New physics contributions to moments of inclusive $b \to c$ decays

Matteo Fael (CERN)

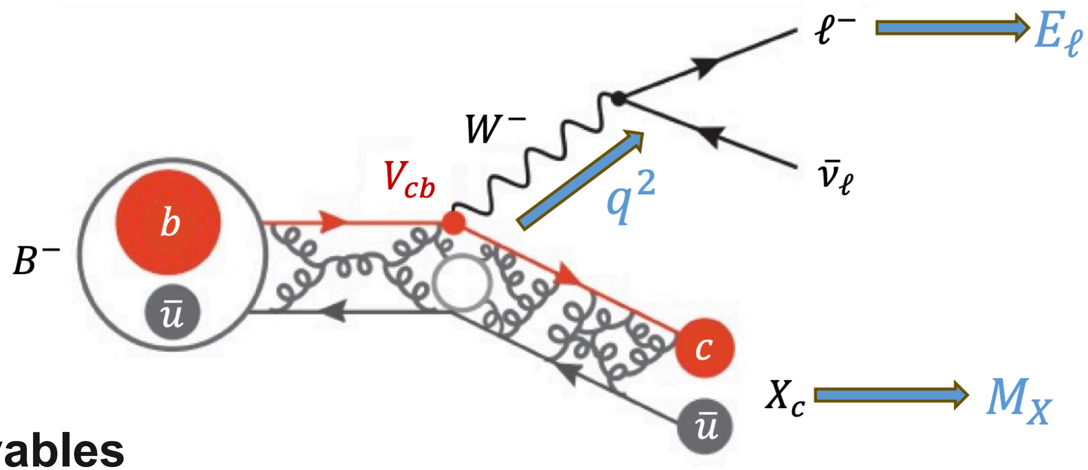
CKM 2023 - Santiago de Compostela - 20 Sept. 2023

in collaboration with M. Rahimi, K. Vos

MARIE CURIE ACTIONS

Funded by
the European Union

Extraction of V_{cb} from inclusive $B \to X_c l \nu$ decays



Observables

- Total rate $\Gamma_{\rm sl} = \Gamma(B \to X_c \ell \bar{\nu}_\ell)$
- Moments of the differential distribution of an observables O

$$\langle (O)^n \rangle_{\rm cut} = \int_{\rm cut} (O)^n \frac{\mathrm{d}\Gamma}{\mathrm{d}O}\,\mathrm{d}O \Big/ \int_{\rm cut} \frac{\mathrm{d}\Gamma}{\mathrm{d}O}\,\mathrm{d}O$$

- $O = E_\ell$: energy of the charged lepton in the B rest frame
- $O = M_X^2$: hadronic invariant mass
- $O = q^2$: leptonic invariant mass

see talks by M. Prim & K. Vos

Heavy Quark Expansion

Double series expansion in the strong coupling constant α_s and power suppressed terms $\Lambda_{\mathrm{QCD}}/m_b$

- Total rate

$$\Gamma_{\mathrm{sl}} = \frac{G_F^2 m_b^5 A_{\mathrm{ew}}}{192\pi^3} |V_{cb}|^2 \left[\left(1 - \frac{\mu_\pi^2}{2m_b^2}\right)\left(X_0(\rho) + \frac{\alpha_s}{\pi} X_1(\rho) + \left(\frac{\alpha_s}{\pi}\right)^2 X_2(\rho) + \left(\frac{\alpha_s}{\pi}\right)^3 X_3(\rho) + \ldots\right) \right.$$
$$\left. + \left(\frac{\mu_G^2}{m_b^2} - \frac{\rho_D^3}{m_b^3}\right)\left(g_0(\rho) + \frac{\alpha_s}{\pi} g_1(\rho) + \ldots\right) + \frac{\rho_D^3}{m_b^3}\left(d_0(\rho) + \frac{\alpha_s}{\pi} d_1(\rho) + \ldots\right) + O\left(\frac{1}{m_b^4}\right) \right]$$

- Moments of differential distribution

$$\langle O^n \rangle_{\mathrm{cut}} = (m_b)^{mn} \left[X_0^{(O,n)} + \frac{\alpha_s}{\pi} X_1^{(O,n)} + \left(\frac{\alpha_s}{\pi}\right)^2 X_2^{(O,n)} + \frac{\mu_\pi^2}{m_b^2}\left(p_0^{(O,n)} + \frac{\alpha_s}{\pi} p_1^{(O,n)} + \ldots\right) \right.$$
$$\left. + \frac{\mu_G^2}{m_b^2}\left(g_0^{(O,n)} + \frac{\alpha_s}{\pi} g_1^{(O,n)} + \ldots\right) + \frac{\rho_D^3}{m_b^3}\left(d_0^{(O,n)} + \frac{\alpha_s}{\pi} d_1^{(O,n)} + \ldots\right) + \frac{\rho_{LS}}{m_b^2}\left(l_0^{(O,n)} + \frac{\alpha_s}{\pi} l_1^{(O,n)} + \ldots\right) + O\left(\frac{1}{m_b^4}\right) \right]$$

Global fits

$$\mathrm{Br}(E_{\mathrm{cut}}) \quad \langle E^n \rangle_{E_{\mathrm{cut}}} \quad \langle (M_X^2)^n \rangle_{E_{\mathrm{cut}}} \; \langle (q^2)^n \rangle_{q^2_{\mathrm{cut}}}$$

↓

$$\mu_\pi, \mu_G, \rho_D, \rho_{LS}, m_b, (m_c)$$

↓

$$\mathrm{Br}(\bar{B} \to X_c \ell \bar{\nu}) \propto \frac{|V_{cb}|^2}{\tau_B} \left[\Gamma_0 + \Gamma_{\mu_\pi} \frac{\mu_\pi^2}{m_b^2} + \Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + \Gamma_{\rho_D} \frac{\rho_D^3}{m_b^3} \right]$$

