

Status of “B-physics anomalies”

Christoph Bobeth

CPPM Seminar
January 25, 2021

Outline

- ▶ Flavor in the Standard Model
- ▶ b Physics

***B* anomalies:**

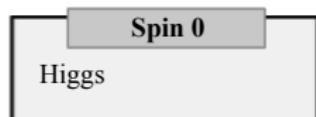
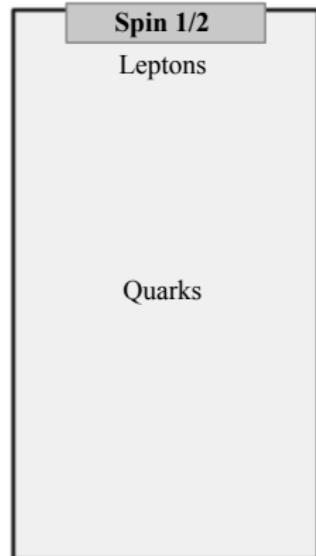
- ▶ Experimental status
- ▶ Comments on Standard Model and prospects
- ▶ New physics interpretation

Flavor in the Standard Model

(of particle physics)

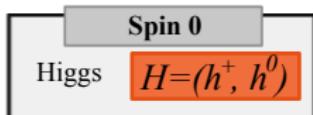
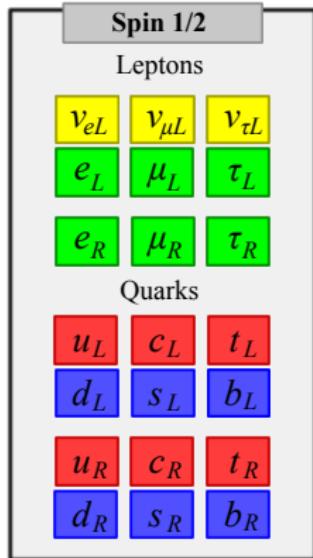
The Standard Model (SM)

We try to test known **general principles** and to find new ones at microscopic length scales



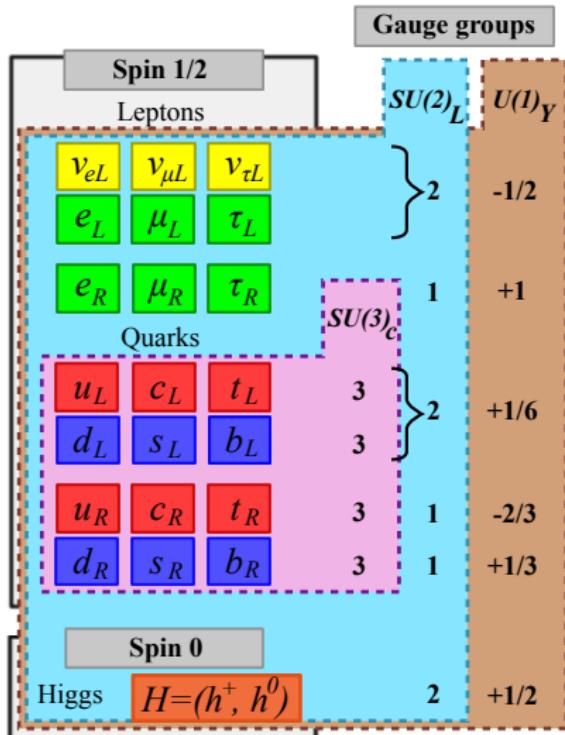
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Relativistic invariance + renormalizability ($\leq \text{dim } 4$)

- Scalar potential:

$$V(H) = -\mu^2 (H^\dagger H) + \Lambda (H^\dagger H)^2$$

- Yukawa potential for quarks:

$$\mathcal{L}_{\text{Yuk}} \sim \sum_{ij=1}^3 \bar{Q}_{L,i} (Y_{U,ij} \tilde{H} u_{R,j} + Y_{D,ij} H d_{R,j}) + \dots$$

3×3 matrices $Y_{U,D}$ distinguish generations \Rightarrow flavor

Local gauge invariance

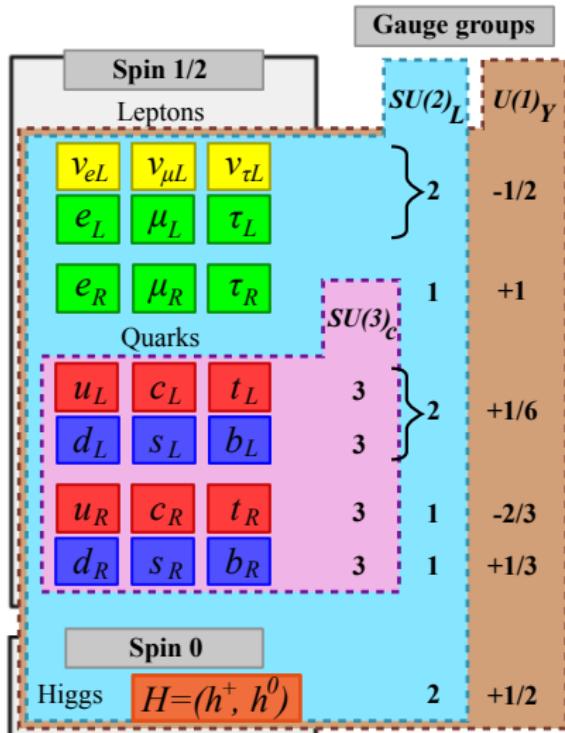
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

- minimal coupling " $\partial_\mu \rightarrow D_\mu = \partial_\mu + ig A_\mu$ "
- 3 gauge couplings: g_3, g_2, g_1
- massless gauge bosons

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$$

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Spontaneous Symmetry Breaking (SSB)

[Englert/Brout & Higgs & Guralnik/Hagen/Kibble mechanism]

- residual symmetry with massless photon: $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{\text{em}}$
- massive gauge bosons: m_W, m_Z
- massive Leptons and Quarks: (but $m_\nu = 0$)
 - $Y_U \rightarrow m_{u,c,t}$, $Y_D \rightarrow m_{d,s,b}$, $Y_L \rightarrow m_{e,\mu,\tau}$

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$$

Flavor changes in SM \rightarrow CKM matrix

Mass eigenstates \Rightarrow diagonalization of mass matrix of quarks and gauge bosons

- ▶ the **only flavor-changing coupling in SM** via W^\pm gauge bosons

$$U_i = \{u, c, t\}:$$

$$Q_u = +2/3$$

$$D_j = \{d, s, b\}:$$

$$Q_d = -1/3$$

$$\mathcal{L}_{udW^\pm} \supset \frac{g_2}{\sqrt{2}} (\bar{u} \bar{c} \bar{t}) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma^\mu P_L \begin{pmatrix} d \\ s \\ b \end{pmatrix} W_\mu^+ U_i \quad D_j$$

~ Cabibbo-Kobayashi-Maskawa (CKM) matrix

- ▶ $V_{\text{CKM}} V_{\text{CKM}}^\dagger = \mathbb{1}_{3 \times 3}$ \Rightarrow **only 4 real parameters**

→ in principle $18 - 9 = 9$ real dof's but phase transformations of 5 quark fields allow to remove unphysical ones

- ▶ **CP violation** via complex phase in V_{CKM}

[Kobayashi/Maskawa Prog.Theor.Phys. 49 (1973) 652]

→ requires existence of at least 3 generations

- ▶ Quark-Yukawa coupl's $\in \mathbb{C}$ depend on **6 quark masses** and **4 CKM parameters**

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The SM has $2|_{\mu, \Lambda} + 3|_{g_1, g_2, g_3} + 9|_{m_q, m_\ell} + 4|_{\text{CKM}} = 18$ parameters

omitting massive neutrino's and θ_{QCD}

These are fundamental parameters of nature \Rightarrow need to determine them as precisely as possible

b Physics

The *b* quark

- ▶ *b* = bottom or *b* = beauty ? (PDG uses “bottom”)
- ▶ introduced by Kobayashi/Maskawa 1973 to explain CP violation \Rightarrow discovered 1977
- ▶ heaviest quark of light quarks
- ▶ heaviest quark that forms hadronic bound states
- ▶ large mass opens more decay channels than for lighter quarks *c, s*
- ▶ hierarchy with QCD binding scale
 $m_b \sim 4.2 \text{ GeV} \ll m_W \sim 80 \text{ GeV}$
- ⇒ *b* quark acts as static color source in background of “brown muck” [Nathan Isgur]
- ⇒ puts theory predictions for hadronic matrix elements on firmer grounds

$$\Lambda_{\text{QCD}} \lesssim 0.5 \text{ GeV} \ll m_b$$

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b Mesons:

Particle Data Group (PDG) convention: $\bar{B}_q = (\bar{q}b)$ and $B_q = (q\bar{b})$ + excited states

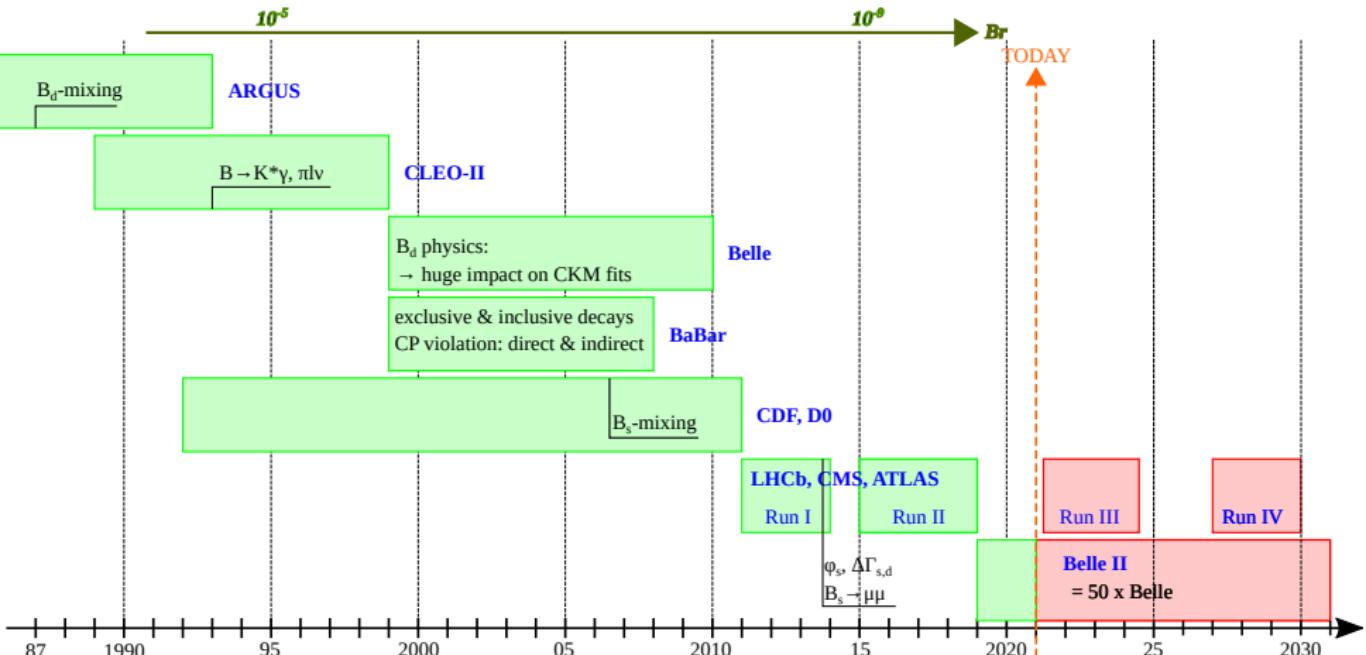
$$\begin{array}{llll}\bar{B}_u = B^- = (\bar{u}b) & \bar{B}_d = \bar{B}^0 = (\bar{d}b) & \bar{B}_s = \bar{B}_s^- = (\bar{s}b) & \bar{B}_c = B_c^- = (\bar{c}b) \\ m_{B_u} = 5.2793 \text{ GeV} & m_{B_d} = 5.2796 \text{ GeV} & m_{B_s} = 5.3669 \text{ GeV} & m_{B_c} = 6.2749 \text{ GeV}\end{array}$$

b Baryons:

PDG convention: $\Lambda_b^0 = (udb)$ and more exotic $\Xi_b^0 = (usb)$, $\Xi_b^- = (dsb)$, $\Omega_b^- = (ssb)$ $m_{\Lambda_b} = 5.6196 \text{ GeV}$

$\Rightarrow b$ physics studies properties and decays of these mesons and baryons

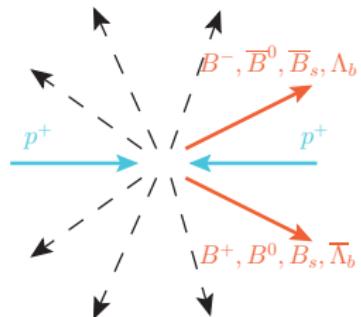
b Experiments: Past & Future



b Experiments: LHCb and Belle II

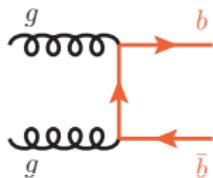
LHCb

- at Large Hadron Collider (LHC)



