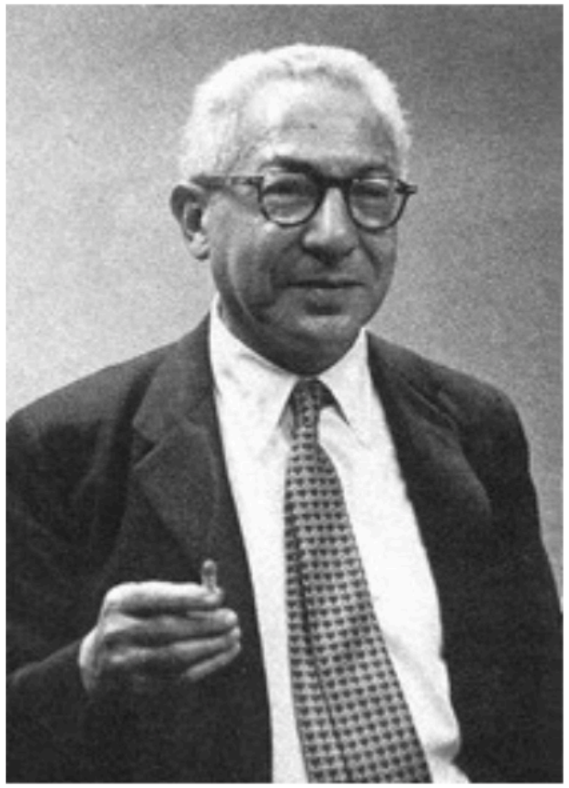
WHO ORDERED THAT?

INTERPRETING LFUV AND OTHER NEW PHYSICS SIGNALS FROM FLAVOUR

Alexander Lenz
IPPP Durham

Bristol 27.3.2018

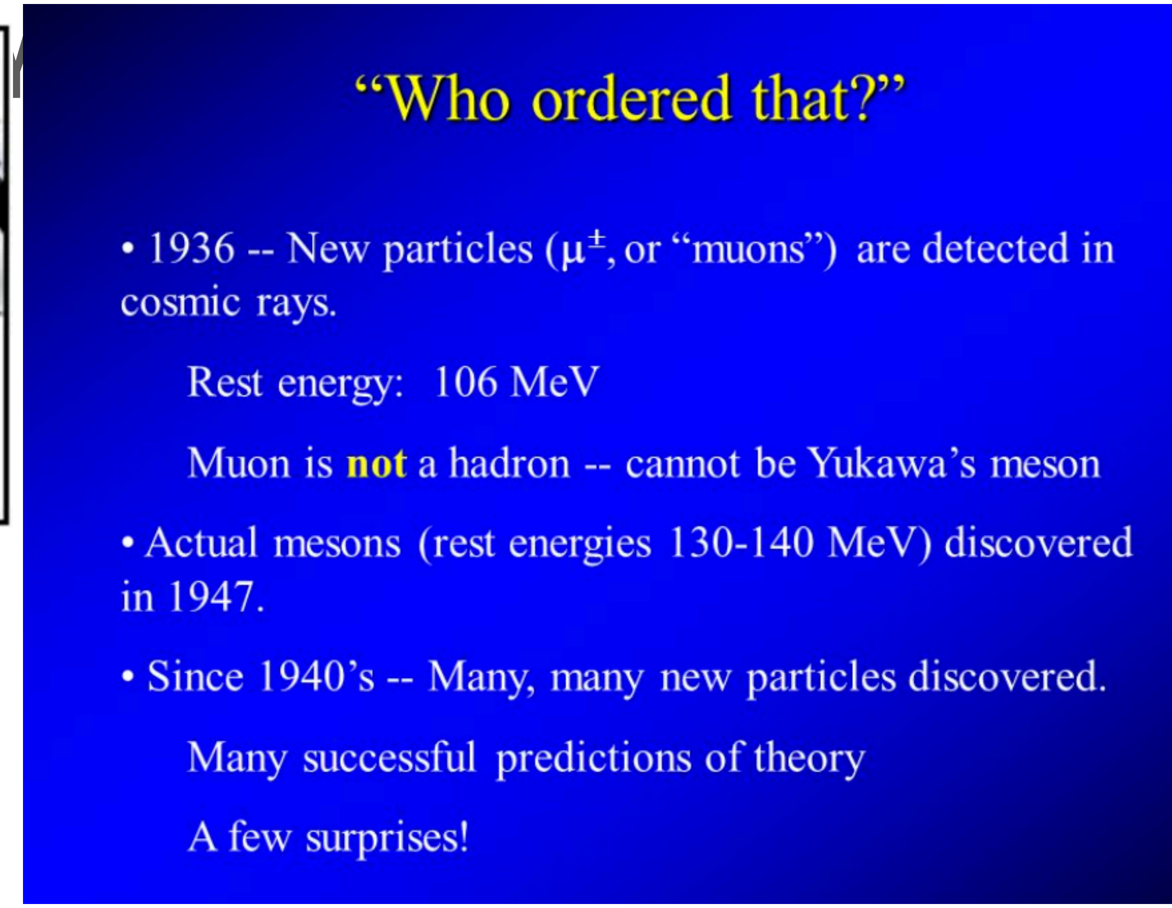
WHO ORDERED THAT?



Isidor Issac Rabi

(1898—1988)

Who ordered that ?



A HOT TOPIC!

53rd Rencontres de Moriond - EW 2018

10-17 March 2018
Europe/Paris timezone

	In Memoriam Pierre Binetruy	Louis Fayard	08:30 - 08:45
09:00	Measurements of CPV in beauty at LHC	Julián García Pardiñas	08:50 - 09:05
	Vcb and R(D*): a fresh look	Paolo Gambino	09:10 - 09:25
	B to D and D*: R(D(*)), |Vcb|, and new physics	Michele Papucci	09:30 - 09:45
10:00	Very rare decays at LHC	Maarten van Veghel	09:50 - 10:05
	Break		10:10 - 10:40
	Measurement of CPV in charm at LHC	Pietro Marino	10:45 - 11:00
11:00	B-anomalies: A Model Builder's Guide	Admir Greljo	11:05 - 11:20
	Status and prospects in b to sll decays	Francesco Dettori	11:25 - 11:40
	Gauged flavour symmetry for B anomalies	Dr. Rodrigo Alonso	11:45 - 12:00
12:00			
17:00	Lepton flavour universality (LFU) tests in B decays as a probe for new physics	Christoph Langenbruch	17:00 - 17:15
	UV-complete model for B anomalies and SM flavor hierarchies	Javier Fuentes-Martin	17:20 - 17:35
	Search for leptoquarks in CMS	Yuta Takahashi	17:40 - 17:55
18:00	Isospin asymmetry for B to K* gamma & hint for B+ to mu+ nu (|Vub|) (Belle)	Gagan Mohanty	18:00 - 18:15
	break		18:20 - 18:35
	Flavour anomalies and UV completion after R_K (*)	Marco Nardecchia	18:40 - 18:55
19:00	Various |Vcs| measurements in Ds+, D0 decays and LU test in D -> pi l nu decays	Ms. Huijing Li	19:00 - 19:15
	A viable scenario to accommodate current B-physics anomalies	Dr. Damir BECIREVIC	19:20 - 19:35
	"K+ -> pi+ nunubar: first NA62 results"	Radoslav Marchevski	19:40 - 19:55
20:00	Status of KL→π0νν analysis at J-PARC KOTO	Kota Nakagiri	20:00 - 20:15

STORIES BY GUY WILKINSON

Beautiful Physics: The Search for New Particles at LHCb

November 16, 2017 — Guy Wilkinson

Rencontres de Moriond
QCD and High Energy Interactions

LA THUILE, MARCH 17 - MARCH 24, 2018

MONDAY	Heavy Flavour session, *chairperson Chris Quigg*		
	08:30 - 08:50	Gudrun Hiller (Dortmund)	Introductory talk to the Heavy Flavour session
	08:55 - 09:10	Sasha Zenaiev (DESY)	Recent rersults on heavy quark production at HERA
	09:15 - 09:30	Abi Soffer (Tel Aviv)	Quarkonium-related results from Babar and Belle
	09:35 - 09:50	Bob Hirosky (Virginia)	Recent Heavy Flavor Results from the Tevatron
	09:55 - 10:10	Adam Barton (Lancaster)	Heavy flavour production and properties at ATLAS and CMS
	10:15 - 10:35	*Coffee Break*	
	10:35 - 10:50	Giulia Tellarini (Ferrara)	Mixing and CP violation in beauty and charm at LHCb
	10:55 - 11:10	Ilya Komarov (DESY)	Status and perspective of Belle II at SuperKEKB
	11:15 - 11:30	Roman Zwicky (Edinburgh)	Parity doublers as a tool for right-handed currents searches
	Heavy Flavour and New Physics session, *chairperson Nazila Mahmoudi*		
	17:00 - 17:15	Andrew Crocombe (Coventry-Warwick)	Rare decays, radiative decays and b→sll transitions at LHCb
	17:20 - 17:35	Robert Fleischer (NIKHEF,Vrije)	New Probes of New Physics with Leptonic Rare B Decays
	17:40 - 17:55	Ruben Jaarsma (Nikhef)	Utilising B→πK Decays at the High-Precision Frontier
	18:00 - 18:15	Johannes Albrecht (Dortmund)	Lepton Flavour Universality tests with B decays at LHCb
	18:20 - 18:40	*Coffee Break*	
	18:40 - 18:55	Andreas Crivellin (PSI)	Explaining the Flavour anomalies with Leptoquarks
	19:00 - 19:15	Abhishek Iyer (Napoli)	Flavour issues in warped custodial models: B anomalies and rare K decays
	19:20 - 19:35	Tevong You (Cambridge)	Prospects for uncovering the source of B→Kμμ anomalies at future hadron colliders
		discussion session: Heavy Flavour indirect search for New Physics, chair Gudrun Hiller	

INTRODUCTION

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

IOP Prize Lecture: Charm Physics
Marco Gersabeck, The University of Manchester, UK

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

NA62…

Overview of experimental heavy flavour physics
Greig Cowan, University of Edinburgh, UK

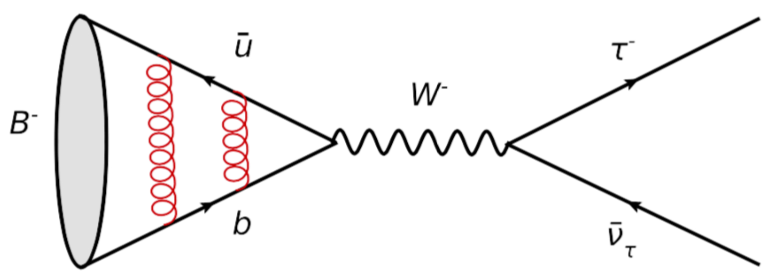
- Proton p = $|uud\rangle$
- **(Heavy) Flavour Physics** describes hadrons with a charm- or a bottom-quark

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

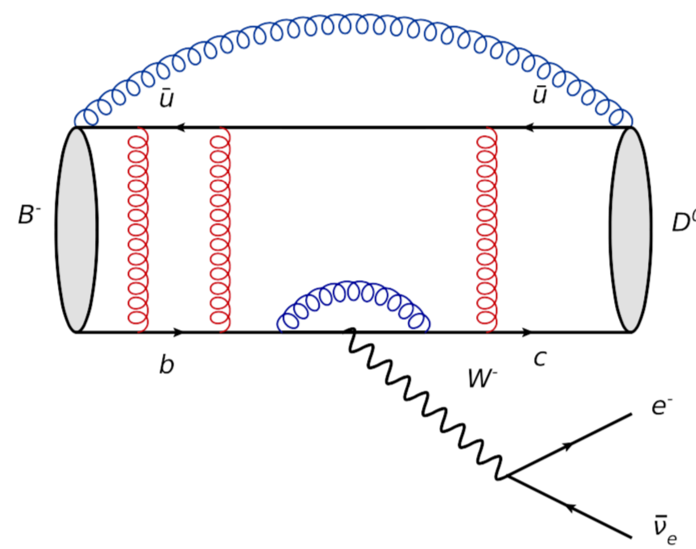
	$B_d = (\bar{b}d)$	$B^+ = (\bar{b}u)$	$B_s = (\bar{b}s)$	$B_c^+ = (\bar{b}c)$	$\Lambda_b = (udb)$
Mass (GeV)	5.27958	5.27926	5.3667	6.2745	5.6194
Lifetime(ps)	1.519	1.638	1.512	0.500	1.451

