B Physics Anomalies and High Energy Collider

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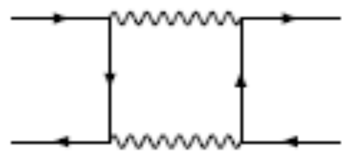
Why is flavor physics interesting?

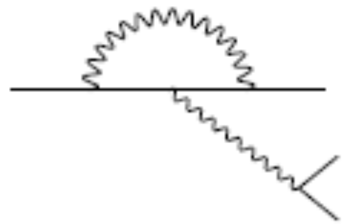
From the historic view, flavor physics had played important roles in searching for the " New Physics"

- 1963: concept of flavour mixing [Cabibbo].
- 1964: discovery of CP violation in $K_L \to \pi^+\pi^-$ [Christenson *et al.*].
- 1970: introduction of the charm quark to suppress the flavour-changing neutral currents (FCNCs) [Glashow, Iliopoulos & Maiani].
- 1973: quark-flavour mixing with 3 generations allows us to accommodate CP violation in the SM [Kobayashi & Maskawa].
- 1974: estimate of the charm-quark mass with the help of the K^0–$\bar{K}^0$ mixing frequency [Gaillard & Lee].
- 1980s: the large top-quark mass was first suggested by the large B^0–$\bar{B}^0$ mixing seen by ARGUS (DESY) and UA1 (CERN).

Main Driving Force for Flavor Studies

- New Physics (NP): → typically new patterns in the flavour sector
  - supersymmetric (SUSY) scenarios;
  - left–right-symmetric models;
  - models with extra Z' bosons;
  - scenarios with extra dimensions;
  - "little Higgs" scenarios ...





- Sensitivity to NP through virtual quantum effects:
- Interplay with direct NP searches at ATLAS & CMS:[1]
  - If NP particles are produced and detected through their decays at the LHC, flavour-physics information helps to determine/narrow the underlying NP model and to establish new sources of CP violation.
  - NP effects could in fact show up *first* in the flavour sector, also if NP particles are too heavy to be produced directly at the LHC.
  - Fortunately, theory will be confronted with LHC data soon...

Challenging the Standard Model through Flavor Studies

Before searching for NP, we have to understand the SM picture!

- The key problem:

  ◇ *impact of strong interactions* → "hadronic" uncertainties

- The B-meson system is a *particularly promising* flavour probe:

  – Offers various strategies to eliminate the hadronic uncertainties and to determine the hadronic parameters from the data.

  – Simplifications through the large b-quark mass.

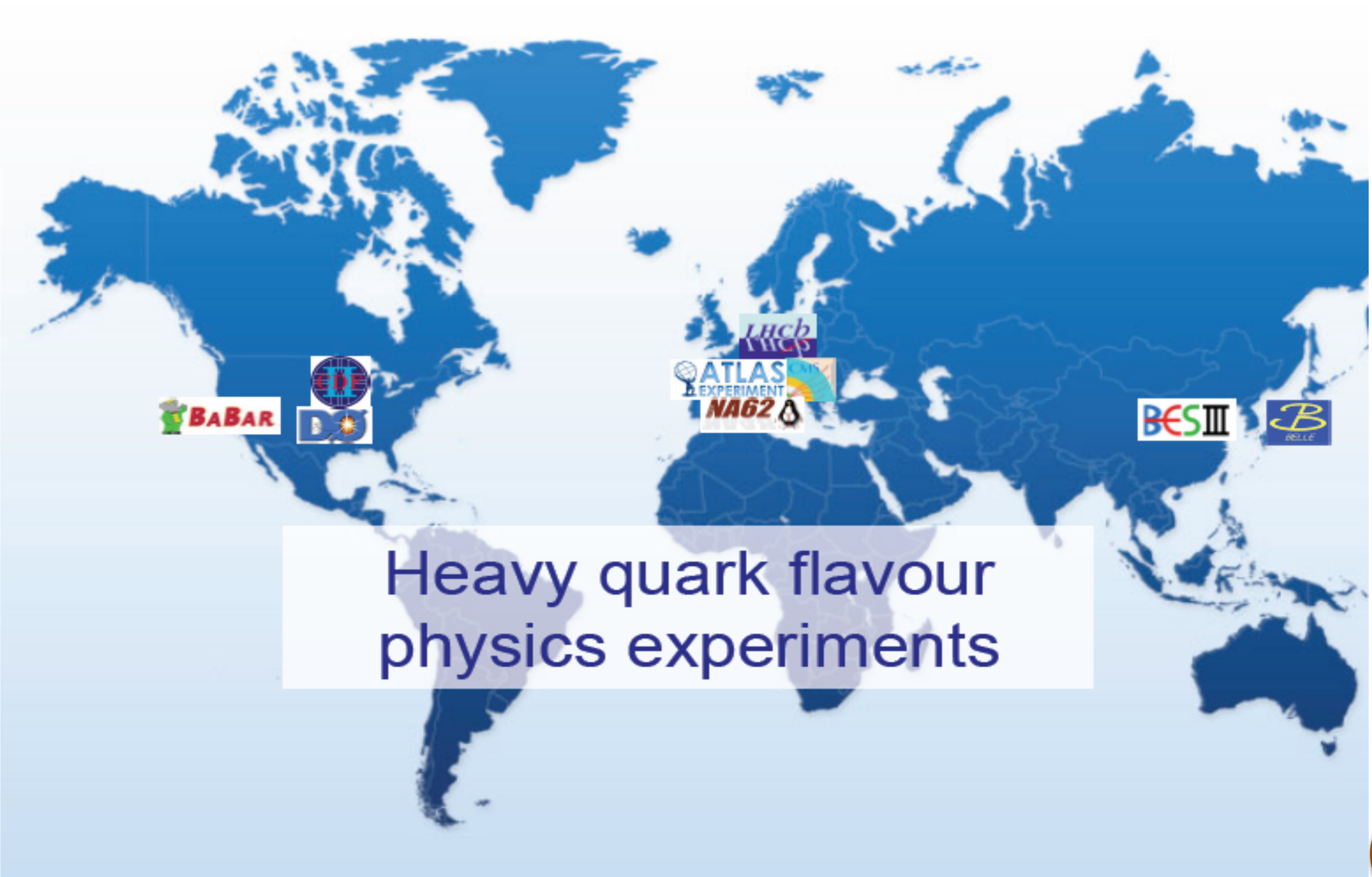
  – Tests of clean SM relations that could be spoiled by NP ...

- This feature led to the "rise of the B mesons":

  – K decays dominated for more than 30 years: *discovery* of (indirect) CP violation [$\to \varepsilon_K$] and direct CP violaton [$\to$ Re$(\varepsilon'/\varepsilon)$].

  – Since this decade the stage is governed by B mesons → our focus

Where do we study Flavor Physics



LHCb 50/fb Summary

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\,K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

