UNIVERSITÀ DI TORINO

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

***Semileptonic B decays at the junction of experiment and theory* workshop**

**12/06/2025 - Turin**

Based on 250x.xxxx, AC, G. Finauri, P. Gambino, M. Jung

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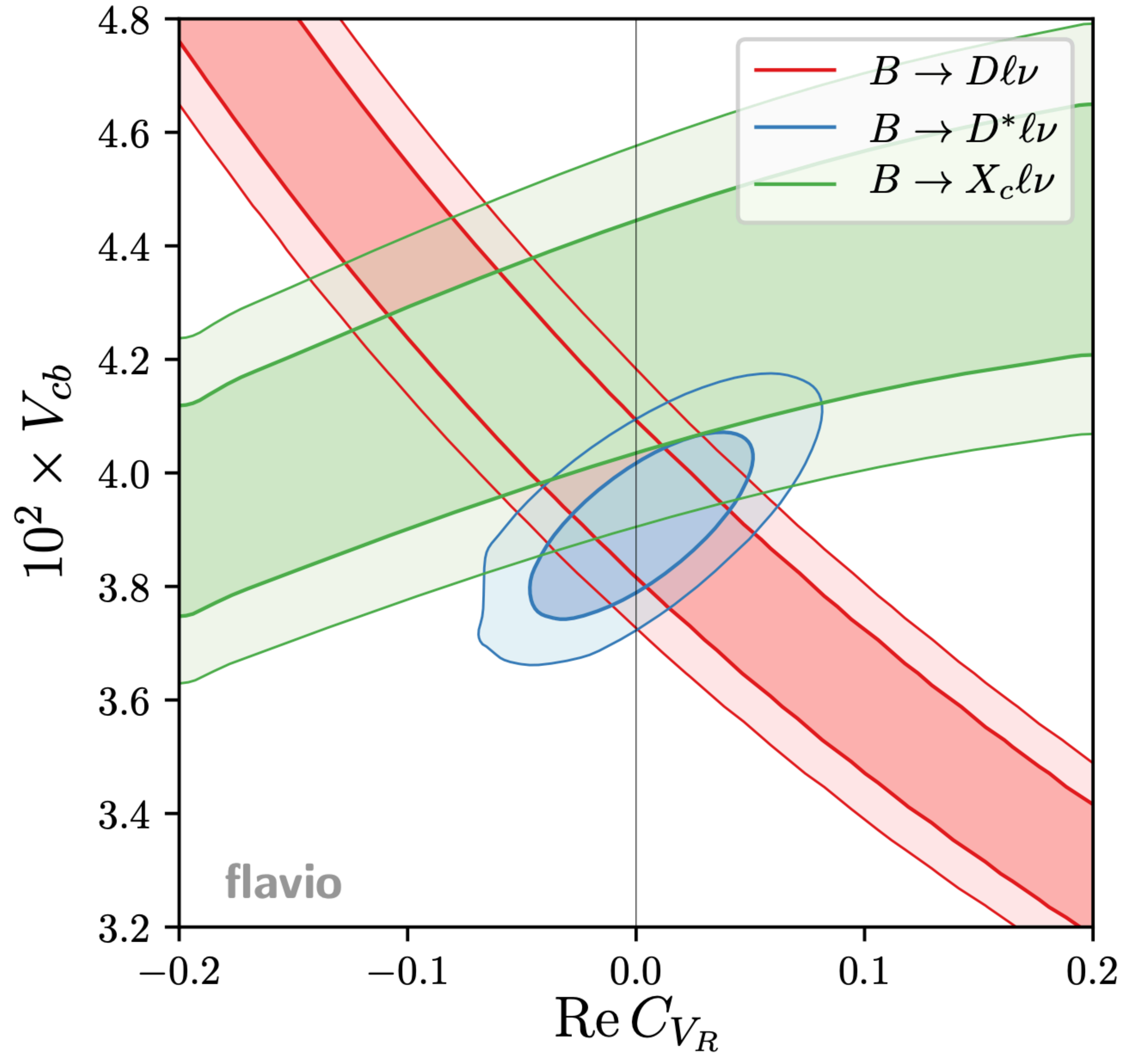
# Why look for New Physics in $B \to X_c \ell \bar{\nu}$?

- There are ***still*** anomalies in some semileptonic $B$ decays, e.g. $BR(B \to K\ell\ell)$, $R(D^{(*)})$,($\Delta A_{FB}$?)
- Can the $V_{cb}$ puzzle in exclusive vs inclusive $b \to c\ell\bar{\nu}$ ($\ell = e, \mu$) be explained by NP? [Crivellin et al. 1407.1320]
- Observables in inclusive decays provide complementary information to exclusive decays
- Measurements of inclusive $B \to X_c \ell \bar{\nu}$ observables use different analysis techniques from exclusive decays.




M. Jung, D. Straub (1801.01112)

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

**See Gael's talk**

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

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

- Successfully describes the experimental data $\chi^2/\mathrm{dof} = 42.58/74$: no hint of NP
- Determination of HQE matrix elements and $V_{cb}$ at high precision level ( $\sim 1\,\%$ )
- Based solely on an OPE, no knowledge of the form factors is needed

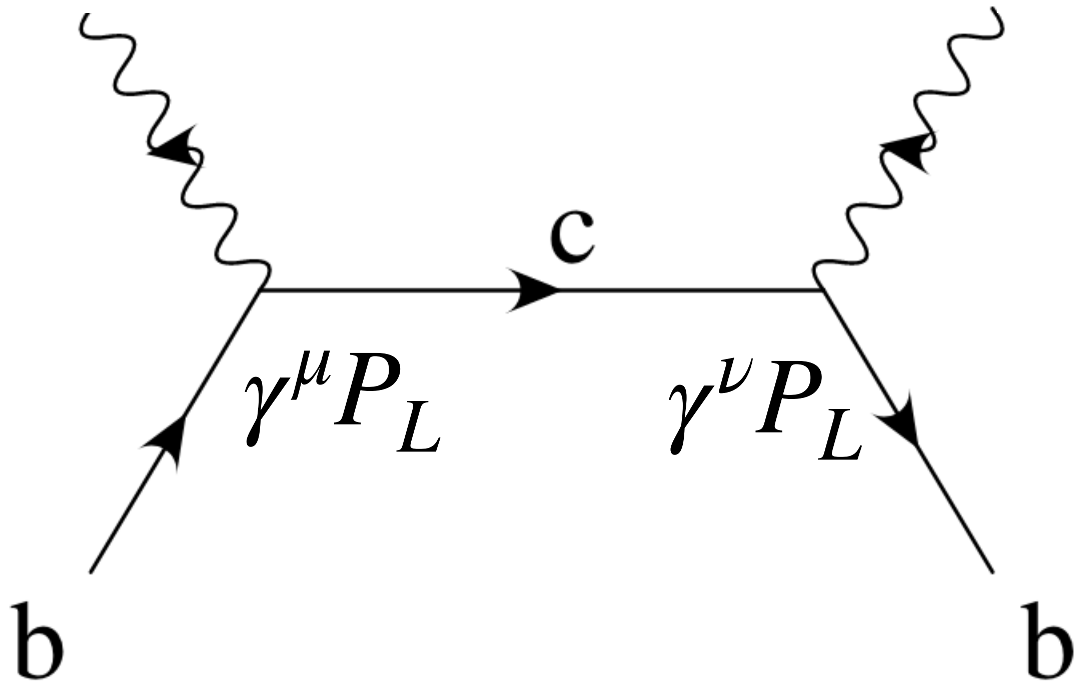
$$L_{\mu\nu} \propto \sum_{\text{spins}} \langle \bar{\nu}_\ell \ell | J_{\mu,\ell} | 0 \rangle \langle \bar{\nu}_\ell \ell | J_{\nu,\ell} | 0 \rangle^\dagger$$ known exactly

