New Physics in Inclusive $\bar{B} \to X_c \ell \bar{\nu}$

Alexandre Carvunis - TU Dortmund

Based on *JHEP 01 (2026) 037* and *arXiv:2601.16129*
in collaboration with P. Gambino, G. Finauri, M. Jung, S. Mächler

60th Rencontres de Moriond - EW+U
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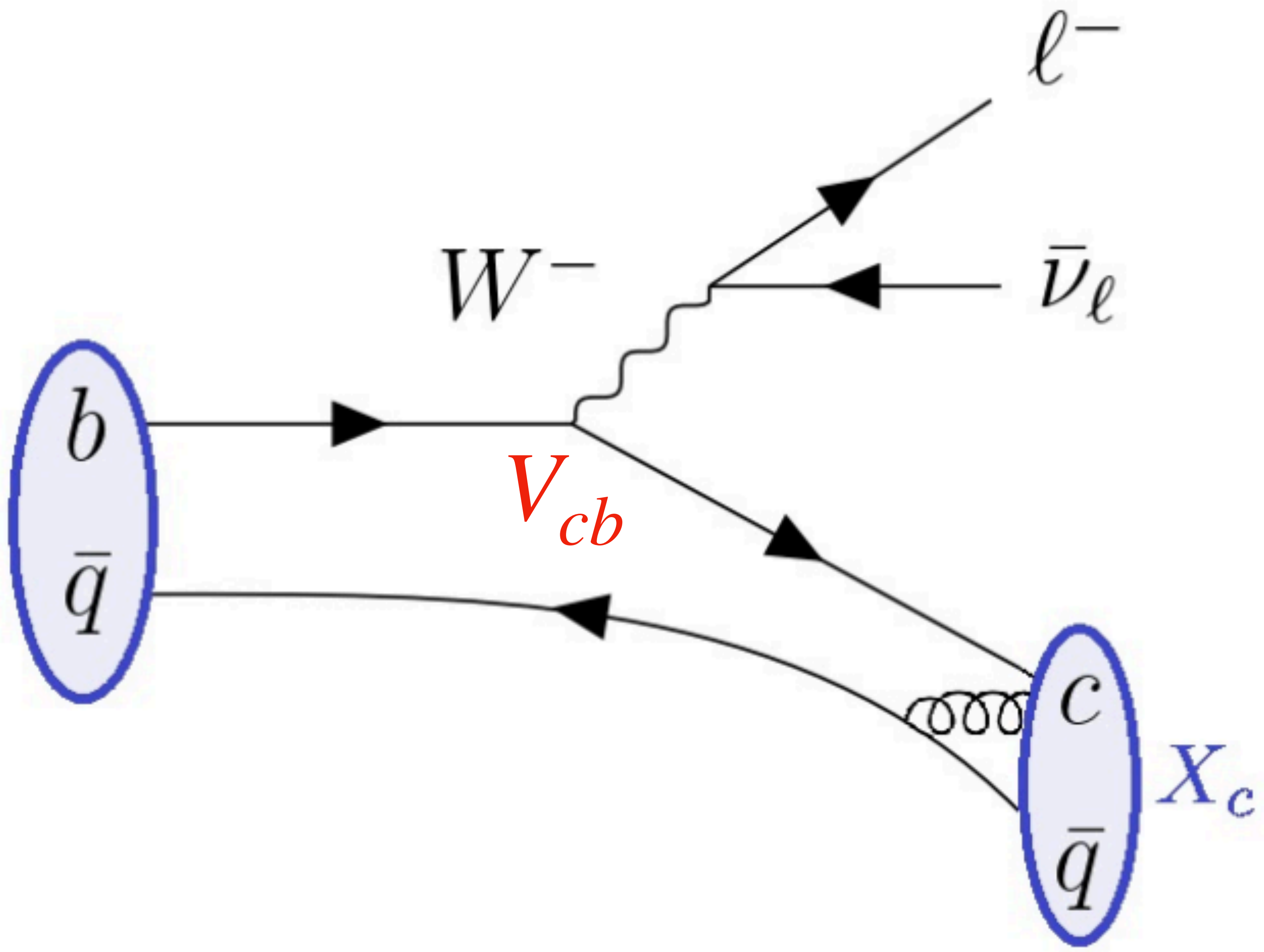
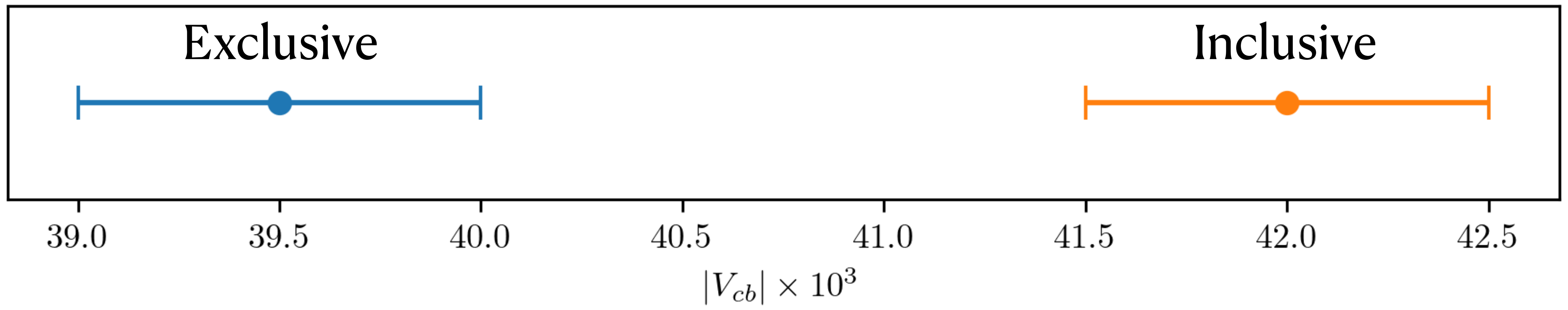
Exclusive vs Inclusive $b \to c\ell\bar{\nu}$



$$\Gamma(b \to c\ell\bar{\nu}) \propto |V_{cb}|^2$$

Vcb puzzle

PDG 2025 averages



Inclusive measurements

$$\bar{B} \to X_c\ell\bar{\nu}$$

$X_c = D, D^*, D^{**}, D\pi, \ldots$ = any once charmed hadron(s)

measured in B factories (BaBar, Belle, Belle II,…)

Prospects for $\Lambda_b \to X_c\ell\bar{\nu}$ at LHCb

TH input: optical theorem + local OPE

Exclusive channels

$$\bar{B}_{(s)} \to D^{(*)}_{(s)}\ell\bar{\nu}$$

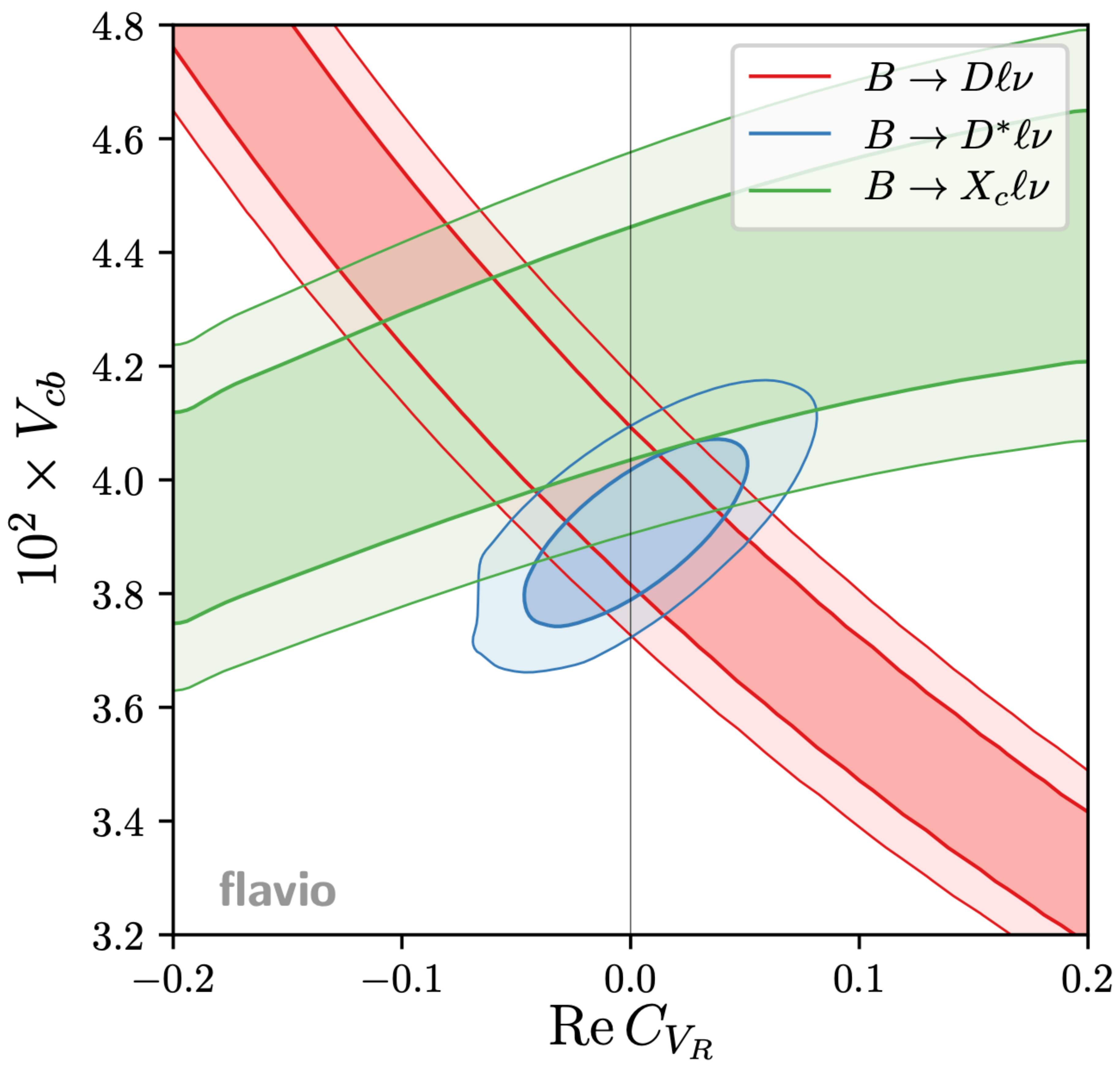
$\bar{B} \to D^{(*)}\ell\bar{\nu}$ measurements from B factories

$\bar{B}_s \to D_s^{(*)}$ by LHCb

TH input: lattice, LCSR, HQE

Why look for New Physics in $B \to X_c \ell \bar{\nu}$?

- There are still anomalies in some semileptonic B decays: BR($B \to K\mu\mu$), ang($B \to K^*\mu\mu$), and $R(D^{(*)})$
- Can the V_{cb} puzzle be explained by NP? [Crivellin et al. 1407.1320] says no but performed a 'zero-th order analysis' only
- Observables in inclusive and exclusive decays have different sensitivities to NP
- Measurements of inclusive $B \to X_c \ell \bar{\nu}$ observables provide an independent check of exclusive modes
- $B \to X_c \ell \bar{\nu}$ phenomenology has reached the $\mathcal{O}(1\%)$ precision in the SM, can be sensitive to small NP effects



M. Jung, D. Straub (1801.01112)

$B \to X_c \ell \bar{\nu}$ in the SM

At the b scale:

$$H_W = \frac{4G_F}{\sqrt{2}} V_{cb} (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) = \frac{4G_F}{\sqrt{2}} V_{cb} (J_q^\mu \times J_{\ell,\mu})$$

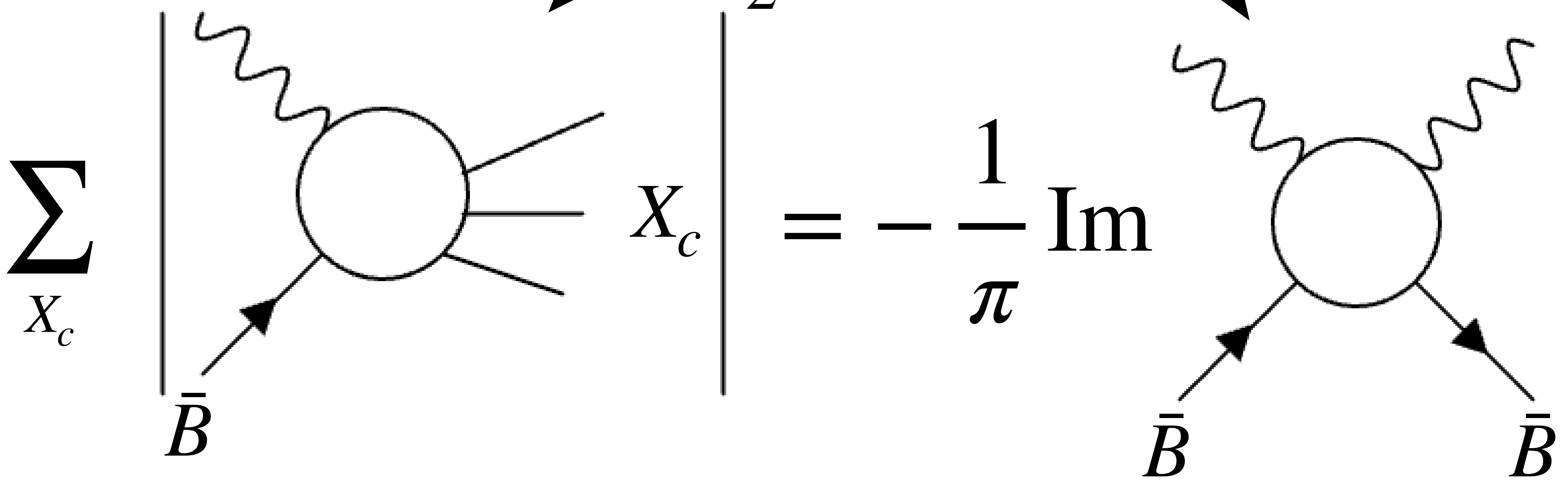
$$d\Gamma(\bar{B} \to X_c \ell \bar{\nu}_\ell) \propto \sum_{X_c} |\langle X_c \ell \bar{\nu}_\ell | H_W | \bar{B} \rangle|^2 \propto |V_{cb}|^2 L_{\mu\nu} W^{\mu\nu} + \mathcal{O}(\alpha_{em})$$