- Many measurements with direct BSM sensitivity improve by a factor $5-10$

Belle II 50/ab summary

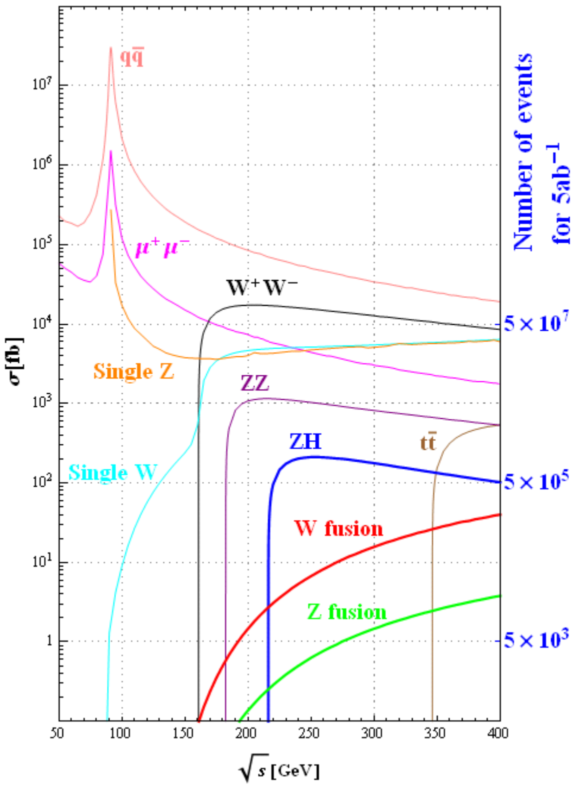
Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008	6
α		$\pm 2°$	$\pm 1°$	
γ	$\pm 14°$	$\pm 6°$	$\pm 1.5°$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011	>50
$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033	44
$\lvert V_{cb}\rvert$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\lvert V_{cb}\rvert$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\lvert V_{ub}\rvert$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\lvert V_{ub}\rvert$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\lvert V_{ub}\rvert$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$	3
$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	96 ± 26	$\pm 10\%$	$\pm 5\%$	46
$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	5σ	$>> 5\sigma$	>50
$R(B \to D\tau\nu)$	$\pm 16.5\%$	$\pm 5.6\%$	$\pm 3.4\%$	4
$R(B \to D^*\tau\nu)$	$\pm 9.0\%$	$\pm 3.2\%$	$\pm 2.1\%$	3
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ [10^{-6}]	< 40		$\pm 30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ [10^{-6}]	< 55		$\pm 30\%$	>50
$\mathcal{B}(B \to X_s\gamma)$ [10^{-6}]	$\pm 13\%$	$\pm 7\%$	$\pm 6\%$	< 1
$A_{CP}(B \to X_s\gamma)$		± 0.01	± 0.005	8
$S(B \to K^0_S\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 0.11	± 0.035	> 50
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	± 0.23	± 0.07	> 50
C_7/C_9 $(B \to X_s\ell\ell)$	$\sim 20\%$	10%	5%	
$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	± 0.3		
$\mathcal{B}(B_s \to \tau^+\tau^-)$ [10^{-3}]		< 2		

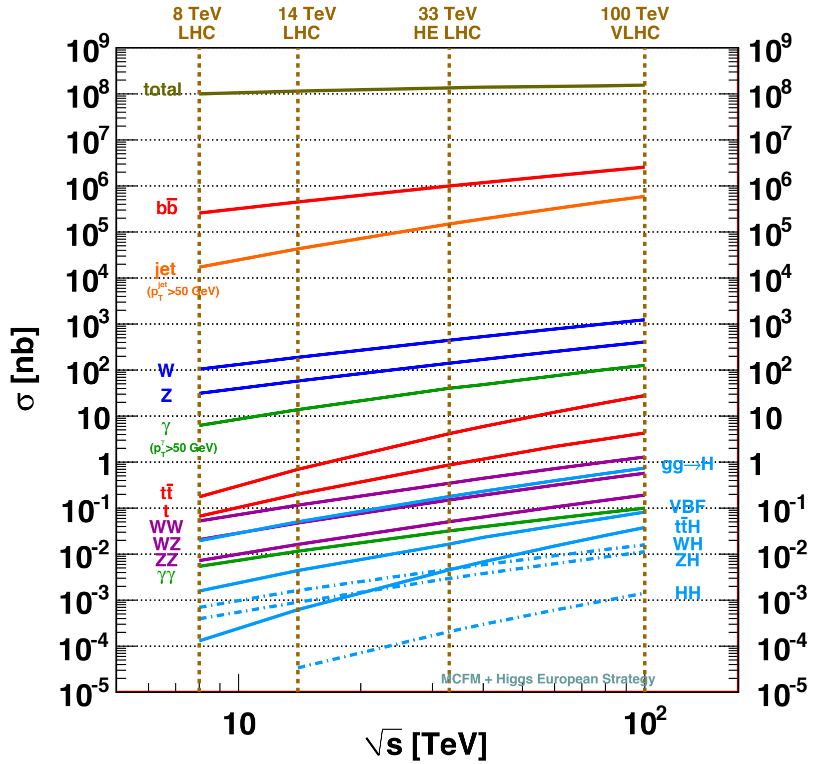
Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm 2.9\%$	$\pm(0.9\%$-$1.3\%)$	> 50
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm(3.5\%$-$4.3\%)$	$\pm(2.3\%$-$3.6\%)$	3-5
y_{CP} [10^{-2}]	$1.11 \pm 0.22 \pm 0.11$	$\pm(0.11$-$0.13)$	$\pm(0.05$-$0.08)$	5-8
A_Γ [10^{-2}]	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm(0.03$-$0.05)$	7 - 9
$A_{CP}^{K^+K^-}$ [10^{-2}]	$-0.32 \pm 0.21 \pm 0.09$	± 0.11	± 0.06	15
$A_{CP}^{\pi^+\pi^-}$ [10^{-2}]	$0.55 \pm 0.36 \pm 0.09$	± 0.17	± 0.06	> 50
$A_{CP}^{\phi\gamma}$ [10^{-2}]	± 5.6	± 2.5	± 0.8	> 50
$x^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	± 0.14	± 0.11	3
$y^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	± 0.08	± 0.05	15
$\lvert q/p\rvert^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ [°]	$-6 \pm 11 \pm {}^{4}_{5}$	± 6	± 4	10
$A_{CP}^{\pi^0\pi^0}$ [10^{-2}]	$-0.03 \pm 0.64 \pm 0.10$	± 0.29	± 0.09	> 50
$A_{CP}^{K^0_S\pi^0}$ [10^{-2}]	$-0.10 \pm 0.16 \pm 0.09$	± 0.08	± 0.03	> 50
$Br(D^0 \to \gamma\gamma)$ [10^{-6}]	< 1.5	$\pm 30\%$	$\pm 25\%$	2
	$\tau \to \mu\gamma$ [10^{-9}]	< 45	< 14.7	< 4.7
	$\tau \to e\gamma$ [10^{-9}]	< 120	< 39	< 12
	$\tau \to \mu\mu\mu$ [10^{-9}]	< 21.0	< 3.0	< 0.3

Clear physics cases in my opinion!

Broad program, large improvements !