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

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

$$2m_B T^{\mu\nu} = -i \int d^4x e^{-iqx} \langle \bar{B} | T\left[ J_q^\nu(x)^\dagger J_q^\mu(0) \right] | \bar{B} \rangle$$ calculable via OPE:

$T^{\mu\nu} =$




$+\mathcal{O}(\alpha_s)$

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

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

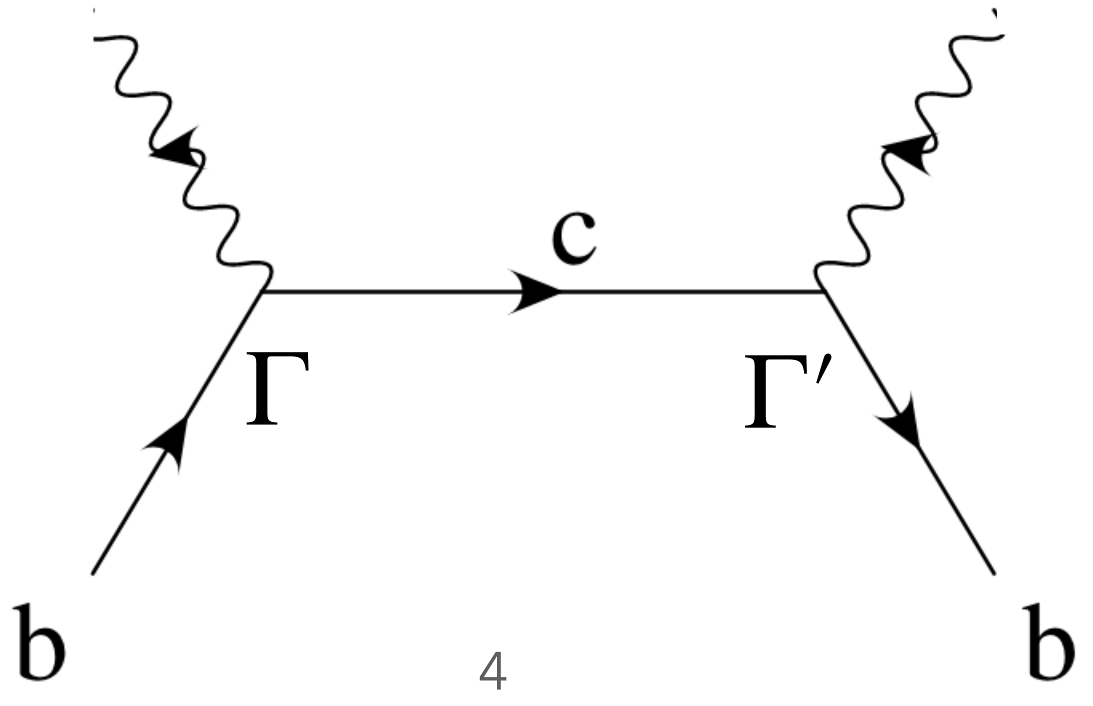
$$H_W^{NP} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[ (1 + C_{VL})[\bar{c}\gamma^\mu P_L b][\bar{\ell}\gamma_\mu P_L \nu_\ell] + C_{V_R}[\bar{c}\gamma^\mu P_R b][\bar{\ell}\gamma_\mu P_L \nu_\ell] + C_T[\bar{c}\sigma^{\mu\nu} P_L b][\bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell]$$

$$+ C_S[\bar{c}b][\bar{\ell} P_L \nu_\ell] + C_P[\bar{c}\gamma_5 b][\bar{\ell} P_L \nu_\ell] \Big] \qquad \tilde{V}_{cb} \equiv V_{cb}(1 + C_{VL}),\ \tilde{C}_X \equiv C_X/(1 + C_{V_L})$$

- 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

- Schematically, the result of the OPE looks like:

$$\frac{d\Gamma(B \to X_c \ell \bar{\nu})}{dq^2 dE_\nu dE_\ell} \propto \sum_{\Gamma,\Gamma'} W_{\Gamma\Gamma'} L_{\Gamma\Gamma'}$$

$$\begin{aligned} W_{\Gamma\Gamma'} = \frac{C_\Gamma C^*_{\Gamma'}}{m_b}\Big[ & (\ldots) + (\ldots)\frac{\mu_\pi^2}{m_b^2} + (\ldots)\frac{\mu_G^2}{m_b^2} + (\ldots)\frac{\rho_D^3}{m_b^3} + (\ldots)\frac{\rho_{LS}^3}{m_b^3} + \ldots \\ & \alpha_s\big[(\ldots) + (\ldots)\frac{\mu_\pi^2}{m_b^2} + \ldots\big] + \\ & \alpha_s^2[\ldots] + \ldots \Big] \end{aligned}$$

- The SM only interferes with $C_{VR}$: only NP that contributes linearly to $d\Gamma$
- We work with the following power counting: $C_\Gamma^i \times \alpha_s^j$, $i + j \leq 2$ and up to order $\frac{1}{m_b^3}$
  - SM : $\mathcal{O}(1/m_b^3) + \mathcal{O}(\alpha_s/m_b^2) + \mathcal{O}(\alpha_s^2)$, for $\Gamma_{tot}$ : $\mathcal{O}(1/m_b^3) + \mathcal{O}(\alpha_s/m_b^3) + \mathcal{O}(\alpha_s^3)$ (See Gael's Talk)
  - $C_{V_R}$ : $\mathcal{O}(1/m_b^3) + \mathcal{O}(\alpha_s)$ [Blok et al. 9307247],[Manohar et al. 9308246],[Feger et al. 1003.4022], [Kamali 1811.07393]
  - Other NP : $\mathcal{O}(1/m_b^3)$ [Grossman et al. 9403376],[Colangelo et al. 1611.07387],[Fael et al. 2208.04282]

