An introduction to the B-anomalies

- Lecture 2 -

Model-independent interpretation

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Summary of this lecture

1) General considerations

2) EFT approach and global fits

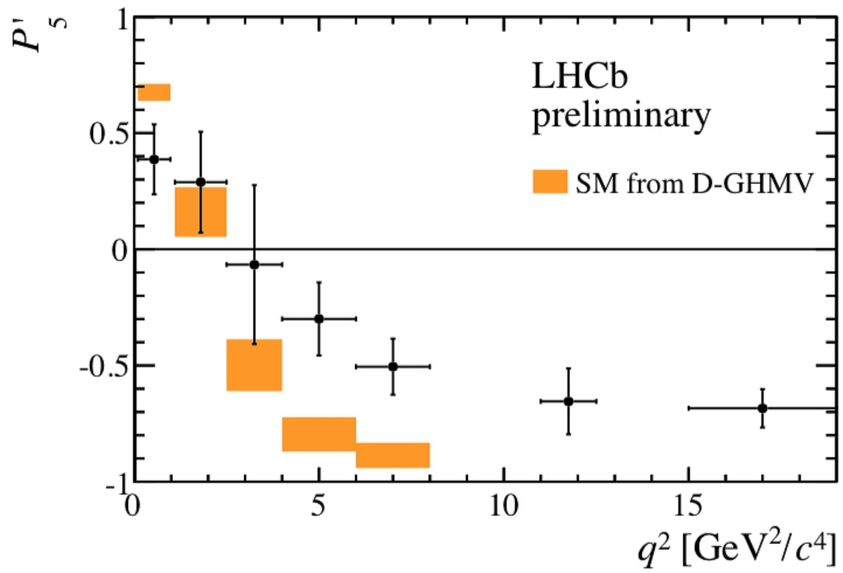
3) Gauge-invariant EFT approach: the SMEFT

General considerations

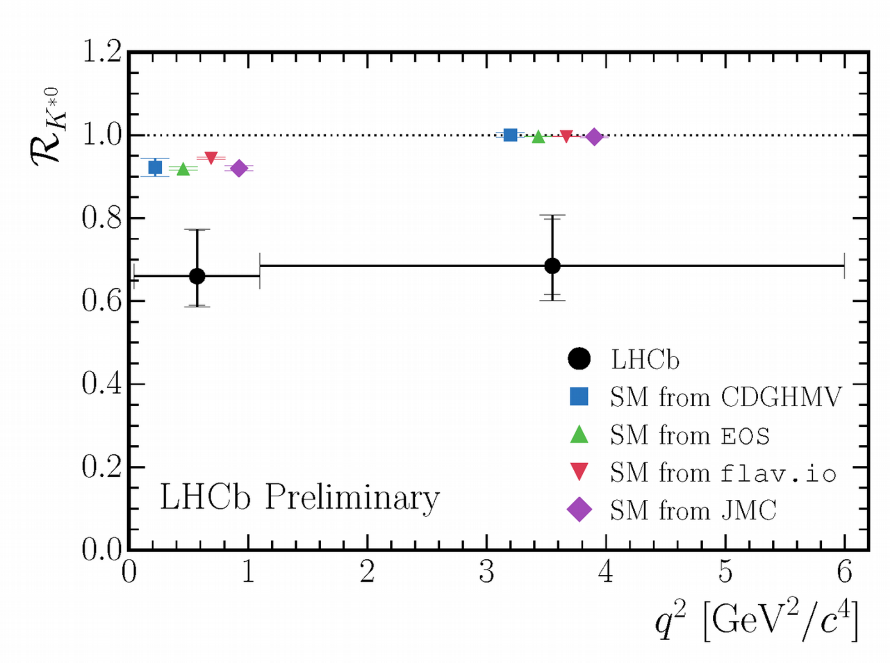
First of all, a warning!

Anomalies can go away

The $b \to s$ anomalies



Angular anomalies (such as P_5') are full of hadronic uncertainties... they might be just QCD effects



LFU ratios are clean... but the deviations from the SM predictions are still below 3σ

The $b \to s$ anomalies

Beyond the **S**tandard Model

The $b \to s$ anomalies

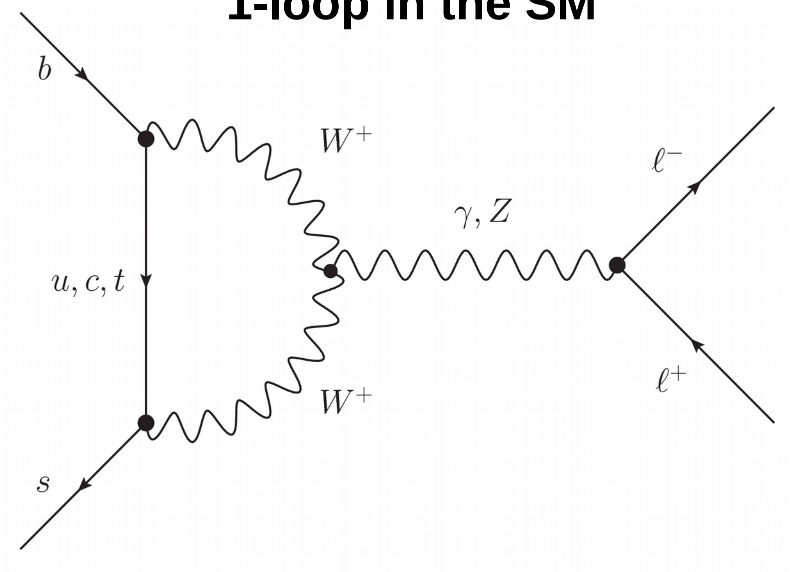
Boring **S**izable corrections

Assuming the anomalies are caused by **NP**... what is its **energy scale**?

b → s anomalies

b → c anomalies

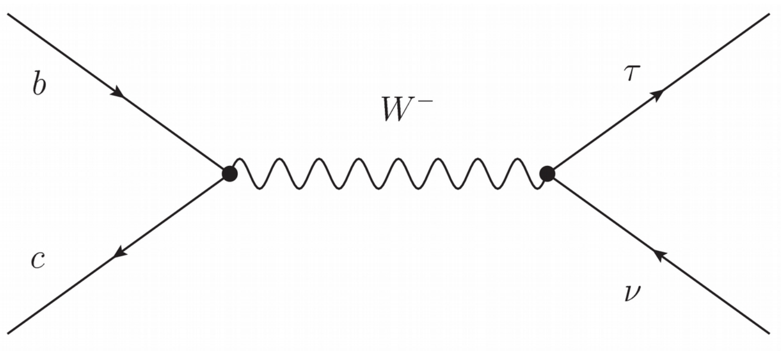
1-loop in the SM



The scale of NP can be "*high*"

$$\Lambda \sim 30 - 50 \, \text{TeV}$$

Tree-level in the SM



The scale of NP must be "low"

$$\Lambda \sim \, \text{TeV}$$

Summary

$b \to s$ anomalies	**$b \to c$ anomalies**
Found by LHCb (and perhaps hinted by Belle)	Found by several experiments (LHCb, BaBar and Belle)
Many observables: global pattern	Two observables: R(D) and R(D*)
Neutral current	Charged current
1-loop (and CKM-suppressed) in the SM	Tree-level in the SM
The New Physics can be heavy	The New Physics must be light

EFT approach and global fits

Interpreting the anomalies

From now on...

