
- *1704.05835 Becirevic, Sumensari A leptoquark model to accommodate RK and RK**
- *T1704.05849 Cai, Gargalionis, Schmidt, Volkas Reconsidering the One Leptoquark solution: flavou*
- *1704.06005 Kamenik, Soreq, Zupan Lepton Flavour Universality violation without new sources o*
- *1704.06188 Sala, Straub A new light particle in B decays*
- *1704.06200 Di Chiara, Fowlie, Fraser, Marzo, Marzola, Raidal, Christian Spethmann. Minimal fl*
- *1704.06240 Gosh Explaining RK and RK* anomalies*
- *1704.06659 Altmannshofer, Dev, Son I RD(*) anomaly: a possible hint for natural SUSY with R-*
- *1704.07397 Alok, Bhattacharya, Datta, Kumar, Kumar, LondON, New physics in b->s mu mu aft*
- *1704.07347 Alok, Sharma, Kumar, Kumar Lepton-Flavour non-universality in the B-sector: a glo*
- *1704.08158 Alonso, Cox, Han, Yamagida Anomaly-free local horizontal symmetry and anomaly-fu*
- *1704.08168 Wang, Zhao Implications of the RK and RK* anomalies*
- *1704.09015 Admir Greljo, David Marzocca High-pT dilepton tails and flavour physics*
- *1705.00915 Cesar Bonilla, Tanmoy Modak, Rahul Srivastava, Jose W. F. Valle U(1)B3−3Lμ gau*
- *1705.00929 Ferruccio Feruglio, Paride Paradisi, Andrea Pattori On the Importance of Elect*

STATUS QUO II: ANOMALIES $2\sigma - 7\sigma$

Tree-level semi leptonic decays



again simple hadronic structure

form factor: lattice, sum rules

3σ V_{ub}, V_{cb}: long standing discrepancy between exclusive and inclusive CKM determination

3.9σ $R_{D^{(*)}} = \frac{Br(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{Br(\bar{B} \to D^{(*)} l^- \bar{\nu}_l)}$ more recent problem

hadronic uncertainties **expected to cancel** in ratio to some extend

individually:

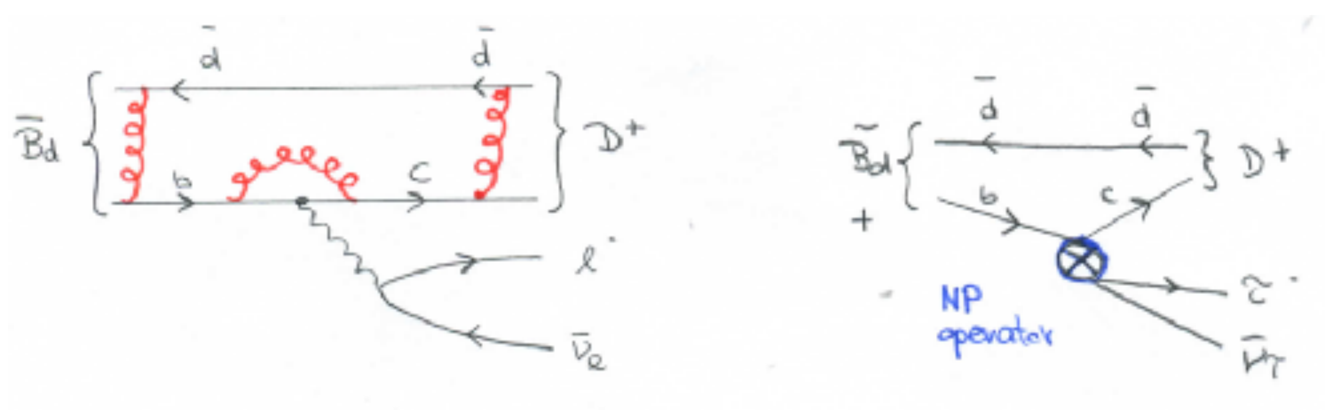
R_D :2.2σ R_{D^*} :3.4σ

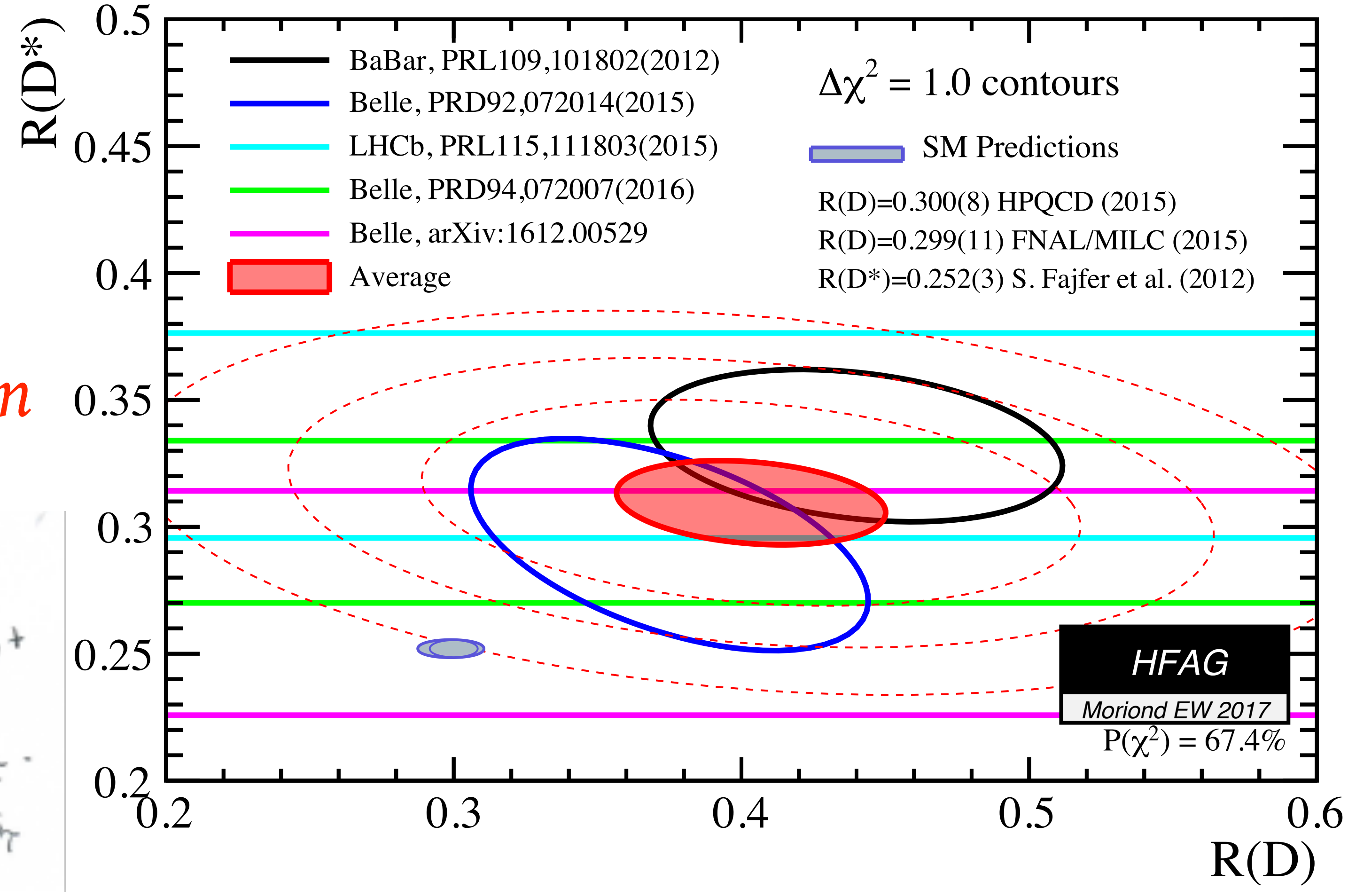
talks by Soni, Umasankar, Westhoff

STATUS QUO II: ANOMALIES $2\sigma - 7\sigma$

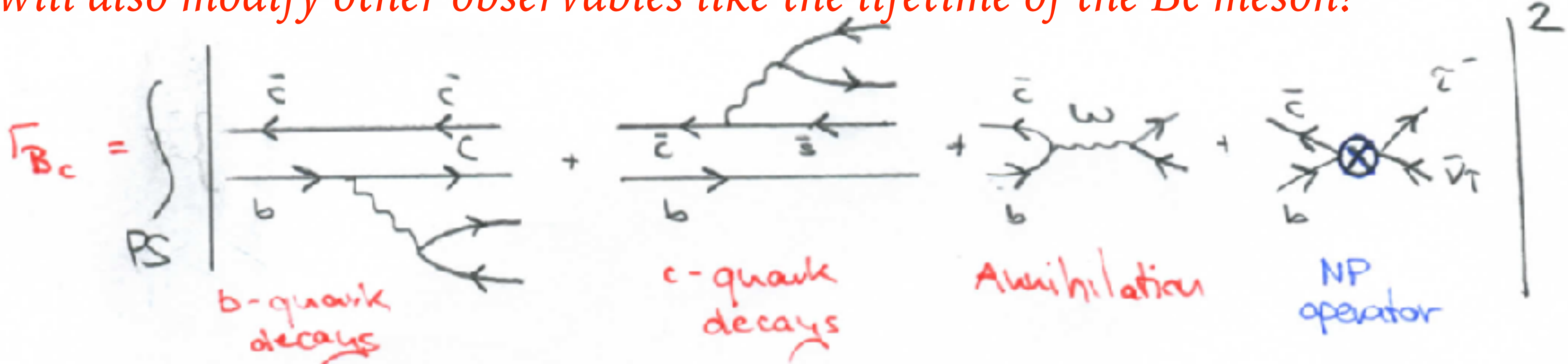
$$R_{D^{(*)}} = \frac{Br(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{Br(\bar{B} \to D^{(*)} l^- \bar{\nu}_l)}$$