$L_{\mu\nu}$: known exactly

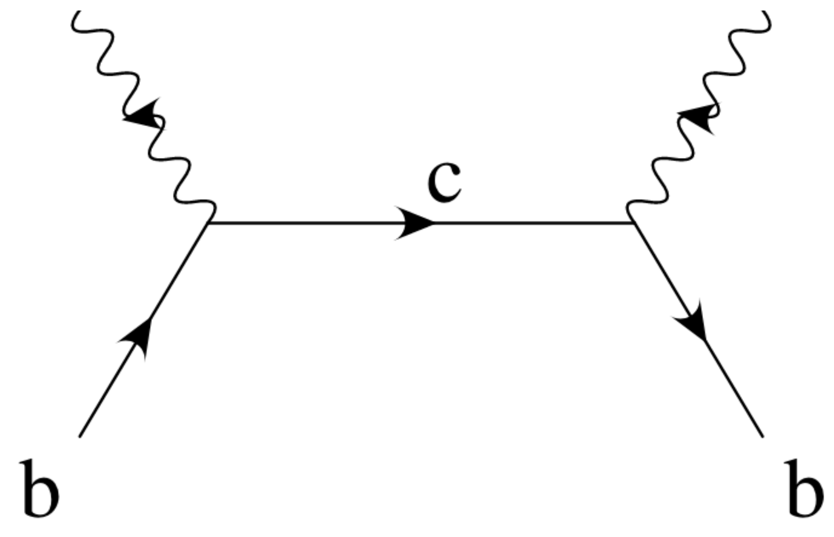
$$W^{\mu\nu} \propto \sum_{X_c} \langle X_c | J_q^\mu | \bar{B} \rangle \langle X_c | J_q^\nu | \bar{B} \rangle^\dagger$$

Optical Theorem

$$W^{\mu\nu} = -\frac{1}{\pi} \mathrm{Im} T^{\mu\nu}$$



OPE in HQET

$T^{\mu\nu} =$  $+ \mathcal{O}(\alpha_s)$

$$T^{\mu\nu} = T^{\mu\nu}_{LP} + T^{\mu\nu}_{\mu_\pi^2} \frac{\mu_\pi^2}{m_b^2} + T^{\mu\nu}_{\mu_G^2} \frac{\mu_G^2}{m_b^2} + T^{\mu\nu}_{\rho_D^3} \frac{\rho_D^3}{m_b^3} + T^{\mu\nu}_{\rho_{LS}^3} \frac{\rho_{LS}^3}{m_b^3} + \mathcal{O}\left(\frac{\Lambda^4_{\mathrm{QCD}}}{m_b^4}\right) + \mathcal{O}(\alpha_s)$$

$\Lambda_{\mathrm{QCD}} \sim \mu_\pi \sim \mu_G \sim \rho_D \sim \rho_{LS} \equiv$ *a priori* unknown parameters encoding non-perturbative ME's

What can this calculation do?

- We obtain an expression for the triple differential decay rate:

$$\frac{d\Gamma(\bar{B} \to X_c \ell \bar{\nu})}{dE_\ell dE_\nu dq^2} = |V_{cb}|^2 G_F^2 \frac{m_b^5}{16\pi^3} \left[f_{LP} + f_{NLP}^{\mu_\pi} \frac{\mu_\pi{}^2}{m_b^2} + f_{NLP}^{\mu_G} \frac{\mu_G^2}{m_b^2} + f_{NNLP}^{\rho_{LS}} \frac{\rho_{LS}^3}{m_b^3} + f_{NNLP}^{\rho_D} \frac{\rho_D^3}{m_b^3} + \mathcal{O}(\Lambda_{QCD}^4/m_b^4) + \mathcal{O}(\alpha_s) \right]$$

- $\mathcal{O}(\Lambda_{QCD}^n/m_b^n)$ terms $\propto \delta^{(n-1)}[(m_b v - q)^2 - m_c^2] \to \dfrac{d\Gamma}{dE_\ell dE_\nu dq^2}$ *is not physical.*
- The OPE is only valid for observables integrated over a range $\Delta E_\ell, \Delta E_\nu, \Delta q^2 \gg \Lambda_{QCD}^{(2)}$ (smearing). Higher power contributions are enhanced if the integration range is too small.
- The relevant observables are the moments: $\boxed{\mathcal{M}_n = \langle X^n \rangle = \dfrac{\int dX \frac{d\Gamma}{dX} X^n}{\int dX \frac{d\Gamma}{dX}}, X = E_\ell, q^2, m_{X_c}^2}$ with lower cuts on E_ℓ, q^2.
- Ratios independent of V_{cb} → we can fit the HQE parameters to data
- In practice central moments are used $\equiv \langle (X - \langle X \rangle)^n \rangle$ for $n \geq 2$ and for $n \geq 4$ the TH error diverges.

State-of-the-art SM calculation

	dE_ℓ	dm_X^2	dq^2	Γ
1	α_s^2 [Melnikov 2008] [Pak, Czarnecki 2008]	α_s^2	α_s^2 [Fael, Herren 2024]	α_s^3 [Fael, Schönwald, Steinhauser 2020]
$1/m_b^2$	α_s [Alberti, Ewerth, Gambino, Nandi 2012, 2013]	α_s	α_s	α_s
$1/m_b^3$	1 [Gremm, Kapustin 1997]	1	α_s [Mannel, Moreno Pivovarov 2021]	α_s [Mannel, Pivovarov 2019]
$1/m_b^{4,5}$ $1/(m_b^3 m_c^2)$	[.............. Updated in GF 2501.09090....................] 1 [Mannel, Turczyk, Uraltsev 2010]	1	1 [Mannel, Milutin, Vos 2023]	1 [Mannel, Turczyk, Uraltsev 2010]

Slide by Gael Finauri

Data and Fit strategy

Available measurements

- E_ℓ and m_{X_c}-moments from Babar, CLEO, DELPHI, CDF, Belle
- q^2-moments from Belle and Belle II
- $\mathrm{BR}_{E_{\ell\mathrm{cut}}}(B \to X_c \ell \bar{\nu})$ from Babar and Belle

Fit Strategy

1. Extract HQE matrix elements by fitting the kinematic moments and R^*

   <u>Fit parameters</u>: $m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_{LS}^3, \rho_D^3, \mathrm{BR}(\bar{B} \to X_c \ell \bar{\nu})$

$$R^*(E_{\ell\mathrm{cut}}) \equiv \frac{\mathrm{BR}_{E_{\ell\mathrm{cut}}}(\bar{B} \to X_c \ell \bar{\nu})}{\mathrm{BR}(\bar{B} \to X_c \ell \bar{\nu})}$$

2. Extract $|V_{cb}|$ from the total decay rate using the result of the fit

$$\Gamma_{B \to X_c \ell \nu} = |V_{cb}|^2 f(m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_{LS}^3, \rho_D^3) = \frac{\mathrm{BR}(\bar{B} \to X_c \ell \bar{\nu})}{\tau_B}$$

SM result

m_b [GeV]	m_c [GeV]	μ_π^2 [GeV^2]	μ_G^2 [GeV^2]	ρ_D^3 [GeV^3]	ρ_{LS}^3 [GeV^3]	BR$_{c\ell\bar{\nu}}$ [%]	$10^3\lvert V_{cb}\rvert$
4.574	1.090	0.435	0.278	0.164	-0.090	10.62	41.64
0.012	0.010	0.040	0.048	0.018	0.089	0.15	0.47
1	0.390	-0.229	0.560	-0.022	-0.181	-0.064	-0.421
	1	0.015	-0.238	-0.028	0.084	0.034	0.071
		1	-0.097	0.535	0.266	0.144	0.346
			1	-0.261	0.004	0.001	-0.271
				1	-0.014	0.025	0.172
					1	-0.010	0.056
						1	0.694
							1

Updates:

- Inclusion of α_s^2 corrections in the q^2-moments
  [Fael et al. 2403.03976]
- Full α_{em} correction in the total decay width
  [Bigi et al. 2309.02849]

JHEP 01 (2026) 037, AC, P. Gambino, G. Finauri, M. Jung, S. Mächler

$B \to X_c \ell \bar{\nu}$ with New Physics

- Assuming $\Lambda_{NP} \gg m_b$, no LFV, no RH neutrinos, dim 6 operators, the Hamiltonian is:

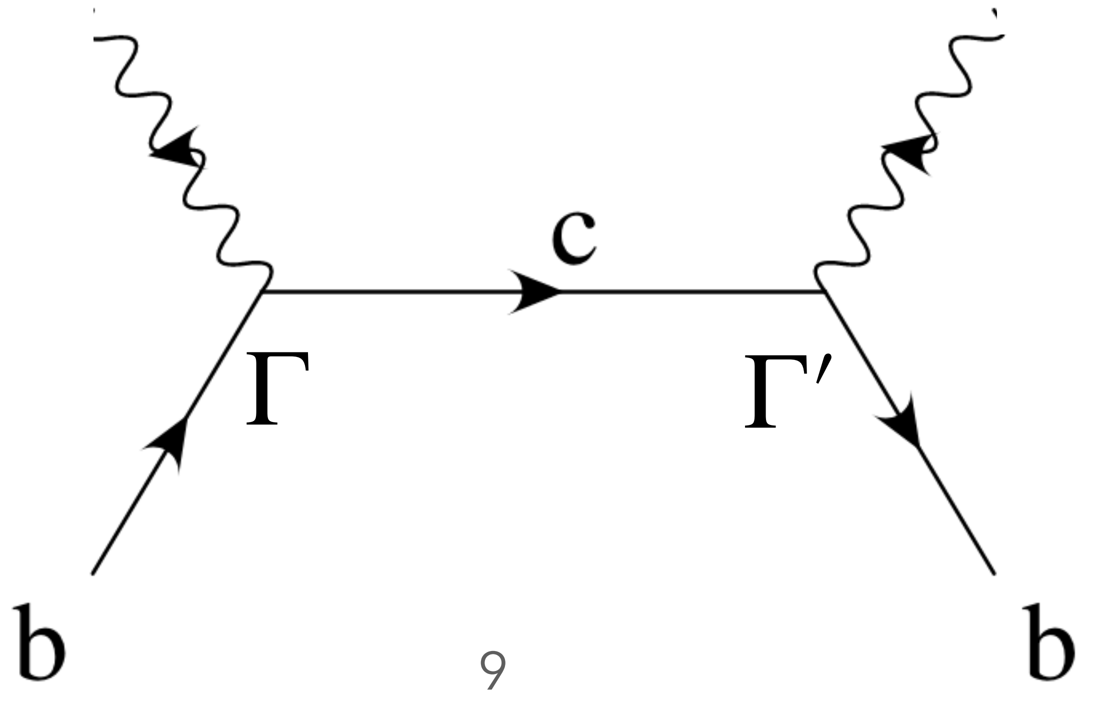
$$H_W^{NP} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(1+C_{VL})[\bar{c}\gamma^\mu P_L b][\bar{\ell}\gamma_\mu P_L \nu_\ell] + C_{V_R}[\bar{c}\gamma^\mu P_R b][\bar{\ell}\gamma_\mu P_L \nu_\ell] + C_T[\bar{c}\sigma^{\mu\nu} P_L b][\bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell]$$

$$+ C_S[\bar{c}b][\bar{\ell} P_L \nu_\ell] + C_P[\bar{c}\gamma_5 b][\bar{\ell} P_L \nu_\ell] \Big]$$

$$\tilde{V}_{cb} \equiv V_{cb}(1 + C_{VL}),\ \tilde{C}_X \equiv C_X/(1 + C_{V_L})$$

- This introduces new terms to compute in the hadronic tensor OPE

$$2m_B T_{\Gamma\Gamma'} = -i \int d^4x e^{-iqx} \left\langle \bar{B} \,|\, \left[J_{\Gamma'}(x)^\dagger J_\Gamma(0) \right] |\, \bar{B} \right\rangle \qquad \Gamma, \Gamma' \in \left\{ \gamma^\mu P_L, \gamma^\mu P_R, \sigma^{\mu\nu} P_L, \mathbf{1}, \gamma_5 \right\}$$