# Fit setup

- Observables: $E_\ell, q^2, m_X^2$ moments (1st,2nd and 3rd), $\Gamma(E_\ell^{cut})$, and $\Gamma_{\text{tot}}$ to extract $\tilde{V}_{cb}$
- Up-to-date dataset (see Finauri et Gambino 2310.20324)
- 14 free parameters in the fit:
  - $\text{BR}_{c\ell\bar{\nu}}$
  - Quark masses: $m_b, m_c$
  - HQE matrix elements: $\mu_\pi^2, \mu_G^2, \rho_{LS}^3, \rho_D^3$
  - NP Wilson coefficients: $a_{V_R}, a_T, a_P, a_S, c(\delta_{V_R}), c(\delta_S), c(\delta_P)$
- **This is the first global fit for inclusive B decays with New Physics**

$$\frac{C_X}{1 + C_{V_L}} \equiv a_\Gamma e^{i\delta_X}$$

For $m_\ell = 0$ freedom of choice: $\delta_T = 0$

# Fit Results

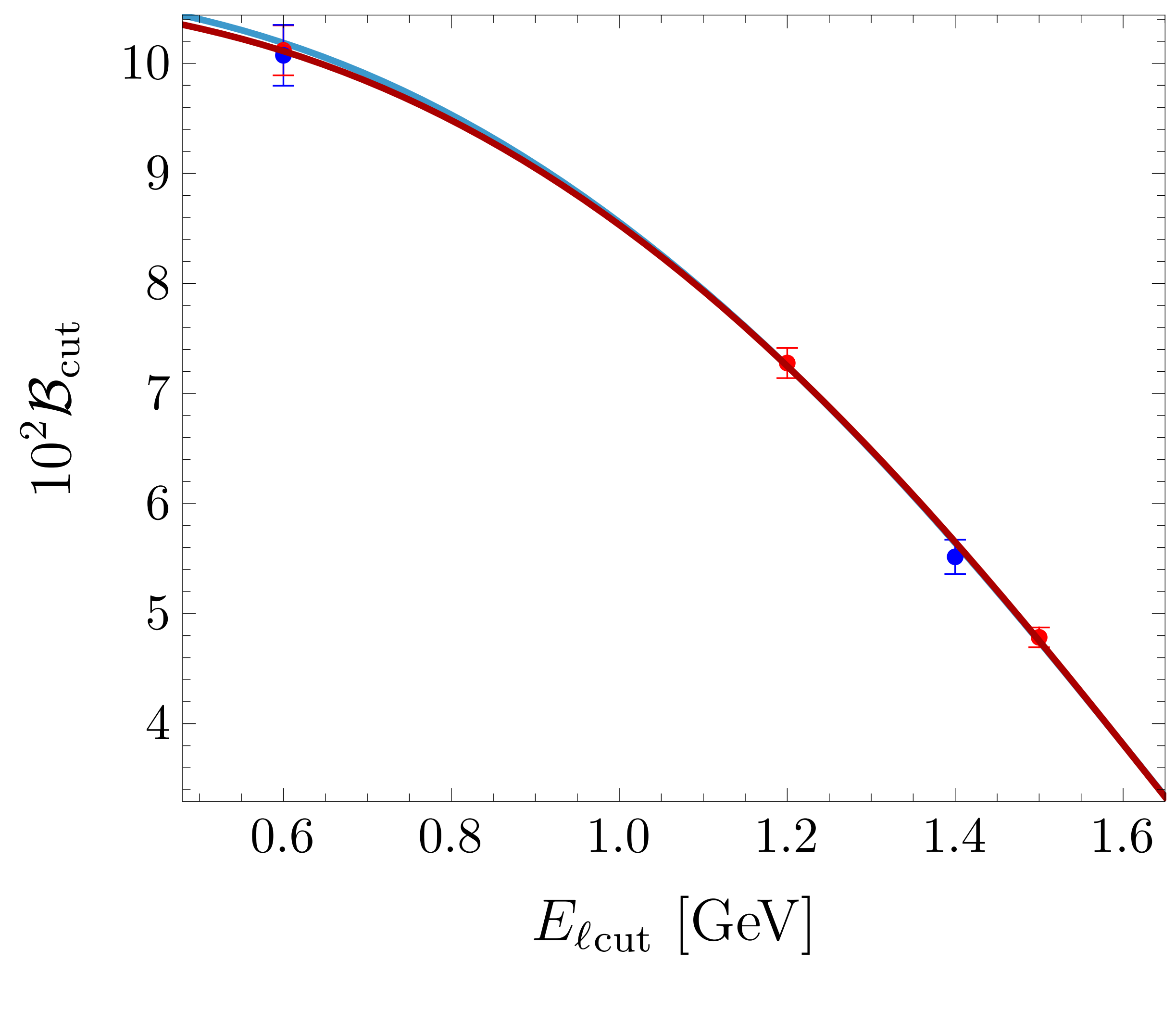