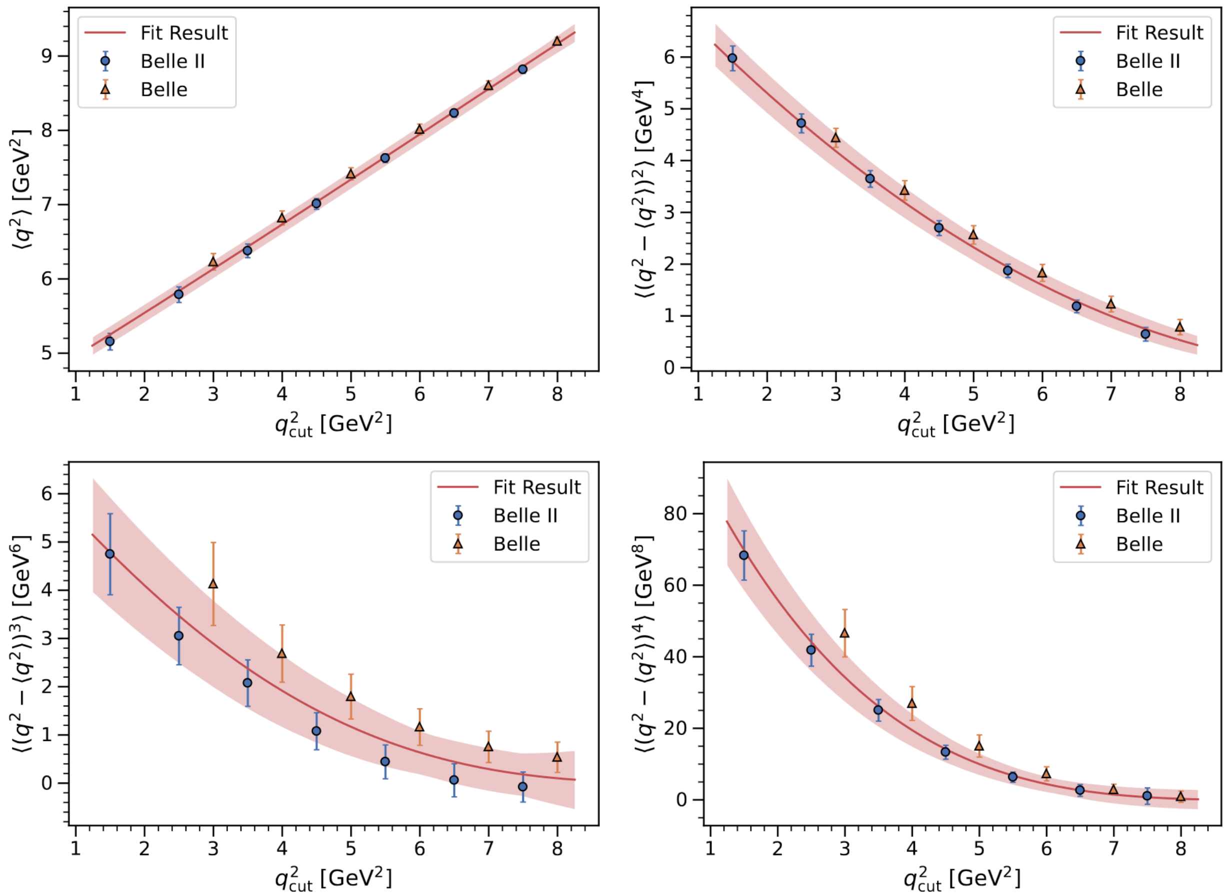
↓

$$|V_{cb}| = (42.16 \pm 0.51) \times 10^{-3}$$

Bordone, Gambino, Capdevila, PLB 822 (2021) 136679

$$|V_{cb}|^{q^2} = (41.69 \pm 0.63) \times 10^{-3}$$

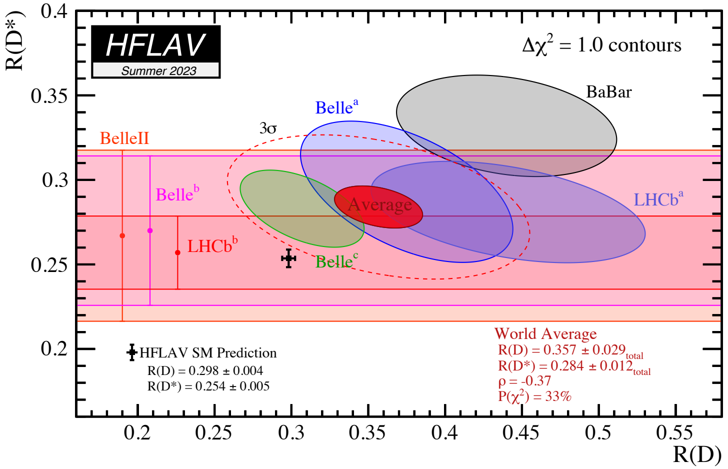
Bernlochner, **MF,** Olschewsky, Persson
van Tonder, Vos, Welsch *JHEP* 10 (2022) 068

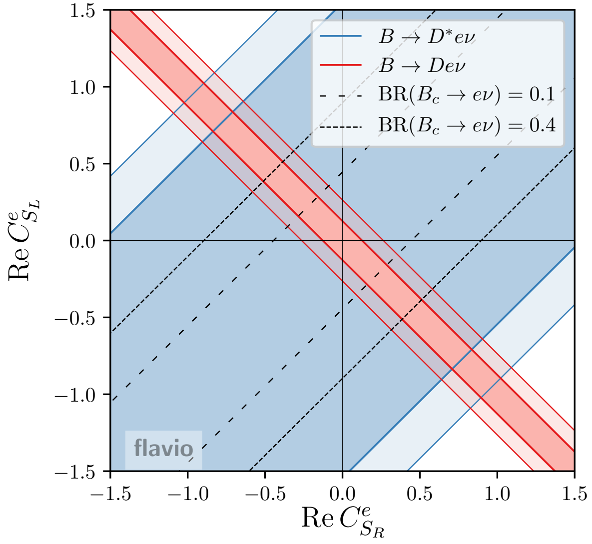


Bernlochner, et al, *JHEP* 10 (2022) 068

- HQE parameters extracted from global fits
- Experimental data from CLEO, CDF, DELPHI, BaBar, Belle, Belle II
- Extraction is perform within the SM

Motivation





Jung, Straub, *JHEP* 01 (2019) 009

- Tree-level processes in principle affected by NP
- Long-standing **tensions between excl. and incl.**
- Significant deviations from SM in $b \to c\tau\bar{\nu}_\tau$
- Fit of exclusive $b \to c\ell\bar{\nu}_\ell$ decays.

Jung, Straub, *JHEP* 01 (2019) 009

- Precision measurements of the moments by *B*-factories
- Ongoing studies inclusive $b \to c\ell\bar{\nu}_\ell$ on lattice

Barone, Hashimoto, Jüttner, Kanedo, Kellermann, JHEP (2023) 145
Hashimoto, Gambino, Phys.Rev.Lett. 125 (2020) 032001 and hep-lat/2203.11762
Gambino, Melis, Simula, Phys.Rev.D 96 (2017) 014511
Hansen, Meyer, Robaina, Phys.Rev.D 96 (2017) 9, 094513

see talk by R. Kellernann

GOAL: comprehensive model-independent analysis of all possible types of NP effects in $B \to X_c\ell\bar{\nu}_\ell$

NP contributions

Effective Hamiltonian

$$\mathscr{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[\left(1 + C_{V_L}\right) O_{V_L} + \sum_{i=V_R,S_L,S_R,T} C_i \, O_i \right]$$

Dimension-six operators

$$O_{V_{L(R)}} = \left(\bar{c}\gamma_\mu P_{L(R)} b\right) \left(\bar{\ell}\gamma^\mu P_L \nu_\ell\right)$$

$$O_{S_{L(R)}} = \left(\bar{c} P_{L(R)} b\right) \left(\bar{\ell} P_L \nu_\ell\right)$$

$$O_T = \left(\bar{c}\, \sigma_{\mu\nu} P_L b\right) \left(\bar{\ell}\, \sigma^{\mu\nu} P_L \nu_\ell\right)$$

- In the SM all $C_i = 0$
- In the **Weak Effective Theory** the expansion parameter is $1/v^2$, i.e. Wilson coefficients are $O(1)$
- NP effects from SMEFT are suppressed by $1/\Lambda_{\text{NP}}^2$. The matching to WET lead to a suppression $(v/\Lambda_{\text{NP}})^2$

Aebischer, Crivellin, **MF**, Greub, *JHEP* 05 (2016) 037

- In the following we assume $|C_i| \ll 1$

Heavy Quark Expansion with NP effects

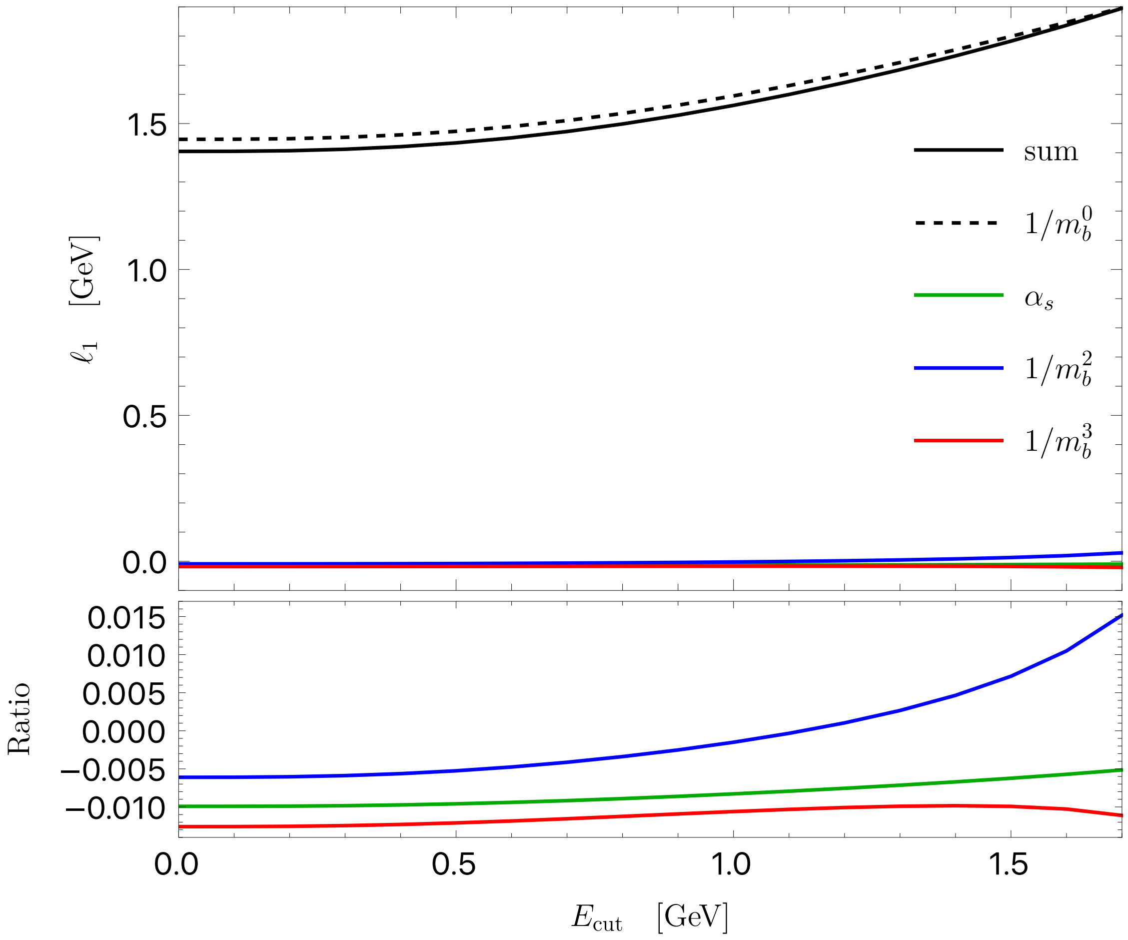
$$\ell_1 = \langle E_e \rangle_{E_{\rm cut}}$$

Series expansion in three parameters:

- Λ_{QCD}/m_b
- α_s
- $(v/\Lambda_{\rm NP})^2$

To properly catch the leading effects:

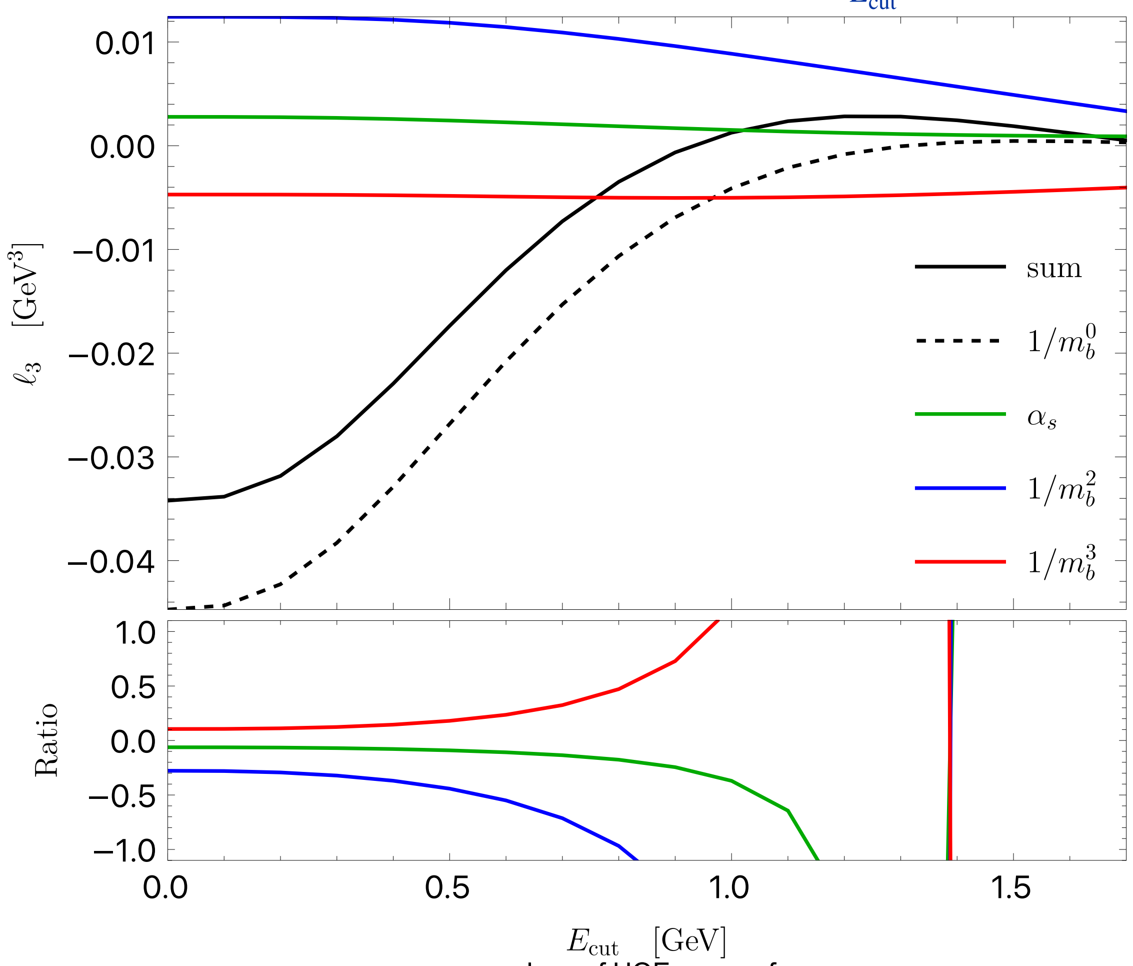
- $(v/\Lambda_{\rm NP})^2 \times \alpha_s^0 \times (1/m_b)^0$: NP at tree level in the free-quark approximation.



values of HQE param. from
Bordone, Gambino, Capdevila, PLB 822 (2021) 136679

Heavy Quark Expansion with NP effects

$$\ell_e = \left\langle \left(E_e - \langle E_e \rangle \right)^3 \right\rangle_{E_{\text{cut}}}$$



values of HQE param. from
Bordone, Gambino, Capdevila, PLB 822 (2021) 136679

Series expansion in three parameters:

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To properly catch the leading effects:

- $(v/\Lambda_{\text{NP}})^2 \times \alpha_s^0 \times (1/m_b)^0$: NP at tree level in the free-quark approximation.
- $(v/\Lambda_{\text{NP}})^2 \times \alpha_s^0 \times (1/m_b)^{2,3}$: power-suppressed terms for NP effects

Heavy Quark Expansion with NP effects

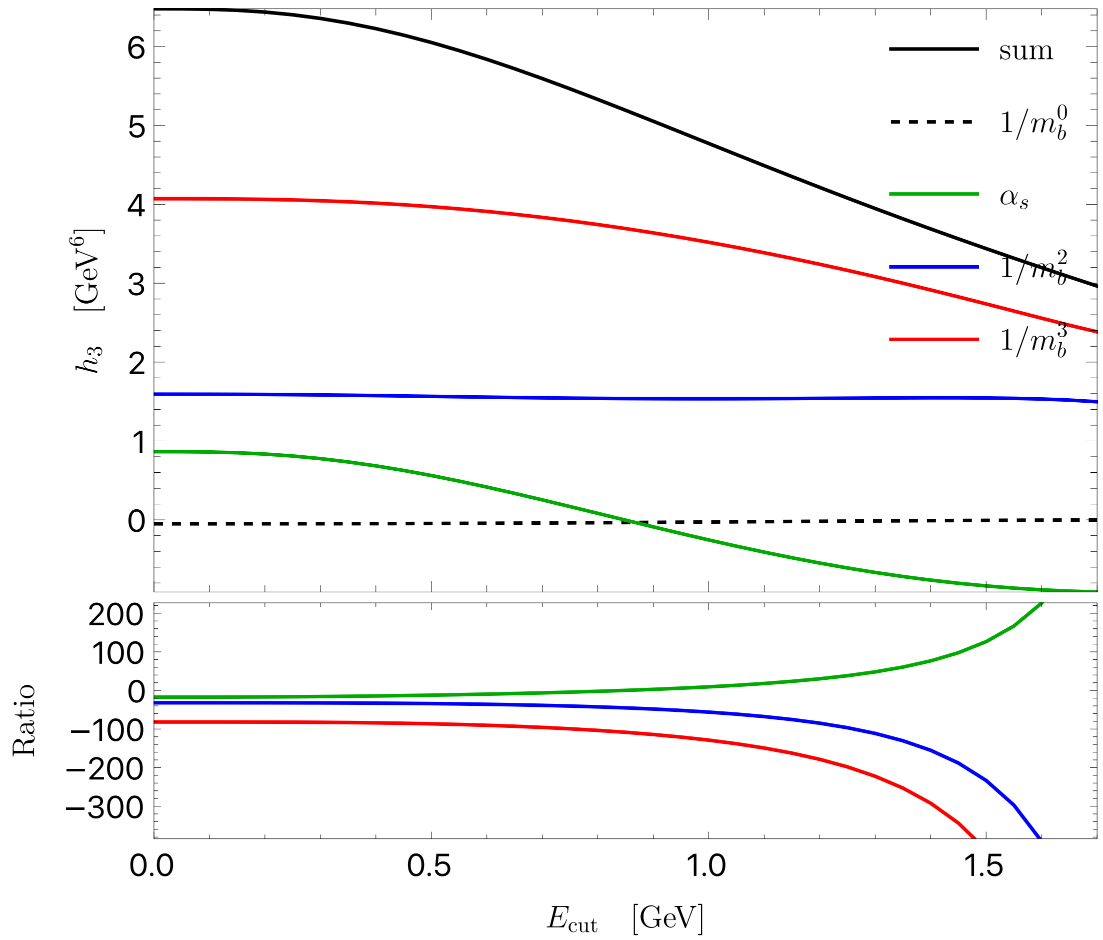
$$h_3 = \left\langle \left(M_X^2 - \langle M_X^2 \rangle \right)^3 \right\rangle_{E_{\text{cut}}}$$

Series expansion in three parameters:

- Λ_{QCD}/m_b
- α_s
- $(v/\Lambda_{\text{NP}})^2$

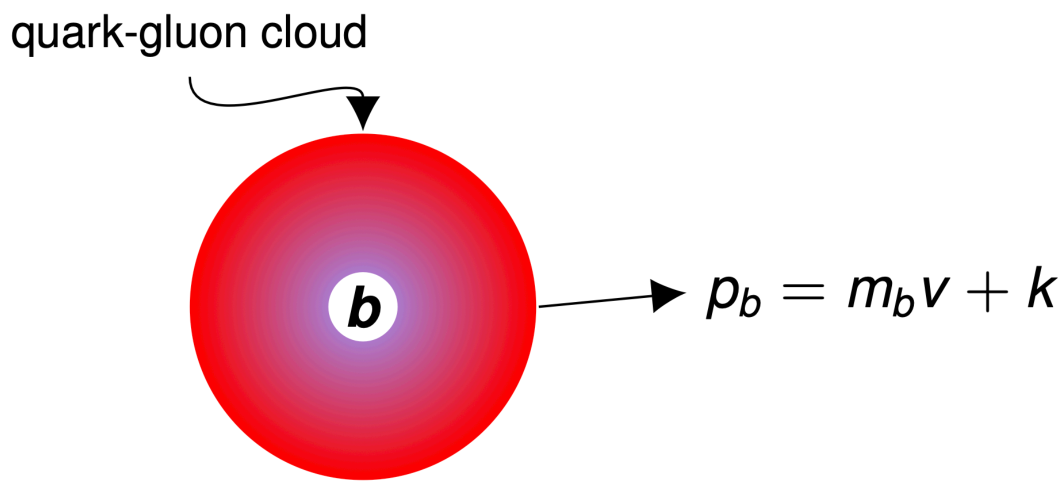
To properly catch the leading effects:

- $(v/\Lambda_{\text{NP}})^2 \times \alpha_s^0 \times (1/m_b)^0$: NP at tree level in the free-quark approximation.
- $(v/\Lambda_{\text{NP}})^2 \times \alpha_s^0 \times (1/m_b)^{2,3}$: power-suppressed terms for NP effects
- $(v/\Lambda_{\text{NP}})^2 \times \alpha_s^1 \times (1/m_b)^0$: QCD NLO corrections to NP effects



values of HQE param. from
Bordone, Gambino, Capdevila, PLB 822 (2021) 136679

The calculation



We calculate triple differential rate

$$\frac{d\Gamma_{\rm SM+NP}}{dE_\ell dq^2 dE_\nu} = \frac{d\Gamma^{\rm LO}_{\rm SM+NP}}{dE_\ell dq^2 dE_\nu} + \frac{d\Gamma^{\rm Pow}_{\rm SM+NP}}{dE_\ell dq^2 dE_\nu} + \left(\frac{\alpha_s}{\pi}\right) \frac{d\Gamma^{\rm NLO}_{\rm SM+NP}}{dE_\ell dq^2 dE_\nu}$$

$$= \frac{G_F^2 |V_{cb}|^2}{16\pi^3} \tilde{W} \otimes \tilde{L}$$

- leptonic tensor

$$L = \sum_{\text{lepton spin}} \langle 0 | J_L^\dagger | \ell \bar{\nu}_\ell \rangle \langle \ell \bar{\nu}_\ell | J_{L'} | 0 \rangle$$

- hadronic tensor

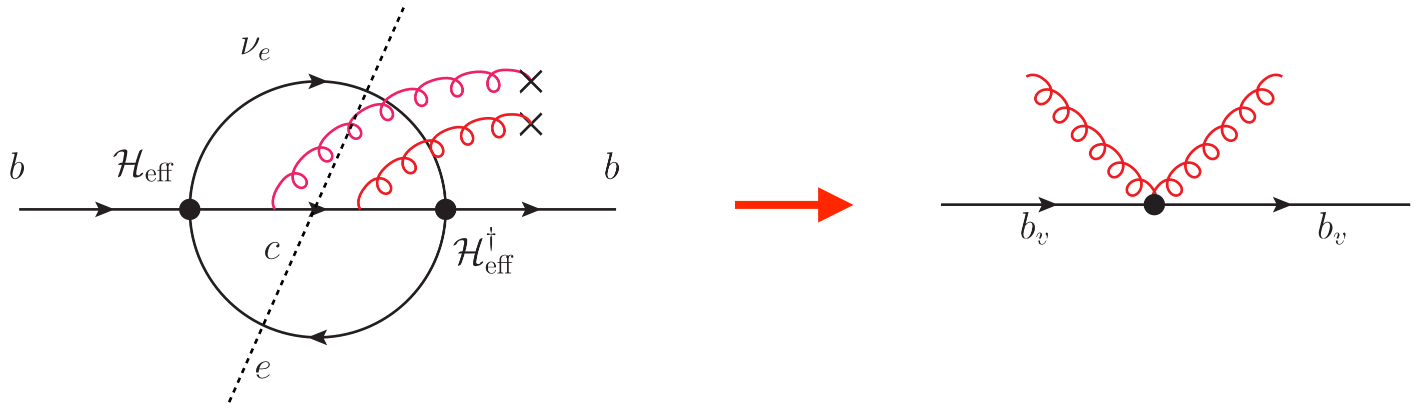
$$W = \sum_{X_c} \frac{1}{2m_B} (2\pi)^3 \langle \bar{B} | J_H^\dagger | X_c \rangle \langle X_c | J_{H'} | \bar{B} \rangle \delta^{(4)}(p_B - q - p_{X_c}) = \frac{1}{m_B} \mathrm{Im} \int dx\, e^{i m_b v \cdot x} \langle \bar{B} | T\{J_H^\dagger(x) J_{H'}(0)\} | \bar{B} \rangle$$

$$= \sum_{n=0}^{\infty} \frac{C^{(n)}(v,q)}{m_b^n} \langle B | \mathcal{O}_n | B \rangle$$

The calculation

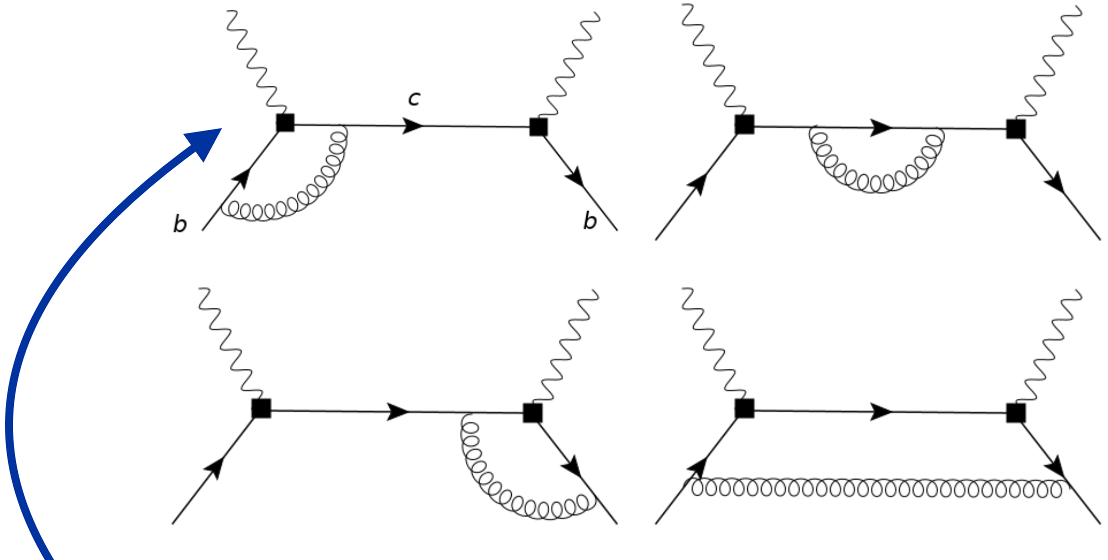
- Power corrections
  - Background field method
  - Trace formulas up to $1/m_b^3$
  - Analytic integration

  Manohar, Wise, Heavy quark physics;
  Mannel, *Phys.Rev.D* 50 (1994) 428;
  Gramm, Kapustin, *Phys.Rev.D* 55 (1997) 6924.



- NLO corrections
  - Dimensional regularisation for both UV and IR divergences
  - Larin scheme for γ_5 Larin, *Phys.Lett.B* 303 (1993) 113.
  - Numerical phase space integration

    see also: Alberti et al, Nucl.Part.Phys.Proc. 273(2016) 1325



Insertion of any NP effective operator

Moments of differential distributions

We obtain results for:

- Charged-lepton energy moments, lower cut on E_ℓ

$$L_n = \frac{1}{\Gamma_0} \int_{E_\ell > E_{\rm cut}} \left(\frac{E_\ell}{m_b} \right)^n \frac{d\Gamma}{dq^2\, dE_\ell\, dE_\nu} dq^2\, dE_\ell\, dE_\nu \,.$$

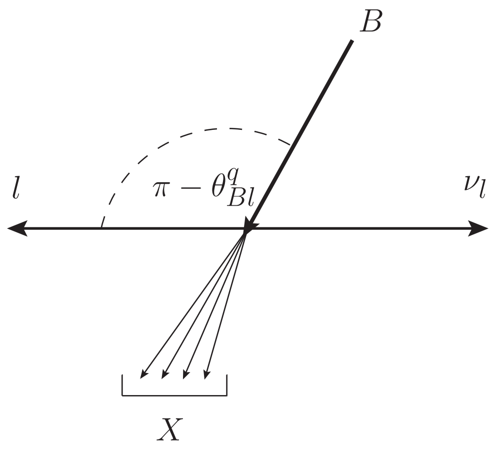
- Leptonic invariant mass moments, lower cut on q^2

$$Q_n = \frac{1}{\Gamma_0} \int_{q^2 > q^2_{\rm cut}} \left(\frac{q^2}{m_b^2} \right)^n \frac{d\Gamma}{dq^2\, dE_\ell\, dE_\nu} dq^2\, dE_\ell\, dE_\nu \,.$$