Flavor Physics @CepC &SppC

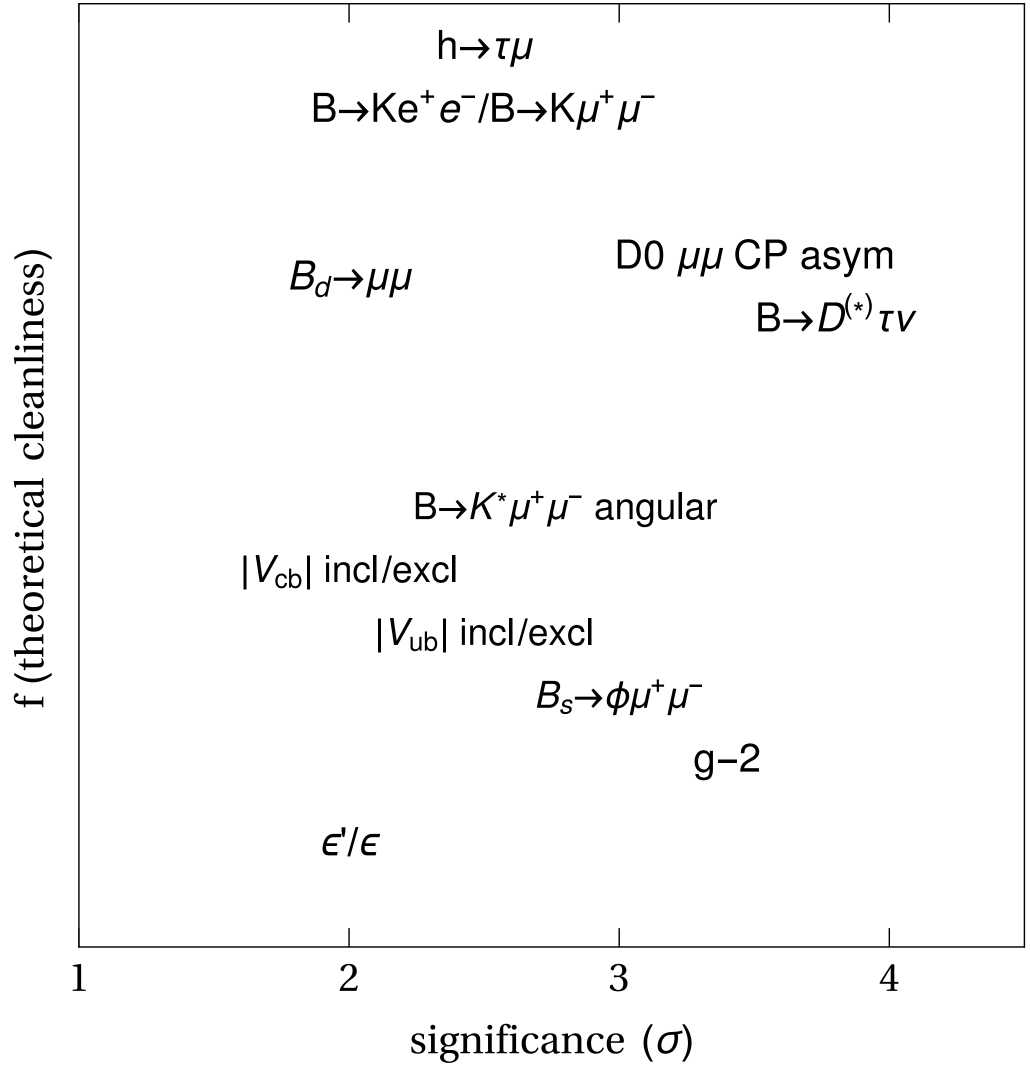




b-hadron species	Fraction in decays of $Z^0 \to b\bar{b}$	Number of b-hadron at Z^0 peak	Fraction in $\Upsilon(4S)/(5S)$ decays	Number of b-hadron at $\Upsilon(4S)/(5S)$
B^0	0.404 ± 0.009	22.0×10^{10}	0.486 ± 0.006 ($\Upsilon(4S)$)	4.9×10^{10}
B^+	0.404 ± 0.009	22.0×10^{10}	0.514 ± 0.006 ($\Upsilon(4S)$)	5.1×10^{10}
B_s	0.103 ± 0.009	5.4×10^{10}	0.201 ± 0.030 ($\Upsilon(5S)$)	0.6×10^{10}
b baryons	0.089 ± 0.015	4.8×10^{10}	–	–

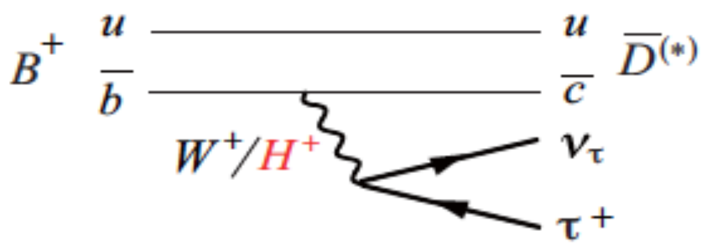
CepC will be a big Z-Factory & a flavor factory!

Status of Flavor Anomalies



Ligeti'talk, QCD Moriond, 2016,

The B → D(*)τ ν̄ Anomaly



Z. Phys, C46, 93 (1990)

xiao

- S.L. decays involving a $\tau^\pm$ have an additional helicity amplitude (for $D^*\tau\nu$)

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \left|V_{cb}\right|^2 \left|\mathbf{p}^*_{D^{(*)}}\right| q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2 \left[\left(|H_+|^2+|H_-|^2+|H_0|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3m_\tau^2}{2q^2}|H_s|^2\right]$$

For $D\tau\nu$, H_+ and H_- do not contribute!

- A charged Higgs (2HDM type II) of spin 0 coupling to the τ will only affect H_s

$$H_t^{2\mathrm{HDM}} = H_t^{\mathrm{SM}} \times \left(1 - \frac{\tan^2\beta}{m_{H\pm}^2}\frac{q^2}{1 \mp m_c/m_b}\right)$$

\- for $D\tau\nu$
\+ for $D^*\tau\nu$

PRD 78, 015006 (2008)
PhD 85, 094025 (2012)

This could enhance or decrease the BF, depending on $\tan\beta/m_H$

The $B \to D^{(*)}\tau\bar{\nu}$ Anomaly

A charged Higgs(2HDM type II)of spin0 coupling to the τ will only affect H_S

$$H_s^{2HDM} = H_s^{SM} \times \left(1 - \frac{\tan^2\beta}{m_H^2}\frac{q^2}{1 \mp \frac{m_c}{m_b}}\right)$$

We estimate the effect of 2HDM, accounting for difference in signal yield and efficiency.

The data match 2HDM Type II contribution at

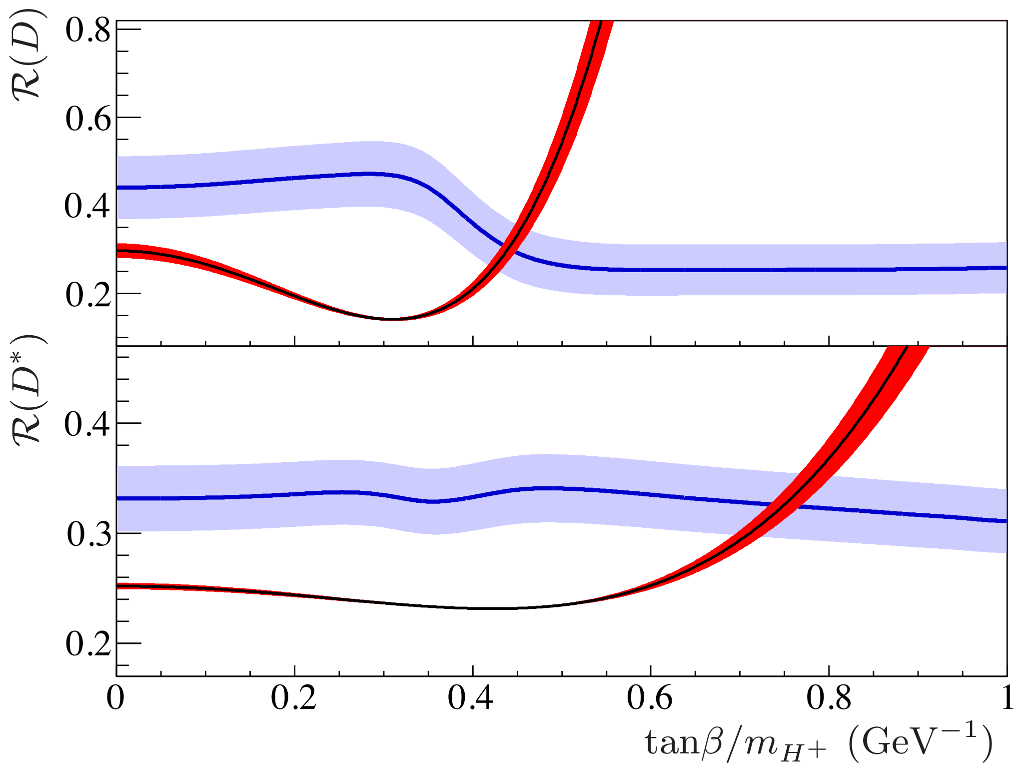
$\tan\beta/m_H = 0.44 \pm 0.02$ for R(D)

$\tan\beta/m_H = 0.75 \pm 0.04$ for R(D*)

The combination of R(D) and R(D*)

excludes the Type II 2HDM in the full tanβ-m_H parameter space with

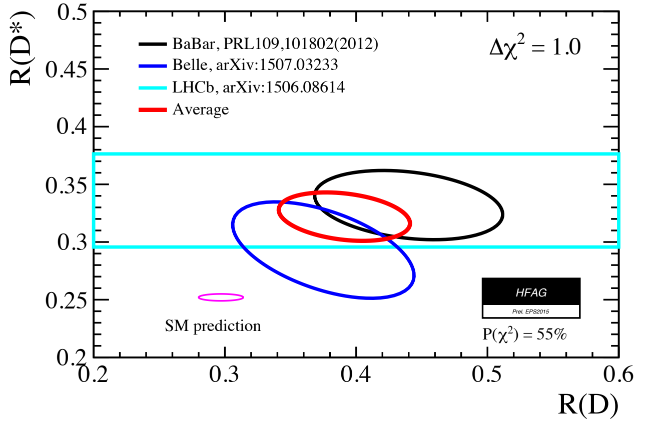
P >99.8%, provided M_H>15 GeV !



