Anomalies in B Decays:

A first hint at physics beyond the Standard Model?

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Outline

1. Introduction: FCNC Processes
2. *B* Physics Anomalies: Experiment
3. *B* Physics Anomalies: Theory
   - Controlling the SM part
   - “New Physics” Interpretations

Introduction

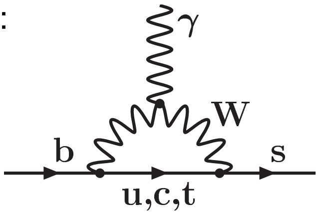
Where to search for new effects?

- Decays which are forbidden in the SM
  - … by symmetries: e.g. Baryon number: $B \to \Lambda_c \mu$ and alike
  - … by approximate symmetries: e.g. Lepton Flavour: $\mu \to e\gamma$ and alike
- decays which are rare in then SM
  - … by small couplings: e.g. CKM parameters: $B \to \pi \ell \bar{\nu}$ and alike
  - … by loop suppression: e.g. FCNC processes: $B \to K^* \gamma$ and alike
- "Bread and Butter" Decays, where we have an excellent theoretical SM prediction
  - … Purely leptonic decays $B \to \tau \bar{\nu}$ and alike
  - … inclusive / exclusive semileptonic decays $B \to X \ell \bar{\nu}$, $B \to D^{(*)} \ell \bar{\nu}$ and alike

FCNC Processes

FCNC Processes are special: Test of the GIM mechanism

Example: $b \to s\gamma$:



$$\mathcal{A}(b \to s\gamma) = V_{ub} V_{us}^* f(m_u) + V_{cb} V_{cs}^* f(m_c) + V_{tb} V_{ts}^* f(m_t)$$

In case of degenarate masses up-type masses:

$$\mathcal{A}(b \to s\gamma) = f(m) \left[V_{ub} V_{us}^* + V_{cb} V_{cs}^* + V_{tb} V_{ts}^* \right] = 0$$

The loop yields a finite result, also for non-degenerate quark masses!

- The finite result is a function of $m_t^2 - m_u^2$ and $m_t^2 - m_c^2$
- The loop generates a factor $1/(16\pi^2)$
- Top mass is dominant: $\mathcal{A}(b \to s\gamma) \sim \frac{G_F^2}{16\pi^2} V_{tb} V_{ts}^* \frac{m_t^2}{M_W^2}$
- In the up quark sector $t \to c\gamma$ and alike

$$\mathcal{A}(t \to c\gamma) \sim \frac{G_F^2}{16\pi^2} V_{cb} V_{tb}^* \frac{m_b^2}{M_W^2}$$

  much smaller!
  However, long distance effects from QCD ...
- FCNC transitions $b \to s$ have been heavily scrutinized experimentally, in particular $b \to s\ell^+\ell^-$

B Physics Anomalies: Experiment

Landscape of Anomalies: Experimental Situation

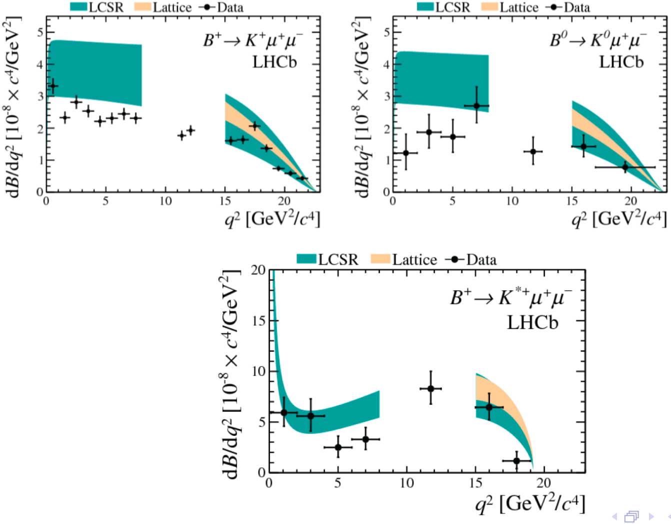
Seven “sets” of anomalies:

- Branching ratios of $b \to s\,\mu\mu$ processes
- Angular distributions in $b \to s\,\mu\mu$ processes
- Ratios of $b \to s\,ee$ versus $b \to s\,\mu\mu$
- Ratios of exclusive $b \to c\tau\bar{\nu}$ versus $b \to c\ell\bar{\nu}$