Assumption 1: The anomalies are caused by New Physics

Assumption 2: The New Physics states are heavy $(\Lambda \gg m_b)$

This is the perfect ground for...

Effective Field Theory

- All the heavy degrees of freedom are integrated out
- Physics described by a collection of non-renormalizable operators
- Model-independent language

Interpreting the anomalies

From now on...

Assumption 1: The anomalies are caused by New Physics

Assumptio ... $b)$

This is the perfec

I will now concentrate on the $b \to s$ anomalies

Effective Field Theory

- All the heavy degrees of freedom are integrated out
- Physics described by a collection of non-renormalizable operators
- Model-independent language

$b \to s$ Effective Field Theory

$b \to s$ Effective Hamiltonian

Weak EFT

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

C_i : Wilson coefficients

$\mathcal{O}_i$: Operators

$$\mathcal{O}_7 = (\bar{s} \sigma_{\mu\nu} P_R b) F^{\mu\nu}$$

$$\mathcal{O}_9 = (\bar{s} \gamma_\mu P_L b) \left(\bar{\ell} \gamma^\mu \ell\right)$$

$$\mathcal{O}_{10} = (\bar{s} \gamma_\mu P_L b) \left(\bar{\ell} \gamma^\mu \gamma_5 \ell\right)$$

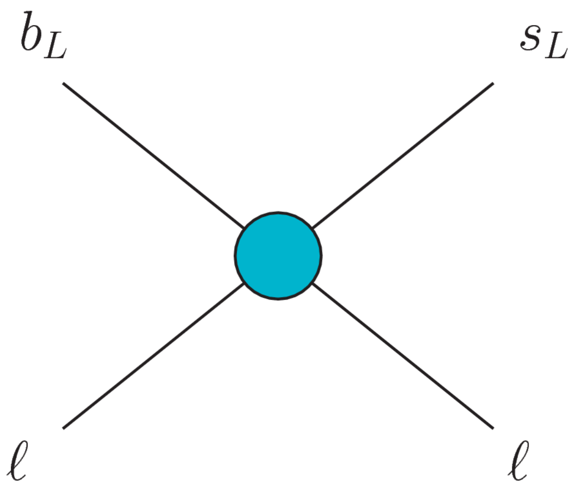
$$\mathcal{O}_7' = (\bar{s} \sigma_{\mu\nu} P_L b) F^{\mu\nu}$$

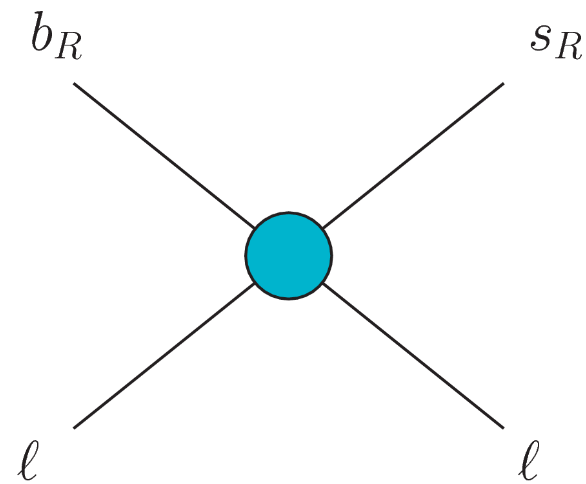
$$\mathcal{O}_9' = (\bar{s} \gamma_\mu P_R b) \left(\bar{\ell} \gamma^\mu \ell\right)$$

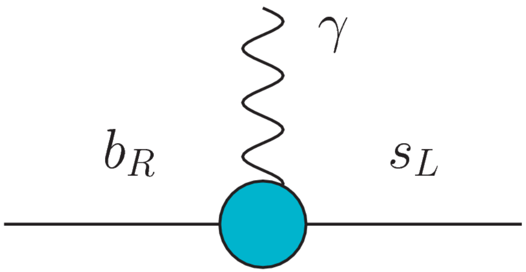
$$\mathcal{O}_{10}' = (\bar{s} \gamma_\mu P_R b) \left(\bar{\ell} \gamma^\mu \gamma_5 \ell\right)$$

$b \to s$ Effective Field Theory

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







$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\ \left(\bar{\ell}\gamma^\mu \ell\right)$ $\mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)\ \left(\bar{\ell}\gamma^\mu \ell\right)$ $\mathcal{O}_7 = (\bar{s}\sigma_{\mu\nu} P_R b)\, F^{\mu\nu}$

$b \to s$ Effective Field Theory

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

$$C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$$

[analogous for primed operators]

C_i^{SM}: calculable

C_i^{NP}: what we want to know

Standard Model contributions at $Q = m_b$:

$$C_7^{\text{SM}} = -0.3 \qquad C_9^{\text{SM}} = 4.1 \qquad C_{10}^{\text{SM}} = -4.3 \qquad C_{\text{rest}}^{\text{SM}} \lesssim 10^{-2}$$

Processes and observables

Inclusive

$B \to X_s \gamma$ (BR) ---------------------------- $C_7^{(\prime)}$

$B \to X_s \ell^+ \ell^-$ (dBR/dq²) ------------------ $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

Exclusive leptonic

$B_s \to \ell^+ \ell^-$ (BR) ---------------------------- $C_{10}^{(\prime)}$

Exclusive radiative/semileptonic

$B \to K^* \gamma$ (BR, S, A_I) --------------------- $C_7^{(\prime)}$

$B \to K \ell^+ \ell^-$ (dBR/dq²) -------------------- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

$B \to K^* \ell^+ \ell^-$ (dBR/dq², angular obs.) --- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

$B_s \to \phi \ell^+ \ell^-$ (dBR/dq², angular obs.) --- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

Processes and observables

Examples:

[Celis, Fuentes-Martín, AV, Virto, 2017]

$$[R_K]_{[1,6]} \simeq 1.00(1) + 0.230(\mathcal{C}^{\rm NP}_{9\mu-e} + \mathcal{C}'_{9\mu-e}) - 0.233(2)(\mathcal{C}^{\rm NP}_{10\mu-e} + \mathcal{C}'_{10\mu-e})$$

$$[R_{K^*}]_{[0.045,1.1]} \simeq 0.92(2) + 0.07(2)\mathcal{C}^{\rm NP}_{9\mu-e} - 0.10(2)\mathcal{C}'_{9\mu-e} - 0.11(2)\mathcal{C}^{\rm NP}_{10\mu-e} + 0.11(2)\mathcal{C}'_{10\mu-e} + 0.18(1)\mathcal{C}^{\rm NP}_7$$

$$[R_{K^*}]_{[1.1,6]} \simeq 1.00(1) + 0.20(1)\mathcal{C}^{\rm NP}_{9\mu-e} - 0.19(1)\mathcal{C}'_{9\mu-e} - 0.27(1)\mathcal{C}^{\rm NP}_{10\mu-e} + 0.21(1)\mathcal{C}'_{10\mu-e}$$

$$\Rightarrow \; C_7, \, C_9, \, C_9', \, C_{10}, \, C_{10}'$$

Analogously with other observables...