The B → D(*)τ ν̄ Anomaly

- Belle & LHCb results on the anomaly seen by BaBar in $R(X) = \dfrac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X(e/\mu)\bar{\nu})}$

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Average	0.391 ± 0.050	0.322 ± 0.022
my SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005



New last week: Belle semileptonic tag, $R(D^*) = 0.302 \pm 0.030 \pm 0.011$ [1603.06711]

Slightly reduce WA, higher significance (no HFAG update yet, correlations)

SM predictions: heavy quark symmetry + lattice QCD, only $R(D)$ [1503.07237, 1505.03925]

- Unexpected to see such an effect in a large tree-level SM rate
- Need NP at fairly low scales: leptoquarks, W', etc., likely visible in LHC Run 2

Consider redundant set of operators

Freytsis,et.al, 1506.08896

	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\rm int}$
SM $\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		$(1,3)_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L)W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			
$\mathcal{O}_{S_R}$	$(\bar{c} P_R b)\,(\bar{\tau} P_L \nu)$		$\rangle (1,2)_{1/2}$	$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$
$\mathcal{O}_{S_L}$	$(\bar{c} P_L b)\,(\bar{\tau} P_L \nu)$			
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$			
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \mathcal{O}_{V_L}\langle$	$(3,3)_{2/3}$	$\lambda\, \bar{q}_L \boldsymbol{\tau}\gamma_\mu \ell_L \boldsymbol{U}^\mu$
			$\rangle (3,1)_{2/3}$	$(\lambda\, \bar{q}_L \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{d}_R \gamma_\mu e_R)U^\mu$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow -2\mathcal{O}_{S_R}$		
$\mathcal{O}'_{S_R}$	$(\bar{\tau} P_R b)\,(\bar{c} P_L \nu)$	$\longleftrightarrow -\frac{1}{2}\mathcal{O}_{V_R}$		
$\mathcal{O}'_{S_L}$	$(\bar{\tau} P_L b)\,(\bar{c} P_L \nu)$	$\longleftrightarrow -\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$	$(3,2)_{7/6}$	$(\lambda\, \bar{u}_R \ell_L + \tilde{\lambda}\, \bar{q}_L i\tau_2 e_R)R$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)\,(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow -6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$		
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow -\mathcal{O}_{V_R}$		
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow -2\mathcal{O}_{S_R}$	$(\bar{3},2)_{5/3}$	$(\lambda\, \bar{d}^c_R \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{q}^c_L \gamma_\mu e_R)V^\mu$
$\mathcal{O}''_{S_R}$	$(\bar{\tau} P_R c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow \frac{1}{2}\mathcal{O}_{V_L}\langle$	$(\bar{3},3)_{1/3}$	$\lambda\, \bar{q}^c_L i\tau_2 \boldsymbol{\tau} \ell_L \boldsymbol{S}$
			$\rangle (\bar{3},1)_{1/3}$	$(\lambda\, \bar{q}^c_L i\tau_2 \ell_L + \tilde{\lambda}\, \bar{u}^c_R e_R)S$
$\mathcal{O}''_{S_L}$	$(\bar{\tau} P_L c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow -\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$		
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow -6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$		

Data → Operator Analysis → Model Building → Model Verify

Possible Models

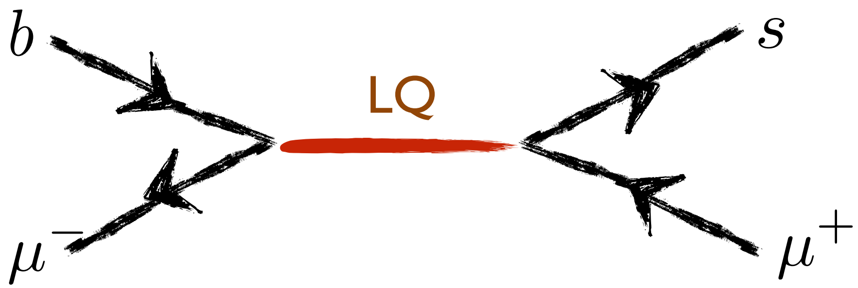
Freytsis,et.al, 1506.08896

- Good fits for several mediators: scalar, "Higgs-like" $(1,2)_{1/2}$
  vector, "W'-like" $(1,3)_0$
  "scalar leptoquark" $(\bar{3},1)_{1/3}$ or $(\bar{3},3)_{1/3}$
  "vector leptoquark" $(3,1)_{2/3}$ or $(3,3)_{2/3}$

- Which BSM scenarios can be MFV? [1506.08896]

  Not scalars, nor vectors, possibly viable LQ: scalar $S(\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$ or vector $U_\mu(\mathbf{1},\mathbf{1},\mathbf{3})$

  Bounds: $b \to s\nu\bar{\nu}$, D^0 & K^0 mixing, $Z \to \tau^+\tau^-$, LHC contact int., $pp \to \tau^+\tau^-$, etc.



Many signals, tests, consequences

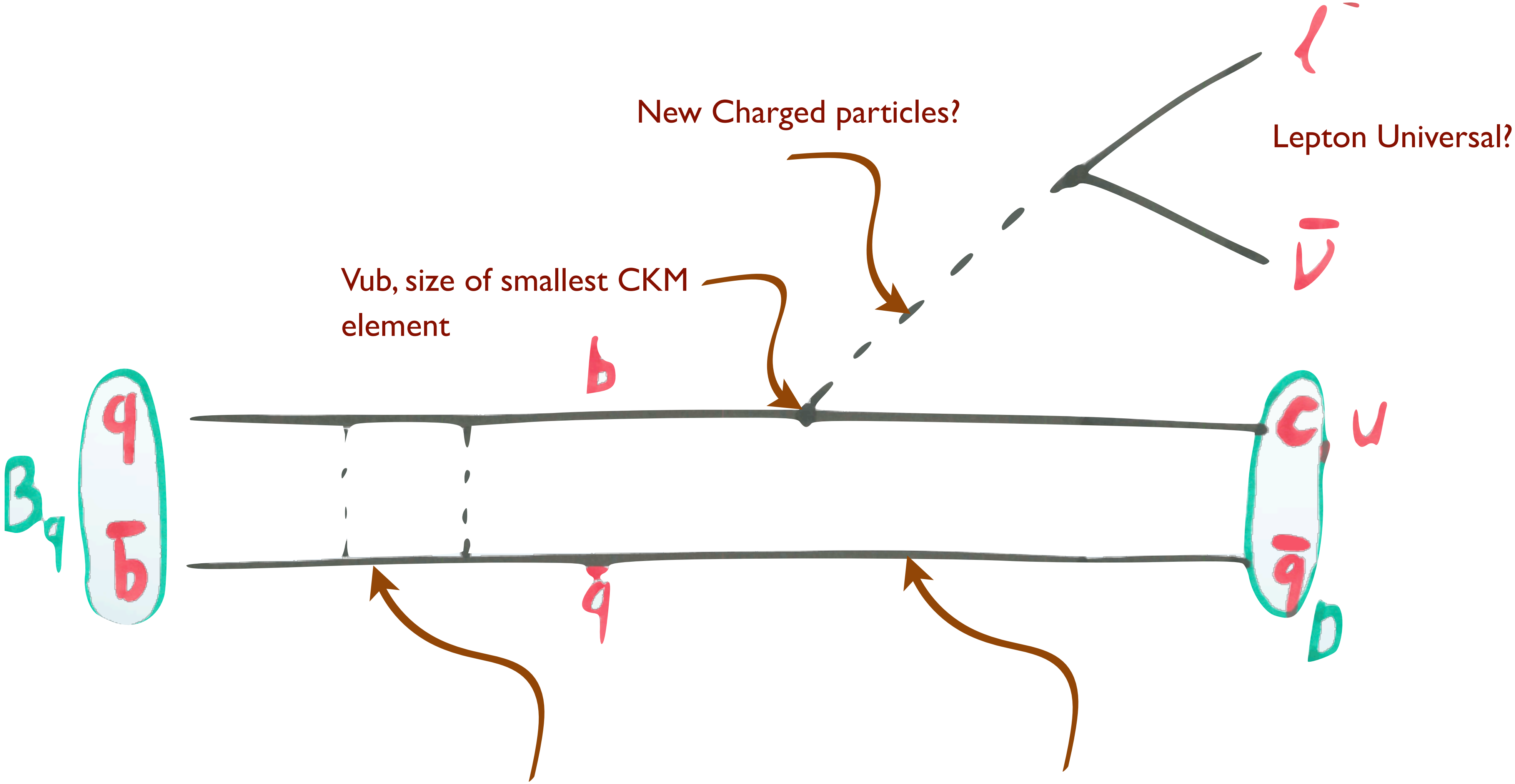
- LHCb, maybe soon: measure $R(D)$? use hadronic τ? measure $\Lambda_b \to \Lambda_c^{(*)}\tau\nu$?