$T_{\Gamma\Gamma'} =$  $+\mathcal{O}(\alpha_s)$

$B \to X_c \ell \bar{\nu}$ with New Physics

- The OPE of the hadronic tensor depends on the Lorentz structure $\Gamma\Gamma'$

$$\frac{d\Gamma(B \to X_c \ell \bar{\nu})}{dq^2 dE_\nu dE_\ell} \propto \sum_{\Gamma,\Gamma'} W_{\Gamma\Gamma'} L_{\Gamma\Gamma'} \qquad W_{\Gamma\Gamma'} = -\frac{1}{\pi} \mathrm{Im} T_{\Gamma\Gamma'}$$

$$T_{\Gamma\Gamma'} = C_\Gamma C^*_{\Gamma'} \sum_{i,n} g^{(i,m)}_{\Gamma\Gamma'} \alpha_s^i \frac{\Lambda^n_{\mathrm{QCD}}}{m_b^n}$$

- We include the following contributions
  - SM : $\mathcal{O}(1/m_b^3) + \mathcal{O}(\alpha_s/m_b^2) + \mathcal{O}(\alpha_s^2)$, for Γ_{tot} : $\mathcal{O}(1/m_b^3) + \mathcal{O}(\alpha_s/m_b^3) + \mathcal{O}(\alpha_s^3)$ [cf. slide 6]
  - NP : $\mathcal{O}(1/m_b^3) + \mathcal{O}(\alpha_s)$ [Blok et al. 9307247],[Manohar et al. 9308246],[Feger et al. 1003.4022], [Kamali 1811.07393] [Grossman et al. 9403376],[Colangelo et al. 1611.07387],[Fael et al. 2208.04282]

- In *JHEP 01 (2026) 037* we recompute the NP $\mathcal{O}(1/m_b^3)$ contribution and provide analytic expressions for $W_{\Gamma\Gamma'}$
- In arXiv:2601.16129 (AC, G. Finauri) we rederive the NP $\mathcal{O}(\alpha_s)$ corrections and provide for the first time the analytic expressions for all three kinematic moments up to $n = 3$

Data and Fit strategy

- Same dataset as for the SM: cf. slide 7
- « Pure » V_{cb} cannot be extracted anymore, we only have access to $|\tilde{V}_{cb}| \equiv |V_{cb}(1 + C_{VL})|$
- We use a polar representation of the normalized WCs: $\boxed{\frac{C_X}{1 + C_{V_L}} \equiv a_X e^{i\delta_X}}$, $X = V_R, T, S, P$
- For $m_\ell = 0$ we can get rid of one WC phase

14 free parameters in the fit

- 7 SM-like parameters: $m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_{LS}^3, \rho_D^3$, $\mathrm{BR}_{c\ell\bar{\nu}}$
- 7 NP parameters: $a_{V_R}, a_T, a_P, a_S, c(\delta_{V_R}), c(\delta_S), c(\delta_P)$

This is the first global fit of inclusive B decays with New Physics!

Fit Results

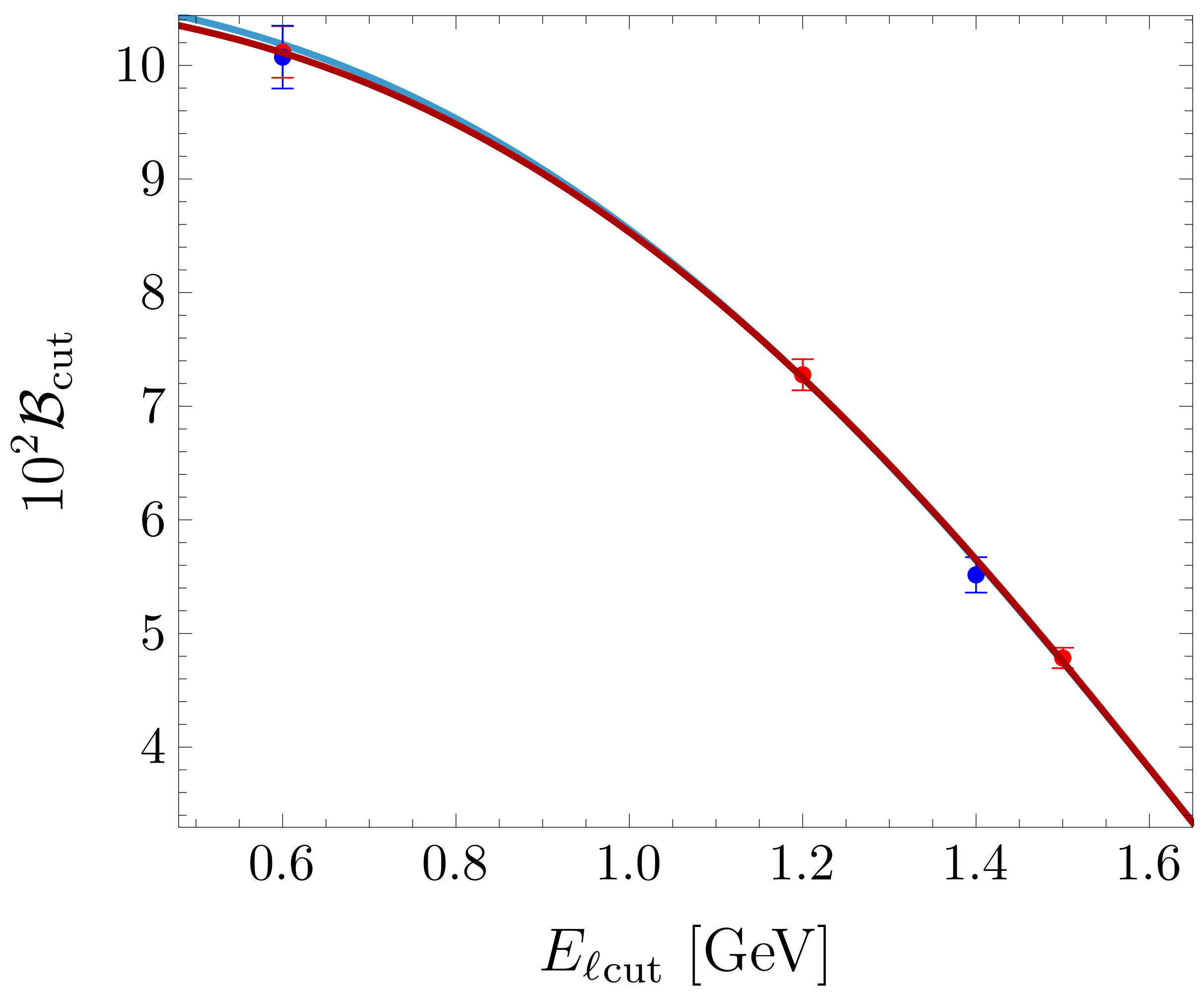
With agnostic New Physics

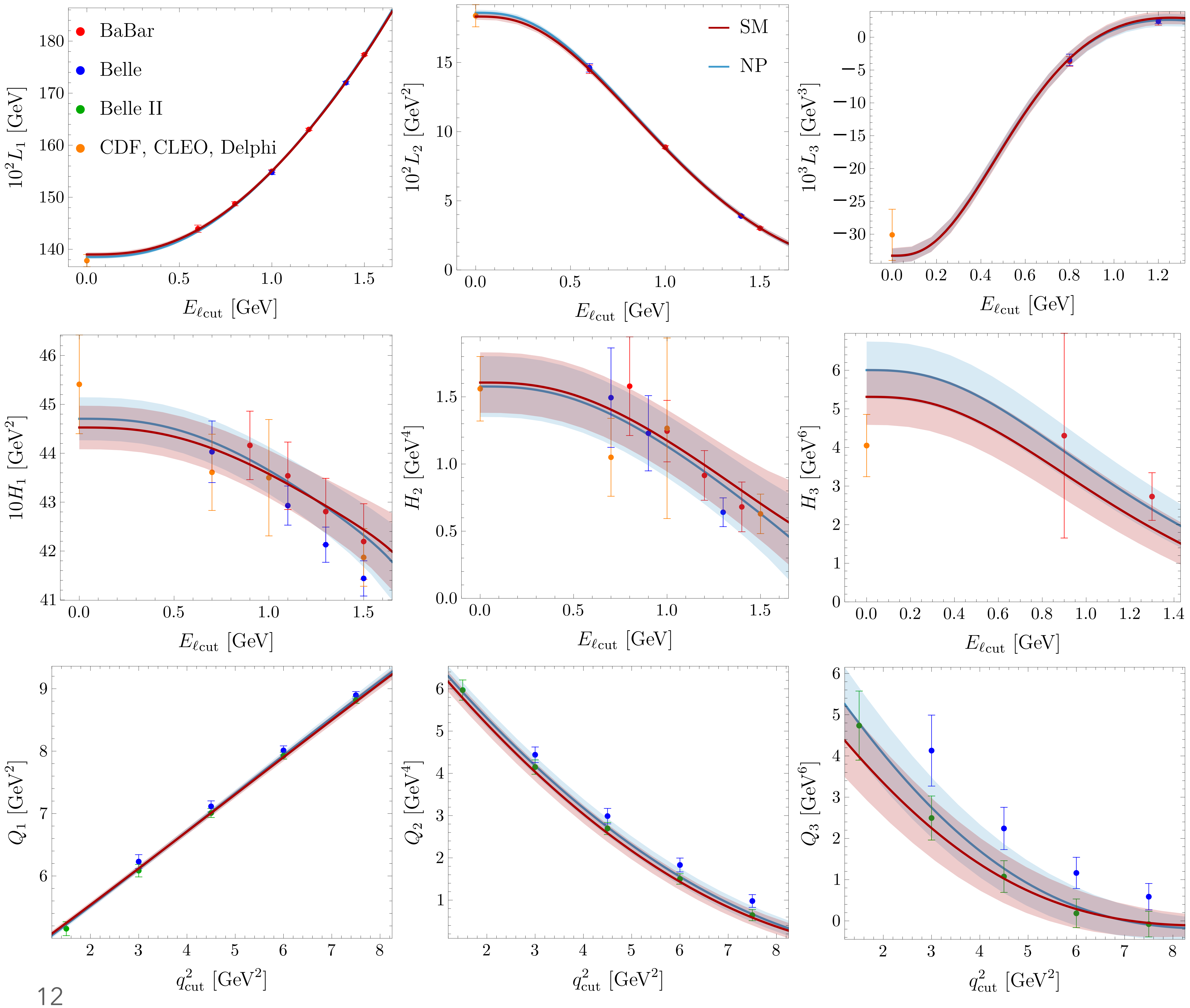
$$\chi^2_{SM}/\text{d.o.f.} = 42.58/74$$

↓

$$\chi^2_{NP}/\text{d.o.f.} = 36.08/67$$

SM compatible with the NP fit at the 0.7σ level. No preference for NP.



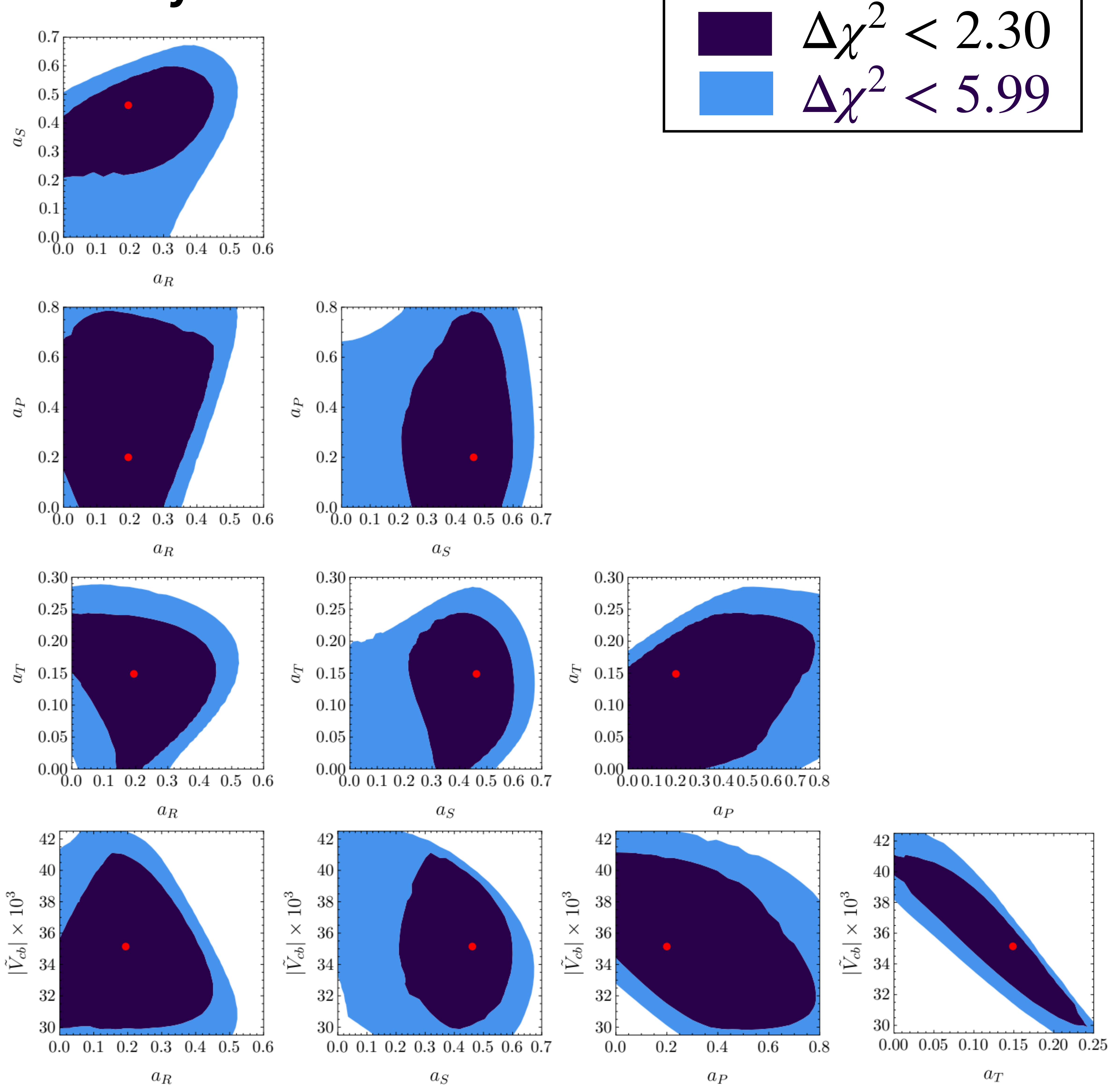


Fit Results

With agnostic New Physics

- HQE parameters are SM-like
- All single NP WCs are compatible with zero within the 68 % C.L. interval (< 95 % for a_S)
- Upper bounds competitive with bounds from exclusive decays ✅
- Important correlation between a_T and $\tilde{V}_{cb}$ gives the profiled $\tilde{V}_{cb}$ a large uncertainty:

$$|\tilde{V}_{cb}| = 35.3^{+4.4}_{-3.6} \cdot 10^{-3}$$



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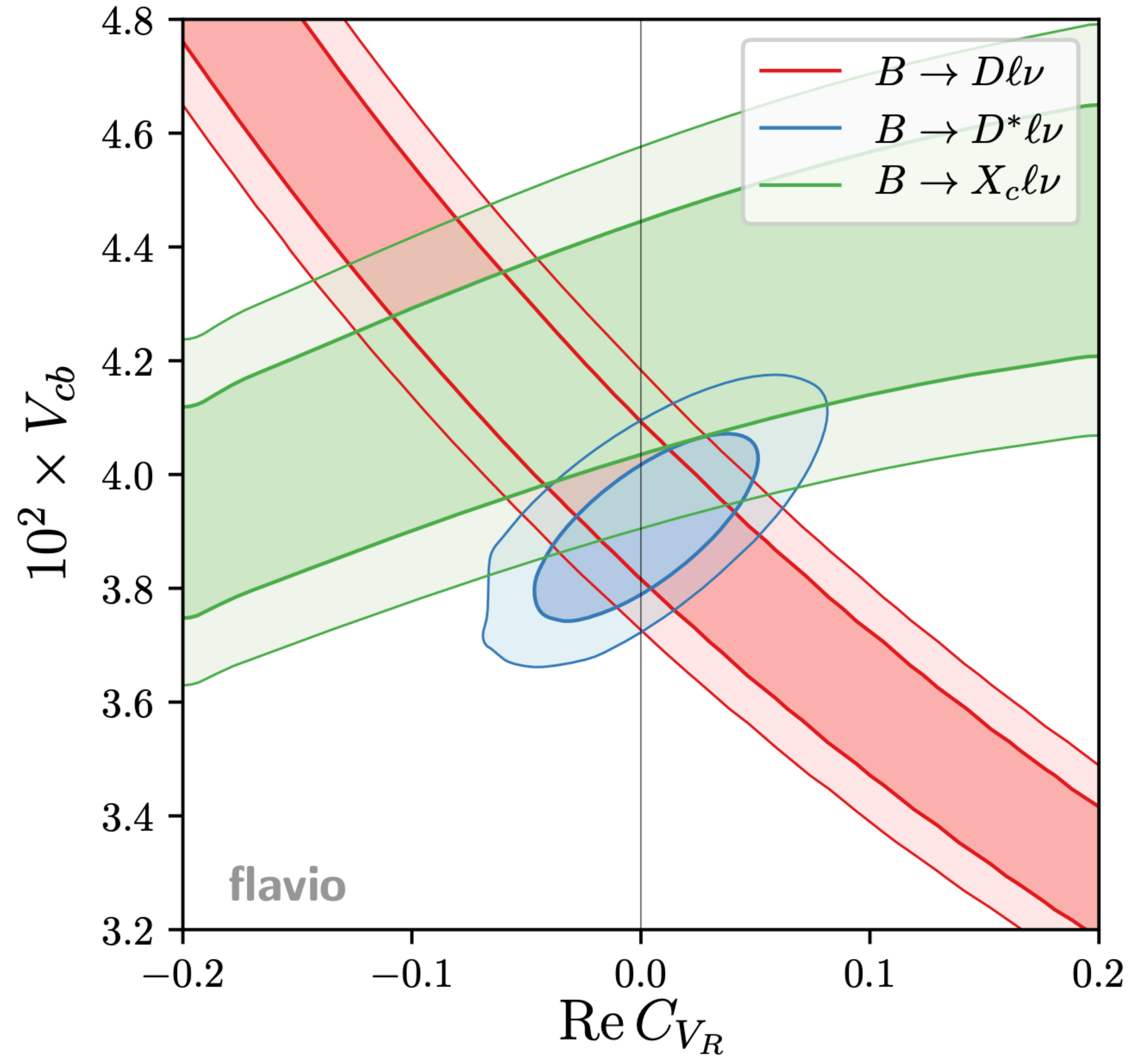
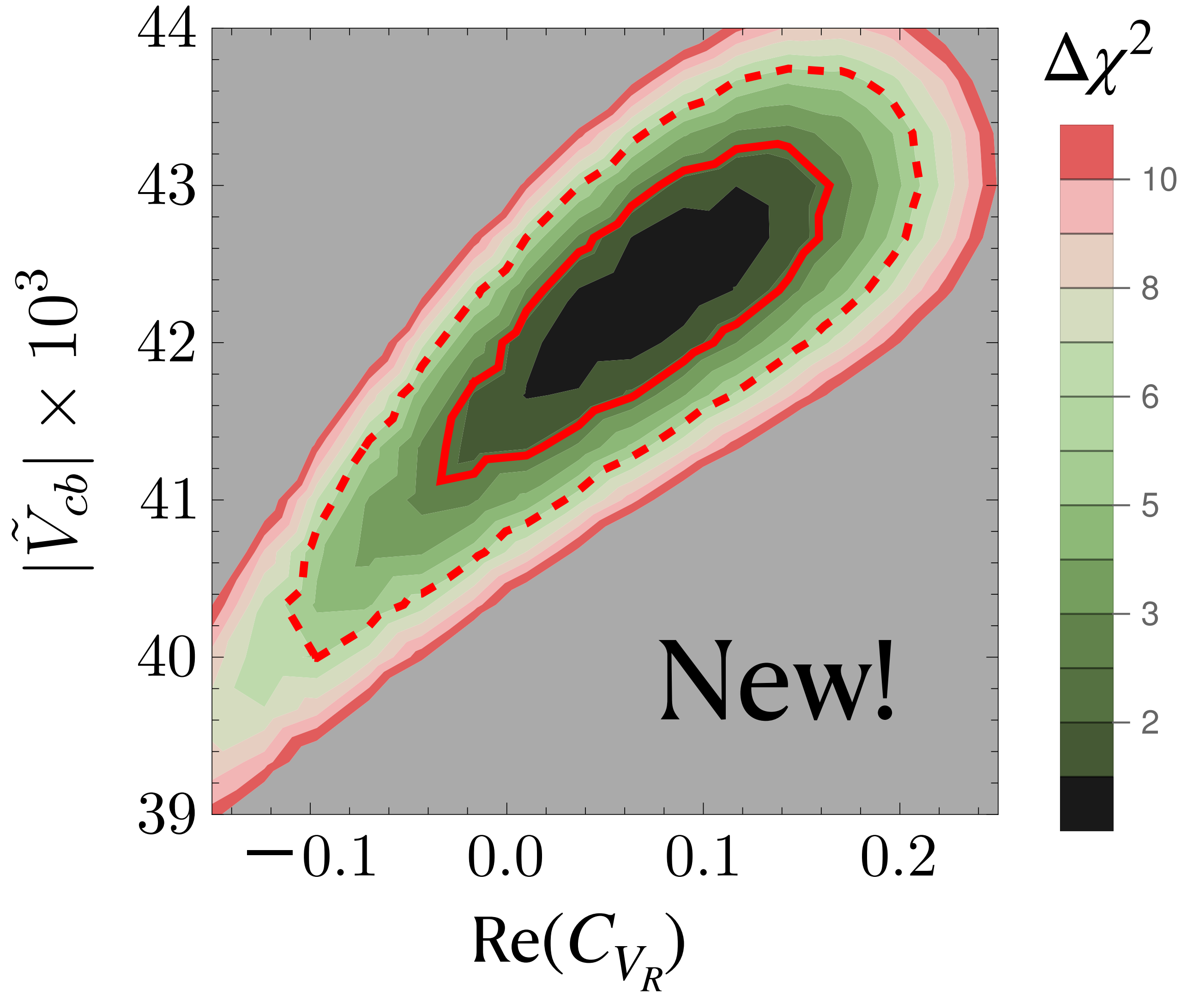
A simple NP scenario

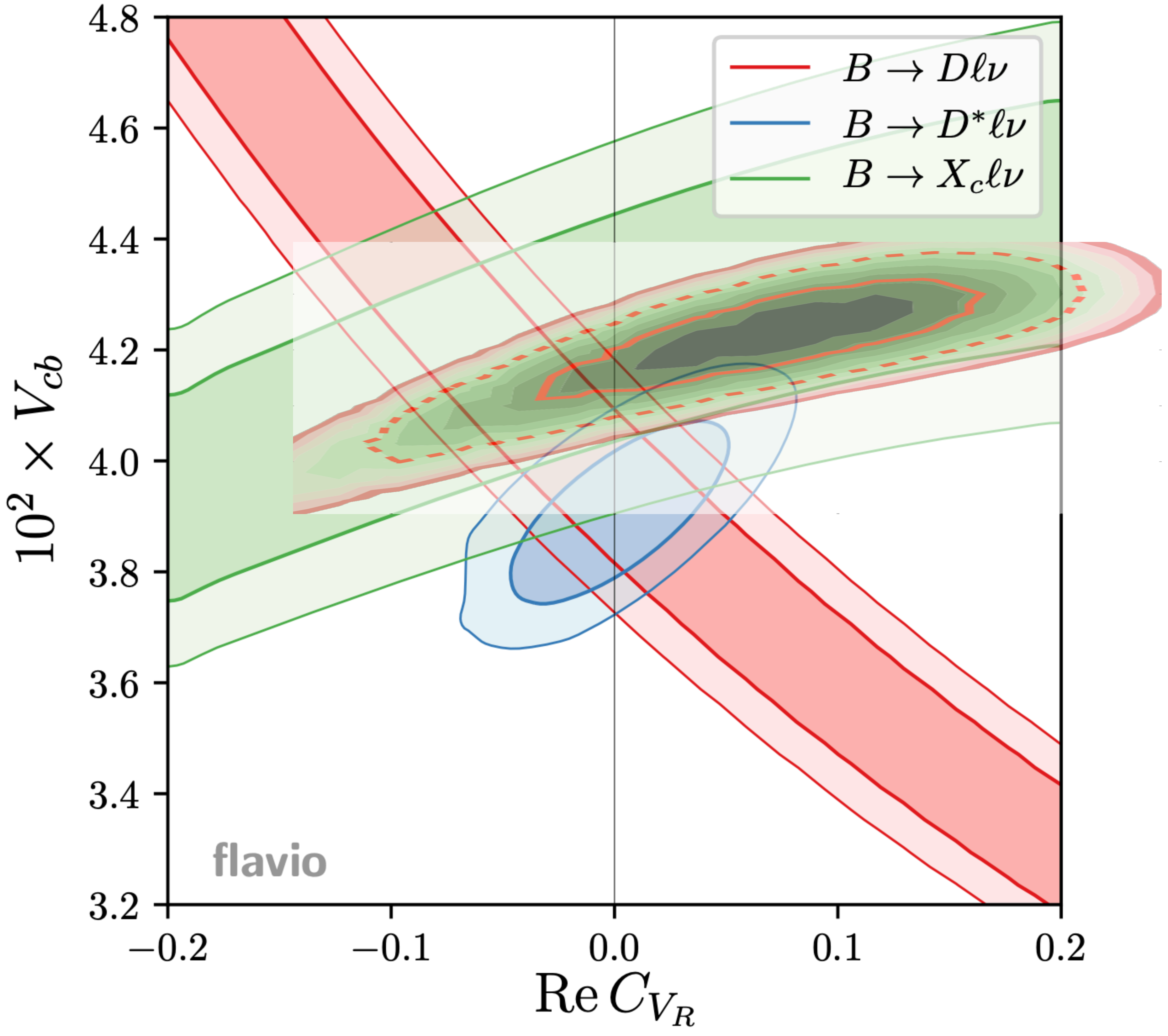
Back to the V_{cb} puzzle



M. Jung, D. Straub (1801.01112)



68 % C.L.
95 % C.L.



Exclusive bounds need to be updated and included in a global fit!