## With agnostic New Physics

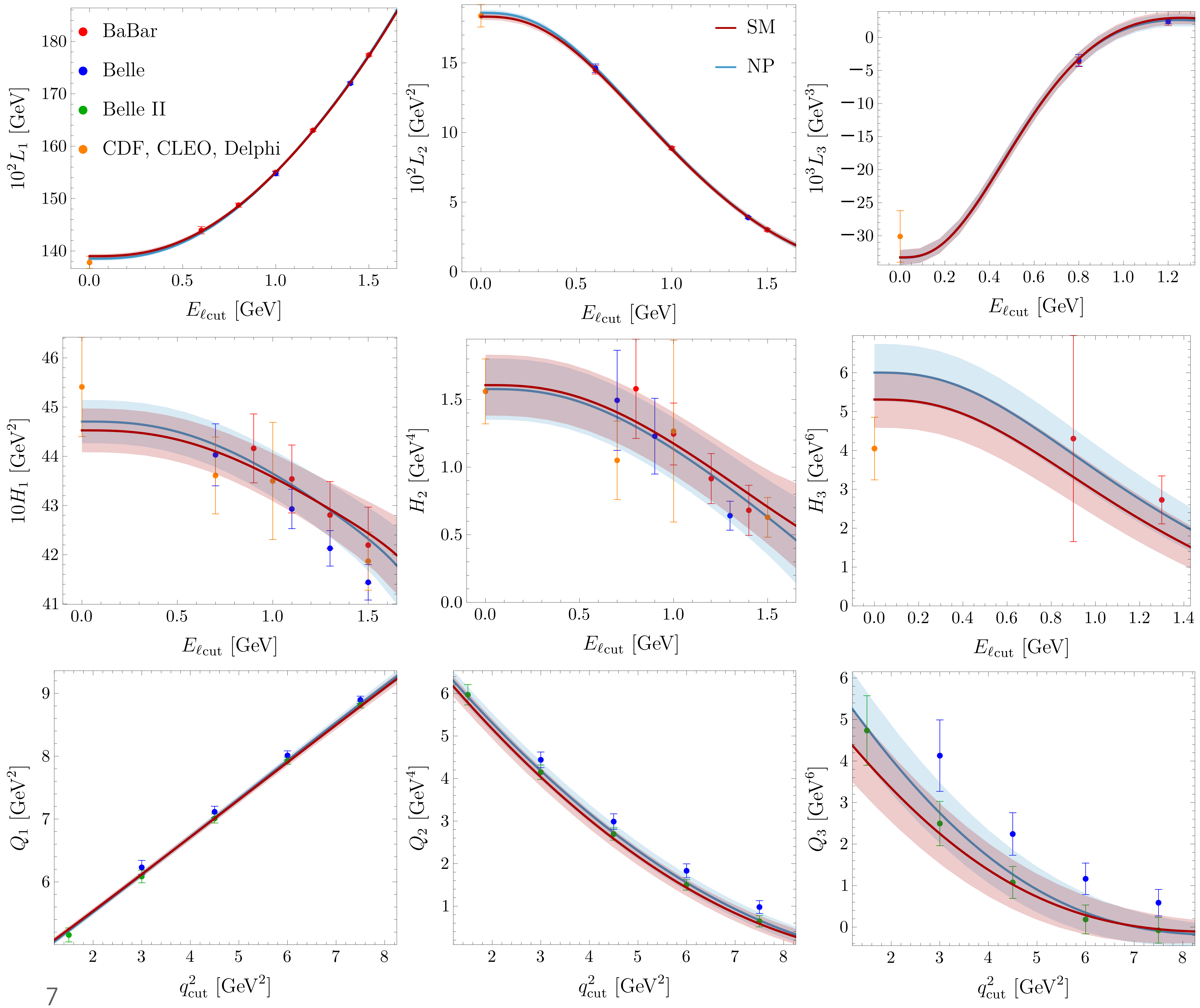
$\chi^2_{SM}/\text{d.o.f.} = 42.58/74$

↓

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

SM compatible with the NP fit at the $0.7\sigma$ level. No preference for NP.



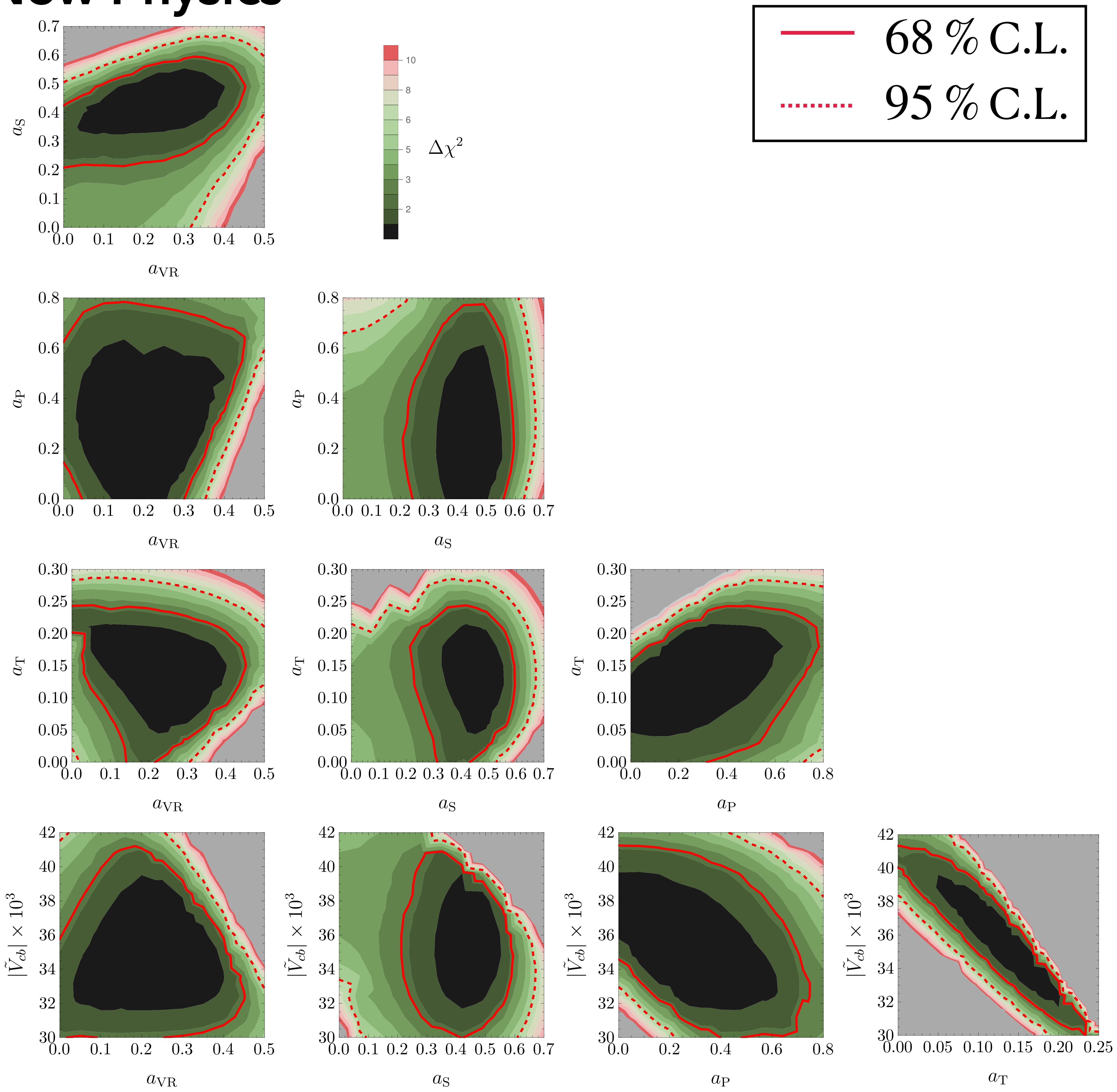



# Fit Results

## With agnostic New Physics

- HQE parameters and quark masses 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:

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



# Semi-Numerical Results

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

« 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 $|\tilde V_{cb}|$
$a_P \sim 3a_T$ $\quad c(\delta_P) = 1$ $\quad a_P$