  Ratios of c/u besides τ/μ? e.g.: $\Lambda_b \to \Lambda\tau\bar{\nu}$, $B \to \pi\tau\bar{\nu}$, $B \to \rho\tau\bar{\nu}$?

- longer term: refine $R(D^{(*)})$ and spectra; attempt inclusive (Belle II?)
  - Smaller theor. error in $[\mathrm{d}\Gamma(B \to D^{(*)}\tau\bar{\nu})/\mathrm{d}q^2]/[\mathrm{d}\Gamma(B \to D^{(*)}l\bar{\nu})/\mathrm{d}q^2]$ at same q^2
  - Improve bounds on $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$; $\mathcal{B}(B_s \to \tau^+\tau^-) \sim 10^{-3}$ possible?
  - $\mathcal{B}(D \to \pi\nu\bar{\nu}) \sim 10^{-5}$ possible, maybe BES III; enhanced $\mathcal{B}(D \to \mu^+\mu^-)$

- ATLAS & CMS: several extensions to current searches would be interesting
  - Searches for $t\tau$ and $b\tau$ resonances
  - Extensions of stop/sbottom searches to higher prod. cross sections ($t\nu$ and $b\nu$)
  - Searches for states appearing on-shell in t- but not in s-channel
  - Enhanced $h \to \tau^+\tau^-$ rate (and $t \to b\tau\bar{\nu}$ and/or $t \to c\tau^+\tau^-$)

More Physics on Semi-leptonic Decays

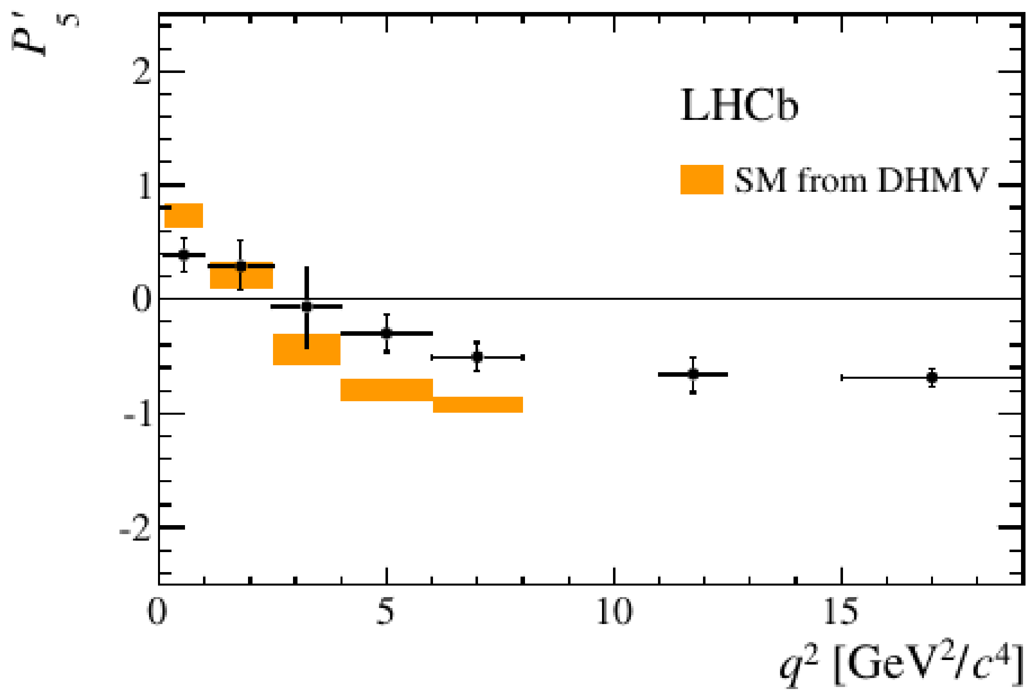


B oscillations (Δm_d) and *CP*(*T*) violation in mixing

How to calculate the transition form factors reliably.

The B → $K^*\mu^+\mu^-$ Anomaly

LHCb 1512.04442



- Statistical fluctuation
- Underestimated SM uncertainties? (Khodjamirian,Jager, Martin, Camalich, Lyon, Zwicky,Descotes-Genon,Wolfgang Altmannshofer ...)
- New Physics?

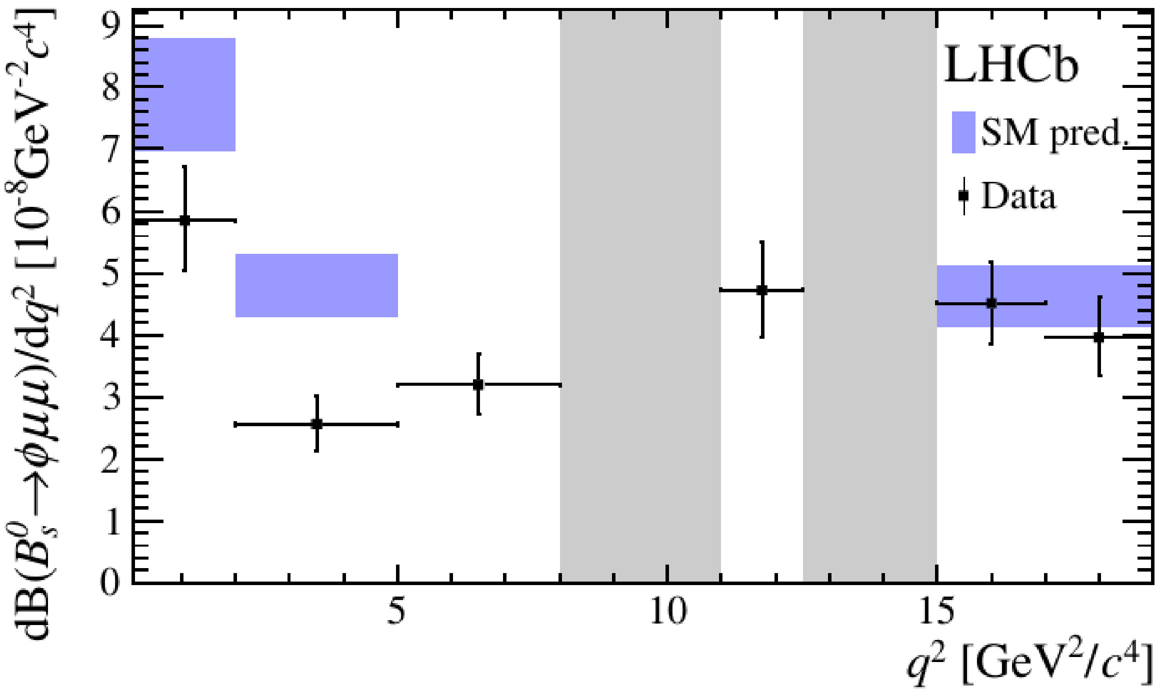
- can anomaly be explained model independently?
- can anomaly be explained in concrete NP models?