- Hadronic invariant mass moments, lower cut on E_ℓ

$$M_n = \frac{1}{\Gamma_0} \int_{E_\ell > E_{\rm cut}} \left(\frac{M_B^2 + q^2 - 2 M_B q_0}{m_b^2} \right)^n \frac{d\Gamma}{dq^2\, dE_\ell\, dE_\nu} dq^2\, dE_\ell\, dE_\nu \,.$$

Forward-backward asymmetry



$$A_{FB} \equiv \frac{\int_{-1}^{0} dz \frac{d\Gamma}{dz} - \int_{0}^{1} dz \frac{d\Gamma}{dz}}{\int_{-1}^{1} dz \frac{d\Gamma}{dz}}$$

where $$z \equiv \cos\theta = \frac{v \cdot p_{\bar{\nu}_\ell} - v \cdot p_\ell}{\sqrt{(v \cdot q)^2 - q^2}}$$

- Study of A_{FB} with a lower cut on q^2
- Good sensitivity to the power corrections

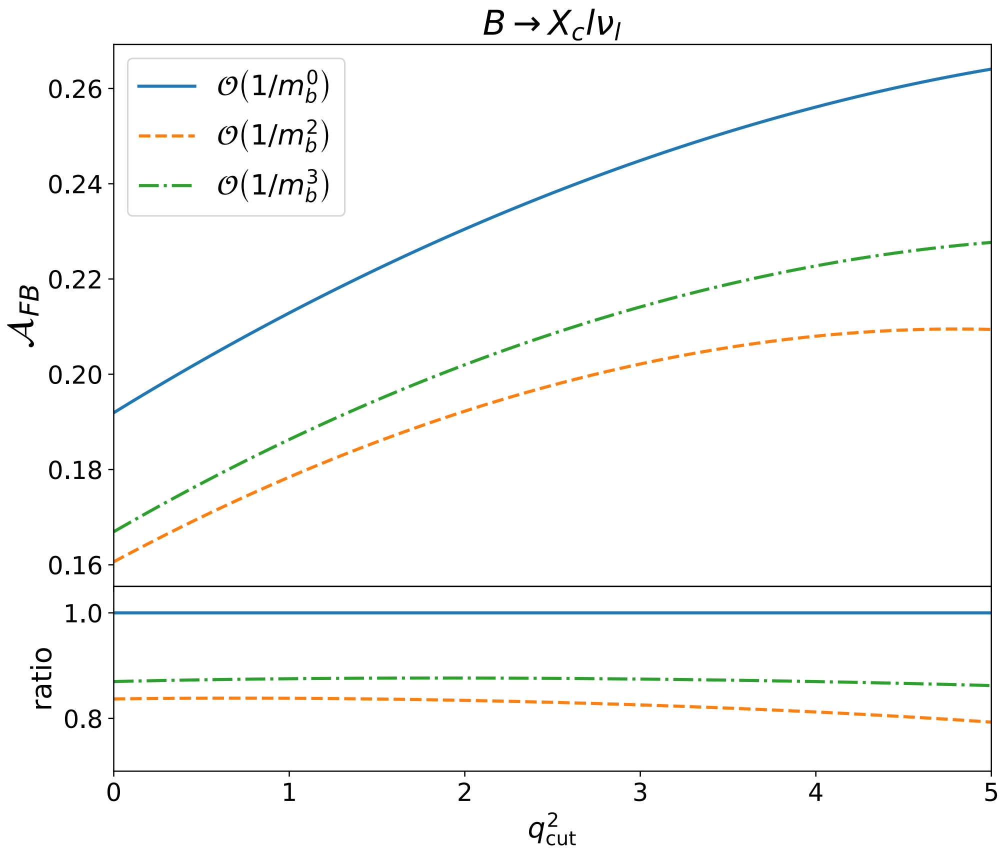


fig: Herren, SciPost Phys. 14 (2023) 020

Turczyk, JHEP 04 (2016) 131
Herren, SciPost Phys. 14 (2023) 020

Git repository

https://gitlab.com/vcb-inclusive/npinb2xclv

README.md

New physics contributions to moments of inclusive b→c semileptonic decays

by M. Fael, M. Rahimi, K. K. Vos, hep-ph/2208.04282

Content

This repository contains the analytic expressions for the evaluation of the various kinematic moments in the presence of NP operators. All expressions are given in the on-shell scheme. We include power corrections up to $1/m_b^3$ and NLO corrections at LO in $1/m_b$. Content of the directories:

- `Eemoments_Eecut` : the directory contains expressions for the electron energy moments up to the third moment, with a lower cut on the electron energy.
- `MXmoments_Eecut` : the directory contains expressions for the hadronic invariant mass moments up to the third moment, with a lower cut on the electron energy.
- `Q2moments_q2cut` : the directory contains expressions for the dilepton invariant mass (q^2) moments up to the third moment, with a lower cut on q^2.
- `AFB` : the directory contains expressions for the total rate, with emission in the forward and backward direction (in the rest frame of the two leptons). They corresponds to the two terms at numerator in Eq. (13).
- `alphas` : expressions of the NLO corrections. The NLO corrections can be evaluated with the Mathematica package `EvaluateAlphaSNP.m` .

QCD NLO Corrections

The files contained in the directories `AFB`, `Eemoments_Eecut`, `MXmoments_Eecut` and `Q2moments_q2cut` give analytic expressions for the moments at LO. However the coefficients of order α_s is represented in this files by the functions:

```
X1AFBForward[cNP,q2cuthat,m2,mu2hat]
X1AFBBackward[cNP,q2cuthat,m2,mu2hat]
X1mix[nq2,nq0,cNP,Ycut,m2,mu2hat]
X1El[n,cNP,Ycut,m2,mu2hat]
X1Q2[n,cNP,q2cuthat,m2,mu2hat]
```

The numerical evaluation of the NLO corrections requires non-trivial numerical integration over the phase-space. The package `EvaluateAlphaSNP.m` provides the necessary subroutines for the integration. One needs to load the package in Mathematica:

```
In[]:=<< "alphas/EvaluateAlphaSNP.m"
```

Afterwards, calling these functions with numerical arguments will execute the numerical integration. For example, the NLO correction the the first q^2 moment, with a cut $q^2_{\rm cut} = 4\,{\rm GeV}^2$ is evaluated in the following way:

```
In[] := mb = 4.6; mc = 1.15; mus = mb; q2cut = 1; q2hatcut = q2cut/mb^2;
In[] := X1Q2[1, SM^2, q2hatcut, (mc/mb)^2, (mus/mb)^2]
Out[]:= -0.215785
```

Illustration for specific NP scenarios

Centralized moments:

$$\langle (O)^n \rangle_{\text{cut}} = \int_{\text{cut}} (O)^n \frac{\mathrm{d}\Gamma}{\mathrm{d}O} \mathrm{d}O \Big/ \int_{\text{cut}} \frac{\mathrm{d}\Gamma}{\mathrm{d}O} \mathrm{d}O$$

$$\left\langle \left(O - \langle O \rangle \right)^n \right\rangle = \sum_{i=0}^{n} \binom{n}{i} \langle O^i \rangle (\langle O \rangle)^{n-i}$$

- Expansion in α_s and $1/m_b$
- Kinetic scheme for m_b and $\overline{\text{MS}}$ for m_c
- Numerical inputs from

Bordone, Gambino, Capdevila, PLB 822 (2021) 136679

NP Scenarios	C_{V_L}	C_{V_R}	C_{S_R}	C_{S_L}	C_T
I	0	0	1	1	0
II	0	0	0	-1	0.5
III	-1	0.5	0	0	0

- The 3 scenarios are for illustration!
- Scen. II excluded by exclusive $B \to D^{(*)} \ell \bar{\nu}_\ell$
- In this case, we do not reexpand in v/Λ_{NP}
- SM uncertainty:
  - Renormalization scale $m_b/2 \leq \mu_s \leq 2m_b$
  - Parametric uncertainty on HQE parameters