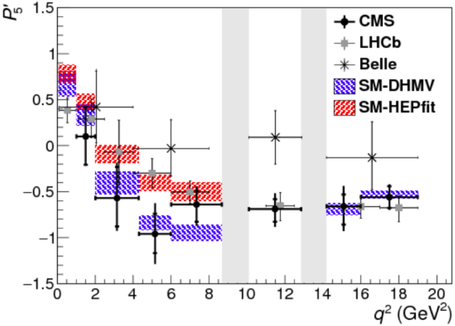
- CP Violation: Δa_{CP} in Charm and Kaon ϵ'/ϵ
- Exclusive versus inclusive V_{xb}
- Anomalous magnetic moment of the muon

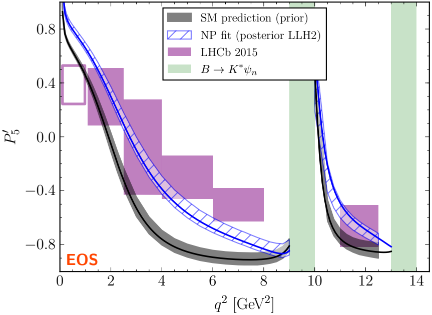
Leptoquark Anomalies | Non-Leptoquark Anomalies

Branching ratios of $b \to s\mu\mu$ processes



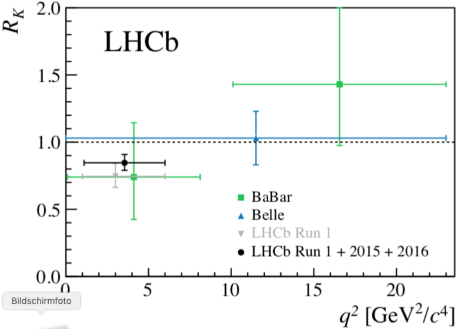
Angular Distributions in $b \to s\mu\mu$ processes

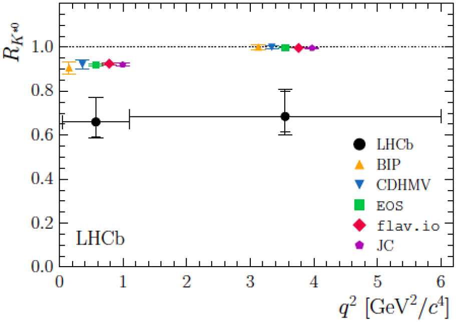




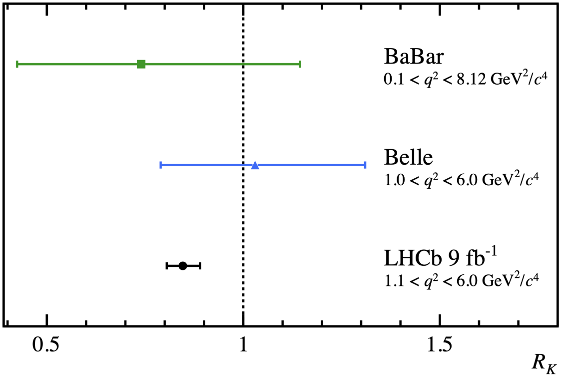
Ratios of $b \to s\, e^+ e^-$ and $b \to s\, \mu^+ \mu^+$ rates

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to \mu^+ \mu^-) K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to J/\psi\,(\to e^+ e^-) K^+)}\,.$$