2.8σ deviation in [4,6] GeV^2 bin   ($+3.0\sigma$ in [6,8] GeV^2 bin)

- Cross checks: different regions of phase space, also study in B_s and Λ_b decays?
- Connected to many other processes: can one calculate form factors (ratios) reliably at small q^2? (semileptonic & nonleptonic decays, interpreting CP viol., etc.)

The Bs →Φμ⁺μ⁻ Anomaly

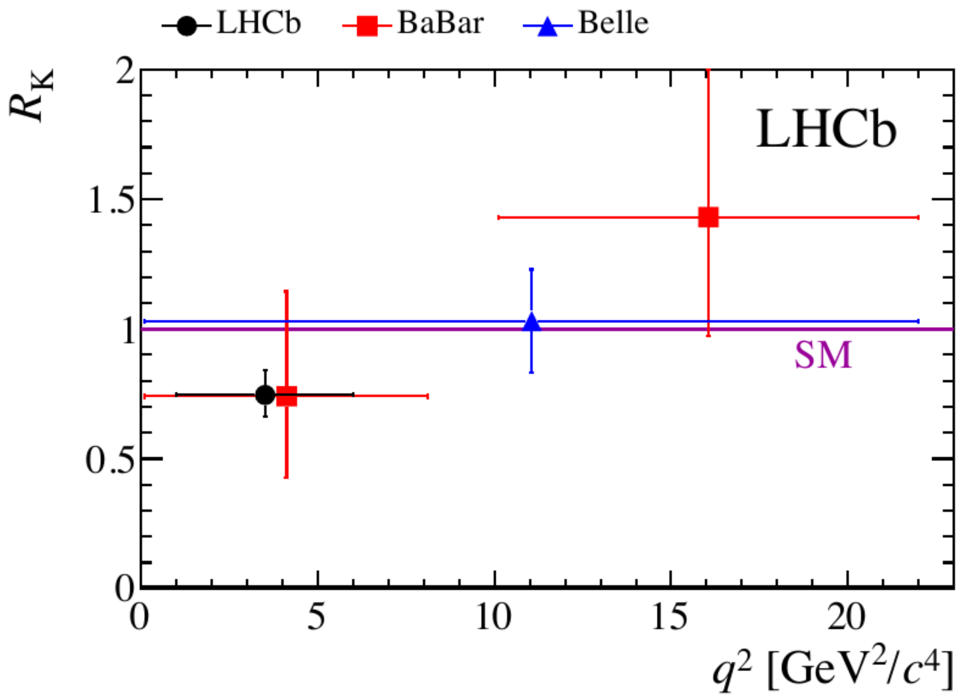
LHCb 1506.08777



branching ratio is 3.5σ below SM prediction for $1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$

The R_K Anomaly

LHCb 1406.6482



2.6σ hint for violation of lepton flavor universality (LFU)

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathrm{BR}(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

More Tensions

A number of rare decay observables deviate from SM expectations. 1411.3161

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[2, 4.3]$	0.44 ± 0.07	0.29 ± 0.05	LHCb	$+1.8$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[16, 19.25]$	0.47 ± 0.06	0.31 ± 0.07	CDF	$+1.8$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$
$B \to X_s e^+e^-$	10^6 BR	$[14.2, 25]$	0.21 ± 0.07	0.57 ± 0.19	BaBar	-1.8

Several global fits find significances up to 4 sigma.

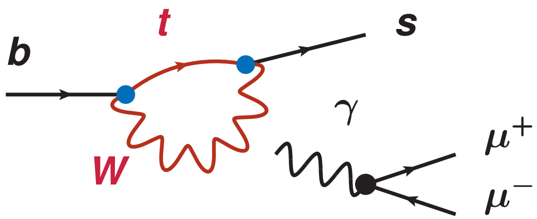
Significances depend on treatment of several nonperturbative effects.

Descotes-Genon, Altmannshofer, Straub Hurth, Mahmoudi, Martin Camlich, Lu, Wang, ...

What Could It Be ?

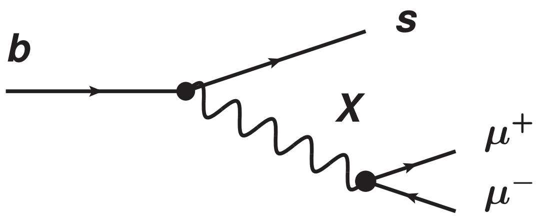
	branching ratios	angular observables	LFU ratios
millisecond pulsars?	?	?	?
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
underestimated hadronic effects?	✓	✓	✗
New Physics?	✓	✓	✓

A New Physics Scale from Rare B Decays



$$\sim \frac{g^4}{16\pi^2}\frac{1}{M_W^2}V_{ts}^*V_{tb}$$

SM amplitude is
loop suppressed and
CKM suppressed



$$\sim \frac{1}{\Lambda_{NP}^2}$$

Generic NP
not necessarily
suppressed

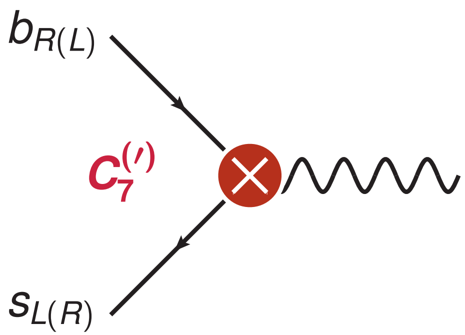
- O(1) non-standard effects in rare B decays correspond to new physics in reach of a 100 TeV collider

$$\Lambda_{NP} \sim \frac{M_W}{g^2}\sqrt{\frac{16\pi^2}{|V_{ts}^*V_{tb}|}} \sim 10\text{ TeV}$$

New Physics in b → s Decays

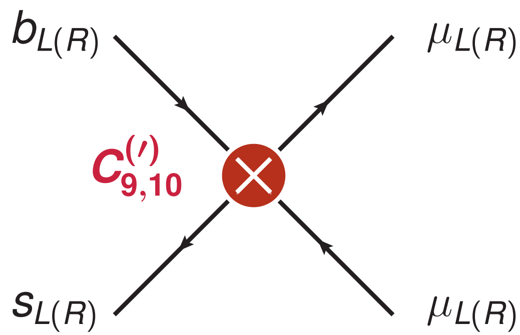
$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators



$\propto 1/q^2$

semileptonic operators



$\propto 1$

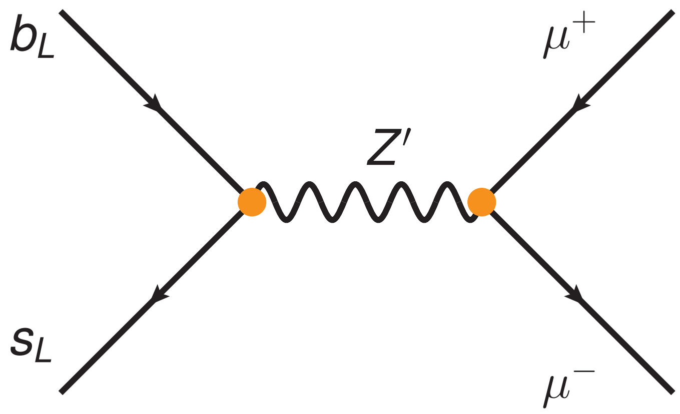
	C_7, C_7'	C_9, C_9'	C_{10}, C_{10}'
$B \to (X_s, K^*)\,\gamma$	★		
$B \to (X_s, K, K^*)\,\mu^+\mu^-$	★	★	★
$B_s \to \phi\,\mu^+\mu^-$	★	★	★
$B_s \to \mu^+\mu^-$			★

neglecting tensor operators (secretly dimension 8)

neglecting scalar operators (strongly constrained by $B_s \to \mu^+\mu^-$)