→ symmetric $p^+(6.5 \text{ TeV}) + p^+(6.5 \text{ TeV})$

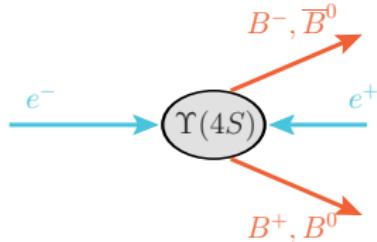
- gluon + gluon $\rightarrow b\bar{b}$



► $10^{12} b\bar{b}$ pairs in Run 1 + 2

Belle II

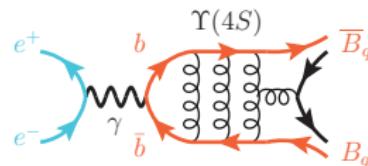
- at KEKB Tsukuba Japan
- at $\Upsilon(4S) = (b\bar{b})$ resonance:



when running at $\Upsilon(5S)$ also access to B_s mesons \rightarrow Belle I

→ asymmetric $e^+(3.1 \text{ GeV}) + e^-(9 \text{ GeV})$

- $e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$



► $\sim 5 \times 10^{10} B\bar{B}$ pairs at Belle II (2019-2025)

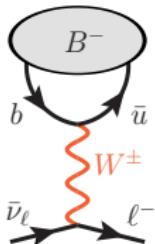
$\sim 4.69 \times 10^8 B\bar{B}$ pairs at BaBar (2000-2008)

$\sim 7.71 \times 10^8 B\bar{B}$ pairs at Belle I (2000-2010)

FCCC = Flavor-changing charged-current

Simplest decay $B^- \rightarrow \ell^-\bar{\nu}_\ell$ = “Tree decay”

$B^- = (\bar{u}b)$ meson: $Q_b \neq Q_u \Leftarrow$ charged current



Fermi constant in SM @ tree-level

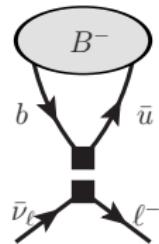
$$G_F = \frac{\sqrt{2} g_2^2}{8 m_W^2} = \frac{1}{\sqrt{2} v^2}$$

← SM = full theory

EFT = effective theory →

Matching

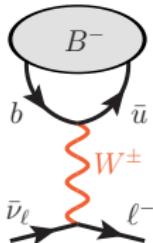
$$iA_{SM} = -\frac{g_2^2}{2} V_{ub} \frac{1}{q^2 - m_W^2} [\bar{u} \gamma^\mu P_L b] [\bar{\ell} \gamma_\mu P_L \nu_\ell] \underbrace{\approx \frac{q^2 \ll m_W^2}{\sqrt{2}} \frac{4 G_F}{\sqrt{2}} V_{ub} [\bar{u} \gamma^\mu P_L b] [\bar{\ell} \gamma_\mu P_L \nu_\ell]}_{\text{can be obtained from EFT}} + \mathcal{O}\left(\frac{m_b^2}{m_W^2}\right)$$



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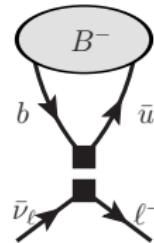
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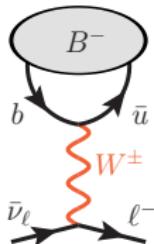
$$\mathcal{L}_{EFT} = \mathcal{L}_{QCD \times QED} - C_{V_L} Q_{V_L} \quad \xrightarrow{C_{V_L}|_{SM} = \frac{4 G_F}{\sqrt{2}} V_{ub}} \quad \xrightarrow{Q_{V_L} \equiv [\bar{u} \gamma_\mu P_L b] [\bar{\ell} \gamma^\mu P_L \nu_\ell]}$$

EFT = Wilson coefficient × operator

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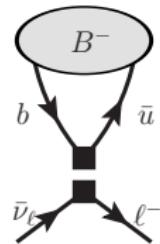
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Need hadronic matrix elements to calculate observables

neglecting QED

$$i\mathcal{A}_{\text{EFT}} \propto \langle \bar{\ell} \nu_\ell | Q_{V_L} | B^- \rangle \propto \langle \bar{\ell} \nu_\ell | \bar{\ell} \gamma_\mu P_L \nu_\ell | 0 \rangle \times \langle 0 | \bar{q} \gamma^\mu P_L b | B^-(p_B) \rangle \propto f_{B^-} m_\ell [\bar{u}(p_\ell) \gamma_5 v(p_\nu)]$$

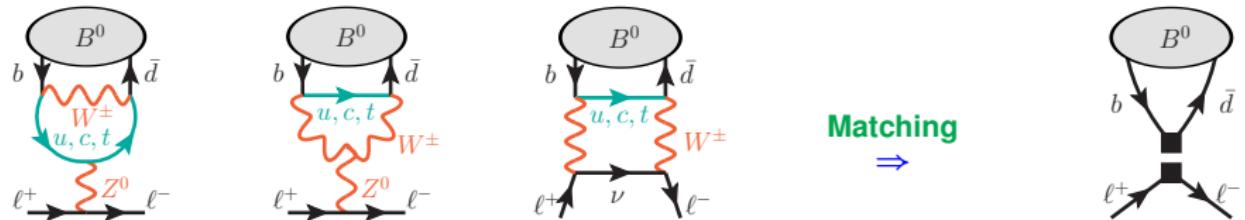
⇒ hadronic effects in B^- decay constant $f_{B^-} = (189.4 \pm 1.4)$ MeV from Lattice QCD

$$Br[B^- \rightarrow \ell \bar{\nu}_\ell] \propto \frac{1}{2m_{B^-}} \oint d\Pi_2 |\mathcal{A}_{\text{EFT}}|^2 \propto \tau_{B^-} [m_\ell^2 (f_{B^-})^2 |C_{V_L}|^2]$$

FCNC = Flavor-changing neutral-current

Simplest decay $B^0 \rightarrow \ell\bar{\ell}$ = “Loop decay”

$B^0 = (\bar{d}b)$ meson: $Q_b = Q_d \Leftarrow$ neutral current

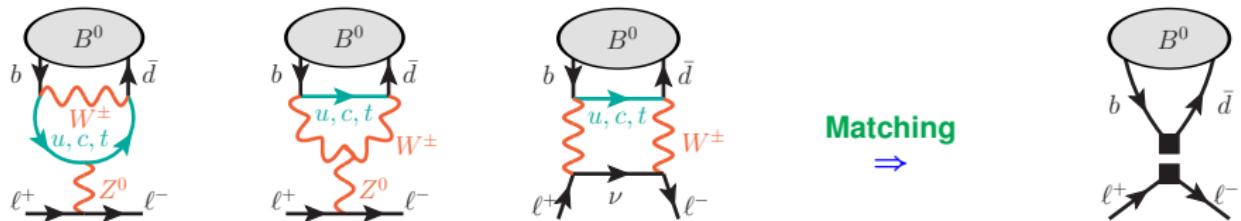


$$\mathcal{L}_{\text{EFT}} \propto C_{10} Q_{10} + \dots \quad C_{10}|_{\text{SM}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha_e}{4\pi} \sum_q V_{qb} V_{qd}^* F(m_q) \quad Q_{10} \equiv [\bar{d} \gamma_\mu P_L b][\bar{\ell} \gamma^\mu \gamma_5 \ell]$$

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- ▶ $F(m_q)$ function of quark masses m_q for $q = u, c, t$
- ▶ for $m_u = m_c = m_t = M$ have **GIM mechanism** [Glashow/Iliopoulos/Maiani PRD 2 (1970) 1285]

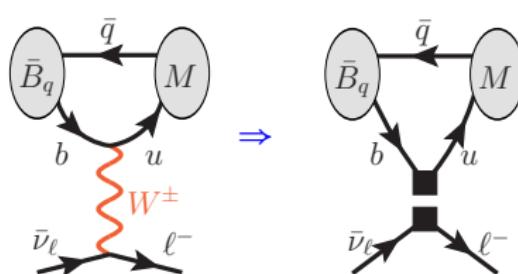
$\sum_q V_{qb} V_{qd}^* F(m_q) = F(M) \sum_q V_{qb} V_{qd}^* = 0$

 by unitarity of CKM \Rightarrow no FCNC's in this limit
- ▶ GIM mechanism is broken by huge top-quark mass $m_t \sim 170 \text{ GeV} \gg m_{u,c}$
 - ⇒ Can investigate FCNC decays of $B_{d,s}$ mesons ($K_L \rightarrow \mu\bar{\mu}$ was used to estimate m_c in early 70's)

$$Br[B^0 \rightarrow \ell\bar{\ell}] \propto \frac{1}{2m_{B^0}} \oint d\Pi_2 |\mathcal{A}_{\text{EFT}}|^2 \propto \tau_{B^0} \boxed{m_\ell^2} \boxed{(f_{B^0})^2} \boxed{|C_{10}|^2}$$

Semileptonic FCCC decays

Semileptonic decays $\bar{B} \rightarrow M \ell \bar{\nu}_\ell$ = “Tree decay” \Rightarrow same EFT as for $B^- \rightarrow \ell \bar{\nu}_\ell$



\Rightarrow New type of matrix element (at LO QED)

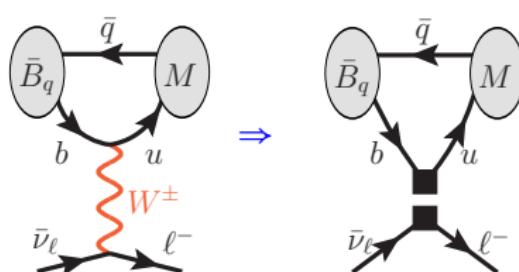
$$i\mathcal{A}_{\text{EFT}} \propto \langle \ell \bar{\nu}_\ell M | [\bar{u} \gamma_\mu P_L b] [\bar{\ell} \gamma^\mu P_L \nu_\ell] |\bar{B} \rangle$$

$$\propto \underbrace{\langle M | \bar{q} \gamma^\mu P_L b | \bar{B} \rangle}_{\text{form factor}} \times \langle \ell \bar{\nu}_\ell | \bar{\ell} \gamma_\mu P_L \nu_\ell | 0 \rangle$$

\rightarrow depend on momentum transfer $q \equiv p - k = p_\ell + p_\nu$

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$M = P$ seudoscalar form factors $F_i(q^2)$ = scalar functions

$$\langle M(k) | \bar{q} \gamma_\mu b | B(p) \rangle = F_+ (p+k)_\mu + [F_0 - F_+] \frac{m_B^2 - m_P^2}{q^2} q_\mu, \quad \langle M | \bar{q} \gamma_\mu \gamma_5 b | B \rangle = 0$$

q^2 -differential branching ratio

\Rightarrow only F_+ relevant if $m_\ell \ll q^2$ ($\ell = e, \mu$), F_0 important for $\ell = \tau$

$$\frac{dBr[\bar{B} \rightarrow P \ell \bar{\nu}_\ell]}{dq^2} \propto \tau_B |C_{V_L}|^2 \left\{ m_B^2 |\vec{p}|^2 \left(1 - \frac{m_\ell^2}{2q^2}\right)^2 (F_+)^2 + \frac{3m_\ell^2}{8q^2} (m_B^2 + m_P^2)^2 (F_0)^2 \right\}$$

\Rightarrow Lepton-flavor universal (LFU) Wilson coefficient $C_{V_L} \sim \mathcal{G}_F V_{ub}$

Lattice QCD

Most important **nonperturbative method** to calculate hadronic matrix elements

⇒ evaluate Feynman path-integral numerically with some modifications:

- ▶ 1) discretize space-time continuum
- ▶ 2) finite volume
- ▶ 3) use Euclidean correlators
- ▶ 4) (not always) use unphysical quark content

!!! depending on “quantity”, result can be related to the quantity in the continuum (real world)

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- ▶ **Decay constants** $\langle 0 | \dots | \bar{B} \rangle \propto f_B$

Very good control on decay constants f_B (< 1% rel. error)

- ▶ **$B \rightarrow P$ form factors** $\langle P | \dots | \bar{B} \rangle \propto F_i(q^2)$ ($P = \pi, K, D$)

Good control on $B \rightarrow P$ (pseudo-scalar) form factors (< 10% rel. error),
but only for $q^2 \rightarrow q_{\text{max}}^2$

- ▶ **$B \rightarrow V$ form factors** $\langle V | \dots | \bar{B} \rangle \propto F_i(q^2)$ ($V = K^*, D^*$)

!!! V not stable ⇒ experimentally detected by subsequent decay $V \rightarrow P_1 P_2$

→ Currently assume stable V in Lattice QCD

→ in future might calculate $\langle P_1 P_2 | \dots | \bar{B} \rangle \propto F_i(q^2, k^2)$

- ▶ **Baryon form factors** $\langle \Lambda_q | \dots | \Lambda_b \rangle \propto F_i(q^2)$ ($\Lambda_q = p^+, \Lambda_c$)

So far “CKM-picture” of SM works

⇒ fit of CKM-Parameters . . .