Summary

We compute New Physics (dim 6 WET) effects in the moments of $B \to X_c \ell \bar{\nu}$ at $\mathcal{O}(\Lambda^3_{\mathrm{QCD}}/m_b^3, \alpha_s)$

➡ First fully analytic results are provided for α_s corrections [arXiv:2601.16129] → easy to use!

First global fit of inclusive $B \to X_c \ell \bar{\nu}$ with model-independent New Physics

➡ Provides **new and competitive bounds on New Physics in $b \to c \ell \bar{\nu}$ transitions**!

Perspectives:

- Global fit including exclusive $b \to c \ell \bar{\nu}$ decays (can NP explain the V_{cb} puzzle?)
- Implementation in flavour phenomenology open source codes (flavio/EOS/other?)

Thank you!

Supplementary material

Single Mediator NP models

- We also investigate 5 single-mediator scenarios which only contribute to some of the 5 WCs in the WET Hamiltonian

SMEFT
$\mu = \Lambda_{NP} = 1$ TeV

running and matching to WET

WET
$\mu = 5$ GeV

(Vector-like quark doublet) $\rightarrow \{\hat{C}_{V_R}\}\,,$ (I)

Charged scalar $(H^\pm) \rightarrow \{\hat{C}_{S_L}, \hat{C}_{S_R}\}\,,$ (II)

Leptoquarks:

$(S_1) \rightarrow \{\hat{C}_T, \hat{C}_{S_L} = -4\hat{C}_T\}\,,$ (III)

$(R_2) \rightarrow \{\hat{C}_T, \hat{C}_{S_L} = 4\hat{C}_T\}\,,$ (IV)

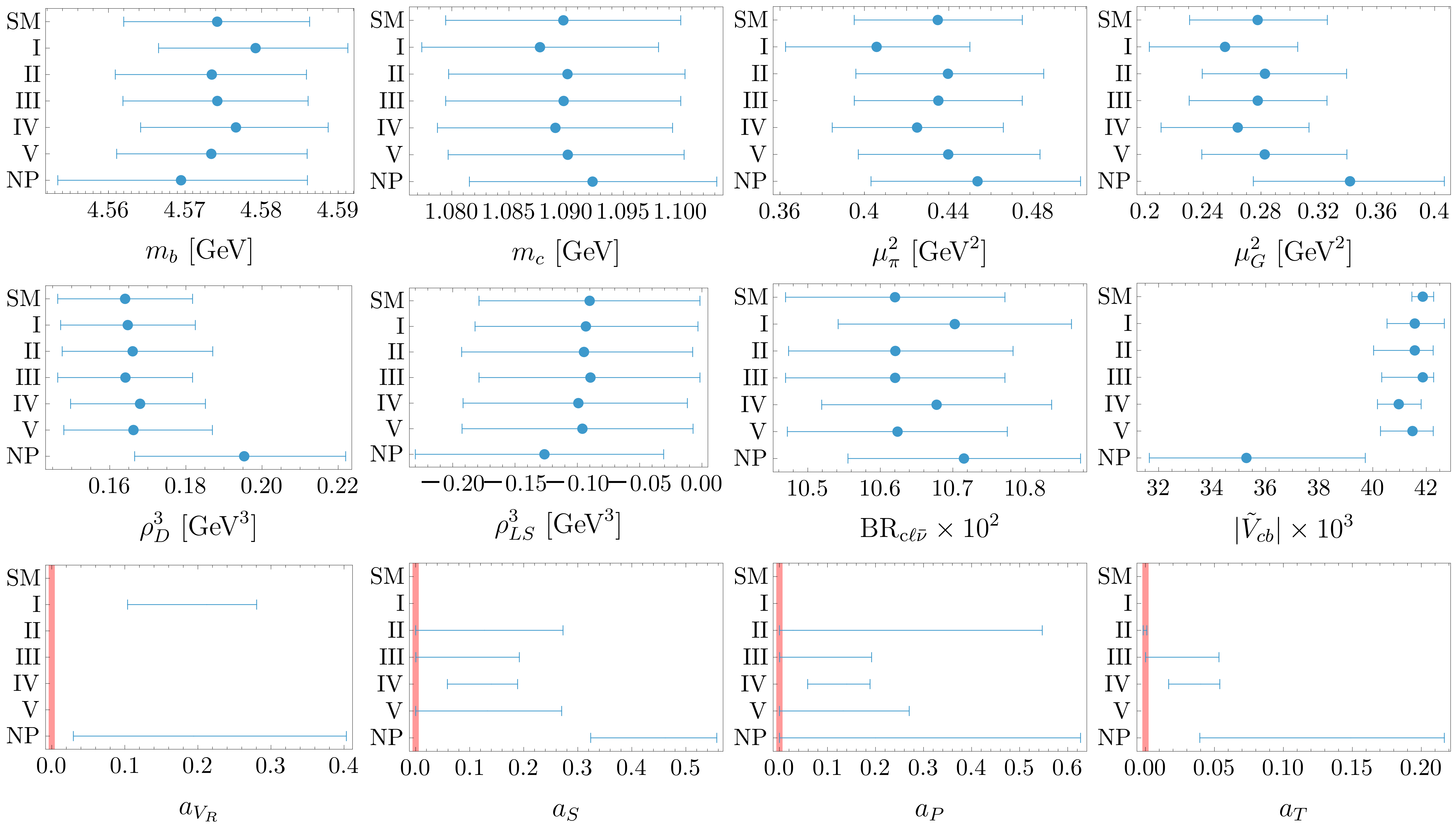
$(U_1, V_2) \rightarrow \{\hat{C}_{S_R}\}\,,$ (V)

	I	II	III	IV	V
C_{V_R}	$0.689[\hat{C}_{V_R}]_3$	0	0	0	0
C_S	0	$-0.57([\hat{C}_{S_L}]_3 + [\hat{C}_{S_R}]_3)$	$2.34[\hat{C}_T]_3$	$-2.18[\hat{C}_T]_3$	$-0.57[\hat{C}_{S_R}]_3$
C_P	0	$0.57([\hat{C}_{S_L}]_3 - [\hat{C}_{S_R}]_3)$	$-2.34[\hat{C}_T]_3$	$2.18[\hat{C}_T]_3$	$-0.57[\hat{C}_{S_R}]_3$
C_T	0	$0.003[\hat{C}_{S_L}]_3$	$-0.65[\hat{C}_T]_3$	$-0.63[\hat{C}_T]_3$	0

Fit Results

Legend:

- I - Vector-like quark (C_{V_R})
- II - Charged scalar (C_S, C_P)
- III - S_1 LQ ($C_T, C_{S_L} = -7C_T$)
- IV - R_2 LQ ($C_T, C_{S_L} = 7C_T$)
- V - U_1, V_2 LQ (C_{S_R})
- NP - All WCs
- 68% C.L. interval
- Best-fit point



Most distributions are non-Gaussian

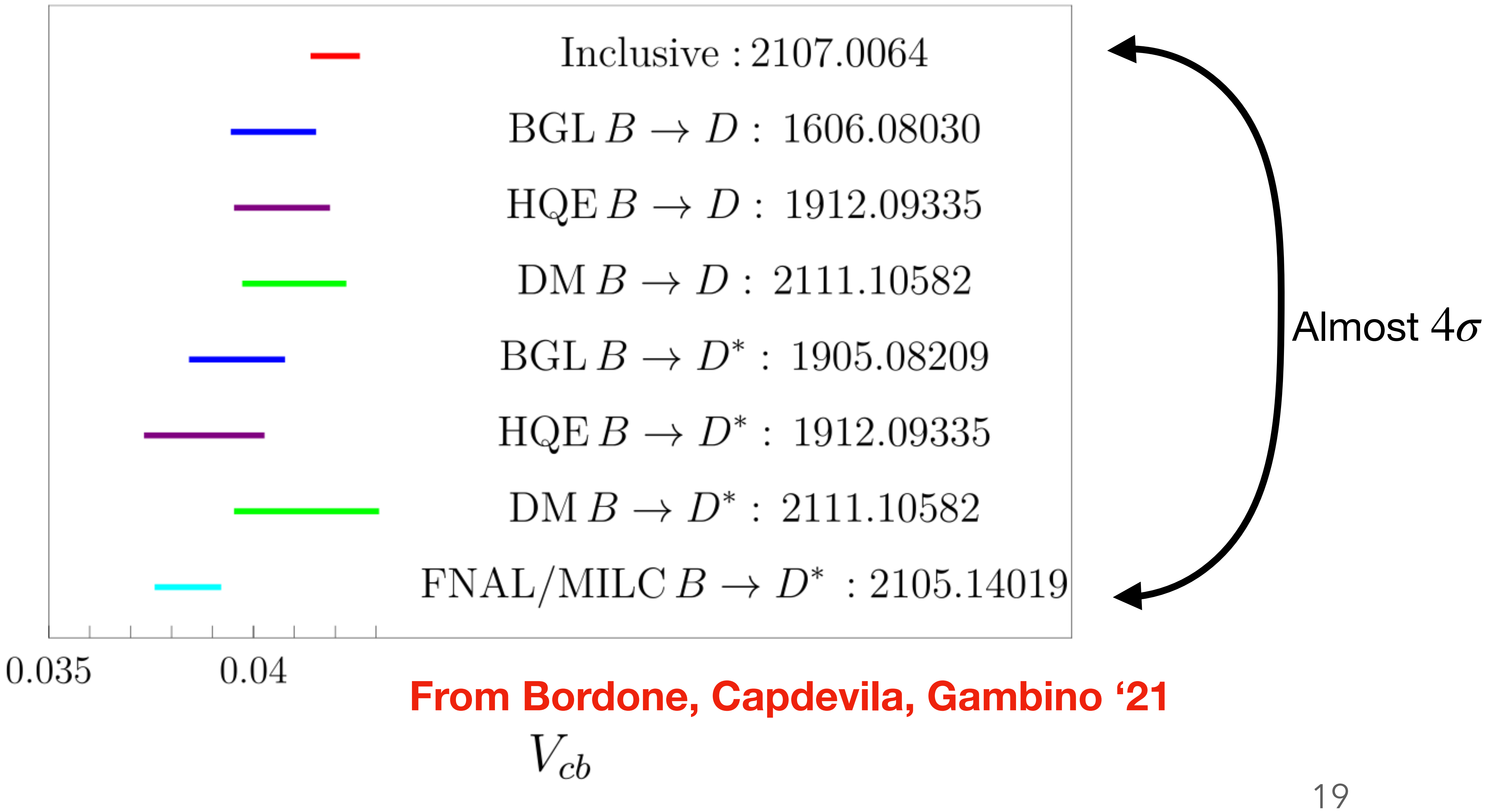
The Vcb Puzzle

Exclusive

$$|V_{cb}^{\mathrm{excl}}| = (39.62 \pm 0.47) \times 10^{-3}$$

Average by HFLAV 2023

Large variability between determinations using different channels, FF parameterization, lattice input, etc…

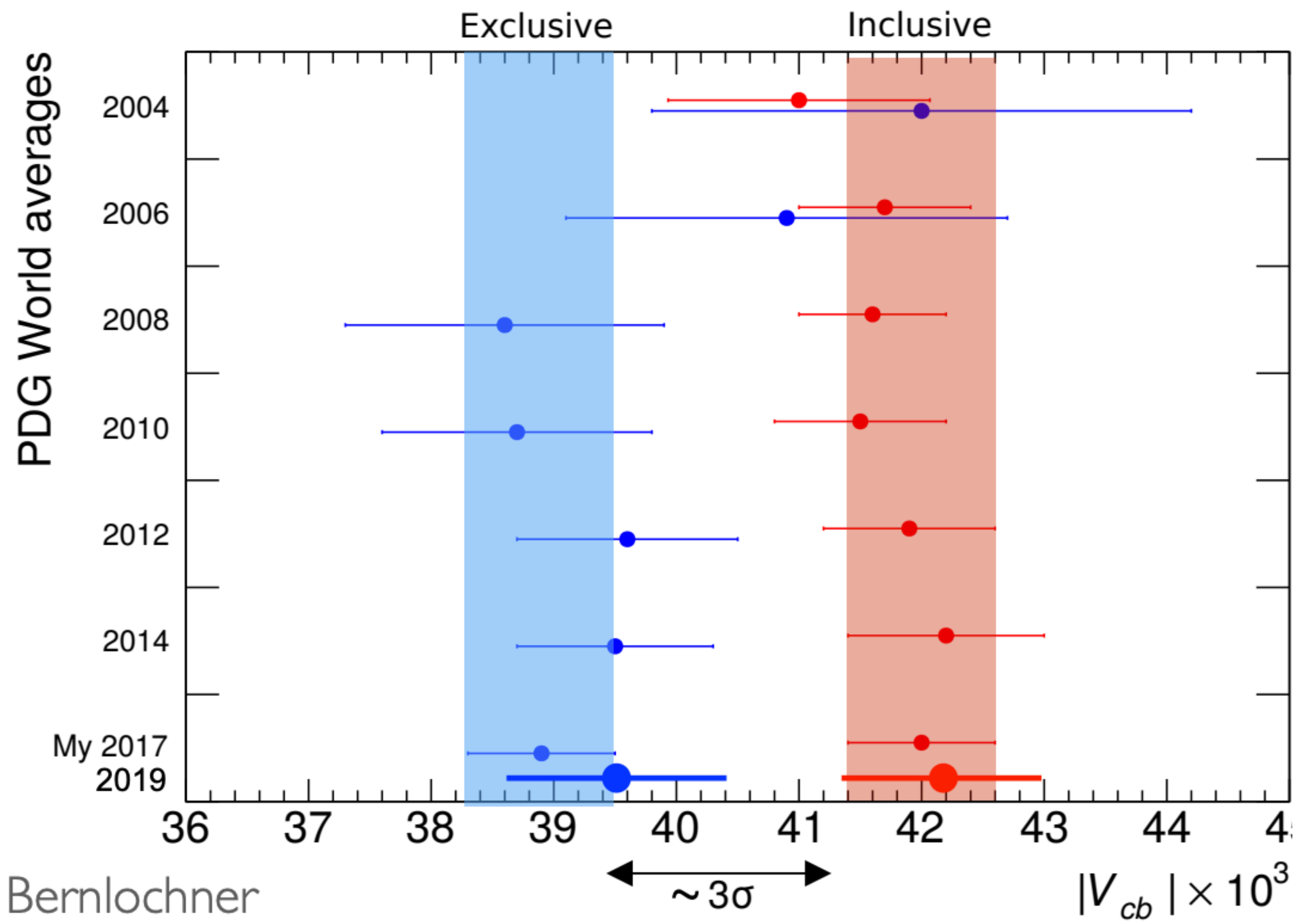


From Bordone, Capdevila, Gambino '21

Inclusive

$$|V_{cb}^{\mathrm{incl}}| = (41.97 \pm 0.48) \times 10^{-3}$$

Finauri Gambino '23



OPE of the forward scattering amplitude

$$T^{\mu\nu}(q) = \frac{i}{2m_B}\int d^4x e^{i(m_b v - q)\cdot x}\langle \bar{B}|\bar{b}_v(x)\gamma^\mu P_L S_{\rm BGF}(x,0)\gamma^\nu P_L b_v(0)|\bar{B}\rangle \,,$$