INTRODUCTION

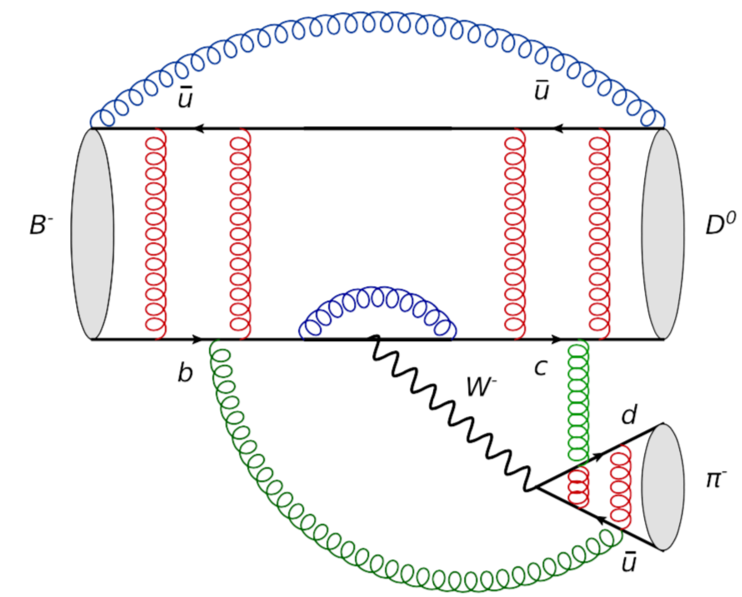
- **Leptonic decays**



- **Semi-Leptonic decays**

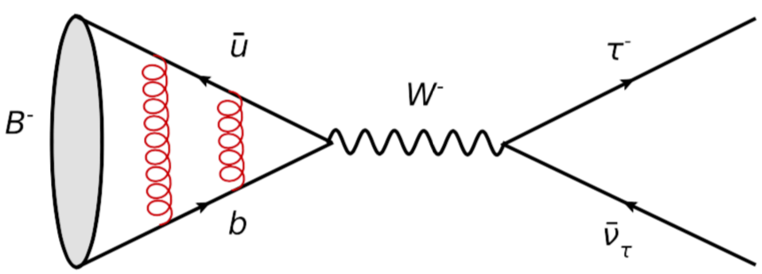


- **Non-Leptonic decays**

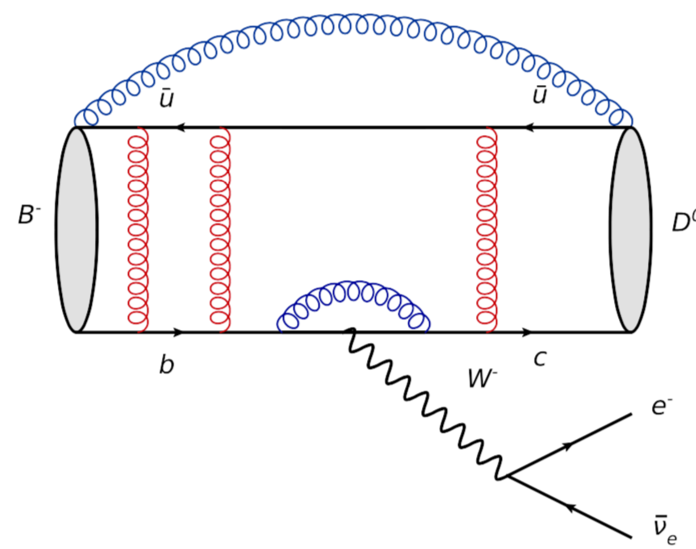


INTRODUCTION

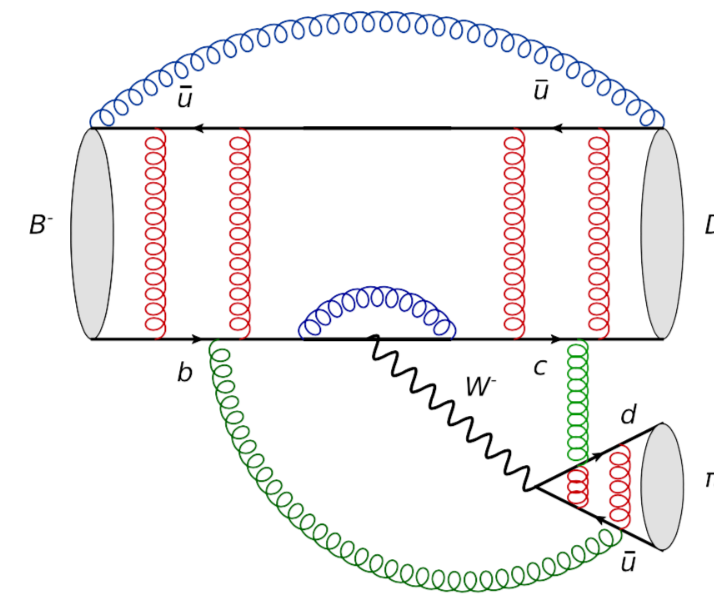
- **Leptonic decays**



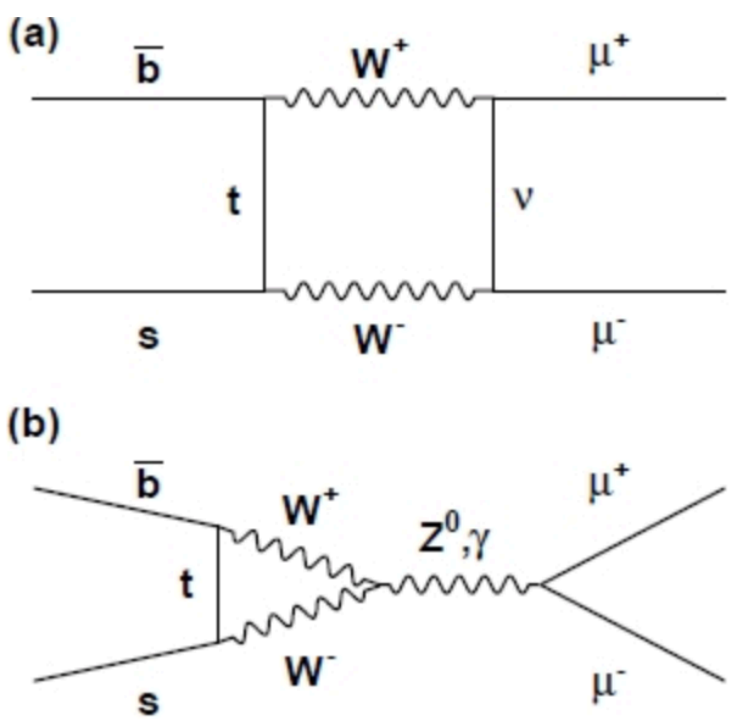
- **Semi-Leptonic decays**



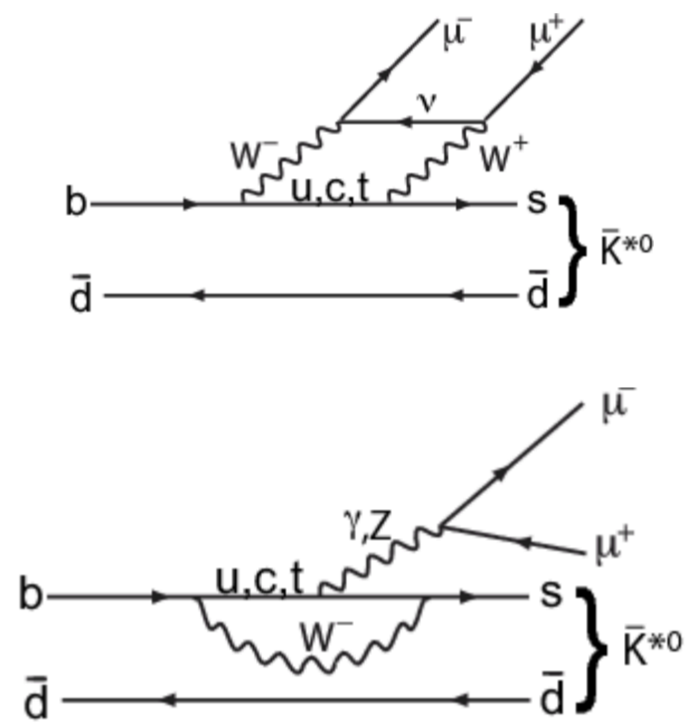
- **Non-Leptonic decays**



- **Leptonic decays**

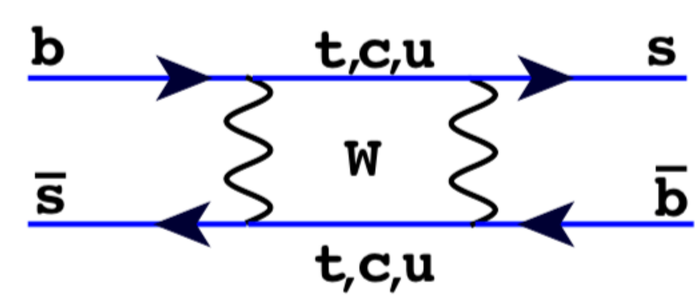


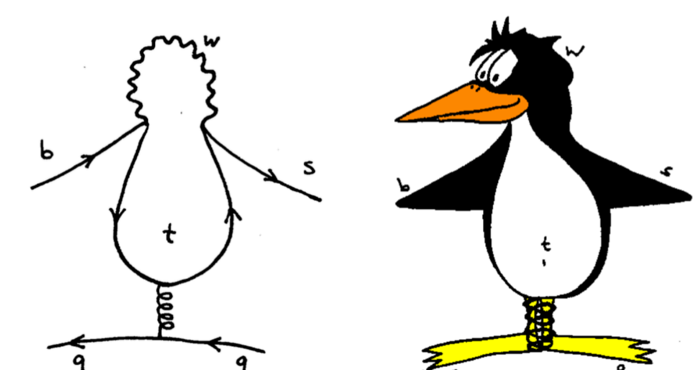
- **Semi-Leptonic decays**



like $K \to \pi\nu\nu$

- **Mixing**





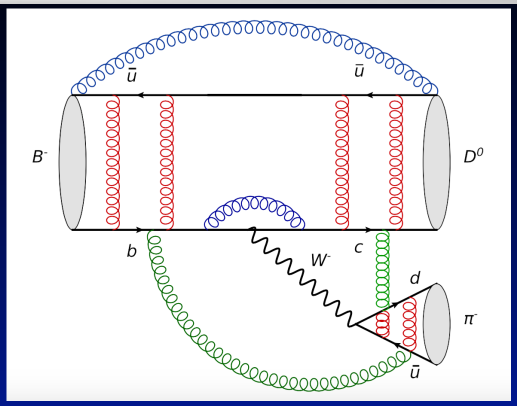
MOTIVATION FOR FLAVOUR PHYSICS

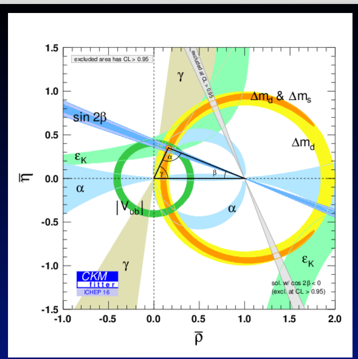
Baryon Asymmetry in the Universe:
A violation of the CP symmetry - which causes matter and anti-matter to evolve differently with time - seems to be necessary to explain the existence of matter in the Universe.
CP violation has so far only been found in hadron decays, which are experimentally investigated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

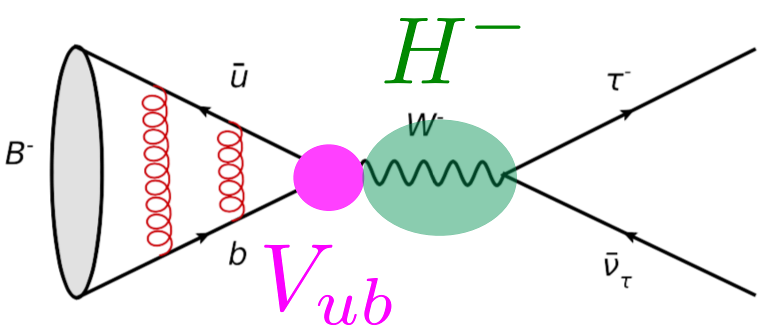


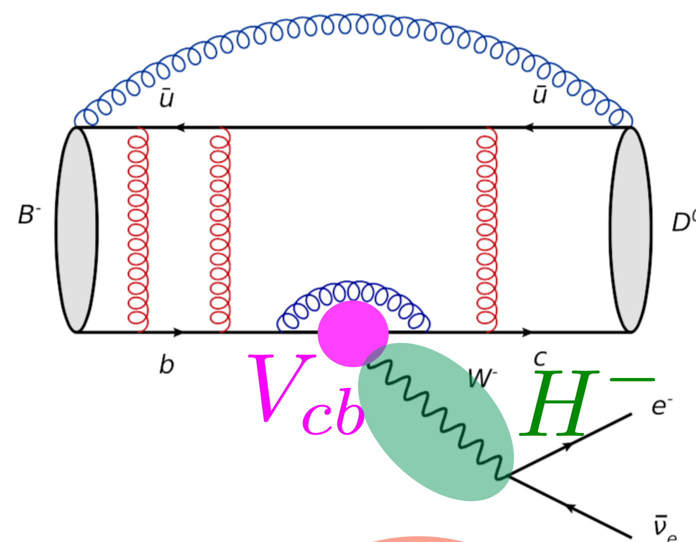


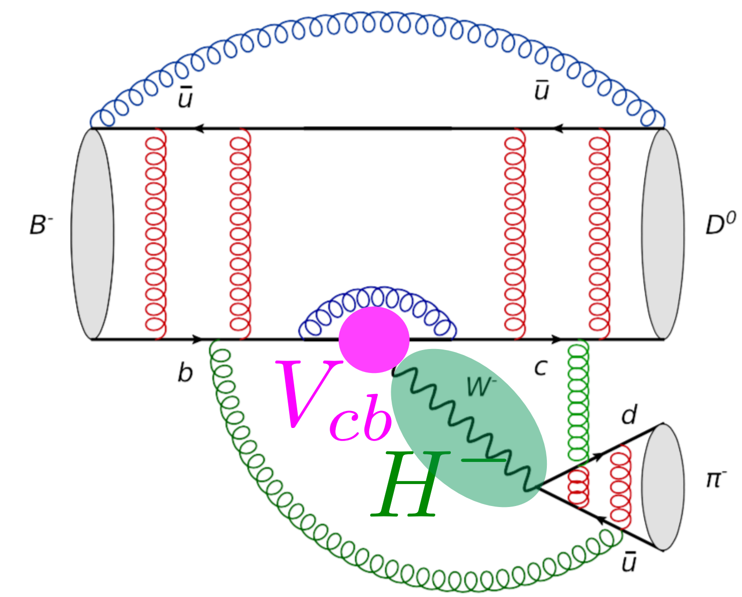
Standard Model parameters:
Hadron decays depend strongly on Standard Model parameters like quark masses and CKM couplings (which are the only known source of CP violation in the SM). A precise knowledge of these parameters is needed for all branches of particle physics.

INTRODUCTION

- **Leptonic decays**
- **Semi-Leptonic decays**
- **Non-Leptonic decays**







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

$$\langle D^0(p_D)|\bar{c}\gamma_\mu b|B^-(p_B)\rangle = f_+^{B^-\to D^0}(q^2)\Big(p_B^\mu + p_D^\mu - \frac{m_B^2 - m_D^2}{q^2}$$

$$\langle D^0\pi^-|\bar{c}\gamma_\mu(1-\gamma_5)b\cdot\bar{u}\gamma^\mu(1-\gamma_5)d|B^-\rangle$$
$$\approx \langle D^0|\bar{c}\gamma_\mu(1-\gamma_5)b|B^-\rangle \cdot \langle\pi^-|\bar{u}\gamma^\mu(1-\gamma_5)d|0\rangle$$

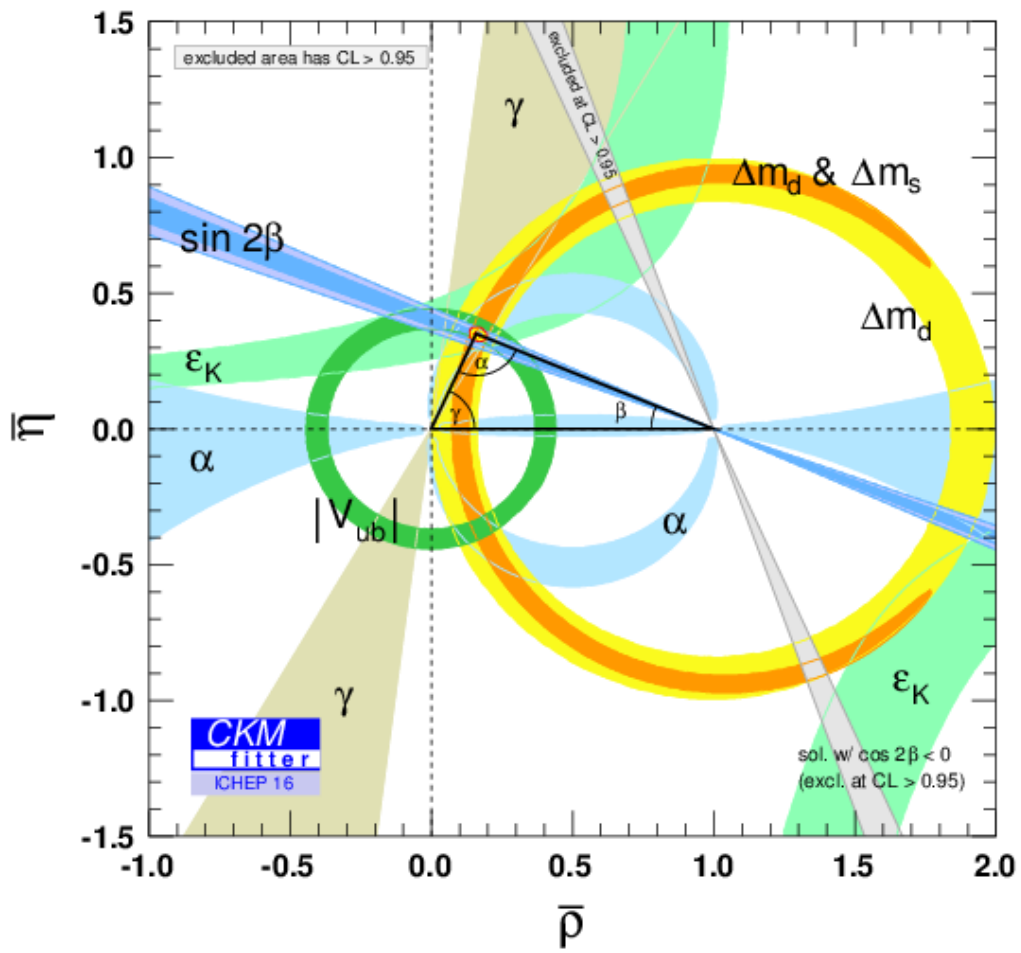
1. Imaginary part in CKM elements = CP violation
2. Instead of a W a charged Higgs H might be exchanged = BSM
3. QCD effects are crucial: decay constant, form factors,...
4. Determination of SM parameter