[experimental input from CKMfitter homepage]

CKM matrix in terms of
4 Wolfenstein parameters

$$\lambda, \quad A, \quad \bar{\rho}, \quad \bar{\eta}$$

⇒ nowadays a sophisticated fit:
“combine and overconstrain”

!!! numerous b -physics measurements

$\lambda \approx 0.225$
Cabibbo angle

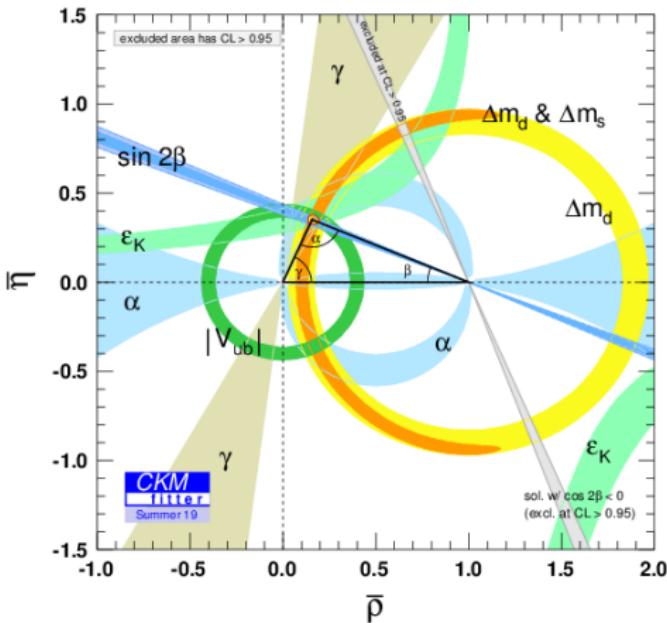
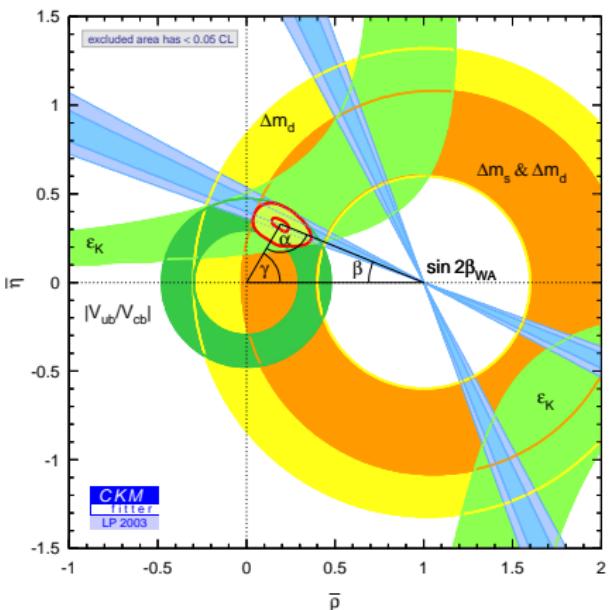
$$V_{\text{CKM}} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 A \\ -\lambda & 1 & \lambda^2 A \\ \lambda^3 A & -\lambda^2 A & 1 \end{pmatrix}$$

$ V_{ud} $ (nuclei)	$0.97425 \pm 0 \pm 0.00022$
$ V_{us} f_+^{K \rightarrow \pi}(0)$	0.2163 ± 0.0005
$ V_{cd} (\nu N)$	0.230 ± 0.011
$ V_{cs} (W \rightarrow c\bar{s})$	$0.94^{+0.32}_{-0.26} \pm 0.13$
$ V_{ub} $ (semileptonic)	$(4.01 \pm 0.08 \pm 0.22) \times 10^{-3}$
$ V_{cb} $ (semileptonic)	$(41.00 \pm 0.33 \pm 0.74) \times 10^{-3}$
$\mathcal{B}(\Lambda_p \rightarrow p \mu^- \bar{\nu}_\mu)_{q^2>15} / \mathcal{B}(\Lambda_p \rightarrow \Lambda_c \mu^- \bar{\nu}_\mu)_{q^2>7}$	$(1.00 \pm 0.09) \times 10^{-2}$
$\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau)$	$(1.08 \pm 0.21) \times 10^{-4}$
$\mathcal{B}(D_s^- \rightarrow \mu^- \bar{\nu}_\mu)$	$(5.57 \pm 0.24) \times 10^{-3}$
$\mathcal{B}(D_s^- \rightarrow \tau^- \bar{\nu}_\tau)$	$(5.55 \pm 0.24) \times 10^{-2}$
$\mathcal{B}(D^- \rightarrow \mu^- \bar{\nu}_\mu)$	$(3.74 \pm 0.17) \times 10^{-4}$
$\mathcal{B}(K^- \rightarrow e^- \bar{\nu}_e)$	$(1.581 \pm 0.008) \times 10^{-5}$
$\mathcal{B}(K^- \rightarrow \mu^- \bar{\nu}_\mu)$	0.6355 ± 0.0011
$\mathcal{B}(\tau^- \rightarrow K^- \bar{\nu}_\tau)$	$(0.6955 \pm 0.0096) \times 10^{-2}$
$\mathcal{B}(K^- \rightarrow \mu^- \bar{\nu}_\mu) / \mathcal{B}(\pi^- \rightarrow \mu^- \bar{\nu}_\mu)$	1.3365 ± 0.0032
$\mathcal{B}(\tau^- \rightarrow K^- \bar{\nu}_\tau) / \mathcal{B}(\tau^- \rightarrow \pi^- \bar{\nu}_\tau)$	$(6.431 \pm 0.094) \times 10^{-2}$
$\mathcal{B}(B_s \rightarrow \mu\mu)$	$(2.8^{+0.7}_{-0.6}) \times 10^{-9}$
$ V_{cd} f_+^{D \rightarrow \pi}(0)$	0.148 ± 0.004
$ V_{cs} f_+^{D \rightarrow K}(0)$	0.712 ± 0.007
$ \varepsilon_K $	$(2.228 \pm 0.011) \times 10^{-3}$
Δm_d	$(0.510 \pm 0.003) \text{ ps}^{-1}$
Δm_s	$(17.757 \pm 0.021) \text{ ps}^{-1}$
$\sin(2\beta)_{[c\bar{c}]}$	0.691 ± 0.017
$(\phi_s)_{[b \rightarrow c\bar{s}s]}$	-0.015 ± 0.035
$S_{\pi\pi}^{+-}, C_{\pi\pi}^{+-}, C_{\pi\pi}^{00}, \mathcal{B}_{\pi\pi}$ all charges	Inputs to isospin analysis
$S_{\rho\rho}^{+-}, C_{\rho\rho}^{+-}, S_{\rho\rho}^{00}, C_{\rho\rho}^{00}, \mathcal{B}_{\rho\rho, L}$ all charges	Inputs to isospin analysis
$B^0 \rightarrow (\rho\pi)^0 \rightarrow 3\pi$	Time-dependent Dalitz analysis
$B^- \rightarrow D^{(*)} K^{(*)-}$	Inputs to GLW analysis
$B^- \rightarrow D^{(*)} K^{(*)-}$	Inputs to ADS analysis
$B^- \rightarrow D^{(*)} K^{(*)-}$	GGSZ Dalitz analysis

So far “CKM-picture” of SM works

⇒ fit of CKM-Parameters ... 2003 → 2019

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



More on CKM fits

http://ckmfitter.in2p3.fr/www/html/ckm_main.html
<http://www.utfit.org/UTfit/>

Beyond the SM

A model that successfully explains phenomena over large scales of energy

⇒ electromagnetism

 ⇒ atomic physics

 ⇒ nuclear physics

 ⇒ radioactivity

 ⇒ particle physics

...

Beyond the SM

A model that successfully explains phenomena over large scales of energy

- ⇒ electromagnetism
- ⇒ atomic physics
- ⇒ nuclear physics
- ⇒ radioactivity
- ⇒ particle physics
- ...

BUT

Empirical issues

- ▶ Neutrino masses
- ▶ Matter–antimatter asymmetry
- ▶ Dark matter
- ▶ Isotropy and flatness of CMB
- ▶ Several tensions in various sectors
 $(g - 2)_\mu$, B -anomalies, ...

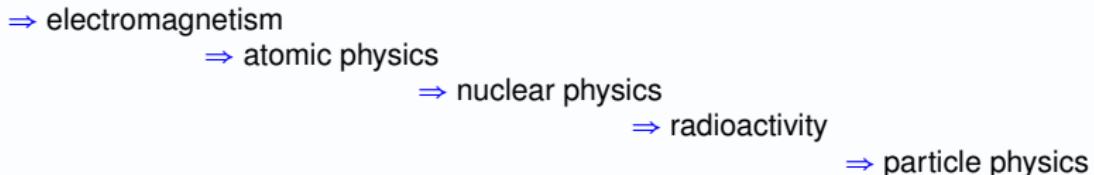
Theoretical issues

- ▶ Why $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$?
- ▶ Why three generations?
- ▶ Why large hierarchies in flavor sector?
- ▶ How to include/quantize gravity?

...

Beyond the SM

A model that successfully explains phenomena over large scales of energy



Empirical issues

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- ▶ Dark matter
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- ▶ Why three generations?
- ▶ Why large hierarchies in flavor sector?
- ▶ How to include/quantize gravity?

Hints for new scales based on assumptions on physics beyond SM

- ▶ $\mu_{\text{Planck}} \sim 10^{19} \text{ GeV}$: Planck scale \Rightarrow effects of quantum gravity not negligible
- ▶ $\mu_{\text{GUT}} \sim 10^{16} \text{ GeV}$: grand unification of $SU(3)_c$, $SU(2)_L$ and $U(1)_Y$ into some GUT-group but no real evidence ...

\Rightarrow need experimental guidance

B anomalies: Status

“LFU ratios”

Can test **Lepton-Flavor Universality (LFU)** of SM in ratios involving different $\ell = e, \mu, \tau$

- ▶ SM Wilson coefficients of EFT are independent of lepton flavor = **universal**
- ▶ LF-non-universal effects in observables are from phase-space integration

$$R^{\ell\ell'}(M) \equiv \frac{\int_{q_{a,\ell}^2}^{q_{b,\ell}^2} dq^2 \frac{dBr[\bar{B} \rightarrow M + (\ell\nu, \ell\bar{\ell})]}{dq^2}}{\int_{q_{a,\ell'}^2}^{q_{b,\ell'}^2} dq^2 \frac{dBr[\bar{B} \rightarrow M + (\ell'\nu', \ell'\bar{\ell}')] }{dq^2}}$$

- ▶ note different phase-space integral
- ▶ in SM overall factor $\propto G_F^2 |V_{CKM}|^2$ cancels
- ▶ strong cancellation of $B \rightarrow M$ form factor uncertainties

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FCCC $b \rightarrow c \ell \bar{\nu}$

$\ell = \tau$

$\ell' = e + \mu$

LHCb measures $\ell' = \mu$

$M = D \rightarrow R^{\tau\ell}(D)$

$M = D^* \rightarrow R^{\tau\ell}(D^*)$

FCNC $b \rightarrow s \ell \bar{\ell}$

$\ell = \mu$

$\ell' = e$

$M = K \rightarrow R^{\mu e}(K)$

$M = K^* \rightarrow R^{\mu e}(K^*)$

First signs of tensions with SM (previous measurements had large errors)

2012 $R^{\tau\ell}(D, D^*)$

[Babar 1205.5442]

2014 $R^{\mu e}(K)$

[LHCb 3/fb 1406.6482]

2015/16/19 $R^{\tau\ell}(D, D^*)$

[Belle 1507.03233, 1603.06711, 1910.05864]

2017 $R^{\mu e}(K^*)$

[LHCb 3/fb 1705.05802]

2015/18 $R^{\tau\mu}(D^*)$

[LHCb 1506.08615, 1708.08856, 1711.02505]

2019 update of $R^{\mu e}(K)$

[LHCb 5/fb 1903.09252]

2017 $R^{\tau\mu}(J/\psi)$

[LHCb 1711.05623]