Illustration for specific NP scenarios

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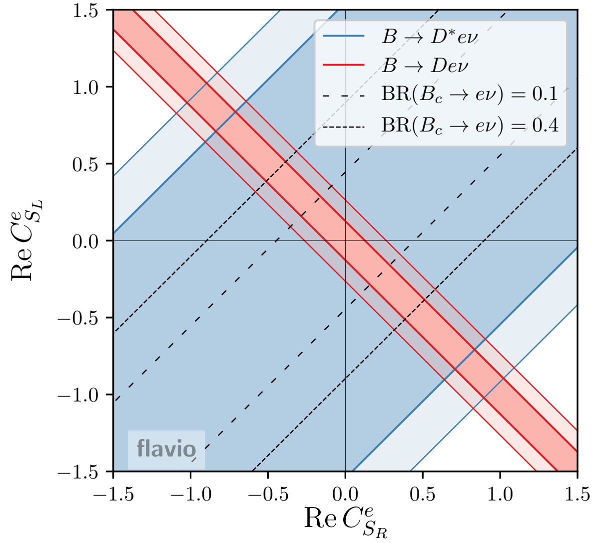
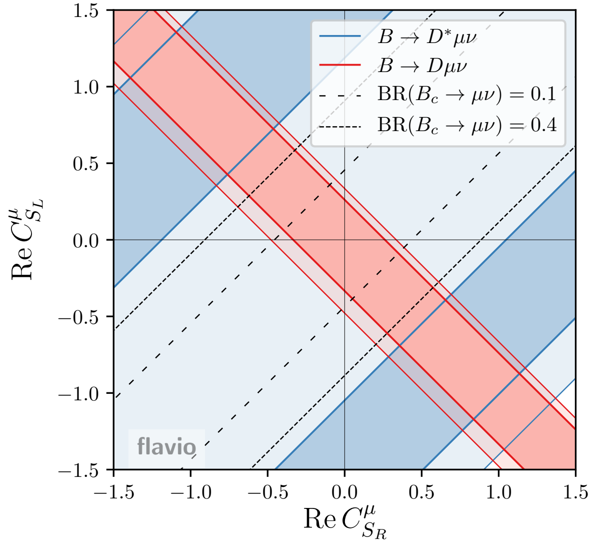
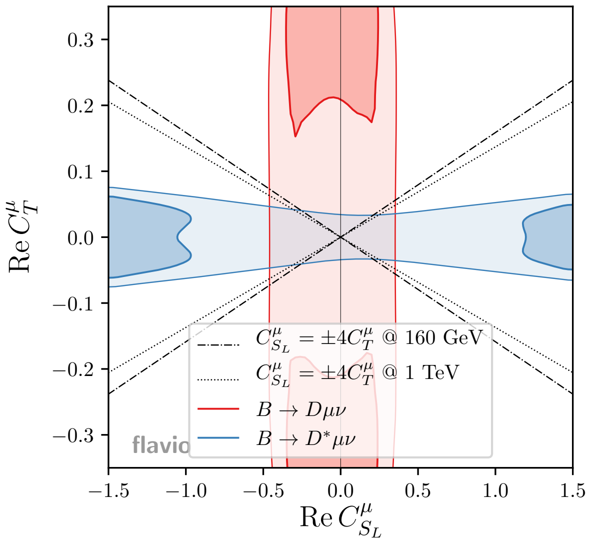
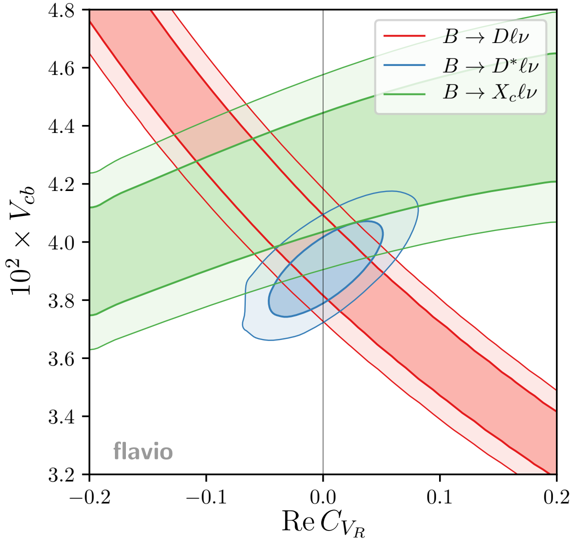


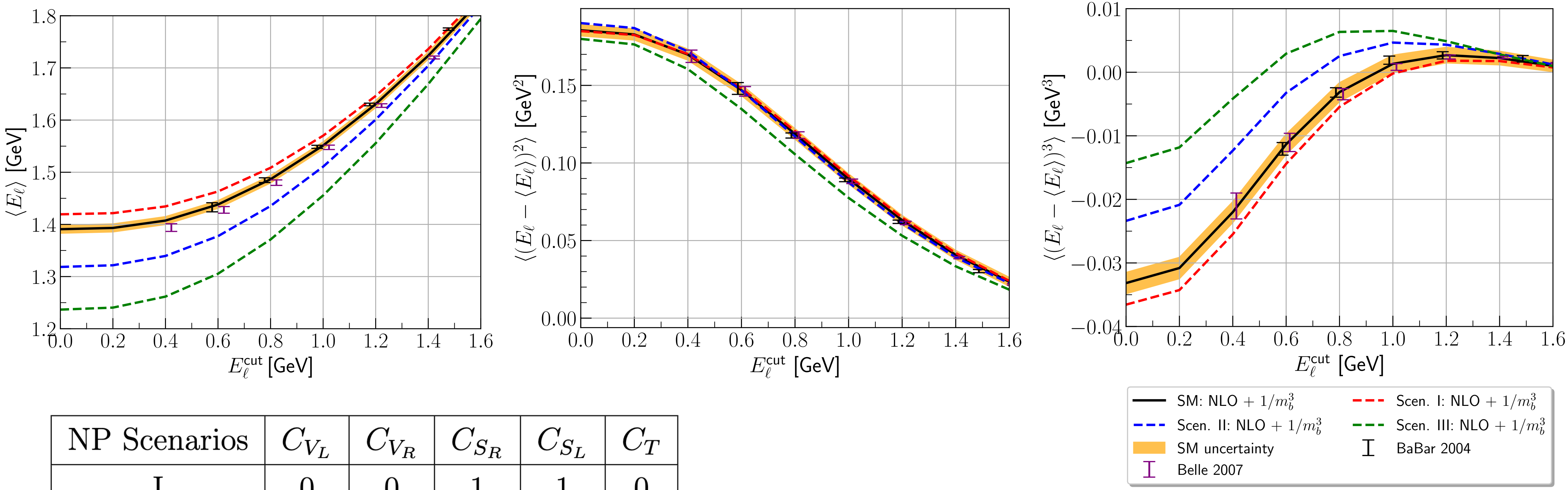






plots from Jung, Straub, *JHEP* 01 (2019) 009

Electron energy moments



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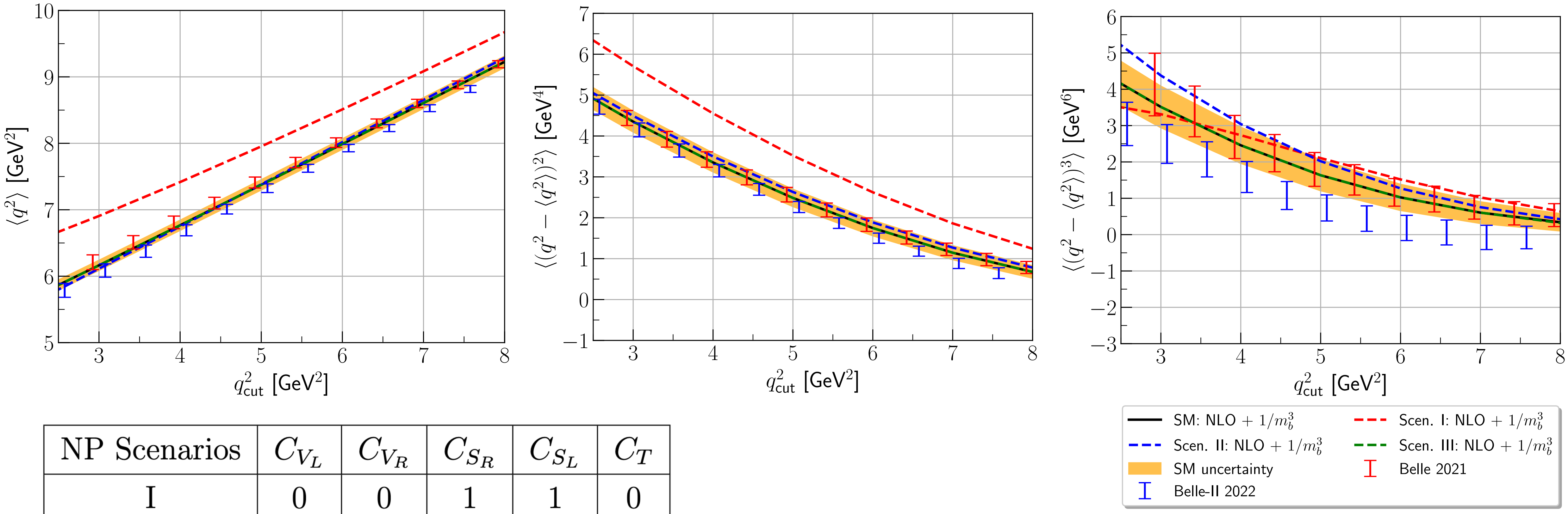
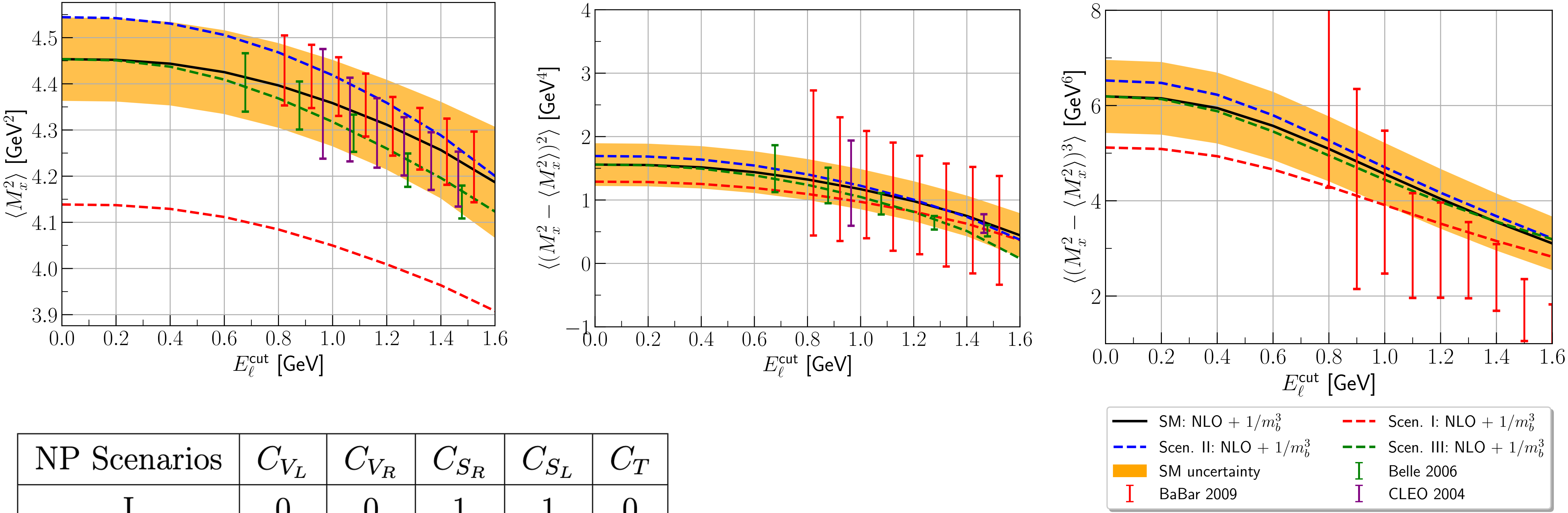
III	-1	0.5	0	0	0