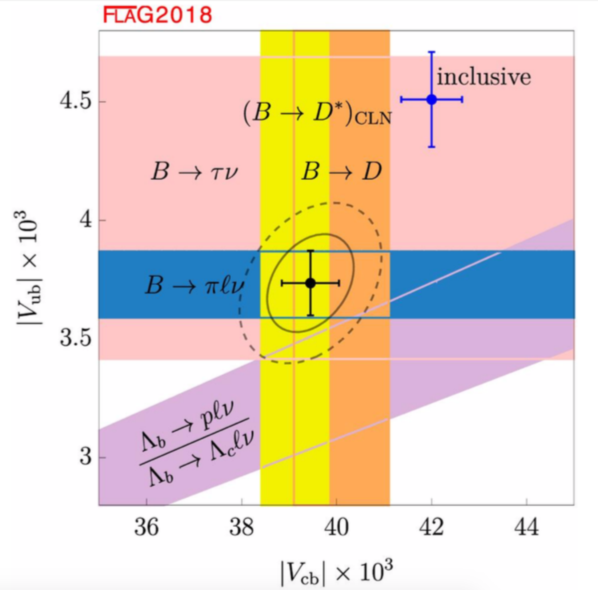
New results of this year



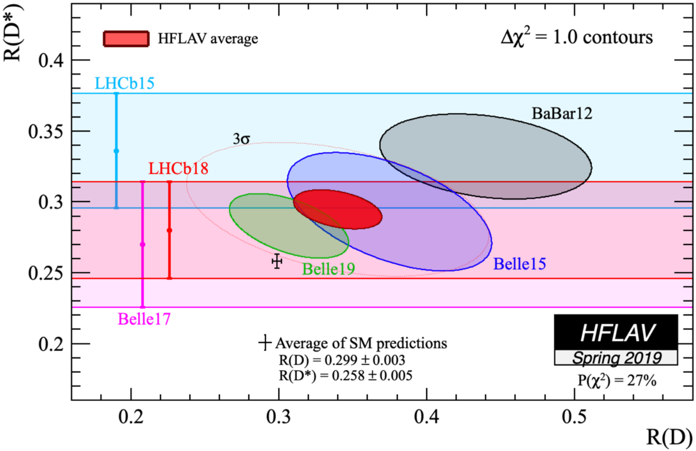
Inclusive versus Exclusive V_{xb}

Charged Current Semileptonics are under scrutiny:

- Tensions between inclusive and exclusive determinations of V_{cb}
- Tensions between inclusive and exclusive determinations of V_{ub}


FLAG2018
inclusive
$(B \to D^*)_{\mathrm{CLN}}$
$B \to \tau\nu$
$B \to D$
$B \to \pi\ell\nu$
$\frac{\Lambda_b \to p\ell\nu}{\Lambda_b \to \Lambda_c\ell\nu}$
4.5
4
3.5
3
$|V_{\mathrm{ub}}| \times 10^3$
36
38
40
42
44
$|V_{\mathrm{cb}}| \times 10^3$

Charged Currents: $B \to D^{(*)}\ell\bar{\nu}$



B Physics Anomalies:

Theory

Exclusive Determinations of V_{cb}

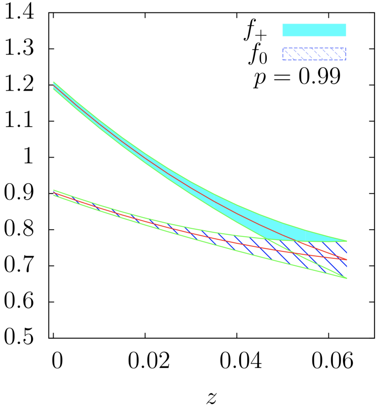
- Kinematic variable for a heavy quark: Four Velocity v
- Differential Rates

$$\frac{d\Gamma}{d\omega}(B \to D^* \ell \bar{\nu}_\ell) = \frac{G_F^2}{48\pi^3} |V_{cb}|^2 m_{D^*}^3 (\omega^2 - 1)^{1/2} P(\omega) (\mathcal{F}(\omega))^2$$
$$\frac{d\Gamma}{d\omega}(B \to D \ell \bar{\nu}_\ell) = \frac{G_F^2}{48\pi^3} |V_{cb}|^2 (m_B + m_D)^2 m_D^3 (\omega^2 - 1)^{3/2} (\mathcal{G}(\omega))^2$$

- with $\omega = vv'$ and
- $P(\omega)$: Calculable Phase space factor
- $\mathcal{F}$ and $\mathcal{G}$: Form Factors

$B \to D$ Form Factors from the Lattice

There are results over the full phase space (Milc/Fermilab)



Results off $vv' = 1$ for $B \to D^*$ are not yet available!

Extracting exclusive V_{cb} from $B \to D^* \ell \bar{\nu}$

$B \to D^* \ell \bar{\nu}$

- Use the Lattice value of $\mathcal{F}(1)$
- Extrapolate the data to the point $vv' = 1$
- This extrapolation depends on the form factor shape!
- Recent discussion on form factor parametrizations
  - One-parameter form (CLN) seems too simple
    (Caprini, Lellouch, Neubert)
  - Recent fits in terms of BGL parametrization
    (Boyd, Grinstein Lebed)
  - No large impact on V_{cb}

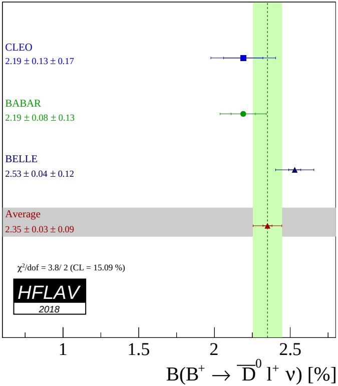
Results for exclusive V_{cb} from $B \to D^* \ell \bar{\nu}$