# 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 ($C_T, C_{S_L} = -7C_T$)

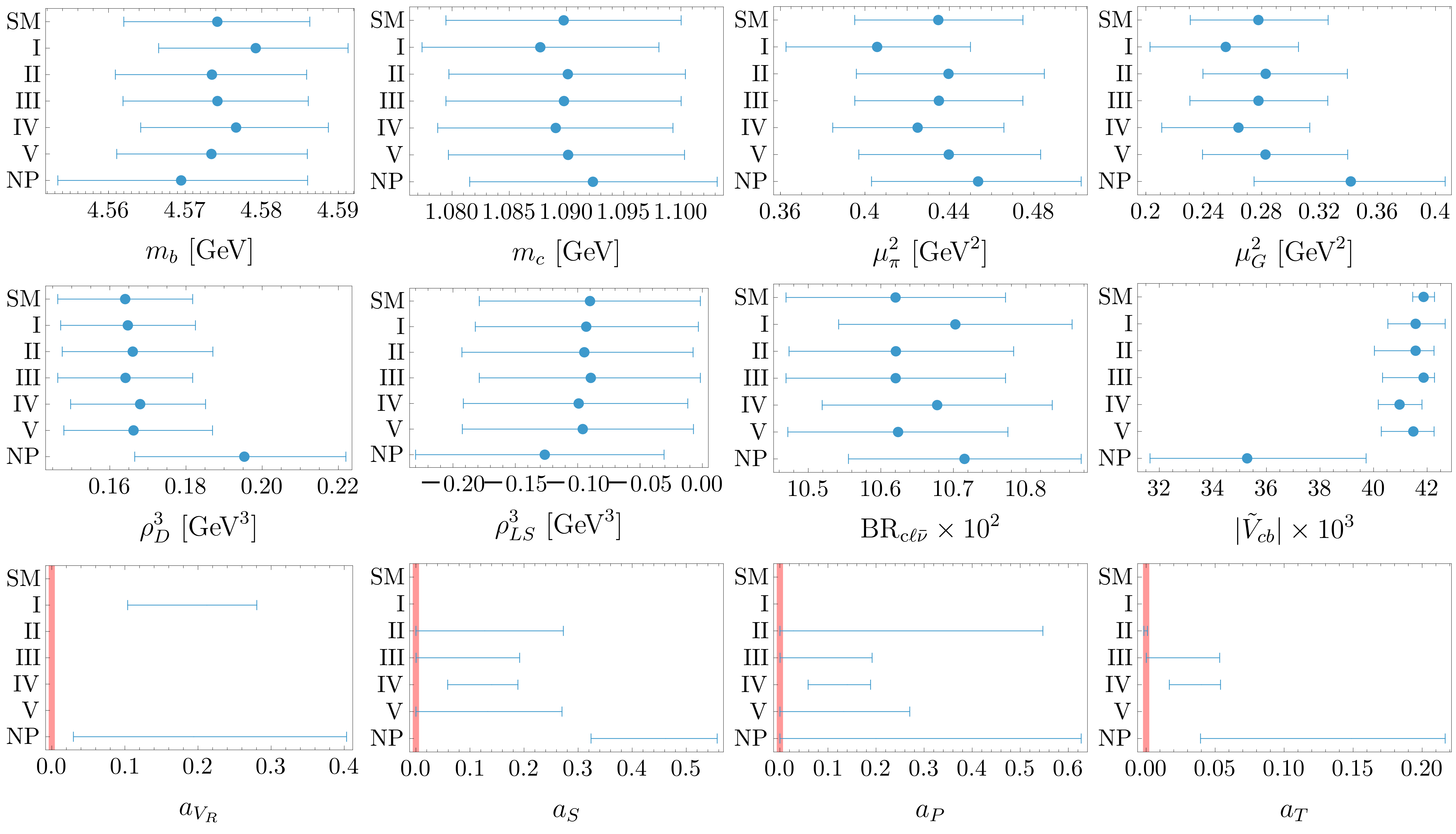
IV - $R_2$ LQ ($C_T, C_{S_L} = 7C_T$)

V - $U_1$, $V_2$ LQ ($C_{S_R}$)

NP - All WCs

68% C.L. interval

Best-fit point

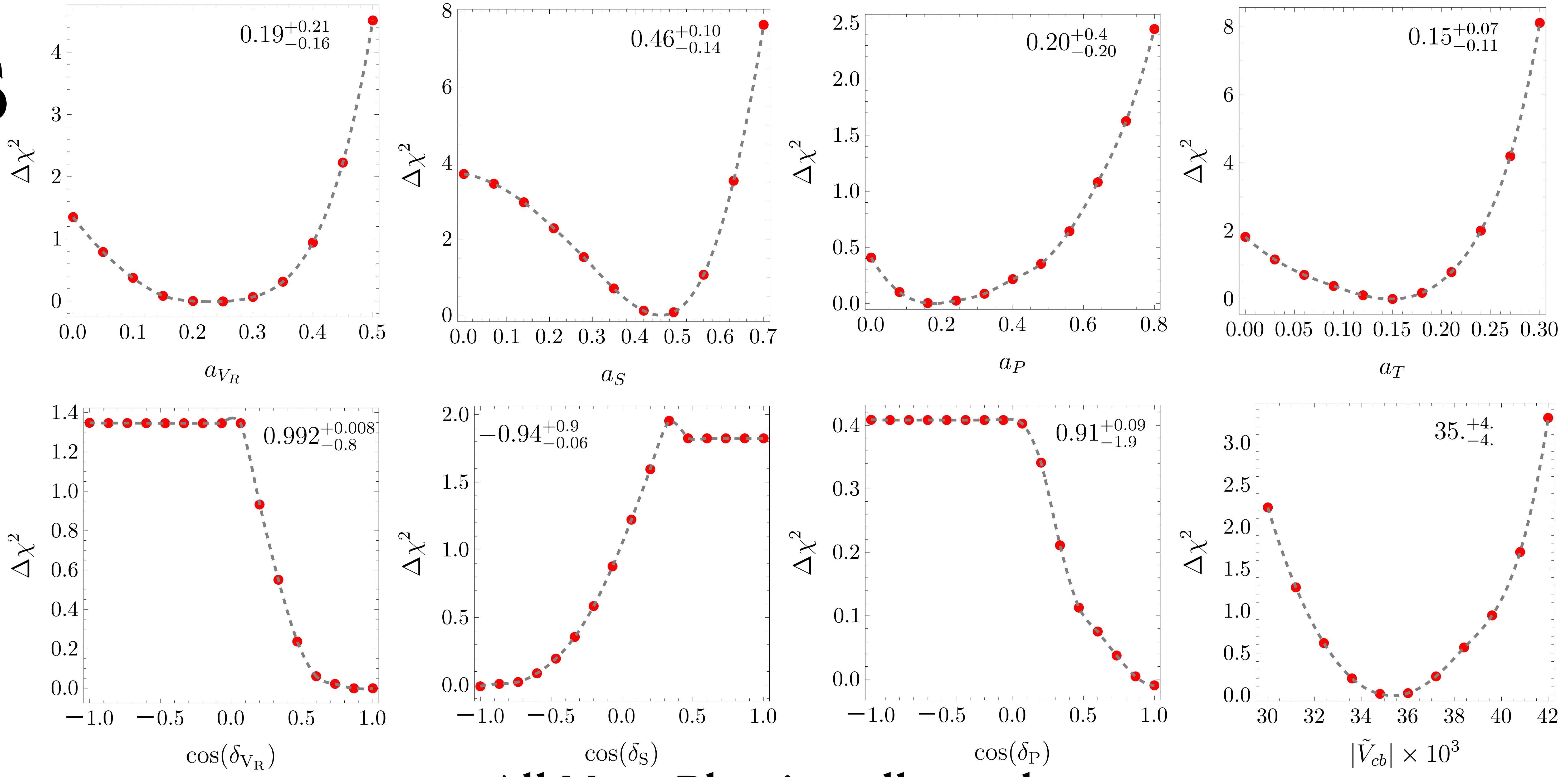



« Flat direction » in the fit for $a_S \sim 3a_T$ and $c(\delta_S) = -1$ found at the best fit point for $a_S, a_T$ in 'NP'