$$S_{\rm BGF}(x,0) = i\int \frac{d^4p}{(2\pi)^4}e^{-ip\cdot x}\frac{\not{p}+m_c}{p^2-m_c^2+i\eta}\sum_{n=0}^{\infty}(-1)^n\left[i\not{D}\frac{\not{p}+m_c}{p^2-m_c^2+i\eta}\right]^n .$$

D3 (exact)

$$\langle \bar{B}|\bar{b}\gamma^\mu b|\bar{B}\rangle = 2m_B v^\mu \,,$$

$$\langle \bar{B}|\bar{b}\gamma^\mu\gamma^5 b|\bar{B}\rangle = 0 \,,$$

D4

related to higher dimensional parameters through EOM

D5: 2 parameters

$$2m_B\mu_\pi^2 = -\langle \bar{B}|\bar{b}_v iD_\perp^\mu iD_{\perp\mu} b_v|\bar{B}\rangle \,,$$

$$2m_B\mu_G^2 = \frac{1}{2}\langle \bar{B}|\bar{b}_v[iD_\perp^\mu, iD_\perp^\nu](-i\sigma_{\mu\nu})b_v|\bar{B}\rangle$$

D6: 2 parameters

$$2m_B\rho_D^3 = \frac{1}{2}\langle \bar{B}|\bar{b}_v\left[iD_\perp^\mu,\left[iv\cdot D, iD_{\perp\mu}\right]\right]b_v|\bar{B}\rangle \,,$$

$$2m_B\rho_{LS}^3 = \frac{1}{2}\langle \bar{B}|\bar{b}_v\left\{iD_\perp^\mu,\left[iv\cdot D, iD_\perp^\nu\right]\right\}(-i\sigma_{\mu\nu})b_v|\bar{B}\rangle \,.$$

D7: 9 independent parameters

D8: 18 (!)

Mannel,Turczyk,Uraltsev 2010
Mannel,Milutin,Vos 2023
Finauri 2025

Only 4 unknown HQE ME at order Λ_{QCD}^3/m_b^3 !

Why is the error on $\tilde{V}_{cb}$ so large?

Here we take:

$m_b^{\rm kin}(\mu_k)$	4.573 GeV
$\overline{m}_c(\mu_c)$	1.090 GeV
$\mu_\pi^2(\mu_k)$	0.454 GeV^2
$\mu_G^2(\mu_k)$	0.288 GeV^2
$\rho_D^3(\mu_k)$	0.176 GeV^3
$\rho_{LS}^3(\mu_k)$	-0.113 GeV^3

The predictions for each observables can be written as a quartic polynomial in NP WC:

$$\xi = \xi_{\rm SM} + a_{V_R} c(\delta_{V_R})\xi_{LR} + a_{V_R}^2\xi_{RR} + a_S^2\xi_{SS} + a_P^2\xi_{PP} + a_T^2\xi_{TT} + a_{V_R}^2 c(\delta_{V_R})^2\xi_{LR^2} + a_S a_T c(\delta_S)\xi_{ST} + a_P a_T c(\delta_P)\xi_{PT}\,,$$

Total decay rate

	$10\times\Gamma/\Gamma_0$
$\tilde{\Gamma}_{SM}$	$6.580 - 0.461_{\rm pow} - 0.560_{\alpha_s} - 0.009_{\alpha_s/m_b^2} - 0.034_{\alpha_s/m_b^3} - 0.105_{\alpha_s^2} + 0.003_{\alpha_s^3}$
$\tilde{\Gamma}_{RR}$	$6.580 - 0.461_{\rm pow} - 0.560_{\alpha_s}$
$\tilde{\Gamma}_{LR}$	$-4.280 + 0.634_{\rm pow} + 0.464_{\alpha_s}$
$\tilde{\Gamma}_{TT}$	$78.964 - 7.865_{\rm pow}$
$\tilde{\Gamma}_{SS}$	$5.430 + 0.240_{\rm pow}$
$\tilde{\Gamma}_{PP}$	$1.150 - 0.118_{\rm pow}$

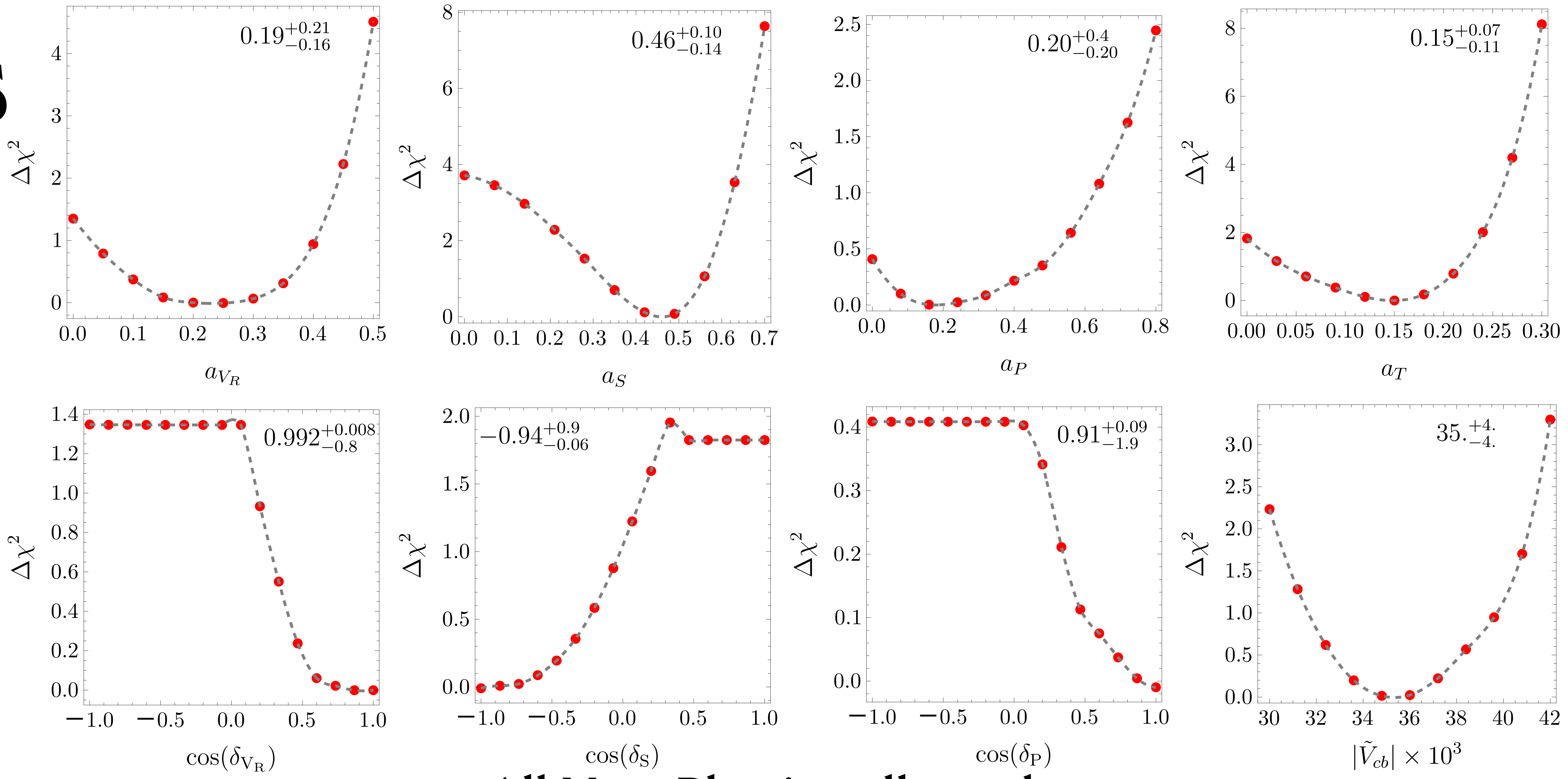
$< E_\ell >$ with $E_\ell^{cut} = 1$ GeV

	L_1 $[10^{-2}$ GeV$]$
ξ_{SM}	$157.276 - 1.676_{\rm pow} - 0.312_{\alpha_s} - 0.463_{\frac{\alpha_s}{m_b^2}} + 0.084_{\alpha_s^2}$
ξ_{RR}	$-9.760 + 1.114_{\rm pow} + 0.208_{\alpha_s}$
ξ_{LR}	$-0.368 + 0.606_{\rm pow} - 0.197_{\alpha_s}$
ξ_{LR^2}	$-0.247 + 0.427_{\rm pow} - 0.128_{\alpha_s}$
ξ_{TT}	$-78.076 + 9.286_{\rm pow}$
ξ_{SS}	$0.184 + 3.006_{\rm pow}$
ξ_{PP}	$-0.184 + 0.191_{\rm pow}$
ξ_{ST}	$-19.519 - 2.147_{\rm pow}$
ξ_{PT}	$19.519 - 0.025_{\rm pow}$

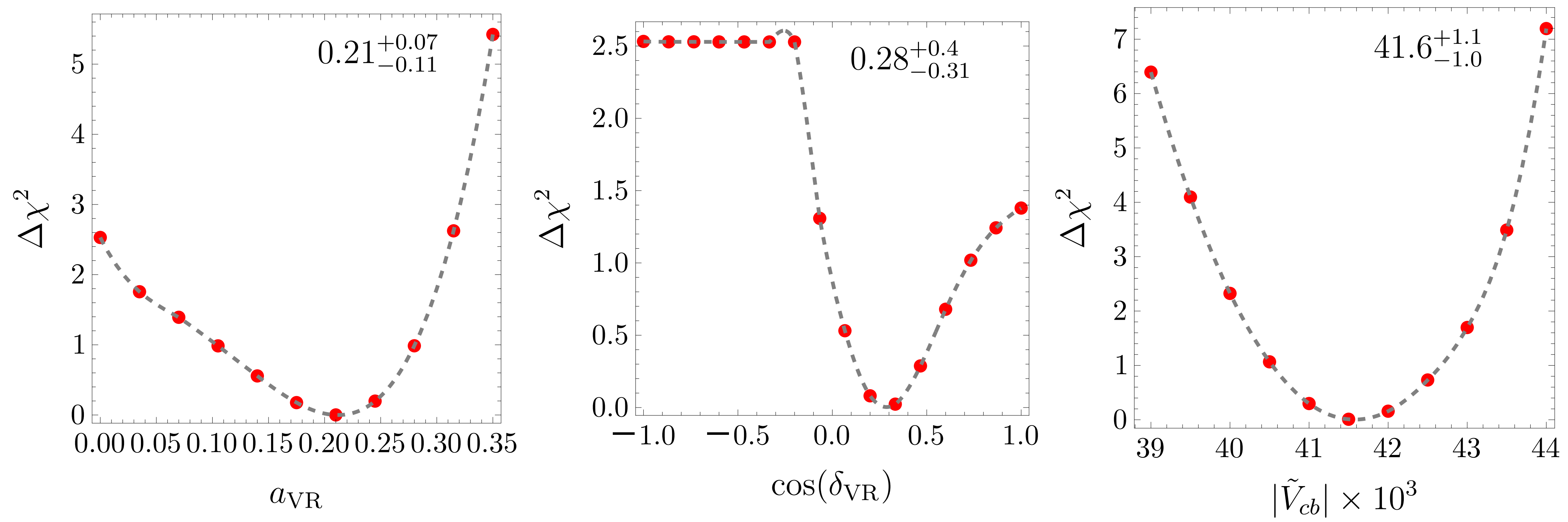
« Flat direction » in the fit for $a_S \sim 3a_T$ and $c(\delta_S) = -1$ which allow for large shifts in a_S, a_T and $|\tilde{V}_{cb}|$
$a_P \sim 3a_T$ $\quad c(\delta_P) = 1$ $\quad a_P$