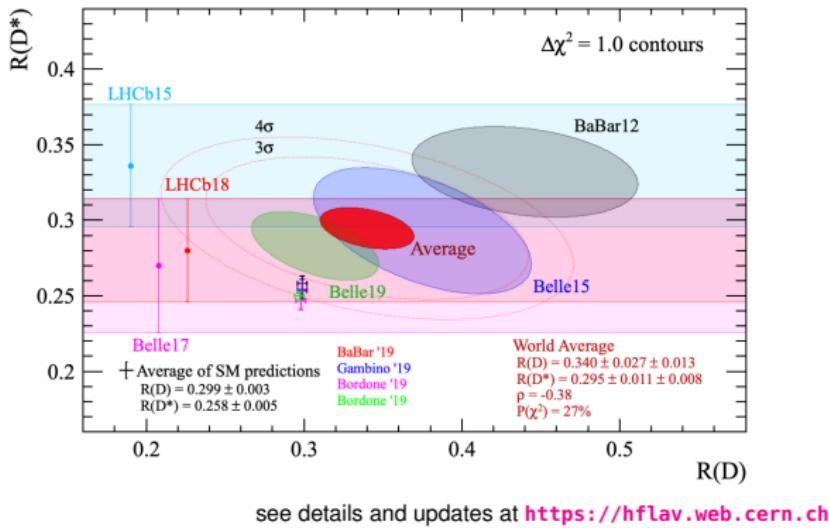
2019 $R^{\mu e}(K^*)$

[Belle 1904.02440]

2019 $R^{\mu e}(K)$

[Belle 1908.01848]

Measurements of $R^{\tau\ell}(D)$ and $R^{\tau\ell}(D^*)$



► $R(D)$ & $R(D^*)$ comb. deviation from SM (HFLAV)

3.1σ

⇒ would increase to 3.8σ with SM prediction using FF's from
LCSR + LQCD + UB + HQET [Bordone/Gubernari/Jung/van Dyk 1912.09335]

► single dev's from SM:

$R(D) \rightarrow 1.4\sigma$ and $R(D^*) \rightarrow 2.5\sigma$

► $R^{\tau\mu}(J/\psi) = 0.71 \pm 0.25 \Rightarrow 2\sigma$ tension with SM

Combining experiments tricky:

⇒ treat common systematics

Example:

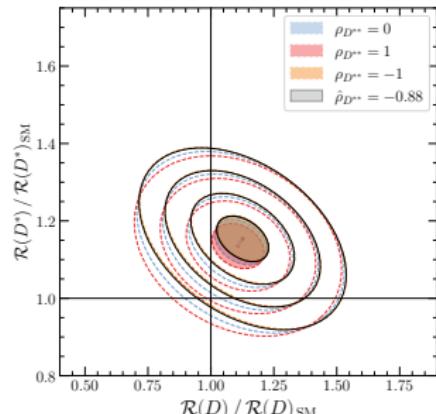
$B \rightarrow D^{**} \ell \bar{\nu}$ background

in $R(D)$ and $R(D^*)$

correlation impacts the tension:

$$(2.9 - 3.6)\sigma$$

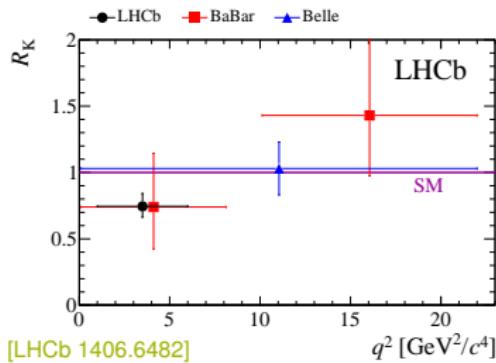
[Bernlochner/Sevilla/Robinson/Wormser
2101.08326]



Measurements of $R^{\mu e}(K)$ and $R^{\mu e}(K^*)$

- same q^2 -region in numerator and denominator $q^2 \in [q_a^2, q_b^2]$

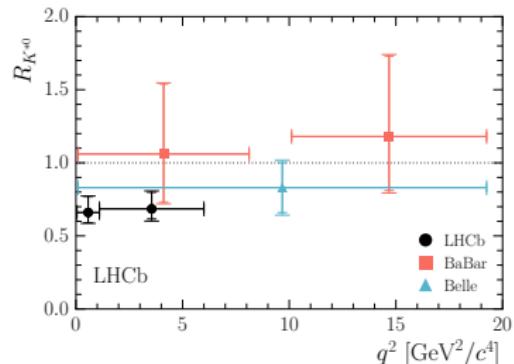
Measurement $R^{\mu e}(K)$



$$R^{\mu e}(K)[1, 6] = 0.846^{+0.062}_{-0.056} \quad 2.5\sigma$$

[LHCb 1903.09252]

Measurement $R^{\mu e}(K^*)$



$$R^{\mu e}(K^*)[0.045, 1.1] = 0.66^{+0.11}_{-0.07} \pm 0.03 \quad 2.2\sigma$$

$$R^{\mu e}(K^*)[1.1, 6.0] = 0.69^{+0.11}_{-0.07} \pm 0.05 \quad 2.4\sigma$$

SM prediction

- “universality”
- estimating QED

$$R^{\mu e}(M) \approx 1 + \mathcal{O}(m_\ell^4/q^4) + \mathcal{O}(\alpha_e) \quad [\text{CB/Hiller/Piranishvili 0709.4174}]$$

$$R^{\mu e}(M)[1, 6] = 1.00 \pm 0.01 \quad (M = K, K^*) \quad [\text{Bordone/Isidori/Pattori 1605.07633}]$$

Latest Belle $R^{\mu e}(K, K^*)$ consistent with SM and LHCb
(larger errors)

[Belle 1904.02440, 1908.01848]

Tensions in $b \rightarrow s \mu \bar{\mu}$ rates

Leptonic FCNC decay

$$B_s \rightarrow \mu \bar{\mu}$$

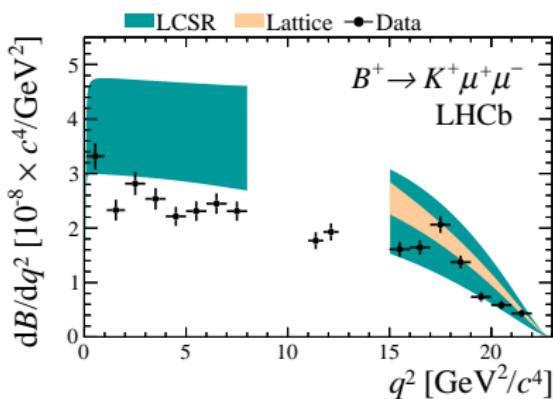
$$Br|_{\text{exp}} = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$

[LHCb-CONF-2020-002, CMS-PAS-BPH-20-003, ATLAS-CONF-2020-049]

$$Br|_{\text{th}} = (3.66 \pm 0.14) \times 10^{-9}$$

[Beneke/CB/Szafron 1908.07011]

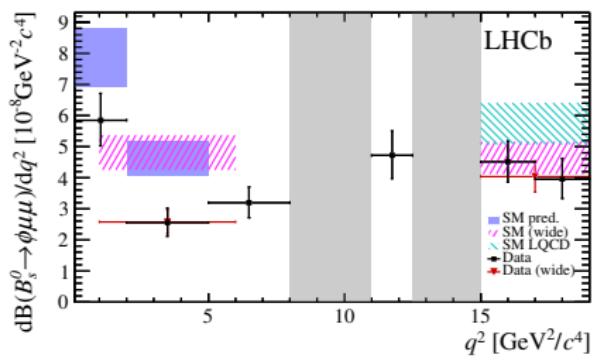
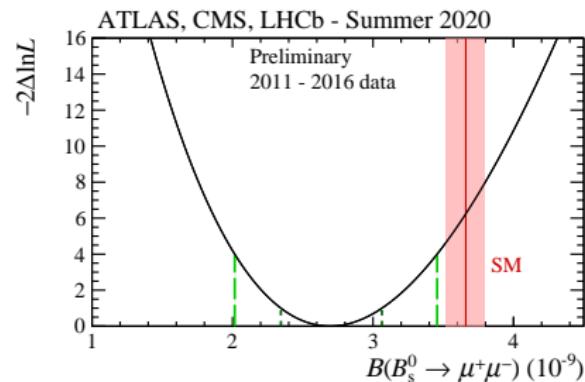
\Rightarrow tension 2.4σ



$B^+ \rightarrow K^+ \mu \bar{\mu}$ data below SM prediction

[LHCb 1403.8044]

\Rightarrow measured LHCb rates ($\ell = \mu$) systematically below SM predictions

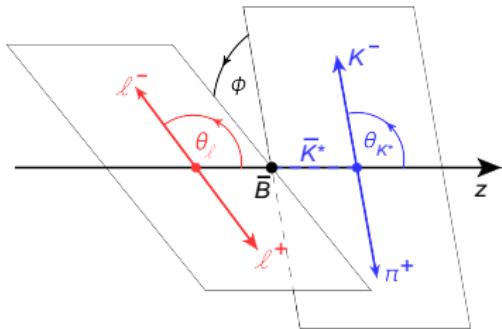


$B_s \rightarrow \phi \mu \bar{\mu}$ data below SM prediction 2.2σ

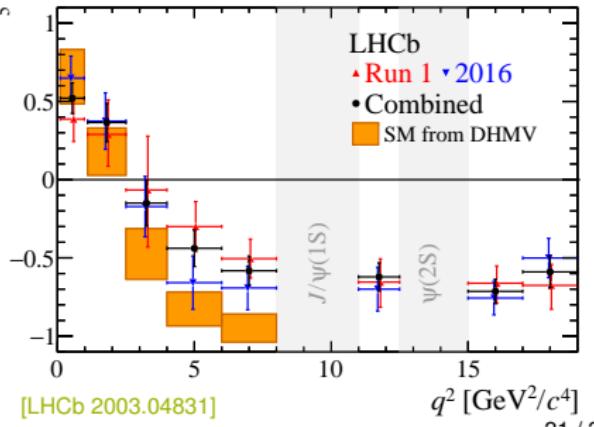
[LHCb 1506.08777]

Tensions in angular distribution $B \rightarrow K^* \mu \bar{\mu}$

$$\begin{aligned} \frac{d^4\Gamma[\bar{B} \rightarrow \bar{K}^*(\rightarrow \bar{K}\pi)\ell\bar{\ell}]}{dq^2 d\cos\theta_\ell d\cos\theta_K d\phi} &\simeq J_{1S} \sin^2\theta_K + J_{1C} \cos^2\theta_K \\ &+ (J_{2S} \sin^2\theta_K + J_{2C} \cos^2\theta_K) \cos 2\theta_\ell + J_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi \\ &+ J_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_K \sin\theta_\ell \cos\phi \\ &+ (J_{6S} \sin^2\theta_K + J_{6C} \cos^2\theta_K) \cos\theta_\ell + J_7 \sin 2\theta_K \sin\theta_\ell \sin\phi \\ &+ J_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \end{aligned}$$



- ▶ $12 J_i(q^2)$ from $\bar{B} \rightarrow \bar{K}^* \ell\bar{\ell}$ + $12 \bar{J}_i(q^2)$ from $B \rightarrow K^* \ell\bar{\ell}$ = **24 angular observables**
⇒ key to constrain all Wilson coefficients
- ▶ LHCb: $B^0 \rightarrow K^{*0} \mu \bar{\mu}$ [LHCb 4.7/fb 2003.04831]
 $B^+ \rightarrow K^{*+} \mu \bar{\mu}$ [LHCb 9/fb 2012.13241]
[also Belle, CMS, ATLAS, BaBar]
- ▶ $P'_5 \equiv \frac{J_5/2}{\sqrt{-J_{2C} J_{2S}}}$
- ▶ tensions in bins $q^2 \in [4, 6], [6, 8] \text{ GeV}^2$ of about 2.5σ and 2.9σ
- ▶ $q^2 \in [6, 8]$ theory might not under control
⇒ hadronic $c\bar{c}$ -contributions



B anomalies:
**Comments on SM
and prospects**

LFU ratios in $b \rightarrow c \ell \bar{\nu}_\ell$

SM predictions

different approaches used to determine FF's

A) theory + experimental info on FF shape from $b \rightarrow c \ell \bar{\nu}_\ell$ to predict $b \rightarrow c \tau \bar{\nu}_\ell$

$$!!! \text{ assuming no NP in light } \ell = e + \mu \Rightarrow R^{e\mu}(D^*) = 1.01 \pm 0.01 \pm 0.03$$

[Belle 1809.03290]

B) only theory info on FF's

⇒ No real issues with theory at current level of precision

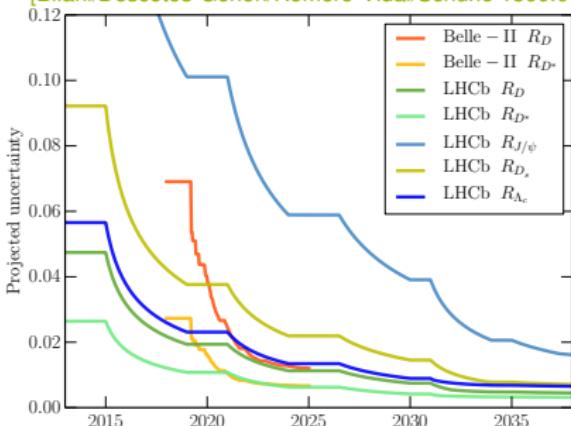
Experiment

- ▶ tension seen by several experiments, **but** τ is in general difficult
!!! have seen in the past for $Br(B^- \rightarrow \tau \bar{\nu})$ too high in first measurements and later in agreement with SM
- ▶ latest Belle and LHCb measurements moved towards SM
LHCb: 2015(lep), 2018(3 π); Belle: 2015(had,lep), 2017(had, π), 2019(sl,lep)

In future

- ⇒ improved measurements from Belle II and LHCb
- ▶ alternative ratio's $R^{\tau\mu}(M)$ with $M = J/\psi, X_c, \Lambda_c, \dots$ can be interesting,
but usually modes that have lower statistics
⇒ can be cross checks if different experimental systematics

[Bifani/Descotes-Genon/Romero-Vidal/Schune 1809.06229]



Theory of exclusive $b \rightarrow s \ell \bar{\ell}$

Dipole & Semileptonic op's

$$Q_{7\gamma(7\gamma')} = m_b [\bar{s} \sigma^{\mu\nu} P_{R(L)} b] F_{\mu\nu}$$

$$Q_{9(9')}^{\ell\ell} = [\bar{s} \gamma^\mu P_{L(R)} b] [\bar{\ell} \gamma_\mu \ell]$$

$$Q_{10(10')}^{\ell\ell} = [\bar{s} \gamma^\mu P_{L(R)} b] [\bar{\ell} \gamma_\mu \gamma_5 \ell]$$

Factorisation into form factors (@ LO QED)

⇒ No conceptual problems !!!