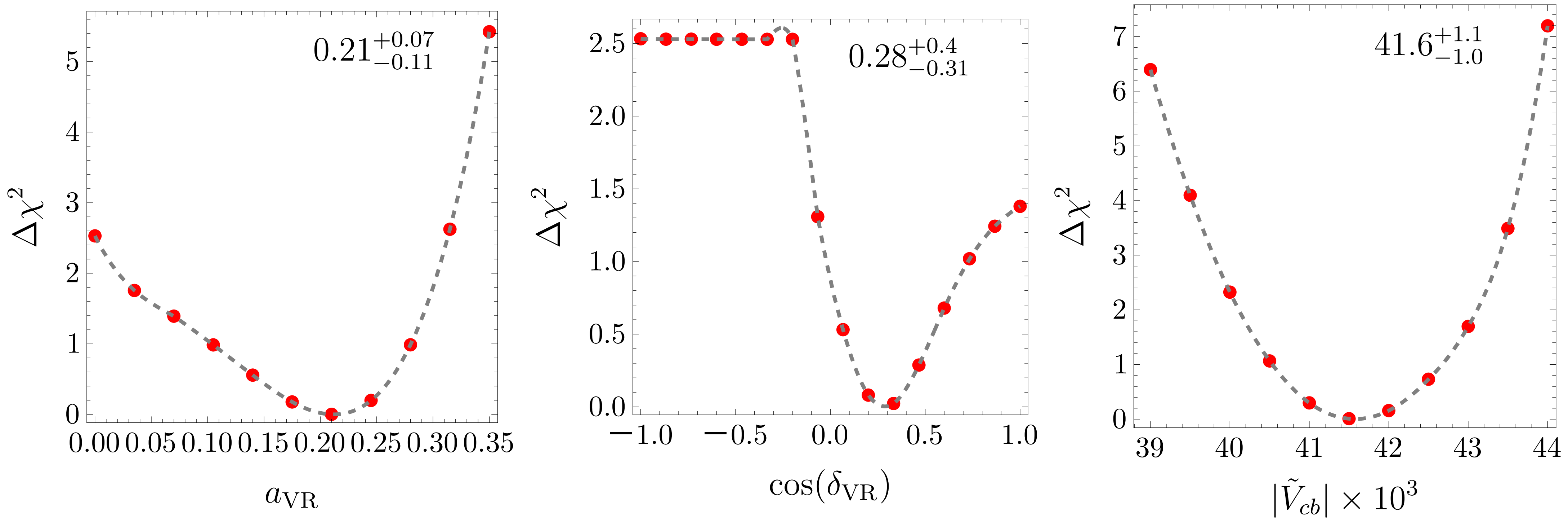
Most distributions are non-Gaussian

# 1D profile likelihoods

- 1D profile likelihoods of WCs are non-Gaussian
- E.g. $a_S$ ($a_{V_R}$) is compatible with 0 at the $2\sigma$ 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