Beware: *any new* $b \to c\tau\bar{\nu}_\tau$ *contribution*





will also modify other observables like the lifetime of the Bc meson!



e.g. Li, Yang, Zhang; Alonso, Grinstein, Camalich; Celis, Jung, Li, Pich

STATUS QUO II: ANOMALIES $2\sigma - 7\sigma$

B mixing

3.6 σ : D0 result $$A^{\mathrm{Di-muon}} = C_s a_{sl}^s + C_d a_{sl}^d + \frac{1}{2} C_\Delta \Delta\Gamma_d$$

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

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

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

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

seems to be the largest individual deviation

2 σ **: New lattice results** $$\Delta M_s = 2|M_{12}^s|\,, \quad \Delta\Gamma_s = 2|\Gamma_{12}^s| \cos\phi_{12}^s\,, \quad a_{sl}^s = \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| \sin\phi_{12}^s$$

Observable	SM – conservative	SM – aggressive	Experiment
ΔM_s	$(18.3 \pm 2.7)\ \mathrm{ps}^{-1}$	$(20.11 \pm 1.37)\ \mathrm{ps}^{-1}$	$(17.757 \pm 0.021)\ \mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$(0.088 \pm 0.020)\ \mathrm{ps}^{-1}$	$(0.098 \pm 0.014)\ \mathrm{ps}^{-1}$	$(0.082 \pm 0.006)\ \mathrm{ps}^{-1}$
a_{sl}^s	$(2.22 \pm 0.27) \cdot 10^{-5}$	$(2.27 \pm 0.25) \cdot 10^{-5}$	$(-7.5 \pm 4.1) \cdot 10^{-3}$

B(s)-mixing matrix elements from lattice QCD for the SM and beyond
Fermilab Lattice and MILC Collaborations
Phys.Rev. D93 (2016) no.11, 113016, arXiv:1602.03560 [hep-lat]

On the ultimate precision of meson mixing observables
Thomas Jubb, Matthew Kirk, AL, Gilberto Tetlalmatzi-Xolocotzi
Nucl.Phys. B915 (2017) 431-453

STATUS QUO II: ANOMALIES $2\sigma - 7\sigma$

List of models:

- ***Z' - new U(1) or SU(2)***
- ***Leptoquarks***
- *W'- new SU(2)*
- *Composite Models*
- *WED*
- *SUSY*
- *2HDM*
- ….
- ….

hundreds of papers…

"Qual der Wahl"

=

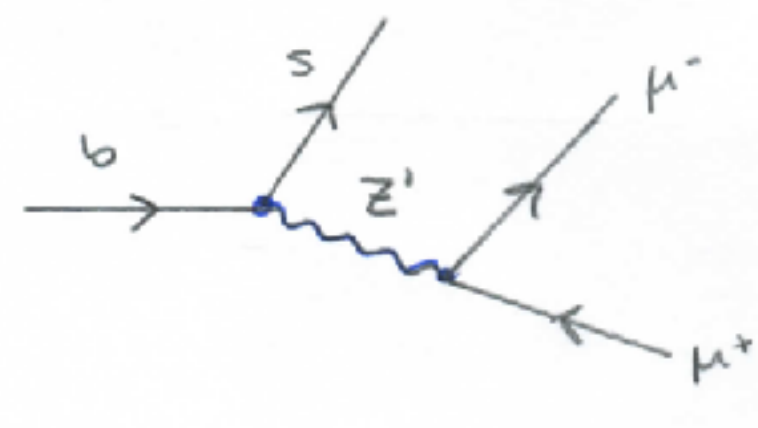
agony of choice

or

choice of agony?

STATUS QUO II: ANOMALIES 2 σ - 7 σ

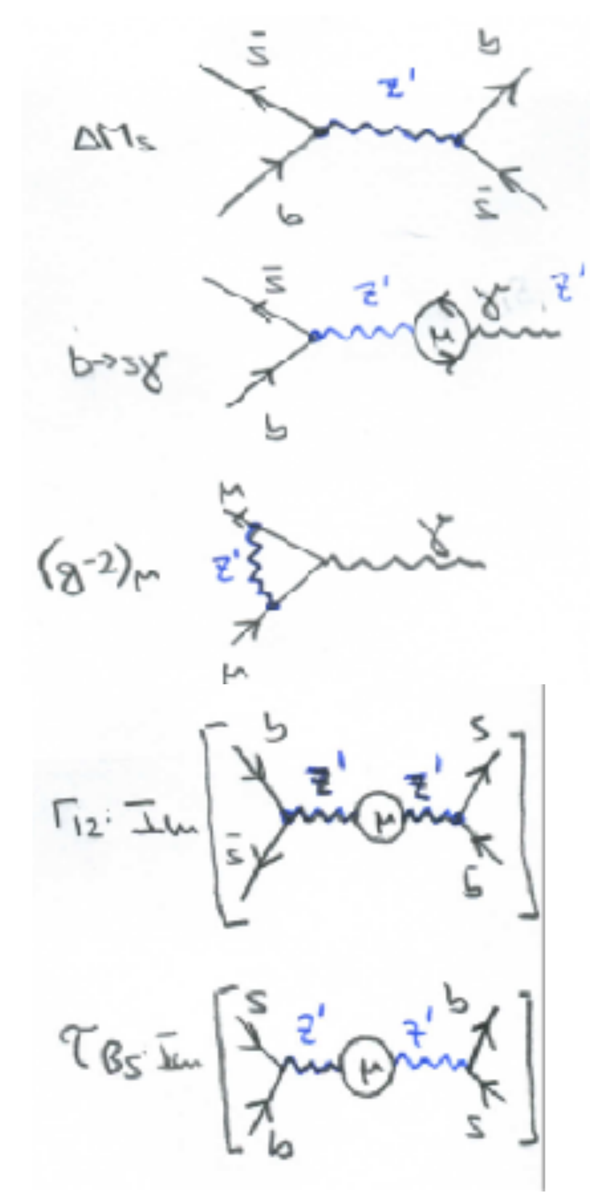
A popular BSM model for solving the anomalies related to loop-level (semi) leptonic decays are Z' models:



Such a new tree-level transition will also affect many other observables,

most notably **B-mixing at tree-level**,

but also many loop processes.



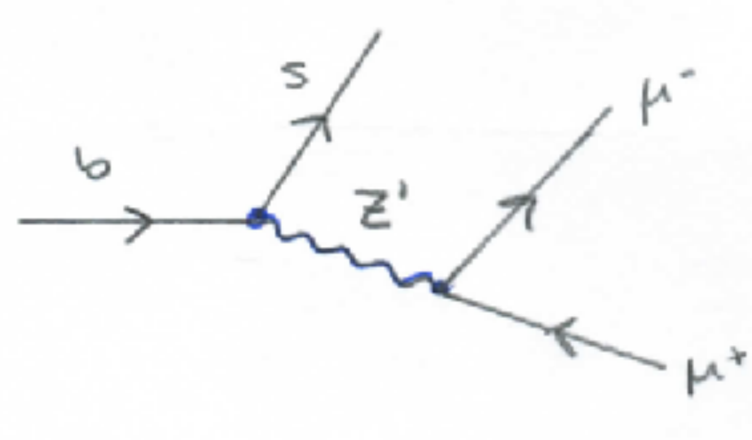
Make sure all relevant bounds are included, e.g. electro-weak precision bounds