@ low q^2 : FF's from LCSR
(10 – 15)% accuracy

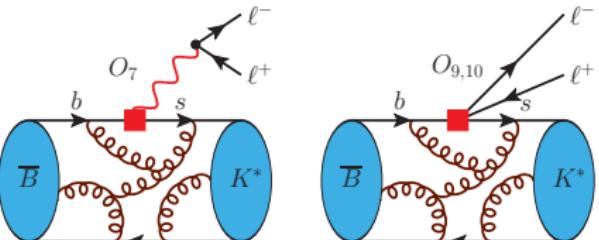
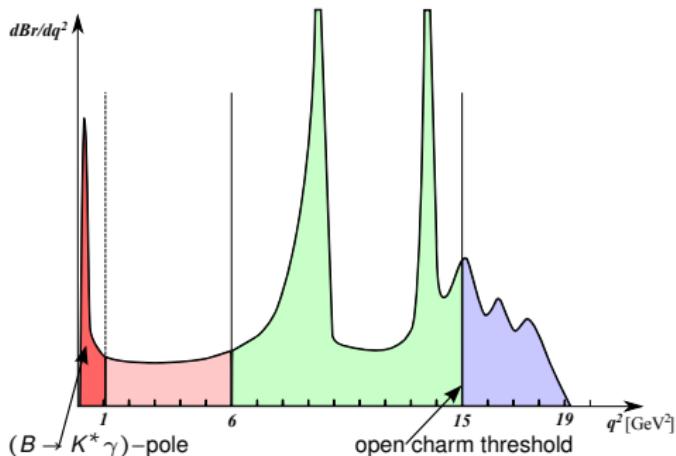
$B \rightarrow K$
 $B \rightarrow K^*$

[Ball/Zwicky hep-ph/0406232, Khodjamirian et al. 1006.4945
Bharucha/Straub/Zwicky 1503.05534]

@ high q^2 : FF's from lattice
(6 – 9)% accuracy

$B \rightarrow K$
 $B \rightarrow K^*$

[Bouchard et al. 1306.2384
Horgan/Liu/Meinel/Wingate 1310.3722 + 1501.00367]



Theory of exclusive $b \rightarrow s \ell \bar{\ell}$

Nonleptonic

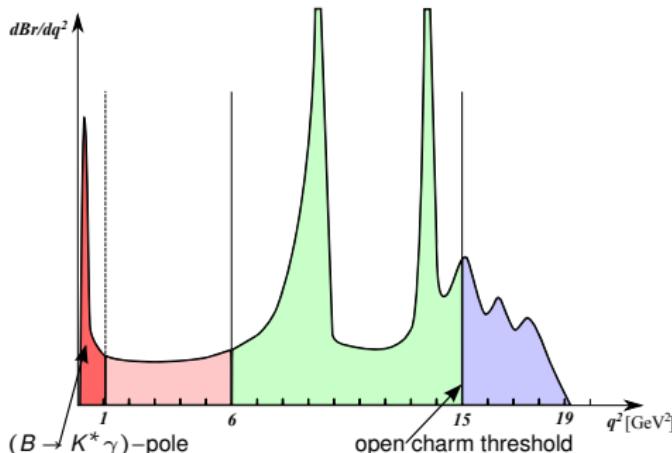
$$Q_{(1)2} = [\bar{s} \gamma^\mu P_L(T^a) c] [\bar{c} \gamma_\mu P_L(T^a) b]$$

$$Q_{3,4,5,6} = [\bar{s} \Gamma_{sb} P_L(T^a) b] \sum_q [\bar{q} \Gamma_{qq}(T^a) q]$$

$$Q_{8g(8g')} = m_b [\bar{s} \sigma^{\mu\nu} P_{R(L)} T^a b] G_{\mu\nu}^a$$

at LO in QED

$$\int d^4x e^{i\vec{q}\cdot\vec{x}} \left\langle M_\lambda^{(*)} \left| T\left\{ j_\mu^{\text{em}}(x), \sum_i C_i Q_i(0) \right\} \right| \bar{B} \right\rangle$$



Large Recoil (low- q^2)

- 1) QCD factorization or SCET,
- 2) LCSR
- 3) non-local OPE of $\bar{c}c$ -tails
- + comb. with parametrizations from analyticity

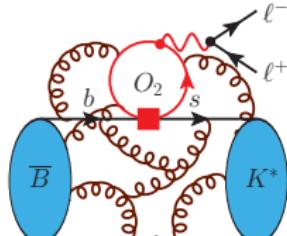
[Beneke/Feldmann/Seidel hep-ph/0106067 + 0412400
Lyon/Zwicky et al. 1212.2242 + 1305.1976
Khodjamirian et al. 1006.4945 + 1211.0234 + 1506.07760
CB/Chrzaszcz/van Dyk/Virto 1707.07305
Gubernari/van Dyk/Virto 2011.09813]

Low Recoil (high- q^2)

local OPE (+ HQET) \Rightarrow theory only for sufficiently large q^2 -integrated obs's

[Grinstein/Pirjol hep-ph/0404250
Belych/Buchalla/Feldmann 1101.5118]

\Rightarrow theoretically least understood
can't exclude at present as origin of P'_5 anomaly



Tensions in $b \rightarrow s \ell \bar{\ell}$

SM predictions

- $Br[B_s \rightarrow \mu\bar{\mu}]$ tension can be reduced by using V_{cb} from exclusive $B \rightarrow (D, D^*)\ell\bar{\nu}$
 $\Rightarrow V_{cb}|_{\text{excl}} = (40.0 \pm 0.9) \times 10^{-3}$ [Bordone et al. 1912.09335] gives $Br(B_s \rightarrow \mu\bar{\mu}) = (3.32 \pm 0.17) \times 10^{-9} \rightarrow 1.6\sigma$
- $B^+ \rightarrow K^+ \mu\bar{\mu}$ & $B_s \rightarrow \phi \mu\bar{\mu}$: problems with $B \rightarrow K$ and $B_s \rightarrow \phi$ FFs particularly at low- q^2 ?
- P'_5 anomaly: FF's cancel to some extend, maybe $c\bar{c}$ contributions underestimated

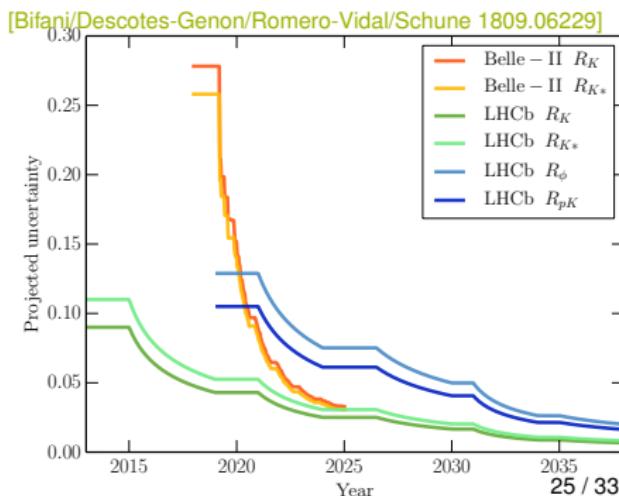
Experiment

- $R^{\mu e}(K, K^*)$ only from LHCb \Rightarrow maybe issues with e^- , despite many cross checks

In future

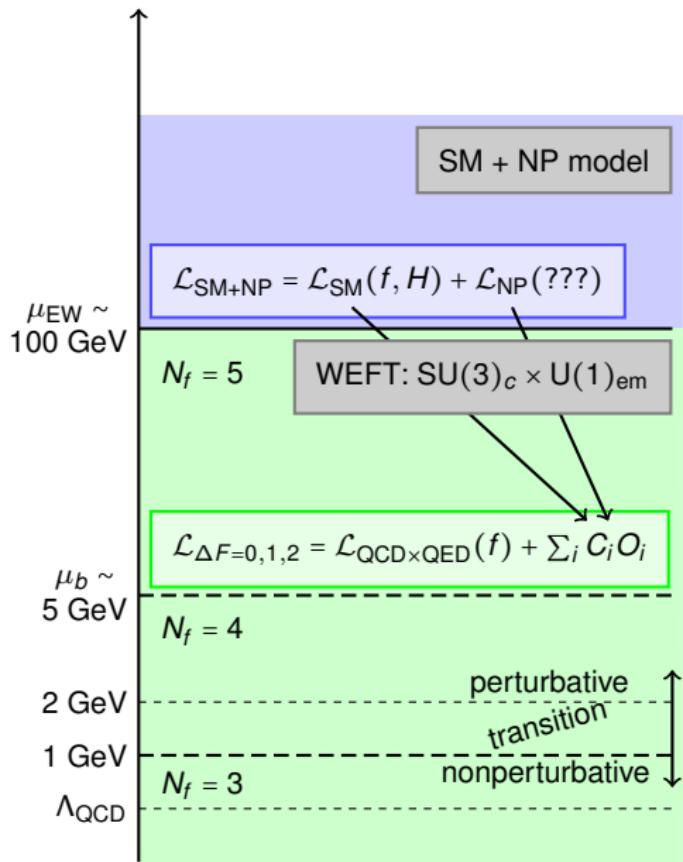
- $R^{\mu e}(K, K^*)$ independent measurements from Belle II
- P'_5 : using parametrizations of $(c\bar{c})$ contr.
 \Rightarrow combination of theory input and data-driven determination from narrow-width region $B \rightarrow J/\psi + (K, K^*)$

[CB/Chrzaszcz/van Dyk/Virto 1707.07305
Chrzaszcz/Mauri/Serra/Coutinho/van Dyk 1805.06378
Mauri/Serra/Coutinho 1805.06401
Gubernari/van Dyk/Virto 2011.09813]



B anomalies:
New physics interpretation

Factorization via stack of effective theories (EFT)

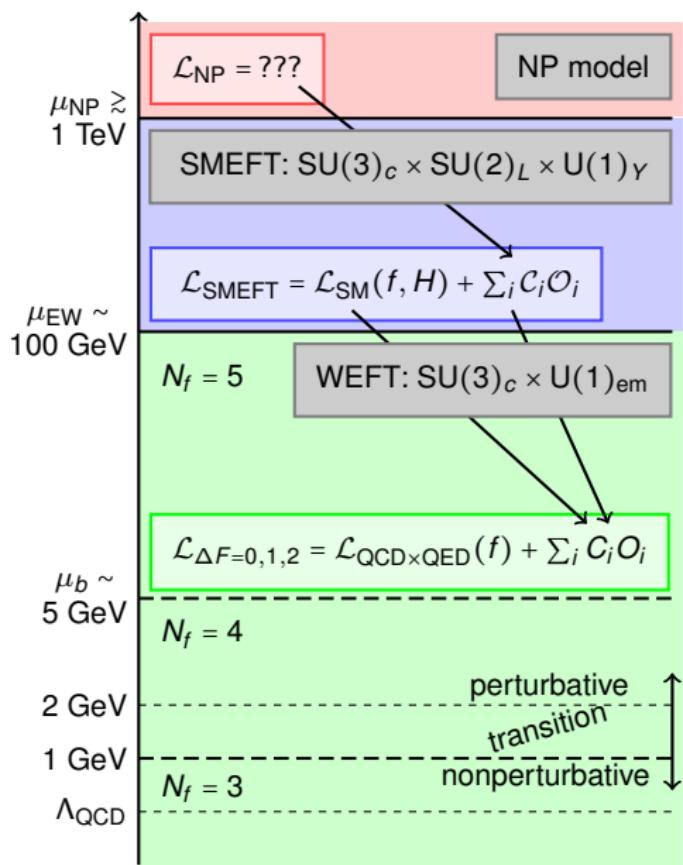


- decoupling of SM and potential NP at electroweak scale μ_{EW}
- assumes no other (relevant) light particles below μ_{EW} (some Z' , ...)