Global fits

The same Wilson coefficients enter several observables $\Longrightarrow$ A pattern of deviations rather than a single anomaly $\Longrightarrow$ **Global fit**

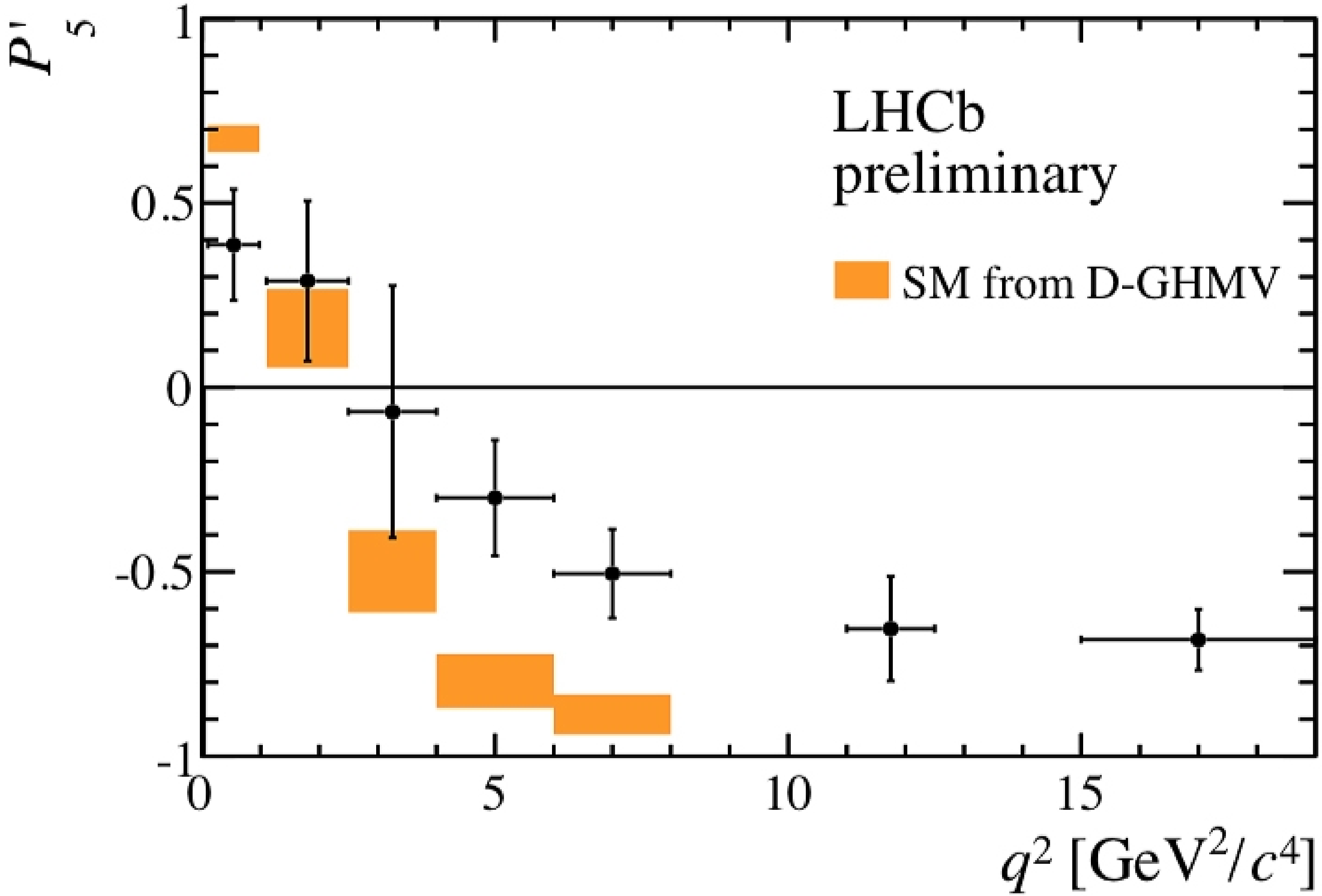
Idea (very simplified):

$$\chi^2(C_i) = [O_{\rm exp} - O_{\rm th}(C_i)]_m \left[{\rm Cov}^{-1}\right]_{mn} [O_{\rm exp} - O_{\rm th}(C_i)]_n$$

- ${\rm Cov} = {\rm Cov}^{\rm exp} + {\rm Cov}^{\rm th}$
- Minimize $\chi^2 \longrightarrow \chi^2_{\rm min} = \chi^2(C_i^0)$ $\quad C_i^0$ = best-fit point
- Confidence level regions $\chi^2(C_i) - \chi^2_{\rm min} < \Delta\chi^2_{n\sigma}$

And use as many observables as possible!

Global fits



Each bin is <u>an observable</u>

Global fits: results

Table from Capdevila et al, 1704.05340

	All					LFUV				
1D Hyp.	Best fit	1 σ	2 σ	Pull_{SM}	p-value	Best fit	1 σ	2 σ	Pull_{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.10	$[-1.27, -0.92]$	$[-1.43, -0.74]$	5.7	72	-1.76	$[-2.36, -1.23]$	$[-3.04, -0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.61	$[-0.73, -0.48]$	$[-0.87, -0.36]$	5.2	61	-0.66	$[-0.84, -0.48]$	$[-1.04, -0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9\mu}'$	-1.01	$[-1.18, -0.84]$	$[-1.33, -0.65]$	5.4	66	-1.64	$[-2.12, -1.05]$	$[-2.52, -0.49]$	3.2	31
$\mathcal{C}_{9\mu}^{\text{NP}} = -3\mathcal{C}_{9e}^{\text{NP}}$	-1.06	[-1.23,-0.89]	[-1.39,-0.71]	5.8	74	-1.35	$[-1.82, -0.95]$	$[-2.38, -0.59]$	4.0	71

All observables
"clean" + "dirty"

Only LFUV observables
"clean"