1705.00929 Ferruccio Feruglio, Paride Paradisi, Andrea Pattori

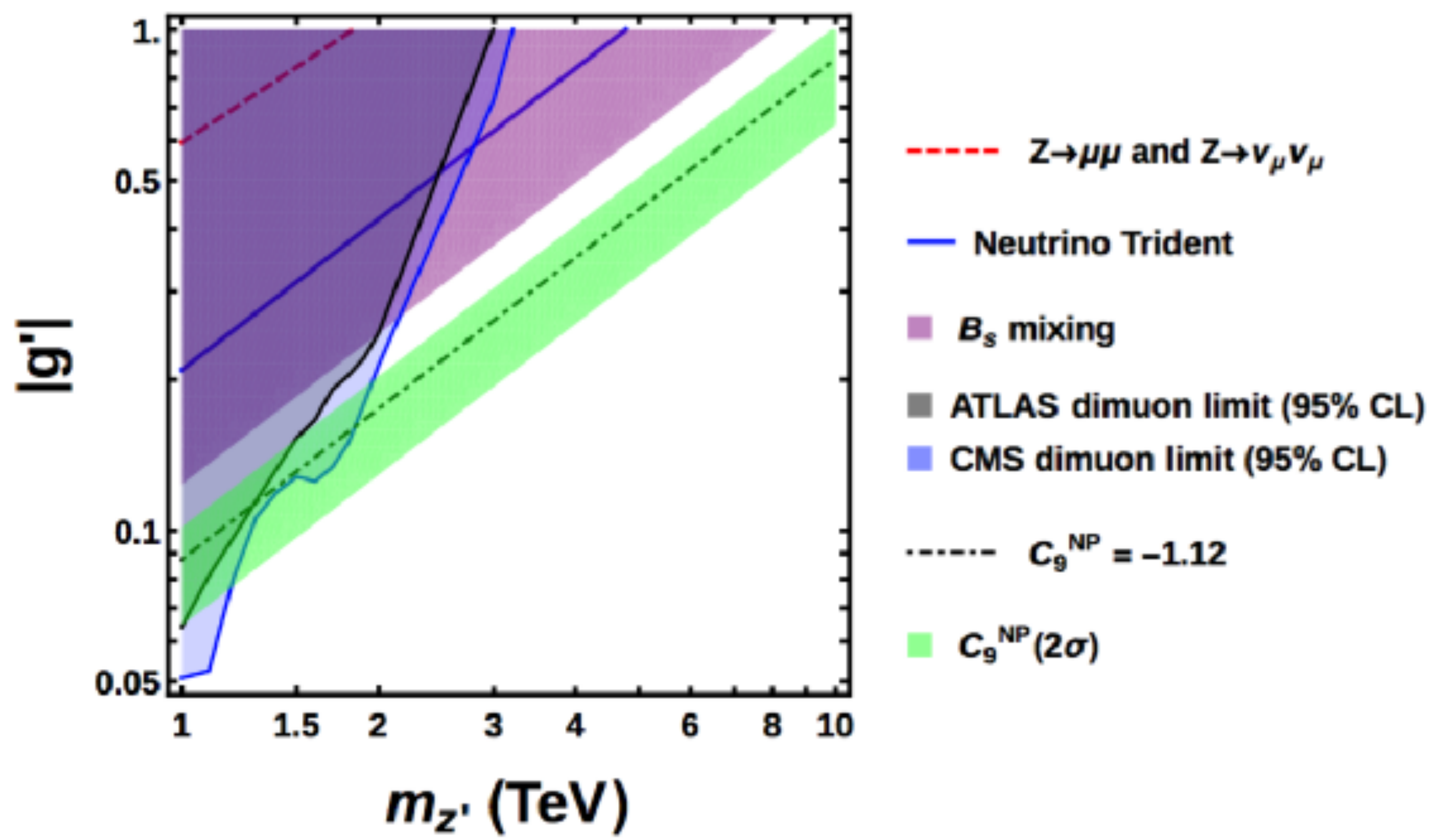
On the Importance of Electroweak Corrections for B Anomalies

STATUS QUO II: ANOMALIES $2\sigma - 7\sigma$

A popular BSM model for solving the anomalies related to loop-level (semi) leptonic decays are Z' models:



e.g.

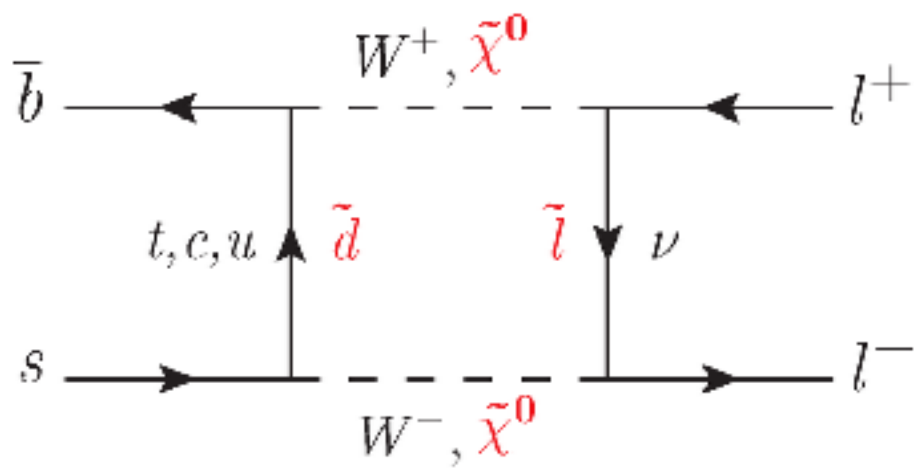


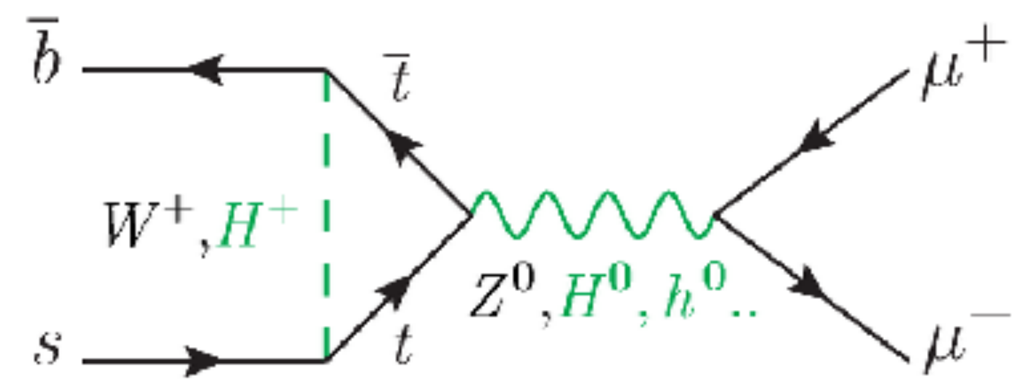
1705.00915 Bonilla, Modak, Srivastava, Valle

$U(1)_{B_3-3L_\mu}$ gauge symmetry as the simplest description of $b \to s$ anomalies

INDIRECT NP SEARCHES: NON-MAIN STREAM

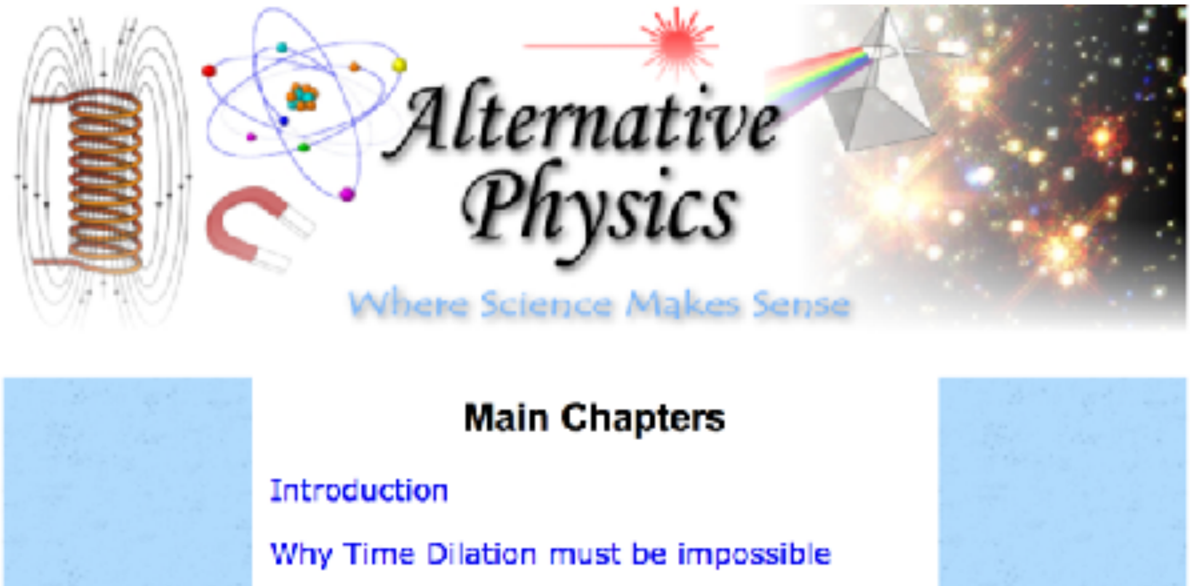
- Main stream: BSM effects hide in loop processes





- Non-main stream:
  Consider BSM effects in non-leptonic tree-level decays?
  - typically not considered, but: **Bauer, Dunn; hep-ph/1006.1629**
  as an explanation for the dimuon asymmetry
  - can clearly not be O(100%), but what about 20%?