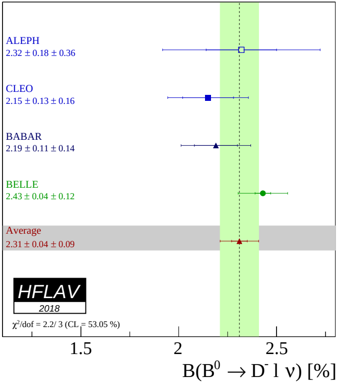
$$\boxed{|V_{cb}| = 39.6^{+1.1}_{-1.0} \times 10^{-3}}$$

(Gambino, Jung, Schacht, based on Lattice $\mathcal{F}(1)$)

Extracted V_{cb} is mainly driven by the value of $\mathcal{F}(1)$

$B \to D\ell\bar{\nu}_\ell$





$$\boxed{|V_{cb}| = 40.49 \pm 0.97 \times 10^{-3}}$$ (D. Bigi, Gambino)

Inclusive V_{cb} Determination

- Standard tool: Heavy Quark Expansion
- Structure of the expansion (@ tree):

$$
\begin{aligned}
d\Gamma &= d\Gamma_0 + \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^2 d\Gamma_2 + \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 d\Gamma_3 + \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^4 d\Gamma_4 \\
&\quad + d\Gamma_5 \left(a_0 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^5 + a_2 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 \left(\frac{\Lambda_{\rm QCD}}{m_c}\right)^2 \right) \\
&\quad + \ldots + d\Gamma_7 \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^3 \left(\frac{\Lambda_{\rm QCD}}{m_c}\right)^4
\end{aligned}
$$

- Power counting $m_c^2 \sim \Lambda_{\rm QCD} m_b$

- Γ_0 is the decay of a free quark ("Parton Model")
- Γ_1 vanishes due to Heavy Quark Symmetries
- Γ_2 is expressed in terms of two parameters

$$\begin{aligned} 2M_H\mu_\pi^2 &= -\langle H(v)|\bar{Q}_v(iD)^2 Q_v|H(v)\rangle \\ 2M_H\mu_G^2 &= \langle H(v)|\bar{Q}_v\sigma_{\mu\nu}(iD^\mu)(iD^\nu)Q_v|H(v)\rangle \end{aligned}$$

μ_π: Kinetic energy and μ_G: Chromomagnetic moment

- Γ_3 two more parameters

$$\begin{aligned} 2M_H\rho_D^3 &= -\langle H(v)|\bar{Q}_v(iD_\mu)(ivD)(iD^\mu)Q_v|H(v)\rangle \\ 2M_H\rho_{LS}^3 &= \langle H(v)|\bar{Q}_v\sigma_{\mu\nu}(iD^\mu)(ivD)(iD^\nu)Q_v|H(v)\rangle \end{aligned}$$

ρ_D: Darwin Term and ρ_{LS}: Spin-Orbit Term

- Γ_4 and Γ_5 have been computed Bigi, Uraltsev, Turczyk, TM, ...

Current Status of the calculation:

- Tree level terms up to and including $1/m_b^5$ known
  (Bigi, ThM, Turczyk, Uraltsev, ...)
- $\mathcal{O}(\alpha_s)$ and full $\mathcal{O}(\alpha_s^2)$ for the leading term known
  (Melnikov, Czarnecki ...)
- $\mathcal{O}(\alpha_s)$ for the μ_π^2/m_b^2 and μ_G^2/m_b^2 known
  (Becher, Boos, Lunghi, Alberti, Gambino, Nandi, ThM, Pivovarov, Rosenthal ...)
- First results on α_s/m_b^3 corrections
  (ThM, Pivovarov 1907.09187)
- Modelling for the HQE matrix elements beyond $1/m^3$
  (ThM, Uraltsev, Heinonen, ...)

Strategy to extract V_{cb}

- Based on the HQE for the inclusive rates and for moments of spectra
- (Cut) moments of the charged lepton energy, hadronic energy and hadronic invariant mass spectra
- Extract the HQE parameters from this data
- Obtain V_{cb} from the total semileptonic rate

Problem: Number of HQE parameters in higher orders!