WEFT (weak EFT)

- # of op's [Jenkins/Manohar/Stoffer 1709.04486]
($L + B$ conserving) dim-5: 70, dim-6: 3631
- **perturbative part** → in SM under control
 - ⇒ decoupling @ NNLO QCD + NLO EW
 - ⇒ RGE @ NNLO QCD + NLO QED
- **hadronic matrix elements**
 - ⇒ **B-physics**
 - $1/m_b$ exp's → universal hadr. objects
 - Lattice
 - light-cone sum rules (LCSR)

Factorization via stack of effective theories (EFT)



SMEFT (SM EFT)

- ▶ assume mass gap
(not yet experimentally justified)
- ▶ parametrize NP effects by dim-5 + 6 op's
of op's $(L + B \text{ conserving})$
dim-5: 1, dim-6: 2499
- ▶ 1-loop RGE [Alonso/Jenkins/Manohar/Trott 1312.2014]

WEFT (weak EFT)

- ▶ # of op's $(L + B \text{ conserving})$ [Jenkins/Manohar/Stoffer 1709.04486]
dim-5: 70, dim-6: 3631
- ▶ **perturbative part** → in SM under control
⇒ decoupling @ NNLO QCD + NLO EW
⇒ RGE @ NNLO QCD + NLO QED
- ▶ **hadronic matrix elements**
⇒ **B-physics**
 - ▶ $1/m_b$ exp's → universal hadr. objects
 - ▶ Lattice
 - ▶ light-cone sum rules (LCSR)

$R^{\mu e}(K, K^*)$ – Which operators in WEFT?

- dipole and four-quark op's can not induce $R_H \neq 1$
- scalar op's: strongly disfavored [Hiller/Schmaltz 1408.1627]
- tensor op's: only for $\ell = e$, but require interference with other op's [Bardhan et al. 1705.09305]

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$R^{\mu e}(K, K^*)$ – Which operators in WEFT?

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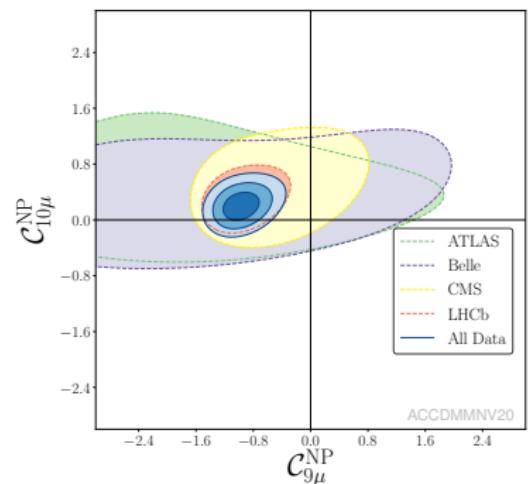
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- chirality-flipped C'_i disfavored
- preference for $\ell = \mu$ over $\ell = e$
- best single-WC scenario $C_9^\mu = -C_{10}^\mu$

- $C_9^{\text{SM}} \simeq 4.2$ and $C_{10}^{\text{SM}} \simeq -4.3$

[Aebischer et al. 1903.10434]

Coeff.	best fit	1σ	pull
C_9^μ	-0.97	[-1.12, -0.81]	5.9σ
C_{10}^μ	+0.75	[+0.62, +0.89]	5.7σ
C_9^e	+0.93	[+0.66, +1.17]	3.5σ
C_{10}^e	-0.83	[-1.05, -0.60]	3.6σ
$C_9^\mu = -C_{10}^\mu$	-0.53	[-0.61, -0.45]	6.6σ
$C_9^e = -C_{10}^e$	+0.47	[+0.33, +0.59]	3.5σ
C'_9^μ	+0.14	[-0.03, +0.32]	0.8σ
C'_{10}^μ	-0.24	[-0.36, +0.12]	2.0σ
C'_9^e	+0.39	[-0.05, +0.65]	1.2σ
C'_{10}^e	-0.27	[-0.57, -0.02]	1.1σ



[Alguero et al. 1903.09578]

$$\text{pull} = \sqrt{\chi_{\text{SM}}^2 - \chi_{\text{b.f.}}^2} \text{ in 1-dim}$$

[also 1903.09632, 1903.09617, 2006.04213, 2012.12207]

Interpretation within SMEFT

SMEFT operators \Rightarrow most interesting semileptonic

$$L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}, \quad Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$[\mathcal{O}_{lq}^{(1)}]_{abij} = (\bar{L}_L^a \gamma_\mu L_L^b)(\bar{Q}_L^i \gamma^\mu Q_L^j)$$

$$[\mathcal{O}_{lq}^{(3)}]_{abij} = (\bar{L}_L^a \gamma_\mu \tau^I L_L^b)(\bar{Q}_L^i \gamma^\mu \tau^I Q_L^j)$$

describe $u_j \rightarrow u_i \nu_a \bar{\nu}_b, \quad d_j \rightarrow d_i \nu_a \bar{\nu}_b$

FCNC's $u_j \rightarrow u_i \ell_a \bar{\ell}_b, \quad d_j \rightarrow d_i \ell_a \bar{\ell}_b$

FCCC's $d_j \rightarrow u_i \ell_a \bar{\nu}_b + \text{h.c.}$

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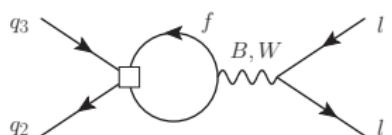
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Renormalization group mixing in SMEFT from $\mu_\Lambda \sim \mathcal{O}(\text{TeV})$ to $\mu_{\text{ew}} \sim 100 \text{ GeV}$:

- ▶ of semileptonic op's via $SU(2)_L \otimes U(1)_Y$ gauge bosons
- ▶ resummation of large log's $L \equiv \ln(\mu_\Lambda / \mu_{\text{ew}})$

$$[\mathcal{C}_{lq}^{(i)}]_{\ell\ell 23}(\mu_{\text{ew}}) = \underbrace{[\mathcal{C}_{lq}^{(i)}]_{\ell\ell 23}(\mu_\Lambda)}_{\text{self-mixing}} + \frac{\gamma_{ij} L}{(4\pi)^2} \sum_f [\mathcal{C}_{lq}^{(j)}]_{ff 23}(\mu_\Lambda)$$

- ▶ **universal** contribution = same for all lepton-flavor's ℓ



[Alonso/Jenkins/Manohar/Trott 1312.2014]

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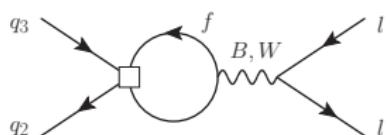
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[Alonso/Jenkins/Manohar/Trott 1312.2014]

Matching SMEFT \rightarrow WEFT on $b \rightarrow c\tau\bar{\nu}$ and $b \rightarrow s\ell\bar{\ell}$ at tree-level at $\mu_{\text{ew}} \sim 100 \text{ GeV}$

$$C_{V_L} \propto \sum_i V_{2i} [\mathcal{C}_{lq}^{(3)}]_{\tau\tau i3} + \dots$$

$$C_9^\ell \propto [\mathcal{C}_{lq}^{(1)}]_{\ell\ell 23} + [\mathcal{C}_{lq}^{(3)}]_{\ell\ell 23} + \dots$$

$$C_{10}^\ell \propto -[\mathcal{C}_{lq}^{(1)}]_{\ell\ell 23} - [\mathcal{C}_{lq}^{(3)}]_{\ell\ell 23} + \dots$$

Combined $b \rightarrow c\tau\bar{\nu}_\tau$ and $b \rightarrow s\ell\bar{\ell}$ in SMEFT

Scenario with two parameters at $\mu_\Lambda = 2 \text{ TeV}$:

$$[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323} \quad \leftarrow \ell = 3 = \tau$$

$$[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223} \quad \leftarrow \ell = 2 = \mu$$

If there was no mixing from $\mu_\Lambda \rightarrow \mu_{\text{ew}}$, would expect at μ_{ew}

$$C_9^\mu \propto +[C_{lq}^{(1)}]_{2223} + [C_{lq}^{(3)}]_{2223}$$

$$C_{10}^\mu \propto -[C_{lq}^{(1)}]_{2223} - [C_{lq}^{(3)}]_{2223}$$

$$C_{V_L}^\tau \propto \sum_x V_{2x} [C_{lq}^{(3)}]_{33x3}$$

The mixing in SMEFT from semi-tauonic \rightarrow semi-muonic, provides a C_9^{univ}

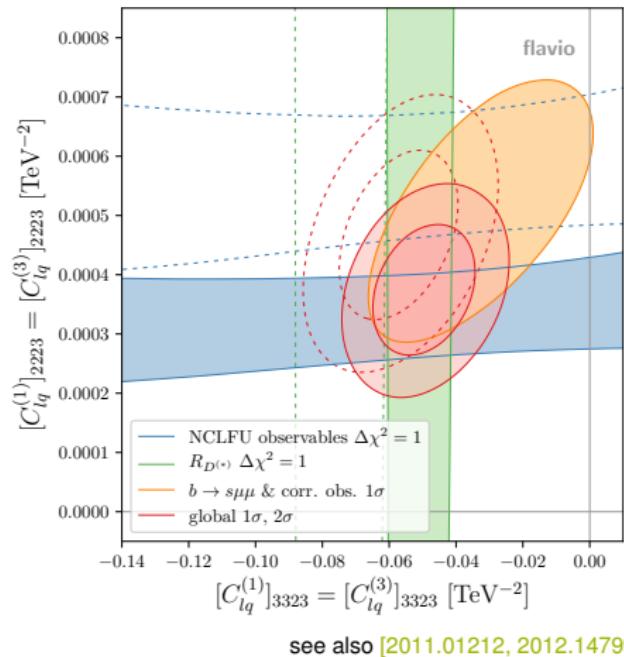
BFP $[C_{lq}^{(1)}]_{3323} = -5.0 \cdot 10^{-2} \text{ TeV}^{-2}$

$$[C_{lq}^{(1)}]_{2223} = +3.9 \cdot 10^{-4} \text{ TeV}^{-2}$$

pull: 7.8σ

no bound from $B \rightarrow K^{(*)}\nu\bar{\nu}$, because depends on $C_{lq}^{(1)} - C_{lq}^{(3)}$

[Aebischer et al. 1903.10434]



see also [2011.01212, 2012.14799]

can explain both $b \rightarrow c\tau\bar{\nu}$ and $b \rightarrow s\ell\bar{\ell}$

Assuming tree-level and (couplings)² = 1:

$$1/\sqrt{0.05} \approx 4.5 \text{ TeV}$$

$$1/\sqrt{0.0004} \approx 50 \text{ TeV}$$

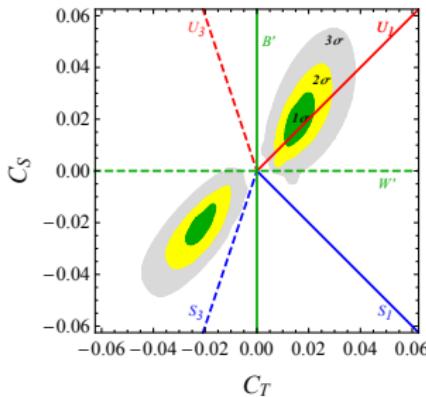
very different scales for semi-tauonic and semi-muonic operators

UV completions

“Grand-scheme” models (MSSM etc.) usually predict $C_9 \ll C_{10}$ (modified Z-penguin)

⇒ contradict global fits $C_9 \sim -C_{10}$

“Simplified” models in B -physics: massive bosonic mediators at $\mu_\Lambda \sim \mathcal{O}(\text{TeV})$



[Buttazzo/Greljo/Isidori/Marzocca 1706.07808]

Colorless $S = 1$:

$$B' = (1, 1, 0), W' = (1, 3, 0)$$

LQ's (LeptoQuarks) $S = 0$:

$$S_1 = (\bar{3}, 1, 1/3), S_3 = (\bar{3}, 3, 1/3)$$

LQ's $S = 1$:

$$U_1 = (3, 1, 2/3), U_3 = (3, 3, 2/3)$$

⇒ U_1 most promising single-mediator scenario

⇒ combinations of several LQs (also other rep's)