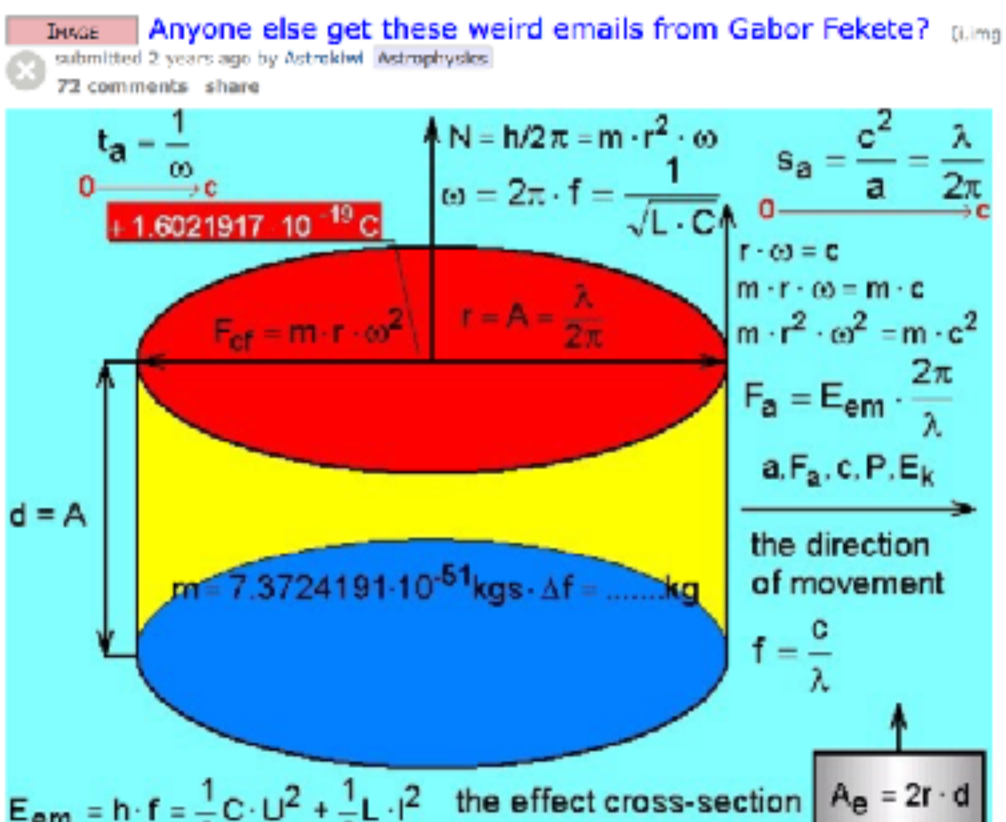
NP IN TREE-LEVEL DECAYS

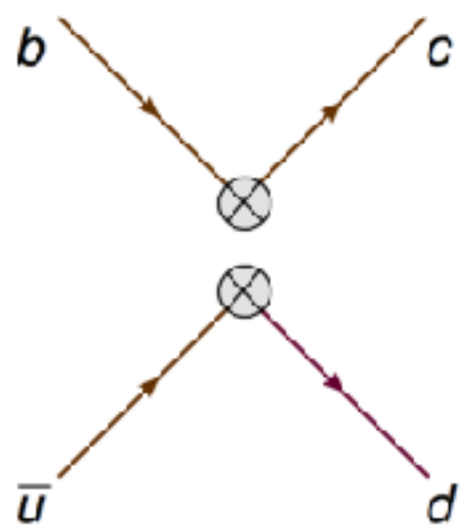


Do a systematic study of tree-level observables that are both well known in experiment and theory

$$C_{1,2}^{SM} \to C_{1,2}^{SM} + \Delta C_{1,2}$$

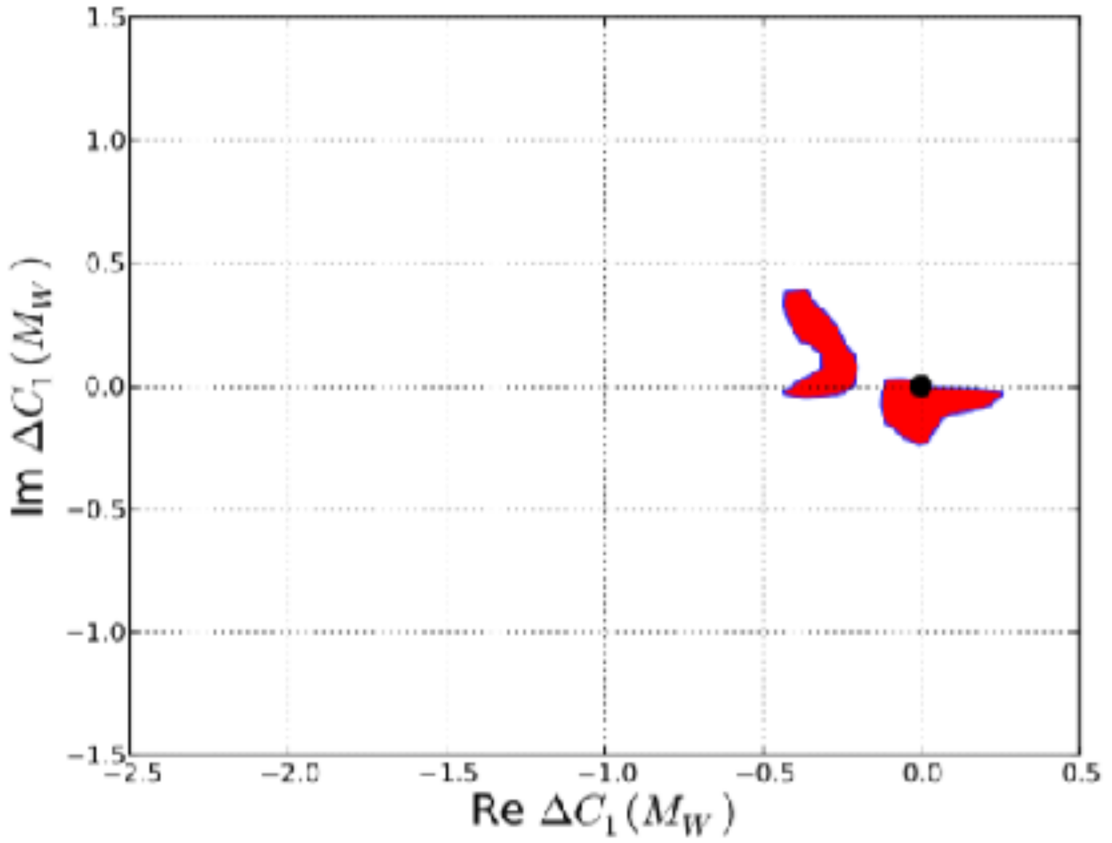
$$\hat{\mathcal{H}}_{eff} = \frac{V_{cb} V_{ud}^{*}}{\sqrt{2}} \left(C_1 \hat{Q}_1 + C_2 \hat{Q}_2 \right)$$