- 4 up to $1/m^3$
- 13 up to $1/m^4$ (tree level)
- 31 up to order $1/m^5$ (tree level)
- Factorial Proliferation

Result of the Fit in the kinetic scheme

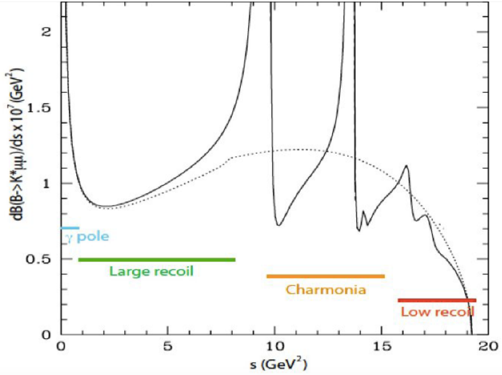
(Gambino, Schwanda 2014)

m_b^{kin}	m_c	μ_π^2	ρ_D^3	μ_G^2	ρ_{LS}^3	$\mathrm{BR}_{c\ell\nu}(\%)$	$10^3\,\lvert V_{cb}\rvert$
4.541	0.987	0.414	0.154	0.340	-0.147	10.65	42.42
0.023	0.013	0.078	0.045	0.066	0.098	0.16	0.86

FCNC Decays

FCNC Semileptonics: $B \to K^{(*)}\ell^+\ell^-$

What is the problem?



How to compute $\langle B|H_{\rm eff}|K^{(*)}\ell^+\ell^-\rangle$?

Hadronic matrix elements

Decay Amplitude for $B \to K^{(*)}\ell\ell$ (Schematically):

$$\mathcal{A}(B \to K^{(*)}\ell\ell) = \mathcal{N}\left[(C_9 L_V^\mu + C_{10} L_A^\mu) F_\mu - \frac{L_V^\mu}{s}(C_7 F_{T,\mu} + \mathcal{H}_\mu)\right]$$

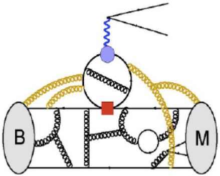
Hadronic matrix elements are the limiting factors for precise predictions!

- Local matrix elements: Form factors ($M = K, K^*$):

$$\mathcal{F}_\mu^{B\to M}(k,q) \equiv \langle M(k)|\bar{s}\gamma_\mu P_L\, b|\bar{B}(q+k)\rangle\ ,$$

$$\mathcal{F}_{T,\mu}^{B\to M}(k,q) \equiv \langle M(k)|\bar{s}\sigma_{\mu\nu}q^\nu P_R\, b|\bar{B}(q+k)\rangle\ ,$$

- Non-local matrix elements



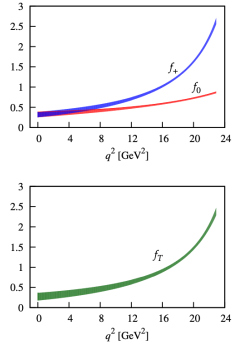
$$\mathcal{H}_\mu^{B\to M}(k,q) \equiv i\int d^4x\, e^{iq\cdot x}\,\langle M(k)|T\{j_\mu^{\rm em}(x), (C_1\mathcal{O}_1 + C_2\mathcal{O}_2)(0)\}|\bar{B}(q+k)\rangle$$

Form Factors

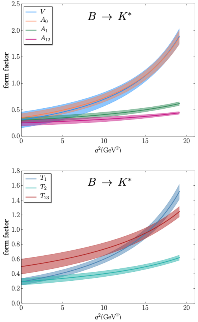
relatively well under control:

- Lattice simulations at high s (i.e. low hadronic recoil)
- Light-cone Sum-rule estimates at $s \sim 0$
- Inter-/Extrapolation using the z expansion

$\boxed{\text{Uncertainty} \sim 10\%}$

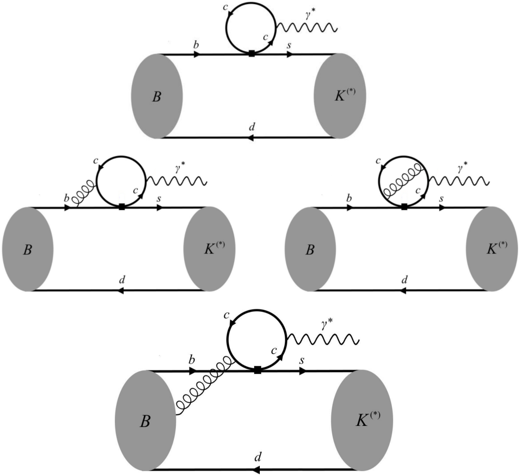


(HPQCD 2013)



(Horgan, Liu, Meinel, Wingate, 2013)

Non-Local contributions: Charm loop Contribution



Options for the charm loop:

- Local Expansion for $s \ll m_c^2$
  Expansion parameter s/m_c^2

  Valid in the pole region
  (Buchalla, Isidori, Rey 1997, Voloshin 1996)