STATUS QUO I: GREAT EXPERIMENTS

- **Huge** experimental progress: **B-factories, Tevatron** and LHC (**ATLAS, CMS, LHCb**) and soon **Belle II**
- **LHCb**: >400 paper, >25k citations, >6.8fb-1, see/saw **Greig Cowan**

STATUS QUO II: THE SM RULES

- **Message 1:** SM and CKM work well - they dominate flavour structure of nature



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

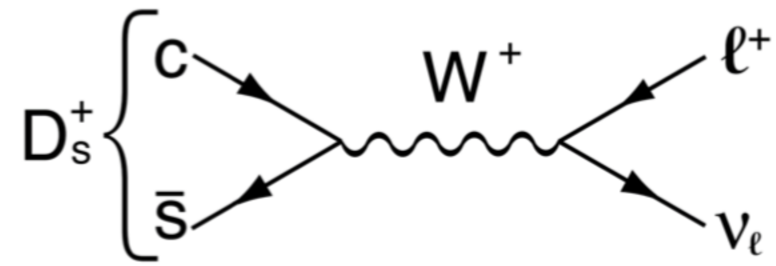
$$\gamma^{\rm HFAG} = 71.3^\circ{}^{+5.7^\circ}_{-6.1^\circ} \quad \text{vs.} \quad \gamma^{\rm CKMfitter} = 65.33^\circ{}^{+0.96^\circ}_{-2.54^\circ}$$

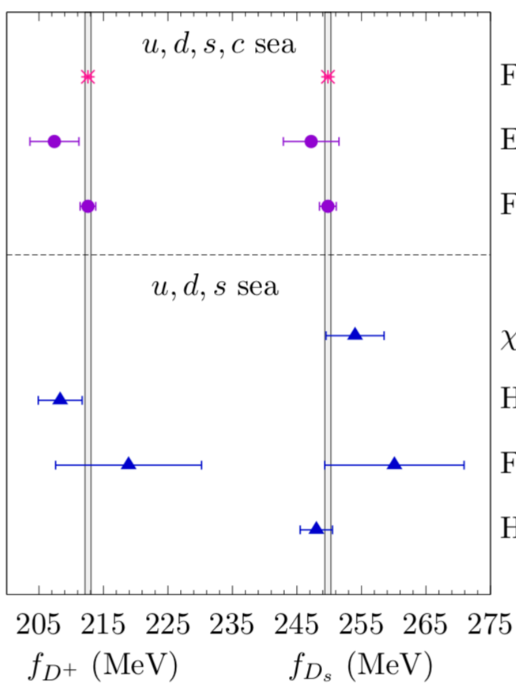
similar results from UTfit; Eigen et al.; Laiho et al

STATUS QUO III: THE SM RULES!!!

- **Message 2:** Theory tools work perfectly, e.g. non-perturbative methods

lattice vs. experiment





$$\Gamma\left(D_s^+ \to \ell^+\nu_\ell\right) = \frac{G_F^2}{8\pi} f_{D_s^+}^2 m_\ell^2 m_{D_s^+} \left(1 - \frac{m_\ell^2}{m_{D_s^+}^2}\right)^2 |V_{cs}|^2,$$

1608.06732 BESSIII $f_{D_s^+} = (241.0 \pm 16.3 \pm 6.6)$ MeV,

PDG $|V_{cs}| f_{D_s^+} = 248.8 \pm 5.8$ MeV

arXiv:0803.0512v2

Accumulating evidence for nonstandard leptonic decays of D_s mesons

Bogdan A. Dobrescu and Andreas S. Kronfeld
Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois, USA

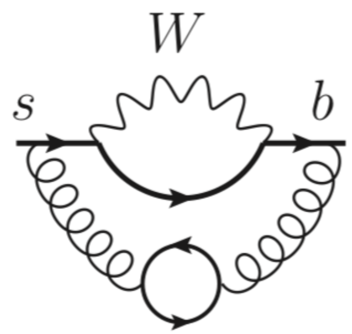
(Dated: March 4, 2008; revised April 28, 2008)

The measured rate for $D_s^+ \to \ell^+\nu$ decays, where ℓ is a muon or tau, is larger than the standard model prediction, which relies on lattice QCD, at the 3.8σ level. We discuss how robust the theoretical prediction is, and we show that the discrepancy with experiment may be explained by a charged Higgs boson or a leptoquark.

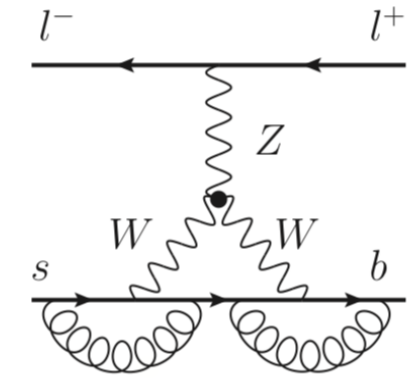
$$(f_{D_s})_{\text{expt}} = 277 \pm 9 \text{ MeV}.$$

urate calculation from lattice

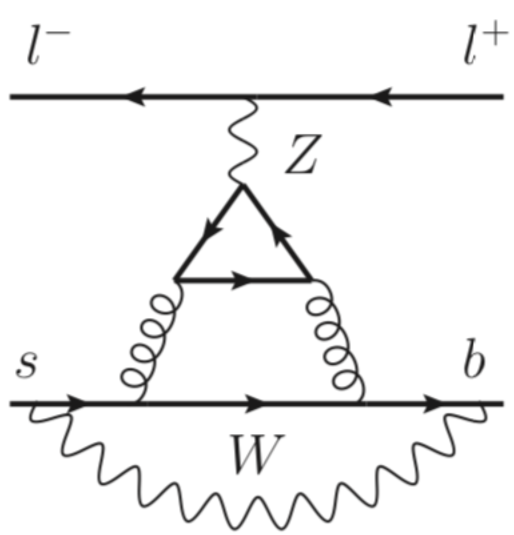
$$(f_{D_s})_{\text{QCD}} = 241 \pm 3 \text{ MeV},$$



STATUS QUO III: THE SM RULES!!!



➤ **Message 2:** Theory tools work perfectly e.g. multiloop

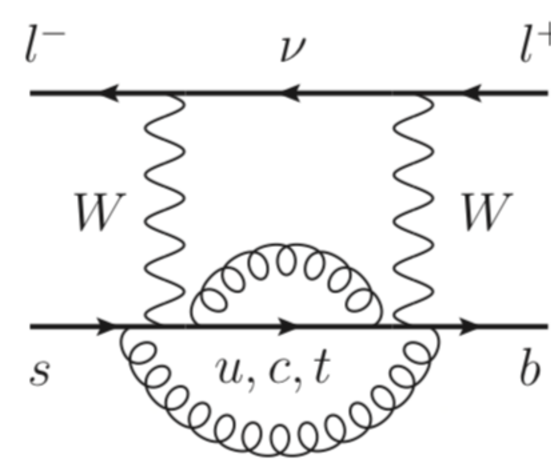


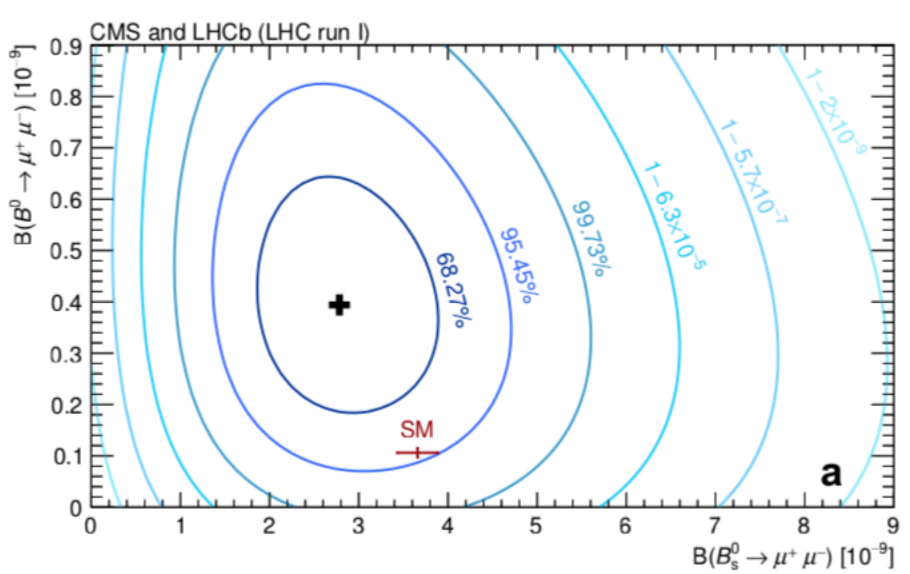
- **perturbative corrections under control**
  - at μ_W: NLO EW + NNLO QCD [CB/Gorbahn/Stamou 1311.1348, Hermann/Misiak/Steinhauser 1311.1347]
  - $\mu_W \to \mu_b$: RGE NLO QED + NNLO QCD [CB/Gambino/Gorbahn/Haisch hep-ph/0312090]
  - $\mu_b \to \Lambda_{\rm QCD}$: **power-enhanced QED correction** $\delta Br \sim \mathcal{O}(-1\%)$ [Beneke/CB/Szafron 1708.09152]
- **hadronic uncertainty** only decay constant f_{B_q} (at LO in QED)

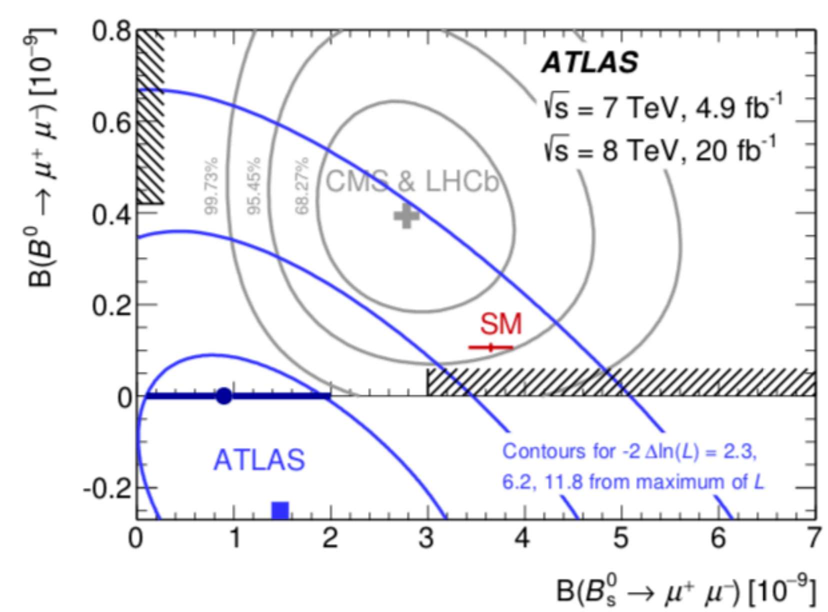
  $\Rightarrow$ lattice $\delta f_{B_q} \lesssim 0.5\%$: $f_{B_d} = (189.4 \pm 1.4)$ MeV & $f_{B_s} = (230.7 \pm 1.2)$ MeV [FNAL/MILC 1712.09262]

  !!! only other compareable precision in flavor: $Br(K^+ \to \pi^+ \nu\bar\nu)$ (NA62), $Br(K_L \to \pi^0 \nu\bar\nu)$ (KOTO), $\Delta M_{d,s}$ (lattice)
- **Error budget** [2017: f_{B_s} from FLAG, CKM from CKMfitter/UTfit, τ_H^s HFLAV]

$$10^9 \times \overline{Br}(B_s \to \mu\bar\mu)_{\rm SM} = 3.57 \pm 0.022|_{\tau_H^s} \pm 0.116|_{f_{B_s}} \pm 0.053|_{\rm non-pmr} \pm 0.030|_{\rm pmr-PE-QED} \pm 0.039|_{m_t} \pm 0.111|_{V_{cb}} \pm 0.003|_{\alpha_s}$$







STATUS QUO III: THE SM RULES!!!

- **Message 2:** Theory tools work perfectly - e.g. Heavy Quark Expansion

Total decay rate can be expanded in inverse powers of mb

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

Each term in the series can be further expanded in the strong coupling

$$\Gamma_j = \Gamma_j^{(0)} + \frac{\alpha_s(\mu)}{4\pi}\Gamma_j^{(1)} + \frac{\alpha_s^2(\mu)}{(4\pi)^2}\Gamma_j^{(2)} + \ldots$$

Each term is a product of a perturbative function and the matrix element of **Delta B = 0 operators** (lattice , sum rules)

Mixing obeys a similar HQE

$$\Gamma_{12}^q = \left(\frac{\Lambda}{m_b}\right)^3 \Gamma_3 + \left(\frac{\Lambda}{m_b}\right)^4 \Gamma_4 + \ldots$$

Now **Delta B = 2 operators appear** (lattice , sum rules)

STATUS QUO III: THE SM RULES!!!