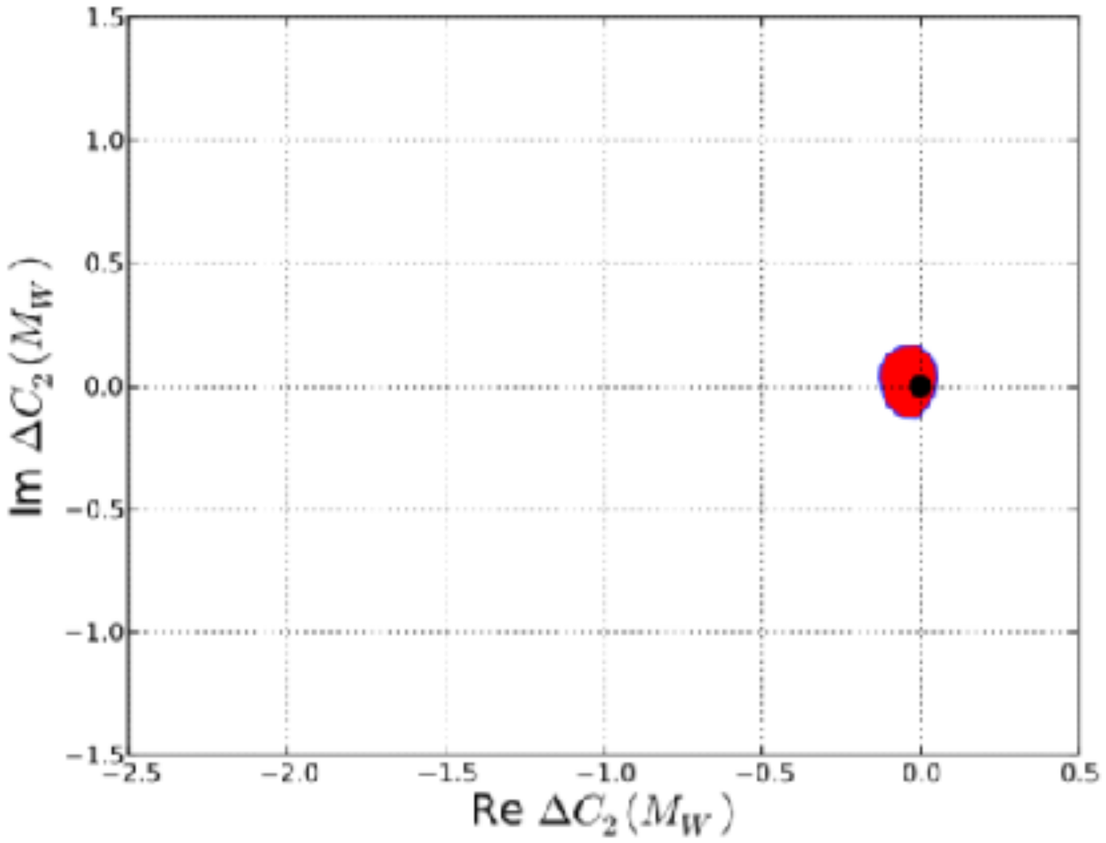




NP IN TREE-LEVEL DECAYS

Result:





What does this mean?

Is this an important effect?

NP IN TREE-LEVEL DECAYS

- Decay rate difference of neutral Bd mesons, $\Delta\Gamma_d$, can be enhanced by several 100%

  work triggered by D0 di-muon asymmetry - **Borissov**

  work triggered ATLAS measurement of $\Delta\Gamma_d$ - **Borissov**

On new physics in $\Delta\Gamma_d$
Bobeth, Haisch, Lenz, Pecjak, Tetlalmatzi-Xolocotzi
JHEP 1406 (2014) 040

- Extraction of CKM angle γ can be modified by several degrees

  SM precision: 1 ppm

  Experimental precision: now 6deg, future 1 deg

NP effects in tree-level decay and the precision of γ
Brod, Lenz, Tetlamatzi-Xolocotzi Alexander Lenz
Rev.Mod.Phys. 88 (2016) no.4,045002

- More profound analysis in progress **AL,Tetlalmatzi-Xolocotzi**

till now only SM Dirac structures

NP IN RARE B DECAYS AND MIXING

Is there a connection between mixing and rare decays?

Charming new physics in rare B-decays and mixing
Jaeger, Kirk, Lenz, Leslie
arXiv: 1701.09183

Consider NP in tree-level b -> ccs traditions with general Dirac structures

$$\mathcal{H}_{\rm eff}^{c\bar{c}} = \frac{4G_F}{\sqrt{2}} V_{cs}^* V_{cb} \sum_{i=1}^{10} (C_i^c Q_i^c + C_i^{c\prime} Q_i^{c\prime})$$

$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i), \qquad Q_2^c = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j),$$
$$Q_3^c = (\bar{c}_R^i b_L^j)(\bar{s}_L^j c_R^i), \qquad Q_4^c = (\bar{c}_R^i b_L^i)(\bar{s}_L^j c_R^j). \quad (2)$$

This affects rare decays and mixing/lifetimes:

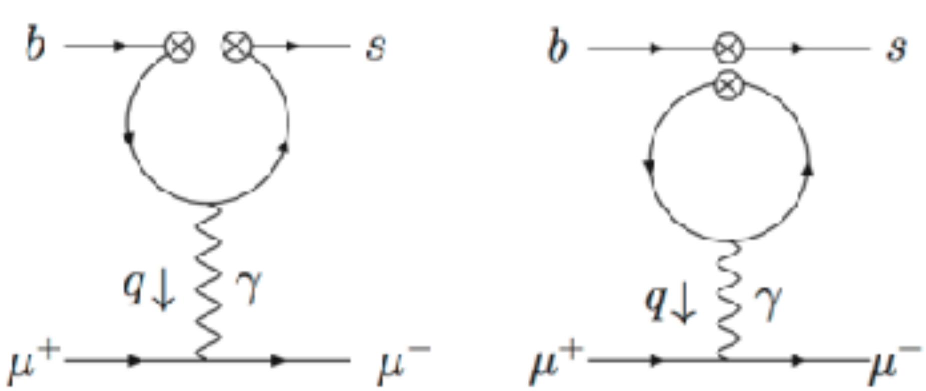


FIG. 1. Leading Feynman diagrams for CBSM contributions to rare and semileptonic decays. With our choice of Fierz-ordering, only the diagram on the left is relevant.

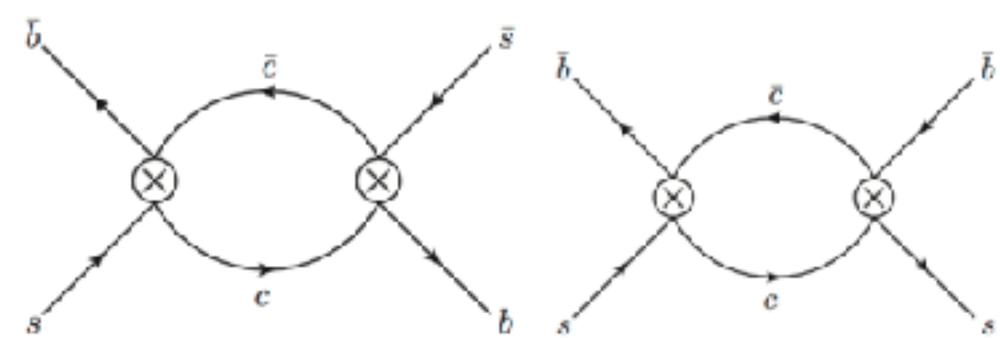
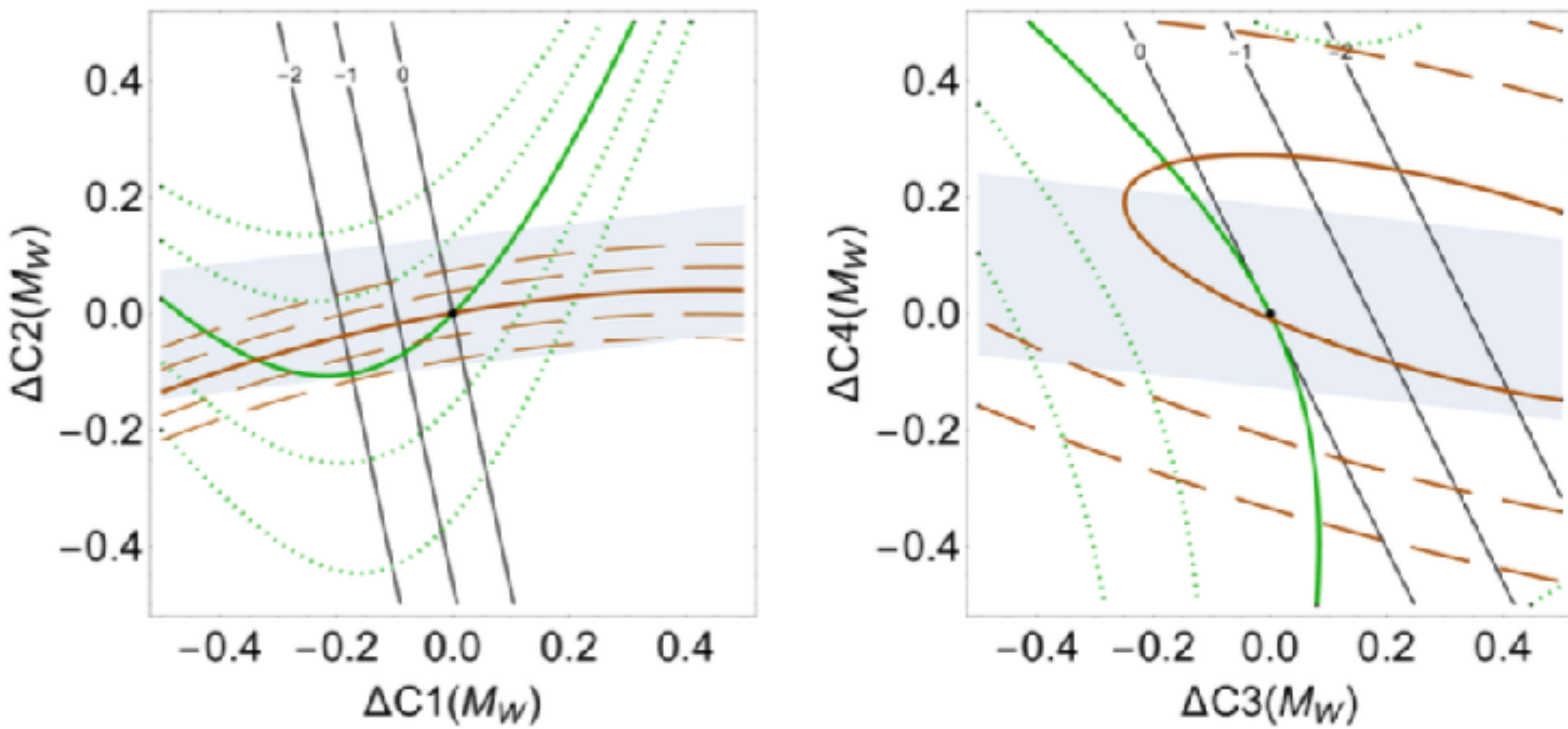