- Light-Cone expansion for $4m_c^2 - s \ll \Lambda_{\rm QCD}^2$

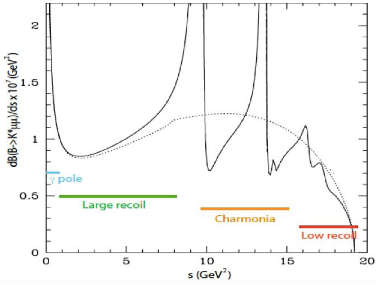
  Expansion parameter $\Lambda_{\rm QCD}/\sqrt{4m_c^2 - s}$

  Valid for $0 \leq s \leq 4m_c^2$

- Narrow Resonances: Approximate by
  $B \to (J/\psi, \psi')K^{(*)} \to \ell^+\ell^- K^{(*)}$

  Valid for $4m_c^2 \leq s \leq M_{\psi'}^2$

- Above $s \leq M_{\psi'}^2$: difficult! (Grinstein, Pirjol, 2004)



This is still the largest source of uncertainties!

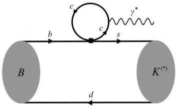
.. to give you an impression

Interesting region for hunting anomalies: $0 \leq s \leq 4m_c^2$
Decompose the non-local matrix element into helicity components

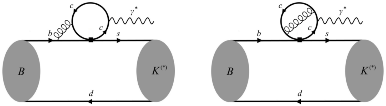
$$\mathcal{H}_\mu^{B\to K} = S_\mu^P \mathcal{H}_0^{B\to K} \quad \text{and} \quad \mathcal{H}_\mu^{B\to K^*} \sum_\lambda S_\mu^\lambda \mathcal{H}_0^{B\to K^*}, \quad \lambda = \perp, ||, 0$$

$$\mathcal{H}_\lambda(q^2) = C_\lambda(q^2)\mathcal{F}_\lambda(q^2) + \tilde{C}_\lambda(q^2)\mathcal{V}_\lambda(q^2) + \cdots$$

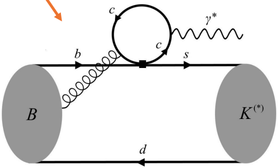
leading power (LO in α_s)



+ hard gluons (α_s) corrections



soft gluon correction
non-perturbative
$\Longrightarrow$ not α_s suppressed



Light Cone OPE for $\mathcal{V}_\lambda$:

$$\langle 0 | \bar{d}(x) G_{\alpha\beta}(uy) h_v(0) | B(v) \rangle$$
$$= \frac{f_B m_B}{4} \mathrm{Tr}\left\{ \gamma_5 P_+ \left[(v_\alpha \gamma_\beta - v_\beta \gamma_\alpha)(\boldsymbol{\Psi_A} - \boldsymbol{\Psi_V}) - i\sigma_{\alpha\beta} \boldsymbol{\Psi_V} - (y_\alpha v_\beta - y_\beta v_\alpha) \frac{\boldsymbol{X_A}}{v \cdot y} + (y_\alpha \gamma_\beta - y_\beta \gamma_\alpha) \frac{\boldsymbol{Y_A}}{v \cdot y} \right] \right\} (\boldsymbol{x}, \boldsymbol{uy})$$

(Khodjamirian, M, Pivovarov, Wang 2010)

$$= \frac{f_B m_B}{4} \mathrm{Tr}\left\{ \gamma_5 P_+ \left[(v_\alpha \gamma_\beta - v_\beta \gamma_\alpha)(\boldsymbol{\Psi_A} - \boldsymbol{\Psi_V}) - i\sigma_{\alpha\beta} \boldsymbol{\Psi_V} - (y_\alpha v_\beta - y_\beta v_\alpha) \frac{\boldsymbol{X_A}}{v \cdot y} + (y_\alpha \gamma_\beta - y_\beta \gamma_\alpha) \frac{\boldsymbol{W} + \boldsymbol{Y_A}}{v \cdot y} \right.\right.$$
$$\left.\left. - i\epsilon_{\alpha\beta\sigma\rho} y^\sigma v^\rho \gamma_5 \frac{\widetilde{\boldsymbol{X}}_{\boldsymbol{A}}}{v \cdot y} + i\epsilon_{\alpha\beta\sigma\rho} y^\sigma \gamma^\rho \gamma_5 \frac{\widetilde{\boldsymbol{Y}}_{\boldsymbol{A}}}{v \cdot y} - (y_\alpha v_\beta - y_\beta v_\alpha) y_\sigma \gamma^\sigma \frac{\boldsymbol{W}}{(v \cdot y)^2} + (y_\alpha \gamma_\beta - y_\beta \gamma_\alpha) y_\sigma \gamma^\sigma \frac{\boldsymbol{Z}}{(v \cdot y)^2} \right] \right\} (\boldsymbol{x}, \boldsymbol{uy})$$