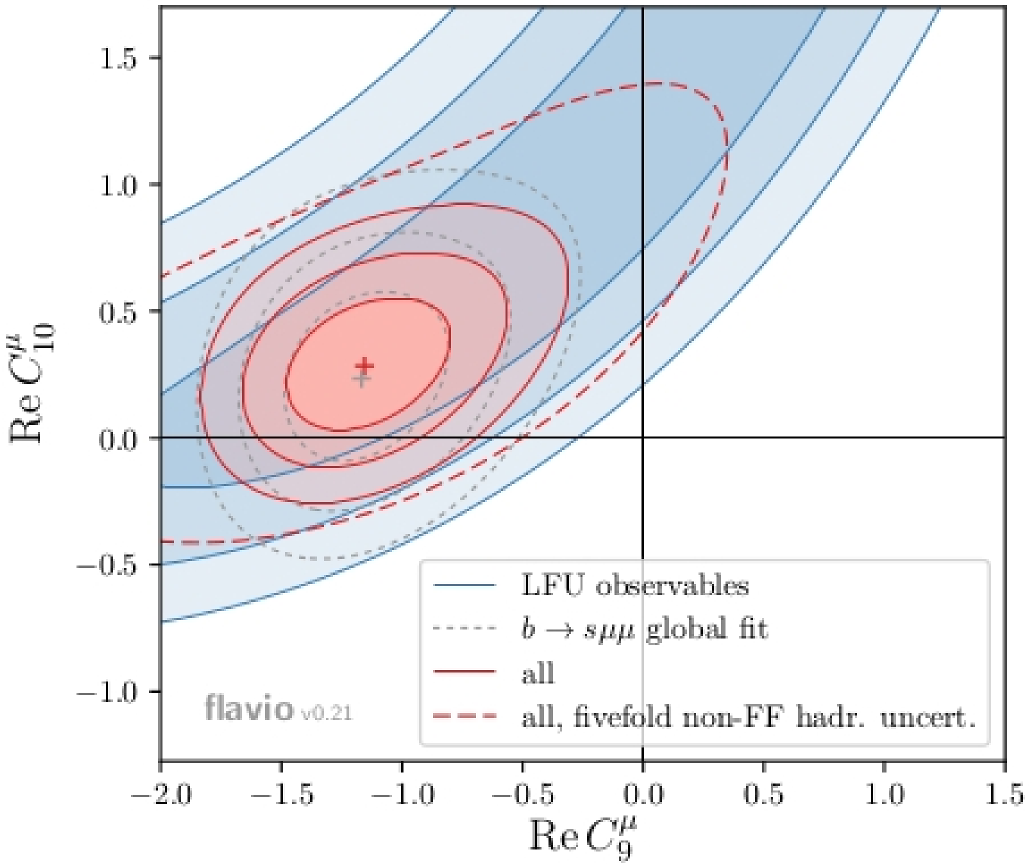
New Physics hypothesis preferred over SM by more than 5 σ (4 σ if only LFUV)

The $\mathcal{C}_{9\mu}$ coefficient seems to be crucial

Qualitatively similar results in 1704.05435 and 1704.05438

Global fits: results

Plot from Altmannshofer et al, 1704.05435



The "clean" and "dirty" anomalies are compatible

Global fits: conclusions

Different fits agree qualitatively, although they differ quantitatively (form factors, treatment of uncertainties...)

In some fits, New Physics hypothesis preferred over SM by more than 5 σ (4 σ if only LFUV)

The $C_{9\mu}$ coefficient seems to be crucial

Other muonic coefficients may have NP contributions as well ($C_{10\mu}$ for instance)

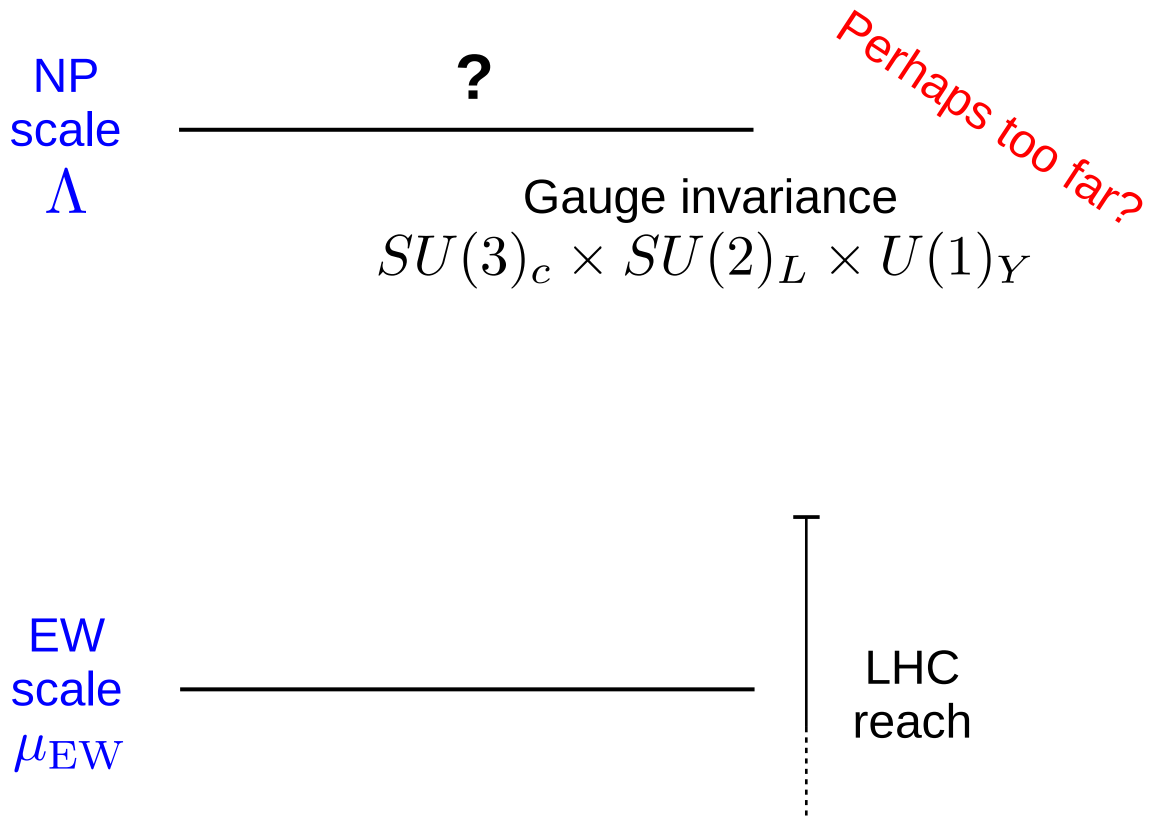
No evidence of NP contributions in electronic coefficients

Exciting results!

Gauge-invariant EFT approach: the SMEFT

Gauge-invariant EFT

No sign of New Physics at the LHC... a message from Nature?



Gauge-invariant EFT

If the NP states are heavy, the hypothetical UV model must respect the SM gauge invariance

Analyses based on non-gauge-invariant EFTs miss relations among operators

Example: $\mathcal{O}_9$ and $\mathcal{O}_{10}$ from the same gauge-invariant operator

$$\underbrace{\left(\bar{\ell}_a \gamma_\mu \ell_a\right)\left(\bar{q}_2 \gamma^\mu q_3\right)} \propto \mathcal{O}_9 - \mathcal{O}_{10} \quad \Rightarrow$$

One gauge-invariant operator

Two non-gauge-invariant operators

Gauge invariant EFT approach

SMEFT

The SMEFT

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

SMEFT

Super Mega Epic Fun Time

Gauge invariant operators

Operators up to dimension-6

Warsaw basis

[Grzadkowski et al, 2010]

2499 real parameters (3045 with B-violation)