FIG. 2. Leading Feynman diagrams for CBSM contributions to the width difference $\Delta\Gamma_s$ (left) and the lifetime ratio $\tau(B_s)/\tau(B_d)$ (right).

NP IN RARE B DECAYS & MIXING

- Deviation in some rare B-decays can be explained without violating other bounds



- it is possible that NP in rare decays is q^2 dependent! (more profound study in progress: **Jaeger, Kirk, Lenz, Leslie**)
- **A UV complete model will typically produce loop-contributions to our anomalous observables (main-stream) but in general also new tree-level contributions (non main stream) - both have to be considered in the end!**

CONTENT

- Introduction - Motivation for Flavour Physics

- Message 1: SM and CKM work perfectly
- Message 2: Many times $\delta^{\text{Exp}} < \delta^{\text{Theory}}$
- Message 3: !!!Higher precision in theory needed!!!
- Message 4: !!!Standard assumptions might have to be reconsidered!!!
- Message 5: SM/CKM dominance gives important bounds on BSM models
- Message 6: There are very interesting anomalies
- Message 7: We are still waiting for a single 5 sigma deviation
- Message 8: All relevant observables have to be identified for BSM searches
- Message 9: Alternative paths for BSM searches can be interesting

END

NP IN RARE B DECAYS

C_7 and C_9 depend on different new physics contributions!

$$\Delta C_9^{\rm eff}(q^2) = \left(C_{1,2}^c - \frac{C_{3,4}^c}{2}\right) h - \frac{2}{9} C_{3,4}^c\,,$$

$$\Delta C_7^{\rm eff}(q^2) = \frac{m_c}{m_b}\left[\left(4C_{9,10}^c - C_{7,8}^c\right) y + \frac{4C_{5,6}^c - C_{7,8}^c}{6}\right]$$

with $C_{x,y}^c = 3\Delta C_x^c + \Delta C_y^c$ and the loop functions

New physics contributions to rare b decays are now q2 dependent!

$$h(q^2, m_c, \mu) = -\frac{4}{9}\left[\ln\frac{m_c^2}{\mu^2} - \frac{2}{3} + (2+z)a(z) - z\right],$$

$$y(q^2, m_c, \mu) = -\frac{1}{3}\left[\ln\frac{m_c^2}{\mu^2} - \frac{3}{2} + 2a(z)\right];$$

where $a(z) = \sqrt{|z-1|}\arctan\frac{1}{\sqrt{z-1}}$ and $z = 4m_c^2/q^2$.

Interesting RGE effects

$$\begin{pmatrix}\Delta C_1(\mu)\\ \Delta C_2(\mu)\\ \Delta C_3(\mu)\\ \Delta C_4(\mu)\\ \Delta C_7^{\rm eff}(\mu)\\ \Delta C_9(\mu)\end{pmatrix} = \begin{pmatrix} 1.12 & -0.27 & 0 & 0\\ -0.27 & 1.12 & 0 & 0\\ 0 & 0 & 0.92 & 0\\ 0 & 0 & 0.33 & 1.92\\ 0.02 & -0.19 & -0.01 & -0.13\\ 8.65 & 2.00 & -4.33 & -1.95\end{pmatrix}\begin{pmatrix}\Delta C_1(\mu_0)\\ \Delta C_2(\mu_0)\\ \Delta C_3(\mu_0)\\ \Delta C_4(\mu_0)\end{pmatrix}.$$

Charming new physics in rare B-decays and mixing
Jaeger, Kirk, Lenz, Leslie
arXiv: 1701.09183

NP IN MIXING & LIFETIMES

The decay rate difference of neutral B mesons is again a very strong constraint

$$\Gamma_{12}^{cc} = -G_F^2 (V_{cs}^* V_{cb})^2 m_b^2 M_{B_s} f_{B_s}^2 \frac{\sqrt{1-4x_c^2}}{576\pi} \times \Big\{ \Big[16(1-x_c^2)(4C_2^{c,2} + C_4^{c,2}) + 8(1-4x_c^2) \times (12C_1^{c,2} + 8C_1^c C_2^c + 2C_3^c C_4^c + 3C_3^{c,2}) - 192 x_c^2 \times (3C_1^c C_3^c + C_1^c C_4^c + C_2^c C_3^c + C_2^c C_4^c) \Big] B + 2(1+2x_c^2) \times (4C_2^{c,2} - 8C_1^c C_2^c - 12C_1^{c,2} - 3C_3^{c,2} - 2C_3^c C_4^c + C_4^{c,2}) \tilde{B}_S' \Big\}$$

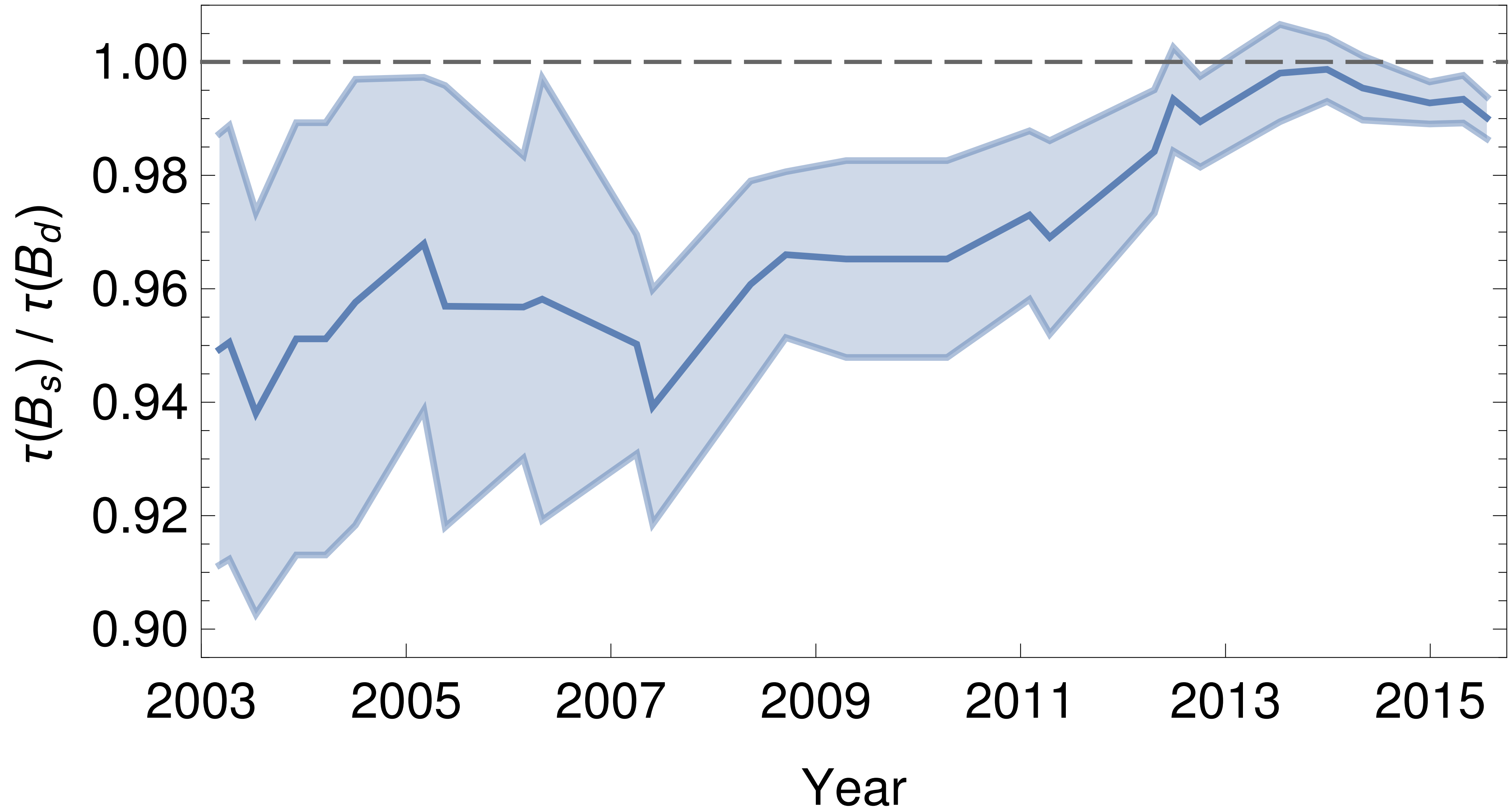
The lifetime ratio of neutral B mesons is more or less exactly one in the SM