Models with Flavor Changing Z'Bosons

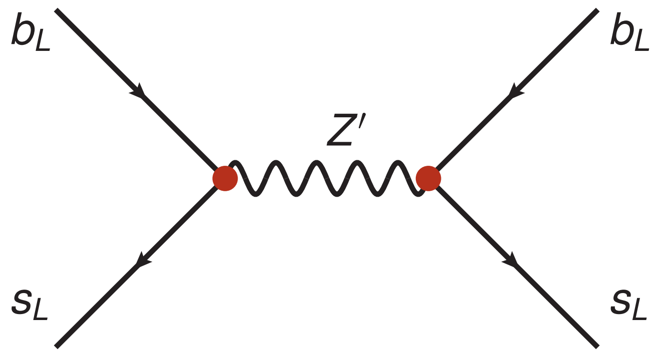
$$\mathcal{L} \supset \bar{f}_i \gamma^\mu \left[\Delta_L^{f_i f_j} P_L + \Delta_R^{f_i f_j} P_R \right] f_j Z'_\mu$$



want vectorial coupling to muons: $\Delta_L^{\mu\mu} = \Delta_R^{\mu\mu} = \frac{1}{2}\Delta_V^{\mu\mu}$

$$C_9^{\rm NP} = -\frac{\Delta_L^{bs}\Delta_V^{\mu\mu}}{V_{tb}V_{ts}^*}\frac{v^2}{M_{Z'}^2}\frac{4\pi^2}{e^2} \simeq -\frac{\Delta_L^{bs}\Delta_V^{\mu\mu}}{V_{tb}V_{ts}^*}\frac{(5\text{ TeV})^2}{M_{Z'}^2}$$

Z'Bosons in Bs-Mixing



- flavor changing Z' contributes also to B_s mixing at tree level

$$\frac{M_{12}}{M_{12}^{\rm SM}} - 1 = \frac{v^2}{M_{Z'}^2}(\Delta_L^{bs})^2 \left(\frac{g_2^2}{16\pi^2}(V_{tb}V_{ts}^*)^2 S_0\right)^{-1}$$

- constraint on the Z' mass and the flavor changing coupling (allowing for 10% NP in B_s mixing)

$$\frac{M_{Z'}}{|\Delta_L^{bs}|} \gtrsim 244 \text{ TeV} \simeq \frac{10 \text{ TeV}}{|V_{tb}V_{ts}^*|}$$

Z'Bosons Constraints from Exp.

- assume the couplings of the Z' are lepton flavor universal
- LEP bounds on four lepton contact interactions

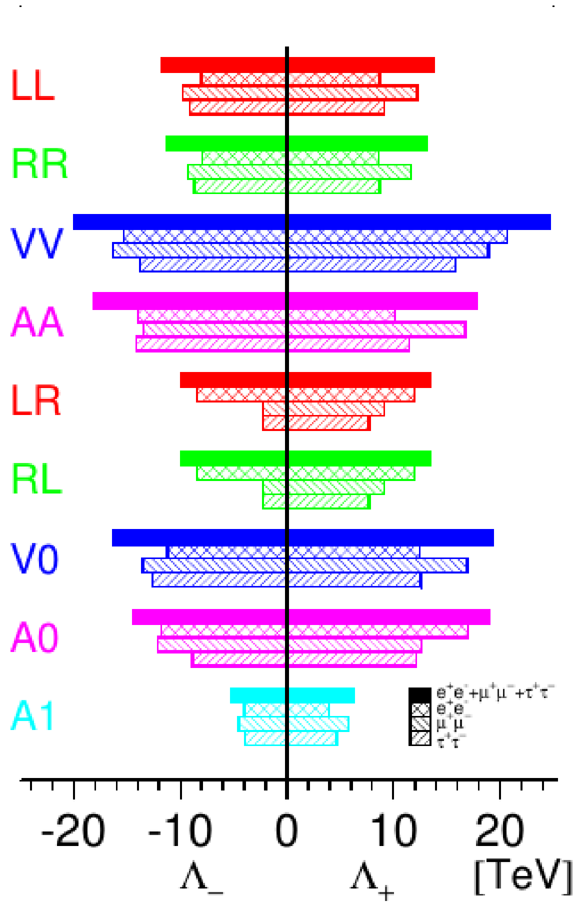
$$\mathcal{L} = \frac{4\pi}{\Lambda_{\pm}^2}(\bar{e}\gamma_\mu e)(\bar{\ell}\gamma^\mu \ell)$$

- constraint on the Z' mass and the vector coupling to leptons

$$\frac{M_{Z'}}{|\Delta_V^{\ell\ell}|} \gtrsim 3.5 \text{ TeV}$$

(can be improved at a CepC/FCC-ee/TLEP)

LEP: $e^+e^- \to l^+l^-$



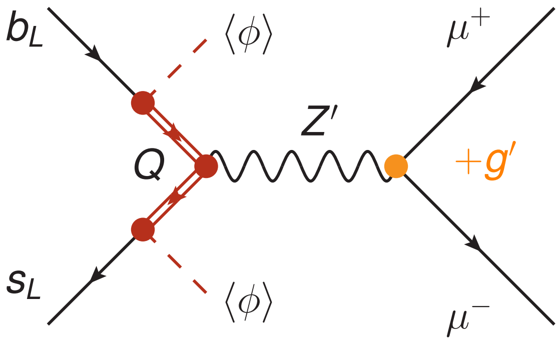
LEP Electroweak Working Group

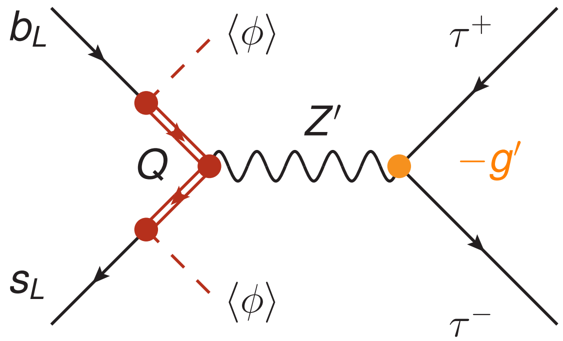
1302.3415

Model Based on Gauged Lμ − Lτ

Wolfgang,et.al, 1403.1269

New vector quark will be introduced





- the Z' model based on gauged $L_\mu - L_\tau$ predicts:

  1) opposite effects in the $\mu^+\mu^-$ and $\tau^+\tau^-$ final state
  2) no effect in the e^+e^- final state

→ prediction for LFU observables, e.g. ratios of branching ratios:

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathrm{BR}(B \to Ke^+e^-)_{[1,6]}} \simeq 0.82 \pm 0.11 \qquad (R_K^{\mathrm{SM}} \simeq 1)$$