q^2 moments



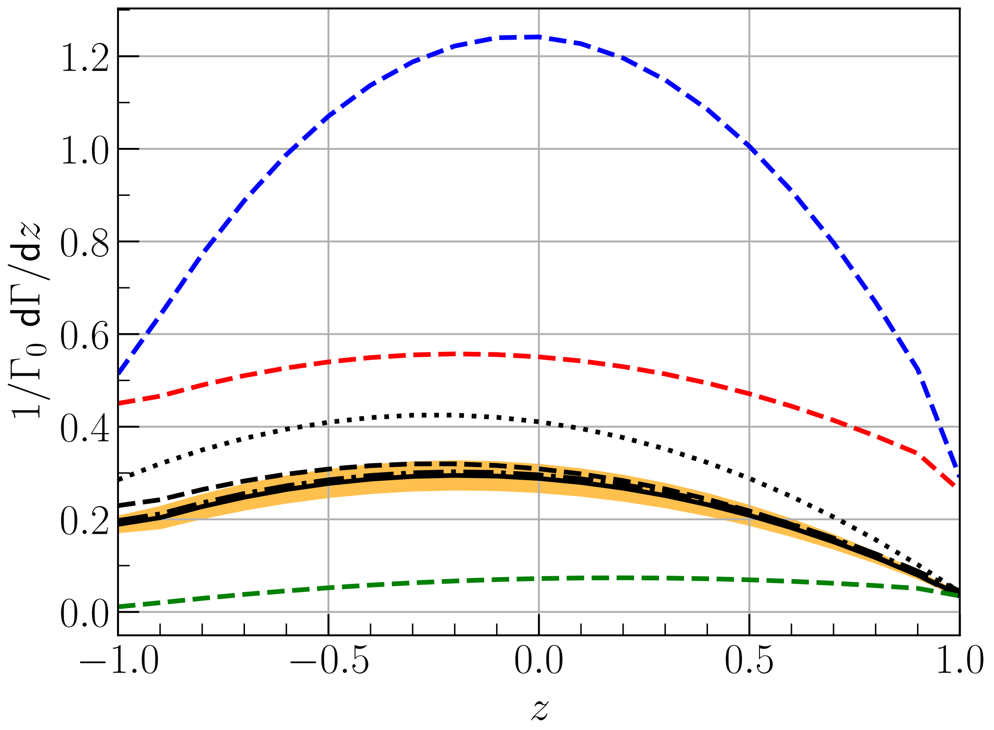
NP Scenarios	C_{V_L}	C_{V_R}	C_{S_R}	C_{S_L}	C_T
I	0	0	1	1	0
II	0	0	0	-1	0.5
III	-1	0.5	0	0	0

M_X moments



NP Scenarios	C_{V_L}	C_{V_R}	C_{S_R}	C_{S_L}	C_T
I	0	0	1	1	0
II	0	0	0	-1	0.5
III	-1	0.5	0	0	0

Forward-backward asymmetry



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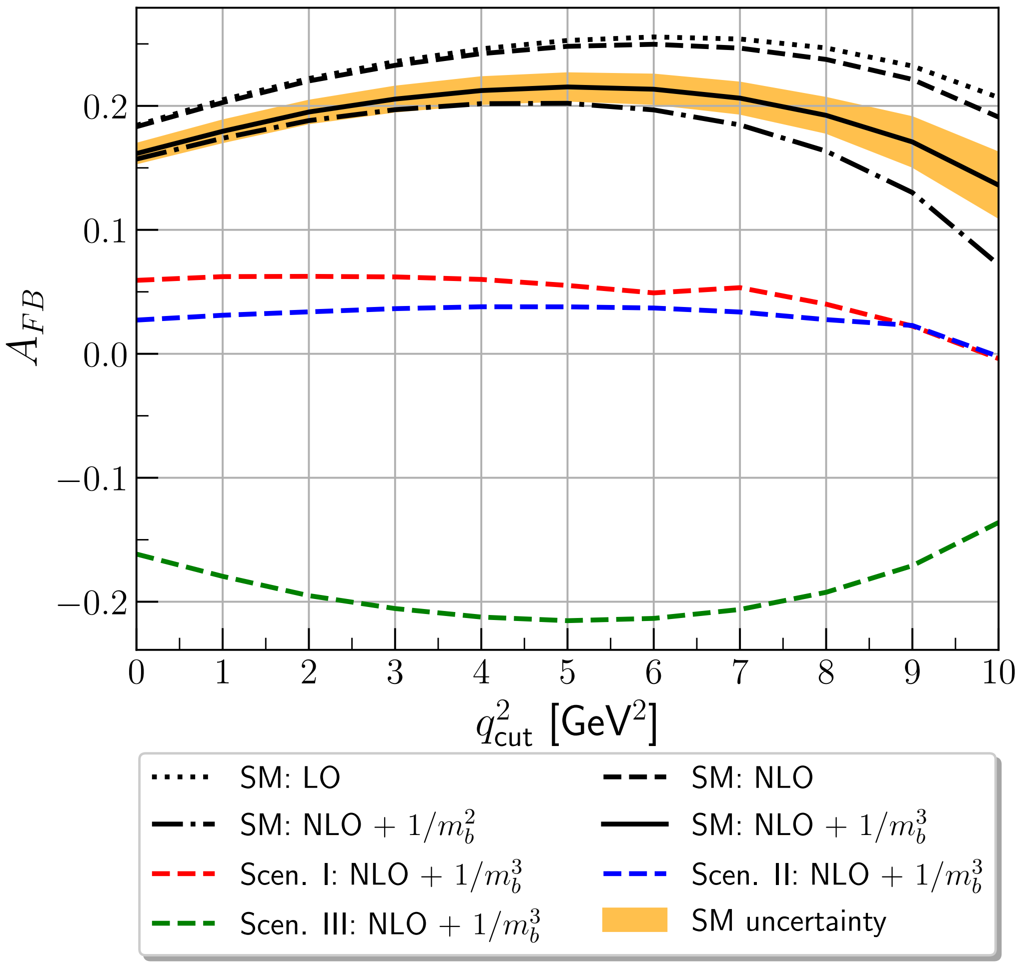


Towards a global fit with NP effects

with F. Bernlochner, M. Prim, K.K. Vos

https://gitlab.com/vcb-inclusive/kolya

- **Open-source** python package
- Python interface to CRunDec for automatic α_s, m_b^{kin} and $\overline{m}_c$ RGE evolution

Chetyrkin,, Kühn, Steinhauser, Comput. Phys. Commun. 133 (2000) 43
Herren, Steinhauser, Comput.Phys.Commun. 224 (2018) 333
see also: https://github.com/DavidMStraub/rundec-python

- We included SM and NP effects
- Kinetic scheme

Bigi, Shifman, Uraltsev, Vainshtein, *Phys.Rev.D* 56 (1997) 4017
Czarnecki, Melnikov, Uraltsev, Phys.Rev.Lett. 80 (1998) 3189
MF, Schönwald, Steinhauser, *Phys.Rev.Lett.* 125 (2020) 052003