-> still more precise experimental values needed

$$\left(\frac{\tau_{B_s}}{\tau_{B_d}}\right)_{\text{NP}} = G_F^2 |V_{cb} V_{cs}|^2 m_b^2 M_{B_s} f_{B_s}^2 \tau_{B_s} \frac{\sqrt{1-4x_c^2}}{144\pi} \times \Big\{ (1-x_c^2) \Big[(4C_{1,2}^{c,2} + C_{3,4}^{c,2}) B_1 + 6(4C_2^{c,2} + C_4^{c,2}) \epsilon_1 \Big] - 12x_c^2 \Big(C_{1,2}^c C_{3,4}^c B_1 + 6C_2^c C_4^c \epsilon_1 \Big) - (1+2x_c^2) \times \Big[(4C_{1,2}^{c,2} + C_{3,4}^{c,2}) B_2 + 6(4C_2^{c,2} + C_4^{c,2}) \epsilon_2 \Big] \Big\}, \quad (13)$$

Charming new physics in rare B-decays and mixing
Jaeger, Kirk, Lenz, Leslie
arXiv: 1701.09183

NP IN LIFETIMES



Current experimental precision is not sufficient

B_s^0	**1.505 ± 0.005 ps**	$B_s^0/B^0 = 0.990 \pm 0.004$

TEST OF UNDERLYING THEORY ASSUMPTIONS: DUALITY

1970 Blom, Gilman for e-p scattering

1979 Poggio, Quinn, Weinberg for e+e- to hadrons

Basic idea: Sum overall hadrons = quark level

Our definition: duality violation is deviation from HQE

$$\Gamma = \Gamma_0 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \frac{\Lambda^4}{m_b^4}\Gamma_4 + \dots$$

Actual expansion parameter is momentum release $\frac{\Lambda}{M_i^2 - M_f^2}$

Taylor expansion of exp[-1/x] in x does give zero

Channel	Expansion parameter x	Numerical value	$\exp[-1/x]$
$b \to c\bar{c}s$	$\frac{\Lambda}{\sqrt{m_b^2 - 4m_c^2}} \approx \frac{\Lambda}{m_b}\left(1 + 2\frac{m_c^2}{m_b^2}\right)$	$0.054 - 0.58$	$9.4 \cdot 10^{-9} - 0.18$
$b \to c\bar{u}s$	$\frac{\Lambda}{\sqrt{m_b^2 - m_c^2}} \approx \frac{\Lambda}{m_b}\left(1 + \frac{1}{2}\frac{m_c^2}{m_b^2}\right)$	$0.045 - 0.49$	$1.9 \cdot 10^{-10} - 0.13$
$b \to u\bar{u}s$	$\frac{\Lambda}{\sqrt{m_b^2 - 4m_u^2}} = \frac{\Lambda}{m_b}$	$0.042 - 0.48$	$4.2 \cdot 10^{-11} - 0.12$

Best candidate:

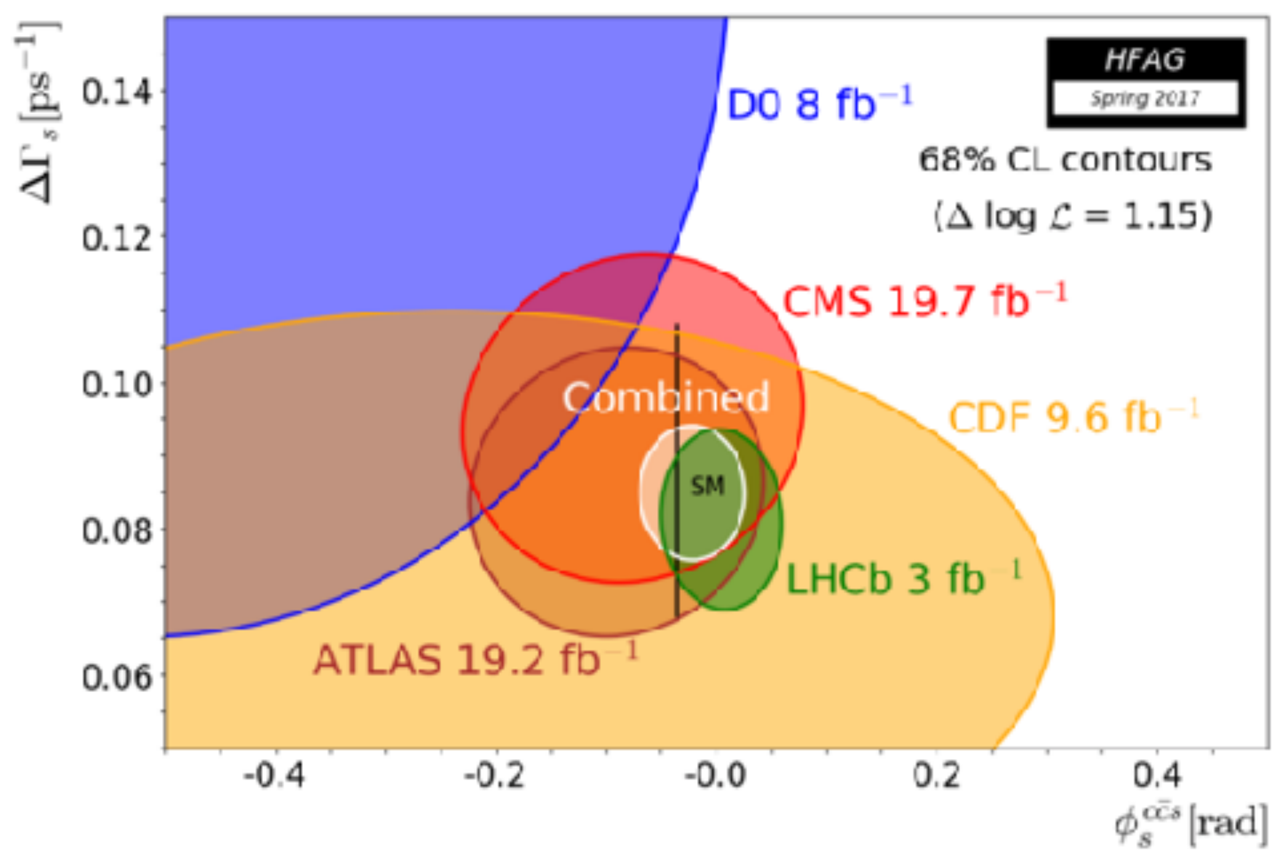
$$b \to c\bar{c}s$$

DUALITY VIOLATION

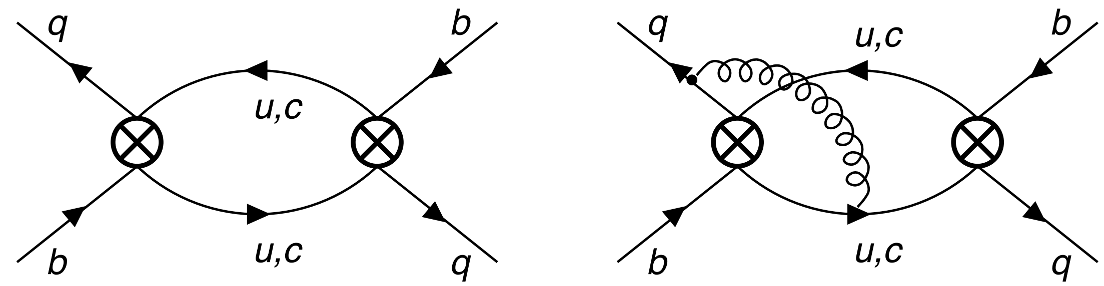
- Many historic hints for possible duality violation:
  missing charm puzzle, Λ_b-lifetime, dimuon asymmetry,...
- Duality cannot be proofed - QCD solution would be required:
  test whether duality based predictions agree with experiment
- Since Moriond 2012:

size of duality violations is severely constrained by perfect agreement of experiment and theory for

$$\frac{\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\mathrm{SM}}}{\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\mathrm{Exp}}} = 0.99 \pm 0.20$$