1D profile likelihoods

- 1D profile likelihoods of WCs are non-Gaussian
- E.g. a_S (a_{V_R}) is compatible with 0 at the 2σ level in 'NP' (I),
- $|\tilde{V}_{cb}|$ is moderately affected in single mediator models
- Only scenario I (slightly) prefers a complex NP WC (C_{V_R})



All New Physics allowed



Scenario I

Numerical Results

$$\xi = \xi_{\text{SM}} + a_R \cos(\delta_R)\xi_{LR} + a_R^2\left(\xi_{RR} + \cos(\delta_R)^2\xi_{LR^2}\right) + a_S^2\xi_{SS} + a_P^2\xi_{PP}$$
$$+ a_T^2\xi_{TT} + a_S a_T \cos(\delta_{ST})\xi_{ST} + a_P a_T \cos(\delta_{PT})\xi_{PT} \,.$$

$$\xi = \{R^*, L_n, H_n, Q_n\}$$

	L_1 $[10^{-2}$ GeV$]$			L_2 $[10^{-2}$ GeV$^2]$			L_3 $[10^{-3}$ GeV$^3]$		
ξ_{SM}	157.276	-1.676_{pow}	-0.312_{α_s}	8.726	$+0.279_{\text{pow}}$	-0.034_{α_s}	-3.096	$+3.201_{\text{pow}}$	$+0.986_{\alpha_s}$
		$-0.463_{\frac{\alpha_s}{m_b^2}}$	$+0.084_{\alpha_s^2}$		$-0.192_{\frac{\alpha_s}{m_b^2}}$	$+0.057_{\alpha_s^2}$		$-0.364_{\frac{\alpha_s}{m_b^2}}$	$+0.672_{\alpha_s^2}$
ξ_{RR}	-9.760	$+1.114_{\text{pow}}$	$+0.208_{\alpha_s}$	0.004	-0.287_{pow}	$+0.021_{\alpha_s}$	9.004	-1.541_{pow}	-0.431_{α_s}
ξ_{LR}	-0.368	$+0.606_{\text{pow}}$	-0.197_{α_s}	0.279	$+0.105_{\text{pow}}$	-0.013_{α_s}	0.576	$+0.235_{\text{pow}}$	$+0.047_{\alpha_s}$
ξ_{LR^2}	-0.247	$+0.427_{\text{pow}}$	-0.128_{α_s}	0.186	$+0.060_{\text{pow}}$	-0.013_{α_s}	0.418	$+0.087_{\text{pow}}$	$+0.040_{\alpha_s}$
ξ_{TT}	-78.076	$+9.286_{\text{pow}}$	$+1.044_{\alpha_s}$	0.033	-1.071_{pow}	$+0.163_{\alpha_s}$	72.030	-6.863_{pow}	-3.405_{α_s}
ξ_{SS}	0.184	$+3.006_{\text{pow}}$	$+0.096_{\alpha_s}$	-0.139	$+0.471_{\text{pow}}$	-0.015_{α_s}	-0.288	-2.420_{pow}	$+0.026_{\alpha_s}$
ξ_{PP}	-0.184	$+0.191_{\text{pow}}$	$+0.288_{\alpha_s}$	0.139	$+0.030_{\text{pow}}$	$+0.051_{\alpha_s}$	0.288	-0.169_{pow}	-0.172_{α_s}
ξ_{ST}	-19.519	-2.147_{pow}	-1.332_{α_s}	0.008	-1.988_{pow}	$+0.039_{\alpha_s}$	18.007	-3.218_{pow}	$+0.767_{\alpha_s}$
ξ_{PT}	19.519	-0.025_{pow}	$+1.332_{\alpha_s}$	-0.008	$+0.776_{\text{pow}}$	-0.039_{α_s}	-18.007	$+0.502_{\text{pow}}$	-0.767_{α_s}

Table 1: Lepton energy moments with $E_{\ell\text{cut}} = 1$ GeV.

Numerical Results

$$\xi = \xi_{\rm SM} + a_R \cos(\delta_R)\xi_{LR} + a_R^2\left(\xi_{RR} + \cos(\delta_R)^2\xi_{LR^2}\right) + a_S^2\xi_{SS} + a_P^2\xi_{PP} + a_T^2\xi_{TT} + a_S a_T \cos(\delta_{ST})\xi_{ST} + a_P a_T \cos(\delta_{PT})\xi_{PT} \,.$$

$$\xi = \{R^*, L_n, H_n, Q_n\}$$

	H_1 $[10^{-1}$ GeV$^2]$			H_2 $[10^{-1}$ GeV$^4]$			H_3 $[10^{-1}$ GeV$^6]$		
ξ_{SM}	42.959	$+0.031_{\rm pow}$ $+0.418_{\frac{\alpha_s}{m_b^2}}$	$+0.491_{\alpha_s}$ $-0.113_{\alpha_s^2}$	2.236	$+7.089_{\rm pow}$ $-1.146_{\frac{\alpha_s}{m_b^2}}$	$+2.043_{\alpha_s}$ $+1.066_{\alpha_s^2}$	-0.213	$+47.209_{\rm pow}$ $-4.032_{\frac{\alpha_s}{m_b^2}}$	-3.632_{α_s} $-3.975_{\alpha_s^2}$
ξ_{RR}	-0.213	$-0.085_{\rm pow}$	-0.052_{α_s}	0.146	$-1.072_{\rm pow}$	-0.054_{α_s}	0.059	$-0.499_{\rm pow}$	-0.491_{α_s}
ξ_{LR}	2.135	$-2.023_{\rm pow}$	$+0.019_{\alpha_s}$	-0.365	$+5.087_{\rm pow}$	$+0.011_{\alpha_s}$	-0.405	$+8.232_{\rm pow}$	-0.395_{α_s}
ξ_{LR^2}	1.434	$-1.477_{\rm pow}$	-0.011_{α_s}	-0.701	$+4.301_{\rm pow}$	$+0.003_{\alpha_s}$	-0.038	$+2.071_{\rm pow}$	-0.266_{α_s}
ξ_{TT}	7.917	$+6.888_{\rm pow}$	$+0.134_{\alpha_s}$	0.492	$+12.225_{\rm pow}$	$+0.697_{\alpha_s}$	-1.625	$+37.872_{\rm pow}$	$+1.442_{\alpha_s}$
ξ_{SS}	-2.271	$-2.994_{\rm pow}$	-0.501_{α_s}	0.267	$-2.385_{\rm pow}$	-0.255_{α_s}	0.464	$-9.426_{\rm pow}$	-1.363_{α_s}
ξ_{PP}	-0.136	$+0.021_{\rm pow}$	-0.339_{α_s}	-0.098	$-0.793_{\rm pow}$	-0.732_{α_s}	0.059	$-1.135_{\rm pow}$	-2.430_{α_s}
ξ_{ST}	-0.427	$+0.542_{\rm pow}$	-0.123_{α_s}	0.292	$-2.504_{\rm pow}$	-0.003_{α_s}	0.117	$-1.537_{\rm pow}$	-0.535_{α_s}
ξ_{PT}	0.427	$-0.258_{\rm pow}$	$+0.123_{\alpha_s}$	-0.292	$+1.367_{\rm pow}$	$+0.003_{\alpha_s}$	-0.117	$+0.863_{\rm pow}$	$+0.535_{\alpha_s}$

Table 2: Hadronic mass moments with $E_{\ell{\rm cut}} = 1$ GeV.

Numerical Results

$$\xi = \xi_{\rm SM} + a_R \cos(\delta_R)\xi_{LR} + a_R^2\big(\xi_{RR} + \cos(\delta_R)^2\xi_{LR^2}\big) + a_S^2\xi_{SS} + a_P^2\xi_{PP}$$
$$+ a_T^2\xi_{TT} + a_S a_T \cos(\delta_{ST})\xi_{ST} + a_P a_T \cos(\delta_{PT})\xi_{PT}\,.$$

$$\xi = \{R^*, L_n, H_n, Q_n\}$$

	Q_1 [GeV^2]			Q_2 [GeV^4]			Q_3 [GeV^6]		
ξ_{SM}	7.077	$-0.425_{\rm pow}$	$+0.012_{\alpha_s}$	4.293	$-1.639_{\rm pow}$	$+0.060_{\alpha_s}$	3.795	$-4.475_{\rm pow}$	$+0.477_{\alpha_s}$
	$-0.028_{\frac{\alpha_s}{m_b^2}}$	$-0.024_{\frac{\alpha_s}{m_b^3}}$	$+0.041_{\alpha_s^2}$	$-0.050_{\frac{\alpha_s}{m_b^2}}$	$-0.041_{\frac{\alpha_s}{m_b^3}}$	$+0.168_{\alpha_s^2}$	$+0.040_{\frac{\alpha_s}{m_b^2}}$	$+0.177_{\frac{\alpha_s}{m_b^3}}$	$+0.578_{\alpha_s^2}$
ξ_{LR}	-0.693	$+0.101_{\rm pow}$	$+0.006_{\alpha_s}$	-0.769	$+0.233_{\rm pow}$	$+0.092_{\alpha_s}$	2.117	$-0.768_{\rm pow}$	$+0.165_{\alpha_s}$
ξ_{LR^2}	-0.681	$+0.129_{\rm pow}$	$+0.008_{\alpha_s}$	-1.236	$+0.402_{\rm pow}$	$+0.101_{\alpha_s}$	0.481	$-0.129_{\rm pow}$	$+0.360_{\alpha_s}$
ξ_{TT}	-2.179	$+0.484_{\rm pow}$	$+0.036_{\alpha_s}$	-1.598	$+1.228_{\rm pow}$	-0.019_{α_s}	8.239	$-1.608_{\rm pow}$	-0.696_{α_s}
ξ_{SS}	0.619	$+0.677_{\rm pow}$	$+0.104_{\alpha_s}$	0.584	$+2.189_{\rm pow}$	$+0.091_{\alpha_s}$	-2.088	$+4.671_{\rm pow}$	-0.280_{α_s}
ξ_{PP}	-0.074	$+0.004_{\rm pow}$	$+0.000_{\alpha_s}$	-0.185	$+0.029_{\rm pow}$	$+0.058_{\alpha_s}$	0.028	$-0.018_{\rm pow}$	$+0.162_{\alpha_s}$

Table 3: q^2 moments with $q^2_{\rm cut} = 4$ GeV^2. We have omitted the lines for $\xi_{RR} = \xi_{ST} = \xi_{PT} = 0$.

Numerical Results

$$\xi = \xi_{\text{SM}} + a_R \cos(\delta_R)\xi_{LR} + a_R^2\left(\xi_{RR} + \cos(\delta_R)^2\xi_{LR^2}\right) + a_S^2\xi_{SS} + a_P^2\xi_{PP} + a_T^2\xi_{TT} + a_S a_T \cos(\delta_{ST})\xi_{ST} + a_P a_T \cos(\delta_{PT})\xi_{PT}\,.$$

$$\xi = \{R^*, L_n, H_n, Q_n\}$$

	$10 \times R^*$			
ξ_{SM}	8.175	-0.125_{pow}	-0.001_{α_s}	$-0.016_{\alpha_s/m_b^2} - 0.004_{\alpha_s^2}$
ξ_{RR}	-1.039	$+0.020_{\text{pow}}$	$+0.003_{\alpha_s}$	
ξ_{LR}	-0.174	$+0.038_{\text{pow}}$	-0.033_{α_s}	
ξ_{LR^2}	-0.113	$+0.033_{\text{pow}}$	-0.019_{α_s}	
ξ_{TT}	-8.316	$+0.024_{\text{pow}}$	-0.149_{α_s}	
ξ_{SS}	0.087	$+0.150_{\text{pow}}$	$+0.038_{\alpha_s}$	
ξ_{PP}	-0.087	-0.002_{pow}	$+0.005_{\alpha_s}$	
ξ_{ST}	-2.079	-0.081_{pow}	-0.172_{α_s}	
ξ_{PT}	2.079	$+0.063_{\text{pow}}$	$+0.172_{\alpha_s}$	