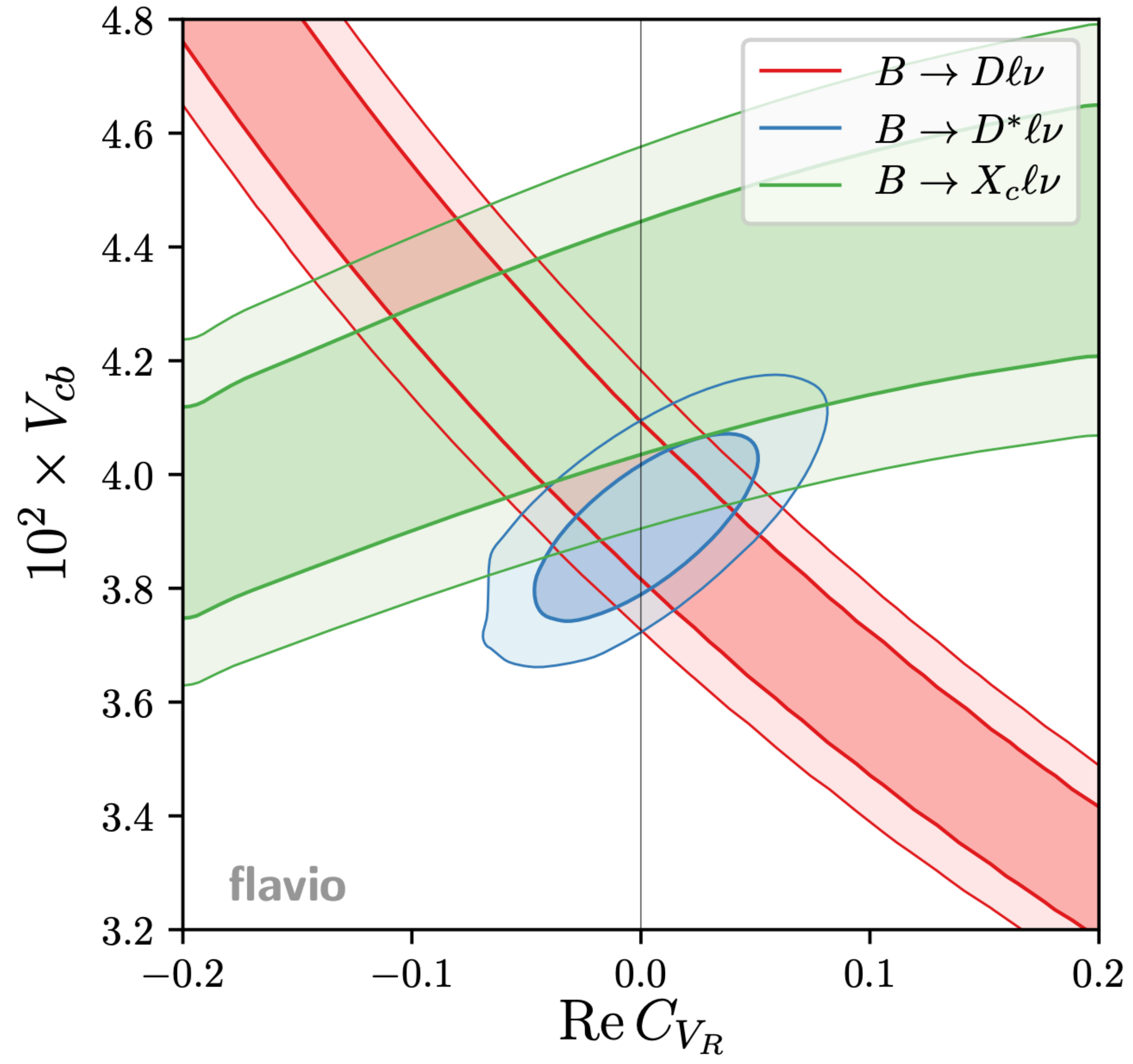





Scenario I

# Back to the Vcb puzzle

E.g. for NP in $Re(C_{V_R})$

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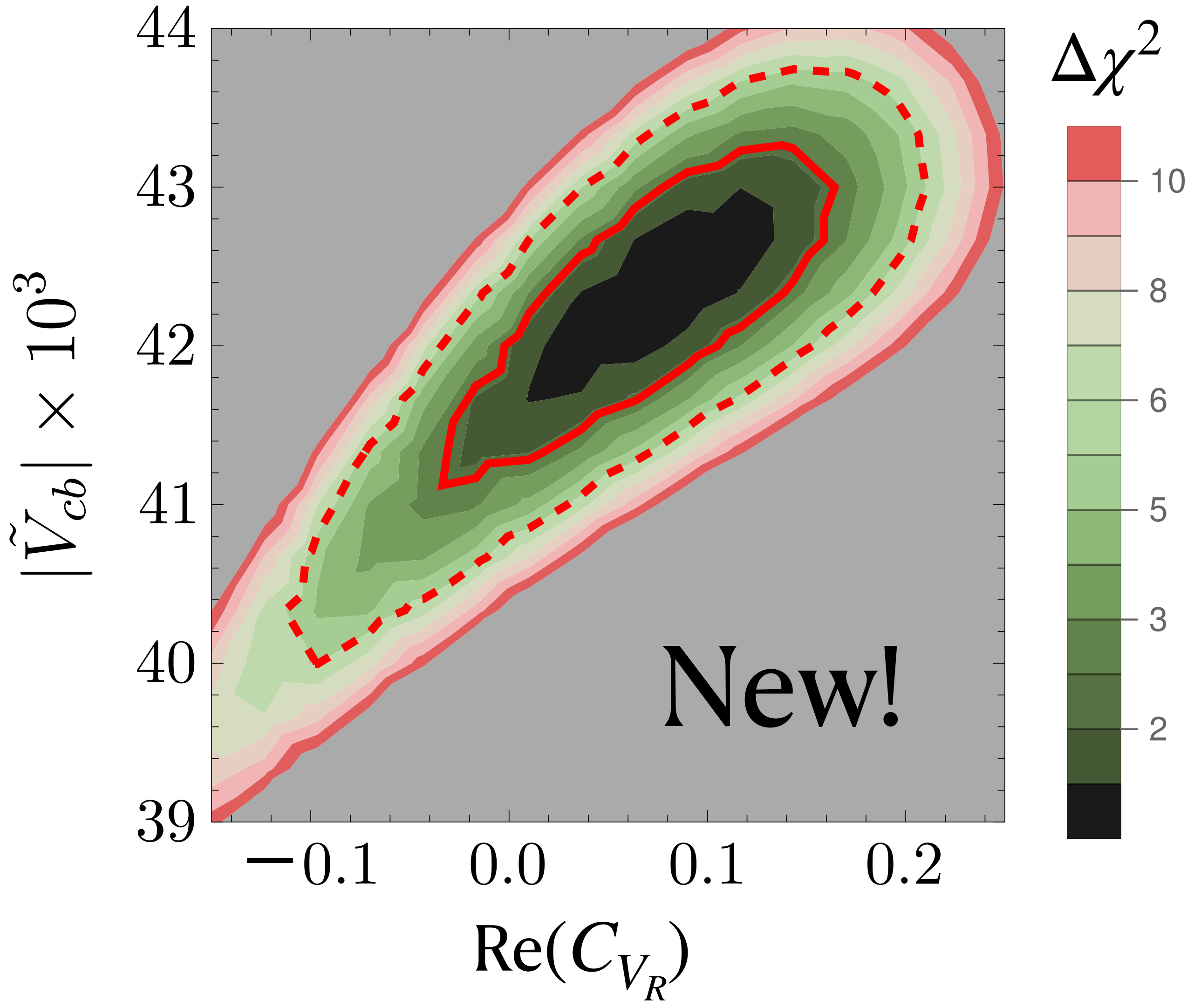
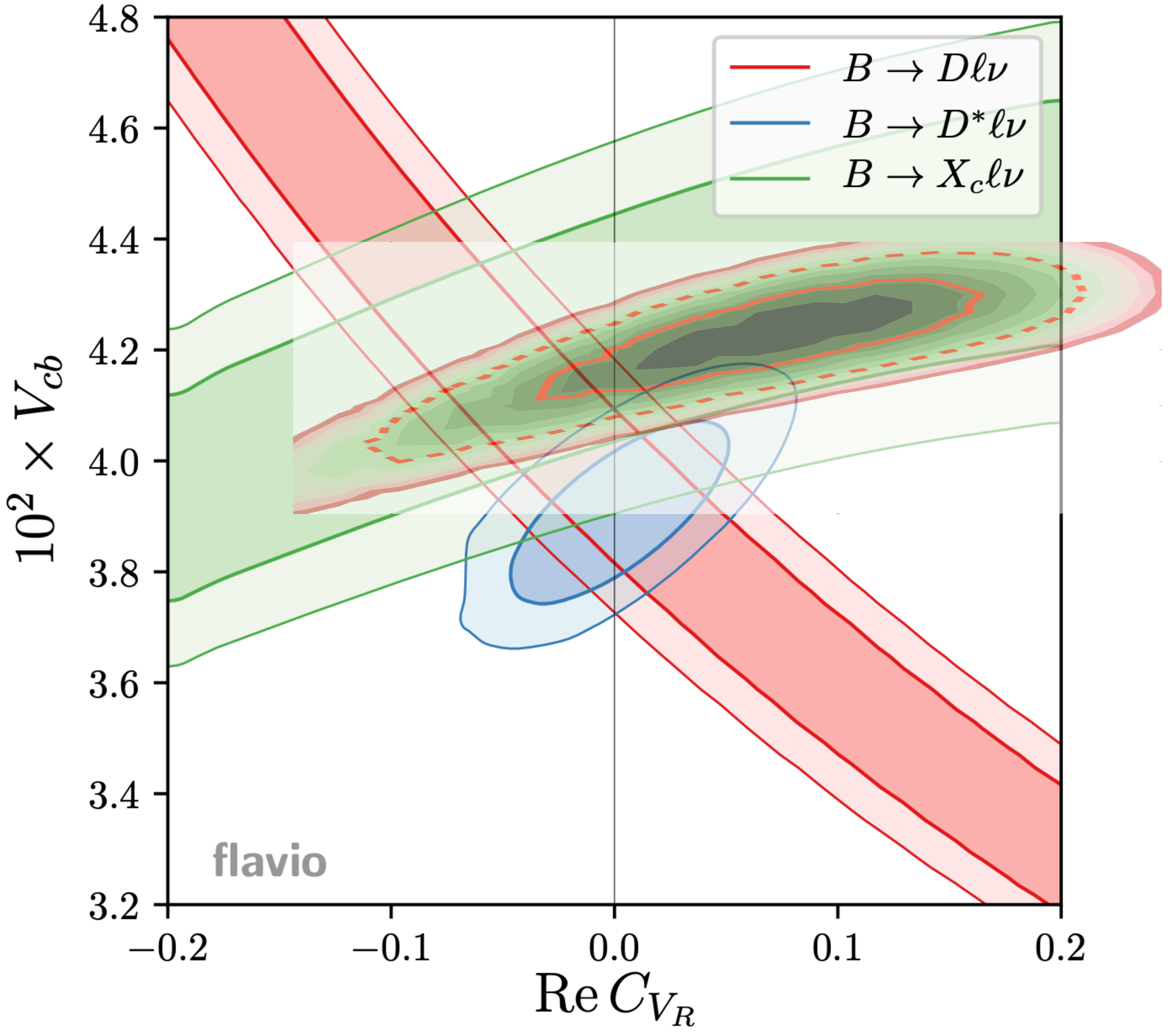