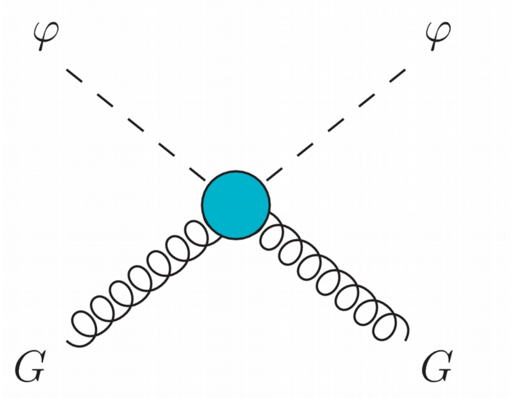
Full 1-loop RGEs computed

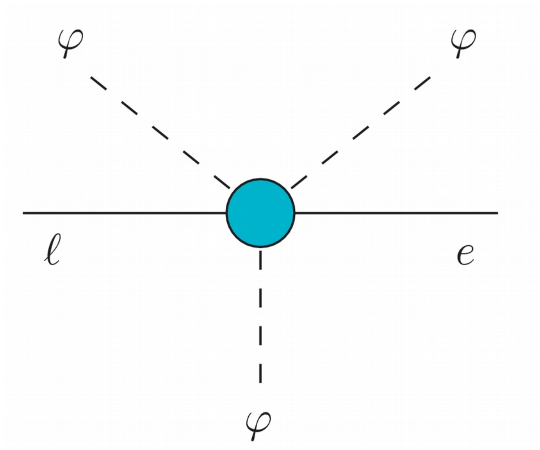
[Alonso, Chang, Jenkins, Manohar, Shotwell, Trott, 2013-2014]

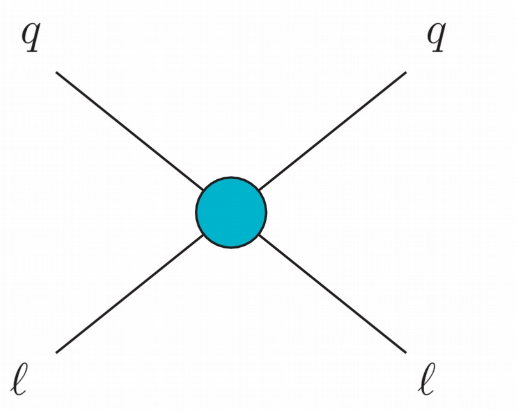
[Antusch, Drees, Kersten, Lindner, Ratz, 2001]

The SMEFT

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$







$$Q_{\varphi G} = \varphi^\dagger \varphi \, G^A_{\mu\nu} G^{A\mu\nu}$$

$$Q_{e\varphi} = \left(\varphi^\dagger \varphi\right) \left(\overline{\ell} e \varphi\right)$$

$$Q_{\ell q}^{(1)} = \left(\overline{\ell} \gamma_\mu \ell\right) \left(\overline{q} \gamma^\mu q\right)$$

...and many more...

The SMEFT

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Thousands of parameters, coupled RGEs...
a non-trivial system

Computers are known to be good at
complex games...

Alternative:
Simplyfing
assumptions

Careful!

DsixTools

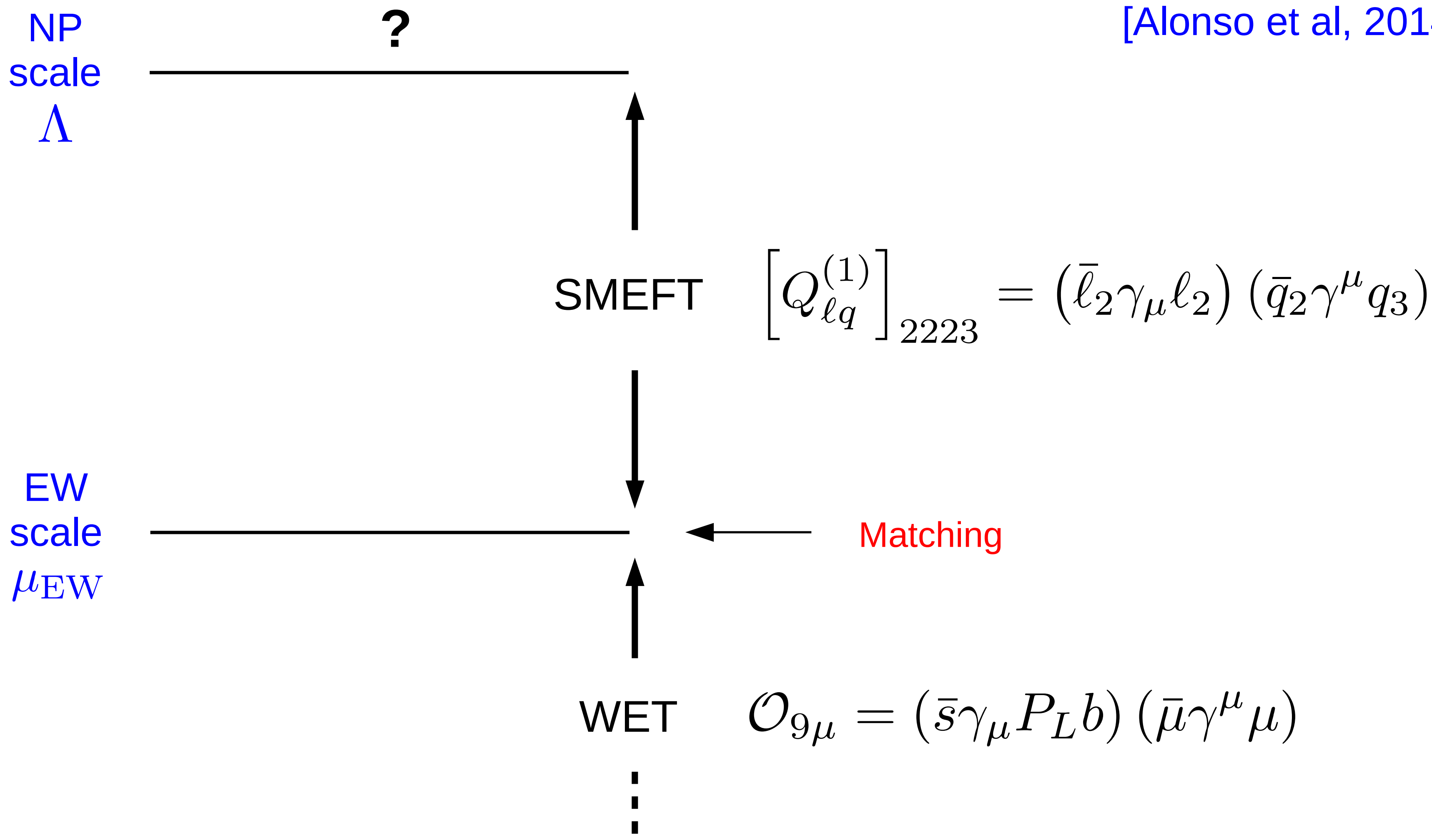
A. Celis, J. Fuentes-Martín, A. Vicente, J. Virto

Manual: arXiv:1704.04504
Website: https://dsixtools.github.io/

Interpretation in terms of the SMEFT

[Celis, Fuentes-Martin, AV, Virto, 2017]

[Alonso et al, 2014]



Interpretation in terms of the SMEFT

Gauge-invariant operators for the b-s anomalies

[Celis, Fuentes-Martin, AV, Virto, 2017]