QUANTIFY THE POSSIBLE SIZE OF DUALITY VIOLATIONS

$\Gamma_{12}^q =$ 

We expect duality violations to be more pronounced if the final state phase space is becoming smaller

our ansatz:

$$\Gamma_{12}^{s,cc} \to \Gamma_{12}^{s,cc}(1+4\delta) \; ,$$

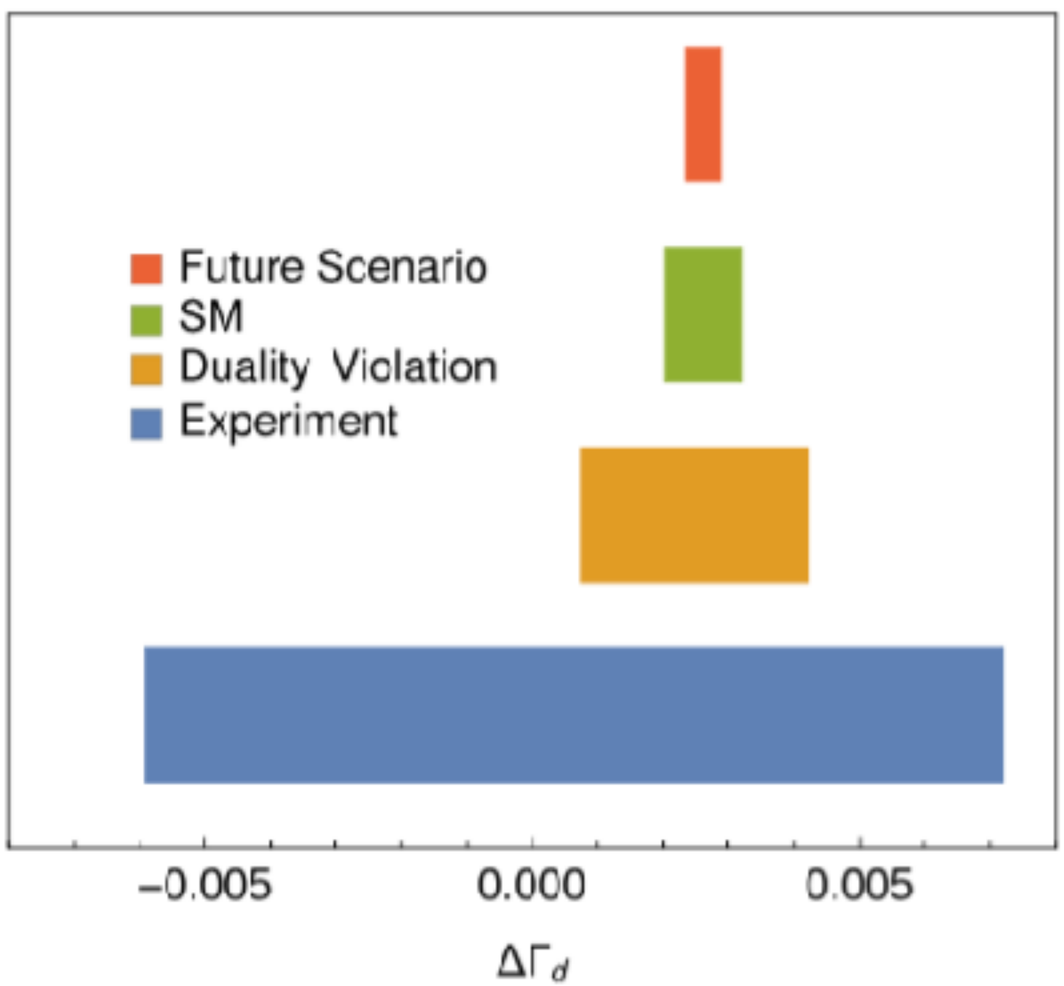
$$\Gamma_{12}^{s,uc} \to \Gamma_{12}^{s,uc}(1+\delta) \; ,$$

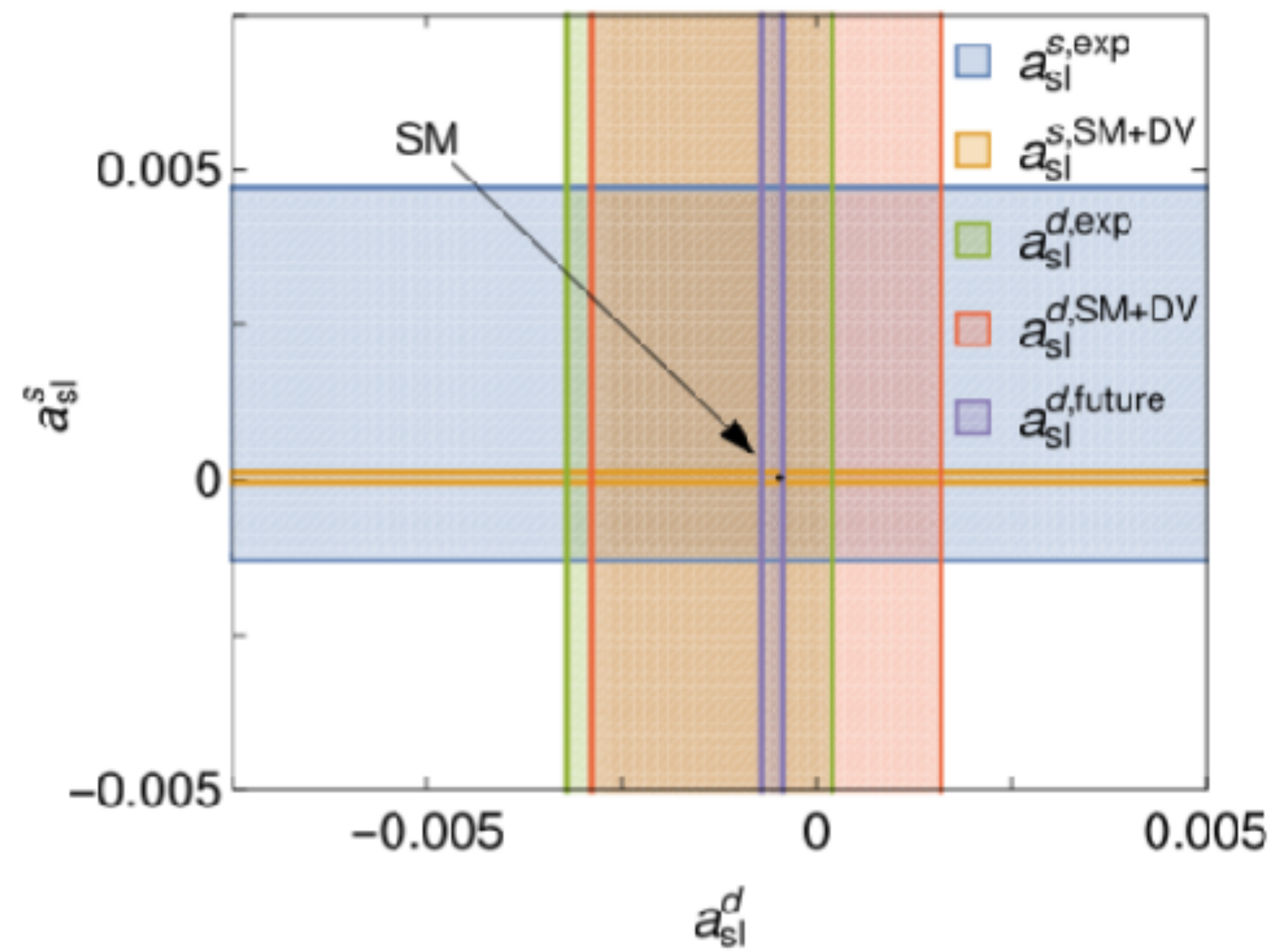
$$\Gamma_{12}^{s,uu} \to \Gamma_{12}^{s,uu}(1+0\delta) \; .$$

We get the following dependence of mixing observables

Observable	B_s^0	B_d^0
$\frac{\Delta\Gamma_q}{\Delta M_q}$	$48.1(1+3.95\delta)\cdot 10^{-4}$	$49.5(1+3.76\delta)\cdot 10^{-4}$
$\Delta\Gamma_q$	$0.0880(1+3.95\delta)\ \mathrm{ps}^{-1}$	$2.61(1+3.759\delta)\cdot 10^{-3}\ \mathrm{ps}^{-1}$
a_{sl}^q	$2.225(1-22.3\delta)\cdot 10^{-5}$	$-4.74(1-24.5\delta)\cdot 10^{-4}$

QUANTIFY THE POSSIBLE SIZE OF DUALITY VIOLATIONS





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Published in Nucl.Phys. B915 (2017) 431-453