- Observables
  - Γ_{sl}, $\Delta\text{Br}(E_{\text{cut}})$
  - Centralised moments $\langle E_\ell \rangle_{E_{\text{cut}}}$, $\langle M_X^2 \rangle_{E_{\text{cut}}}$
  - Centralised moments $\langle q^2 \rangle_{q^2_{\text{cut}}}$

Nikolai Uraltsev 1957 - 2013

- Complete: NLO corrections at order $1/m_b^0$
- Completing:
  - NNLO QCD corrections at $1/m_b^0$ in the SM
  - NLO QCD corrections for power-suppressed terms in the SM

Included in Kolya

- Total rate

NLO: Nir, *Phys.Lett.B* 221 (1989) 184
NNLO: Czarnecki, Pak, *Phys.Rev.Lett.* 100 (2008) 241807, *Phys.Rev.D* 78 (2008) 114015
N3LO: **MF**, Schönwald, Steinhauser, *Phys.Rev.D* 104 (2021) 016003, *JHEP* 08 (2022) 039\
NLO at $1/m_b^2$: Mannel, Pivovarov, Rosental, *Phys.Rev.D* 92 (2015) 5, 054025

- E_ℓ and M_X^2 moments

NLO differential rate: Aquila, Gambino, Ridolfi, Uraltsev, *Nucl.Phys.B* 719 (2005) 77;
MF, Rahimi, Vos, *JHEP* 02 (2023) 086.
NNLO: Biswas, Melnikov, JHEP 02 (2010) 089; Gambino, JHEP 09 (2011) 055.

NLO at $1/m_b^2$: Alberti, Gambino, Nandi, *Nucl.Phys.B* 870 (2013) 16, *JHEP* 01 (2014) 147

- q^2

NLO: Jezebel, Kühn, *Nucl.Phys.B* 320 (1989) 20
NLO up to $1/m_b^2$: Mannel, Moreno, Pivovarov, *JHEP* 08 (2020) 089

see talk by D. Moreno

- Kinetic scheme

Bigi, Shifman, Uraltsev, Vainshtein, *Phys.Rev.D* 56 (1997) 4017
Czarnecki, Melnikov, Uraltsev, Phys.Rev.Lett. 80 (1998) 3189
MF, Schönwald, Steinhauser, *Phys.Rev.Lett.* 125 (2020) 052003, *Phys.Rev.D* 103 (2021) 1, 014005

[1]:
```python
import kolya
import numpy as np
```

Physical parameters

They are declared in the class `parameters.physical_parameters`. Initialization set default values

[5]:
```python
par = kolya.parameters.physical_parameters()
```

Bottom mass in the kinetic scheme $m_b^{\mathrm{kin}}(\mu_{WC})$ in GeV

[6]:
```python
par.mbkin
```

[6]:
```
4.573
```

HQE parameters

They are declared in the class `parameters.HQE_parameters`. They are initalized to zero. We can set their values in the following way

[8]:
```
hqe = kolya.parameters.HQE_parameters(
    muG = 0.306,
    rhoD = 0.185,
    rhoLS = -0.13,
    mupi = 0.477,
)
```

Wilson coefficients

They are declared in the class parameters.WCoefficients. They are initialized to zero and can be set in the following way

[9]:
```
wc = kolya.parameters.WCoefficients(
    VL = 0,
    VR = 0,
    SL = 0.1,
    SR = 0,
    T = 0,
)
```

Total Rate

The branching ratio is given by the function `BranchingRatio_KIN_MS(Vcb,par,hqe,wc)`

[10]:
```
Vcb = 42.2e-2
kolya.TotalRate.BranchingRatio_KIN_MS(Vcb,par,hqe,wc)
```

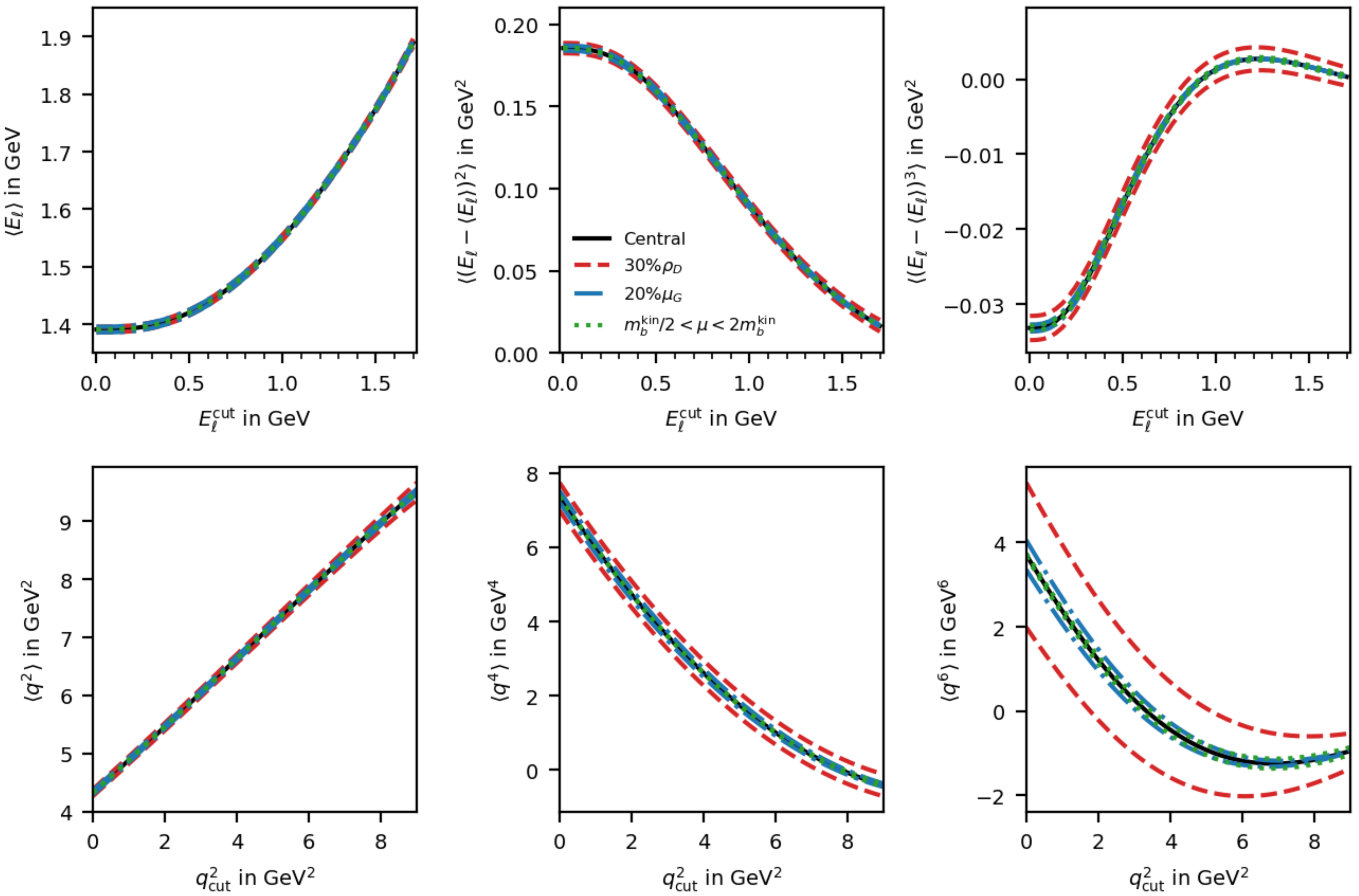
[10]:
```
10.64996041511315
```

Centralized Q2 moments

Q2 moments are evaluated with `Q2moments.moment_n_KIN_MS(q2cut, par, hqe, wc)`, for instance

[11]:
```
q2cut = 8.0
kolya.Q2moments.moment_1_KIN_MS(q2cut,par,hqe,wc)
```

[11]:
```
8.971188963587162
```



$\langle E_\ell \rangle$ in GeV
E_ℓ^{cut} in GeV
$\langle (E_\ell - \langle E_\ell \rangle)^2 \rangle$ in GeV^2
$\langle (E_\ell - \langle E_\ell \rangle)^3 \rangle$ in GeV^2
Central
$30\% \rho_D$
$20\% \mu_G$
$m_b^{\text{kin}}/2 < \mu < 2 m_b^{\text{kin}}$
$\langle q^2 \rangle$ in GeV^2
$\langle q^4 \rangle$ in GeV^4
$\langle q^6 \rangle$ in GeV^6
q^2_{cut} in GeV^2

Conclusions and Outlook

- We plan to scrutinise data on inclusive $B \to X_c \ell \bar{\nu}_\ell$ for NP contributions.
- Good place to look are moments of the **electron energy** spectrum and A_{FB}.
- M_X^2 and q^2 moments more sensitive to $1/m_b$ corrections. More difficult to disentangle NP.
- We developed open-source python package **Kolya**

- Ongoing global fit of available inclusive data from *B*-factories.
- Future **use lattice results** for inclusive decays for non-pert. inputs.
- Study interplay with exclusive decays $B \to D^{(*)} \ell \bar{\nu}_\ell$