68 % C.L.
95 % C.L.



# Outlook

- We perform a state-of-the-art calculation of $B \to X_c \ell \bar{\nu}$ with New Physics
  - First global fit of inclusive $B \to X_c \ell \bar{\nu}$ with model-independent New Physics
  - Provide new competitive constraints on New Physics in $b \to c \ell \bar{\nu}$ transitions
- Perspectives:
  - $\mathcal{O}(\alpha_s)$ radiative corrections to all New Physics contributions
  - Global fit including exclusive $b \to c \ell \bar{\nu}$ decays

Thank you!

# Appendix

# Hadronic Tensor Structure

- We provide a (non-trivial) minimal form for the decomposition of the hadronic tensor, based on symmetries in the Lorentz indices and behavior under time-reversal.

$$
\begin{aligned}
W_{\mathbb{1},\mathbb{1}} &= w_0\,, \\
W_{\gamma^\mu,\gamma^\nu} &= -g^{\mu\nu}w_1 + v^\mu v^\nu w_2 + i\epsilon^{\mu\nu\alpha\beta}v_\alpha \hat{q}_\beta w_3 + \hat{q}^\mu \hat{q}^\nu w_4 + (\hat{q}^\mu v^\nu + \hat{q}^\nu v^\mu)w_5\,, \\
W_{\sigma^{\kappa\lambda},\sigma^{\rho\sigma}} &= (v^\kappa \hat{q}^\lambda - v^\lambda \hat{q}^\kappa)(v^\rho \hat{q}^\sigma - v^\sigma \hat{q}^\rho)w_6 + \left(g^{\kappa\rho}g^{\lambda\sigma} - g^{\kappa\sigma}g^{\lambda\rho}\right)w_7 \\
&\quad + \left[v^\kappa\left(v^\sigma g^{\lambda\rho} - v^\rho g^{\lambda\sigma}\right) - v^\lambda\left(v^\sigma g^{\kappa\rho} - v^\rho g^{\kappa\sigma}\right)\right]w_8 \\
&\quad + \left[\hat{q}^\kappa\left(\hat{q}^\sigma g^{\lambda\rho} - \hat{q}^\rho g^{\lambda\sigma}\right) - \hat{q}^\lambda\left(\hat{q}^\sigma g^{\kappa\rho} - \hat{q}^\rho g^{\kappa\sigma}\right)\right]w_9 \\
&\quad + \Big[g^{\kappa\sigma}\left(v^\lambda \hat{q}^\rho + v^\rho \hat{q}^\lambda\right) - g^{\lambda\sigma}\left(v^\kappa \hat{q}^\rho + v^\rho \hat{q}^\kappa\right) \\
&\qquad - g^{\kappa\rho}\left(v^\lambda \hat{q}^\sigma + v^\sigma \hat{q}^\lambda\right) + g^{\lambda\rho}\left(v^\kappa \hat{q}^\sigma + v^\sigma \hat{q}^\kappa\right)\Big]w_{10} \\
&\quad + i\left(v^\kappa \epsilon^{\lambda\rho\sigma\alpha} - v^\lambda \epsilon^{\kappa\rho\sigma\alpha} + v^\sigma \epsilon^{\kappa\lambda\rho\alpha} - v^\rho \epsilon^{\kappa\lambda\sigma\alpha}\right)(w_{11}v_\alpha + w_{12}\hat{q}_\alpha) \\
&\quad + i\left(\hat{q}^\kappa \epsilon^{\lambda\rho\sigma\alpha} - \hat{q}^\lambda \epsilon^{\kappa\rho\sigma\alpha} + \hat{q}^\sigma \epsilon^{\kappa\lambda\rho\alpha} - \hat{q}^\rho \epsilon^{\kappa\lambda\sigma\alpha}\right)(w_{13}v_\alpha + w_{14}\hat{q}_\alpha)
\end{aligned}
$$

$$
\begin{aligned}
W_{\mathbb{1},\gamma^\mu} &= \hat{q}^\mu w_{17} + v^\mu w_{18}\,, \\
W_{\mathbb{1},\sigma^{\rho\sigma}} &= i(v^\rho \hat{q}^\sigma - v^\sigma \hat{q}^\rho)w_{19} + \epsilon^{\rho\sigma\alpha\beta}v_\alpha \hat{q}_\beta w_{20}\,, \\
W_{\gamma^\mu,\sigma^{\rho\sigma}} &= i(g^{\rho\mu}v^\sigma - g^{\sigma\mu}v^\rho)w_{21} + i(g^{\rho\mu}\hat{q}^\sigma - g^{\sigma\mu}\hat{q}^\rho)w_{22} + i(v^\rho \hat{q}^\sigma - v^\sigma \hat{q}^\rho)(v^\mu w_{23} + \hat{q}^\mu w_{24}) \\
&\quad + \epsilon^{\mu\rho\sigma\alpha}(v_\alpha w_{25} + \hat{q}_\alpha w_{26}) + \epsilon^{\rho\sigma\alpha\beta}v_\alpha \hat{q}_\beta (v^\mu w_{27} + \hat{q}^\mu w_{28})\,. \qquad (2.10)
\end{aligned}
$$

# $\tilde{V}_{cb}$ vs complex $C_{V_R}$