!!! single-mediator B' , W' problems with B_s -mix & high- p_T

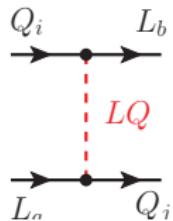
UV completions

- ▶ extended gauge & Higgs sectors
- ▶ LQ's: weakly interacting (elementary scalar or gauge boson)
- ▶ LQ's: strongly interacting (scalar as LQ as GB, composite vector LQ)

⇒ explicit models based on Pati-Salam group $SU(4) \otimes SU(2)_L \otimes SU(2)_R$ with LQ's

⇒ NP mainly coupled to 3rd generation

→ correlations to $b \rightarrow s\tau\bar{\tau}$, LFV signals $b \rightarrow s\tau\bar{\mu}$, $\tau \rightarrow \mu\gamma$ and collider physics $pp \rightarrow \tau\tau$



Summary

Summary

- ▶ **b Physics** is important sector to test SM and search for NP
- ▶ two complementary experiments **LHCb** and **Belle II** with unprecedented statistics
⇒ the future will bring many “anomalies”, which will need to be resolved
- ▶ currently **violation of lepton-flavor universality (LFU)** in
 - $b \rightarrow c l \bar{\nu}$ for τ/ℓ @ $(3 - 4) \sigma$ and $b \rightarrow s l \bar{\ell}$ for μ/e @ $(2 - 3) \sigma$
 - ⇒ solid SM theory!
- ▶ other tensions in $b \rightarrow s \mu \bar{\mu}$ (mainly from LHCb)
 P'_5 anomaly and $b \rightarrow s \mu \bar{\mu}$ rates ⇒ theory issues! (resort to data-driven strategies)

Intriguing part that LFU violation and tensions in $b \rightarrow s \mu \bar{\mu}$ can be explained rather economically:

- ▶ **new physics** explanations require (20-30)% modifications of Wilson coefficients of SM
⇒ fits indicate huge improvement of goodness of fit w.r.t. SM “($> 6 \sigma$)”
- ▶ separate and combined explanation in SMEFT possible
- ▶ NP couples preferably to 3rd generation ⇒ **Leptoquark scenarios** most efficient
- ▶ explicit **UV completions** with Pati-Salam groups $SU(4) \otimes SU(2)_L \otimes SU(2)_R$

Other tensions in b physics

Other tensions in b physics

V_{cb} puzzle

Tensions between different determinations of $|V_{cb}|$ from $B \rightarrow M \ell \bar{\nu}_\ell$

$$V_{cb}|_D = (40.7 \pm 1.1) \times 10^{-3} \quad V_{cb}|_{D^*} = (38.8 \pm 1.4) \times 10^{-3} \quad V_{cb}|_{X_c} = (42.00 \pm 0.64) \times 10^{-3}$$

[Bordone/Gubernari/Jung/van Dyk 1912.09335, Gambino/Healey/Turczyk 1606.06174]

2.1σ tension between $M = D^*$ and $M = X_c$ (inclusive)

$\bar{B}_{(s)}^0 \rightarrow D_{(s)}^+ (\pi^-, K^-)$ puzzle

$$b \rightarrow c \bar{u} s(d)$$

[Bordone/Gubernari/Huber/Jung/van Dyk 2007.10338]

4.4σ deviation for $Br[\bar{B}^0 \rightarrow D^{(*)+} K^-]$ and $Br[\bar{B}_s \rightarrow D_s^{(*)+} \pi^-]$ from SM predictions

NNLO QCDF + $1/m_b$ corrections

$B_{d,s} \rightarrow K^{*0} \bar{K}^{*0}$ puzzle

[Alguero/Crivellin/Descotes-Genon/Matias/Novoa-Brunet 2011.07867]

2.6σ deviation of $\frac{\tau_{B_d} \Pi_d}{\tau_{B_s} \Pi_s} \frac{Br[B_s \rightarrow (K^{*0} \bar{K}^{*0})_L]}{Br[B_d \rightarrow (K^{*0} \bar{K}^{*0})_L]} \Big|_{\text{exp}} = 4.43 \pm 0.92$ from SM $\approx 19.5_{-6.8}^{+9.3}$ using QCDF
 $(|V_{ts}| / |V_{td}|)^2 \approx 24$

Backup Slides

Flavor phenomenon

Phenomenon of “**Flavor**” was important in shaping the Standard Model (SM)

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- ▶ **β -decay:** ${}^A Z \rightarrow {}^A(Z+1) + e^- + \bar{\nu}_e$

“ β -decay energy crisis” (J. Chadwick 1914) \Rightarrow W. Pauli proposes ν (1930)

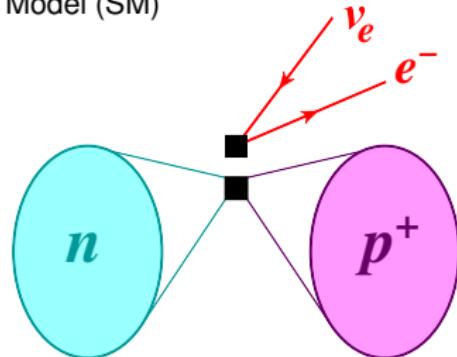
- ▶ **4-Fermi-theory**

[E. Fermi 1933/34]

$$\sim G_F \times [\bar{\Psi}(p^+) \Gamma \Psi(n)] [\bar{e} \Gamma' \nu_e]$$

Fermi coupling $G_F \sim 1/M^2$

\Rightarrow **Effective Theory (EFT)** of electroweak IA in SM



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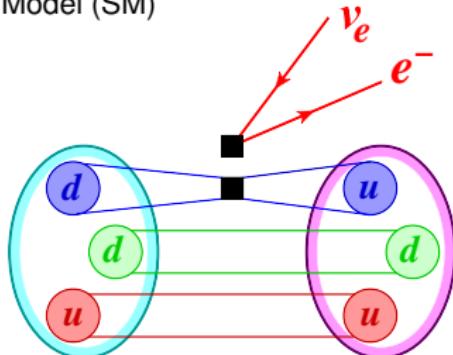
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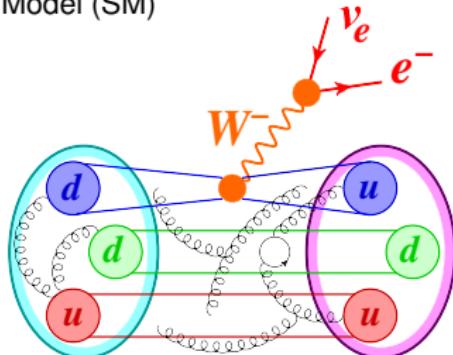
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Electroweak IA & QCD via locally gauge-invariant QFT with spontaneously broken symmetry

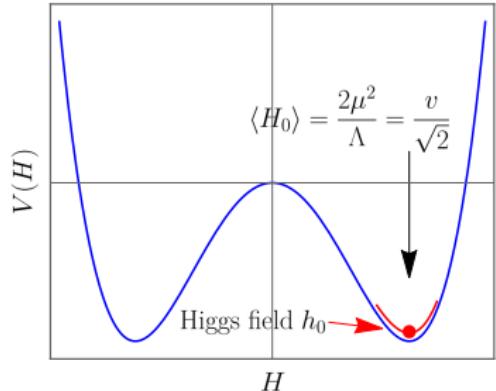
- ▶ conservation of charges in weak and strong interactions \Leftarrow Noether-theorem
- ▶ forces are transmitted by spin-1 gauge bosons \Leftarrow Gluons in QCD & massive W^\pm and Z^0 in EW IA
- ▶ simplest symmetry breaking by postulation of a single spin-0 field \Leftarrow Englert/Brout-Higgs-Guralnik/Hagen/Kibble mechanism
- ▶ Fermi constant is an **effective coupling** $G_F \propto g_2^2/m_W^2$

Yukawa couplings → origin of Flavor

Scalar potential of $SU(2)_L$ doublet

$$V(H) = -\mu^2 (H^\dagger H) + \Lambda (H^\dagger H)^2 \quad H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

implies “mexican hat potential”



Yukawa interactions of Higgs-doublet with quarks

$$\tilde{H} = i\sigma^2 H^*$$

$$\mathcal{L}_{\text{Yukawa}} \propto \sum_{i,j=1}^3 Y_{U,ij} [\bar{Q}_{L,i} \tilde{H}] u_{R,j} + Y_{D,ij} [\bar{Q}_{L,i} H] d_{R,j}$$

$$Q_{L,i} = \begin{pmatrix} u_{L,i} \\ d_{L,i} \end{pmatrix}$$

- ▶ 3 × 3 complex-valued **Yukawa couplings** $Y_{U,D} \Rightarrow$ not generation-diagonal !!!
- ▶ invariant under global $G_{\text{SM}} = U(1)_Y \otimes U(1)_B \otimes U(1)_L$, but not under G_{flavor} of $\mathcal{L}_{\text{gauge}}$
 \Rightarrow accidental global symmetries of SM (at dim-4 only): B = baryon number, L = lepton number

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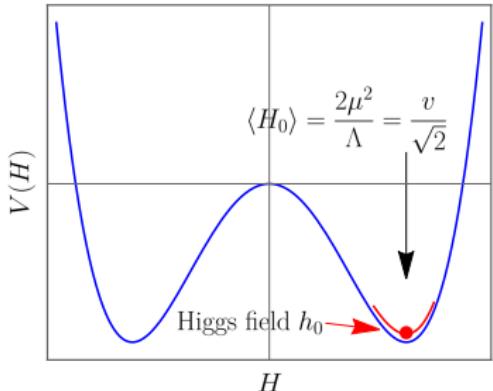
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Parametrization of H close around minimum $\langle H_0 \rangle$

$$H = \left(v/\sqrt{2} \right) + \left((h^0 + iG^0)/\sqrt{2} \right)$$

(in R_ξ -gauge)



⇒ **Higgs particle** described by fluctuations of h^0 around $\langle H_0 \rangle$

⇒ G^\pm and G^0 contribute to massive W^\pm and Z^0

Quark masses when breaking the $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{em}}$

$$\mathcal{L}_{\text{Yukawa}} \propto \sum_{i,j=1}^3 \frac{v Y_{U,ij}}{\sqrt{2}} [\bar{u}_{L,i} u_{R,j}] + \frac{v Y_{D,ij}}{\sqrt{2}} [\bar{d}_{L,i} d_{R,j}] + \dots$$

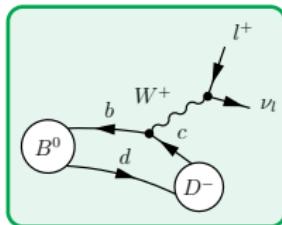
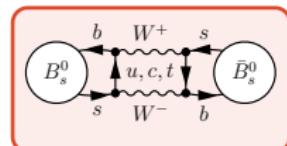
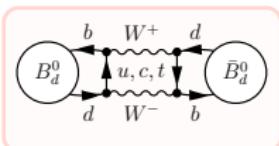
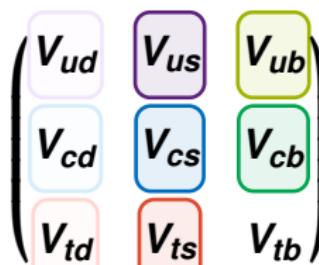
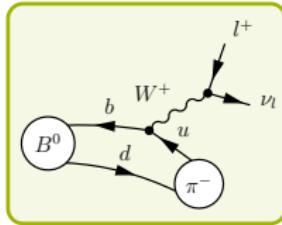
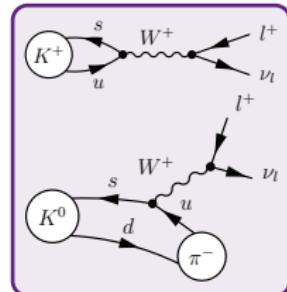
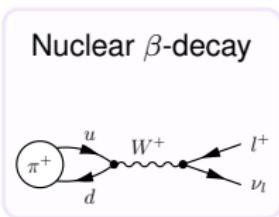
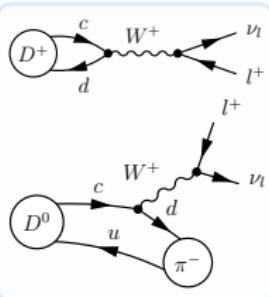
... are terms with $(h^0, G^{0,\pm})$

⇒ Quark masses

distinguish generations → **Flavor**

$$M_{U,ij} \equiv \frac{v Y_{U,ij}}{\sqrt{2}} \quad \text{and} \quad M_{D,ij} \equiv \frac{v Y_{D,ij}}{\sqrt{2}}$$

Overview of decay channels for CKM determination



Also many strategies with hadronic B decays $B \rightarrow M_1 M_2$

[Figures from Lellouch 1104.5484]