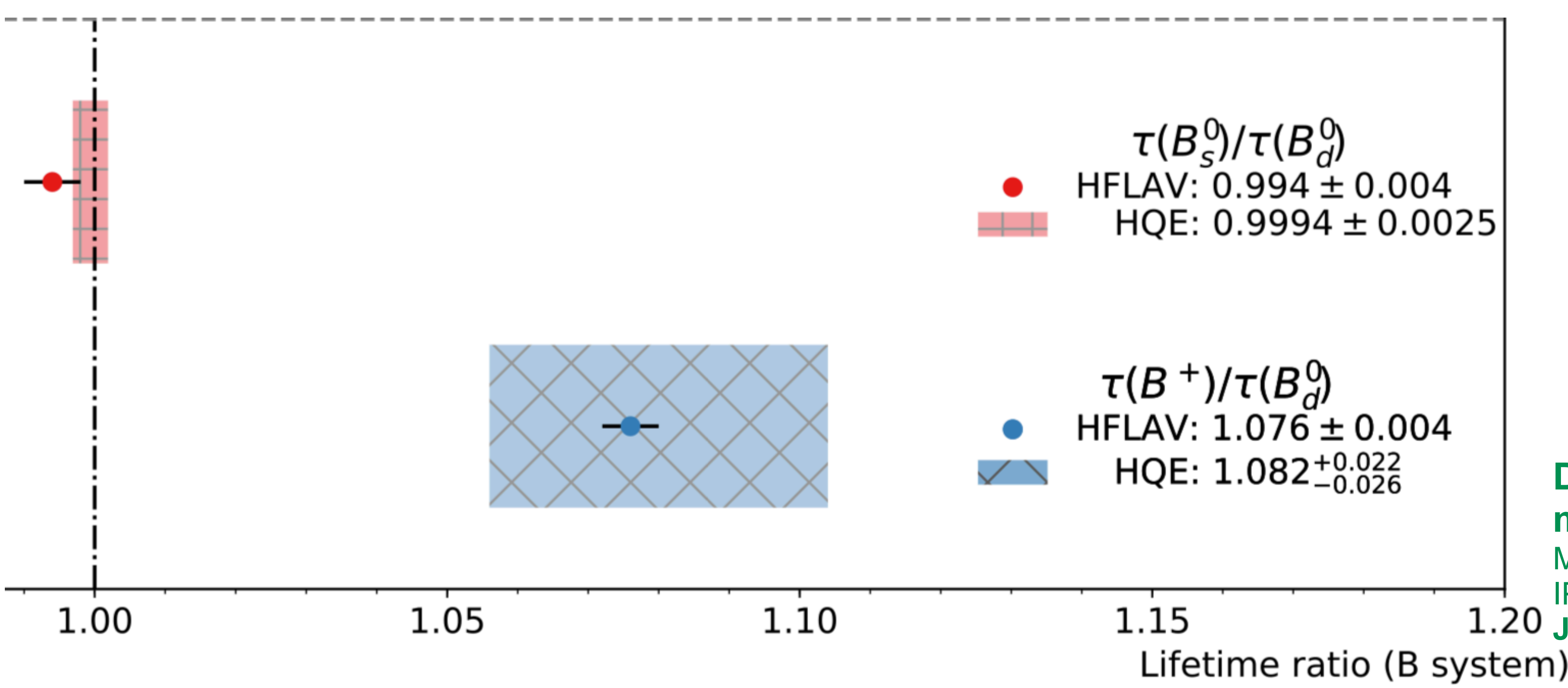
➤ **Message 2:** Theory tools work perfectly

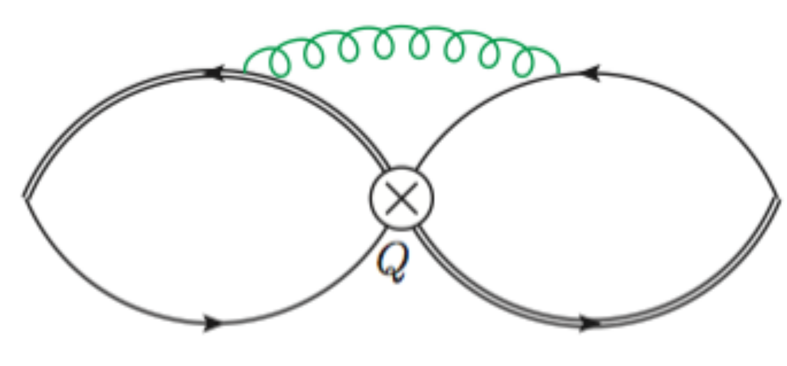
Lifetime ratios of heavy mesons are theoretically well under control

-they test the HQE at 3rd order

-they require perturbative (NLO and NNLO-QCD) calculations

-they require non-perturbative input: lattice, sum rules (advance in multi-loop needed)





Dimension-six matrix elements for meson mixing and lifetimes from sum rules
M. Kirk, A. Lenz, T. Rauh (Durham U. & Durham U., IPPP)
JHEP 1712 (2017) 068 arXiv:1711.02100 [hep-ph]

STATUS QUO IV: THE SM RULES?

- **Message 3:** First deviations start to show up -> think deeper

long standing discrepancy in the determination of V_cb, V_ub from simple semi-leptonic tree-level decays

$$V_{cb}^{\text{Inclusive}} = 0.04219 \pm 0.00078 \quad [66]\,,$$
$$V_{cb}^{B\to D} = 0.03918 \pm 0.00094 \pm 0.00031$$
$$V_{cb}^{B\to D^*,\,\text{CLN}} = 0.03871 \pm 0.00047 \pm 0.00059$$
$$V_{cb}^{B\to D^*,\,\text{BGL}} = 0.0419^{+0.0020}_{-0.0019} \quad [125]\,.$$

see e.g. Grinstein, Kobach; Bigi, Gambino, Schacht; Bernlochner, Ligeti, Papuchi, Robinson; Jaiswal, Nandi, Patra

Probably solved: A parametrisation of the form factors was used in the extraction, that holds only up to a certain accuracy - but not with the current experimental precision

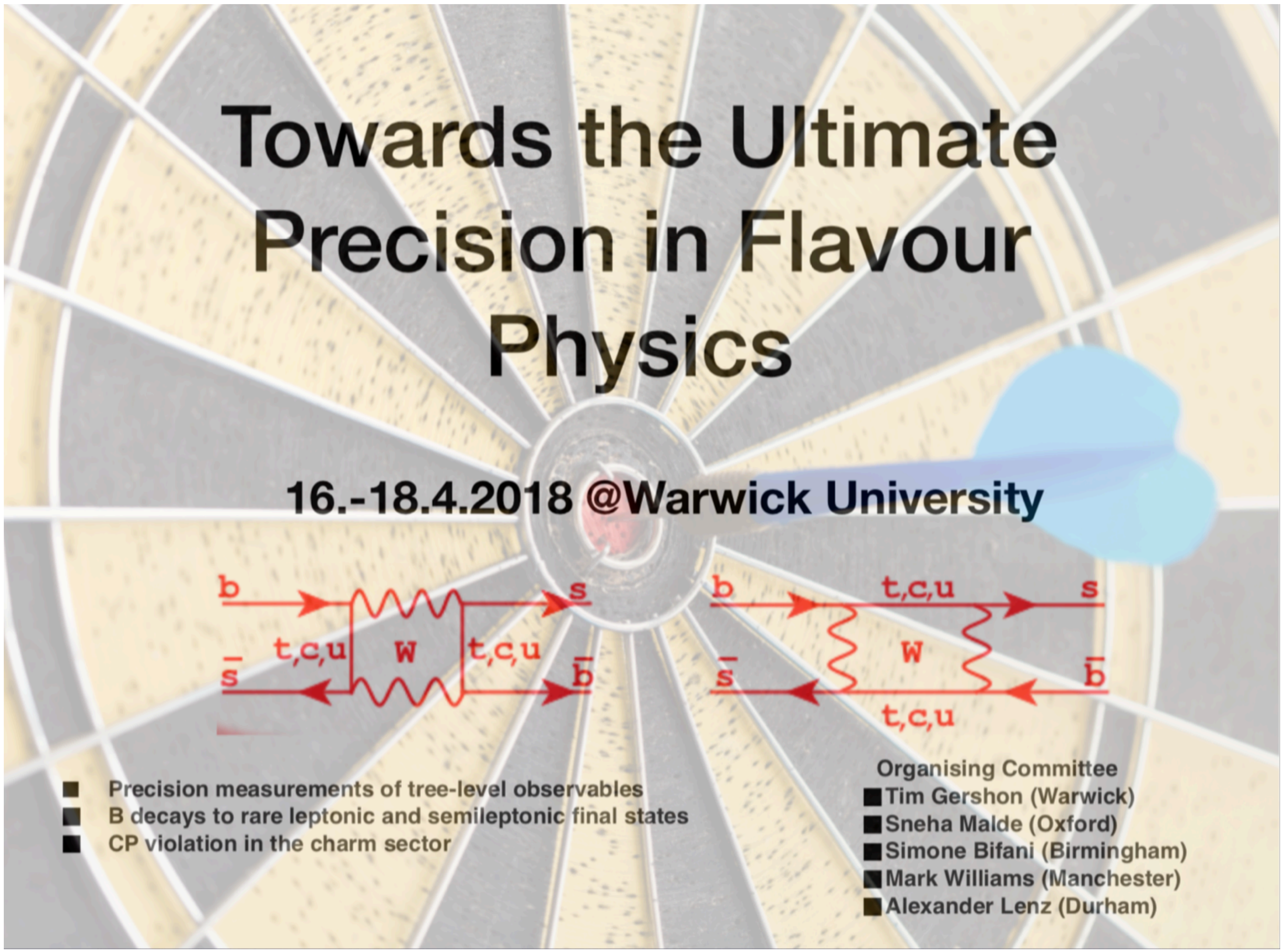
This is a general problem in Flavour Physics:

many assumption that were reasonable10 or 20 years ago have to be reconsidered

STATUS QUO IV: THE SM RULES?

This is a general problem in Flavour Physics:

many theory assumption that were reasonable 10 or 20 years ago have to be reconsidered



financed by IPPP Senior Experimental Fellowship

STATUS QUO IV: THE SM RULES?

- **Message 3:** First deviations start to show up **and they stay**

σ

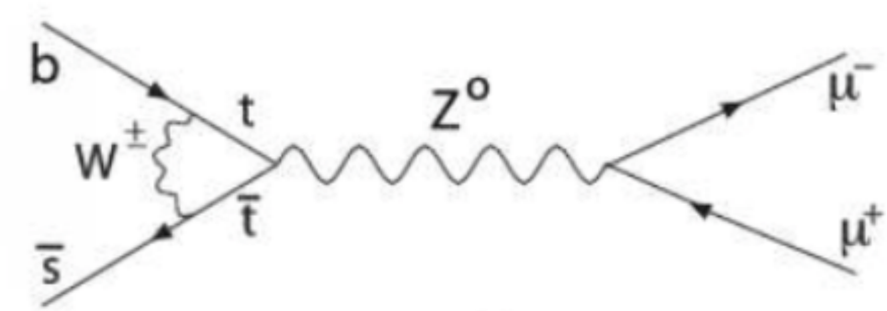
- 3-6: Semi-leptonic loop-level decays (small BSM)
- 3.9: Semi-leptonic tree-level decays (large BSM)
- 3.6: B-mixing phase (dimuon asymmetry)
- 3.5: Muon g-2
- 2.8: K-mixing/ epsilon’ (huge lattice progress)
- 2.6: Zbb coupling (LEP FB asym)
- 2.x: K-pi puzzle
- 2.x: tau to mu nu nu/tau to e nu nu
- 2.x: Vus: K vs. tau
- 2.0: B-mixing modulus (mass difference)

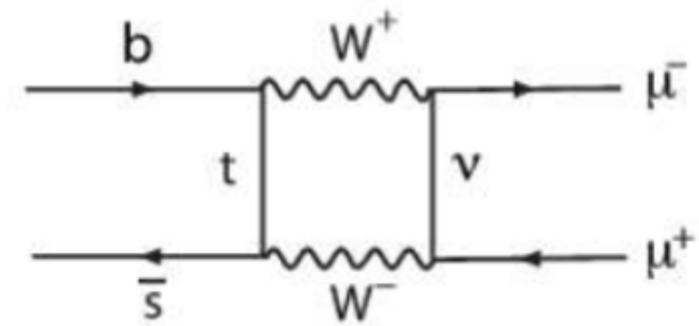
4 σ in neutron lifetime? Proton radius seems to be solved by Hänsch et al

SEMI-LEPTONIC LOOP LEVEL

$$b \to s\mu\mu$$

relatively simple hadronic structure





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

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

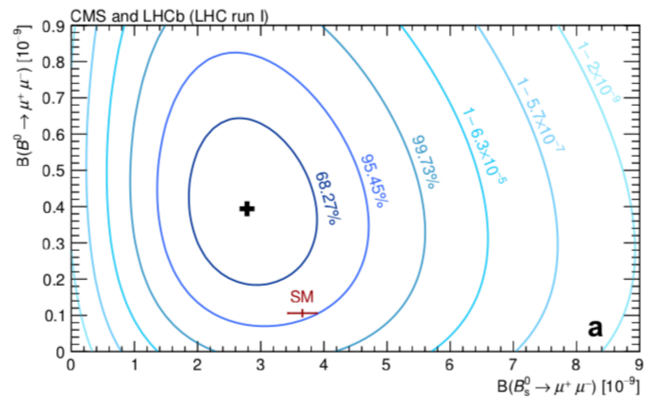
Can be determined with lattice, sum rules,...

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**

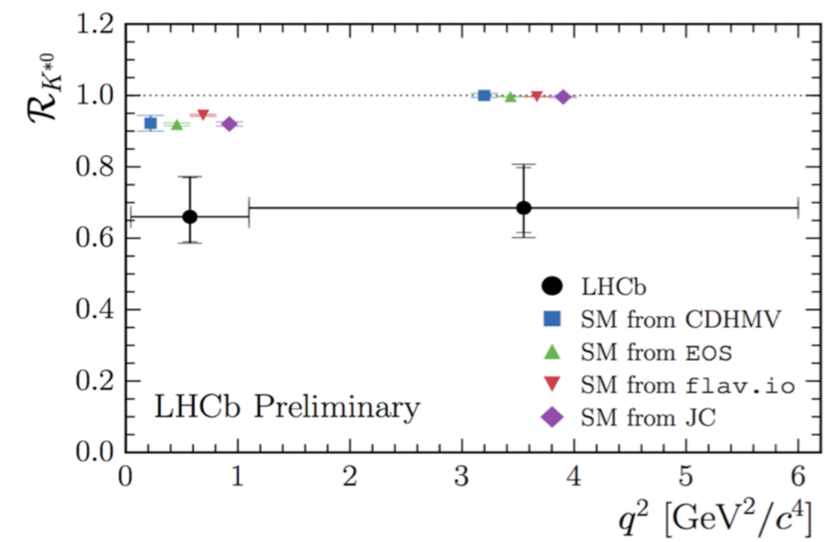
SEMI-LEPTONIC LOOP LEVEL $b \to s\mu\mu$

$B_{d,s} \to \mu\mu$

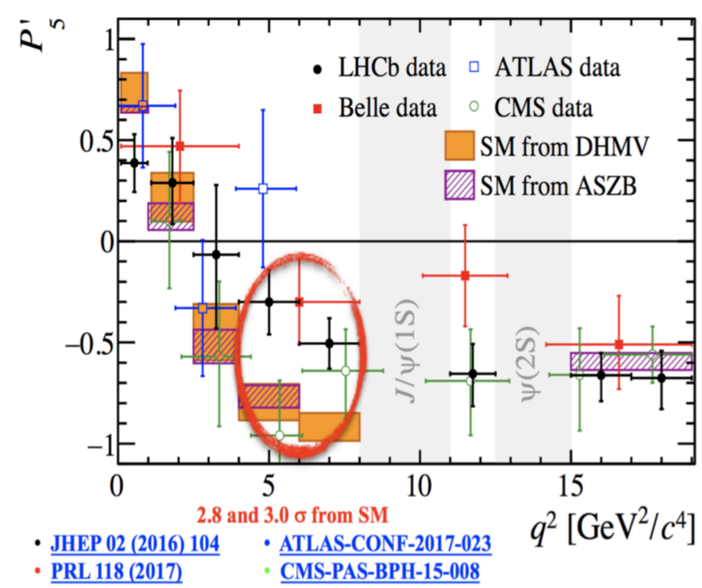


$H_b \to H_q\mu\mu$

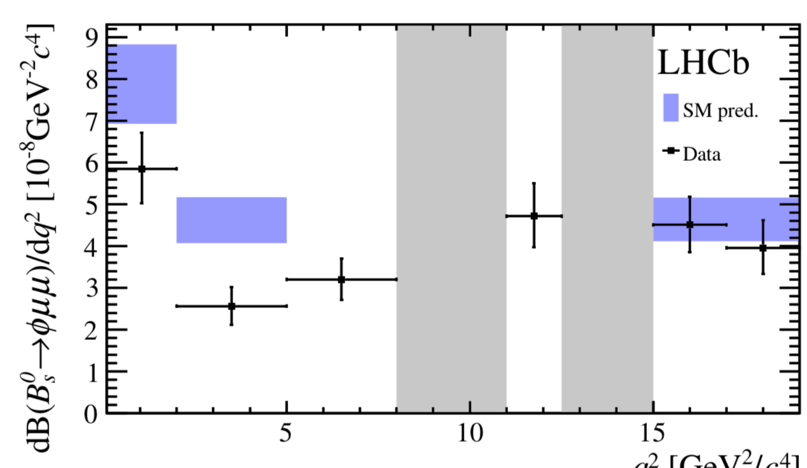
a) $R_K = \frac{Br(B^+ \to K^+\mu^-\mu^+)}{Br(B^+ \to K^+e^-e^+)}$



b) P_5'



c) $Br(B_s \to \phi\mu\mu), \; Br(B \to K^*\mu\mu)$



SEMI-LEPTONIC LOOP LEVEL

Consistent picture of numerous (175) observables

all can be fitted in very simple scenario (BSM = -1/4 SM)

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

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

e.g. just modify the Wilson coefficient C9!