SMEFT operator	Definition	Matching	Order
$[Q_{\ell q}^{(1)}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \ell_a)(\bar{q}_2 \gamma^\mu q_3)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{\ell q}^{(3)}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \tau^I \ell_a)(\bar{q}_2 \gamma^\mu \tau^I q_3)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{qe}]_{23aa}$	$(\bar{q}_2 \gamma_\mu q_3)(\bar{e}_a \gamma^\mu e_a)$	$\mathcal{O}_{9,10}$	Tree
$[Q_{\ell d}]_{aa23}$	$(\bar{\ell}_a \gamma_\mu \ell_a)(\bar{d}_2 \gamma^\mu d_3)$	$\mathcal{O}'_{9,10}$	Tree
$[Q_{ed}]_{aa23}$	$(\bar{e}_a \gamma_\mu e_a)(\bar{d}_2 \gamma^\mu d_3)$	$\mathcal{O}'_{9,10}$	Tree
$[Q_{\varphi\ell}^{(1)}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{\ell}_a \gamma^\mu \ell_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\varphi\ell}^{(3)}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{\ell}_a \gamma^\mu \tau^I \ell_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\ell u}]_{aa33}$	$(\bar{\ell}_a \gamma_\mu \ell_a)(\bar{u}_3 \gamma^\mu u_3)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{\varphi e}]_{aa}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{e}_a \gamma^\mu e_a)$	$\mathcal{O}_{9,10}$	1-loop
$[Q_{eu}]_{aa33}$	$(\bar{e}_a \gamma_\mu e_a)(\bar{u}_3 \gamma^\mu u_3)$	$\mathcal{O}_{9,10}$	1-loop

Tree-level contributions

[Celis, Fuentes-Martin, AV, Virto, 2017]

[Aebischer et al, 2016]

Tree-level matching at $\mu_{\mathbf{EW}}$

$$\mathcal{C}_{9a}^{\rm NP} = \frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ \left[\tilde{\mathcal{C}}_{\ell q}^{(1)}\right]_{aa23} + \left[\tilde{\mathcal{C}}_{\ell q}^{(3)}\right]_{aa23} + \left[\tilde{\mathcal{C}}_{qe}\right]_{23aa} \right\}$$

$$\mathcal{C}_{10a}^{\rm NP} = -\frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ \left[\tilde{\mathcal{C}}_{\ell q}^{(1)}\right]_{aa23} + \left[\tilde{\mathcal{C}}_{\ell q}^{(3)}\right]_{aa23} - \left[\tilde{\mathcal{C}}_{qe}\right]_{23aa} \right\}$$

$$\mathcal{C}_{9a}' = \frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ \left[\tilde{\mathcal{C}}_{\ell d}\right]_{aa23} + \left[\tilde{\mathcal{C}}_{ed}\right]_{aa23} \right\}$$

$$\mathcal{C}_{10a}' = -\frac{\pi}{\alpha \lambda_t^{sb}} \frac{v^2}{\Lambda^2} \left\{ \left[\tilde{\mathcal{C}}_{\ell d}\right]_{aa23} - \left[\tilde{\mathcal{C}}_{ed}\right]_{aa23} \right\}$$

$$(a = e, \mu)$$

1-loop contributions

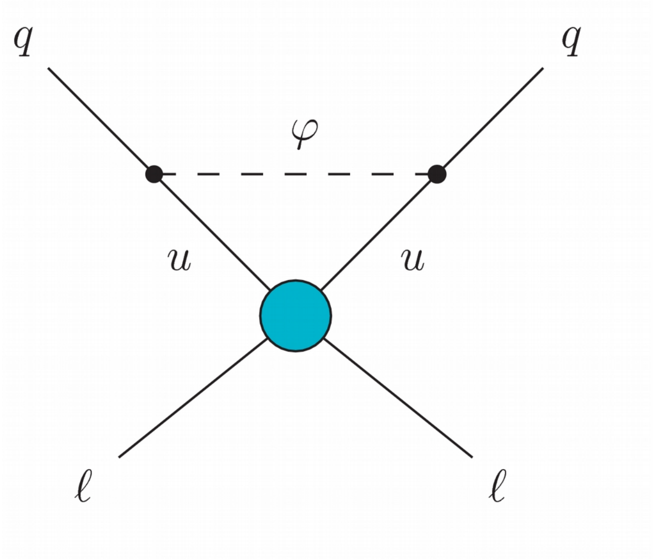
[Celis, Fuentes-Martin, AV, Virto, 2017]

Operator mixing effects add new 1-loop contributions

Example:

$$[\mathcal{C}_{\ell q}^{(1)}(\mu_{\rm EW})]_{aa23} = [\mathcal{C}_{\ell q}^{(1)}(\Lambda)]_{aa23} - \frac{y_t^2 \lambda_t^{sb}}{16\pi^2} \log\left(\frac{\Lambda}{\mu_{\rm EW}}\right) \left([\mathcal{C}_{\varphi \ell}^{(1)}(\Lambda)]_{aa} - [\mathcal{C}_{\ell u}(\Lambda)]_{aa33} \right)$$

(in first leading log approximation)



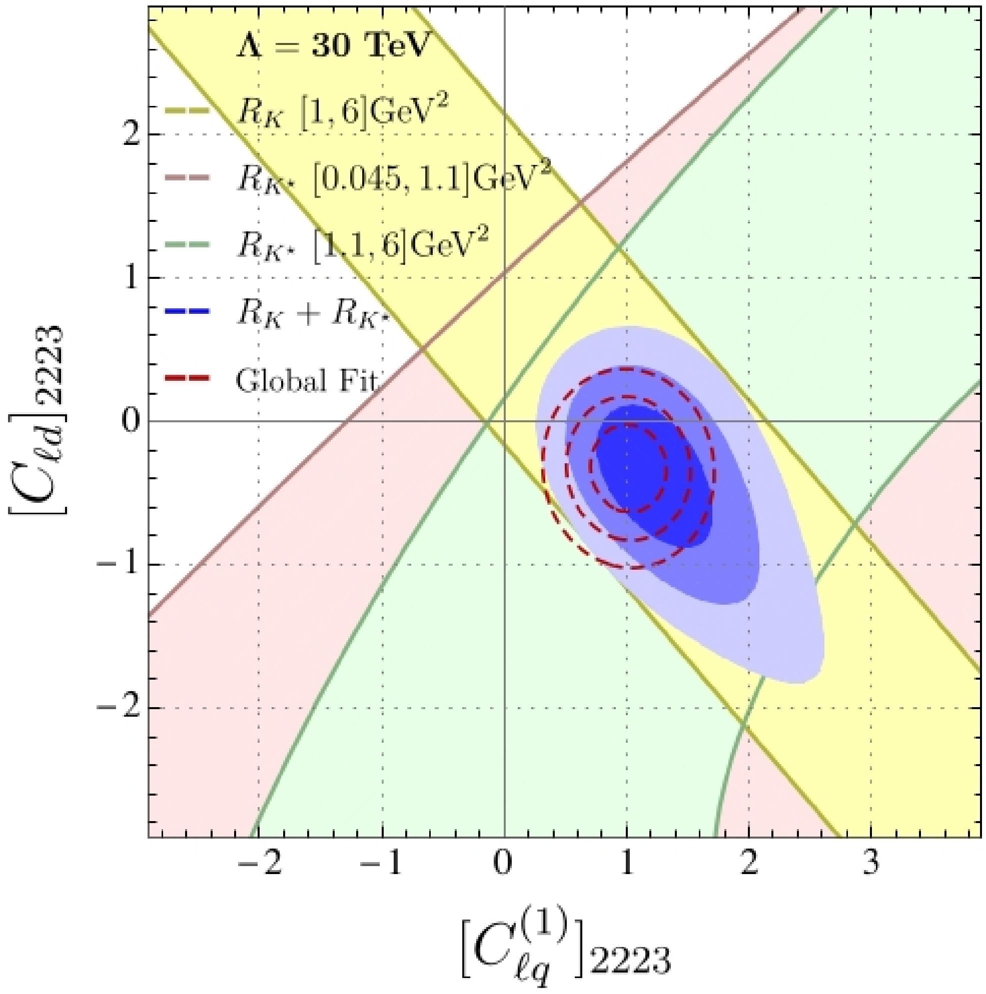
$$\sim \frac{y_t^2}{16\pi^2} \log\left(\frac{\Lambda}{\mu_{\rm EW}}\right) [\mathcal{C}_{\ell u}(\Lambda)]_{aa33}$$