Hierarchies in masses and CKM

The determinations in framework of SM show huge hierarchies that can not be explained in the SM

- ▶ masses within each generation

- ▶ CKM matrix

$$\lambda \approx 0.225$$

Cabibbo angle

$$V_{\text{CKM}} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 A \\ -\lambda & 1 & \lambda^2 A \\ \lambda^3 A & -\lambda^2 A & 1 \end{pmatrix}$$

- ▶ in down-type FCNCs *top*-, *charm*- and *up*-contributions

b → *s*

$$V_{tb} V_{ts}^* \approx -V_{cb} V_{cs}^* \sim \lambda^2 A$$

$$V_{ub} V_{us}^* \sim \lambda^4 A$$

b → *d*

$$V_{tb} V_{td}^* \sim V_{cb} V_{cd}^* \sim V_{ub} V_{ud}^* \sim \lambda^3 A$$

s → *d*

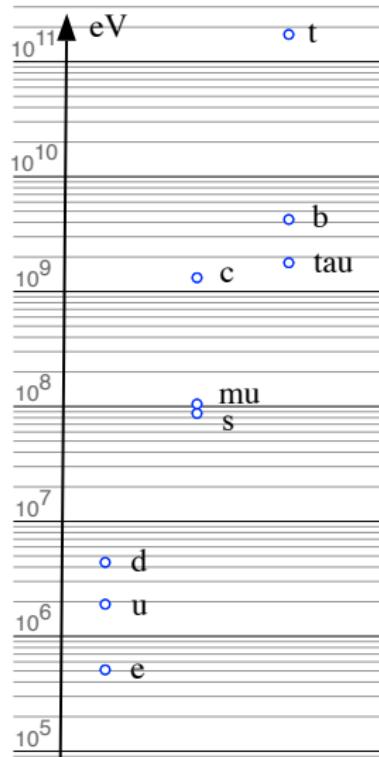
$$V_{cs} V_{cd}^* \approx -V_{us} V_{ud}^* \sim \lambda$$

$$V_{ts} V_{td}^* \sim \lambda^5 A$$

⇒ in *s* → *d* *top* part enhanced by m_t^2 , but CKM-suppressed

$$\lambda^4 A \approx 0.0021 \text{ versus } (m_c/m_W)^2 \approx 0.0003$$

⇒ CKM suppresses dim-6, such that dim-8 phenomenologically not negligible in ΔM_K , ε_K , $K^+ \rightarrow \pi + \nu\bar{\nu}$



SM predictions of $R^{\tau\mu}(D)$ and $R^{\tau\mu}(D^*)$

Prediction requires knowledge of form factors (shape) \Rightarrow two strategies

- A) use **only theory input** from LQCD, LCSR and unitarity bounds (UB) + HQET constraints
 - B) **fit FF-parameters from data** of $B \rightarrow D^{(*)}\ell\bar{\nu}$ for light $\ell = e + \mu$,
assuming new physics only in $\ell = \tau$
- \Rightarrow in the past combination of A) + B), but clearly prefer A)

SM predictions	$R(D)$	$R(D^*)$	Ref.
LCSR only	0.269 ± 0.100	0.242 ± 0.048	[GKvD'18]
LQCD only	0.300 ± 0.008	—	[HPQCD'15]
LCSR + LQCD	0.296 ± 0.006	0.256 ± 0.020	[GKvD'18]
LCSR + LQCD + UB + HQET	0.2989 ± 0.0032	0.2472 ± 0.0050	[BGJvD'19]

[HPQCD'15 = HPQCD collaboration 1505.03925]

[GKvD'18 = Gubernari/Kokulu/van Dyk 1811.00983]

provide method A) results in BGL parametrization \rightarrow [BGJvD'19 = Bordone/Gubernari/Jung/van Dyk 1912.09335]

- LQCD calculations of $B \rightarrow D^*$ FFs away from q_{\max}^2 are work in progress
- Also $R(D_s) = 0.2970 \pm 0.0034$ and $R(D_s^*) = 0.2450 \pm 0.0082$ [BGJvD'19]
- also $R(J\psi)$, $R(\Lambda_c)$, $R(X_c)$ (partial predictions)

LeptoQuarks and $b \rightarrow s\ell\bar{\ell}$: “EW gauge mixing”

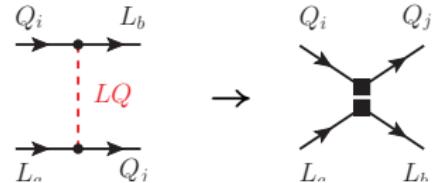
Assumption of hierarchy

$$\mu_\Lambda \approx M_{LQ} > \mathcal{O}(\text{TeV}) \gg \mu_{ew} \approx 100 \text{ GeV}$$

- at μ_Λ : LQ decpl = **match on SMEFT** (Standard Model EFT)

⇒ at tree-level → only **SL- ψ^4** op's (semi-leptonic)

$$\propto (\bar{Q}_j \Gamma Q_i)(\bar{L}_a \Gamma L_b)$$



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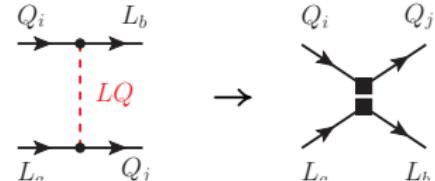
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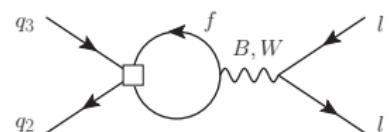


- from $\mu_\Lambda \rightarrow \mu_{ew}$: **SMEFT RG evolution** (renormalization group)

⇒ mixing into **SL- ψ^4** op's $\propto (\bar{Q}_j \Gamma Q_i)(\bar{L}_{a'} \Gamma L_{b'})$

⇒ large log's $\ln \mu_\Lambda / \mu_{ew}$ [Alonso/Jenkins/Manohar/Trott 1312.2014]

$$\mathcal{C}_{\text{SL-}\psi^4}(\mu_{ew}) = \frac{\gamma_{\text{SL,SL}}}{(4\pi)^2} \ln \frac{\mu_\Lambda}{\mu_{ew}} \mathcal{C}_{\text{SL-}\psi^4}(\mu_\Lambda)$$



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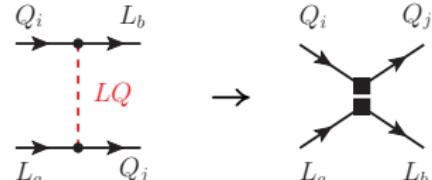
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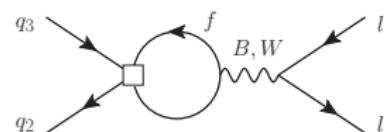


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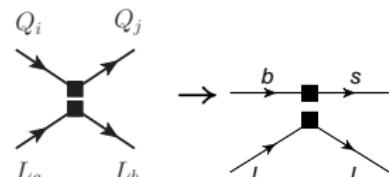


- at μ_{ew} : **matching of SMEFT on $\mathcal{L}_{\Delta B=1}$** for $b \rightarrow s\ell\bar{\ell}$

in terms of $\Delta B = 1$ operators

$$Q_{9(9')}^\ell = [\bar{s} \gamma^\mu P_{L(R)} b][\bar{\ell} \gamma_\mu \ell]$$

$$Q_{10(10')}^\ell = [\bar{s} \gamma^\mu P_{L(R)} b][\bar{\ell} \gamma_\mu \gamma_5 \ell]$$



Interpretation within SMEFT

Matching SMEFT on $b \rightarrow s\ell\bar{\ell}$ at tree-level at μ_{ew}

$$C_9^\ell \propto [\mathcal{C}_{qe}]_{23\ell\ell} + [\mathcal{C}_{lq}^{(1)}]_{\ell\ell 23} + [\mathcal{C}_{lq}^{(3)}]_{\ell\ell 23} - (1 - 4s_W^2) ([\mathcal{C}_{Hq}^{(1)}]_{23} + [\mathcal{C}_{Hq}^{(3)}]_{23})$$

$$C_{10}^\ell \propto [\mathcal{C}_{qe}]_{23\ell\ell} - [\mathcal{C}_{lq}^{(1)}]_{\ell\ell 23} - [\mathcal{C}_{lq}^{(3)}]_{\ell\ell 23} + ([\mathcal{C}_{Hq}^{(1)}]_{23} + [\mathcal{C}_{Hq}^{(3)}]_{23})$$

$$C_{9'}^\ell \propto [\mathcal{C}_{ed}]_{\ell\ell 23} + [\mathcal{C}_{ld}]_{\ell\ell 23} - (1 - 4s_W^2) [\mathcal{C}_{Hd}]_{23}$$

$$C_{10'}^\ell \propto [\mathcal{C}_{ed}]_{\ell\ell 23} + [\mathcal{C}_{ld}]_{\ell\ell 23} - [\mathcal{C}_{Hd}]_{23}$$

- ▶ $C_{9,10}$ depend on 5 Wilson coefficients
- ▶ $C_{9',10'}$ depend on 3 Wilson coefficients
- ▶ modified Z -coupl's $\mathcal{C}_{Hq}^{(1,3)}$ and \mathcal{C}_{Hd} suppressed in $C_{9,9'}$ by $(1 - s_W^2) \sim 0.08$ w.r.t. $C_{10,10'}$
- ▶ $C_{V_L} \propto \mathcal{C}_{lq}^{(3)}$ enters also $b \rightarrow c\tau\nu$

SMEFT operators: Semileptonic ψ^4 and modified Z, W^\pm -couplings $\psi^2 H^2 D$

$$\mathcal{O}_{lq}^{(1)} = (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t) \quad \mathcal{O}_{lq}^{(3)} = (\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$

$$\mathcal{O}_{qe} = (\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t) \quad \mathcal{O}_{ld} = (\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t) \quad \mathcal{O}_{ed} = (\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$$

$$\mathcal{O}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)[\bar{q}_L^i \gamma^\mu q_L^j], \quad \mathcal{O}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^a H)[\bar{q}_L^i \sigma^a \gamma^\mu q_L^j] \quad \mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)[\bar{d}_R^i \gamma^\mu d_R^j]$$

Interlude on SMEFT operators

Consider SMEFT operators, **$ijmn = \text{generation indices}$**

$$[\mathcal{O}_{lq}^{(1)}]_{ijmn} = (\bar{l}_i \gamma_\mu l_j) (\bar{q}_m \gamma^\mu q_n) \quad [\mathcal{O}_{lq}^{(3)}]_{ijmn} = (\bar{l}_i \gamma_\mu \tau^a l_j) (\bar{q}_m \gamma^\mu \tau^a q_n)$$

these operators are made of $SU(2)_L$ doublets

$$q_i = Q_{L,i} = \begin{pmatrix} u_{L,i} \\ d_{L,i} \end{pmatrix} \quad l_i = L_{L,i} = \begin{pmatrix} \nu_{L,i} \\ e_{L,i} \end{pmatrix}$$

If we do expansion in $SU(2)_L$ components (τ^a = Pauli matrices, summation over a)

$$\begin{aligned} [\mathcal{C}_1]_{ijmn} [\mathcal{O}_{lq}^{(1)}]_{ijmn} + [\mathcal{C}_3]_{ijmn} [\mathcal{O}_{lq}^{(3)}]_{ijmn} \\ = [(\mathcal{C}_1 + \mathcal{C}_3)_{ijmn} (\bar{u}_{iL} \gamma^\mu u_{jL}) (\bar{\nu}_{mL} \gamma_\mu \nu_{nL}) + (\mathcal{C}_1 - \mathcal{C}_3)_{ijmn} (\bar{u}_{iL} \gamma^\mu u_{jL}) (\bar{\ell}_{mL} \gamma_\mu \ell_{nL})] \\ + [(\mathcal{C}_1 - \mathcal{C}_3)_{ijmn} (\bar{d}_{iL} \gamma^\mu d_{jL}) (\bar{\nu}_{mL} \gamma_\mu \nu_{nL}) + (\mathcal{C}_1 + \mathcal{C}_3)_{ijmn} (\bar{d}_{iL} \gamma^\mu d_{jL}) (\bar{\ell}_{mL} \gamma_\mu \ell_{nL})] \\ + 2[\mathcal{C}_3]_{ijmn} [(\bar{u}_{iL} \gamma^\mu d_{jL}) (\bar{\ell}_{mL} \gamma_\mu \nu_{nL}) + \text{h.c.}] \quad \leftarrow \text{CC's} \quad \uparrow \text{FCNC's} \end{aligned}$$

Still need to rotate flavor \rightarrow mass basis: $u_L \rightarrow V_u u_L, d_L \rightarrow V_d d_L, \nu_L \rightarrow U_\nu \nu_L, \ell_L \rightarrow U_\ell \ell_L$

Contribute to all semileptonic CC and FCNC processes!