3 σ 1704.05447

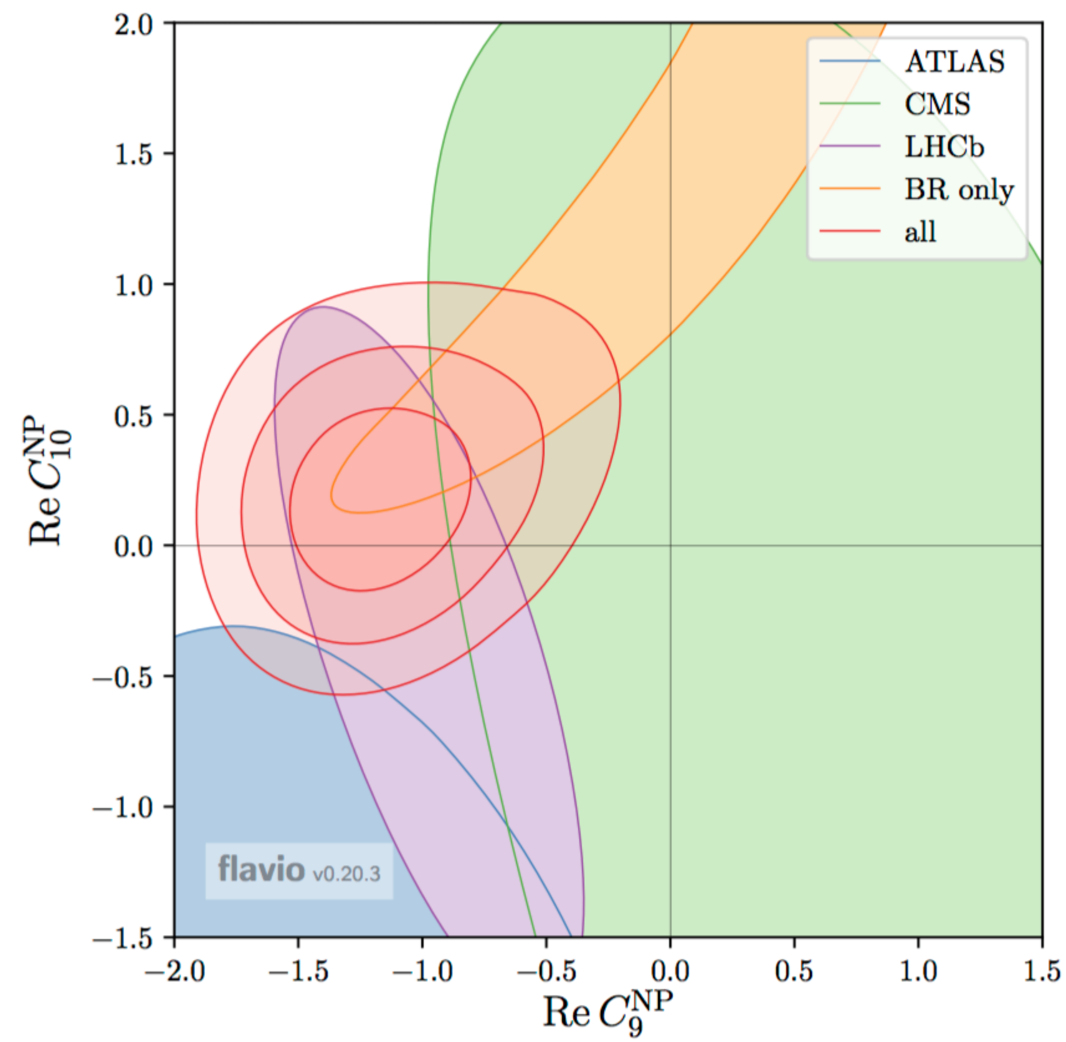
Ciuchini, Coutinho, Fedele, Franco, Paul, Silvestrini, Valli

On Flavourful Easter eggs for NP hunger and LFU violation

5.7σ 1704.05340

Capdevilla, Cvrivellin, Descotes-Genon, Matias, Virto

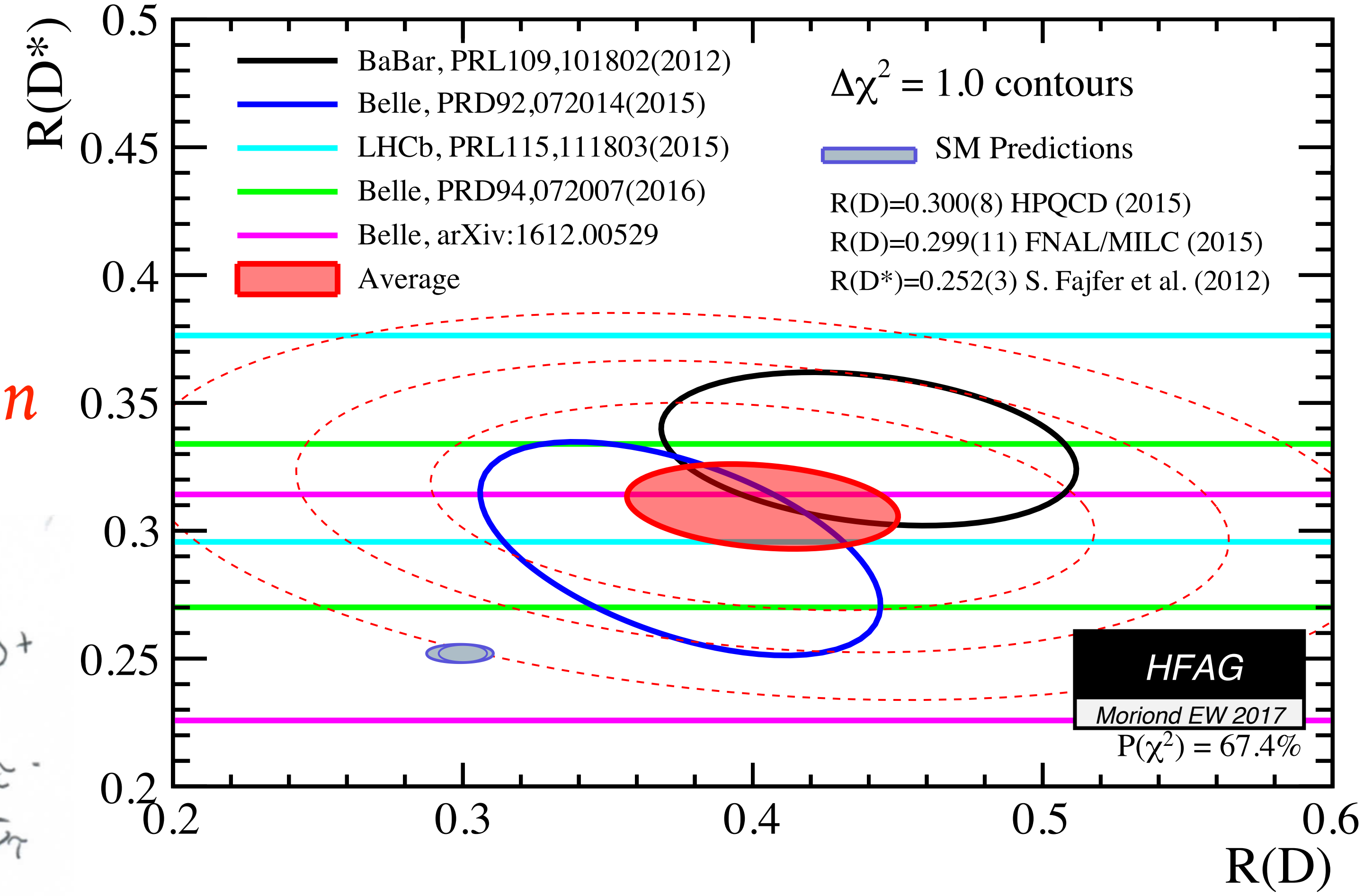
Patterns of NP in b to all transitions in the light of recent data



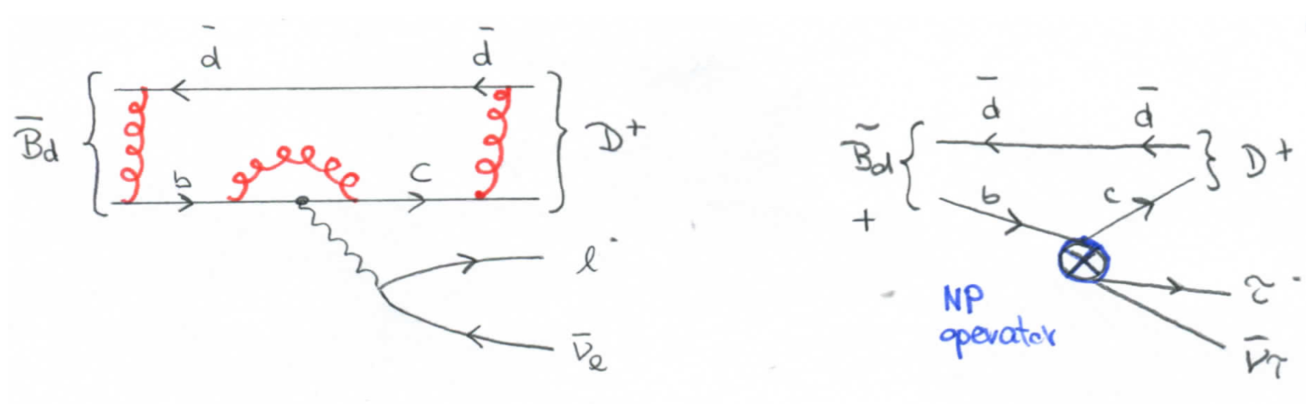
arXiv:1703.09189 [pdf, other]
Status of the $B \to K^*\mu^+\mu^-$ anomaly after Moriond 2017
Wolfgang Altmannshofer, Christoph Niehoff, Peter Stangl, David M. Straub

SEMI-LEPTONIC TREE LEVEL **(THIS IS LARGE!)**

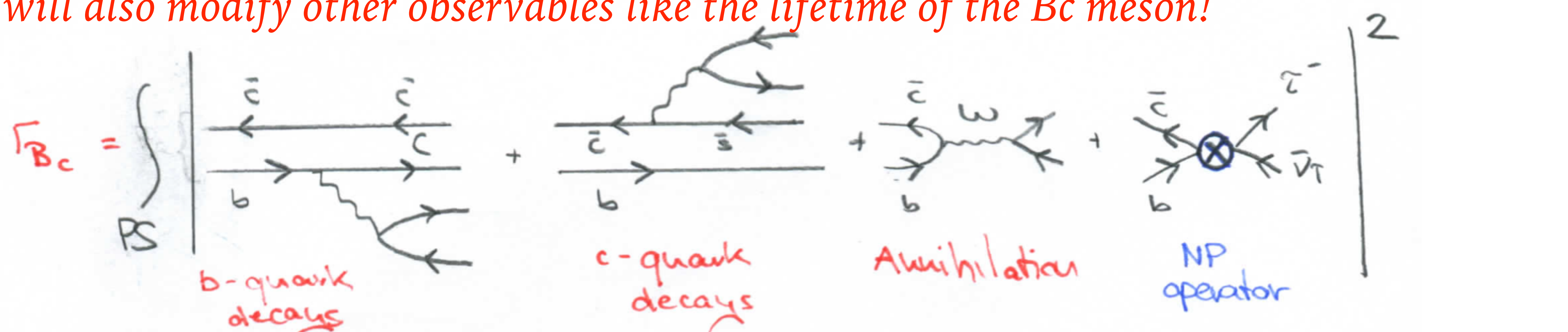
$$R_{D^{(*)}} = \frac{Br(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{Br(\bar{B} \to D^{(*)} l^- \bar{\nu}_l)}$$



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

BSM PHYSICS IS ON THE HORIZON?

List of models:

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

agony of choice

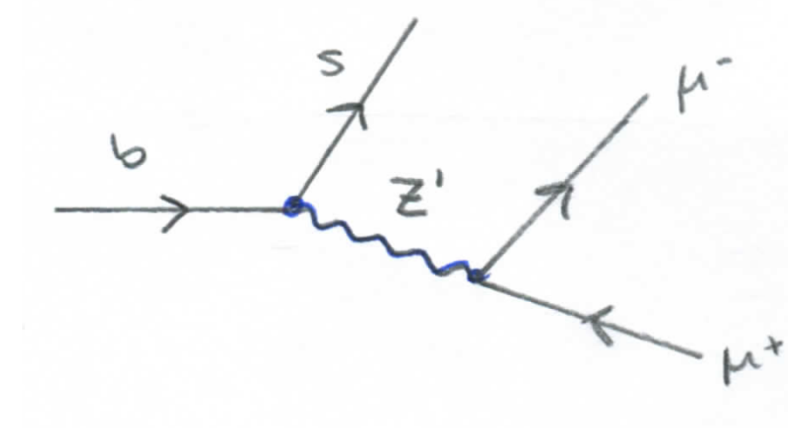
or

choice of agony?

hundreds of papers…

BSM PHYSICS IS ON THE HORIZON?