$Q_{\ell u}$ contribution

Interpretation in terms of the SMEFT

[Celis, Fuentes-Martin, AV, Virto, 2017]

Global fit in terms of the SMEFT



At $\mu = \mu_{\rm EW}$

Anomalies explained by $\left[Q_{\ell q}^{(1,3)}\right]_{2223}$

Other operators fail since they predict opposed deviations in R_K and R_{K^*}

At $\mu = \Lambda$

Tree-level: $\left[Q_{\ell q}^{(1,3)}\right]_{2223}$

$$\Rightarrow \quad \Lambda \sim 1 - 50\,\mathrm{TeV}$$

New viable operator: $[Q_{\ell u}]_{2233}$

$$\Rightarrow \quad \Lambda \sim 1\,\mathrm{TeV}$$

Interpretation in terms of the SMEFT

SMEFT operators that can do the job:

At $\mu = \mu_{\rm EW}$

$$\left[Q_{\ell q}^{(1)}\right]_{2223} = \left(\bar{\ell}_2 \gamma_\mu \ell_2\right) \left(\bar{q}_2 \gamma^\mu q_3\right)$$

$$\left[Q_{\ell q}^{(3)}\right]_{2223} = \left(\bar{\ell}_2 \gamma_\mu \tau^I \ell_2\right) \left(\bar{q}_2 \gamma^\mu \tau^I q_3\right)$$

At $\mu = \Lambda$

$$\left[Q_{\ell q}^{(1)}\right]_{2223} = \left(\bar{\ell}_2 \gamma_\mu \ell_2\right) \left(\bar{q}_2 \gamma^\mu q_3\right)$$

$$\left[Q_{\ell q}^{(3)}\right]_{2223} = \left(\bar{\ell}_2 \gamma_\mu \tau^I \ell_2\right) \left(\bar{q}_2 \gamma^\mu \tau^I q_3\right)$$

$$\left[Q_{\ell u}\right]_{2233} = \left(\bar{\ell}_2 \gamma_\mu \ell_2\right) \left(\bar{u}_3 \gamma^\mu u_3\right)$$

Guideline for model builders

Summary of the lecture

Summary of the lecture

B-physics observables are well described using the language of Effective Field Theory

$$(\text{if } \Lambda \gg m_b)$$

Weak EFT

Gauge-invariant EFT (SMEFT)

Several experimental results in B-meson decays seem to deviate from their SM predicted values

$\Rightarrow$ **Global fits show a <u>consistent pattern of deviations</u>**

But we need <u>more data</u>...

Backup

A DsixTools Program

This notebook loads DsixTools and shows how to use the SMEFTrunner module.

```
SetDirectory[NotebookDirectory[]];
```

Start DsixTools

```
Needs["DsixTools`"]
```

Read input files

```
ReadInputFiles["Options.dat", "WCsInput.dat", "SMInput.dat"];
```

Load SMEFTrunner module

```
LoadModule["SMEFTrunner"]
```

Use SMEFTrunner module

```
LoadBetaFunctions;
```

```
RunRGEsSMEFT;
```

SMEFT WCs input file

```
Block WC4
6 1.0          # phiBtilde
Block IMWCDPHI
1 1 0.1        # dphi(1,1)
1 2 0.2        # dphi(1,2)
1 3 0.3        # dphi(1,3)
2 1 0.1        # dphi(2,1)
2 2 0.2        # dphi(2,2)
2 3 0.3        # dphi(2,3)
3 1 0.4        # dphi(3,1)
3 2 0.5        # dphi(3,2)
3 3 0.6        # dphi(3,3)
Block WCDD
2 3 2 3 1.0    # dd(2,3,2,3)
Block WCPHIQ3
1 3 1.0        # phiq3(1,3)
```

WCsInput.dat

Simple text file

Inspired by the SLHA

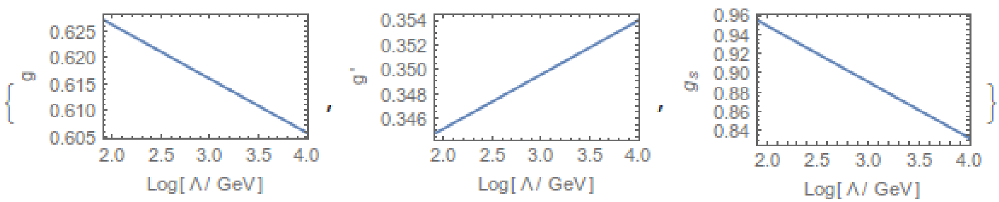
Similar format for the output file

Also possible to give input directly on the notebook

Results after SMEFTrunner

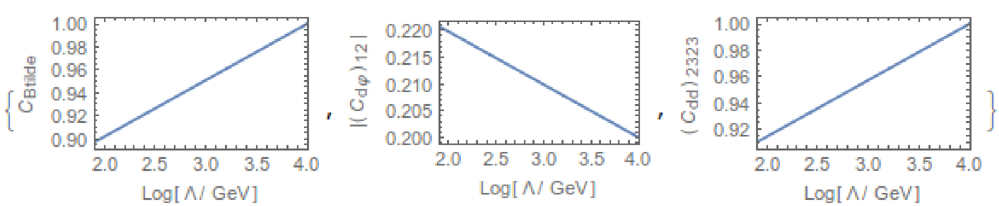
```
In[7]:= (* The results can also be plotted as a function of the energy scale *)

In[8]:= (* Gauge couplings *)
  plotGauge1 = Plot[outSMEFTrunner[[1]], {t, tLOW, tHIGH}, Frame → True, Axes → False, PlotRange → {{tLOW, tHIGH}, Automatic},
     FrameLabel → {"Log[Λ/GeV]", "g", None, None}];
  plotGauge2 = Plot[outSMEFTrunner[[2]], {t, tLOW, tHIGH}, Frame → True, Axes → False, PlotRange → {{tLOW, tHIGH}, Automatic},
     FrameLabel → {"Log[Λ/GeV]", "g'", None, None}];
  plotGauge3 = Plot[outSMEFTrunner[[3]], {t, tLOW, tHIGH}, Frame → True, Axes → False, PlotRange → {{tLOW, tHIGH}, Automatic},
     FrameLabel → {"Log[Λ/GeV]", "gs", None, None}];
  plotGauge = {plotGauge1, plotGauge2, plotGauge3}
```