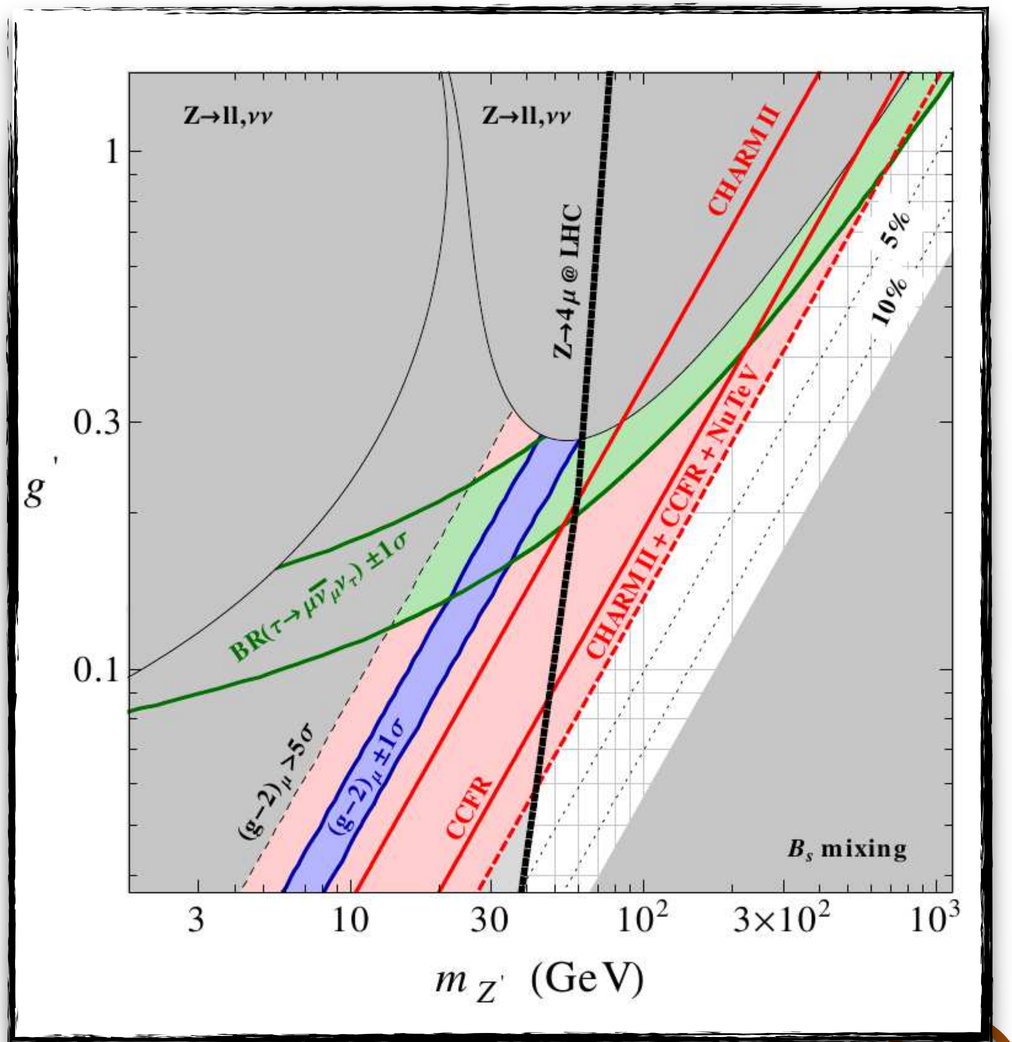
model passed the first test (LHCb Collaboration arXiv:1406.6482)

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Probing the Z ′

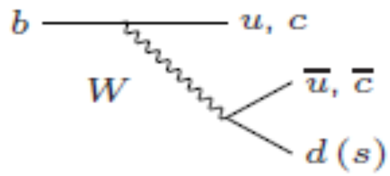
Wolfgang,et.al, 1403.1269

- (g − 2) of the muon tau decays
- *Z* couplings to leptons
- *Z*→4μ @LHC/CepC
- *Bs* mixing (upper bound)
- Neutrino trident production (lower bound)

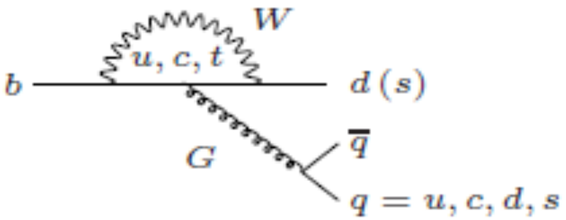


Non-leptonic B Decay

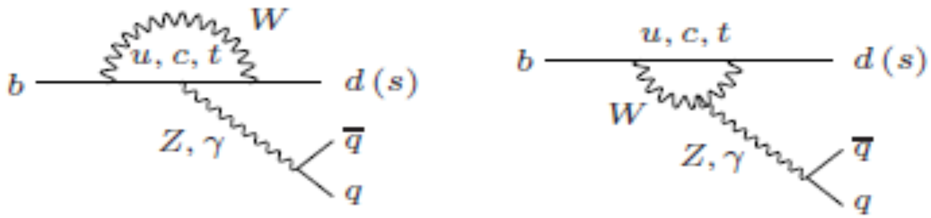
- Tree diagrams:



- Penguin diagrams:
  - ◇ QCD penguins:



  - ◇ Electroweak (EW) penguins:



- Classification (depends on the flavour content of the final state):
  - Only tree diagrams.
  - Tree and penguin diagrams.
  - Only penguin diagrams.

Direct CP Violation

- The most straightforward CP asymmetry ("direct" CP violation):[3]

$$\mathcal{A}_{\rm CP} \equiv \frac{\Gamma(B\to f)-\Gamma(\overline{B}\to\overline{f})}{\Gamma(B\to f)+\Gamma(\overline{B}\to\overline{f})} = \frac{|A(B\to f)|^2-|A(\overline{B}\to\overline{f})|^2}{|A(B\to f)|^2+|A(\overline{B}\to\overline{f})|^2}$$

$$= \frac{2|A_1||A_2|\sin(\delta_1-\delta_2)\sin(\varphi_1-\varphi_2)}{|A_1|^2+2|A_1||A_2|\cos(\delta_1-\delta_2)\cos(\varphi_1-\varphi_2)+|A_2|^2}$$

- Provided the two amplitudes satisfy the following requirements:

  i) non-trivial CP-conserving strong phase difference $\delta_1-\delta_2$;

  ii) non-trivial CP-violating weak phase difference $\varphi_1-\varphi_2$:

  $\Rightarrow$ CP violation originates through interference effects!

- Goal: extraction of $\varphi_1-\varphi_2$ ($\to$ UT angle) from the measured $\mathcal{A}_{\rm CP}$!
- Problem: uncertainties related to the strong amplitudes $|A_{1,2}|e^{i\delta_{1,2}}$ ...

Impact of New Physics

- Theoretical description through effective low-energy Hamiltonians:
  - The NP particles (such as the charginos, squarks in the MSSM) are "integrated out" as the W boson and the top quark in the SM:
    * Initial conditions for RG evolution: $C_k(\mu = M_W) \longrightarrow C_k^{\rm SM} + C_k^{\rm NP}$
  - Operators, which are absent or strongly suppressed in the SM, may actually play an important rôle:
    * Operator basis: $\{Q_k\} \longrightarrow \{Q_k^{\rm SM}, Q_l^{\rm NP}\}$
- Popular NP scenario: *Minimal Flavour Violation (MFV)*
  - Flavour and CP violation still governed by the SM Yukawa matrices.
  - Essentially no effects in CP asymmetries, but various interesting correlations between rare decay observables, mixing parameters, etc.

CPV in beauty baryons' decays

- First and second classes that are CKM suppressed.
- In the first class of Λ_b decays one gets $p\pi^-$, $p\pi^-\pi^0$, pK^-K^0, ΛK^-, $p\pi^-\pi^+\pi^-$, $p\pi^-K^+K^-$, etc.
- In the second class one probes pK^-, $pK^-\pi^0$, $pK_S\pi^-$, ΛK^+K^- etc.
- Ξ^-_b decays lead to $\Lambda^0\pi^-$, $\Lambda^0\pi^-\pi^0$ etc. and Λ^0K^-, $\Lambda^0K^-\pi^0$, $\Lambda^0\bar{K}^0\pi^-$ etc.
- For Ξ^0_b decays one probes $\Sigma^+\pi^-$, $\Lambda^0\pi^+\pi^-$, Σ^+K^-, $\Lambda^0\pi^+K^-$ etc.
- For obvious reasons we list only first class of Ω^-_b, namely $\Xi^0\pi^-$, Ω^-K^0

Conclusions

- In my view, flavor physics remains one of the most promising windows to & beyond the TeV scale.

- Various anomalies require better statistics and further measurements: potential for multiple 5-sigma effects. The higher energy colliders (CepC&SppC) will be necessary and able to deliver these measurements, with important interplay/complementarity with Belle2/LHC

- Numerous models explaining and correlating (and in one case predicting) anomalies exist. Perhaps we are already holding clues to flavor dynamics at relatively low scale?

- Conversely if nothing is found in LHC the new colliders will significantly push up the effective scale of flavor violation (via Bs->mu mu, right- handed current probes, and other observables as theory control improves)

Thanks