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

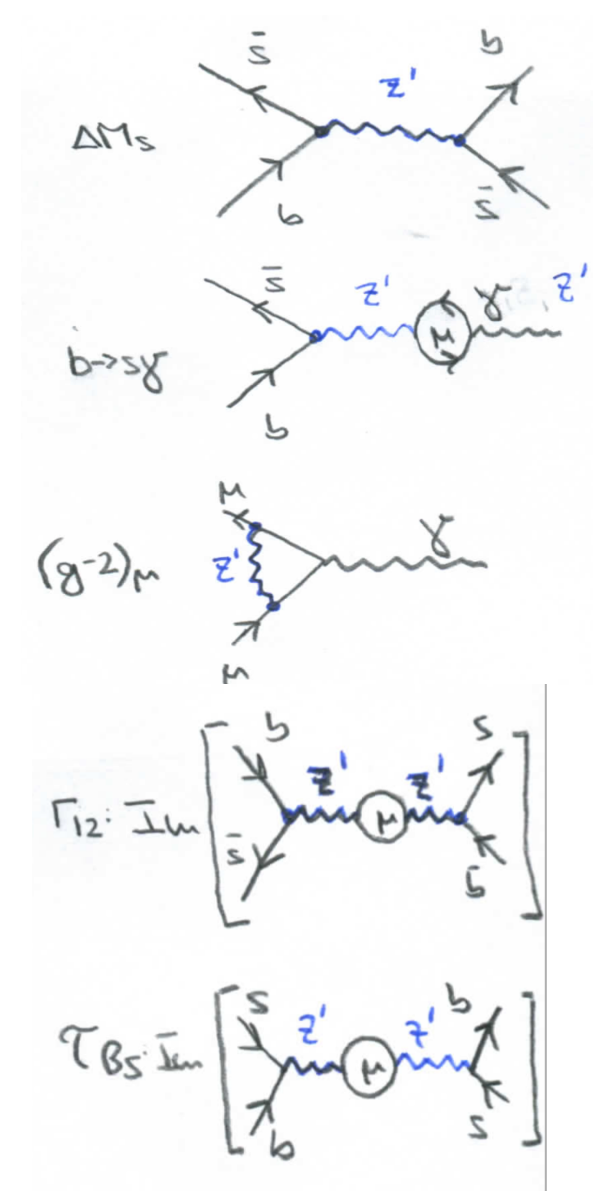


Such a new tree-level transition will also affect many other observables,

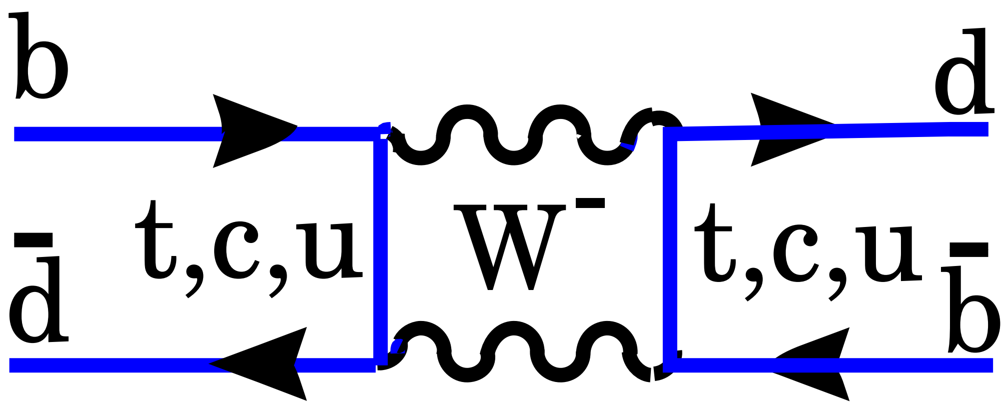
most notably **B-mixing at tree-level**,

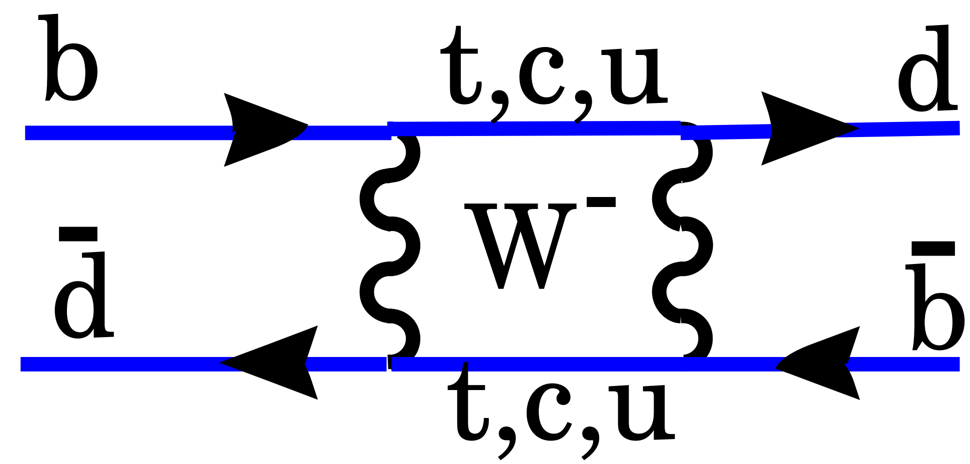
but also many loop processes.

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



B-MIXING IN MORE DETAIL





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

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

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

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

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

Text-book: Bs mixing agrees with the SM

$$\Delta M_s^{\mathrm{SM},\,2011} = (17.3 \pm 2.6)\ \mathrm{ps}^{-1}$$
$$\Delta M_s^{\mathrm{SM},\,2015} = (18.3 \pm 2.7)\ \mathrm{ps}^{-1}$$

$$\Delta M_s^{\mathrm{Exp}} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$$

- BSM contributions have to be within the large theory uncertainties
- they can be both positive and negative
- relatively stringent bound on BSM models that explain the b-> s mu mu anomalies

$$\Delta M_s^{\mathrm{Exp}} = 2\left|M_{12}^{\mathrm{SM}} + M_{12}^{\mathrm{NP}}\right| = \Delta M_s^{\mathrm{SM}}\left|1 + \frac{M_{12}^{\mathrm{NP}}}{M_{12}^{\mathrm{SM}}}\right|$$

NEW: Bs mixing “disagrees” with the SM

using most recent input, in particular most recent lattice values for fBs^2 B from FLAG (dominated by Fermilab/MILC)

$$\Delta M_s^{\mathrm{SM,\,2017}} = (20.01 \pm 1.25)\ \mathrm{ps}$$

$$\Delta M_s^{\mathrm{Exp}} = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}$$

BSM contributions should be **negative**

very stringent bound on many BSM models that explain the b-> s mu mu anomalies

$$\frac{\Delta M_s^{\mathrm{Exp}}}{\Delta M_s^{\mathrm{SM}}} = \left| 1 + \frac{\kappa}{\Lambda_{\mathrm{NP}}^2} \right|$$

$$\frac{\Lambda_{\mathrm{NP}}^{2017}}{\Lambda_{\mathrm{NP}}^{2015}} = \sqrt{\frac{\frac{\Delta M_s^{\mathrm{Exp}}}{(\Delta M_s^{\mathrm{SM}} - 2\delta\Delta M_s^{\mathrm{SM}})^{2015}} - 1}{\frac{\Delta M_s^{\mathrm{Exp}}}{(\Delta M_s^{\mathrm{SM}} - 2\delta\Delta M_s^{\mathrm{SM}})^{2017}} - 1}} \simeq 5.2$$

One constraint to kill them all?

Luca Di Luzio, Matthew Kirk, Alexander Lenz

Institute for Particle Physics Phenomenology, Durham University,
DH1 3LE Durham, United Kingdom
luca.di-luzio@durham.ac.uk, m.j.kirk@durham.ac.uk, alexander.lenz@durham.ac.uk

$$\frac{\Delta M_s^{\mathrm{Exp}}}{\Delta M_s^{\mathrm{SM}}} = \left| 1 + \frac{C_{bs}^{LL}}{R_{\mathrm{SM}}^{\mathrm{loop}}} \right|$$

Abstract

Many BSM models that explain the intriguing anomalies in the quark flavour sector are severely constrained by B_s-mixing, for which the SM prediction and experiment agreed well until recently. New non-perturbative calculations point, however, in the direction of a tiny discrepancy in this observable. Using this new input we find a considerable shift of the bounds on BSM models stemming from B_s-mixing.

$$C_{bs}^{LL} = \frac{\eta^{LL}(M_{Z'})}{4\sqrt{2} G_F M_{Z'}^2} \left(\frac{\lambda_{23}^Q}{V_{tb} V_{ts}^*} \right)^2$$

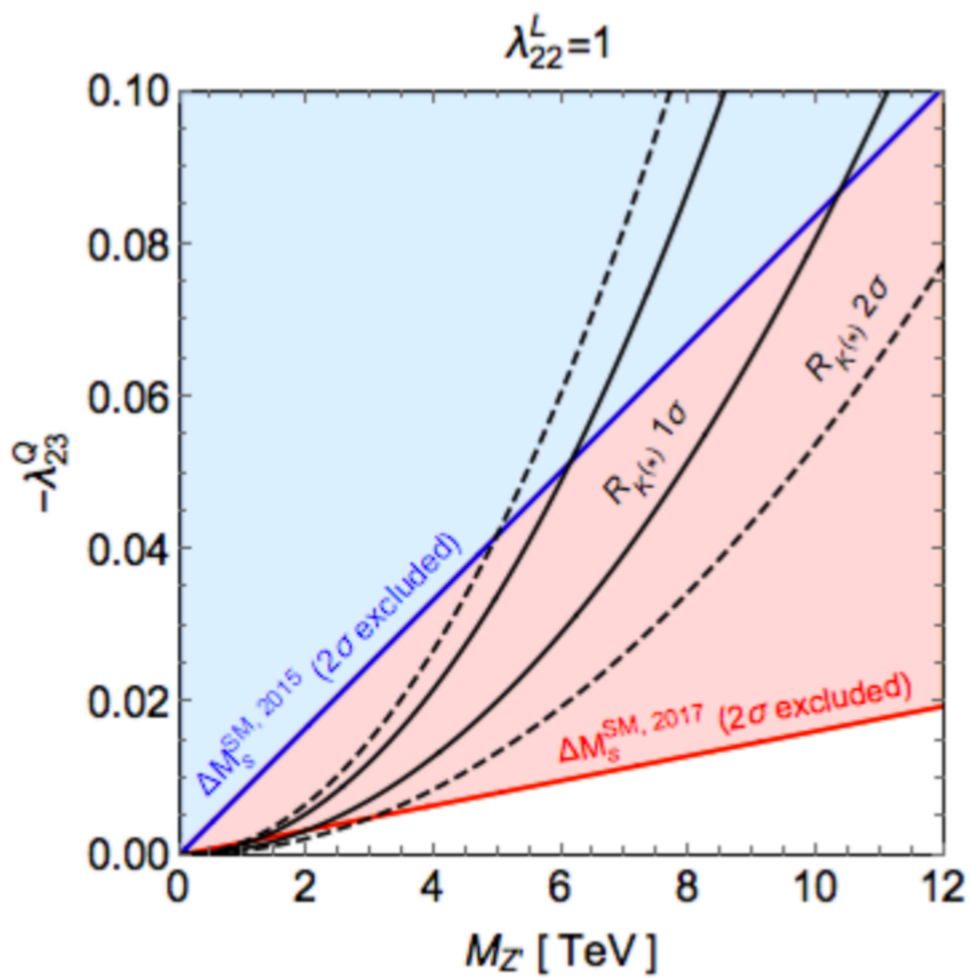


FIG. 2. Bounds from B_s-mixing on the parameter space of the simplified Z' model of Eq. (20), for real λ_{23}^Q and $\lambda_{22}^L = 1$. The blue and red shaded areas correspond respectively to the 2σ exclusions from $\Delta M_s^{\mathrm{SM},\,2015}$ and $\Delta M_s^{\mathrm{SM},\,2017}$, while the solid (dashed) black curves encompass the 1σ (2σ) best-fit region from $R_{K^{(*)}}$.

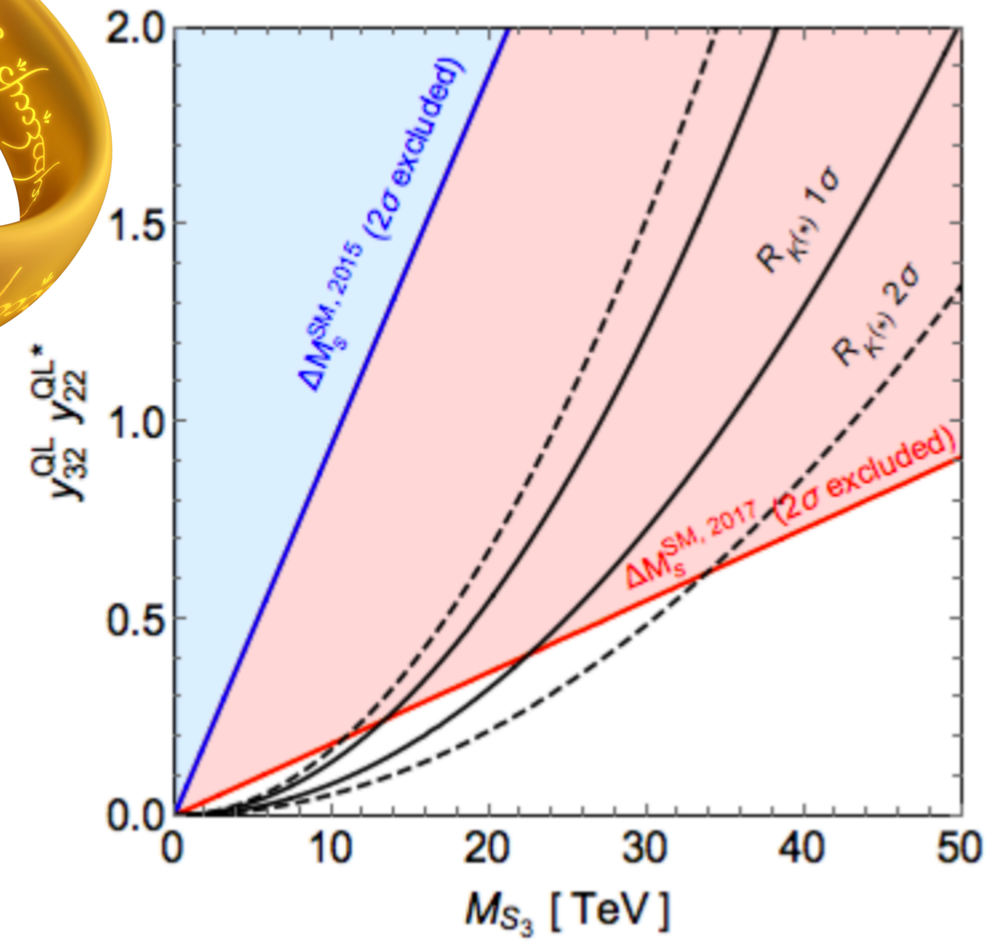


FIG. 3. Bounds from B_s-mixing on the parameter space of the scalar leptoquark model of Eq. (24), for real $y_{32}^{QL} y_{22}^{QL*}$ couplings. Meaning of shaded areas and curves as in Fig. 2.

BSM PHYSICS IS ON THE HORIZON?

Look for the remaining parameter space in Z' models

* *Look for Z' models with complex couplings*

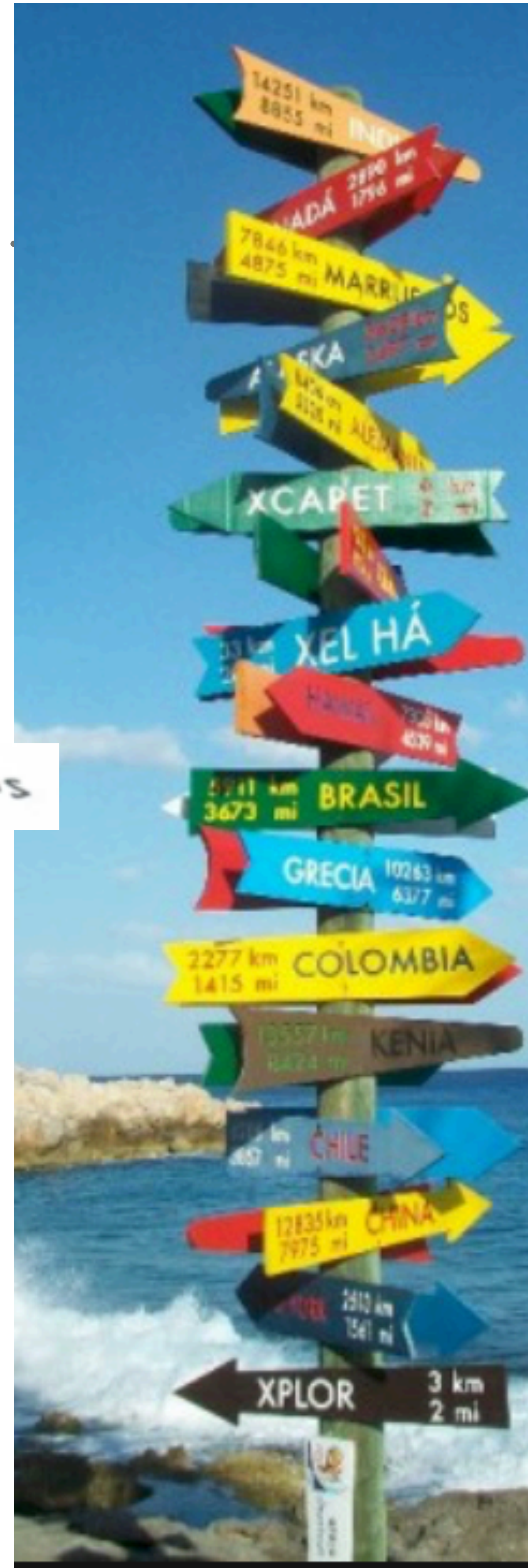
Look for BSM models with negative contributions to ΔM_s

* *Look for BSM models that explain more problems*

* *Look for LHC signatures of these BSM models*

**Look for non-standard BSM models*

.....