Out[11]=




```
In[12]:= (* Wilson coefficients *)
  plotWC1 = Plot[outSMEFTrunner[[48]], {t, tLOW, tHIGH}, Frame → True, Axes → False, PlotRange → {{tLOW, tHIGH}, Automatic},
     FrameLabel → {"Log[Λ/GeV]", "CBtilde", None, None}];
  plotWC2 = Plot[Abs[outSMEFTrunner[[61]]], {t, tLOW, tHIGH}, Frame → True, Axes → False, PlotRange → {{tLOW, tHIGH}, Automatic},
     FrameLabel → {"Log[Λ/GeV]", "|(Cdφ)12|", None, None}];
  plotWC3 = Plot[outSMEFTrunner[[443]], {t, tLOW, tHIGH}, Frame → True, Axes → False, PlotRange → {{tLOW, tHIGH}, Automatic},
     FrameLabel → {"Log[Λ/GeV]", "(Cdd)2323", None, None}];
  plotWC = {plotWC1, plotWC2, plotWC3}
```

Out[15]=



Another simple program: analytics

A DsixTools Program

This notebook shows how to use the SMEFTrunner module to study SMEFT β functions analytically.

```
SetDirectory[NotebookDirectory[]];
```

Start DsixTools

```
Needs["DsixTools`"]
```

Set CP conservation

```
CPV = 0;
```

Load SMEFTrunner module

```
LoadModule["SMEFTrunner"]
```

Compute β functions

```
GetBeta;
```

Results

```
In[6]:= (* Let us compute β1q(1) and β1q(3) assuming top dominance and no NP effects in the 1st fermion family *)

In[7]:= (* Top dominance approximation *)
top = {GD[i_, j_] :> 0, GE[i_, j_] :> 0, GU[i_, j_] :> If[i == j == 3, Vtb yt, If[i == 2 && j == 3, Vts yt, 0]]};

In[8]:= (* No NP in 1st family *)
WCs2F = {φL1, φL3, φQ1, φQ3};
WCs4F = {LQ1, LQ3, LU, QE, QU1, QU8, QD1, QD8, QQ1, QQ3};
nofirst2F = Table[Part[WCs2F, i][a_, b_] → If[AnyTrue[{a, b}, # == 1 &], 0, 1] Part[WCs2F, i][a, b], {i, 1, Length[WCs2F]}];
nofirst4F = Table[Part[WCs4F, i][a_, b_, c_, d_] → If[AnyTrue[{a, b, c, d}, # == 1 &], 0, 1] Part[WCs4F, i][a, b, c, d],
   {i, 1, Length[WCs4F]}];
nofirst = Join[nofirst2F, nofirst4F];

In[13]:= βlq1 = β[lq1][[2, 2, 2, 3]] /. top /. nofirst // Expand
```

Out[13]=
$$\frac{1}{2}\,\mathrm{Vtb\,Vts\,yt}^2\,\mathrm{LQ1}[2,2,2,2]-\frac{1}{3}\,\mathrm{gp}^2\,\mathrm{LQ1}[2,2,2,3]+\frac{1}{2}\,\mathrm{Vtb}^2\,\mathrm{yt}^2\,\mathrm{LQ1}[2,2,2,3]+\frac{1}{2}\,\mathrm{Vts}^2\,\mathrm{yt}^2\,\mathrm{LQ1}[2,2,2,3]+\frac{1}{2}\,\mathrm{Vtb\,Vts\,yt}^2\,\mathrm{LQ1}[2,2,3,3]+\frac{2}{3}\,\mathrm{gp}^2\,\mathrm{LQ1}[3,3,2,3]+9\,g^2\,\mathrm{LQ3}[2,2,2,3]-\mathrm{Vtb\,Vts\,yt}^2\,\mathrm{LU}[2,2,3,3]+\frac{2}{3}\,\mathrm{gp}^2\,\mathrm{QD1}[2,3,2,2]+\frac{2}{3}\,\mathrm{gp}^2\,\mathrm{QD1}[2,3,3,3]+\frac{2}{3}\,\mathrm{gp}^2\,\mathrm{QE}[2,3,2,2]+\frac{2}{3}\,\mathrm{gp}^2\,\mathrm{QE}[2,3,3,3]-\frac{2}{9}\,\mathrm{gp}^2\,\mathrm{QQ1}[2,2,2,3]-\frac{4}{3}\,\mathrm{gp}^2\,\mathrm{QQ1}[2,3,2,2]-\frac{14}{9}\,\mathrm{gp}^2\,\mathrm{QQ1}[2,3,3,3]-\frac{2}{3}\,\mathrm{gp}^2\,\mathrm{QQ3}[2,2,2,3]-\frac{2}{3}\,\mathrm{gp}^2\,\mathrm{QQ3}[2,3,3,3]-\frac{4}{3}\,\mathrm{gp}^2\,\mathrm{QU1}[2,3,2,2]-\frac{4}{3}\,\mathrm{gp}^2\,\mathrm{QU1}[2,3,3,3]+\mathrm{Vtb\,Vts\,yt}^2\,\varphi\mathrm{L1}[2,2]-\frac{1}{3}\,\mathrm{gp}^2\,\varphi\mathrm{Q1}[2,3]$$

```
In[14]:= βlq3 = β[lq3][[2, 2, 2, 3]] /. top /. nofirst // Expand
```

Out[14]=
$$3\,g^2\,\mathrm{LQ1}[2,2,2,3]+\frac{1}{2}\,\mathrm{Vtb\,Vts\,yt}^2\,\mathrm{LQ3}[2,2,2,2]-\frac{16}{3}\,g^2\,\mathrm{LQ3}[2,2,2,3]-\mathrm{gp}^2\,\mathrm{LQ3}[2,2,2,3]+\frac{1}{2}\,\mathrm{Vtb}^2\,\mathrm{yt}^2\,\mathrm{LQ3}[2,2,2,3]+\frac{1}{2}\,\mathrm{Vts}^2\,\mathrm{yt}^2\,\mathrm{LQ3}[2,2,2,3]+\frac{1}{2}\,\mathrm{Vtb\,Vts\,yt}^2\,\mathrm{LQ3}[2,2,3,3]+\frac{2}{3}\,g^2\,\mathrm{LQ3}[3,3,2,3]+\frac{2}{3}\,g^2\,\mathrm{QQ1}[2,2,2,3]+\frac{2}{3}\,g^2\,\mathrm{QQ1}[2,3,3,3]-\frac{2}{3}\,g^2\,\mathrm{QQ3}[2,2,2,3]+4\,g^2\,\mathrm{QQ3}[2,3,2,2]+\frac{10}{3}\,g^2\,\mathrm{QQ3}[2,3,3,3]-\mathrm{Vtb\,Vts\,yt}^2\,\varphi\mathrm{L3}[2,2]+\frac{1}{3}\,g^2\,\varphi\mathrm{Q3}[2,3]$$