(Gubernari, van Dyk, Virto 2020)

Additional contributions up to twist 4

Transition	$\tilde{\mathcal{V}}(q^2 = 1\,\mathrm{GeV}^2)$	This work	Ref. [11]
$B \to K$	$\tilde{\mathcal{A}}$	$(+4.9 \pm 2.8) \cdot 10^{-7}$	$(-1.3^{+1.0}_{-0.7}) \cdot 10^{-4}$
$B \to K^*$	$\tilde{\mathcal{V}}_1$	$(-4.4 \pm 3.6) \cdot 10^{-7}\,\mathrm{GeV}$	$(-1.5^{+1.5}_{-2.5}) \cdot 10^{-4}\,\mathrm{GeV}$
	$\tilde{\mathcal{V}}_2$	$(+3.3 \pm 2.0) \cdot 10^{-7}\,\mathrm{GeV}$	$(+7.3^{+14}_{-7.9}) \cdot 10^{-5}\,\mathrm{GeV}$
	$\tilde{\mathcal{V}}_3$	$(+1.1 \pm 1.0) \cdot 10^{-6}\,\mathrm{GeV}$	$(+2.4^{+5.6}_{-2.7}) \cdot 10^{-4}\,\mathrm{GeV}$

This work = Gubernari, van Dyk, Virto 2020, Model for the functions: Braun, Ji Manashov, 2017

Ref[11] = Khodjamirian, M, Pivovarov, Wang 2010, simple exponential model

Factor more than 100! ... Why?

- Cancellations between the various contributions, which was not present in KMPW2010, may be model dependent?
- More recent calculations of the normalization constants of the $\bar{q}Gh_v$ LCDA

$$\begin{aligned} \lambda_E^2 &\sim \langle 0|g_s\bar{q}\gamma_0(\vec{\gamma}\cdot\vec{E})\gamma_5 h_v|B(v)\rangle \\ \lambda_H^2 &\sim \langle 0|g_s\bar{q}(\vec{\sigma}\cdot\vec{B})\gamma_5 h_v|B(v)\rangle \end{aligned}$$

	Neubert Grozin 96	Nishikawa/Tanaka 14	Rahimi Wald 20
λ_E^2 (GeV^2)	0.11 ± 0.06	0.03 ± 0.02	0.01 ± 0.01
λ_H^2 (GeV^2)	0.18 ± 0.07	0.06 ± 0.03	0.15 ± 0.05

$(\lambda_E^2 = \lambda_E^2(\mu = 1\ GeV),\ \lambda_H^2 = \lambda_H^2(\mu = 1\ GeV))$

- Estimates are based on different! QCD sum rules

... to take home:

- Main source of remaining uncertainties are hadronic matrix elements
- Heavy Quark Methods have helped, but we are now in a precision era
- Lattice QCD methods made enormous progress towards phenomenologically useful results
- There will be an enormous ammount of data in the comming years!

"New Physics" Interpretations

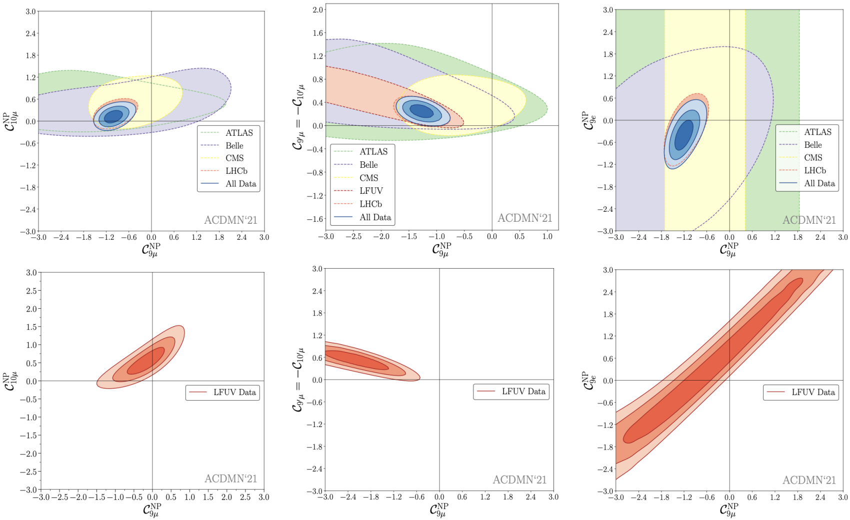
Beyond the Standard Model

Current Highlight: "*B*-Anomalies"