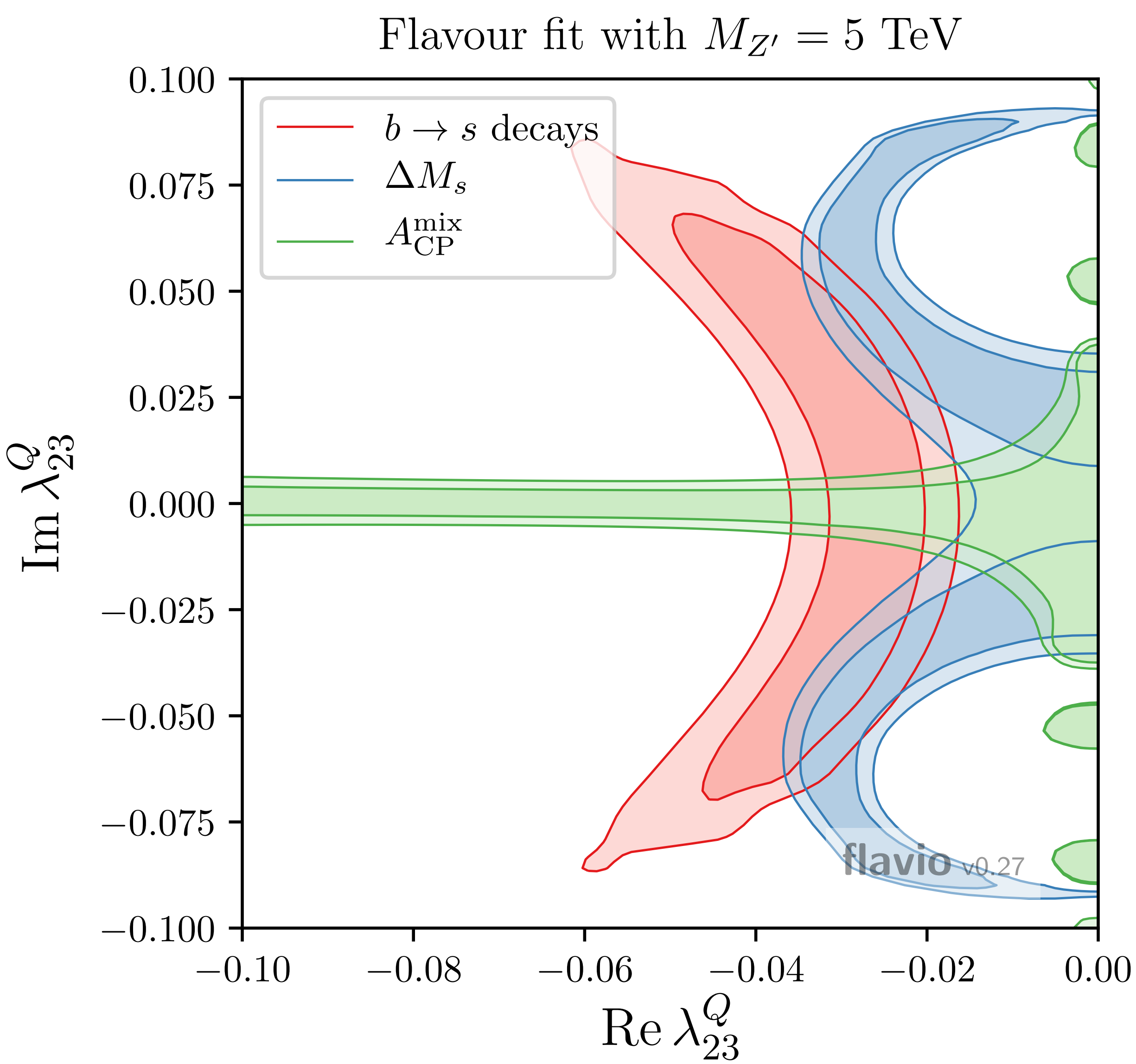


BSM PHYSICS IS ON THE HORIZON?

** Look for Z' models with complex couplings*

- **First idea to avoid positive contributions to M_12: Look for CP violation couplings of a Z' strong constraints from the phase for Bs mixing**

$$B_s \to J/\psi\phi$$



Measurement of the CP violating phase, Phi_s, in Run 2 using B°s→J/PsiK+K− Konstantin Gizdov, University of Edinburgh

BSM PHYSICS IS ON THE HORIZON?

** Look for BSM models that explain more problems*

1803.04430v1 [hep-ph] 12 Mar 2018

Flavourful Z' portal for vector-like neutrino Dark Matter and $R_{K^{(*)}}$

Adam Falkowski,[a] Stephen F. King,[b] Elena Perdomo[b] and Mathias Pierre[a]

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[b] *School of Physics & Astronomy, University of Southampton, Southampton SO17 1BJ, UK*

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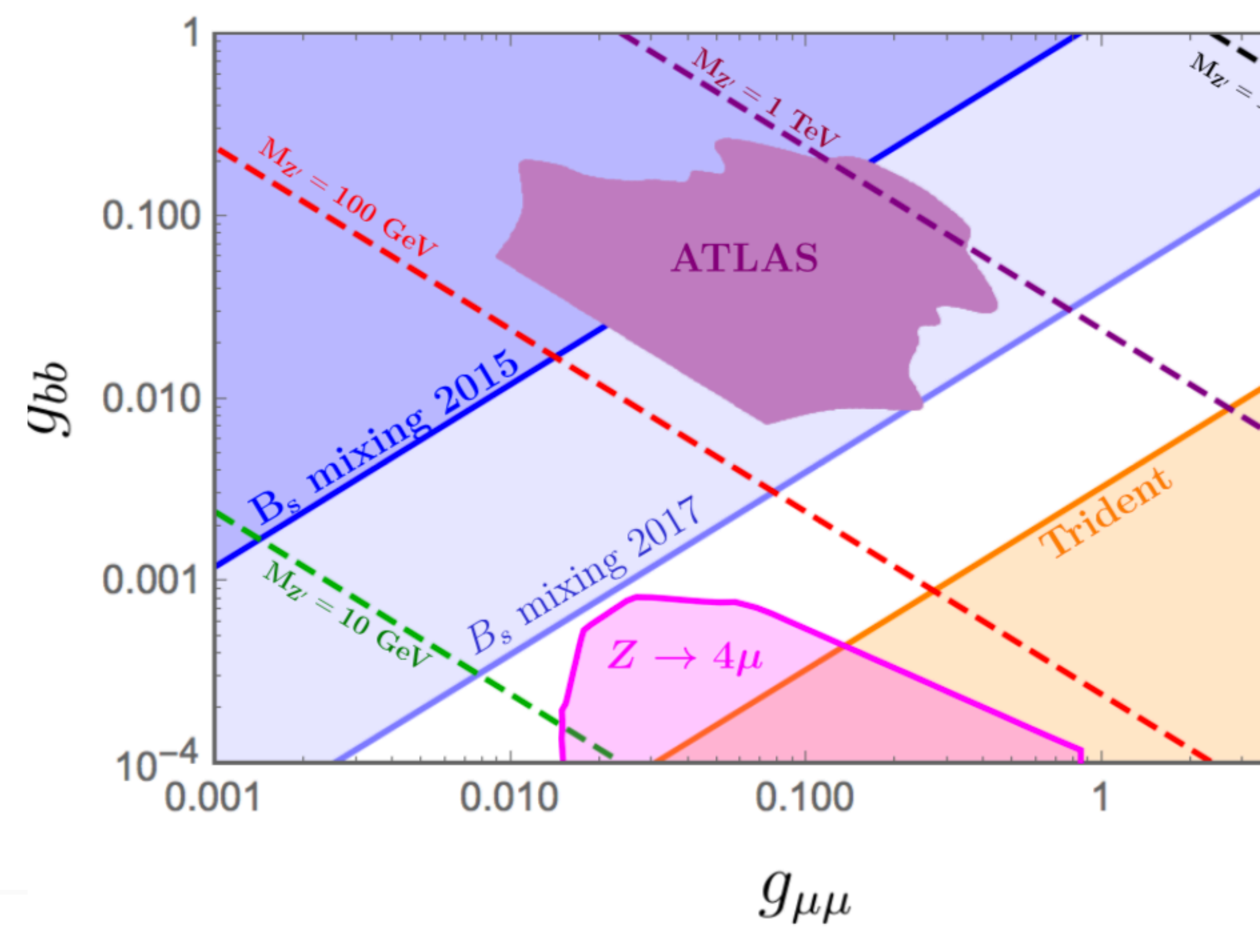
Abstract: We discuss a flavourful Z' portal model with a coupling to fourth-family singlet Dirac neutrino dark matter. In the absence of mixing, the Z' is fermiophobic, having no couplings to the three chiral families, but does couple to a fourth vector-like family. Due to mixing effects, the Z' gets induced couplings to second family left-handed lepton doublets and third family left-handed quark doublets. This model can simultaneously account for the measured B-decay ratios R_K and R_{K^*} and for the observed relic abundance of dark matter. We identify the parameter space where this explanation is consistent with existing experimental constraints from dark matter direct and indirect detection, LHC searches, and precision measurements of flavour mixing and neutrino processes.



BSM PHYSICS IS ON THE HORIZON?

** Look for LHC signatures of these BSM models*

The case for future hadron colliders from $B \to K^{(*)}\mu^+\mu^-$ decays

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Abstract: Recent measurements in $B \to K^{(*)}\mu^+\mu^-$ decays are somewhat discrepant with Standard Model predictions. They may be harbingers of new physics at an energy scale potentially accessible to direct discovery. We estimate the sensitivity of future hadron colliders to the possible new particles that may be responsible for the anomalies at tree-level: leptoquarks or Z's. We consider luminosity upgrades for a 14 TeV LHC, a 33 TeV LHC, and a 100 TeV *pp* collider such as the FCC-hh. In the most conservative and pessimistic models, for narrow particles with perturbative couplings, Z' masses up to 20 TeV and leptoquark masses up to 41 TeV may in principle explain the anomalies. Coverage of Z' models is excellent: a 33 TeV 1 ab^{-1} LHC is expected to cover most of the parameter space up to 8 TeV in mass, whereas the 100 TeV FCC-hh with 10 ab^{-1} will cover all of it. A smaller portion of the leptoquark parameter space is covered by future colliders: for example, in a $\mu^+\mu^- jj$ di-leptoquark search, a 100 TeV 10 ab^{-1} collider has a projected sensitivity up to leptoquark masses of 12 TeV (extendable to 21 TeV with a strong coupling for single leptoquark production).

Keywords: Beyond Standard Model, Heavy Quark Physics

ArXiv ePrint: 1710.06363

JHEP03(2018)021

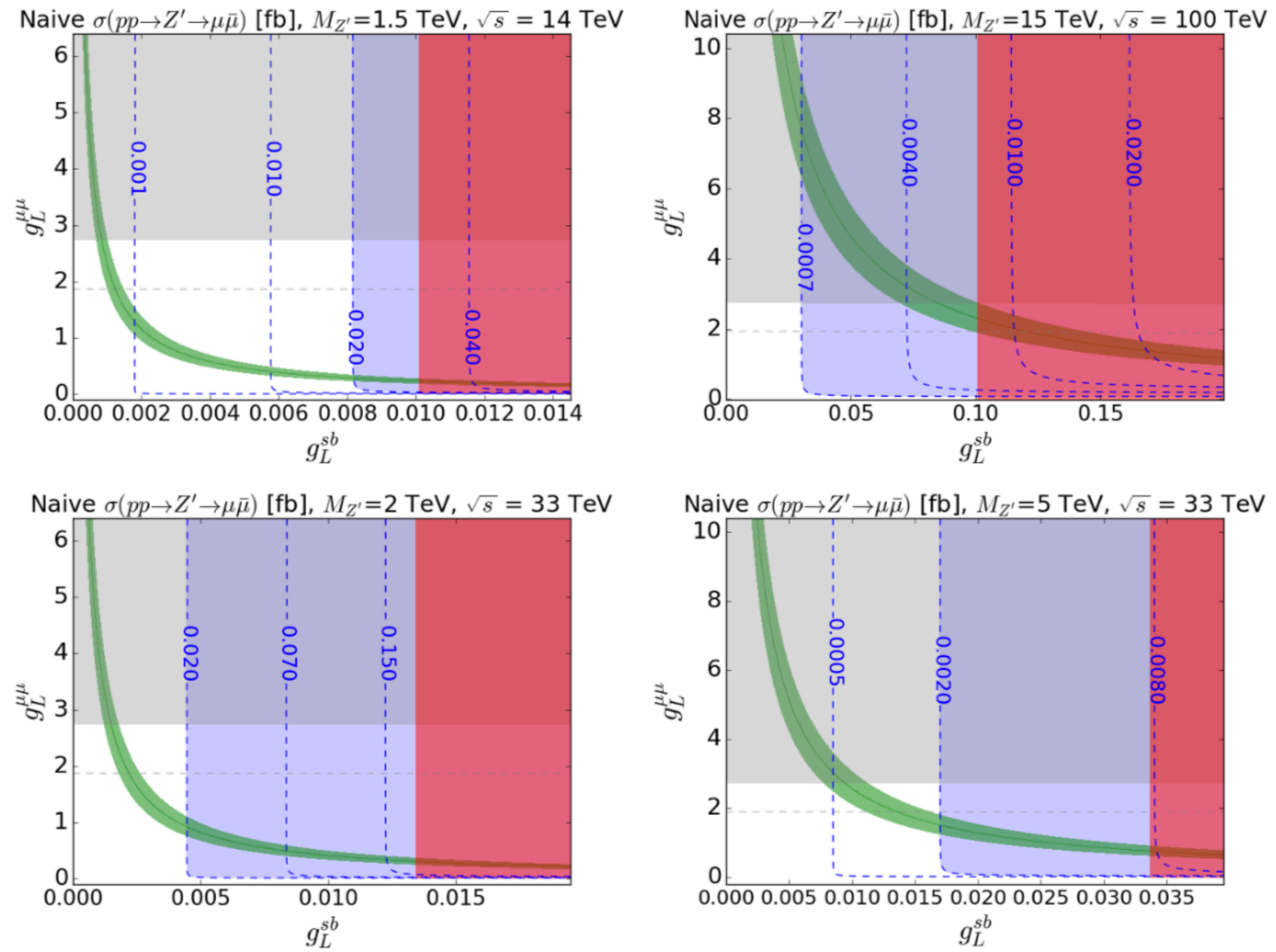


Figure 3. Parameter space of Z' models that explain $B \to K^{(*)}\mu^+\mu^-$ decay results for the naïve Z' model for different future colliders and $M_{Z'}$ assumptions. The horizontal (grey) shaded region violates the narrow width approximation. The vertical (red) region extending to the right hand side of each plot shows the limit coming from $B_s - \bar{B}_s$ mixing measurements. The (green) curve displays the region that fits $B \to K^{(*)}\mu^+\mu^-$ decay results. Above the dashed (grey) horizontal line, the coupling reaches a Landau pole below the Planck scale. The darker dashed (blue) contours are labelled with the expected production cross-section times branching ratio in fb. The shaded (blue) region shows the expected sensitivity at the future collider from di-muon resonance searches derived from figure 2.

BSM PHYSICS IS ON THE HORIZON?