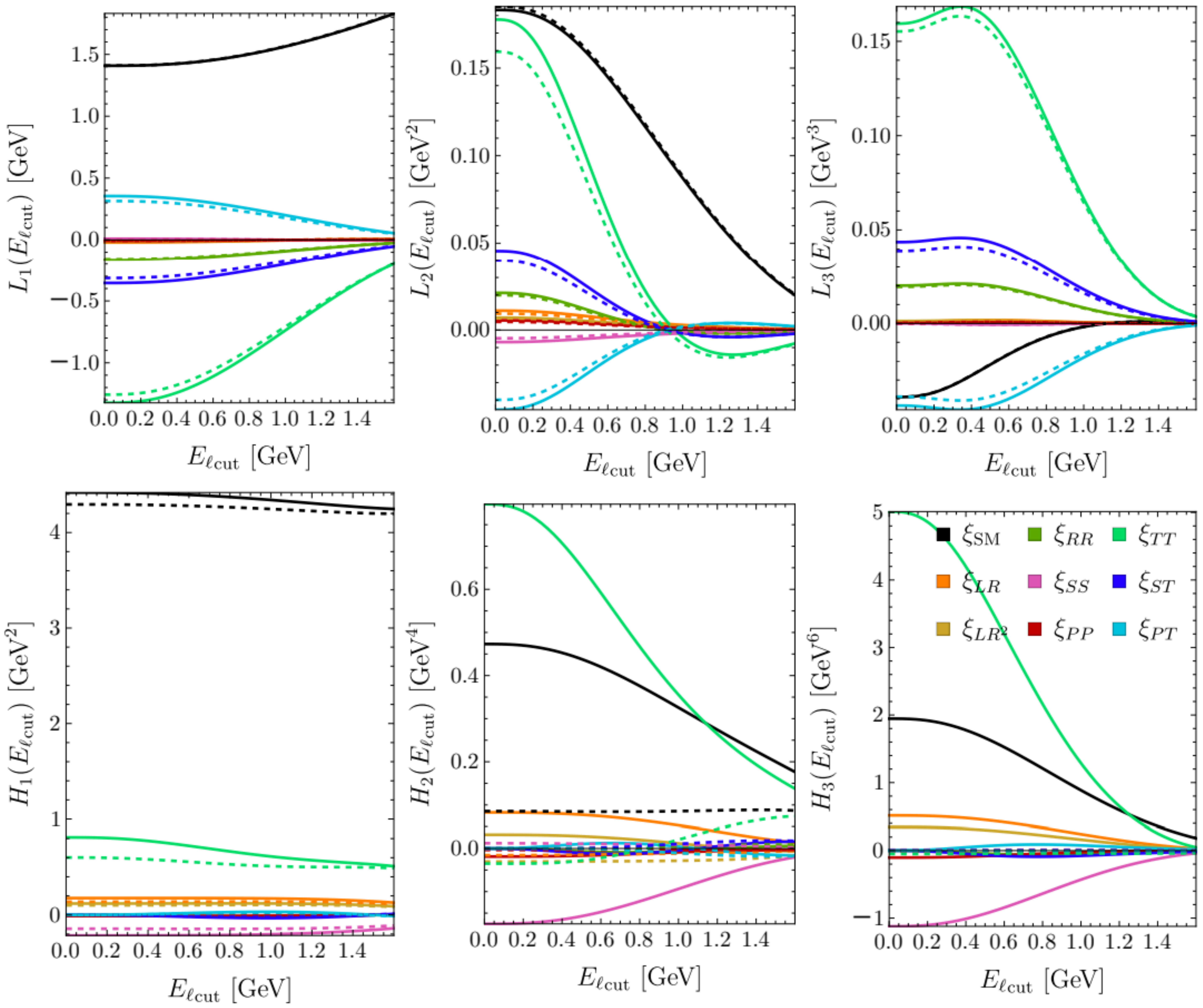
Table 4: R^* with $E_{\ell\text{cut}} = 1$ GeV.

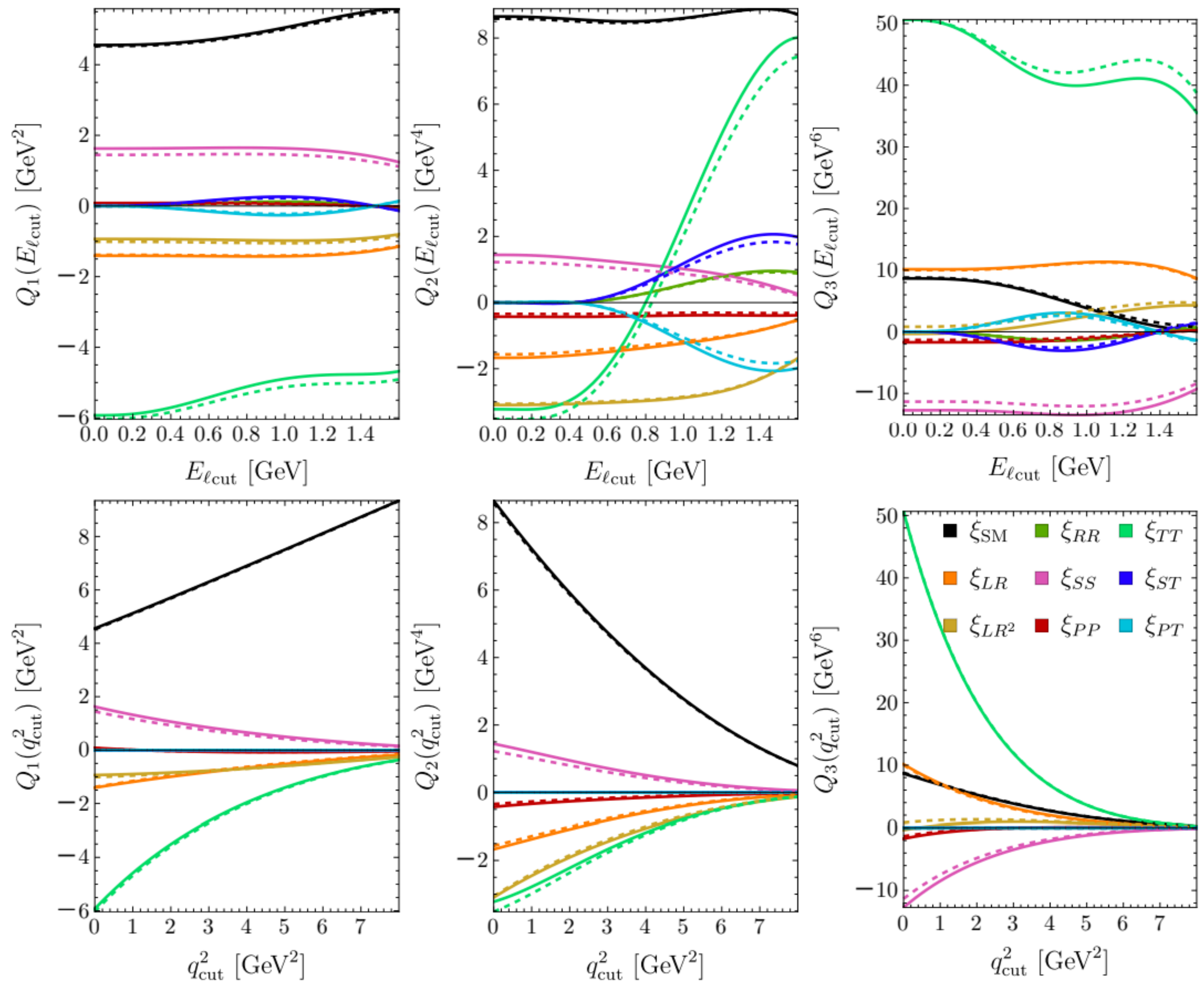
Numerical Results

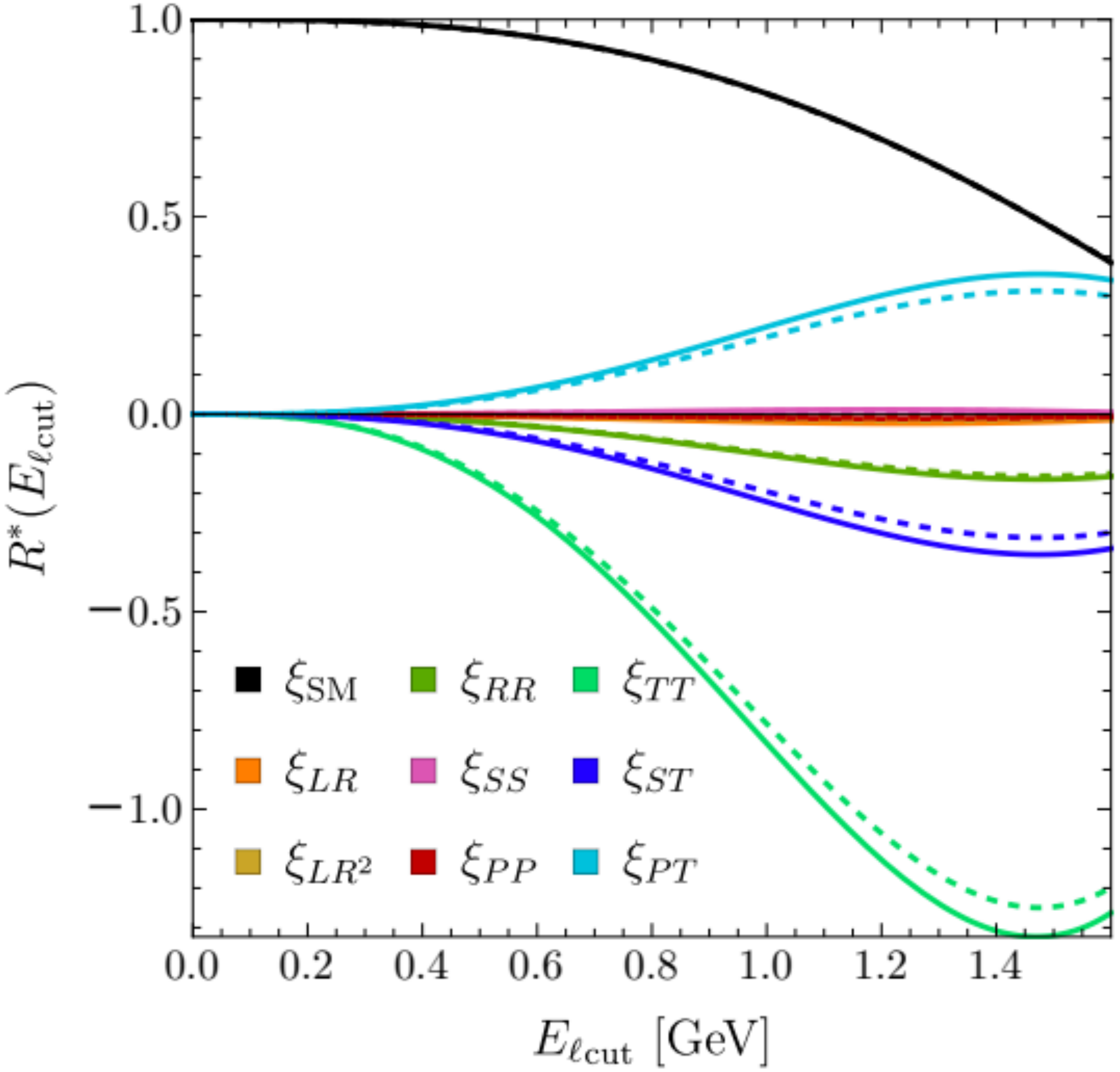
$$\Gamma = \Gamma_0 \left(\zeta_{\rm SM} + a_R \cos(\delta_R) \zeta_{LR} + a_R^2 \zeta_{RR} + a_S^2 \zeta_{SS} + a_P^2 \zeta_{PP} + a_T^2 \zeta_{TT} \right)$$

	$10 \times \Gamma/\Gamma_0$			
ζ_{SM}	6.580	$-0.461_{\rm pow}$	-0.560_{α_s}	$-0.009_{\alpha_s/m_b^2} - 0.034_{\alpha_s/m_b^3} - 0.105_{\alpha_s^2} + 0.003_{\alpha_s^3} + 0.058_{\alpha_{\rm em}}$
ζ_{RR}	6.580	$-0.461_{\rm pow}$	-0.560_{α_s}	
ζ_{LR}	-4.280	$+0.634_{\rm pow}$	$+0.464_{\alpha_s}$	
ζ_{TT}	78.964	$-7.865_{\rm pow}$	-5.694_{α_s}	
ζ_{SS}	5.430	$+0.240_{\rm pow}$	$+0.354_{\alpha_s}$	
ζ_{PP}	1.150	$-0.118_{\rm pow}$	-0.276_{α_s}	

Table 5: Inclusive semileptonic decay width Γ.


$L_1(E_{\ell\text{cut}})$ [GeV]
$L_2(E_{\ell\text{cut}})$ [GeV^2]
$L_3(E_{\ell\text{cut}})$ [GeV^3]
$H_1(E_{\ell\text{cut}})$ [GeV^2]
$H_2(E_{\ell\text{cut}})$ [GeV^4]
$H_3(E_{\ell\text{cut}})$ [GeV^6]
$E_{\ell\text{cut}}$ [GeV]
ξ_{SM} ξ_{RR} ξ_{TT}
ξ_{LR} ξ_{SS} ξ_{ST}
ξ_{LR^2} ξ_{PP} ξ_{PT}


$Q_1(E_{\ell\mathrm{cut}})$ [GeV^2]
$Q_2(E_{\ell\mathrm{cut}})$ [GeV^4]
$Q_3(E_{\ell\mathrm{cut}})$ [GeV^6]
$E_{\ell\mathrm{cut}}$ [GeV]
$Q_1(q^2_{\mathrm{cut}})$ [GeV^2]
$Q_2(q^2_{\mathrm{cut}})$ [GeV^4]
$Q_3(q^2_{\mathrm{cut}})$ [GeV^6]
q^2_{cut} [GeV^2]
ξ_{SM} ξ_{RR} ξ_{TT}
ξ_{LR} ξ_{SS} ξ_{ST}
ξ_{LR^2} ξ_{PP} ξ_{PT}



1.0
0.5
0.0
−0.5
−1.0
$R^*(E_{\ell\mathrm{cut}})$
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
$E_{\ell\mathrm{cut}}$ [GeV]
ξ_{SM} ξ_{RR} ξ_{TT}
ξ_{LR} ξ_{SS} ξ_{ST}
ξ_{LR^2} ξ_{PP} ξ_{PT}