- Partial rates
- Angular Distributions
- Lepton Universality

The EffTh approach is very versatile:

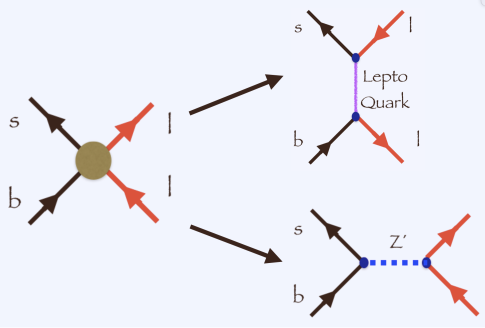
- Modification of Wilson coefficients relative to the SM values
- Additional Operators nor present in the SM
  e.g. Operators with right-handed currents, usually marked with a prime
- ... but it cannot tell you much about the details of BSM physics



(Alguero et al., 2104.08921)

Observations from the fit of the Wilson coefficients: (Alguero et al., 2104.08921)

- Viable possibility: Right handed contributions O_9' and O_{10}' for muons
- LFU violation with $C_{9,\mu} = -C_{10,\mu}$ requires also LF-universal NP contributions
- Move on to simplified models:



Simplified Models

For the *B* anomalies: Two possibilities

- Leptoquark models
  - Leptoquark masses about 3 TeV
  - scalar and vector leptoquarks
  - Scenarios with leptoquark(s) can fit all anomalies
  - Searches at the LHC

$(SU(3)_c, SU(2)_w, U(1)_Y)$	Spin	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ and $R_{K^{(*)}}$
$S_3 \equiv (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	x	✓	x
$R_2 \equiv (\mathbf{3}, \mathbf{2}, 7/6)$	0	✓	x	x
$\tilde{R}_2 \equiv (\mathbf{3}, \mathbf{2}, 1/6)$	0	✓	x	x
$S_1 \equiv (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	✓	x	x
$U_3 \equiv (\mathbf{3}, \mathbf{3}, 2/3)$	1	x	✓	x
$U_1 \equiv (\mathbf{3}, \mathbf{1}, 2/3)$	1	✓	✓	✓

- Extended gauge group (Z') models
  - New Matter particles with masses $\sim$ 3 TeV
  - Additional Gauge Bosons with masses $\sim$ TeV
  - ... can also fit all anomalies
  - Searches at the LHC

	generations	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_1$	$\mathrm{SU}(2)_2$	$\mathrm{U}(1)_Y$
ϕ	1	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
Φ	1	$\mathbf{1}$	$\mathbf{2}$	$\bar{\mathbf{2}}$	0
q_L	3	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$1/6$
u_R	3	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$2/3$
d_R	3	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$
ℓ_L	3	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
e_R	3	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
$Q_{L,R}$	n_{VL}	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$	$1/6$
$L_{L,R}$	n_{VL}	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$-1/2$

(Boucenna et al.)

Towards a BSM Theory ...

Problems with simplified models

- Observations mainly in the third generation:
  What is the flavour stucture of the couplings?
- How can a "UV complete" theory be constructed?
- Is this theory compatible with the observations in the first and second generation?

Towards a BSM Theory ...

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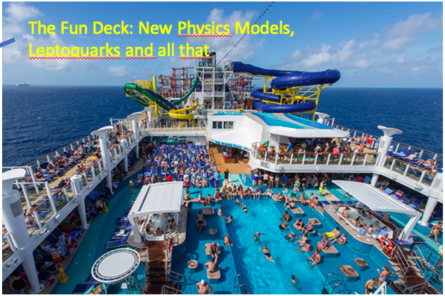
A lot is ahead of us

... and there is some hope
... due to the persistence of the *B* anomalies


Ship of Flavour Theory


The Fun Deck: New Physics Models,
Leptoquarks and all that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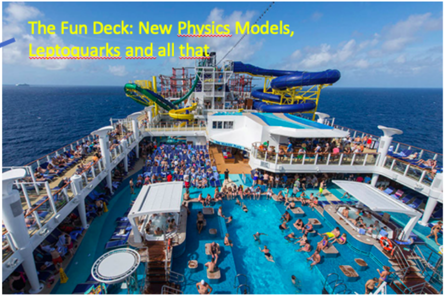
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