**Look for non-standard BSM models*

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

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

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

This affects rare decays and mixing/lifetimes:

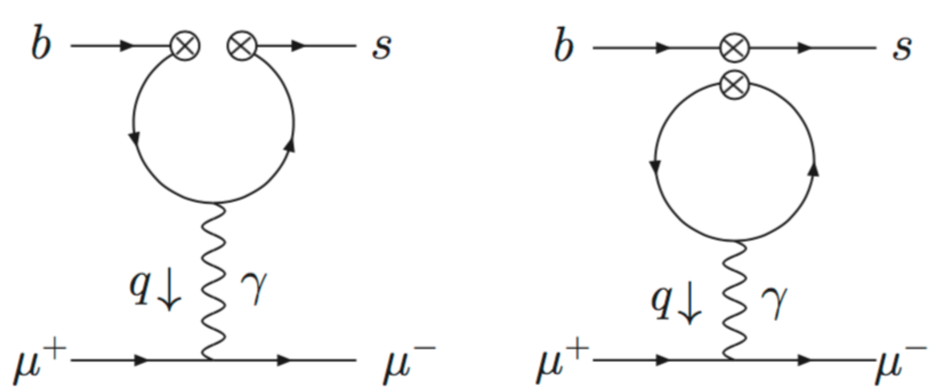


FIG. 1. Leading Feynman diagrams for CBSM contributions to rare and semileptonic decays. With our choice of Fierz-ordering, only the diagram on the left is relevant.

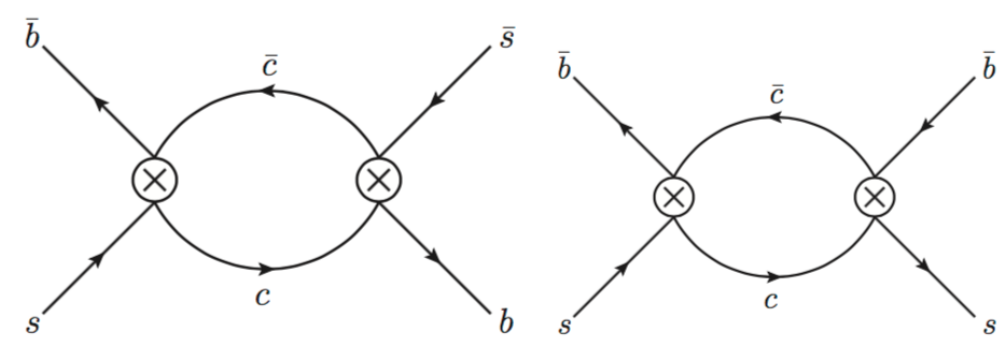


FIG. 2. Leading Feynman diagrams for CBSM contributions to the width difference $\Delta\Gamma_s$ (left) and the lifetime ratio $\tau(B_s)/\tau(B_d)$ (right).

CONCLUSION

- Extremely exciting pattern of anomalies in decays of heavy hadrons
- Many anomalies can be explained simultaneously

- Control of QCD effects is absolutely crucial
- Theory status very promising - can systematically be improved
- Control channels, e.g. baryons, Kaons, charm,..

- Interesting playground for model-building
- Space of allowed models is considerably restricted

END

CONCLUSION

- 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

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

B mixing

$3.6\ \sigma$: 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

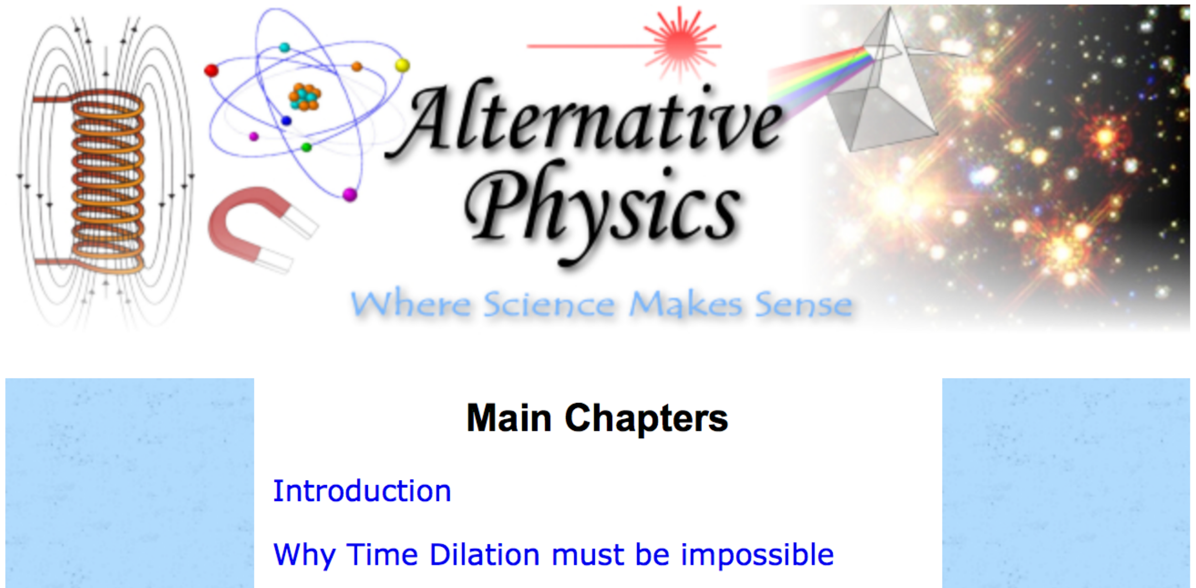
$2\ \sigma$: New lattice results $\Delta M_s = 2|M_{12}^s|\,, \quad \Delta\Gamma_s = 2|\Gamma_{12}^s| \cos\phi_{12}^s\,, \quad a_{sl}^s = \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| \sin\phi_{12}^s$

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

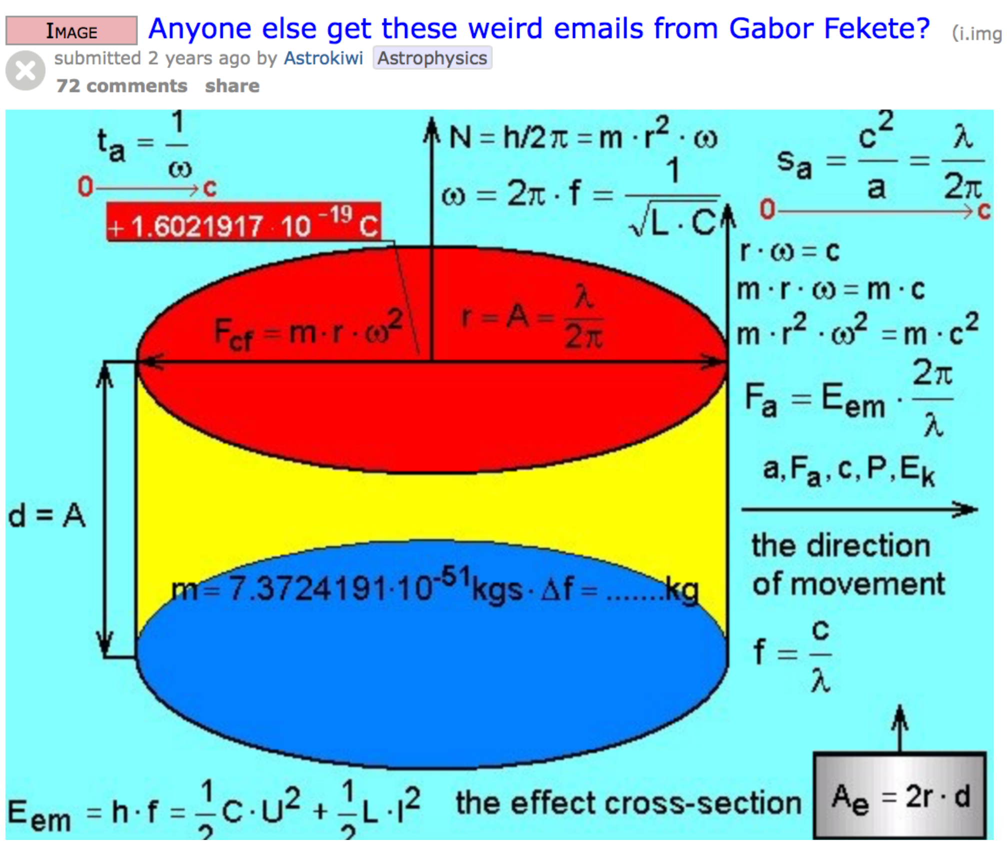
NP IN TREE-LEVEL DECAYS

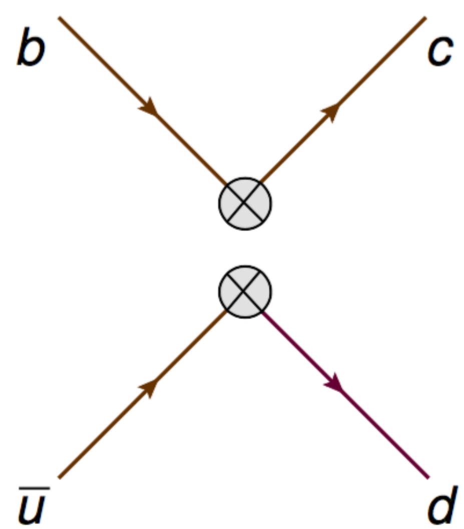


Do a systematic study of tree-level observables that are both well known in experiment and theory

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

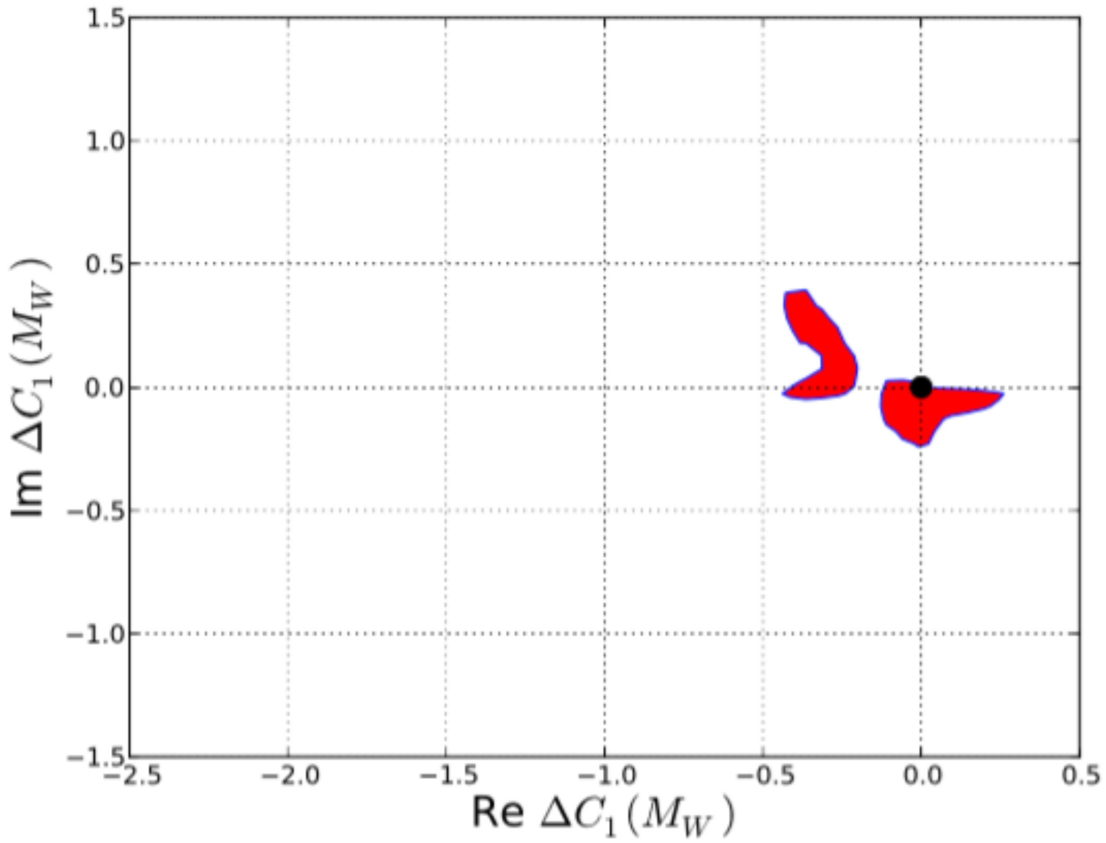
$$\hat{\mathcal{H}}_{eff} = \frac{V_{cb}V_{ud}^*}{\sqrt{2}}\left(C_1\hat{Q}_1 + C_2\hat{Q}_2\right)$$

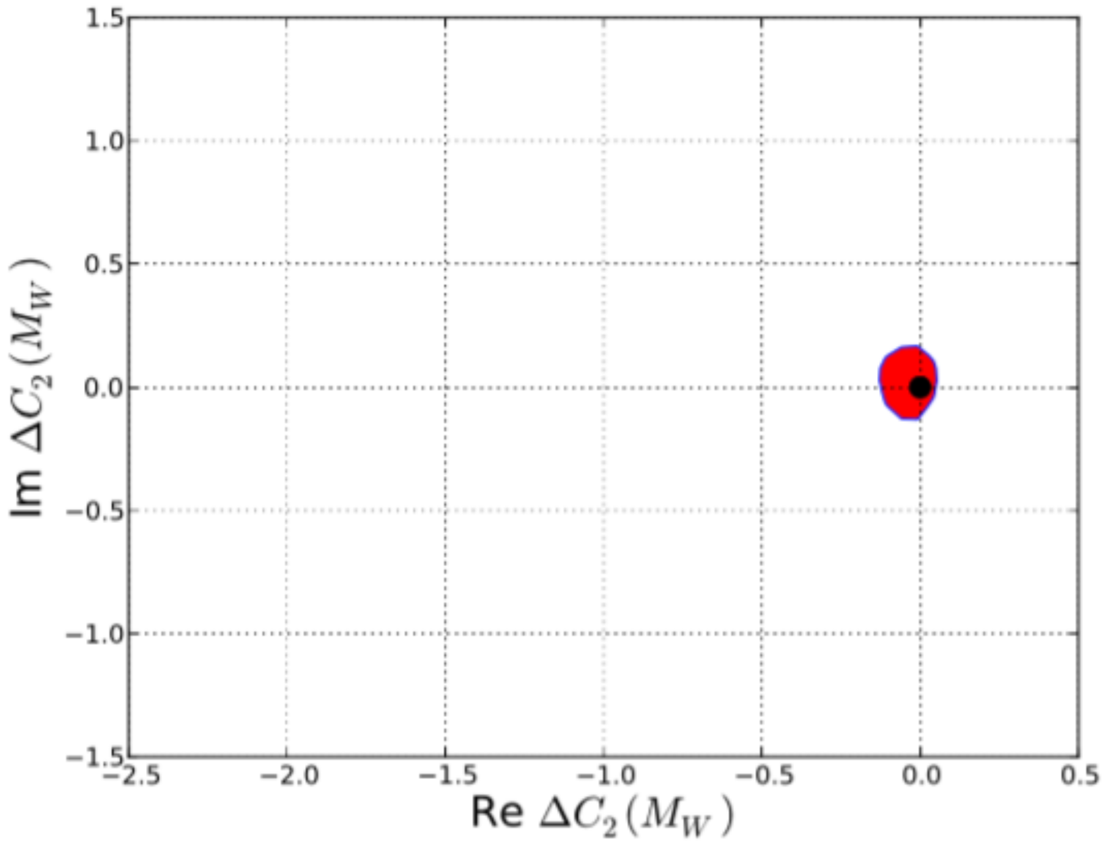




NP IN TREE-LEVEL DECAYS

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